

An Inventory on Black Carbon and Organic Carbon Emission by the Different Vegetative Ecosystem Over India

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Abstract

Fires provoke land degradation, deforestation, imbalance in the ecosystem, and promote changes in land use. To add more vein aerosols such as Black Carbon (BC) and Organic Carbon (OC) were emitted during the combustion event which plays a major role in climate change, pollution, and health. Hence this study aims to estimate the emission, residence, dry deposition flux, and sequestering ability of deposited BC and OC from different vegetative fires across India using MODIS satellite data from 2013 to 2019. It was observed that the mean OC and BC emission were about 5.08×10^7 tonnes 4.48×10^6 tonnes during the fire season across India. On a national scale, cropland fires contributed the largest portion (80%) of total carbonaceous aerosol emissions from open fires. In co-emission of species, forest shares a maximum relationship (> 92 percent) among carbonaceous aerosols. Estimation of deposition flux of emitted species showed cropland has higher deposition rates with a residence period ranging between 7hours to 23days. From the observed results, it is evident that higher aerosol emission combined with negligible deposition will be a potential threat to the environment. Waste utilization promoting strategies has to be adopted in India since agriculture contributes to major aerosols emission.

Introduction

Since the rise of vascular plants on the earth, fires became a natural occurrence and a major threat to the terrestrial ecosystem. In the earth system, fire is an integral component, and it has a complex relationship with climate and influencing changes in the environmental attributes, particularly the carbon cycle ^{1,2,3,4}. Emission from a forest fire is considered one of the major sources of air pollution, and these emissions generate trace gases and aerosols that have both immediate and long-term effects on the atmosphere⁵. The global carbon cycle receives potential feedback from terrestrial ecosystem fires, and carbonaceous aerosols such as black carbon (BC) and organic carbon (OC) are found to be a major portion of such wildfire emissions⁶.

BC is formed out of incomplete combustion. BC is a short-lived climate forcer considered second only to carbon dioxide, forcing +1.1W/m² ^{7,8}. In contrast, OC formed during gas to the particle conversion process⁹ can also impact climate by forming cloud droplets by acting as cloud condensation nuclei and by direct scattering of light¹⁰. The source of BC and OC is highly variable with time and space and is also regionally dependent based on the region's characteristics¹¹. Notably, these aerosols can play a vital role in climate mitigation by serving as a long-term sink for carbon dioxide and cryosphere evolution when deposited into the terrestrial carbon pool¹².

In Asia regions, the characterization of aerosol and Greenhouse Gases (GHG) emissions in the environment and climate have been studied by conducting several international and national field experiments such as INDOEX^{13,14}, ACE-Asia¹⁵, TRACE-P¹⁶, APEX¹⁷, and EAREX¹⁸. However, aerosol deposition studies have not focused on these regions, even though vital in climate mitigation and policymaking. The deposition is a complex process that depends on aerosol properties, land surface

characteristics, and micrometeorological conditions. Modelling studies are predominant in the aerosol deposition flux and lifetime studies. However, modelled studies show limited skill in simulating aerosols' spatial distribution, especially in mid to upper tropics. It has resulted in faster aging, higher scavenging ratio by both dry and wet deposition in the Asian continent^{19,20,21}. The deposition of BC and OC occurs by wet or dry deposition mechanism into the terrestrial or aquatic ecosystem is known as a sink.

A carbon sink is an important factor in the climatic negotiations globally as they have adopted markets for carbon trading since the Kyoto protocol²². Globally, the land ecosystem dominates the anthropogenic sink of carbon by 30%, followed by the ocean accounting for 25%, and the remaining emanated particles and gases stay in the atmosphere²³. Carbon stock (drawn down carbon) varies across forest types, with tropical forest accounting for a stock of 303 tonnes of carbon per hectare, followed by temperate (66 ton/ha) and boreal forests (44 ton/ha)²⁴. However, to date, quantification of the tropical land sink and sources were not spatially and temporally explicit²⁵. The Indian forest's Carbon stock is 6941 million tonnes as of 2011²⁶.

Estimating the burned area is essential in quantifying the impact of emissions on climate-carbon cycle feedback, especially during the climate emergency era of the twenty-first century²⁷. Historically, burned area information is based on ground estimates of fires reported by the fire management team²⁸. Countries' methods to calculate emissions are based on data collected, which were unreliable on global and continental scales. Unearthing the burned area through satellite served as a better alternative to older techniques, especially after satellite-based observation in 1974. Fire emission estimates have been continuously progressing since then, and the values used were best-guessed values of average annual area burned, the efficiency of burning, and biomes density^{29,30}.

India has been adopting strategies to increase the carbon sink by approximately three billion tonnes to combat climate change³¹ because the annual mean temperature will rise by 2.5°C to 4°C in India by the end of the century³². However, a lack of knowledge prevails in understanding the long-term and inter-annual interaction between fire and carbon flux as the effects of altered fire regime on soil carbon, nutrient storage, or limited plant productivity exist. The potential for utilizing satellite-based observation to overcome the aspects mentioned above is widely recognized. Based on our literature for the first time across India, this study addresses the deposition flux and residence time of carbonaceous aerosol. Hence, this study aims to address the following objectives 1) To address fire trends across different land cover types and major contributors to the highest vegetation fire concentration. 2) To estimate carbon stock in burned land cover across study region 3) Understanding the deposition flux of biomass burning aerosol during the study period. These results help us understand fire management, carbon dynamics, climate mitigation, and other related issues.

Results And Discussion

The aerosols emitted during the fire event is majorly composed of BC and OC. Emission of BC and OC from different vegetation types is studied from the year 2013-2019, respectively.

