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Review Article

Analysis and interpretation of forest fire data of Sikkim

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Abstract: Forest ecosystems are depleting and heading towards degradation which would adversely affect the world's socio-economic harmony. Various disasters disturb the cordial relationship of the flora and fauna and impose imbalance in the ecology as a whole; forest fire is one of its kind. India has witnessed a 125% rise in forest fire occurrences between the years 2015 and 2017. This paper presents a study of various factors and the analysis of forest fire in Sikkim. The period of 10 years, forest fire incidences, i.e., from the year 2004 to the year 2014 have been considered for the study. The forest fire data was collected from Forest and Environment Department, Government of Sikkim, and preliminary processing was performed to check for anomalies. The study observed that there has been an increased forest fire incidence over the years and highest being in the year 2009. These fire incidences have damaged a total area of 5,047.16 ha of land damaging various flora and fauna. It was observed that the maximum forest fire cases are below an altitude of 1500m, during winter months (December to February extending to March) and in sub-tropical Sal (*Shorea robusta*) forest. West district of Sikkim recorded the highest number of forest fire incidences and area covered followed by south and east districts; the north district was least affected. As per the visual interpretation of forest fire incidence data and literature review, the main factors responsible for forest fire in Sikkim are low rainfall, dry winter season, and type of vegetation. Also, a linear regression was performed between weather factors like average temperature (°C), relative humidity (%), and wind velocity (Km/h) on incidences of forest fire between the year 2009-2014 (n=389). It was found that the average temperature (r=0.37, Slope=9.59 and SD= ±12.00) and relative humidity (r=-0.6, Slope=-4.52, and SD=±2.68) plays a moderate linear relationship in influencing the incidences of forest fires. However, wind velocity showed almost a flat curve indicating its minimal role in influencing forest fire incidences. Parameter modelling and preparation of forest fire risk zone map would be an effective tool in preventing and managing forest fire in Sikkim.

Keywords: Forest fire; Biodiversity; Ecology; Sikkim; Linear regression

1. Introduction

Forests are dynamic complex structures with varied vegetation, trees performing diverse roles like weather adjustments, carbon level maintenance, the dwelling place for various animals and birds, the livelihood of humans, and above all a source of economic growth by providing the resource i.e., wood (Gigović et al., 2018; Saklani, 2008; Sarab et al., 2014). Forest fire is the natural or deliberate burning of the various fuels in the forest bed or trees. Forest fire adversely affects forest diversity. It reduces forest cover, destroys wildlife, depletes environmental conditions, degrades soil quality, and affects forest regeneration (Kalantar et al., 2020). In addition to the loss of forest biodiversity, the emission of pollutant gases like carbon monoxide, nitrogen oxide, and sulfur oxide from the forest fire leads to global warming, climatic changes, and water level imbalance which affects human health (Rather et al., 2018; Joseph et al., 2009). It is estimated that the forest fire emits about 8 billion tons of CO_2 per year (Van Der Werf et al., 2017). In India, total CO_2 outflow by forest fire was found to be 98.11 Tg in 2014 (Reddy et al., 2017).

In Sikkim, as the winters are increasingly becoming warmer and drier, the subtropical Sal forests are becoming vulnerable to ground fires, affecting the regeneration of ground flora. The dry winter season that extends from December to March is the main forest fire season in Sikkim (Sharma et al.,

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2012). Among all the forest types, East Himalayan Sal (3C/C1a (I)) has the highest forest fire chances. Sub-tropical forests and Sal Forest showed the highest percentage of fire burnt areas as detected using satellite imagery (Sharma et al., 2012). The calorific value is high in oak trees; the fire takes the form of a canopy and burns for several days, affecting the regeneration of these species. Such fire occurred in 1970 in the west district of Sikkim; the coniferous and oak forests have not yet recovered (Sharma et al., 2014). Increasing incidents of forest fires in Sikkim have resulted in forest loss and ecological imbalance. As per the 2009 forest fire data of Sikkim, 905 ha of the area was damaged.

The dry season is becoming more dryer and wet wetter. This is evident from the fact that there is a significant decreasing trend in the mean maximum temperature during monsoon and a decrease in cold wave conditions, resulting in a rise in average minimum temperature, which is the main driving factor for forest fire (Sharma et al., 2014). However, finding climatic data in Sikkim is a major problem as the data collecting station is absent in most areas of concern. In Sikkim state, the forest fire data and studies have revealed that the fire occurrences are mostly ground fires that destroy the biodiversity of the forests to a great extent. Change in rainfall regime, prolonged dry season, and decrease in rainfall are the major factors responsible for a forest fire in Sikkim (Sharma et al., 2012). From literature, the most forest fire in Sikkim is observed to be due to anthropogenic activities (Sharma et al., 2012). Accidental forest fire is caused mainly when local farmers and cattle herders make fire intending to keep away the wild animals from the agricultural fields and wave out the broom grass to improve soil fertility (Sharma et al., 2014; Stocks et al; 1997).

Similar is the case in the Asian context. The 1997 forest fires in South East Asia were completely human-made, which lead to numerous health problems in Singapore, Malaysia, and Brunei (Frankenberg et al., 2005). 95% of such fires occurred in spring and autumn in Mongolia, China (Goldammer, 2001). Land clearing by slash and burn method is attributed as a common cause of forest fire in South East Asia (Varma, 2003; Yong et al., 2016). In Japan, though the climate is humid but yearly, more than 4000 forest fire cases were recorded damaging 4000 ha of forests in the 1980s and 2300 ha in the 1990s (Zorn et. al., 2001), and it was estimated that 99% of these fires are human-made (Nakagoshi et al., 1987). The analysis of forest fire data of south Asia found that moist deciduous forest, followed by dry deciduous forest and semi-evergreen forest, were the most vulnerable forest types in these regions (Reddy et al., 2017). In Indonesia during 1997-98 damaged 5.2 million hectares of forest in East Kalimantan, which was primarily due to the EI-Nino southern oscillation (ENSO) event bringing drought to the area (Hoffmann et al., 1999). It was found that ground fires are frequent in Bhawal National Park, Bangladesh, which destroyed substantial vegetation (Alauddin et al., 2020). A study in Madupur Sal forest, Bangladesh, showed that forest fires are the major causes of deforestation, which are mostly due to illegal human activities and sometimes naturally during the summer season (Hossain et al., 2015). Large forest fire occurrences of different intensities are recorded every year in Asian countries. The 2009 fire occurrences in Nepal lead to many deaths and destruction of human settlements (Matin et al., 2017; Berwyn et al., 2018). In 2019, 35,000 fire incidences were reported in Indonesia, which led to various health problems within and in the neighbouring countries due to air pollution. They also cause various socio-economic issues related to land use, property damage, agriculture, and infrastructure loss (Malik et al., 2013).

