Characterization of forest fire frequency using fire scar mapping of temporal satellite data for forest fire management

Jugal Kishore Mani* and A. O. Varghese

Regional Remote Sensing Centre-Central, NRSC, ISRO, Amravati Road, Nagpur, Maharashtra-440033, India

Date Received: 23-08-2021 Date Accepted: 28-12-2021

Abstract

One of the most complex problems facing in tropical forests, particularly in deciduous forests, is the recurrent incidence of fire. It is well known that fire caused extensive damage in the forest ecosystem by quantitatively and qualitatively. To reduce occurrences of forest fire, proper management of fire is highly important which entails mapping of forest fire frequency and identification of suitable area for watchtowers. In the present study, fire frequency analysis of Melghat Tiger Reserve, Maharashtra was done for the last seven years (2014-2020) based on the fire scar on the temporal Landsat data during fire season (January-June). Fire frequency analysis shows that an area of 1053.64 ha (0.52%) of the reserve was burned all seven years followed by 3050.53 ha (1.49%) for six times, 3849.52 ha (1.88%) for five times, 5520.04 ha (2.70%) for four times, 11845.63 ha (5.80%) for three times, 36863.52 ha (18.03%) for two times, 70126.33 ha (34.31%) for once and 72093.02 ha (35.27%) remains unburned all these seven years. The fire frequency map generated was used as an input for prioritizing the locations of watch towers as well as prioritizing grazing closure areas and fires lines. Identification of suitable sites for locating new watchtowers has been done by integrating and modeling of forest fire frequency map, existing watchtowers and viewshed analysis in GIS. Based on these results only thirteen watchtowers were categorized under retainable among the existing watchtowers and 27 new watchtowers are proposed to cover the entire area.

Keywords: Fire scar, fire frequency, viewshed analysis, forest fire watchtower, geospatial technology

1. Introduction

Forest fire generally is a natural phenomenon, besides natural fire some forests are also get affected by anthropogenic fires. These fires may prove harmful or beneficial depending on the season or forest type. In India, 21.67% of total geographical area is actually covered with forest land (FSI, 2019). Every year large areas of forests are impacted by fires of varying intensity and extent. Based on the forest inventory records, 54.40% of forests in India are exposed to occasional fires, 7.49% to moderately frequent fires and 2.40% to high incidence levels while 35.71% of India's forests have not yet been exposed to fires of any real significance (FSI, 2019). It is well known that fire causes extensive damage in the forest ecosystem by quantitatively as well as qualitatively (Bright et al., 2019; Reddy et al., 2020; Halofsky, 2020). Forest fires have environmental impact in terms of tropical biomass burning, which produce large amount of trace gases, aerosol particles, and play a key role in troposphere chemistry and climate anomalies (Kannemadugu et al., 2015). Precious forest resources, including carbon locked in the biomass, are losing due to forest fires every year (Menon et al., 1999; Varghese, 1997; Juárez-Orozco et al., 2017; Reddy et al., 2018), which adversely impact the flow of goods and services from forests. Indian National Working Plan Code (2014) specify to carry out fire frequency and burnt area mapping for fire vulnerability identification for working plan preparation.

