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Forest fire risk modeling in Uttarakhand Himalaya using TERRA satellite datasets

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Abstract
Forest fire is one of the major causes of degradation in western Himalaya, and is an annual phenomenon in more than 50% in the forests of Uttarakhand state. Fire danger models are useful for the fire managers to mitigate and suppress the fire activates. MODIS 8 day products viz. MODIS Terra Land surface reflectance (MOD09A1), MODIS Terra Land surface Temperature (MOD11A2) and ASTER digital Elevation Model (DEM) were used to develop fire danger model in this paper. Three parameters Modified Normalized Difference Fire Index (*MNDFI*), Perpendicular Moisture Index (*PMI*) and potential surface temperature were computed from the above mentioned satellite products. *MNDFI* has been used for determining the actual fire occurrence in thermal anomaly pixels and PMI has been used for the estimation of live fuel moisture content in the vegetation and litter. The Potential surface temperature was computed using the MODIS Land Surface Temperature and ASTER DEM. Spatial model was developed based on the above parameters and MODIS terra and Aqua thermal anomaly product (fire location) was used for the validation of the model in the study area. The fire danger models showed an accuracy of 87.31%, i.e. the model accurately predict the fire danger over the study area. Further analysis was done based on composite fire danger image and vegetation types; composite fire danger image and fragmentation map of the study area.
Keywords: Fire danger, LST, surface reflectance, thermal anomaly, *MNDFI*, *PMI*.

Introduction
Forest fire is one of the major causes of degradation of forests in western Himalaya and is a regular feature every year causing large scale destruction of the forest ecosystems. More than 50% in Himalayan forests in Uttarakhand are prone to high incidence of fire, mostly due to human activities. In India, majority of fires are due to humans and natural causes of fires such as lightning are very less [Bahuguna et al., 2002] and causing adverse ecological, economic, Health and social impacts in the region. Causes of forest fires in the western Himalayas of India are due to [Bahuguna et al., 2002]: Forest floor is being

burnt by villagers for a good growth of grass in the next season; burning of wild grass or undergrowth in the forest in search of game animals, use of fire for collecting forest products like honey, gum etc. and to destroy stumps of illegal felling activities. Accidental fires are also due to carelessness of humans, such as throwing of burning match stick or cigarettes and spread of fire from picnic sites and other recreational areas.

According to the reports of the forest department, the state of Uttarakhand lost 2000 hectares of forest in 1998, 60,000 hectares in 1999, 2320 hectares in 2000, 1144 hectares in 2001, 3494 hectares in 2002, 4750 hectares in 2003, 4750 hectares (2004) and 3652 hectares in 2005. The State lost 562.44 hectares of forests due to forest fires in 2007; it lost 1595.35 hectares in 2008. In 2012, about 1409 hectares of forests were affected by fires, by the end of fire season. According to the forest department of Uttarakhand, Forest fires occur frequently during the months of March to June, causing loss of valuable timber resources, endangered species and extensive damage to forest ecology as well as the landscape of the area. So, the effective forest fire management is necessary to mitigate these occurring forest fires in Uttarakhand Himalayas. To do this, Forest fire managers require an early warning system to assist them in implementing fire prevention and management plans in controlling the forest fires. In India, National Remote Sensing Centre (NRSC) in collaboration with Forest Survey of India (FSI) presently disseminates in near real time active fire alerts to forest departments during the fire season using MODIS TERRA and AQUA satellite datasets acquired at the NRSC Earth station. Still, robust fire danger rating system is required in India, which can identify the fire proneness of a region on a daily basis. A variety of operational fire danger ratings are used around the world, most popular among these are McArthur Forest Fire Danger Index (*FFDI*) [McArthur, 1967], used in the eastern parts of Australia, the Forest Fire Behavior Tables (*FFBT*) [Sneeuwjagt and Peet 1998], developed for use in Western Australia, the Fire Weather Index (*FWI*) [Van Wagner, 1987] used in Canada, the National Fire Danger Rating System [Deeming et al., 1977] used in the USA, European Forest Fire Information System [Vilar et al., 2015] used in the Europe. These systems require a large amount of ground data and hourly, daily meteorological station parameters such as air temperature, relative humidity, rainfall and wind speed. But, in India, there are very few meteorological stations to cover the forests of India. So, in this study, an attempt has been made to develop forest fire danger model in western Himalayas based on three bio physical parameters, i.e. Potential surface temperature, Modified Normalized Difference Fire Index (*MNDFI*) and Perpendicular Moisture Index (*PMI*).

