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# Assessing Burned Areas in Sikkim, India through Satellite Mapping

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**Abstract**

*Aim of study*: Fire impacts biodiversity and ecosystems, and is crucial for understanding fire causes. This paper aimed to assess burned areas and severity levels in Sikkim's forest fire incidence data from 2004-2019.

*Area of the study*: The study area for the work is the state of Sikkim, situated in the Himalayan Mountain's North-eastern region.

*Material and methods*: Landsat 8 and Landsat 5 satellite image were used for the study and Standard vegetation indices like Delta Normalized Burn Ratio (dNBR) and Relativized Burn Ratio (RBR) are computed. Also, a linear regression analysis was performed between weather parameters like temperature (℃), wind (Km/h), rainfall (mm) on burn severity (dNBR classes) of forest fires in Sikkim between the year 2009-2019.

*Main results*: According to the findings, out of 557 numbers forest fire incidents in Sikkim between 2004 and 2019, 250 numbers were classified as Unburned (46.21 %), 199 numbers as Enhanced Regrowth, Low (35.72 %), and 43 numbers as Enhanced Regrowth, High (7.94 %), while 32 numbers were classified as Low Severity (5.92 %), 9 numbers as Moderate-Low Severity (1.66 %), 5 numbers as Moderate-High Severity (0.92 %), and 2 numbers as High Severity (0.36 %). It was found that the wind (r=0.80, Slope=0.57, SD=0.70) and rainfall (r=0.77, Slope=-0.18, SD=7.00) showed a strong positive and strong negative linear relationships respectively in influencing the burn severity (dNBR). While, temperature (r=0.69, Slope=0.74, SD=0.01) plays a moderate positive role in influencing the burn severity (dNBR).

*Highlights*: The study has shown the effectiveness of burn area mapping and remote sensing data products in analyzing forest fire regions with limited resources and diverse landforms and vegetation. Researchers will be able to identify the regions affected by forest fires and those that have not recovered since the fire. Goal of this research is to improve forest fire planning and management by fostering aid to the responsible authorities to evaluate the pattern of vegetation degradation in burn regions and estimate the impact of forest fires.

***Keywords***: Forest Fire, Burn Area Mapping, Sikkim, Vegetation Indices, Remote Sensing

# Hindistan Sikkim'de Yanan Alanların Uydu Haritalaması Yoluyla Değerlendirilmesi

**Öz**

*Çalışmanın amacı:* Yangın biyolojik çeşitliliği ve ekosistemleri etkiler ve yangın nedenlerinin anlaşılması açısından çok önemlidir. Bu makalede, Sikkim'in 2004-2019 yılları arasındaki orman yangını vaka verilerindeki yanan alanların ve şiddet seviyelerinin değerlendirilmesi amaçlanmıştır.

*Çalışma alanı:* Himalaya Dağı'nın Kuzeydoğu bölgesinde yer alan Sikkim eyaletidir.

*Materyal ve Yöntem:* Çalışmada Landsat 8 ve Landsat 5 uydu görüntüleri kullanılmış ve Delta Normalize Yanma Oranı (dNBR) ve Göreceli Yanma Oranı (RBR) gibi standart bitki örtüsü indisleri hesaplanmıştır. Ayrıca 2009-2019 arasında Sikkim'de yaşanan orman yangınlarının sıcaklık (°C), rüzgar (Km/h), yağış (mm) gibi hava parametreleri ile yanma şiddeti (dNBR sınıfları) arasında doğrusal regresyon analizi yapılmıştır.

*Temel sonuçlar:* Bulgulara göre, 2004 ile 2019 yılları arasında Sikkim'de meydana gelen 557 orman yangını olayından 250 tanesi Yanmamış (%46.21), 199 tanesi Bitki Örtüsünün Yeniden Gelmesi, Düşük (%35.72) ve 43 tanesi Bitki Örtüsünün Yeniden Gelmesi, Yüksek (%7.94), 32 tanesi Düşük seviye (%5.92), 9 tanesi Orta-düşük seviye (%1.66), 5 tanesi Orta-yüksek seviye (%0.92) ve 2 tanesi Yüksek seviye (%0.36) olarak sınıflandırılmıştır. Rüzgarın (r=0.80, Eğim=0.57, SD=0.70) ve yağışın (r=0.77, Eğim=-0.18, SD=7.00) yanma şiddetini (dNBR) etkilemede sırasıyla güçlü pozitif ve güçlü negatif doğrusal ilişki gösterdiği sıcaklığın ise (r=0.69, Eğim=0.74, SD=0.01) yanma şiddetini etkilemede orta derecede pozitif rol oynadığı belirlenmiştir.

*Araştırma vurguları:* Çalışma, sınırlı kaynaklar, çeşitli yer şekilleri ve bitki örtüsüne sahip orman yangını bölgelerinin analizinde yanan alan haritalama ve uzaktan algılama veri ürünlerinin etkinliğini göstermiştir. Araştırmacılar, orman yangınlarından etkilenen ve yangından bu yana iyileşmeyen bölgeleri tespit edebilecektir. Bu araştırmanın amacı, yanan bölgelerdeki bitki örtüsü bozulma modelini değerlendirmek ve orman yangınlarının etkisini tahmin etmek için sorumlu makamlara yardım sağlayarak orman yangını planlamasını ve yönetimini iyileştirmektir.

**Anahtar Kelimeler:** Orman Yangını, Yanan Alan Haritalama, Sikkim, Vejetasyon İndisleri, Uzaktan Algılama

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## Introduction

Forest fires are a natural hazard with serious threats to ecology, biodiversity, habitats, and the human population, leading to financial losses (Parajuli et al., 2020 ; Pausas et al., 2008 ; Bowman et al., 2018). Forest fire is commonly recognised as one of the most significant influences on the atmosphere and ecological structure (Chuvieco et al., 2019 ; Joseph et al., 2009). According to the FOA 2020 study, the global forest cover is 4.06 billion hectares, 31% of the total number of the entire land area on the globe. Each year there is a decrease of around 5.2 million hectares of forest land which is alarming, forest fires are one major cause of this loss (Sewak et al., 2021). According to a national assessment, the Forest Survey of India 2011(b), every year India burns approximately 6,70,000 hectares of forest land, accounting for around 2% of the world's forest land area. India's forest cover is 71.22 Mha, which is 21.67% of the total area (Axel, 2018). The Forest Survey of India reported that approximately 1.45 million hectares of forest are destroyed by fire each year in a national assessment conducted in 1995 (Joseph et al., 2009). Extensive forest fires occur at regular intervals in dry humid deciduous forest of central followed by Northeast, North and South India (World Bank, 2018) leading to destruction of vegetation, animals, limiting species variety, harming natural regeneration, negative influence on forest composition, structure and species diversity (Shijo et al., 2009). Forestry is the second most important land use, contributing for around 1.5% of the country's GDP (World Bank, 2005). Around 6.5 million people are directly affected by fire as they rely on forest for their livelihood (Satendra, 2014). Sikkim experiences increasing trends in forest fire incidences every year, damaging about 5047.16 ha of forest land (Sharma, K., & Thapa, G. (2021). Forest fires involving brief to moderate return intervals are prevalent in Sikkim during the winter season i.e., November to March and the peak fire season lies from March to April. About 40% of forest in Sikkim are exposed to forest fire during the fire season out of the total 45.97% of forest cover (Sharma et al., 2014). East Himalayan Sal (3C/C1a (I)) has the highest forest fire risk of all the forest types. Satellite photography revealed that subtropical woods and the Sal Forest had the greatest proportion of fire scorched areas. Oak trees have a high calorific value ; the fire adopts the form of a canopy and continues over several days, disrupting the regeneration of the species (Sharma et al., 2012). Forest fires are becoming more common in Sikkim, resulting in forest loss and ecological imbalance. According to Sikkim's forest fire data from 2009, 905 hectares of land were destroyed (Sharma et al., 2021). Severity of a burn indicates determining how the fire's intensity impacts the environment in and around the burned area. It is essential to precisely map the fire severity to analyse and comprehend the ecological and economic repercussions and dangers of a specific wildfire and integrate associated control measures (Whitman et al., 2018). Conventional methods make it difficult to map burn intensity, especially in landscapes with varying topography and inaccessible areas. Burn area mapping has resulted in a high level of classification accuracies and is essential for developing several levels of restoration procedures to reduce the harmful effects of a forest fire (Mallinis, G., & Koutsias, N. 2012 ; Mallinis et al.,2009 ; Gaveau et al., 2021).