**Correspondence: correspondence email address: jugalmani@gmail.com*
Tel: 07122851215

Satellite based remote sensing technology and geographic information system (GIS) tools have been effective in better prevention and management of fires through creation of early warning for fire prone areas, monitoring fires on real time basis and estimation of burnt scars (Prasanth et al., 2009; Mani and Varghese, 2018; Axel, 2018). The temporality of the satellite data helps in analyzing the frequency of forest fires of a particular area. The study area, Melghat Tiger Reserve (MTR), covering dry deciduous forest, shed their leaves and spread like a thick carpet on the ground. Tall dry grasses and Lantana all over the study area make thick cover of dry leaf litter contribute potential fuel for surface fire. This surface fires often occur in Melghat forests, which spread very fast to vast areas covering deep valleys and rugged high hills. Due to these reasons mapping of fire frequent zones is necessary to classify the areas into different categories and manage it accordingly. A large variation exists between exact area burnt and area reported by ocular method by the forest staff. Most of times the area reported are always less than reality, or sometimes they are highly exaggerated. Nearly an error of average 17% is present between the ground and reported areas (Varghese and Suryavanshi, 2017). Error is introduced from primary stage as burnt area estimation technique is ocular without surveying in detail. Forest department cannot be blamed for faulty estimation of burnt areas. There are no skilled surveyors to draw maps accurately and moreover scientific instruments preset are also very less. This estimated error increases as data goes on secondary sources. This result into decline of significance in the post fire treatment specified for maintenance of burnt area. The use of geospatial technology in forest fire management will result in minimized work and higher accuracy (Parajuli et al., 2020). It also aims to prove its utility along with the conventional methods for assisting the forest managers to mitigate forest fires. In the present study attempted to map the fire frequency in MTR forest by fire scar mapping on satellite data during the forest fire season and suitability analysis for location of forest fire watchtowers for fire management.

2. Methodology

2.1 The study area

Melghat Tiger Reserve (MTR) is situated in the Satpura hill ranges of Central India. Melghat Tiger Reserve lies in Amravati district in Vidarbha region of Maharashtra, bordering Madhya Pradesh in the North and East. Melghat Tiger Reserve has a huge area covering 2027 square kilometer which is divided into three divisions for management purpose, i. e. Akot, Sipna and Gugamal divisions (Figure 1).