Study Area

Uttarakhand state is situated in the northern part of India and shares an international boundary with China in the north and Nepal in the east. Uttarakhand has an area of 53,483 Km^2 and lies between 28°43' N to 31°27' N latitude and 77°34' E to 81°02' E longitude and the recorded forest area in the state is 34,651 Km^2, which constitute 64.79 % of its total geographical area covered by the state [SFR, 2011]. The state lies in the western part of the great Himalaya range. Climate and vegetation vary greatly with elevation of the region, from the glaciers at the highest elevations to tropical forests at the lower elevations. Physiographically the state can be divided into three zones, the Himalayas, the Shiwaliks and the Terrai region and has a temperate climate in hilly regions, whereas in plain areas, climate is tropical with temperatures ranging from sub-zero in the higher regions to 43 degrees in the plains [SFR, 2009]. The average rainfall in the state is 1550 mm [SFR, 2009]. The state consists of major occurring forest types such as Tropical Moist Deciduous, Tropical Dry Deciduous, Sub Tropical Pine, Himalayan Moist temperate, Himalayan Dry Temperate, Sub Alpine and Alpine forests [SFR, 2005]. Figure 1 shows the study area Uttarakhand.

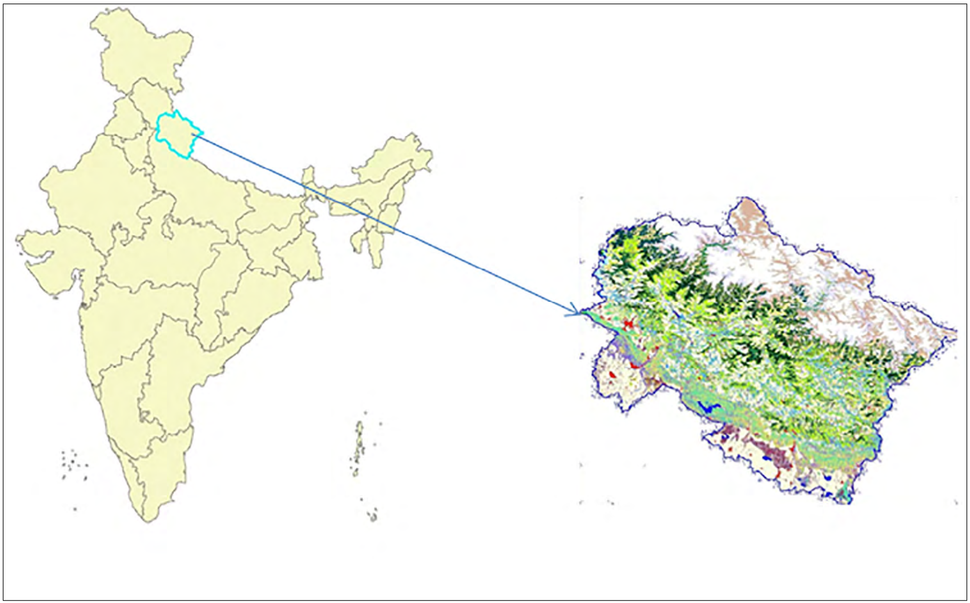

Figure 1 - Study area - Uttarakhand state.

Materials and Methods

Satellite datasets

MODIS (Moderate Resolution Imaging Spectroradiometer) is the 36-channel Spectroradiometer on-board Terra and Aqua satellites from NASA's Earth Observation System (http://modis.gsfc.nasa.gov/). It is one of the widely used satellite sensors for global and regional studies since 1999 and enables viewing the entire surface of the Earth every 1 or 2 days in 36 spectral bands, at moderate resolution varying from 0.25 km to 1 km, for land and ocean surface temperature, vegetation indices, land surface cover, forest fires, volcanoes, clouds, aerosols, temperature profiles and water vapour profiles.

Table 1 shows the information about the satellite datasets used in this study such as product ID, spatial resolution and temporal resolution. MODIS Terra Satellite data sets i.e. MOD09A1, MOD11A2 were downloaded from the REVERB site (http://reverb.echo.nasa.gov/) and the entire study area covering the 4 tiles (h24v05, h24v06, h25v05 and h25v06) were processed using HDF-EOS To GeoTIFF Conversion Tool (HEG) software (http://newsroom.gsfc.nasa.gov/sdptoolkit/HEG/HEGHome.html) and ERDAS imagine software. ASTER TERRA product (ASTGTM -ASTER Global Digital Elevation Model V002 30m) was downloaded from the REVERB website (http://reverb.echo.nasa.gov/) for the state Uttarakhand and mosaicked the entire scenes in ERDAS imagine software.

Table 1 - Satellite datasets used in this study.

S. No	Name of Datasets	Product ID	Spatial Resolution	Temporal Resolution
1	Land Surface Temperature	MOD11A2	1 km	8 days
2	Surface Reflectance	MOD09A1	500 m	8 days
3	Fire and Thermal Anomalies	MOD14	1 km	Daily
4	Digital Elevation Model	ASTER	30 m	-

The MOD09A1 dataset is a MODIS surface reflectance product at 500 m pixel resolution for seven bands (Band 1 to 7) and the product is processed to level 3 gridded using a sinusoidal projection. The processing corrects for the effects of atmospheric gases and aerosols resulting in a band-wise estimate of surface reflectance as it would have been measured at ground level. The MOD11A1 products provide per-pixel temperature and emissivity values in a sequence of swath-based on grid-based global products in the Sinusoidal projection, and produced daily at 1 kilometer spatial resolution (LPDAAC - https://lpdaac.usgs.gov/data_access). Table 2 shows the temporal 8 days MODIS datasets during the fire season of the Uttarakhand state used in this study.