In 2017 wildfire in Canada produced 20 times more aerosols than Pinatubo's volcanic eruption in 1991 (Liu et al., 2017). As per Global Forest Resource Assessment 2010, a forest fire in Australia caused the death of 70 lives in addition to the loss of agriculture and infrastructure (FAO, 2010). The year 2018 and 2019 saw the most devastating forest fire in Australia and California, which covered 6.3 million hectares and 0.72 million hectares of forest area, respectively, and took the lives of 24 humans and millions of animals (Srivastava, 2020). The study reveals that the area burned due to forest fire in the United States increased from 1.62 million ha. In 2002 to 4.05 million ha in 2006, (Satendra & Kaushik, 2014). As per the United Nations Development Program report, the financial losses due to forest fire accounted for Rupees 9000 per hectare per annum (Satendra & Kaushik, 2014). Time of occurrence and area-covered data is crucial for risk assessment and fire zonation (Suryabhagavan et al., 2016; Kappes et al., 2012).

Understanding past forest fire regimes through their locations, burnt area, date, and time plays a crucial role in the prevention and mitigation of major forest fires (Tonini et al., 2020). The present study analyzed and interpreted the historical data of forest fire in the state of Sikkim (2004-2014). The interrelation of the fire incidences in Sikkim with the weather factors like average rainfall (mm), average temperature (°C), relative humidity (%), and wind velocity (Km/h) were also analyzed for the years 2009-2014. This study shall act as a baseline for further studies in these fields with the use of the latest technologies and empirical studies, with the availability of recent year's data. In India, about 6 70,000 km2 of forest land are burnt each year, which is about 2% of the world's forest area, i.e., 35 million hectares of forest area (Rather et al., 2018, Mallik et al., 2013). As per the Forest Survey of India (FSI) Report-1995, about 50% to 54% of Indian forest fires are ground fires (FSI, 1995). In northeastern states, such ground fires occur due to shifting cultivation and human activities (Satendra & Kaushik, 2014). According to FSI report published in 2018, 37,059 fires were detected, of which 64.3% fall under the category of occasional, moderate, and high incidence fire levels, and the rest, 35.71%, have not reported any incidences of fires. India spends nearly 44 million US dollars annually for forest fire patrolling and combating forest fires (Mallik et al., 2013).

1.1. Factors that contribute to forest fire

The vegetation of an area represents the availability of fuel. Fuels are one of the important organic matters that help in fire ignition. The vegetation category, the plant's properties, the species morphology, availability and arrangement of biomass, and cover types are essential for an area's forest fuel characteristics (Keane et al., 2001; Keane et al., 2010). The fuel is available for combustion, the fuel moisture, fuel arrangement, fuel size distribution, and ecosystem influence all aid in fires (Stocks et al., 1997). Dried and decayed vegetation contribute to ground fires and surface fires, respectively. Humus, trees, shrubs, roots, muck, peat, leaves of trees, grasses, weeds, ferns, low bushes, seedlings, saplings of trees, and deadwood are major contributors to ground fires. Standing dried trees, mosses, epiphytic plants, and lichens are aerial fuels (Gupta & Nair, 2012). Different tree types embody various adaptation types to resist forest fire, such as bark thickness, increased moisture level, foliage size, and high oiliness. Wetland vegetation and sparse vegetation are less susceptible to fire (Sharma et al., 2014). Forests mostly consisting of sal, bamboo, pine, chir, deodar, sesame are highly flammable (Rather et al., 2018). Fire generally damages woody plants compared to herbaceous plants because of the growth form and location of the meristematic tissue (Bidwell et al., 2005). Fuels are one of the important organic matters that help fire ignition; hence, the mapping of fuels is essential for forest fire management. Fuel structure in the forest acts as an initiator and facilitator of fire in the forest (Keane et al., 2001).

The amount of compressed moisture in the air compared to the total amount that it is capable of holding at that temperature and pressure is called relative humidity, which when reaches 60%, causes chances of forest fire (Malik et al., 2013). Fuels in the forest get dried faster in higher temperatures. As suggested by the intergovernmental panel on climate change 2007, droughts due to drier weather, shortage in rainfall, rise in temperature, and decrease in the level of precipitation are the fundamental reasons for the cause of forest fire in Asia (Berwyn, 2018).

There are various changes in the vegetation of the forest, like an increase in dissimilarity index of plant species, increase in supremacy, climatic changes that may increase the vegetation's sensitivity to forest fires (Berwyn, 2018). The area burnt is an important parameter for fire trend analysis as it helps estimate carbon emissions by a forest fire (Randerson et al., 2012). Extreme fire can produce a huge amount of CO2 in a very small duration of burning, resulting in global warming, devastating fires, and further warming the land. According to International Energy Agency, the summative emission of CO2 recorded in 2017 was 32.5 billion tons (Berwyn, 2018). Fuel phenological patterns also affect anthropogenic fire seasonal behavior, directly shaping the Spatio-temporal distribution of fire ignitions across the landscape (Bajocco et al., 2017).

The slope is another important factor contributing to the forest fire. It is referred to as the gradient of the land expressed in percentage or the land's steepness. With the rise in slope and heating of fuels due to increase heat transmitted by radiation and the transfer of heat from one place to another, the occurrence and spread of fire intensify. The slope acts as a chimney and accelerates the fire upwards. In the hills where steep slopes are prominent, fire damages vegetation and loosens the organic matter in the soil, leading to erosion and debris flow (Ajin et al., 2016). In steep slopes, where wind speed and closer angle of fire to the ground's surface, convection applies, leading to faster movement of fire. The speed of winds in the downhill is much lesser i.e., 2 to 3mph, than the up slopes i.e., 5 to 10 mph, which intensifies the fire spread (Cannon et al., 2001).