Forest fire suppression is based on a combination of contemporary technology and traditional wisdom. Identification and analysis of various indicators of forest fire is essential for combatting the losses done by forest fire (Pourtaghi et al., 2016 ; Bajocco et al., 2017 ; Jafarzadeh et al., 2017). Technology such as geographic information systems (GIS), remote sensing, and computer modelling are being used in many aspects of wildland fire suppression (Elmahdy et al., 2022 ; Tiwari et al., 2021 ; Vega Orozco et al., 2012). In mapping fire zones, estimating fire intensity, and mapping fire burnt regions, remote sensing techniques combined with GIS have proven to be successful (Reddy et al., 2017 ; Gomez et al., 2019 ; Parajuli et al., 2020). For forest fire analysis, GIS has been used in conjunction with a number of methods, including logistic regression, analytic hierarchy process (AHP), multicriteria analysis and fuzzy analysis, and neural network analysis (Petković et al., 2020 ; Sevinc et al., 2020 ; Gigovic et al., 2018 ; Pourghasemi, 2016 ; Tien Bui et al., 2016 ; Adab et al., 2013 ; Malik et al., 2013 ; Safi, Y., & Bouroumi, A. 2013). Satellite data enables the systematic detection and mapping of resources, ecology, and activities. The statistics obtained from the analysis of these data can be utilized for various scientific, organizational, and commercial purposes (Reddy et al., 2017). The Monitoring Trends in Burn Severity (MTBS) Project, a collaboration between USDA Forest Service and the US Geological Survey, has been instrumental in advancing the use of Landsat data for wildfire monitoring both nationally and internationally in recent years (Ghorbanzadeh et al., 2019 ; Tonini et al., 2017). There are a variety of satellite-based products with spatial resolutions ranging from medium (30 m) to high (10 m) that may be used to precisely map burned areas at the global and regional levels. Landsat-8, the most recent generation of Landsat satellites, as well as prior generations of Landsat satellites such as Landsat Thematic and Landsat Enhanced thematic, have already been extensively utilized to identify and map forest and land fires (Harvey et al., 2019 ; Key et al., 2006 ; Mouillot et al., 2014 ; Kumari & Pandey, 2020 ; Bar et al., 2020). Burn severity mapping is more successful when the ratio of near-infrared and shortwave infrared of the electromagnetic spectrum is combined, according to several researchers, since the burned region has a higher reflectance than green vegetation in the Short-Wave Infrared Region (SWIR) (Fitriana et al., 2018; Miller et al., 2009; Cansler, C.A., & Mckenzie 2012). Opposite impacts of fire in NIR and SWIR reflectance are the most commonly researched methods for mapping burn severity-associated spectral variance. The difference in Normalized Burn Ratio (dNBR) and its derivations have become a popular method for analysing spectrum fire affects fast. The two most often used Landsat-based burn severity metrics are the delta normalised burn ratio (dNBR) and its relativized counterpart (RBR), both based on the normalised burn ratio (Parks et al., 2014; Key et al., 2006). The NBR is calculated using the normalised difference between a bandwidth containing the NIR (0.76–0.90 m) and a SWIR (2.08–2.35 m).

The result is dNBR, which is obtained by subtracting a post-fire NBR image from a pre-fire NBR image (Whitman et al., 2018 ; Cansler, C.A., & Mckenzie 2012 ; Sharma et al., 2012). The quantity of chlorophyll in vegetation, wetness, and charcoal or ash in the soil are all factors that affect NBR. To measure spectral change, the equations for dNBR and RBR use NBR obtained from pre/post satellite images. Both indicators are substantially correlated with field-based burn severity evaluations and are sensitive to changes caused by fire (Miller et al., 2007 ; Key et al., 2006). The main purpose of creating a forest fire potential map is to locate zones vulnerable to forest fires, where there is a higher risk of fire initiation, development, and spread in the immediate area (Nikhil et al., 2021 ; Ahmad et al., 2018).

The zone identification helps to identify areas with a higher danger of fire which generates optimal conditions for minimising the number of fires that occur (Sachdeva et al., 2018 ; Toujani et al., 2018).

Forest fire, in addition to other natural dangers such as landslides and earthquakes, is one of the most serious threats in Sikkim's forests. Many indigenous and endangered species in the forests of Sikkim are adversely affected due to these forest fires. The forest fire affects the environment and biodiversity. From the literature it is found that there is some study on the impact of environmental change due the forest fire in this Himalayan state. Sharma et al., 2012 made an attempt and prepared a forest fire database of Sikkim using IRS LISS III imagery. Similarly, potential threat caused by forest fires in Himalayan environment was reported by Sachdeva et al. (2018) and Thakur, A. K., & Singh, D. (2014).

In literature, the authors do not find any work on the burn area mapping of data for a long period in the forest area in Sikkim. Burn area mapping helps in the segmentation of the forest area into fire prone forest and the forest area that is not susceptible to forest fire. The major goal of this study was to determine where forest fires are most likely to occur, which is important for understanding the variables that cause forest fires and for designing actions to prevent, manage, and decrease the effect of forest fires.

In this paper, Landsat 5 (2004-2011) and Landsat 8 (2014 -2019) satellite datasets are used to map the burn severity of State of Sikkim, India. Both the Landsat 5 and Landsat 8 data were downloaded freely from www.earthexplorer.com. However, the year 2012, 2013 and 2015 was not considered for the study due to the unavailability of reliable datasets. Both Landsat 8 and Landsat 5 satellite data have a spatial resolution of 30m and a revisiting period of 16 days.

The research will help the future researchers to 1) detect and map recent burnt area with the use of remotely sensed data 2) relate the areas identified with the burn area map for identifying the related biophysical factors for forest fire 3) ascertain the spatial distribution of the areas prone to fire 4) identify the weather parameters that have influence on forest fire.

## Materials and Methods

*Study Area*

The study area for the work is the state of Sikkim, situated in the Himalayan Mountain's North-eastern region. With a size of 7096 square kilometres, it is India's second-smallest state. The 78A1 through 78A15 series of Survey of India topographic sheets cover the area between 27° 5' S and 28° 9' N latitude and 87° 9' W and 88°56' E longitude (Sharma et al., 2012). Figure 1 depicts the study area.

The terrain of Sikkim is varied, with altitudes ranging from 300 metres to 8586 metres above mean sea level. The yearly rainfall ranges from 2700 mm to 3200 mm, and the annual temperature ranges from minus 20°C in the winter to 28°C in the summer (Sharma et al., 2012).

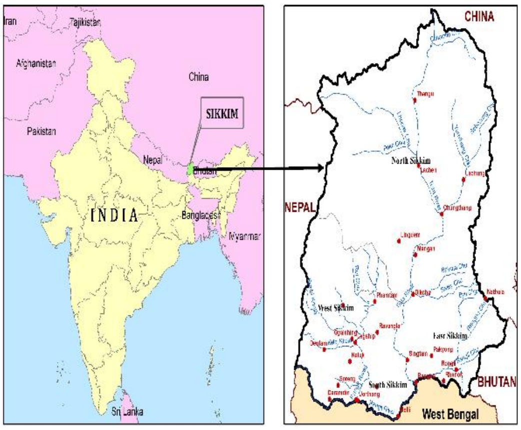


Figure 1. Location map of Sikkim (Sharma et al., 2021)

Sikkim's forest cover accounts for 47.11% of the total land area, with canopy densities varying from extremely thick forest (15.53%), moderately dense forest (12.88%), and open forest (12.88%) (9.70%). Tropical moist deciduous woods, subtropical broadleaved Hill forests, Montane wet temperate forests, Himalayan moist temperate forests, Subalpine forests, and Moist alpine scrub are the six principal forest types found in Sikkim (Sharma et al., 2012). Figure 2 depicts the study area.

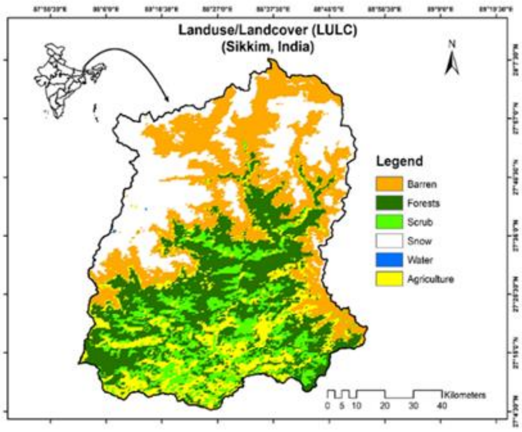


Figure 2. Map showing Land Use Land Cover state of Sikkim

According to research done in Sikkim, the incidence of forest fires has increased over time, with the highest number occurring in 2009. Woodland fires are most common below 1500 metres in the subtropical Sal (*Shorea robusta*) forest, especially during the winter months (December to February extending into March).

The forest fires in Sikkim's west district burned the most land, followed by the south and east districts, with the north district suffering the least (Sharma & Thapa, 2021).

*Data Collection and Pre-processing*

Landsat 8 and Landsat 5 satellite datasets of pre fire (before the fire) and post fire (after the fire) incidence was downloaded from earthexplorer.com (Table 1). The study area was clipped and appropriate boundary was considered for the study. The datasets consist of 9 spectral bands for Landsat 8 and 7 spectral bands with spatial resolution of 30m.The format of the dataset is GeoTIFF. Level of Landsat 8 and Landsat 5 data collected is level one terrain corrected product (L1T).