Table 2 - Julian day and corresponding date of temporal MODIS datasets.

DOY	Date
81	22-March-2015
89	30-March-2015
97	07-April-2015
105	15-April-2015
113	23-April-2015
121	01-May-2015
129	09-May-2015
137	17-May-2015
145	25-May-2015
153	2-June-2015
161	10-June-2015

Seven spectral band reflectance data (500m resolution) were derived from MOD09A1 data using “HEG” software and multiplied by a corresponding scale factor to generate the final data products using a Modeler tool in ERDAS software. The resulting images, i.e. Land Surface Temperature and Reflectance products have been clipped to the Uttarakhand boundary using ARCMAP software.

Methods
MODIS reflectance bands 2, 5 and 7 and Land surface temperature were used to compute three parameters viz. Potential surface temperature, Modified Normalized Difference Fire Index (*MNDFI*) and Perpendicular Moisture Index (MSI). Figure 2 shows the methodology used to compute fire danger model based on MODIS TERRA and ASTER satellite datasets.

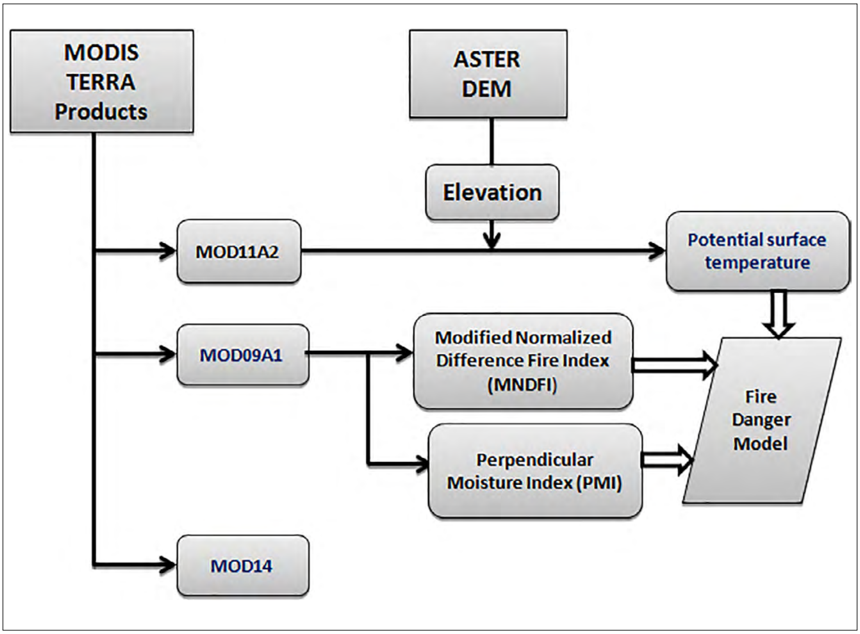

Figure 2 - Methodology for modeling the fire danger.

Potential Surface Temperature
Potential surface temperature for each day during the fire season was computed from the MOD11A2 product by the following equations. According to Barometric formula, we can find the relationship between Atmospheric Pressure and Digital Elevation Model (DEM) over the study area at every pixel can be computed. Pressure at an elevation at z can be computed from the Equation [1].

$$p = p_0 \left(1 - \frac{Lz}{T_0}\right)^{\frac{g.M}{R.L}} \qquad [1]$$

Where p is Atmospheric pressure; p_0 is the Standard atm. pressure at mean sea level (101.3 kPa); z is the elevation above mean sea level; L is Temperature lapse rate (0.0065 K/m); R is Gas constant (8.31447 J/ mol-K); g is Earth-surface gravitational acceleration (9.80665 m/s^2); M is Molar mass of dry air (0.0289644 kg/mol) and T_0 represents sea level standard temperature (20°).

Pressure data generated at 30m resolution was converted to 1 km spatial resolution data using Reproject tool in ERDAS. Potential surface temperature for each day was computed from the following Equation [2]:

$$\theta_s = T_s \left[\frac{p_0}{p} \right]^{\frac{R}{C_p}} \quad [2]$$

Where:
T_s: Surface temperature (in K);
R: Gas constant (287 J kg^{-1} K^{-1});
C_p: Specific heat capacity of air (~1004 J kg^{-1} K^{-1});
θ_s: Potential surface temperature (in K).

Perpendicular Moisture Index (PMI)

Vegetation moisture is one of the factors that dictate the susceptibility to fire ignition and propagation in forests. Several spectral indices have been developed based on a function of NIR and SWIR reflectance such as Normalized Difference Infrared Index [Hardisky et al., 1983], the Normalized Difference Water Index [Gao, 1996], and the Global Vegetation Moisture Index [Ceccato et al., 2002] for the assessment of the vegetation equivalent water thickness (*EWT*). However, many fire models depend on live fuel moisture content (*LFMC*) as a measure of vegetation moisture. Recently Perpendicular Moisture Index (*PMI*) [Maffei and Meneti, 2014] has been proposed as a direct measure of LFMC.