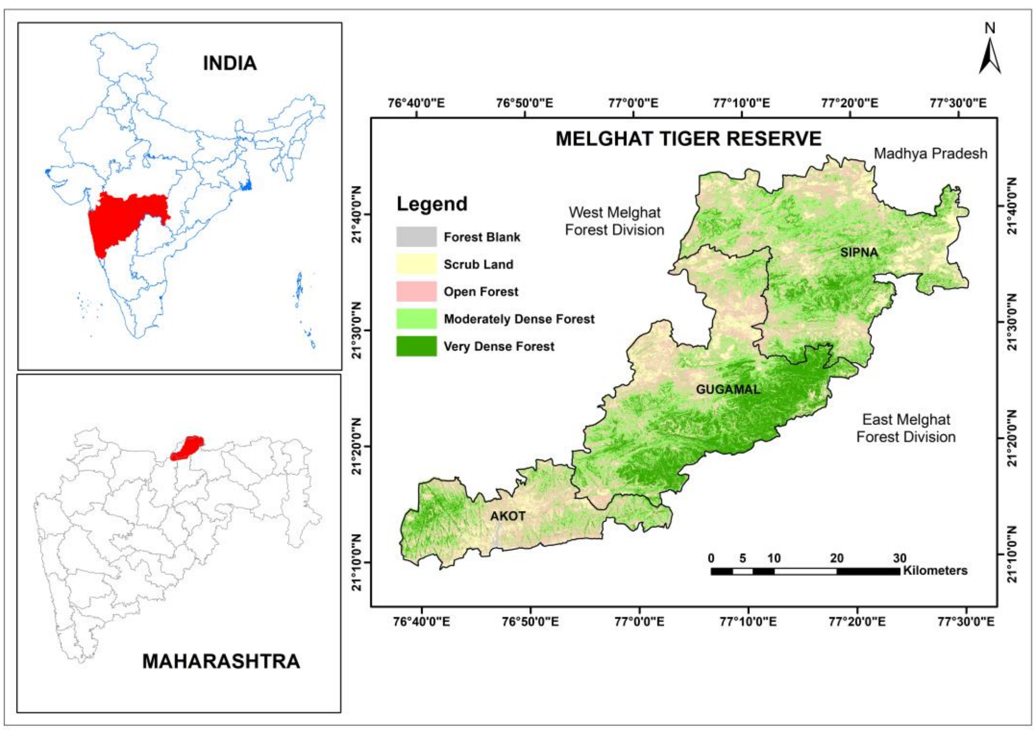

Figure 1. Location map of the Melghat Tiger Reserve with forest density classes

Most of the forest is dry deciduous, consisting of teak and bamboo species along with patches of other species like *Madhuca latifolia* (Mahuwa), *Diospyrous melanoxylon* (Tendu), etc. Lantana has severely invaded majority of the area (Varghese and Suryavanshi, 2017). The leaves of all these species and grass together acts as catalyst for frequent forest fire. Vegetation and climate both are interdependent on one another; climate itself determines the type of vegetation present in the reserve i.e dry deciduous forest. Summer is very hot having a maximum temperature of 48˚C and winter is cool with a minimum temperature recorded is 4˚C. Good rainfall is received during monsoons which varies from 950 to 1400 mm. Average height ranges between 381 m and 1100 m above mean sea level. These hills and valleys have constant abrupt variation in aspect and gradient, about 8 to 10% of the area is steep escarpment. Fire usually spreads more quickly up on slope as compared to the down slope. As flames rise up the vegetation present on the upper side gets fire and spreads ahead.

2.2 Data used and approach

Melghat Tiger Reserve is located in Central India, which consists of dry deciduous forest, prone to forest fires. Annually, wildfire crops up from 15th February to 15th June in summer months. But in some rare circumstances, November to January is also seen as fire season (Varghese and Suryavanshi, 2017). Forest policy infers that, after each fire, the amount of area that is burnt due to fire has to be estimated, damage caused is calculated and reported to the ministry. Based on the area burnt, post fire treatments are carried out. In the present study, January to June have been considered as fire season and these six months Landsat satellite series data downloaded from USGS website (https://earthexplorer.usgs.gov/, Accessed 16 February 2021) and mosaicked to cover the full extent of the study area. January to June monthly data of 2014 to 2020 have been prepared for the fire season months. Forest fire scars are clearly visible on these satellite image and this information was digitized on-screen. To avoid the duplication of fires scar in one fire season, only fire scar map of each year has been generated. So, fire scars of each of the months have been put together and generated the area burned in that particular year. The fire scar map generated for all the seven years were integrated and derived fire frequency map. Existing fire watchtowers do not cover the entire area of MTR for monitoring the incidence of fire, so the fire frequency map generated was used as an input for prioritizing the locations for installation of watchtowers. Identification of suitable sites for locating new watchtowers has been done by integrating and modelling of forest fire frequency map, existing watchtowers and visibility analysis in GIS. There are three main methods of computing visibility analyses i.e., line of sight, viewshed and visibility. Here viewshed analysis is used with present and proposed watchtowers as observer points/cell. Viewshed is created over a DEM using an algorithm that estimates the difference in elevation in the observer's cell and the target cell. Viewshed will analyze an unobstructed view from an observer point (also called a view source) to an object of interest (target) in any direction, where the target is coincident with the ground. The analysis uses the elevation value of each cell of the digital elevation model (DEM, https://bhuvan.nrsc.gov.in/, Accessed 8 December 2020) to determine visibility to or from a particular cell. Radius for the line of sight for each tower was given 10 km with a height of observation of 10 m.

3. Results

As illustrated in the previous section, year wise fire occurrence maps are generated and utilized for the preparation of fire history or fire frequency map. Fire frequency map was generated by adding together individual years fire occurrence data for the last seven years (Figure 2). As shown in figure 2, 2016 recorded the highest area burned with 94767.16 ha followed by the year 2015 (47448.80 ha), 2014 (32731.28), 2017 (29556.31), 2020 (22090.68), 2018 (14245.77) and 2019 (6224.76). Area wise burned scar are more registered in Sipna division and Akot is more susceptible to fire with percentage wise of burned area. Some areas in MTR are targets for fire due to grazing, non-wood forest produce (NWFP) collection etc., by local people.