Table 1. Satellite data description for pre and post forest fire incidences of Sikkim

| Sl. No. | Year | Day/Month/Year (Pre, Post) | Sensor | GSD (m) |
|---|---|---|---|---|
| 1 | 2004 | 27/12/2003, 29/12/2004 | Landsat 5(TM) | 30 |
| 2 | 2005 | 29/12/2004, 5/11/2005 | Landsat 5(TM) | 30 |
| 3 | 2006 | 14/11/2005, 3/12/2006 | Landsat 5(TM) | 30 |
| 4 | 2007 | 04/01/2007, 03/10/2007 | Landsat 5(TM) | 30 |
| 5 | 2008 | 03/10/2007, 21/10/2008 | Landsat 5(TM) | 30 |
| 6 | 2009 | 09/01/2009, 25/11/2009 | Landsat 5(TM) | 30 |
| 7 | 2010 | 11/12/2009, 02/04/2010 | Landsat 5(TM) | 30 |
| 8 | 2011 | 14/12/2010, 27/08/2011 | Landsat 5(TM) | 30 |
| 9 | 2012 | No data | | |
| 10 | 2013 | No data | | |
| 11 | 2014 | 06/12/2013, 07/11/2014 | Landsat 8 (OLI) | 30 |
| 12 | 2016 | 29/01/2016, 27/10/2016 | Landsat 8 (OLI) | 30 |
| 13 | 2017 | 30/12/2016, 17/12/2017 | Landsat 8 (OLI) | 30 |
| 14 | 2018 | 01/12/2017, 04/12/2018 | Landsat 8 (OLI) | 30 |
| 15 | 2019 | 04/12/2018 21/11/2019 | Landsat 8 (OLI) | 30 |

The incidence data (2004-2019) is collected from Forest and Environment Department, Government of Sikkim. The incidence data was collected immediately after the forest fire incidence by the concerned department officers and recorded the GPS locations.

The incidence data in excel format is converted to .csv format for further processing. The data’s various fields are Date, Location, Area Cover, Vegetation, District, Range, Year, Latitude and Longitude. The data points of the incidence were laid into the satellite imagery for cross verification and the burn severity is computed.

Weather data (monthly) of Sikkim was collected from https://www.worldweatheronline.com for the years 2009-2019. The weather data used for the analysis were temperature (°C), wind (Km/h), rainfall (mm).

*Methodology*

The methodology for finding the burn severity is performed with the use of Landsat 8 and Landsat 5 Pre and post fire satellite imagery of the state of Sikkim. Indices like Normalised Burn Ratio (NBR), Normalised Difference Water Index (NDWI), Delta Normalised Burn Ratio (dNBR), and Relativised Burn Ratio (RBR) were computed for the study (Figure 3).

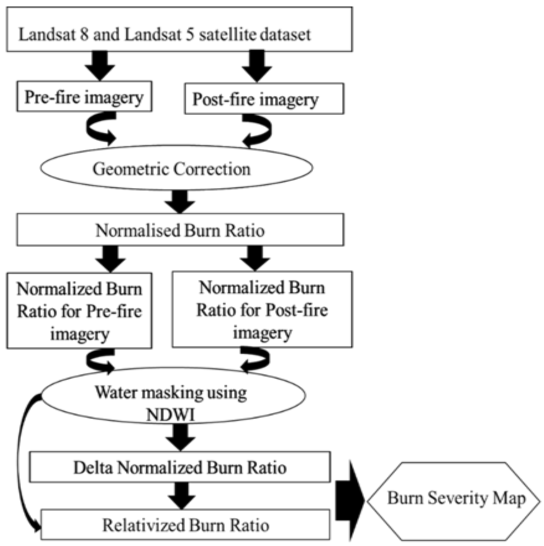


Figure 3. Methodology for the proposed work

The Normalized Burn Ratio (NBR) is a technique for assessing burned areas in fire areas (Bar, Somnath et al.; 2020) and is computed by the equation (1).

$$NBR = \frac{Near\ Infrared - Shortwave\ Infrared}{Near\ Infrared - Shortwave\ Infrared} \quad (1)$$

The Normalised burn ratio was computed for pre (before fire) and post (after fire) imagery for the years i.e., (2004-2011) and (2014 -2019). The Normalized Burn Ratio (NBR) pre and Normalized Burn Ratio (NBR) post for Landsat 8 is computed using the band combinations as shown the equation (2).

$$NBR\ Landsat\ = \frac{Band\ 5 - Band\ 7}{Band\ 5 + Band\ 7} \quad (2)$$

$$NBR\ Landsat\ 5 = \frac{Band\ 4 - Band\ 7}{Band\ 4 + Band\ 7} \quad (3)$$

To differentiate the spectral reflectance of the burnt areas with water bodies Normalised Difference Water Index (NDWI) (Özelkan, 2020 ; Han-Qiu, 2005) was computed for both the NBR pre and NBR post Imagery for the years i.e., (2004-2011) and (2014 -2019)., hence making the water body pixels prominent. The NDWI was computed using the (equation (4))

$$DWI = \frac{Green - Near\ Infrared}{Green + Near\ infrared} \quad (4)$$

The NDWI pre and post for Landsat 8 and Landsat 5 was computed using the band combinations as shown in the (equation (5)) and (equation (6)) respectively ;

$$NDWI\ Landsat\ 8 = \frac{Band\ 3 - Band\ 6}{Band\ 3 + Band\ 6} \quad (5)$$

$$NDWI\ Landsat = \frac{Band\ 3 - Band\ 6}{Band\ 3 + Band\ 6} \quad (6)$$

The Delta Normalised Burn Ratio (dNBR) (Bar, Somnath.; 2020) was computed for the years i.e., (2004-2011) and (2014 -2019) using the (equation (7)),

$$dNBR = NBR\ (Prefire) - NBR\ (Postfire) \quad (7)$$

The Relativised burn ratio (RBR) (Parks et al., 2014) is computed by dividing the Delta Normalised burn ratio (dNBR) by the pre-fire NBR. The denominator will never be 0 after adding 1.001 to the numerator, keeping the calculation from nearing infinity and failing. Relativised burn ratio (RBR) was computed for the years i.e., (2004-2011) and (2014 -2019) using the equation (8)

$$RBR = \frac{dNBR}{NBR\ pre + 1.001} \quad (8)$$

**Result**

Forest fire incidence data for the year 2004-2019 were collected from the Forest and Environment Department, Government of Sikkim. Landsat 8 and Landsat 5 satellite datasets of pre fire (before the fire) and post fire (after the fire) incidence with reference to the forest fire incidence data was downloaded from earthexplorer.com. However, the year 2012,2013 and 2015 was not considered for the study due to the unavailability of reliable datasets. Weather data (monthly) of Sikkim was collected from https://www.worldweatheronline.com, Data were available for the years (2009-2019). The weather data used for the analysis were temperature (°C), relative humidity (%), wind (Km/h), rainfall (mm).

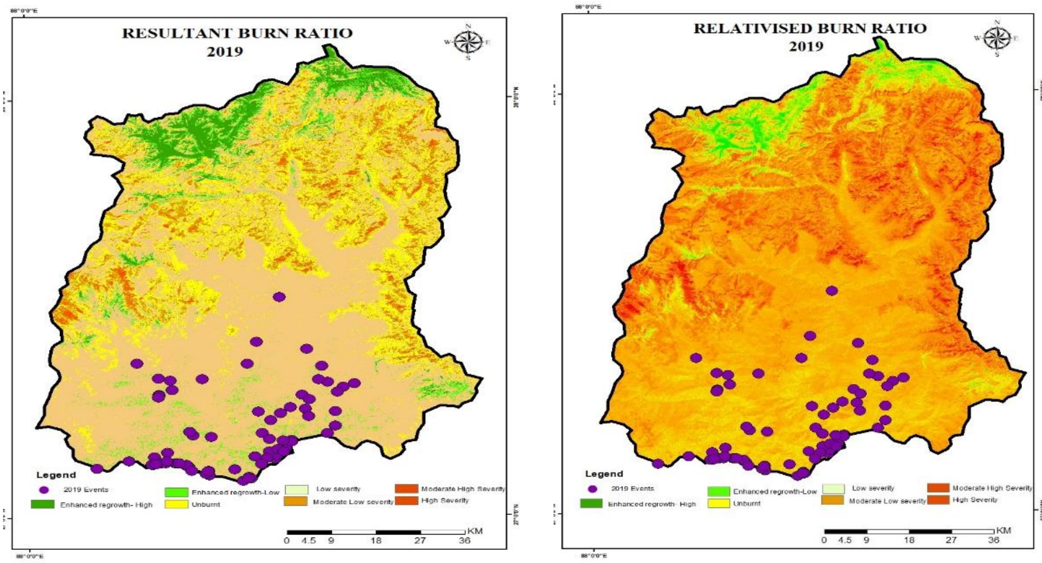


Figure 4. Map showing Delta Normalised Burn (dNBR) burn severity map (on the left) and Relativised Burn ratio (RBR) map (on the right) for 2019 of the State of Sikkim

Figure 4 (on the left), depicts that forest fire incidences of 2019 occurring in the Eastern, Southern and Western part of the state of Sikkim. The forest fire incidences are mostly Unburned regions with spectral resolutions between (-100 to 99) with few regions falling under Enhanced Regrowth, Low with spectral resolutions between (-200 to -101) as shown by dNBR computation. Figure 4 (on the right) shows that forest fire incidences of 2019 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are under High severity with spectral resolution between (660 to 1300) as shown by RBR computation.