Perpendicular Moisture Index (*PMI*) was computed from MODIS bands 2 (0.86 µm) and 5 (1.24 µm) according to the following Equation [3] [Maffei and Meneti, 2014].

$$PMI = -0.73\left(R5 - 0.94R2 - 0.028\right) \quad [3]$$

R2 and R5 are spectral reflectance of Band 2 and 5 respectively generated from MOD09GA products. The PMI values increases with increasing values of *LFMC* so, the higher *PMI* values imply a lower fire spread and vice versa.

Modified Normalized Difference Fire Index (MNDFI)

Modified Normalized Difference Fire Index (*MNDFI)* proposed by Yasuda and Park of Tokyo university of Information sciences [Park et al., 2006] has been used to determine incidence of fire at a location. There is a high correlation between *MODIS Band2* and the chlorophyll content in the vegetation, signifying healthy vegetation activity. *MODIS Band 7* provides the information about reflective and radiation factors of the earth's surface. In the case of forest fires, there is a decrease in value of Band 2 with the decreasing amount of chlorophyll and significant increase in the value of Band 7 with rising temperature.

MNDFI can be determined from the following Equation [4] [Vermote et al., 2002; EijiNunohiro et al., 2007] and these have values ranging from -1 to 1.

$$MNDFI = \left[\frac{MODIS\ Band7 - Modis\ Band2 - 5\%}{MODIS\ Band7 + Modis\ Band2 + 5\%} \right] \quad [4]$$

As discussed in above methods, the potential surface temperature, Modified Normalized Difference Fire Index (*MNDFI*) and Perpendicular Moisture Index (*PMI*) were computed using a Modeler tool in ERDAS Imagine software and the generated datasets were reprojected into 1 km resolution. The resulting images were then clipped to the boundary of the study area using ARCMAP software.

Results and Discussions

A fire danger model was developed based on the above three parameters by applying criterion condition in ERDAS imagine software. Final fire danger images were classified into 5 fire danger classes such as Very high, High, Moderate, Low and No fire danger based on the threshold conditions. Active forest fire location data (MOD14) were downloaded from the FIRMS website (https://earthdata.nasa.gov/data/near-real-time-data/firms). These are the active fire location computed from MODIS thermal anomaly data and were overlaid on fire risk maps to estimate the accuracy of model based on potential surface temperature, Perpendicular Moisture Index and Modified Normalized Difference Fire Index. MODIS TERRA and AQUA active fire location data have been used for the validation due to the lack of ground fire data for the entire study area. Figure 3 showing the fire danger maps generated for eight day interval during fire season overlaid with corresponding composite active fire locations.

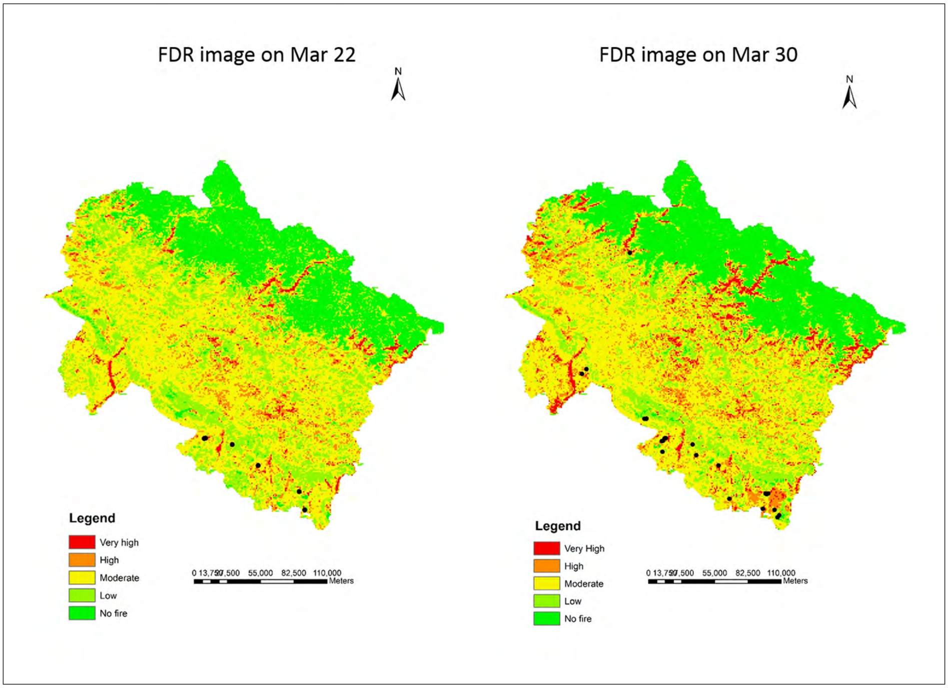

Figure 3 (Continued on the next page) - Potential Fire Danger images overlaid with corresponding fire thermal anomaly product during fire season.