BC and OC emission of different vegetative types

The emission scenario of different plant cover types is shown in Supplementary Fig. (1). From this Fig., we observe that the major components burned in fires are croplands (agricultural and natural crops), which share 80% of the total emission. Forest was next to it with a share of 3-14% of the total burned area, contributing to aerosols emission. While shrubland involves emissions from burning, which is not significant and shows a shrinking trend from 2017 to 2019. The major contribution of cropland to the overall burned area is that India is one of the largest producing countries globally and also evident with its agricultural fire accounting for 43–57% of all cropland fires⁵⁰. A study on Greenhouse gas inventory in Thailand also indicated similar results of more than 80% of emissions by the agricultural sector⁵¹. The decrease in forest fires contribution maybe because of land clearing for collecting Mahua (Madhuca Indica) flowers and the shifting cultivation by the tribal community, which accounts for 23% of annual deforestation in India⁵².

Cropland ecosystem

Cropland emission of BC ranges from 5.16×10³ kg/year to 15.26×10¹⁵ kg/year. The mean BC emission in cropland ecosystem is found to be 2.19×10⁶ kg (2013), 1.31×10¹⁴ kg (2014) 1.01×10⁶ kg (2015), 1.7×10^6 kg (2016), 9.66×10^{12} kg (2017), 1.7×10^6 kg (2018) and 1.5×10^6 kg (2019) respectively. While OC emission varies as 2.56×10^7 kg (2013), 1.53×10^{15} kg (2014) 1.02×10^7 kg (2015), 1.98×10^7 kg (2016), 1.03×10^{13} kg (2017), 1.13×10^{7} kg (2018) and 1.75×10^{7} kg (2019) respectively. The observed variations show that a peak BC concentration is found during 2014 (5.09 ×10¹⁰ Kg), and the lowest BC concentration is observed in the year 2018 with an emission of 3.52 Kg. Similarly, mean OC ranges from 9.03×10⁷ Kg to a maximum of 1.3×10¹⁵ Kg (2014). The reason for the highest recorded BC and OC emission is due to the dry fires⁵³ and the meteorological condition with an annually-averaged temperature hike (0.69°C), making 2014 the warmest year since 1888⁵⁴. Land under cultivation must be considered for reducing emission during 2015 and 2018 as 1.5%, and 2% of the land areas under cultivation were reduced in 2015 and 2018, respectively. It may be caused due to a reduction in rainfall, leading to crop loss during agricultural seasons⁵⁵. A similar satellite study conducted between 1950-2015 across Asia has estimated mean BC (3.89Tg) and OC (6.92Tg), which vary by a factor of ten to the power of five compared to our results⁵⁶. The relationship between BC and OC emission is studied using multiple regression analysis. The regression coefficient (R²) returns a value of fifteen percent showing a lesser significant contribution by OC towards BC emission, which is a characteristic of residential biofuels and agricultural is burning⁵⁷. ANOVA test was carried out to verify the significance of the difference between groups. In the cropland ecosystem, there was a statistically significant difference between the groups of BC and OC groups during the study period as determined by one-way ANOVA (F (6, 14615) =79.702, p=0.001. The emission trend of mean BC and OC in the cropland ecosystem is shown in Fig 1.

Forest ecosystem

BC emission ranges from 2.16×10^7 Kg to 2.9×10^9 kg, and OC is from 1.86×10^8 kg to 2.5×10^{10} kg during the emission events in the study period. The mean BC emission in forests is increasing consistently with each year from 2.16×10⁷ kg (2013) to 2.9×10⁹ kg (2019), respectively. While mean OC emission is found to be 1.31×10¹⁰ kg with a high concentration of 2.5×10¹⁰ kg (2019) and minimum concentration in 1.86 ×10⁸ kg (2013), respectively. Forest cover is observed to decline from 2013 (1.83%) -2015(1.2%), which serves as a major reason for the decline in fire-related emissions⁵⁸. Fire incidents in the forests tended to increase during 2015-2019 due to low priority in managing anthropogenic fire as funds to be spent on fires are reduced⁵⁹. As per the Indian State of Forest Report, the major contributors of a forest during our study period were people who indulge in clearing activities for purposes like cultivation, non-timber forest produces collection, and hunting/poaching purposes. The annual average aerosol emission from forest fires in China was 2.7 Gg, and 27.4 Gg for BC and OC is significantly less than our dry seasonal average emissions⁶⁰. In a continental context, a satellite study put forward the emission of BC (2.3×10⁷kg/year) and OC (2.3×10⁷kg/year) from open non-agricultural fires, which is significantly less than our obtained results of BC (4.16×108 kg/year) and OC (4.84×10⁹ kg/year) respectively⁶¹. The emission returns a significant relationship between the organic and BC with a regression coefficient of R^2 =0.92, p=<0.01. It suggests that the co-emission ratio of OC and BC is high in India's forests. Further, the mean annual OC (1.31×10⁹ kg) is found to be higher than BC (1.50×10⁸ kg), and this ratio is a general characteristic of forest emission⁶². A study ANOVA test was carried out to verify the significance of the difference between group and in forest ecosystem there was a statically significant difference in the emission of BC and OC is observed during the study period as determined by one-way ANOVA (F (6, 1499) =149.026, p=0.001. The emission trend of mean BC and OC in a forest ecosystem is shown in Fig. 2.