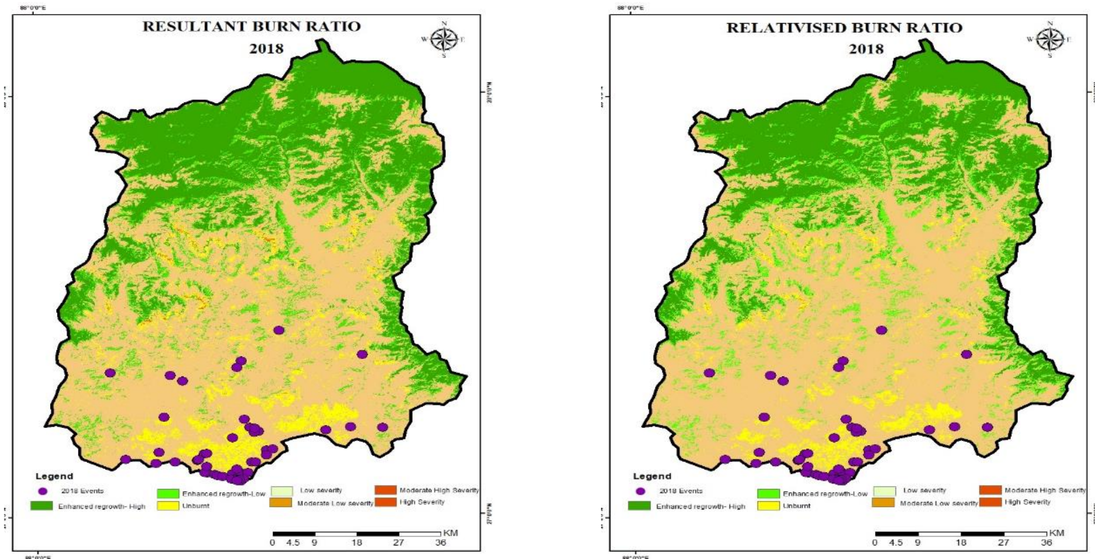


Figure 5. Map showing Delta Normalised Burn (dNBR) burn severity map (on the left) and Relativised Burn ratio (RBR) map (on the right) for 2018 of the State of Sikkim

Figure 5 (on the left), depicts that forest fire incidences of 2018 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are mostly Unburned regions with spectral resolutions between (-100 to 99) in the Western and Eastern part while the forest fire incidences in the southern part are under

Unburned, Low severity and Enhanced regrowth, Low with spectral resolution between (-100 to 99) , (-100 to 99) and -200 to-101) respectively, as shown by the dNBR computation. Figure 5 (on the right) shows that forest fire incidences of 2018 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

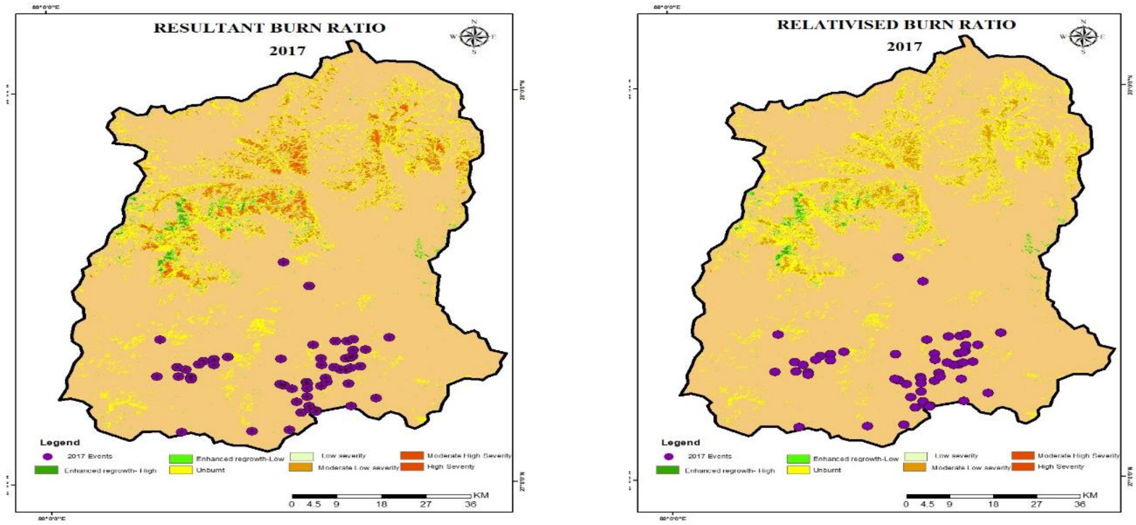


Figure 6. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2017 of the State of Sikkim.

Figure 6 (on the left), depicts that forest fire incidences of 2017 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are mostly Unburned regions with spectral resolutions between (-100 to 99) as shown by the dNBR computation. Figure 6 (on the right) shows that forest fire incidences of 2017 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation for 2017 of the State of Sikkim.

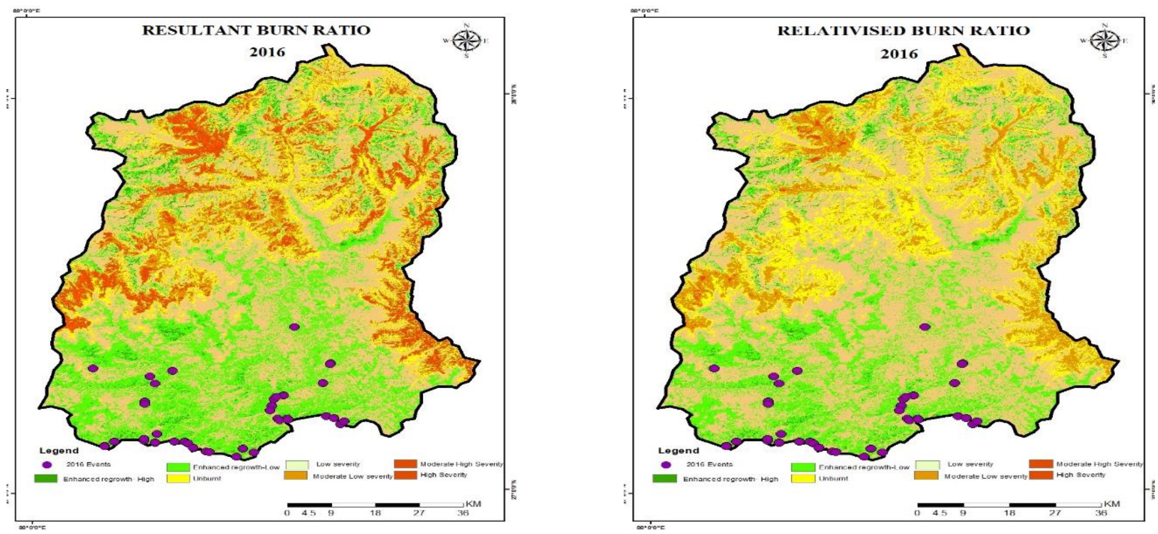


Figure 7. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2016 of the State of Sikkim

Figure 7 (on the left), depicts that forest fire incidences of 2016 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are mostly Unburned, Enhanced regrowth, Low with spectral resolutions between (-100 to 99) and (-200 to-101) respectively, as shown by the dNBR computation. Figure 7 (on the right) shows that forest fire incidences of 2016 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