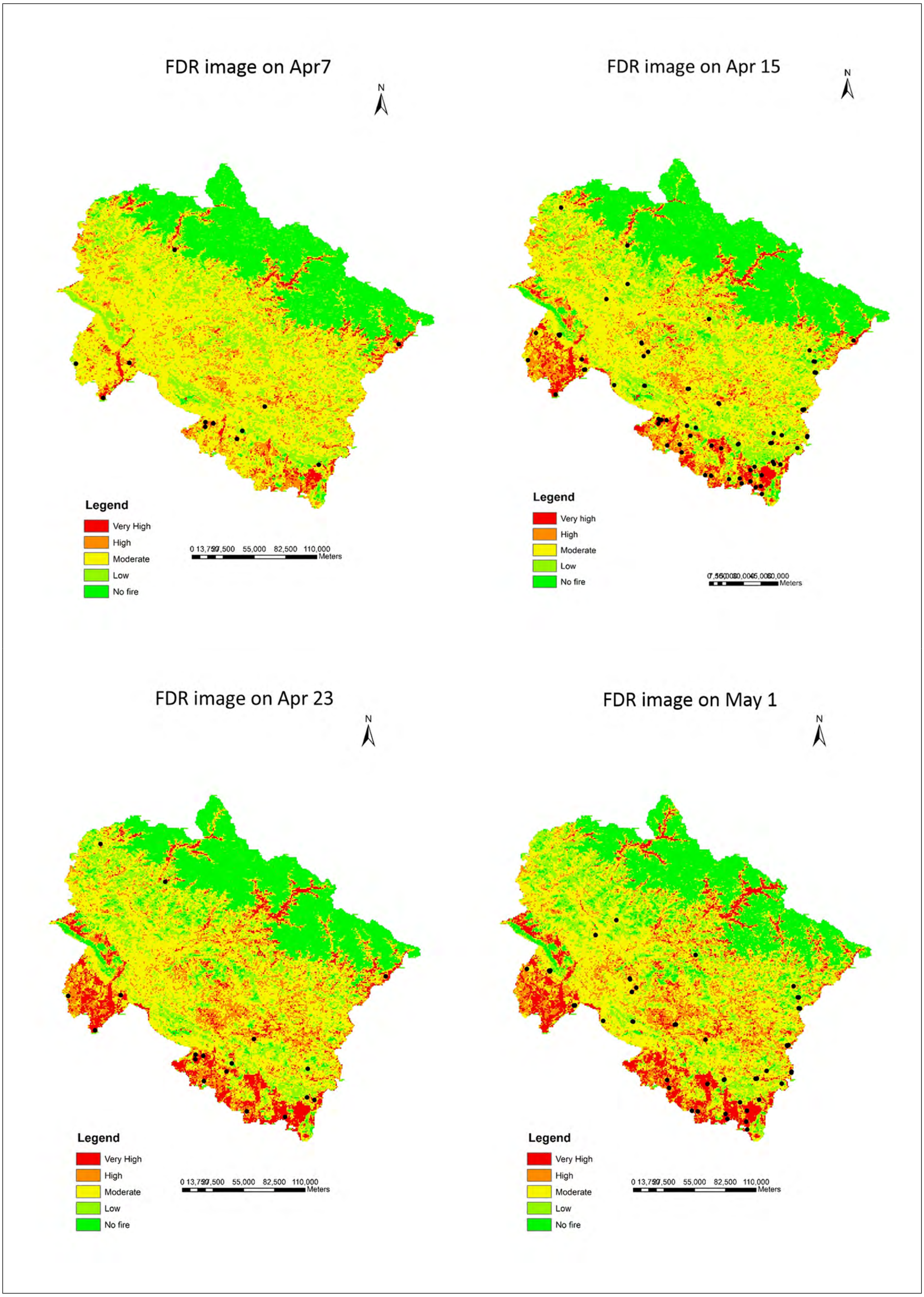

Figure 3 (Continued from preceding page and on the next page) - Potential Fire Danger images overlaid with corresponding fire thermal anomaly product during fire season.