Shrubland ecosystem

Emission of mean BC shows a high spike during the emission events in the year 2014 (3.02×10⁹ kg) and 2017 (2.07 ×10⁷ kg) and then attains a lower bound emission in 2013(1.2×10⁴ kg) and 2015 (1.28×10⁴ kg). While OC ranges from 2.8×10⁸ kg to 8.62×10⁴ kg with upper peak emission in 2017(1.17×10⁸ kg) and bottom peak in 2019 (8.62×10⁴ kg) during the dry season in 2013-2019, respectively. A similar inventory study on shrubland emission using a smaller grid satellite data observed BC (19.4×10³ kg) and OC (13.76×10⁵ kg) as their annual emissions, which are found to be ten times lesser than our emission⁶³. The mean BC and OC emission have a healthy relationship of seventeen percent at a confidence level of 95 percent. We hypothesize that due to much lesser natural fires and a lack of human intervention in forest bush fires during the dry season in the study period. ANOVA test was carried out to verify the significance of the difference between groups and in the shrubland ecosystem. There was a statistically significant difference between the emission of BC and OC during the study period as determined by one-way ANOVA (F (6, 1499) =24.501, p=0.001. The emission trend of mean BC

and OC in the shrubland ecosystem is shown in Fig. 3. A satellite-based global estimated value for Southeast Asia was 5.14×10^{20} kg/year (BC) and 5.3×10^{21} kg /year (OC), respectively⁶⁴. While our results show 3.04×10^{10} kg/year (BC) and 3.53×10^{11} kg/year (OC), which is ten times less than the estimates as it covers the entire region of southeast Asia, but in individual terms, it offers a significant contribution.

A regional analysis of emissions

A Geospatial analysis

The spatial analysis of OC and BC emission in kilograms during 2013-2019 is done using the Geographical Information System (GIS), which is presented as Fig. 4 and 5. The emission is segregated into grids, with each grid covering 27.75 km across the country. The emission is segregated into low (1.09-2.6), medium (2.69-6.11) maximum (greater than 71.2), and no emission (0-1.9). The estimated mean BC and OC emission for India from total biomass burning is around 1.98×10⁷Kg and 1.59×10⁸ Kg for the base year 2013. A significant increase in species emission is observed in the advancing years with 5.73×10¹³ Kg of BC and then 3.06×10¹⁴ Kg of OC until 2017, which then showed a declining trend. Since 2016 stringent enforcement of a ban on stubble burning by the government made major agricultural regions reduce its stubble count from leading to a reduction in emission, which is estimated based on a satellite study by NASA (https://www.downtoearth.org.in/news/air/stubble-burning-down-in-punjab-haryana-up-since-2016-nasa-maps-68331).

Region-wise analysis of BC and OC emission by different vegetation types is presented in Supplementary Table 1. Overall state-wise analysis of BC and OC indicates that Andhra Pradesh has the maximum amount of emission, followed by Arunachal Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Jharkhand, Karnataka, and Kerala. Cropland fires are high in states like Gujarat, Chhattisgarh, Odisha, Madhya Pradesh, Bihar, Tripura, Uttar Pradesh, and Andhra Pradesh. These regions are cultivating six major crops produced in India⁶⁵. The states that accounted for the high cropland emission are the states with high population density and hold the most fertile land for agriculture⁶⁶. Forests share the next major emission of BC and OC in India with the increasing wildfires during the dry season every year. Manipur, Meghalaya, Uttarkhand, and Tripura shares maximum emissions during the study period. These regions come under moist deciduous forest types that are subjected to frequent fires⁶⁷. Uttarkhand is the youngest mountain region of the Himalayas, mainly experiencing annual forest fires, which have worsened during our study period, especially in the year 2016⁶⁸. In a study, the highest concentration of emerging intensified fire hotspots is found in the northeast and central India, which is substantiated by our results⁶⁹. Shrubland fires are frequently observed in the regions of Telangana, Himachal, Jammu& Kashmir, Bihar, and Tamil Nadu. Further, megacities like Mumbai, Delhi, Chennai, and Kolkata are also observed to have higher emissions of OC and BC, which is due to the industrial and high vehicular emissions^{70,71}.

Temporal analysis of emission

BC and OC concentration during biomass burning events for, 2013-2019 are displayed in Supplementary Fig. 2 and 3. Similarly, BC's emission is studied during India's fire season, i.e., January to June, shown in Supplementary Fig. 4 and 5. The highest BC emission is observed in March with 5.37×10⁶ kg (2018), followed by 4.91×10^6 kg (2016). For April, it is pointed at 4.30×10^{14} kg (2014) and 4.80×10^6 kg (2017). While May records emissions of 1.94×10^6 kg (2016), 6.51×10^5 kg (2017), and 5.77×10^5 kg (2018), respectively. Similarly, OC records 2.68×107 kg to 1.93×107 kg between 2018 and 2014, respectively. For April, the mean OC emission ranges from 6.55×10⁴ kg to 2.56×10⁷ kg (2014 and 2017), and then it hikes to 9.64×10⁶ kg (2016) 1.84×10¹⁵ kg (2017) in May. Overall, the carbonaceous aerosol emission is high from March to May, especially with higher fire events between 2014 and 2017. As per the India State of Forest Report, India experienced a jump in forest fires by 125% during 2014-2017 in which most of them are non-dense forest areas. This pattern can be explained by the seasons of India. For forest regions, deciduous trees shed their leaves in January, which primes to add fuel load availability to the prevailing dry weather fires⁷². A Subside in emission is observed in June, which may be attributed to the onset of monsoon season as soil moisture increases due to rainfall. The results in reducing woodburning capacity by absorbing moisture in the woods⁵². However, for cropland fires, observed temporal variation of carbonaceous aerosol emission indicates that the emission is high during March (56%) to May (28%) for the entire study period, which is a stubble burning season in India, especially in northern parts of the country⁷³.