The aspect determines the level of sunlight received by the slope. The ignition period is longer in south-facing slopes as they receive more solar radiation; hence, it results in lower relative humidity, less moisture, and high temperature, which tends to dry the fuel. The slope facing north receives lesser sunlight thus is cooler and greener than the southern slope. Therefore, the aspect of an area also plays an essential role in the spread of forest fire. Elevation relatively affects the moisture content of fuel and humidity; the higher the elevation, the land is somewhat cooler hence the lesser chances of fire. Fire usually travels in the direction of the wind, which heats the fuel (Ajin et al., 2016).

The ill-effects of urbanization and the misuse of forests lead to forest land-use changes, which increase the growth of shrubs and other plants that are highly inflammable. 90% of the fire occurrences in China are due to human activities (Li et al., 2017). The interrelationship between the rise in the ignition and the excessive use of land is a force for the increase in road expansion in North America (Ye et al., 2017). Fire is increasing manifolds with land-use change due to anthropogenic activities, hotter climate, and dry weather. Forest areas nearer to the settlement areas, roads, and cultivated lands are more susceptible to fire, as seen in forested landscapes in tropical, temperate, and subtropical regions of Churia, lowlands in northeast India, and mid-hills (Matin et al., 2017).

2. Methodology

2.1 Feature of the Study Area

This paper presents a study done on forest fires in the state of Sikkim. The state of Sikkim is located in the northeastern part of the Himalayan Mountain range. It is the second smallest Indian state with an area of 7096 square kilometers. The study site is shown in Figure 1. It lies between the latitude of 27° 5'S to 28° 9' N and longitude of 87° 9'W to 88°56' E that falls in Survey of India topographic sheets of 78A1 to 78A15 series (Sharma et al., 2012).

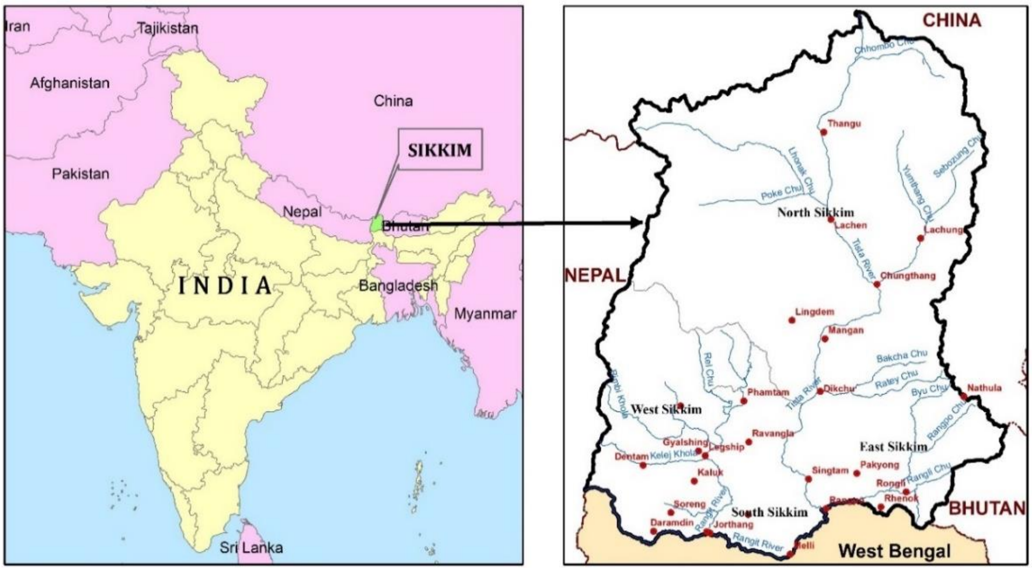

Figure 1. Map showing the location of the state of Sikkim (study area)

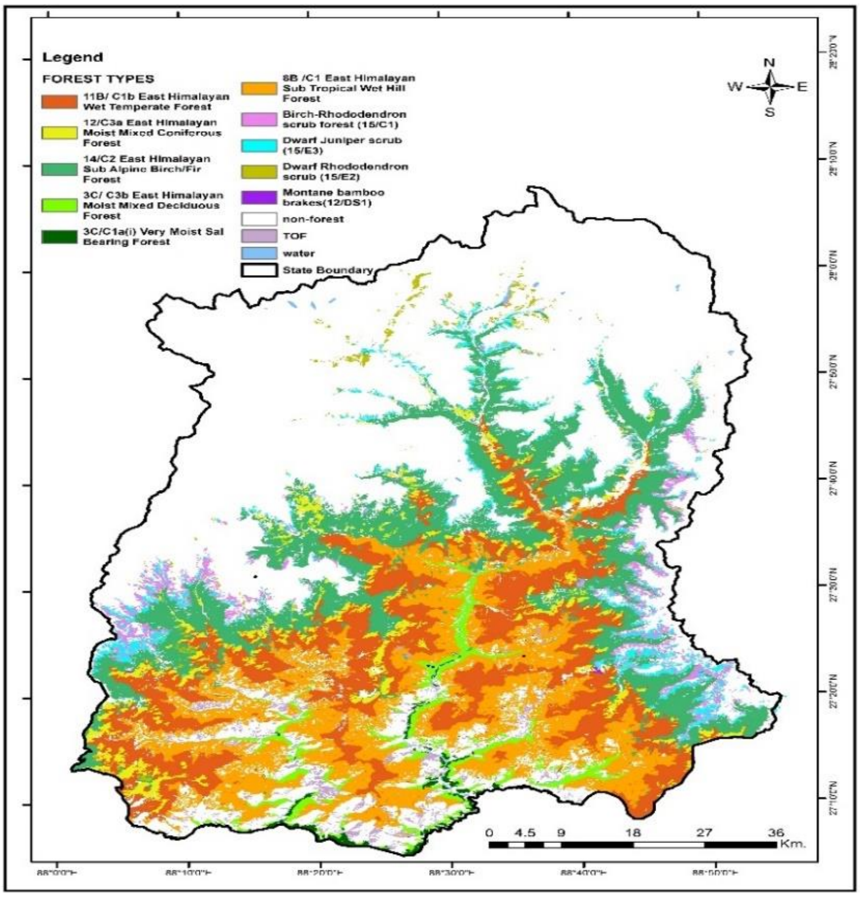

Figure 2. Map showing Forest types in the state of Sikkim

The state being small, has been divided into four districts as East, West, North, and South districts. Its altitude ranges from 300 m to over 8586 m above the mean sea level. The annual rainfall ranges between 2700 mm to 3200 mm, and the annual temperature varies from sub-zero during winter to 28 °C during summer (FSI, 2019). Sikkim is bestowed with more than 4000 flowering plants (Sundriyal et al., 2004) and around 30 % of all the birds found in the Indian subcontinent (Ganguli et al., 2011).