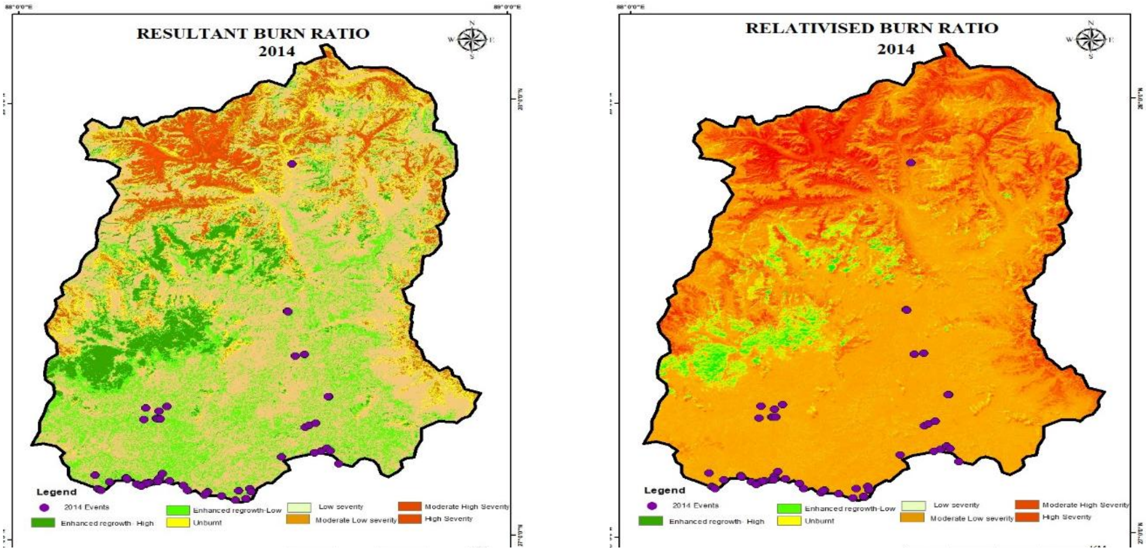


Figure 8. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2014 of the State of Sikkim

Figure 8 (on the left), depicts that forest fire incidences of 2014 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences in the southern part are mostly Unburned with spectral resolutions between (-100 to 99) while the western part fall under Enhanced Regrowth, Low with spectral resolutions between (-200 to -101) as shown by the dNBR computation. Figure 8 (on the right) shows that forest fire incidences of 2014 occurring in the eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are under the High severity with spectral resolution between (660 to 1300) as shown by the RBR computation.

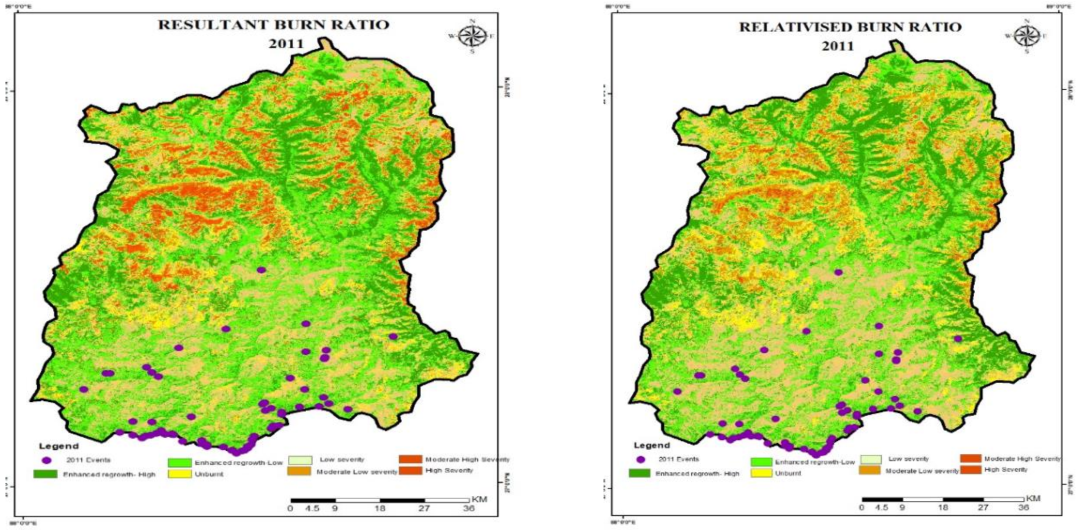


Figure 9. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2011 of the State of Sikkim

Figure 9 (on the left), depicts that forest fire incidences of 2011 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are mostly Enhanced Regrowth, Low and Enhanced Regrowth, High with spectral resolutions between (-200 to-101) and (-500 to -251) respectively with few regions as Unburned, as shown by the dNBR computation. Figure 9 (on the right) shows that forest fire incidences of 2011 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the DNBR computation.

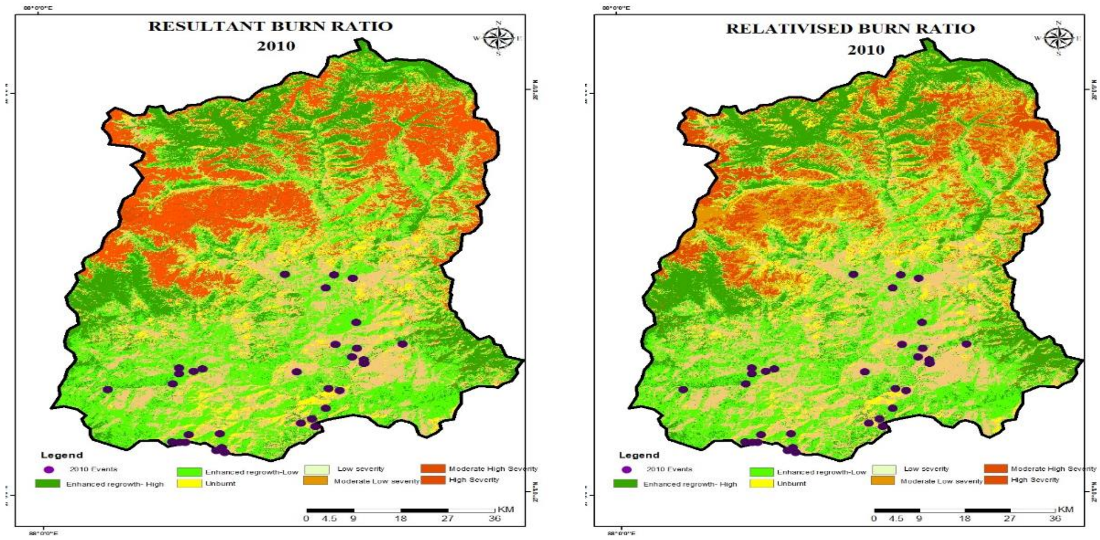


Figure 10. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2010 of the State of Sikkim

Figure 10 (on the left), depicts that forest fire incidences of 2010 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are mostly Unburned, Enhanced Regrowth, Low with spectral resolutions between (-100 to 99) and (-250 to -101) while some regions fall under low severity with spectral resolutions between (100 to 269) as shown by the dNBR computation. Figure 10 (on the right) shows that forest fire incidences of 2010 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

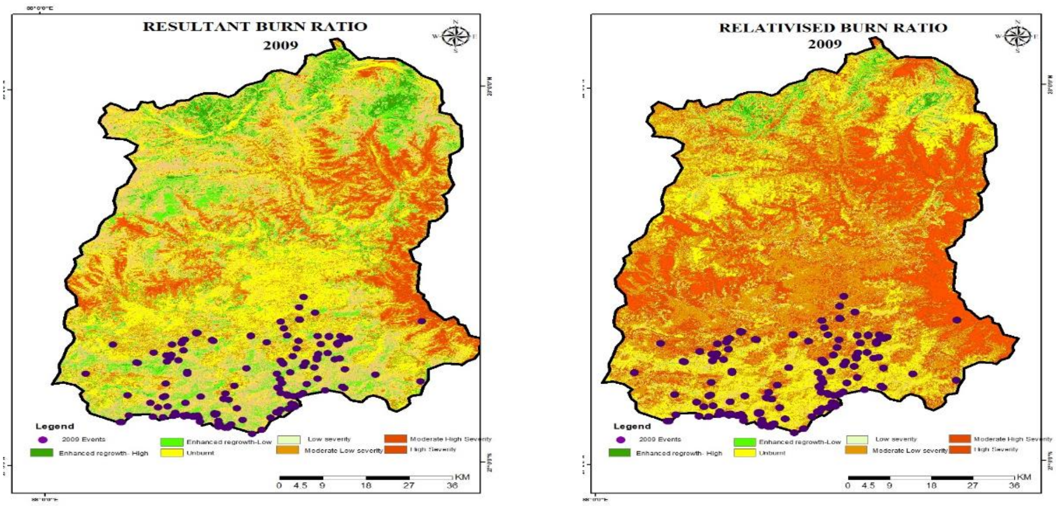


Figure 11. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2009 of the State of Sikkim

Figure 11 (on the left), depicts that forest fire incidences of 2009 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are Unburned, Enhanced Regrowth, Low, Enhanced Regrowth, High, Low Severity and Moderate -Low Severity with spectral resolutions between (-100 to 99), (-250 to -101), (-500 to -251), (100 to 269) and (270 to 439) respectively as shown by the dNBR computation. Figure 11 (on the right) shows that forest fire incidences of 2009 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are Unburned, Enhanced Regrowth, Low, Low Severity with spectral resolutions between (-100 to 99), (-250 to -101) and (100 to 269) as shown by the RBR computation.