Carbon sequestration

The estimated carbon sequestration in cropland was found to be highest at 8.23× 1013 tonnes of carbon per hectare in 2019 with the leakage in 2015 (-4.21 \times 10¹¹ t/ha) and 2017(-1.54 \times 10¹² t/ha). Intensification of the crop in agriculture may result in loss of carbon stock in agricultural lands as the land area was reduced approximately two percent from 2015 to 2017⁵⁵. A modelling study also estimated the loss of carbon stock due to land-use intensification or agricultural land change³³. Agricultural activities such as fertilizer and manure addition contribute to the replenishment of carbon stock, favouring sequestration and long-term storage of OC in the cropland ecosystem during our study period⁷⁴. While in forest carbon sink is observed to be 4.10×10^{10} t/ha (2013), 9.18×10^{10} t/ha (2014), -8.10×10^{10} t/ha (2015), 1.77×10^{11} t/ha (2016), -5.60×10^{10} t/ha (2017), and 2.88×10^{10} t/ha (2018), -5.96×10^{10} t/ha (2019). In the Indian forest ecosystem, the carbon stock is found to be reduced after 2017, which is due to drought experienced for three years consecutive years in major forest regions^{75,76}. Besides, a reduction in dense forest cover of over 20,000 hectares, which is diverted for mining, thermal power projects, and wildfires, also serves as a major causative agent for the reduction in carbon stock after 2015⁵⁸. Similarly, in shrubland ecosystem carbon sink is found to increase consistently from 2013 $(4.89 \times 10^{10} \text{ t/ha})$, 2014 $(1.06 \times 10^{10} \text{ t/ha})$, 2016 $(2.15 \times 10^{11} \text{ t/ha})$ and 2018 $(2.76 \times 10^{11} \text{ t/ha})$ with leakage in 2015(-1.47 \times 10¹¹ t/ha), 2017(-2.78 \times 10¹¹ t/ha) and 2019(-1.01 \times 10¹¹ t/ha) respectively. Grasslands stock lays majorly on above-ground biomass, which dips down mainly because of fire, poor management, deforestation (direct effect), and shifting agriculture (indirect effect). For instance, 31% of

shrublands are lost in a decade by fire, deforestation, and fodder production as demand for feeding livestock has grown by 65%⁷⁷. Besides these, more than eighty percent of India's shrubland is in the poor range class that it is easily affected by weather and soil erosion⁷⁸. The carbon sink of different biomes is represented in supplementary Fig. 6. Carbon sequestration of the burned area accounts for enhancing or degrading the carbon deposits of a region. The estimated current annual carbon stock (CACS) varied between different ecosystems, plotted in Supplementary Table 2. Cropland deposits of carbon decrease consistently from the base year 2013 until 2015 and then the stock seems to improve gradually until 2019 from 1.25×10¹¹t of C per hectare to 1.13×10¹³ t of C per hectare. Similarly, in the shrubland ecosystem, carbon stock increased from 6.70×10⁹ t C/ha to 3.78×10¹¹t of C /ha until 2018 and then reduced to 137% in 2019. A higher variability is observed in forest ecosystem carbon stock reduced from 5.29×109 t of C per hectare to -8.16×10¹⁰t of C per hectare during 2013-2019. The total mean carbon stock of the vegetative ecosystem increased from 48% to 234% during 2013-2019, with dips in 2014-2015 (236%) and 2016-2017 (244%). Overall, the average carbon sink variability differs from yearly in our study, which agrees with a global study conducted in the terrestrial ecosystem using models⁷⁹.

Deposition flux of BC and OC

The size and properties of the BC particles determine the residence time and deposition flux. The deposition flux of BC particles is estimated for different land cover emissions and is calculated with a range of upper and lower limits. The estimated lower limit means deposition flux was observed to be highest in the cropland ecosystem with 0.47 kg of BC deposited per kilometre and 11.9 kg/km (OC) in a day for an atmospheric mean concentration 5.85×10^{10} kg. While upper limit extents to 0.55 kg/km/day (BC) and 11.9 kg/km/day (OC). Interestingly, minimum means deposition flux is observed in shrublands for an average BC concentration $(1.11\times10^5 \text{ kg/km/day})$ and OC concentration $(6.28\times10^6 \text{kg/km/day})$, which has a mean flux of 1.04×10^{-6} kg/km/day for BC, OC has 5.86×10^{-6} kg/km/day as the lower limit and 1.93×10^{-5} (BC) and 1.09×10^{-4} kg/km/day (OC) as the upper limit. Dry deposition flux is most suitable for particles having a higher aerodynamic size (<2.5µm), and the washout mechanism majorly removes sub-micron particles. The dry deposition value of small micron particles in the range of 0-2.5 and 1-2.5µm was $35\pm3\%$ and $21\%^{80}$. The BC and OC coarse particles are not considered.

Mean fluxes of BC deposition for seven years from 2013-2019 were 2.77×10¹Tg/year (BC) and 1.57×10² Tg/year (OC) for shrubland, 9.1×10¹ Tg/year (BC) and 1.41×10³Tg/year (OC) for the forest, and 1.41×10⁶ Tg/year (BC) and 3.1×10⁷ Tg/year (OC) for cropland ecosystem respectively. Overall, the mean deposition flux of BC and OC decreases with years with an exception in 2014. As our study is carried out during the summer season, where the low frequency of rainfall is observed leading to lesser deposition of carbonaceous aerosols and such a declining trend in dry deposition rate is observed across the globe. Global annually averaged dry deposited BC-based on model experiments vary from 0.66 to 1.66 Tg/year, which significantly differs with a ratio of 17.3:1 for shrubland, 56.8:1 for the forest more than a percent difference in cropland. This large variation may be attributed because discrepancies exist in modelling the submicron particles⁴⁷.