The Forest of Sikkim is characterized into three major vegetation types viz. Tropical, Temperate, and Alpine (Hooker, 1854). As per the Forest Survey of India's State of Forest Report 2019, Sikkim has a forest cover of 47.11 % of the state geographic area and has a canopy density class as a very dense forest (15.53 %), moderately dense forest (12.88 %), and open forest (9.70 %). The forests in Sikkim are categorized into six major forest type group viz., Tropical moist deciduous forests, Subtropical broadleaved Hill forests, Montane wet temperate forests, Himalayan moist temperate forests, Subalpine forests and Moist alpine scrub (FSI, 2019). The forest types map is shown in Figure 2.

2.2 Data collection method

The research is based on the secondary data of forest fire (2004-2014). The Forest and Environment Department, Government of Sikkim has collected the GPS location of forest fires immediately after the forest fire incidence. The forest fire data was validated with experts of the Forest and Environment Department, Govt. of Sikkim, and intensive prior study of various related literature and documents of the Forest and Environment Department offices were performed to collect the relevant data for a forest fire. The data's various attributes are date, location, type of fire, time, area damage in a hectare, and species damaged. Weather data was gathered from https://www.worldweatheronline.com. Weather data was available for (2009-2014). The weather data used for the study were average rainfall (mm), relative humidity (%), average temperature (°C), and wind speed (Km/h).

2.3 Data Preprocessing and interpretation

Forest fire data (2004-2014) has been used for the study. After the data was collected, the data was validated and preprocessed to improve the understanding and quality of data. The available forest fire data was segregated concerning;

a. Frequency of fire incidences by analyzing the number of fire incidences each year.
b. Year-wise area damaged was analyzed by taking the highest area covered by the forest fire.
c. Year-wise area damaged in various forest territorial ranges was segregated, and the range with the highest area damage for each year is analyzed.
d. District wise frequency of occurrence of forest fire and area damage by segregating the year-wise data into district wise according to the location of the fire.
e. Finally, numerical data tabulated, and a graphical representation of the numerical values was performed.
f. For map preparation, Arc GIS 10.5.1 was used. Survey of India topographic sheets scale 1:25,000 was geometrically rectified on UTM projection and WGS 84 datum and mosaicking the topographic sheet All ground point locations were collected. Finally, all the ground points were converted into the database and were transferred to the GIS environment (Shapefile format).
g. Monthly weather data was collected for all the districts of Sikkim year-wise from (2009-2014).
h. Finally, linear regression was performed to determine if the weather factors (2009-2014) like relative humidity (%), average temperature (°C), and wind velocity (km/h) influence fire incidences in Sikkim.

3. Results

Forest fire data for the year 2004-2014 were collected from the Forest and Environment Department, Government of Sikkim. Forest fire incidence places were categorized as four districts of Sikkim depending upon the district the places of fire incidences belonged.

3.1 Visual interpretation of forest fire data (2004-2014)

Table 1: District-wise total incidences and area damage (2004-20014) for the state of Sikkim.

District	Incidences (No.)	Area damage (ha)
East	98	976
West	170	1997
North	16	210.5
South	166	1483

The total fire area was computed district-wise based on the area covered in each place of fire incidence. The segregated data are shown in Table 1. The highest number of fire incidence (170 No.), as well as the area covered (1997 ha), was recorded in the West district of Sikkim followed by the South district with forest fire incidences (166 No.) and area cover (1483 ha). The No. of fire incidence in the East district was comparatively lower than the West and South district of Sikkim i.e., (16 No.) and area damage (976 ha). North district of Sikkim recorded the least number of forest fire incidences (16 No.) and area covered 210.5 (ha).

Table 2. Major species damage by forest fires (2004-20014) in the state of Sikkim

Sl. No.	Species damaged		No. of fire incidences
	Common /Local name	Scientific name	
1	Ground bushes	-	261
2	Sal	Shorea robusta	112
3	Chilauna	Schima wallichii	27
4	Bamboo	-	21
5	Teak	Tectona grandis	14
6	Dhalne Katus	Castanpsis indica	6
7	Patle Katus	Castanpsis hystrix	9
8	Salimbo	Cynodon dactylon	14
9	Siris	Albizia Spp.	8
10	Lampatey	Duabangaa sonneratioides	8
11	Thakal	Cycas pectinate	8
12	Dhuppi	Cryptomeriajaponica	7
13	Champ	Mangolia lanuginosa	6
14	Pareng	Cephalostachyum hookeriana	5
15	Uttis	Alnus nepalensis	4
16	Simul	Bombax ceiba	4
17	Gurash	Rhodendron arboretum	14
18	Juniper	Juniperus recurva	3
19	Kaijal	Bischofia javanica	3
20	Panisaj	Terminalia myriocarpa	2
21	Chiuri	Bassia butyracea	5
22	Odal	Sterculia villosa	1
23	Mauwa	Engelhardtia spicata	4
24	Chir pine	Pinus roxburghii	3

Table 2 depicts major species damaged in the forest fire incidences over the period from the year 2004 to 2014 in the state of Sikkim. In most incidences (58%) ground bushes have been damaged. 24.88% of incidences involved damage of Sal (*Shorea robusta*) species. Damages of *Schima wallichii* in 4.88% of incidences, *Rhododendron arboretum* in 3.11% of incidences, Bamboo and *Cynodon dactylon* in 3.11% of incidences were observed which are considerable.