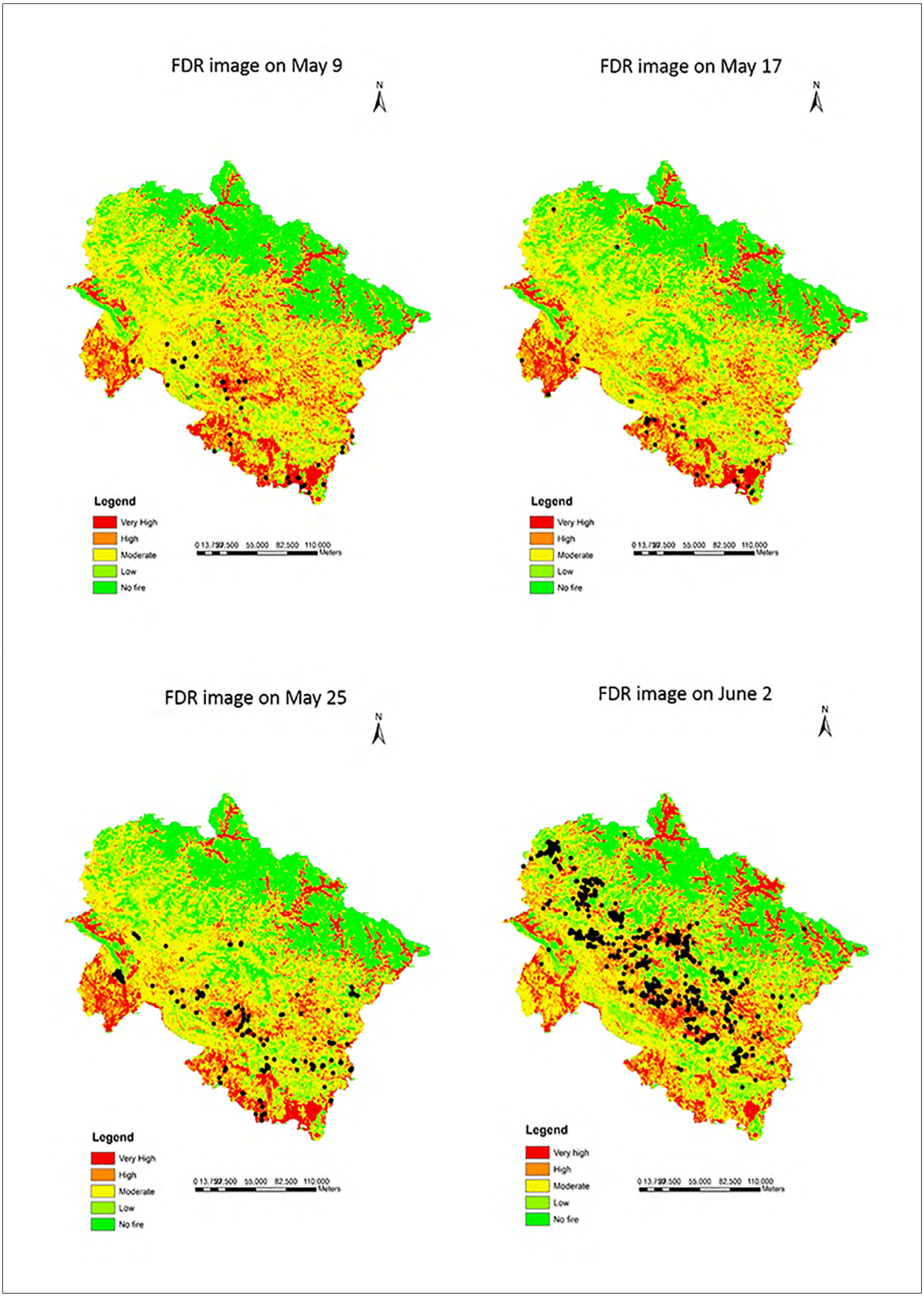

Figure 3 (Continued from preceding page and on the next page) - Potential Fire Danger images overlaid with corresponding fire thermal anomaly product during fire season.

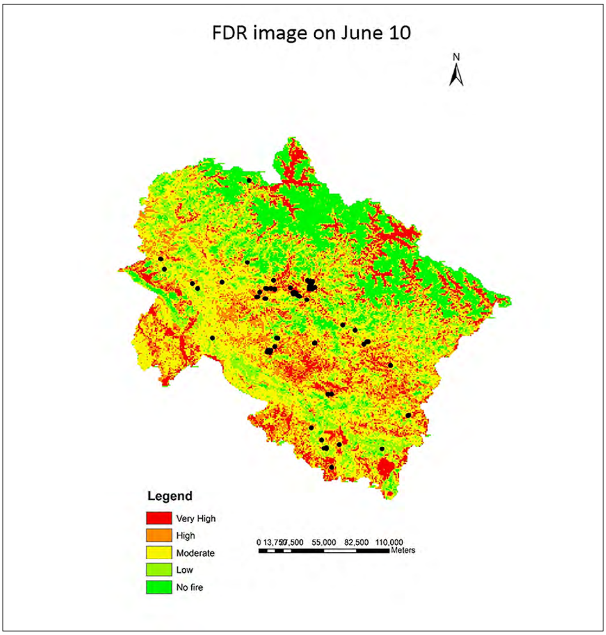

Figure 3 (Continued from preceding page) - Potential Fire Danger images overlaid with corresponding fire thermal anomaly product during fire season.

Accuracy assessment was done for each individual fire danger image on the basis of overlaid active fire point locations. The modeled fire danger map showed an accuracy of 80% to 95% indicating most of the fires fell in High to Very High fire danger classes. Table 3 shows the accuracies of fire danger model for different time periods during the fire season over the study area.

Table 3 - Accuracies of fire danger model.