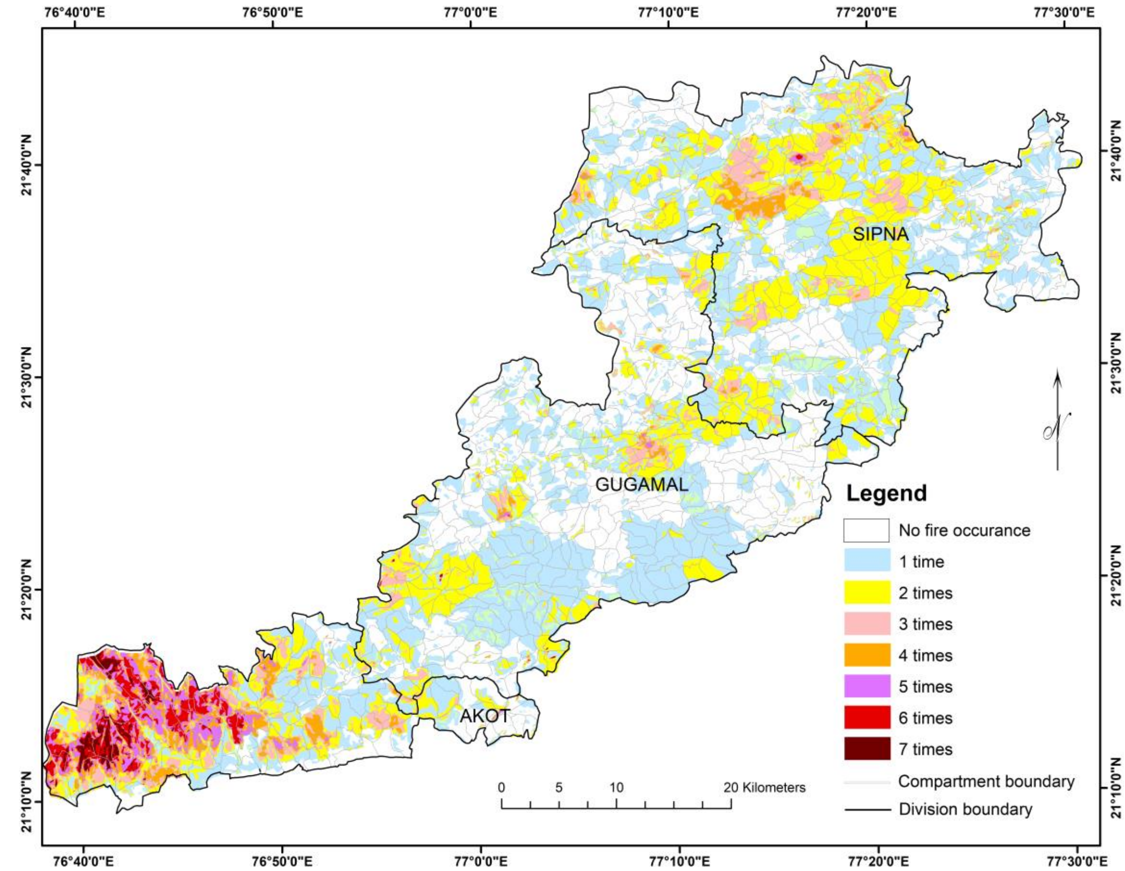

Figure 2. Fire frequency map of Melaght Tiger Reserve overlaid on compartment and range boundaries

Fire frequency map is generated in the scale of 0 to 7 based on the seven years fire history map. Frequency seven denotes all seven years that area is burned and 0 denotes there is no fire occurrence. Fire frequency map shows that an area of 1053.64 ha (0.52%) of the Melghat Tiger Reserve burned all seven years followed by 3050.53 ha (1.49%) for six times, 3849.52 ha (1.88%) for five times, 5520.04 ha (2.70%) for four times, 11845.63 ha (5.80%) for three times, 36863.52 ha (18.03%) for two times, 70126.33 ha (34.31%) for once and 72093.02 ha (35.27%) remains unburned all these seven years. Division wise information on fire frequency shows that percentage of burnt area in high frequency classes is more in Akot forest division. Gugamal division registered less percentage of area in high frequency classes and nearly 46.01% of area falls under unburned category. In Sipna division more area falls under one time burned category (35.78%). Frequent fires contribute to the rapid invasion of exotic fire adopted species. Species like *Lantana camara* and *Chromolaena odorata* colonize regions where frequent fire occurs (Narendran, 2001).