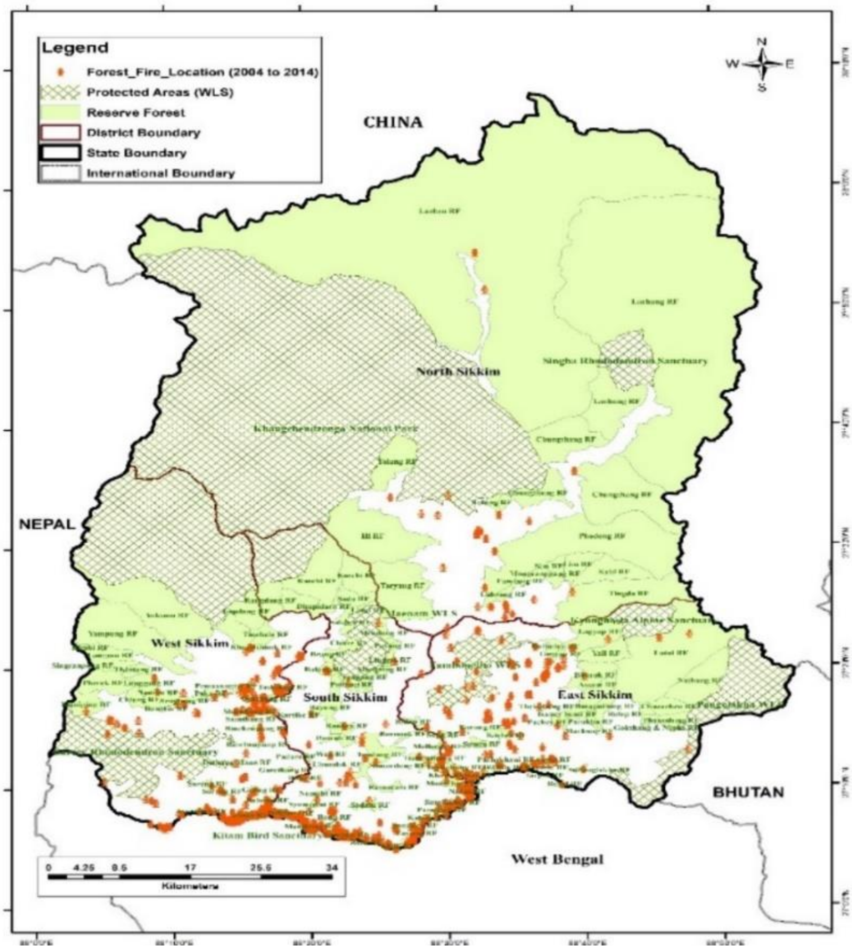

Figure 3. Map showing the forest fire incidences recorded between 2004-2014 in the state of Sikkim.

Figure 3 depicts forest fire area wise and district wise respectively the forest fire incidences in the state of Sikkim. Figure 3 indicates that the maximum forest fire incidences have occurred in the low altitude areas of the South, East, and West district which is also corresponding to the larger area damaged by the forest fire. Also, the incidences are more in the fragmented forest areas in comparison to the continuous unfragmented forests. The forest fire incidences are comparatively low in the Wildlife Protected Areas.

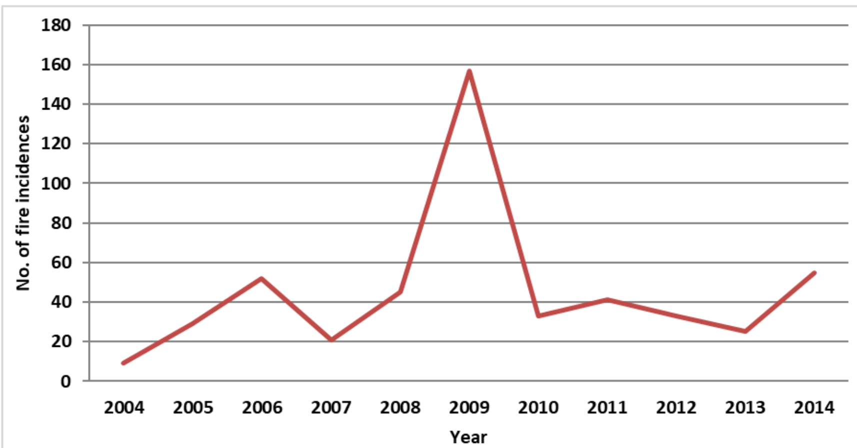

Figure 4. Year-wise Forest fire incidences in Sikkim.

Figure 4 depicts the yearly number of incidences of forest fires in Sikkim. From Figure 4, it is evident that the forest fire frequency has increased over the years. However, it cannot be said that the frequency of the forest fires in Sikkim is continuously increasing as some years like the year 2007, 2010, and 2013 has shown a decrease in forest fire incidences than the preceding year. The year 2009 shows an abrupt increase of forest fire incidences (31.4%) in the total number of incidences that occurred between 2004-2014, while the year 2004 showed the lowest incidences (1.8%) on the total number of incidences between the year 2004-2014.

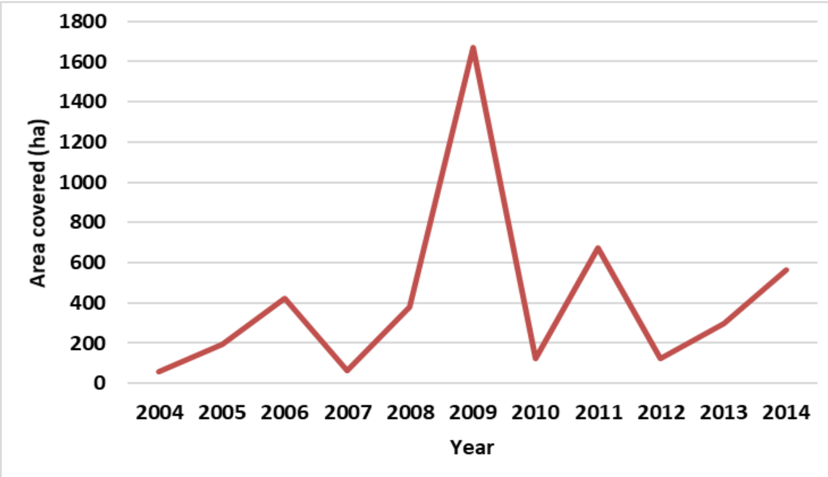

Figure 5. Year-wise fire area coverage due to the forest fire in Sikkim.