Aerosol particles may have individual varying residence time, and it fluctuates with space and time. BC's mean residence time constantly stood for the study period with 0.7 days for upper estimates in the cropland ecosystem while lower estimates fluctuated between 0.1day (4.4×10³ kg/km/day) to 23 days (6.4×10³ kg/km/day). However, shrubland and forest ecosystem emitted aerosols had a similar mean atmospheric residence time of 8.6 days. Deposition flux of BC over grassland and shrubland is estimated to be between 7-11 days, which best fits our results⁸¹. However, the global BC residence time to be 7.85 days, which is very much less than our prediction^{82,83}. The deposition flux of BC and OC is presented in Tables 1 and 2.

Conclusion

In this study, a high spatiotemporal resolution (monthly data in a 0.25° by 0.25° grid) emissions inventory was developed from biomass burning across India based on Fire CCI burned area data for a period of seven years from 2013-2019. The annual average emission of BC and OC emission from the different vegetative systems were assessed. Cropland contributes 1.34×10¹³kg and 1.52×10¹⁴kg as annual mean black and OC emission concentrated in central, north-western, and IGP of India. Forests share a significant emission of mean OC (1.3×1010 kg) and mean BC (1.52×109 kg) in Manipur, Meghalaya, Uttarakhand, and Tripura regions. In contrast, shrublands in hilly regions of the north and southern India are the least contributors with 1.69×108kg and 9.52×108kg of mean black and OC emission respectively. On a national scale, cropland fires contributed the largest portion (80 %) of total carbonaceous aerosol emissions from open fires. Forest fires and shrubland fires ranked second and third places, accounting for 14 % and 6 %, respectively. Individual crop contribution towards agricultural emission is assessed in which wheat serves as a prime contributor with a share of almost ninety percent of total agricultural emission. the co-emission of species, forest shares a maximum BC and OC emission with a relationship greater than 92%. Temporally maximum total aerosol emission is observed in 2014 and a minimum in 2018 with the frequent fire events. The monthly variation of black and OC emission had its peak from March to May of the dry season. The resultant means dry deposition fluxes of BC and OC emission for seven years from 2013-2019 were 1.01×10⁻⁵ kg/km/day and 5.74×10⁻⁵ kg/km/day for shrubland, similarly, 3.32×10⁻⁵ kg/km/day and 5.13×10⁻⁴ kg/km/day, for forest 5.14×10⁻¹ kg/km/day and 11 kg/km/day for cropland ecosystem respectively. The average residence/lifetime of BC emitted from other vegetative ecosystem fires is between 8.6 and 11.6 days. The above estimations were performed by employing appropriate emission factors for carbonaceous aerosols, which are in good agreement with the previous emission inventory studies conducted in India shown in Table 2. Human activities are the major cause of fires in the study region, coupled with natural events like lightning, climate-induced change, and meteorology. Therefore, OC and BC emissions must be mitigated by proper management of anthropogenic interventions leading to wildfire in forests and proper administration of land use, especially in croplands that cover most of India's land as it will lead to land degradation and erosion.

Uncertainties and future recommendation

This work-integrated many different datasets and formulae to estimate the emission of carbonaceous aerosols from wildfires and their carbon dynamics. First, appropriate emission factors were employed to calculate the emission from satellite observations, which may suffer limitations as it is not based on real-time activity data and uncertainties in India's monitoring of fires prevail. However, the factors used were in good agreement with the previous studies conducted in India. Earlier emission inventories studies in India are presented in table 2. Carbon stock and sink of the burned area are also estimated which are not a representation of the individual species, region, or type of fire. Further, estimated carbonaceous aerosol deposition is unlikely to contribute to the carbon stock especially in immediate years. This is a new learning process, conducted in terms of biomass emissions-based lifetime and deposition of particles across India. In general, the deposition velocity of the particle varies with space and time. Hence, we recommend carrying out continuous in-situ measurement of BC concentration and find out representative deposition velocity for that region, which will help reduce the limiting factors in radiative forcing and climate change studies. This study also recommends carrying out activity-based emission inventories across India to reduce the uncertainties in estimating carbonaceous aerosol emission.

Materials And Methods

Study area

India is a subcontinent covering a diversity of terrestrial ecosystems. It is located between 8°4′, 37° 6′N latitudes and 68°7′, 97°25′ E longitude. One of the rich biodiversity hotspots and the seventh-largest country in the world with a land area of 12 lakh square miles (3,286,592 Km2). It has the highest mountains in the north, the Thar desert to its west, the Gangetic delta to its east, and the Deccan plateau (agro-ecological diversity) to the south. It experiences drastic land-use changes, climate, topography, flora (11%), fauna (6.5%), and socio-economic conditions due to the ever-increasing population³³. because of the progressive increase in India's population to 1.27 billion, it has a decadal growth rate of 17.70 %³⁴. The increase in population facilitates food demand, making 70 % of rural livelihoods depend solely on agriculture³⁵. It holds 86 million hectares of agricultural land which is rain-fed and ranks to be one of the top countries in terms of agricultural production³⁶. Besides that, India having potential forest resources covering 70.6 million hectares³⁷ occupies an area of one-fifth of the territory in India with 1, 73,000 villages depend on forest resources for its livelihood³⁸.

Data

In this study, burned area product from Fire_CCI v5.1 (MOD09GQ) Collection 6 Images of 250 m spatial resolution³⁹ was used to define the burned area in India from 2013-2019. Gridded Fire_CCI v5.1 data is generated from the red and near-infrared reflectance and thermal anomaly information of the MODIS (Moderate Imaging Spectro-radiometer) sensor^{39,40} with the resolution of 0.25° by 0.25°. The dataset includes a fraction of burnable area, vegetation name, latitude, longitude, and the number of patches. This study analyzed the monthly burned area and the fraction of burnable area data for seven

years from 2013 to 2019. Further dataset of Normalized Difference Vegetation Index (NDVI) of Advanced Very High-Resolution Radiometer surface reflectance (AVHRR) sensor covering 0.25° by 0.25° resolution which is a softened vegetation index used to obtain the biomass density of different vegetation in India. It has a gridded data for the global level, available from 1980 to the present⁴¹.