A fire watchtower provides housing and protection for the officials whose duty it is to search for wildfires in the wilderness. The fire lookout tower is normally a small structure, usually located on the summit of a mountain or other high vantage point, in order to maximize the viewing distance and range, known as viewshed. The viewshed analysis provided vital information about the viewability of the existing fire watchtowers. Viewshed analysis using digital elevation model (DEM) is a powerful tool to identify visibility a particular location to its preferred periphery. A visual field or isovist is defined as a visual area that is wholly visible across the system from a defined vantage point (Benedikt, 1979). The watchtowers in MTR are categorized into three categories i. e. proposed, removable and retainable based on the visibility and fire frequency (Figure 3).

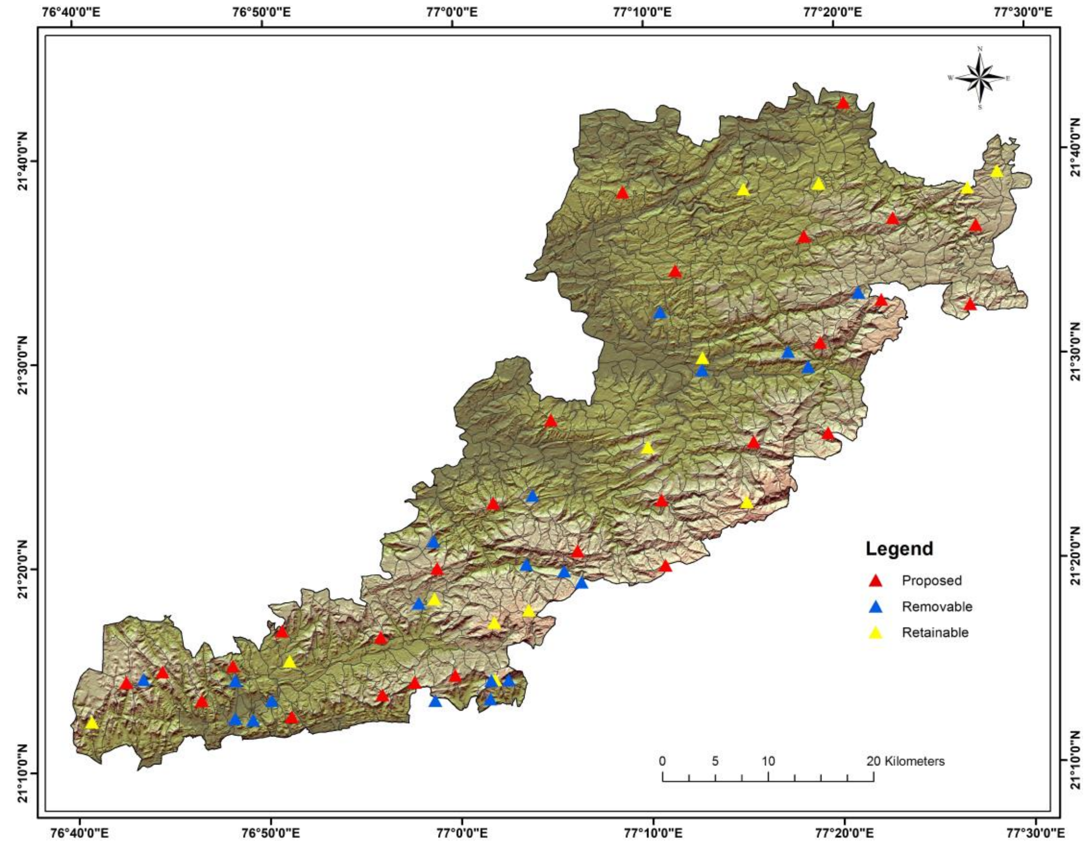

Figure 3. Site suitability for forest fire watchtowers in Melghat Tiger Reserve overlaid on DEM

A total of thirty-three forest fire watchtowers are existing in the tiger reserve. Among the existing watchtowers, only thirteen watchtowers were categorized under retainable. The remaining watchtowers were eliminated due to their locations i. e. close to another watchtower, in the valley from where area visibility is very less, located near to villages, unnecessarily present when other watchtowers could cover the same area and considering tourist watchtower as fire watchtower. Based on the above criteria's and its modelling in GIS and viewshed analysis as mentioned above, twenty-seven new watchtowers were proposed along with the watchtowers that were to be retained. New watchtowers are proposed at a location having a higher elevation to cover the maximum area as MTR is entirely in hilly terrain. Existing watchtowers could not cover newly identified fire prone areas like compartments near Chikali, Kelpani, Dhargad, etc. The retained old watchtowers and newly proposed watchtowers together cover the entire area of Melghat Tiger Reserve without any gap in between.