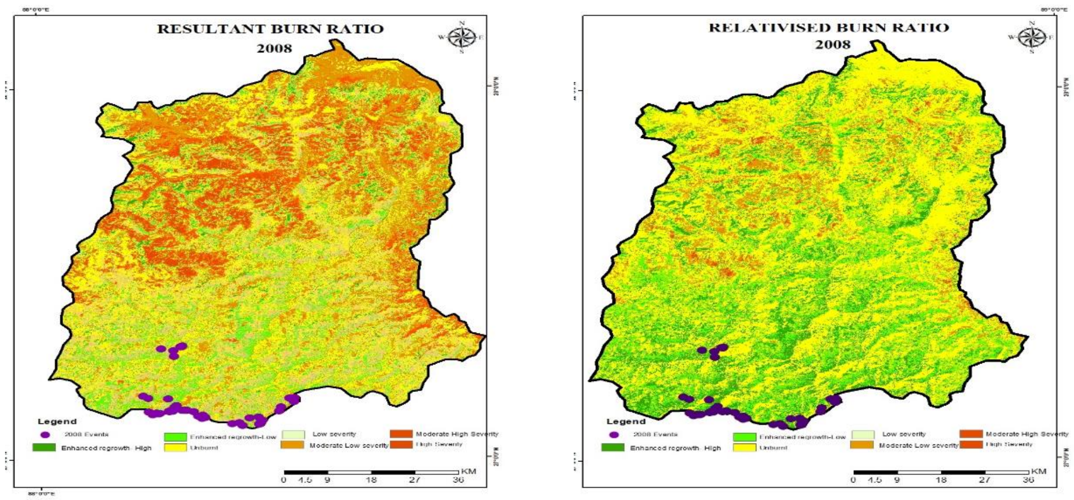


Figure 12. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2008 of the State of Sikkim

Figure 12 (on the left), depicts that forest fire incidences of 2008 occurring in the Southern and Western part of the state of Sikkim, the forest fire incidences are unburned, Enhanced Regrowth, Low, Enhanced Regrowth, High and Low Severity with spectral resolutions between (-100 to 99), (-250 to -101), (-500 to -251) and (100 to 269) as shown by the DNBR computation. Figure 12 (on the right) shows that forest fire incidences of 2008 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

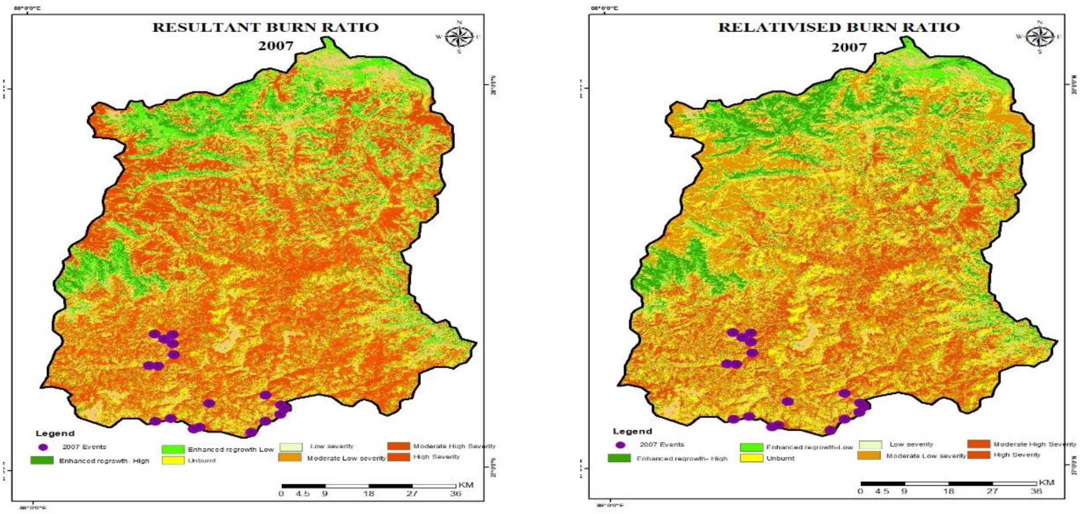


Figure 13. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2007 of the State of Sikkim

Figure 13 (on the left), depicts that forest fire incidences of 2007 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are Low Severity, Moderate Severity Low and Moderate Severity High and High severity with spectral resolutions between (100 to 269), (270 to 439), (440 to 659) and (660 to 1300) as shown by the dNBR computation. Figure 13 (on the right) shows that forest fire incidences of 2007 occurring in the Eastern, Southern and Western part of the state of Sikkim, the fire incidences are Low Severity, Moderate Severity Low and Moderate Severity High with spectral resolutions between (100 to 269), (270 to 439), (440 to 659) as shown by the RBR computation.

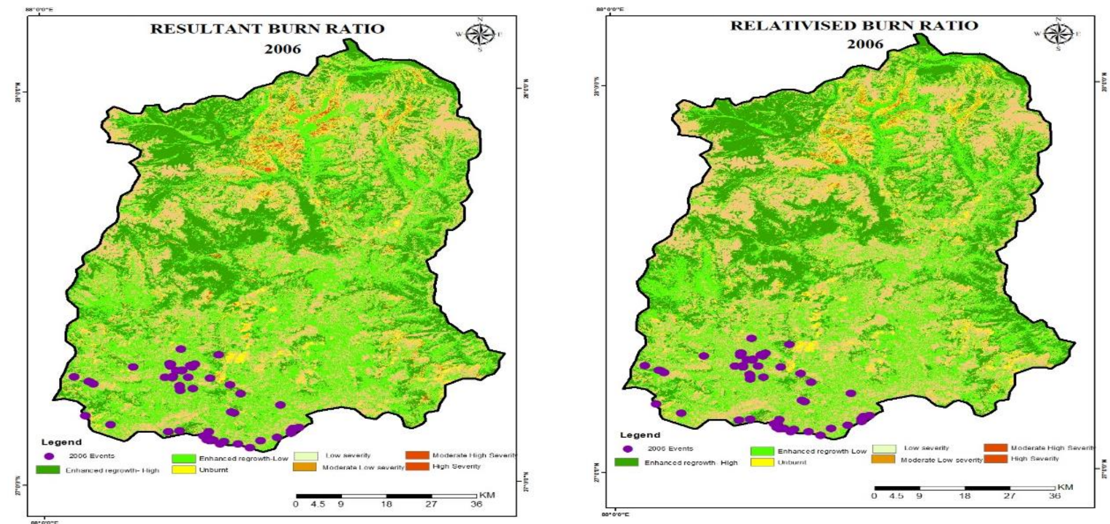


Figure 14. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio map (RBR) for 2006 of the State of Sikkim.

Figure 14 (on the left), depicts that forest fire incidences of 2006 occurring in the Southern and Western part of the state of Sikkim, the forest fire incidences are Unburned, Enhanced Regrowth, Low and Low Severity, with spectral resolutions between (-100 to 99), (-250 to -101) and (100 to 269) as shown by the dNBR computation. Figure 14 (on the right) shows that forest fire incidences of 2006 occurring in the Southern and Western part of the state of Sikkim, the fire incidences are Low Severity, Moderate Severity, Low with spectral resolutions between (100 to 269) and (270 to 439) as shown by the RBR computation.

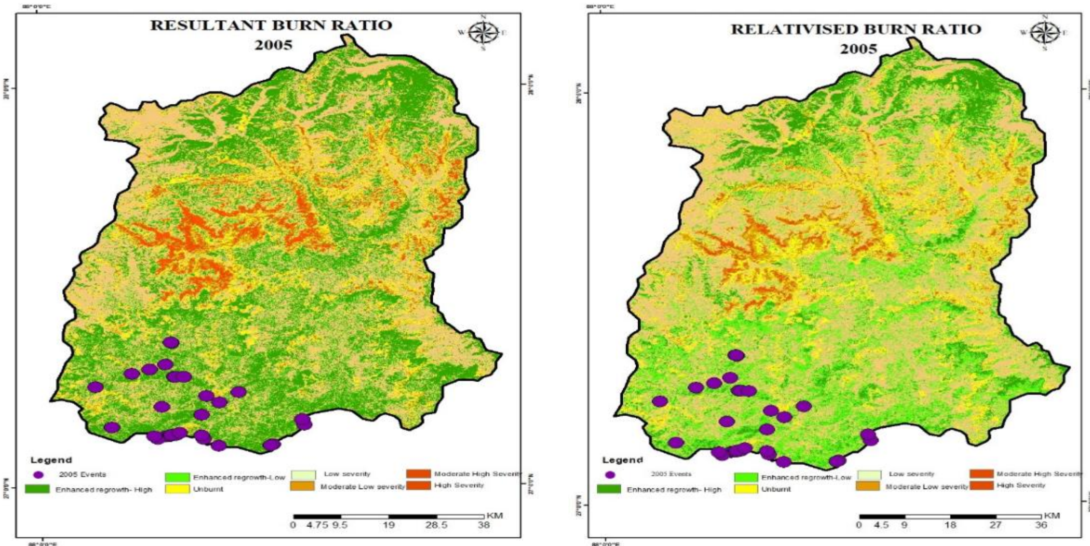


Figure 15. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2005 of the State of Sikkim