Date	No. of fire points in different fire danger classes			Accuracy (%)
	No Fire, Low	Moderate	High, Very High	
22-March-2015	0	1	11	91.66
30-March-2015	0	2	13	86.66
07-April-2015	0	4	22	84.61
15-April-2015	3	3	36	85.71
23-April-2015	0	4	26	86.66
01-May-2015	2	4	31	83.78
09-May-2015	0	9	51	85
17-May-2015	0	4	44	91.66
25-May-2015	0	6	83	93.25
2-June-2015	0	12	120	90.90
10-June-2015	0	2	39	95.12

The fire danger classes were further subsumed into three classes for accuracy assessment wherein no fire and low fire classes were considered together, and high and very high as one group whereas the moderate fire danger class remained separate. From the above table, it was clear that maximum number of fire locations fell in high to very high danger classes while less or zero fires fell in No fire to Low fire danger classes and a few fires in Moderate danger class. Accuracy was computed for each day, assuming that fires fell in No fire, Low and moderate fire regions were as un- identified fire points by the model. Accuracy was computed using the Equation [5].

$$Accuracy\left(\%\right)=\frac{Active\ fires\ fell\ in\ High\ and\ very\ high\ fire\ danger\ classes}{Total\ number\ of\ active\ fire\ points\ on\ that\ day} \qquad [5]$$

Computed accuracy ranged from a minimum of 80% to a maximum of 95% and overall accuracy estimated from the table was 87.31%. So, integrating the three parameters Potential Surface Temperature, Perpendicular Moisture Index (*PMI*) and Modified Normalized Difference Fire Index (*MNDFI*) i.e. the fire danger model accurately predicts the potential fire risk over the western Himalaya.

Influence of forest types on potential fire danger

Fire hotspots during the fire season of 2015 for Uttarakhand Himalayan forests downloaded from the FIRMS website (https://earthdata.nasa.gov/data/near-real-time-data/firms) and these are active fire location data was in shape-file format. Vegetation type map of the study area was overlaid with fire hot spots to determine which type of vegetation type was more prone to fires in 2015.

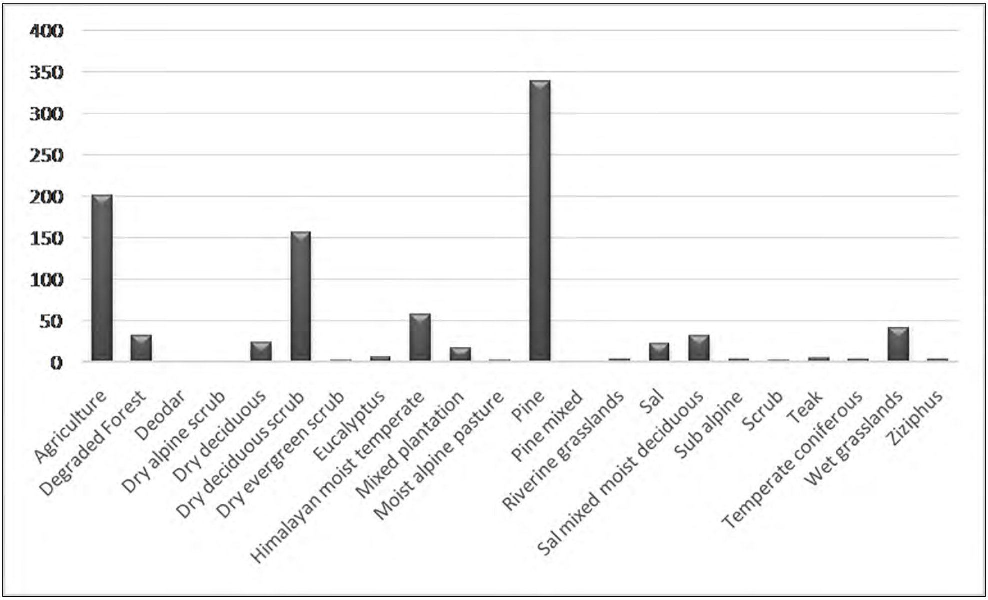

Figure 4 - Forest fire hotspots versus vegetation type of the study area.

It can be observed from the Figure 4 that pine forests in the study area are most prone to fire followed by dry deciduous shrub forests, followed by others since a significant number of fires were in agriculture; these were removed from analysis subsequently. Due to the surface level fine fuel availability for the mentioned forest types and they are more susceptible to forest fire.

Combining all the 8- day potential fire danger images computed during the fire season, a single composite potential fire danger image of 2015 was generated. Vegetation type map of Uttarakhand derived from LISS-III data [Roy et al., 2012] were crossed with the composite potential fire danger map to generate a summary. Figure 5 shows the area statistics of proportion of fire danger classes in in different vegetation types.