Land Use Land Cover (LULC) data was collected from the Glob Land Cover portal as a climate change initiative by the European Space Agency (ESA CCI_LC). It is derived from an automatic and regionally tuned classification of the Medium-Resolution Imaging Spectrometer (MERIS) full-resolution time series. It provides the Food and Agricultural Organization (FAO) approved the Land Cover Classification System (LCCS) consisting of 21 classes⁴². For this study, these 21 classes were grouped into three broad categories: forest (including broadleaf evergreen, broadleaf deciduous, needle leaf evergreen, needle leaf deciduous, and mixed forest); Shrubland (broadleaf or needle leaf, evergreen or deciduous shrubland, grasses, and bushes) and Croplands (post-flooding, irrigated, rainfed, mosaic/vegetation, sparse vegetation). The datasets are collected from January to June for the entire study period, which is India's dry season at that time the fire occurs.

Methodology

Estimating the burned area of different biomes is typically calculated from the combustion efficiency, fuel load, and a fraction of biomass burned along with appropriate emission factors. The satellite data of the burned area of forest, shrubland, and croplands are considered to estimate the emissions of land cover types during the study period from 2013-2019. Parameters used to find species' emissions involve a fraction of burnable area, vegetation name, latitude, longitude, vegetation indices, and land cover class. The most used bottom-up inventory equation prescribed by²⁹ is employed to calculate the emissions.

Burned biomass (Bb) =
$$A \times B \times \beta \times EF \times 10^{-3}$$
 - (1)

Where Bb is the biomass consumption amount (kg); A is the burned area measure (m^2); B is the biomass amount inside the burned area (kg m^{-2}); β is the combustion efficiency or the fraction of fuel that burned, and EF is an emission factor of species (g/kg). An emission factor is a representative value that attempts to relate the quantity of a pollutant released into the atmosphere with an activity associated with the release of that pollutant⁴³. In this study, each land-cover type's emission factors were obtained from a publication⁴⁴, which has an integrated emission factor data of 370 published studies. Emission factor values used in this study were 3 (OC), 0.53 (BC) for Shrublands and grasslands, 4.4 (OC), 0.51 (BC) for Forests, and 4.9 (OC) and 0.42 (BC) for agricultural fires is given in gram species per kilogram of dry matter burned.

Estimation of carbon sequestration and BC flux

Soil OC (SOC) pool of the burned area can be derived from estimating the soil's OC content to a depth of 30cm or by calculating above and below groundmass carbon stocks. The summation of carbon

stock in different segments gives us the total carbon pool of each land-use type of region. A typical carbon stock for a specific region and land use can be derived by multiplying the carbon stock per unit area (t/ha) with the total area covered by specific land use. In our case, we used the reference stock of tropical dry area (38t C ha⁻¹) which is derived from mean estimates of different studies by IPCC⁴⁵.

Where SOCref =Default value of soil OC (carbon in tonnes)

FLU=stock change factor of a specific land-use pattern (dimensionless)

BA=Burned Area (in hectares).

As Indian agriculture is mainly composed of loamy alluvial soil, we used the default value of tropical agricultural land-use factor and shrublands tropical default value for long-term standing factors. For an annual change in the carbon, the stock change method was assessed as per IPCC guidelines.

Where CACS=Change in Annual Carbon Stock

Carbon stock (n) = Carbon stock at the current year

Carbon stock (n-1) = Carbon stock in the previous year.

Deposition flux and Residence time

The dry deposition flux of atmospheric BC was estimated by multiplying the BC concentration and dry deposition velocity.

Flux=C
$$\times$$
 Vd - (5)

Where C is the atmospheric BC concentration (kg/km²) and Vd is the dry deposition velocity. The dry deposition velocity is obtained by summation of the inverse of atmospheric aerodynamic, quasi-laminar sublayer, and surface or canopy resistance. A lower and upper estimate for forest and grasslands is selected for this study, which is 7×10-7 and 1.5×10-5 kilometers per second respectively. These values were derived from global modeled studies, and some uncertainties exist by order of two magnitude due to particle size and microclimatic conditions^{46,47}. These values were derived with certain assumptions for grassland and forest deposition which is found in a study by Pryor and reference cited therein⁴⁸. The settling velocity is generally higher than 1.5×10⁻⁵ km/s in the terrestrial ecosystem, and hence it is considered as a lower bound in-residence time estimation.

The residence time of an aerosol species can be obtained from the ratio of aerosol concentration or load to the total load of the species by its removal rates⁴⁹. The satellite-derived aerosols were considered as atmospheric load in the calculation.

$$\tau$$
=L/ (Rdd+Rwd+Rgs) - (6)

Where

 τ =Residence time in days

L=Aerosol load in Kg/km²

R=Removal rates in Kg/ km²/days.

Data availability

The datasets generated during and/or analysed during the current study are available in the [Google drive-Scientific reports] repository,

(https://drive.google.com/drive/folders/15GZQjdPTvPpOCbNPl3CR4IHZ7TX5ubRd?usp=sharing).

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Declarations

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Contributions

V.B conceived the concept and developed the research questions and conducted the data analysis and provided guidance and interpretation, edited multiple versions of the manuscript. K.V collected the data and wrote the manuscript and analyzed the data. A.K reviewed and provided advice and interpretation of the analysis edited the final version of the manuscript

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Ethics Declaration

Competing interest

We know of no competing of interest associated with this publication, As Corresponding Author, I confirm that the manuscript has been read and approved for submission by all the named authors.