Figure 15 (on the left), depicts that forest fire incidences of 2005 occurring in the Southern and Western part of the state of Sikkim, the forest fire incidences are Unburned, Enhanced Regrowth, Low, Enhanced Regrowth, High and Low Severity, with spectral resolutions between (-100 to 99), (-250 to -101), (-500 to -251) and (100 to 269) as shown by the dNBR computation. Figure 15 (on the right) shows that forest fire incidences of 2005 occurring in the Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

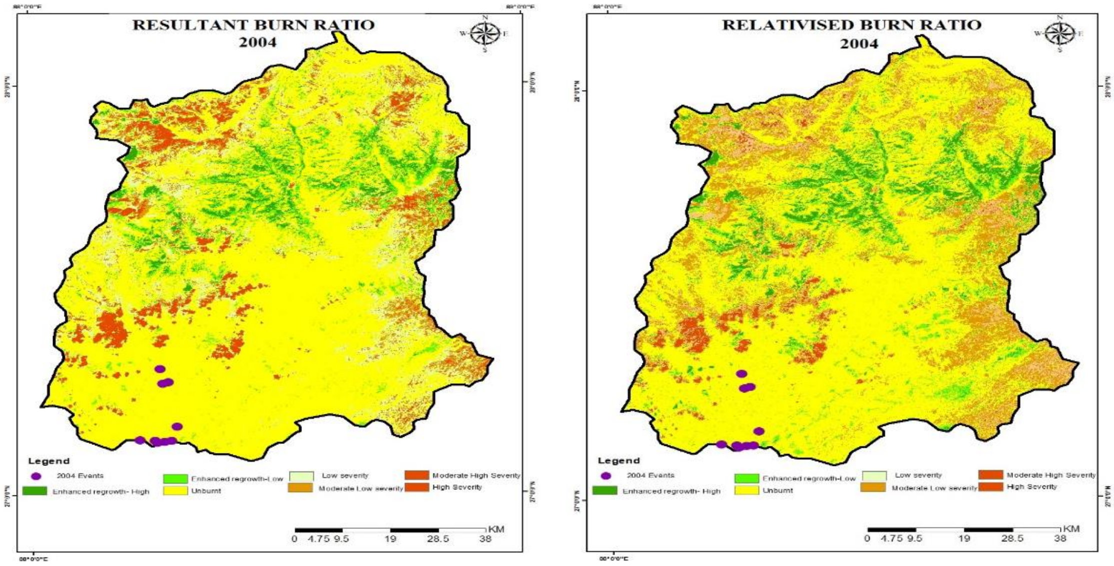


Figure 16. Map showing Delta Normalised Burn (dNBR) burn severity map and Relativised Burn ratio (RBR) map for 2004 of the State of Sikkim

Figure 16 (on the left), depicts that forest fire incidences of 2004 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences are Unburned with spectral resolutions between (-100 to 99) as shown by the dNBR computation. Figure 16 (on the right) shows that forest fire incidences of 2004 occurring in the Eastern, Southern and Western part of the state of Sikkim, the forest fire incidences as shown by the RBR computation showed similar results as the dNBR computation.

*Linear Regression Plots*

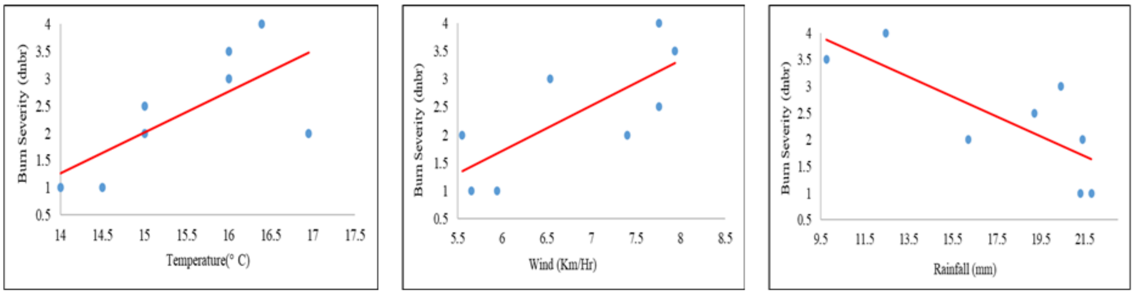


Figure 17. Linear regression plot for burn severity (DNBR classes) with temperature (on the left), wind (on the middle) and rainfall (on the right)

From Figure 17 (on the left), it is evident that there is a moderate positive influence of temperature on burn severity (dNBR) (r=0.69, Slope=0.74, SD=0.01). Figure 16 (on the middle), shows that the wind has a strong positive influence on burn severity (dNBR) wherein the best fit was found for wind (r=0.80, Slope=0.57, SD=0.70) and Figure 16 (on the right), shows strong negative influence of rainfall on burn severity (r=0.77, Slope=-0.18, SD=7.00).

*Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences of various districts in the state of Sikkim (2004-2019).*

Table 2. Delta Normalised Burn Ratio severity levels (DNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2019.

| Sl. No. | District | Range | dNBR Burn Severity | RBR Burn Severity |
|---|---|---|---|---|
| 1 | East | Ranipool | 3 | 7 |
| | | Gangtok | 3 | 7 |
| | | Pakyong | 3 | 7 |
| | | Singtam | 3, 2 | 7 |
| 2 | South | Melli | 3, 2 | 7 |
| | | Lingmo | 3 | 7 |
| | | Namthang | 3, 2 | 7 |
| | | Namchi | 3 | 7 |
| | | Rabong | 3 | 7 |
| 3 | West | Tashiding | 3 | 7 |
| | | Gyalshing | 3 | 7 |
| | | Soreng | 3 | 7 |
| | | Yuksam | 3 | 7 |

Table 3. Delta Normalised Burn Ratio severity levels (dNBR)and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2018.

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | East | Pakyong | 3 |
| | | Rongli | 3 |
| 2 | South | Lingmo | 3, 2 |
| | | Rabong | 3 |
| | | Melli | 3 |
| | | Melli | 3, 4 |
| | | Namchi | 3, 4 |
| | | Namthang | 3, 4 |
| 3 | West | Soreng | 3, 4 |

Table 4. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2017.

| Sl. No. | District | Range | DNBR Burn Severity | RBR Burn Severity |
|---|---|---|---|---|
| 1 | East | Pakyong | 3 | 3 |
| | | Gangtok | 3 | 3 |
| | | Singtam | 3, 4 | 3 |
| | | Ranipool | 3 | 3 |
| 2 | South | Melli | 4 | 3 |
| | | Rabong | 3 | 3 |
| 3 | West | Yuksam | 3 | 3 |
| | | Gyalshing | 3 | 3 |
| | | Soreng | 3 | 3 |

Table 5. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2016

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | East | Singtam | 3, 2 |
| | | Ranipool | 3 |
| | | Gangtok | 3 |
| 2 | South | Melli | 3, 2 |
| 3 | West | Gyalshing | 2 |
| | | Soreng | 3, 2 |
| | | Tashiding | 3 |
| | | Sombaria | 2 |

Table 6. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2014

| Sl. No. | District | Range | dNBR Burn Severity | RBRBurn Severity |
|---|---|---|---|---|
| 1 | East | Pakyong | 3, 2 | 7 |
| | | Gangtok | 3 | 7 |
| | | Singtam | 3, 2 | 7 |
| 2 | South | Melli | 3, 2 | 7 |
| 3 | West | Sombaria | 3, 2 | 7 |
| | | Soreng | 3, 2 | 7 |
| | | Tashiding | 3, 2 | 7 |
| | | Gyalshing | 3, 2 | 7 |

Table 7. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2011

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | East | Gangtok | 2, 1 |
| | | Singtam | 3, 2, 1 |
| | | Rongli | 2 |
| | | Pakyong | 3, 2, 1 |
| 2 | South | Melli | 3, 2, 1 |
| | | Namthang | 3, 2, 1 |
| | | Namchi | 2 |
| | | Lingmo | 1 |
| 3 | West | Soreng | 1, 2, 3 |
| | | Tashiding | 2 |
| | | Dentam | 3 |
| | | Gyalshing | 2, 3 |

Table 8. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2010

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | East | Singtam | 3, 2 |
| | | Gangtok | 1, 3, 2 |
| | | Pakyong | 4 |
| 2 | South | Namthang | 4 |
| | | Melli | 3, 2 |
| 3 | West | Gyalshing | 3, 2 |
| | | Tashiding | 3, 2 |
| | | Dentam | 3 |
| | | Soreng | 3, 2 |

Table 9. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2009

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | East | Singtam | 3, 2, 4 |
| | | Pakyong | 3, 2 |
| | | Barapathing | 3 |
| | | Ranipool | 3, 2 |
| | | Gangtok | 3, 4, 2 |
| | | Tumin | 3, 5, 2 |
| 2 | South | Namchi | 3, 4 |
| | | Namthang | 3, 2 |
| | | Melli | 3, 2, 4 |
| | | Lingmo | 4 |
| | | Rabong | 2 |
| 3 | West | Gyalshing | 3, 2, 4 |
| | | Soreng | 3 |
| | | Sombaria | 3, 2, 5 |
| | | Tashiding | 2, 3, 4, 5 |