4. Discussion

Fire frequency can be defined as the sum of times that fires happen within a distinct area and time period. Fire frequency is also a mathematical expression of fire incidence or rate, such as the average time interval between successive fires or the number of fires within a specific period of time. It is a generic term referring to general fire occurrence or rate (Firewords, 2018).

Fire frequency is one of the key components of fire regime, together with the pattern and the intensity of wildfires which prevail in a region (Pyne et al., 1996). Characterizing fire frequency has many implications for fire ecology and for fire risk assessment. Most of the studies in forest fire focused on mapping of the extent and severity of forest fire but not much emphasis is made on the management practices that prevent further spread of fires and its control with infrastructure developments. Many studies have done by using viewshed analysis for validating the viewable areas for forest fire mitigation (Cheng et al., 1998; Che-Bin and Ahuja, 2004) but integrating fire frequency for site suitability analysis of watchtowers is a novel approach in the present study. For the preparation of management plan to mitigate fire annually, year wise fire frequency map is required to be generated (Rao et al., 2007). Frequency of fire occurrence changes with the change in season and year. Hence, Indian National Working Plan Code (2014) specify to analyze particulars of the places along with area affected by fire and appropriate measures taken for the last five years for the working plan revision.

Mainly three methods are used in fire frequency generation from satellite imageries. The first one is by visual interpretation of temporal satellite data as demonstrated here. The second method is based on digital classification of the satellite data through various supervised or unsupervised classifiers. The third method is by using spectral indices (SI) with threshold classification technique. Various SI are developed for the detection of burn scar and fire severity analysis based on the combination of visible, near infrared, and shortwave infrared domains of the electromagnetic spectrum. Burn Area Index (Martin et al., 1998), Normalized Burn Ratio (Key and Benson, 2006), Normalized Difference Moisture Index (Wilson and Sader, 2002), Burned Area Index Modified-LSWIR (Martin et al., 2006), Burned Area Index Modified-sSWIR (Martin et al., 2006), Mid Infrared Burn Index (Trigg and Flasse, 2001), Tasseled Cap Brightness, Tass Cap Greenness, Tass Cap Wetness index (Crist and Cicone, 1884; Crist, 1985) and Global Environmental Monitoring Index (Pinty and Verstraete, 1992) are some of commonly used SIs. The main disadvantage of using digital or SIs based methods is the low classification accuracy. It is very difficult to digitally classify burn scars from other land cover classes especially wet and barren areas. The burn scar analysis demands high classification accuracy because these inputs are using for various management as well as commercial purposes. Collection of Non-Timber Forest Produce (NTFP) of some of the forest divisions in India are restricted if the burned areas are more than the specified limit. So, the present study outline method for the identification of suitable sites for locating watchtowers by integrating and modeling of forest fire frequency map, existing watchtowers and viewshed analysis in GIS.

5. Conclusion

To formulate the strategy for the forest fire management information, forest fire frequency plays a pivotal role. The present findings documented a methodology to derive fire frequency using fire scar mapping on satellite data considering Melghat Tiger Reserve in Maharashtra as a study site. Fire frequency analysis was done for the last seven years (2014-2020) based on the fire scar on the temporal Landsat satellite series data during the fire season. The fire frequency map generated along with existing forest fire watchtowers and viewshed analysis was used for the identification of suitable sites for installation of watchtowers for monitoring and management of forest fire in MTR. The present findings emphasis that the utility of geospatial technology in forest fire frequency mapping and identification of sites for installation of forest fire watchtowers for an effective forest fire monitoring and management with minimum cost and time.