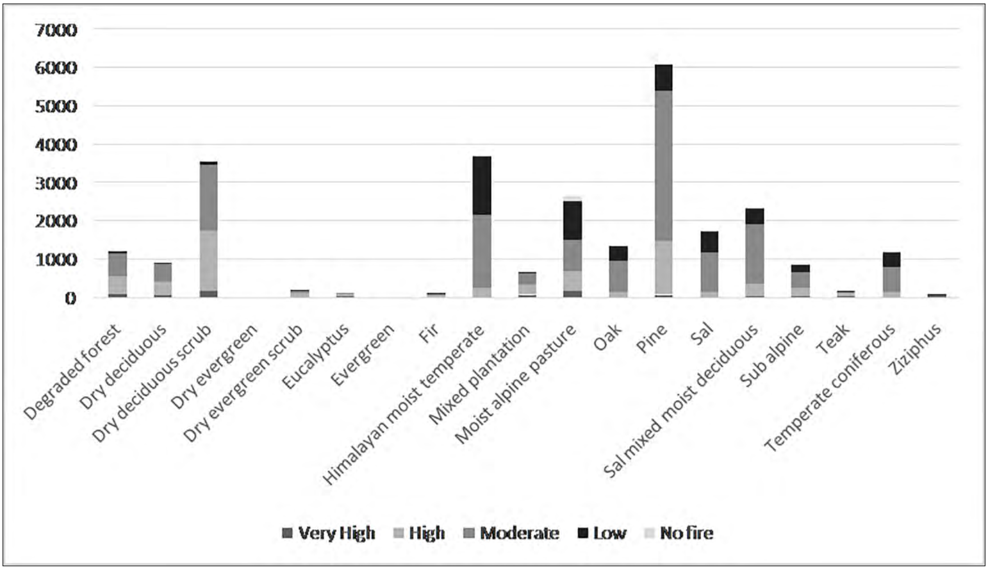

Figure 5 - Potential fire danger area of different forest types.

Figure 5 clearly shows that pine forests in Uttarakhand have a high probability of fire danger followed by dry deciduous scrub according to the model. This accurately matched with the results of actual fire locations in the respective forest types of Uttarakhand [Narendran, 2001]. So, developed model based on Potential surface temperature, Perpendicular moisture index and Modified Normalized Fire Index could accurately model the fire danger in Uttarakhand.

Impact of forest fragmentation in distribution of potential fire danger classes

Further analysis was done by using composite fire danger image and forest fragmentation image of Uttarakhand [Roy et al., 2012] to estimate the impact of forest fragmentation in potential fire risk. A similar analysis with fragmentation was carried out and it was observed that the areas with potential fire risk had high to medium level of forest fragmentation whereas the regions having moderate to low fire risk had moderate to low level of forest fragmentation (Rainforestconservation.org).

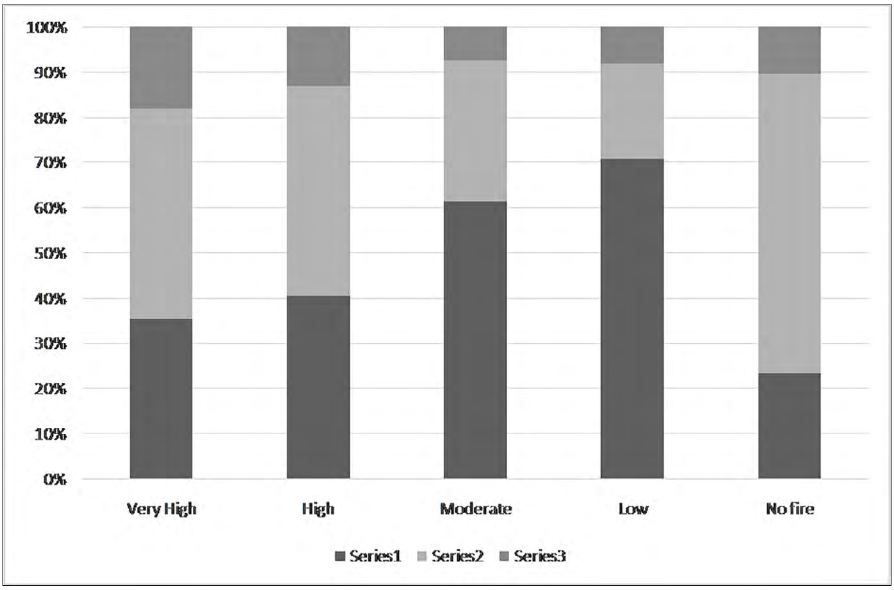

Figure 6 - impact of fragmentation on potential fire danger classes.

It can be inferred from the Figure 6 that high fragmented area was more susceptible to very high fire danger, whereas low fragmented area has a low fire danger.

Conclusion

This study shows the utility of satellite derived products such as MODIS Terra surface reflectance product (MOD09A1), MODIS Terra land surface temperature (MOD11A2) and ASTER Digital Elevation Model (DEM) for estimating the fire danger. Three parameters potential surface temperature, Perpendicular Moisture Index and Modified Normalized Difference Fire Index computed from the above mentioned MODIS and ASTER sensor products can be successfully used to generate the fire risk model. Fire risk model output showed an accuracy of 80% to 95% indicating its robustness and accuracy and the model was also able to correctly predict the regions, Vegetation types more prone to fire.

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