Tables

Table 1: Deposition flux estimate of black carbon in different vegetation system

| Deposition flux estimate of black carbon in different vegetation system in Kg km ⁻¹ s ⁻¹ | | | | | | | | | |
|--|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|--|--|--|
| Years | Forest | | Shrubland | | Cropland | | | | |
| | Upper Estimate | Lower Estimate | Upper Estimate | Lower Estimate | Upper Estimate | Lower Estimate | | | |
| 2013 | 8.18E-2 | 3.82E-3 | 1.39E-01 | 6.48E-03 | 9.71E-02 | 4.53E-03 | | | |
| 2014 | 6.93E+1 | 3.24 | 1.14E+01 | 5.3E-1 | 5.79E+06 | 2.70E+05 | | | |
| 2015 | 1.10E-4 | 5.12E-06 | 6.51E-05 | 3.04E-6 | 3.87E-02 | 1.81E-03 | | | |
| 2016 | 1.90E-4 | 8.88E-06 | 5.07E-05 | 2.36E-6 | 7.52E-02 | 3.51E-06 | | | |
| 2017 | 1.08 | 5.06E-2 | 7.84E-02 | 3.66E-3 | 3.50E+05 | 1.63E+04 | | | |
| 2018 | 1.43E-4 | 6.67E-06 | 6.44E-02 | 3.01E-6 | 4.48E-02 | 2.09E-03 | | | |
| 2019 | 1.45E-4 | 6.78 | 5.80E-05 | 2.71E-6 | 6.64E-02 | 3.10E-03 | | | |

Table 2: Deposition flux estimate of organic carbon in different vegetation system

| Deposition flux estimate of organic carbon in different vegetation system in Kg km ⁻¹ s ⁻¹ | | | | | | | | | |
|--|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|--|--|--|
| Years | Forest | | Shrubland | | Cropland | | | | |
| | Upper Estimate | Lower Estimate | Upper Estimate | Lower Estimate | Upper Estimate | Lower Estimate | | | |
| 2013 | 6.58E+01 | 3.07E+00 | 3.67E-02 | 4.52E-03 | 7.86E-01 | 9.69E-02 | | | |
| 2014 | 5.14E+02 | 2.40E+01 | 3.02E+00 | 2.70E+05 | 6.47E+01 | 5.79E+06 | | | |
| 2015 | 1.00E-03 | 4.69E-05 | 1.72E-05 | 1.82E-03 | 3.69E-04 | 3.89E-02 | | | |
| 2016 | 7.96E+00 | 3.71E-01 | 1.41E-05 | 3.50E-03 | 3.02E-04 | 7.51E-02 | | | |
| 2017 | 5.78E+00 | 2.70E-01 | 2.07E-02 | 1.63E+04 | 4.44E-01 | 3.50E+05 | | | |
| 2018 | 1.24E-03 | 5.77E-05 | 1.70E-05 | 2.06E-03 | 3.65E-04 | 4.42E-02 | | | |
| 2019 | 1.22E-03 | 5.68E-05 | 1.53E-05 | 3.10E-03 | 3.29E-04 | 6.64E-02 | | | |