Acknowledgment

Authors extend their sincere gratitude to Regional Remote Sensing Centre-Central, National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO) and Additional PCCF, Melghat Tiger Reserve, Maharashtra for providing opportunity and facility to conduct the study. The technical support provided by RRSC-Central staff is duly acknowledged. We are also thankful to USGS Earth Explorer maintained by the NASA and bhuvan-Indian Geo Platform maintained by NRSC, ISRO for online accessibility of Landsat data and DEM, respectively. Authors are also thankful to the anonymous reviewers.

References

Axel, A.C., 2018. Burned Area Mapping of an Escaped Fire into Tropical Dry Forest in Western Madagascar Using Multi-Season Landsat OLI Data. *Remote Sensing* 10(3), 371-387. https://doi.org/10.3390/rs10030371.

Benedikt, M.L., 1979. To Take Hold of Space: Isovists and Isovist Fields. *Environment and Planning B: Planning and Design* 6(1), 47-65. https://doi.org/10.1068/b060047.

Bright, B.C., Hudak, A.T., Kennedy, R.E., Braaten, J.D., Khalyani, A.H., 2019. Examining post-fire vegetation recovery with Landsat time series analysis in three Western North American forest types. *Fire Ecology* 15, 1-14. https://doi.org/10.1186/s42408-018-0021-9.

Che-Bin, L., Ahuja, N., 2004. Vision Based Fire Detection. Pp 134-137 in *Proceedings of 17th International Conference on Pattern Recognition*, 23 August 2004, United States. https://doi.org/10.1109/ICPR.2004.1333722.

Cheng, Cuo-Pin, Shih, Tian-Yuan., 1998. The Variation of Viewshed Analysis Result Caused by Different Implementations. *In Proceeding of 19th Asian Conference on Remote Sensing*, 16-20 November 1998, Manila.

Crist, E.P., Cicone, R.C., 1984. A physically-based transformation of Thematic Mapper data-The TM Tasseled Cap. *IEEE Transactions* on *Geoscience* and *Remote Sensing* GE-22(3), 256-263. https://doi.org/10.1109/TGRS.1984.350619.

Crist, E.P., 1985. A TM Tasseled Cap equivalent transformation for reflectance factor data. *Remote Sensing of Environment* 17(3), 301-306. https://doi.org/10.1016/0034-4257(85)90102-6.

Firewords., 2018. Glossary of fire science terminology. http://www.firewords.net/. Accessed 4 October 2021.

FSI., 2019. India State of Forest Report. https://fsi.nic.in/isfr19/vol2/isfr-2019-vol-ii-west-bengal.pdf. Accessed 6 June 2021.

Halofsky, J.E., Peterson, D.L., Harvey, B.J., 2020. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology* 16(4): 1-26. https://doi.org/10.1186/s42408-019-0062-8.

Juárez-Orozco, S.M., Siebe, C., Fernández y Fernández, D., 2017. Causes and Effects of forest fires in tropical rainforest: A Bibliometric Approach. *Tropical Conservation Science* 10, 1-14. https://doi.org/10.1177 /19400829 17737207.

Kannemadugu, H.B.S, Varghese, A. O., Mukkara, S.R., Joshi, A.K., Moharil, S.V., 2015. Discrimination of Aerosol Types and Validation of MODIS Aerosol and Water Vapour Products Using Sun Photometer over Central India. *Aerosol and Air Quality Research* 15, 682–693. https://doi.org/10.4209/aaqr.2014.04.0088.

Key, C.H., Benson, N.C., 2006. Landscape Assessment: Ground Measure of Severity, the Composite Burn Index; and Remote Sensing of Severity, the Normalized Burn Ratio. Pp LA 1-51 in Lutes et al. (Eds.) in *FIREMON: Fire Effects Monitoring and Inventory System*. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, USA.

Mani, J.K., Varghese, A.O., 2018. Remote sensing and GIS in agriculture and forest resource monitoring. Pp 377-400 in G. P. Obi Reddy & S. K. Singh (Eds.) *Geospatial Technologies in Land Resources Mapping, Monitoring and Management*. Springer Nature, Switzerland.

Martín, M.P., 1998. *Cartografía e inventario de incendios forestales en la Península Ibérica a partir de imágenes* NOAA-AVHRR. Doctoral Thesis. Alcalá de Henares, Universidad de Alcalá.