Figure 5 shows the total area damaged due to a forest fire during 2004-2014. The maximum area cover was recorded in 2009 i.e. (36.6%) of the total area covered by the forest fire. The least area covered was recorded in 2004 i.e. (4.24 %) of the total area covered by the forest fire. This directly corresponds to the number of forest fire incidences as shown in Figure 4. The year 2004, 2007, 2010 and 2012 has shown a decrease in forest fire area damaged while the year 2006, 2008, 2009, 2011, 2013 and 2014 has shown increase in forest fire damage area than the preceding year.

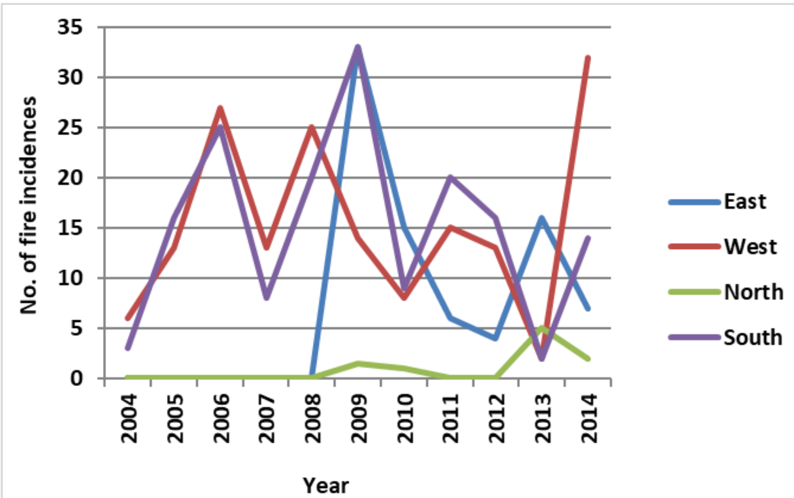

Figure 6. District wise frequency of forest fire in Sikkim.

Figure 6 represents the number of forest fire incidences in each district of Sikkim. The highest incidences were recorded for the East district (33 numbers) in 2009, West district (32 numbers) in 2014, South district (33 numbers) in 2009. The highest incidences (2004-2014) were recorded in the West district (37.7 %) of the total fire incidences, followed by the South district (36.8%) of the total fire incidences. East district of Sikkim showed 21.7% and the North district of Sikkim showed the least forest fire incidences of 3.55% of the total forest fire incidences between the year 2004 and 2014.

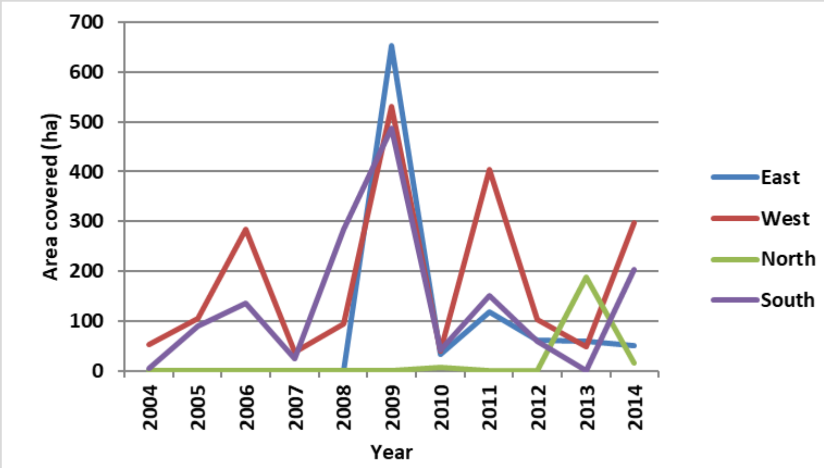

Figure 7. District-wise area coverage by the forest fire in Sikkim.

Figure 7 represents the area covered by the forest fire in each district of Sikkim. West district of Sikkim was found to have the maximum area covered by forest fire i.e., 42.7% of total forest fire covered area between the year 2004-2014. South district of Sikkim recorded 31.7% of the total forest fire area covered and the East district of Sikkim recorded 20.9% of the total forest fire covered area. North district of Sikkim showed the least forest fire covered area of 4.5% of the total forest fire covered area between the years 2004 and 2014.7

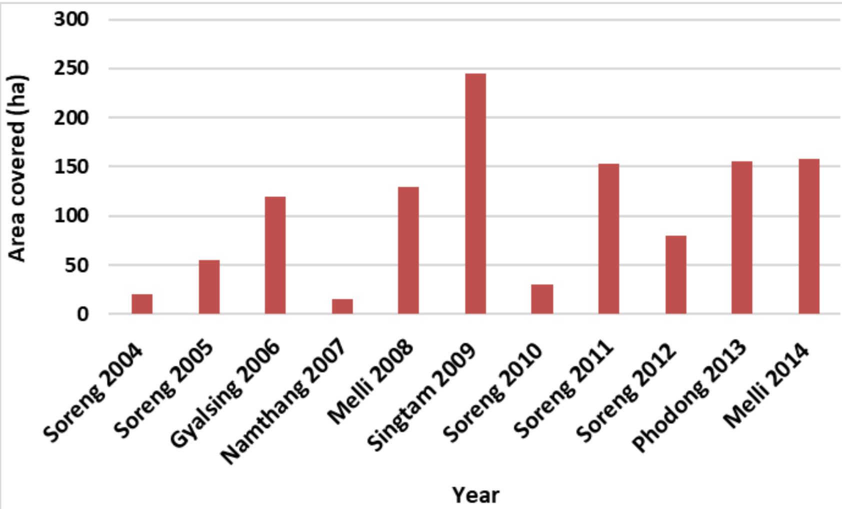

Figure 8. Forest area damaged in the various forest ranges of the state of Sikkim.