Table 10. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2008

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | South | Namthang | 1, 2, 4 |
| | | Rabong | 3 |
| | | Melli | 1, 2, 3 |
| 2 | West | Gyalshing | 1, 3 |
| | | Tashiding | 1, 3 |
| | | Soreng | 1, 2, 3, 4 |

Table 11. Delta Normalised Burn Ratio severity levels (dNBR) (on the left) and Relativised Burn Ratio severity levels (RBR) (on the right) for forest fire incidences in the state of Sikkim for 2007

| Sl. No. | District | Range | dNBR Burn severity | RBR Burn severity |
|---|---|---|---|---|
| 1 | South | Melli | 5, 7 | 5, 6 |
| | | Namchi | 6 | 6 |
| | | Namthang | 4, 6, 7 | 4, 6 |
| 2 | West | Soreng | 4 | 4 |
| | | Gyalshing | 3, 5 | 3, 5 |
| | | Tashiding | 3, 5, 6 | 3, 4, 5 |
| | | Yuksam | 4 | 4 |

Table 12. Delta Normalised Burn Ratio severity levels (dNBR) (on the left) and Relativised Burn Ratio severity levels (RBR) (on the right) for forest fire incidences in the state of Sikkim for 2006

| Sl. No. | District | Range | dNBR Burn Severity | RBR Burn Severity |
|---|---|---|---|---|
| 1 | South | Namchi | 2, 5, 3 | 5, 6 |
| | | Rabong | 2, 3 | 5 |
| | | Melli | 2, 3 | 5, 4 |
| | | Namthang | 3, 3 | 5, 4 |
| 2 | West | Dentam | 2, 3 | 5 |
| | | Sombaria | 2, 3 | 4, 5 |
| | | Tashiding | 2 | 4 |
| | | Gyalshing | 2, 3, 4 | 2, 3, 4 |
| | | Soreng | 2, 3 | 5 |

Table 13. Delta Normalised Burn Ratio severity levels (dNBR) and Relativised Burn Ratio severity levels (RBR) for forest fire incidences in the state of Sikkim for 2005

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | South | Namthang | 1 |
| | | Melli | 1, 2, 3, 5 |
| | | Namchi | 1, 4 |
| | | Rabong | 1 |
| 2 | West | Soreng | 3, 4 |
| | | Gyalshing | 1, 3, 4 |
| | | Tashiding | 1, 2, 4 |
| | | Sombaria | 3 |

Table 14. Delta Normalised Burn Ratio severity levels (dNBR) (on the left) and Relativised Burn Ratio severity levels (RBR) (on the right) for forest fire incidences in the state of Sikkim for 2004

| Sl. No. | District | Range | dNBR/RBR Burn Severity |
|---|---|---|---|
| 1 | West | Gyalshing | 3 |
| | | Soreng | 3 |

## Discussion

The burn area mapping of the forest fire incidences for the year 2004-2019 showed that the forest fire in Sikkim is mostly ground fire and concentrated in the West, South and East region of the State, while negligible incidences of forest fire was recorded in the North. The severity levels of burn area mapping as depicted by the dNBR and RBR computation showed that in the western part of Sikkim, Tikjek Khasmal, Reythang Bhir, Byadong Khasmal in Gyalsing Range, Zoom Sipsoo, Chyandara in Soreng Range, Simaybong Khasmal in Tashiding Range, Salangthang Khasmal in Sombaria Range, Bhalukhop, Karjee in Yuksum Range and Dentam Range are the areas with frequent forest fire incidences with severity levels corresponding to Unburned (no change) (38.74%), 40.31% area experienced moderate fire damage, and vegetation regrowth is occurring at a slower pace (Enhanced Re-growth Low), but contrastingly, 9.94% of area shows improved vegetation recovery after moderate burning (Enhanced Re-growth High), 8.37% of the area experienced low-severity fire, with minor impacts on vegetation and rapid recovery, 2.09% area caused moderate damage, but still had a moderate overall impact on vegetation (Moderate Low Severity) while 0.52% area show severe damage, requiring longer recovery periods and potential ecosystem changes (Moderate High Severity).

In the South district of Sikkim areas of frequent forest fires are Ralong Bhir, Lingding Khasmal, Biring Khasmal, Kartike in Rabong Range, Majhitar, Kateng RF, Bhusuk RF, Chirbirey, Sumbuk in Melli Range, Suminkhor RF, Chalamthang RF, Mamring, Englishey bhir Khasmal, Turung Kirtipur Khasmal, Samardung RF and Kateng
RF in Namthang Range and Kitam Bird Sanctuary, Satan Khasmal in Namchi Range are the areas with frequent forest fires with severity levels falling under Unburned (no change) (45.89%), Enhanced Re-growth Low (33.75%), Enhanced Re-growth High (10.14%), Moderate Low Severity (1.93%), Moderate High Severity (1.45%) and High Severity (0.97%).

In the East district of Sikkim frequent forest fires were encountered in Namli Bhir, Chongey Khasmal in Ranipool Range, Nam Nam Bhir, Bhusuk RF, Malangthang in Gangtok Range, Burung Khas, Mining RF in Singtam Range, Tankilakha, Pachey, Khanikhola, Amba, Bhasmey RF in Pakyong Range and Kyongnosla Range. The severity levels were found to be under Unburned (no change) (56.64%), Enhanced Re-growth Low (33.57%), Enhanced Re-growth High (2.10%), Low Severity (4.90%), and Moderate Low Severity (0.70%). While for the years 2019 and 2014 the RBR computations showed that all the incidence of forest fire falls under the high severity (100%).

According to the study, forest fires occur frequently and intensely in various districts, with the West displaying recurrent events and the South and East having higher fire frequencies. Evidently, the severity ratings in the years 2019 and 2014 were exceptionally high, indicating significant forest fire events during these times. The East district has less area under enhanced re-growth high compared to the South and West districts. This is likely due to the presence of middle hill miscellaneous forests with lower fire tolerance. Whereas, in other districts, most fire occurred in the Sal forests, which are more fire-tolerant species and also have a warmer area where regeneration is rapid. Additionally, Sal seedlings show a die-back phenomenon, aiding in forest recovery post-fire.

The study highlights the various vegetation types destroyed by the forest fires. The affected flora includes Sal (*Shorea robusta*), Teak (*Tectona grandis*), Chilauney (*Schima wallichii*), Chirpine (*Pinus roxburghii*), Patle Katus (*Castanpsis hystrix*), Simul (*Bombax ceiba*), Lampatey (*Duabanga grandiflora*), Saur (*Betula Sp.*), Dhupi (*Cryptomeria japonica*), Dhalne Katus (*Castanpsis indica*), Mauwa (*Engelhardtia spicata*), mixed species of Bamboo, Banana (*Musa Sp.*), and ground flora like Salimbo (*Cynodon dactylon*), Dry leaves, small bushes.

As evident from the linear regression plots (Figure 17), the temperature has a moderate positive relation with forest fire. Drier air and reduced fuel moisture in vegetation brought on by higher temperatures increase the intensity of fires. As a result, fires are more likely to start and spread and burn more intensely (Cansler & McKenzie, 2012 ; Parks et al., 2016). Wind has shown a strong positive influence on forest fire. Wind has a big impact on how a fire behaves and how badly it burns. Strong winds hasten the progress of the fire, sparking spot flames ahead of the main fire front and igniting fresh areas (Taylor et al., 2015 ; Lareau et al., 2020) whereas the linear regression plots has shown inverse relationship of rainfall on forest fires. Rainfall has a negative impact on burn intensity, particularly in areas with sufficient moisture. Abundant rain enhances the moisture content of the fuel, lowers the flammability of the plant, and prevents the spread of fire. Wildfire burn severity decreases as precipitation increases (Kolden et al., 2012 ).

## Conclusion

Burn area maps of forest fire incidences (2004-2019) were computed for the state of Sikkim in this study. The study has demonstrated the importance of burn area mapping and the use of remote sensing data products in analysing forest fire areas with scarce resources and varied landforms and vegetation. This study will allow researchers to identify the areas of forest fires and those that have been unable to recover post-fire. It is intended that this study will contribute to strengthening the planning and management of forest fires by allowing the responsible authorities to observe the pattern of vegetation degradation in burn areas to assess the impact of forest fires.

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## Peer-review

Externally peer-reviewed.

## Author Contributions

Conceptualization, Investigation, Material and Methodology: Mrs. Kapila Sharma; Supervision: DR. Gopal Thapa and DR. Salghuna NN. All authors have read and agreed to the published version of manuscript.

## Conflict of Interest

The authors have no conflicts of interest to declare.

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