Martín, M.P., Gómez, I., Chuvieco, E., 2006. Burnt Area Index (BAIM) for burned area discrimination at regional scale using MODIS data. *Forest Ecology and Management* 234, S221. https://doi.org/10.1016/j.foreco.2006.08.248.

Menon, A.R.R., Varghese, A.O., Martin Lowel, K.J., 1999. Impact of fire on Moist deciduous forest Ecosystem of southern tropical forests of India. In Impacts of Fire and Human Activities on Forest Ecosystems in the Tropics. Pp 52-61 in *proceeding of International Symposium on Asian Tropical Forest Management*. 20-23 September 1999, Samarinda, Indonesia.

Narendran, K., 2001. Forest fires: Origins and ecological paradoxes. *Resonance* 6, 34-41. https://doi.org/10.1007/BF02868242.

National Working Plan Code – 2014. For Sustainable Management of Forests and Biodiversity in India. Forest Research Institute, Dehradun. Ministry of Environment & Forests, Government of India, New Delhi. https://www.forests.tn.gov.in/tnforest/app/webroot/img/document/gov-india-publication/11.pdf. Accessed 1October 2021.

Parajuli, A., Gautam, A.P., Sharma, S.P., Bhujel, K.B, Sharma, G., Thapa, P.B., Bist, B.S., Poudel, S., 2020. Forest fire risk mapping using GIS and remote sensing in two major landscapes of Nepal. *Geomatics, Natural Hazards and Risk* 11(1), 2569-2586. https://doi.org/10.1080/19475705.2020.1853251.

Pinty, B., Verstraete, M.M., 1992. GEMI: A non-linear index to monitor global vegetation from satellites. *Vegetatio* 101, 15-20. https://doi.org/10.1007/BF00031911.

Prasanth, D.K., Ashwini, S.P., Varghese, A.O., Joshi, A.K., 2009. Mapping of forest fire risk zones and identification of suitable sites for fire watch towers using remote sensing and GIS. Pp 17-19 in *Proceeding of the ISRS Symposium on Advances in Geo-spatial technologies with special emphasis on sustainable rainfed Agriculture*. 17-19 September 2009, Nagpur, India.

Pyne, S.J, Andrews, P.L., Laven, R.D., 1996. Introduction to wildland fire. 2nd edition. New York, NY: John Wiley and Sons, Inc. 769p.

Rao, M.K., Varghese, A.O., Krishna Murthy, Y.V.N., 2007. Remote sensing and GIS inputs for Working Plan preparation. *Indian Forester* 133 (1a), 65-76.

Reddy, C.S., Satish, K.V., Prasada Rao, P.V.V., 2018. Significant decline of forest fires in Nilgiri Biosphere Reserve, India. *Remote Sensing Applications: Society and Environment* 11, 172-185.

Reddy, C.S., Unnikrishnan, A., Bird, N.G., Faseela, V.S, Asra, M., Manikandan, T.M., Rao, P.V.N., 2020. Characterizing Vegetation Fire dynamics in Myanmar and South Asian Countries. *Journal of the Indian Society of Remote Sensing* 48, 1829-1843. https://doi.org/10.1007/s12524-020-01205-5.

Trigg, S., Flasse, S., 2001. An evaluation of different bi-spectral spaces for discriminating burned shrub-savannah. *International Journal of Remote Sensing* 22, 2641-2647. https://doi.org/10.1080/01431160110053185.

Varghese, A.O., Suryavanshi, A., 2017. Forest cover transformation analysis and management of Melghat Tiger Reserve using remote sensing and GIS. Technical Report No. RRSC-C/NRSC/2017/9. https://doi.org/10.13140/RG.2.2.27068.49280.

Varghese, A.O., 1997. Ecological studies of the forests of Peppara Wildlife Sanctuary using remote sensing techniques. PhD Thesis, Forest Research Institute, Dehradun, pp 286.

Wilson, E.H., Sader, S.A., 2002. Detection of forest harvest type using multiple dates of Landsat TM imagery. *Remote Sensing of Environment* 80, 385-396. https://doi.org/10.1016/S0034-4257(01)00318-2.