Figure 8 shows the forest area damaged in the various forest ranges of the state. The figure shows that most forest fire occurrences are in the Soreng forest territorial range, followed by the Gyalshing forest territorial range and the Tashiding forest territorial range in the west district. The South district of Sikkim encountered frequent forest fires in Melli and Namthang forest territorial Range. Figure 8 shows that the most vulnerable territorial forest range to forest fires in the East district is Singtam and Pakyong territorial range followed by Gangtok and Ranipool range. The Forest territorial ranges in the North district are the least forest fire-affected ranges. Singtam forest territorial range recorded the highest forest fire-covered area with 245 Ha in the year 2009.

3.2 Linear regression plots

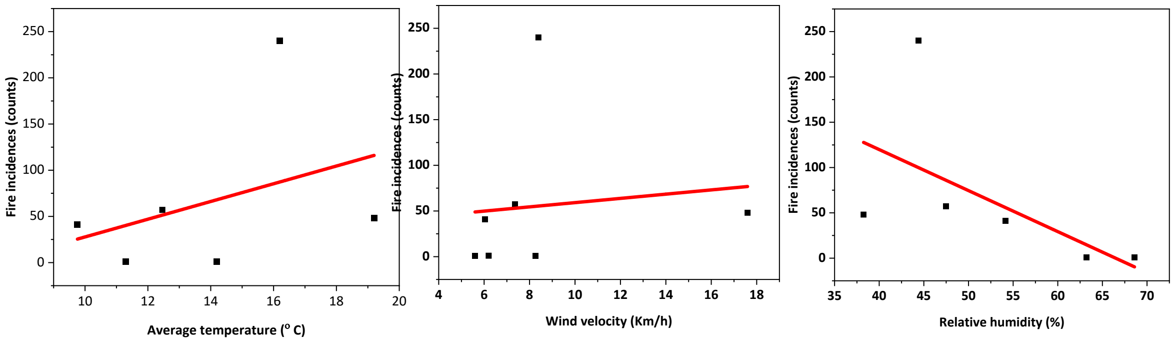

Figure 9. Linear regression plot concerning No. of forest fire incidences for average temperature (on the left), wind velocity (on the middle), and relative humidity (on the right).

From Figure 9 (on the left), it is evident that there is an increasing trend of forest fire incidences concerning an increase in temperature (r=0.37, Slope=9.59, SD= ±12.00). Figure 9 (on the middle) shows the linear plot for wind velocity and No. of forest fire incidences which shows almost a flat curve (r=0.11, Slope=2.32, SD=±9.05). Figure 9 (on the right) shows a linear regression plot of relative humidity and No. of fire incidences wherein the best fit was found for relative humidity (r=-0.6, Slope=-4.52, and SD=±2.68).

4. Discussion

The forest fire data of the year 2004-2014 upon interpretation shows that the forest fire incidences and area damage have increased over years. Lower hill forests like Zoom Reserve Forest, Sipsoo Reserve Forest, Sirithang Reserve Forest, and Sudhir Khasmal Forest recorded frequent forest fires in the West district. Simultaneously, middle hill forests like Sakyong Reserve Forest also encountered repeated forest fire cases in Gyalshing Forest Territorial Range. The forest fire was mostly seen to be occurring in Sal (*Shorea robusta*), Teak (*Tectona grandis*) and Chir (*Pinus sp.*) forest in lower hills whereas miscellaneous forest with Oak, Alder (*Alnus nepaulensis*), Mauwa (*Engelhardtia spicata*), Odal (*Sterculia villosa*), and Chewri (*Bassia butyracea*) also recorded frequent forest fires in Gyalshing and Tashiding Forest Territorial Range.

In the South district of Sikkim, Salghari Reserve Forest, Majhitar Reserve Forest, Narak Reserve Forest, and Mamring Reserve Forest recorded a maximum number of forest fire incidences and area coverage. The species involved are Sal (*Shorea robusta*), Thakal (*Cycas pectinate*), Teak (*Tectona grandis*), and associate species in lower hill forest and species like Chilauney (*Schima wallichi*), Panisaj (*Terminalia myriocarpa*), Salimbo (grass), Katus (*Castanopsis sp.*), bamboo, etc. in the middle hill forest.

In the Singtam Forest Territorial Range in the East district of Sikkim, Reserve Forests like Tumlabong, Salingay, Sittey, and Khanikhola encountered major forest fires whereas, in Pakyong Forest Territorial Range, forest like Bhasmey, Damlakha, Linkey, Pachey, Bagpani encounters most fire cases. In Gangtok and Ranipool Forest Territorial Range, there are fewer forest fire cases at forests of Syari, Namnang, Kambal, Ranka, etc. Kyongnosla Forest Territorial Range encounters rare forest fire cases, but the area coverage is large once there is a fire incidence. This must account for dense grooves of small bamboo of Ningal (*Arundinaria sp.*) and Malingo (*Arundinaria maling*) in those areas (Tamang et al., 2013). Table 2 depicts that there is an increased fire incidence damaging ground bushes but it cannot be made out from the data whether these damages of ground bushes account for forest fire incidences in any specific type of forest. Table 2 also depicts that the Sal (*Shorea robusta*) species was damaged in the greatest number of incidences followed by *Schima wallichii*, Bamboo, *Tectona grandis*, and *Rhododendron arboretum*. *Cynodon dactylon* which is again a grass species has been damaged with a considerable number of incidences.

From Figure 8 it is obvious that the Soreng Forest Territorial Range in the West district of Sikkim encounters repeated forest fires and it exhibits the highest forest fire coverage area in most of the years. In 2009, Singtam Forest Territorial Range in the East District of Sikkim encountered the largest forest fire area coverage within the studied years. In the South district of Sikkim, the Melli Forest Territorial Range encounters repeated forest fires and larger area coverage followed by Namthang Forest Territorial Range. Though the North District of Sikkim encounters the least forest fire cases, Phodong Forest Territorial Range exhibited the largest forest fire coverage in the year 2008.