Figures

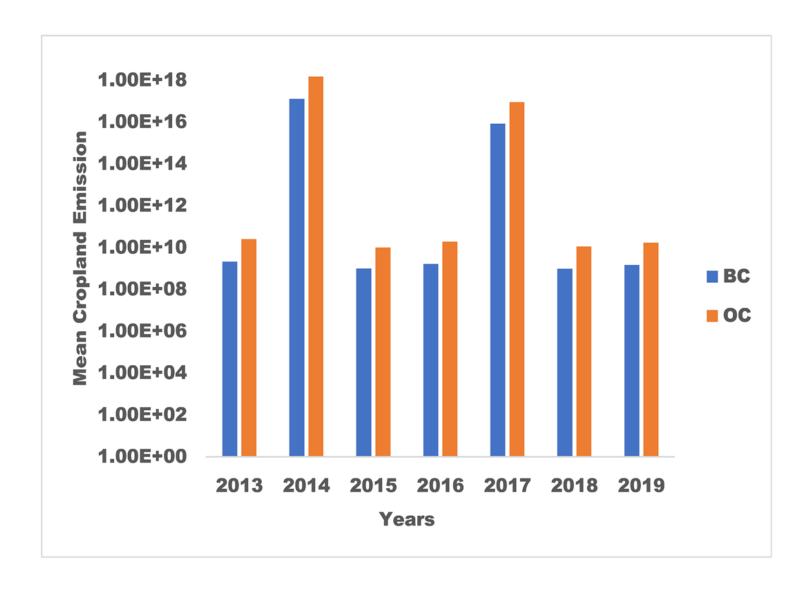


Figure 1

Emission of BC and OC in cropland ecosystem in million kilograms

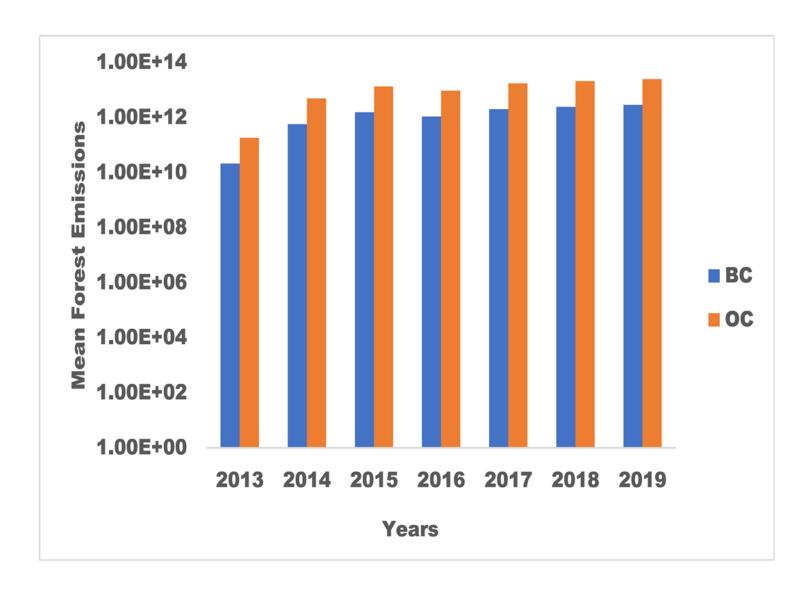


Figure 2

Emission of BC and OC in tropical forest ecosystem in million kilograms

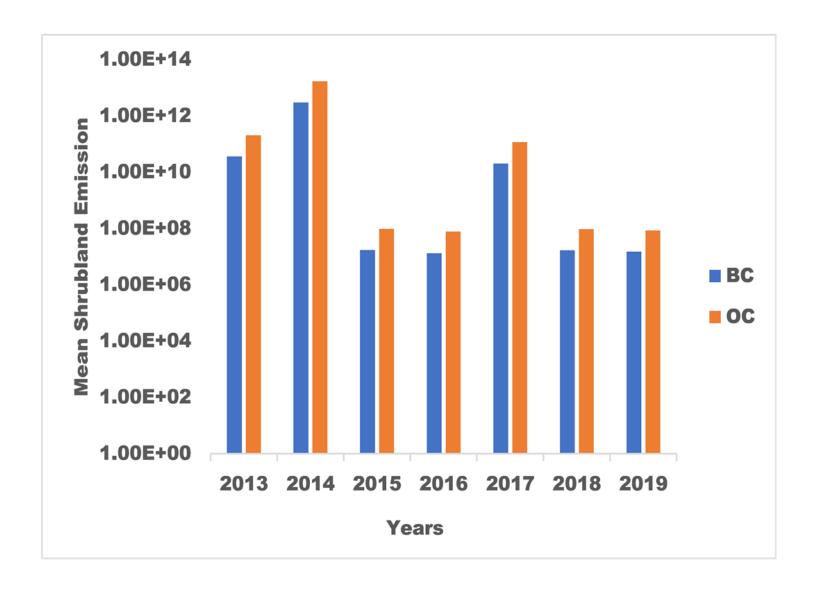


Figure 3

Emission of BC and OC in shrubland ecosystem in million kilograms

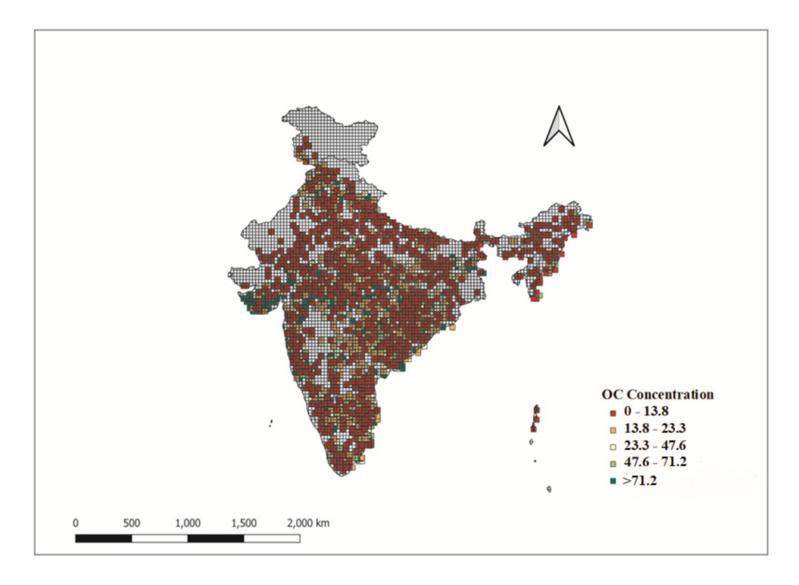


Figure 4

Spatial distribution of fire derived OC in kilograms per grid in India. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

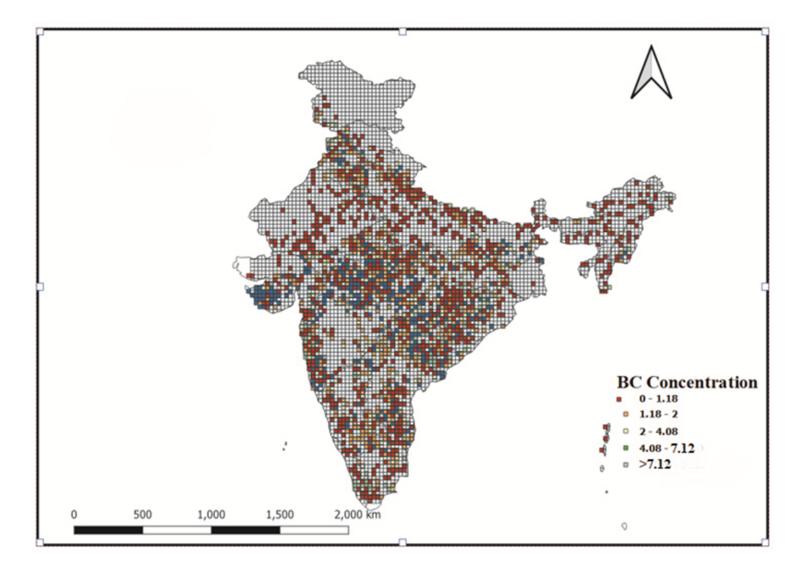


Figure 5

Spatial distribution of fire derived BC in kilogram per grid in India. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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