Forest fire is rare in the upper hills because of low temperature and altitude (Sharma et al., 2014). However, forest fire incidences have been recorded in 2009, 2010, 2013, and 2014 in Mangan, Phodong, and Dzongu Forest Territorial Range in the miscellaneous forests of lower elevations. The highest area covered by forest fire in the North district was in 2013 i.e., 188 ha. This indicates how global warming and climate change have made the high altitude of the North district also vulnerable to forest fire (Sharma et al; 2014).

Table 1 depicts that the forest fire cases are comparatively higher in the West, South, and East districts than that of the North district in Sikkim. This accounts for the higher temperature of >20°C and lowers the humidity of <50% during fire season i.e., January to March (https://www.worldweatheronline.com) in these districts. On the contrary North district of Sikkim exhibit comparatively lower temperature < 10°C and higher humidity > 50% (https://www.worldweatheronline.com). Moreover, North Sikkim represents less low altitude areas and Sal (Shorea robusta) forests. From the data, it was also revealed that the highest number of forest fire incidences from 2009-2014 was recorded in March (240 No.), followed by February (57 No.), January (48 No.), and April (41 No.) and an average rainfall <300 mm was recorded during these months (Das et al., 2017). So, it can be concluded that the rate of rainfall and forest fire incidences are inversely related.

Forest fires in India are human-made in around 95% of cases (Srivastava et al., 2020). Most cases of forest fires in Sikkim are either accidental or intentional. The outbreak generally starts from the roadside due to live bidi/cigarette butt thrown by the passer-by (Sharma et al., 2014). Other reasons are intentional fire left out by the villagers to clear agricultural debris and better regeneration of grasses. Sometimes fire gets broken accidentally because of the torch (pultho) villagers use while passing through the forest areas. Winter is also a season for picnickers where they use fire for cooking and leave it live. Also, accidental forest fire happens due to faulty electricity lines and transformers (Sharma et al., 2014). While as per the villagers, the natural forest fire breaks due to falling boulders and rattling of bamboo in the groove.

Figure 4 shows that the forest fire incidences were abruptly higher in the year 2009. This corresponds with the weather condition in that particular year where there was an extended drought season and the rainfall was scanty (Sharma et al., 2012). The year 2009 was the warmest year on record since 1901 (until 2014). The year 2009 experienced low precipitation <2751.62 mm and lowest rainfall 2548.86 mm (Rahman et al., 2012) whereas, higher annual rainfall during 2010 coupled with higher winter rain also resulted in lesser forest fire incidences in 2010 (Sharma et al., 2014). In 2009 Barsey Rhododendron Sanctuary, West Sikkim alone, encountered the damage of 200 ha though the forest fires are not very frequent in this area. Similar was the case in Fambonglho Wildlife Sanctuary in East Sikkim, where a single forest fire incident damaged 240 ha of miscellaneous forest.

From figure 5 it can be interpreted that every succeeding year of low area coverage has shown an increase in forest fire area coverage. In the year 2009, forest fire recorded the highest area coverage of over 1625 ha with around 157 Nos. of incidences recorded. Though 2006, 2011, and 2014 recorded similar forest fire incidences, the year 2014 showed comparatively less area coverage.

Figures 6 & 7 indicate that the number of fire incidences and corresponding area covered is highest in West and South districts covered by low-lying Sal Forest. This low-lying area extends from Mamring, Jorethang to Salghari in the South district of Sikkim and Nayabazar, Sipsoo to Tashiding in the West district of Sikkim. This must account for the scanty rainfall in the said area because these areas fall in the rain-shadow of Darjeeling hills. Amongst all the forest types, subtropical forest and Sal (*Shorea robusta*) found mostly in these two districts, have the highest percentage of burnt areas detected using satellite imagery (Sharma et al., 2012).

The analysis and interpretation of forest data for 2004-2014 reveal that the maximum forest fire cases in Sikkim are below 1500 m during the winter months. Sub-tropical forest and Sal (Shorea robusta) forest in Sikkim have the highest frequency of forest fires and the highest percentage of forest fire burnt area. Very negligible forest fire incidences were observed in the alpine and temperate forests. Also, middle hill to high hill miscellaneous forests showed a smaller number of forest fires in comparison. The number of forest fires is greater in southern and western aspects than in northern aspects, which could be due to a longer period of exposure to sunlight.

Figure 9 (i.e., on the left and the right) shows that relative humidity (%) and average temperature (°C) have a moderate effect on the no. of fire incidences than the wind velocity (on the middle) for the state of Sikkim. Figure 9 (on the right) shows the best fit plot for relative humidity (%) on a number of forest fire incidences (r=-0.6, slope=-4.52, SD= ±2.68) having a moderate negative linear relationship which can be interpreted as more the relative humidity the lesser will be the chances of forest fire incidences. Figure 9 (on the left) shows the moderate positive linear relationship for average temperature (°C) on a number of forest fire incidences (r=0.37, slope=9.59 and SD= ±12.00) which can be interpreted as more the average temperature the more will be the chances of forest fire incidences. Figure 9 (on the middle) shows almost a flat curve indicating that the wind velocity (km/h) has a minimal influence over the occurrence of forest fire incidences.

5. Conclusions

In this study, apart from visual interpretation of forest fire data, a linear regression analysis was performed between the average temperature, relative humidity, and wind velocity with the number of fire incidences. This study shall act as a baseline for various such parametric studies with the use of the latest technology and empirical studies, with the availability of data in the future. This study will also help the researchers and forest managers analyze the trend of forest fire in Sikkim. From this study, it is evident that the main reason for the forest fire incidences in Sikkim is anthropogenic, and natural forest fire cases are very rare. In Sikkim, factors like humidity, temperature, vegetation type, and rainfall play a crucial role in influencing forest fire incidences.

The Disaster Management Act (2005) recognizes forest fire as one of the major natural disasters in the country. In comparison to other natural disasters like landslides or earthquakes, a forest fire is far more predictable and thus can be prevented. This study would also allow the authority to prepare an administrative and management plan like road approach, water facilities, deployment of resources, equipment, etc., well in time, thus helping prevent and mitigate forest fires in the state.

However, parameter modeling and preparation of forest fire risk zone map with the application of Geo-spatial and other latest technologies is the need of the hour to enable the concerned authority to deploy appropriate resources at places prone to forest fires.

Conflicts of Interest: The authors declare no conflict of interest.

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