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# Remote sensing-based assessment of fire danger conditions over boreal forest

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**Abstract:**

Forest fire is an integral part in many forested ecosystems including boreal forests, that influences forest productivity, biodiversity and socio-economy, among others. In this paper, we evaluated the potential of three selected satellite (i.e., MODIS)-based variables/indices at 8-day temporal resolution, i.e., surface temperature ($T_S$), normalized multiband drought index (NMDI) and temperature vegetation wetness index (TVWI) in predicting/forecasting the fire danger conditions over boreal forest regions of Alberta during the period 2006-2008. The method was based on the assumption that the fire danger conditions during i+1 period would be high if the instantaneous values of: (i) $T_S$ values were either higher or equal; or (ii) NMDI or TVWI values were either lower or equal; with compare to their respective study area-specific average during i period. The analyses were conducted on the basis of either individual variable or combining all of the three together. We found that 60.59% for $T_S$, 72.41% for NMDI, and 54.19% for TVWI of fires fell under the high fire danger conditions. The combination of all of the three individual variables, it revealed that 91.63% of the fires fell in the categories of “very high” (i.e., all three variables indicated high danger), “high” (i.e., at least two of them indicated high danger), and “moderate” (i.e., at least one of the variables indicated high danger) fire danger classes. These results showed that the applicability of the proposed method in predicting fire danger conditions over the boreal forest regions.

**Index Terms:** surface temperature; temperature vegetation wetness index; normalized multiband drought index; MODIS

## 1. Introduction

Forest fire is an integral part in many forested ecosystems across the world including Canadian boreal forests that occupies approximately 35% of its landmass and represents 77% of total forested area [1]. It impacts us in numerous ways [2]-[4]: (i) economic loss due to burning of the tress and properties adjacent to the location of fire, (ii) releasing enormous amount of $CO_2$ into the atmosphere, (iii) health hazard due to smokes, and (iv) loss of human life in fighting large fires, among others. Despite, there are a number of benefits [4]-[6]: (i) controls the disease and insects, (ii) expose the mineral soils to support regeneration of the trees, (iii) more exposure to the incident solar radiation, (iv) release of seeds for certain tree-species, and (v) small fires are extremely helpful in reducing the excessive loading of the dead vegetation, that helps to control the large fires. In the Canadian province of Alberta (where boreal forest occupies approximately 58% of the area [7]), on an average, there are 1400 fires per annum that burn about 135 thousand hectares of forests during the period 2000-2009 [8]. A number of critical factors are involved in the fire occurrences (defined as the number of fires started in a given area over a particular time period [9]), those include the conditions of weather and fuel, and source of ignition [10]-[13]. The probability of fire occurrences is known as "fire danger" [14], which is different from the term "fire risk". In fact, fire risk represents the fire starting probability or chance due to the potential number of ignition sources in a given area [15]. Here, we intend to understand fire danger conditions on the basis of weather and fuel conditions in particular.

In Canadian context, the forest fire danger is determined using the Forest Fire Weather Index (FWI) system (i.e., a component of Canadian Forest Fire Danger Rating System) [16]. The FWI system uses maps of several weather variables of noon-time air temperature, relative humidity, and wind speed; and 24-hour accumulated rainfall. These maps are generated from a dataset acquired at point locations across the landscape using GIS interpolation techniques. In theory, various interpolation techniques (e.g., kriging, inverse distance weighing, natural neighbour etc.) may potentially generate different maps even using the same input dataset [17]. The uncertainty associated with interpolation techniques can be reduced by incorporating more point-based measurements of the required weather variables, which is expensive and also difficult to acquire in the remote areas of the landscape. In addition, not only the weather conditions, but also the presence of fuel (i.e., vegetation composition) and its status are important in describing fire danger conditions [18], [19]. In order to address the limitation of interpolation techniques and also incorporate fuel conditions, we intend to employ remote sensing data which is capable of providing continuous surfaces for the variables of interest.

During the last two decades, remote sensing-based methods have been widely used in describing fire danger conditions. Some of such example cases are the determination of:

- the codes of the Canadian FWI system (e.g., fine fuel moisture content, duff moisture code, drought code, buildup index, and fire weather index code) using normalized difference vegetation index (NDVI) and surface temperature ($T_S$) images [20]-[22];
- live fuel moisture conditions as a function of NDVI and $T_S$ [23], [24] or a set of vegetation greenness indices [i.e., NDVI, enhanced vegetation index (EVI), vegetation index green (VIgreen), visible atmospherically resistant index (VARI)] and vegetation wetness indices [i.e., normalized difference water index (NDWI) using infrared and short wave infrared reflectance-values centered at 1240, 1640, and 2130 nm] [25]-[27];

- dead fuel moisture by combining MSG–SEVIRI derived weather variables of air temperature ($T_a$) and relative humidity [28]. Note that air temperature is calculated on the basis of exploiting relations between NDVI and $T_S$ data; on the other hand relative humidity is determined upon considering the relations between vapour pressure and perceptible water;
- dynamic fire risk index as a function of NDVI and area specific variables (that include slope, elevation, solar insolation, proximity to main road, and vegetation cover types) [29].
- fire potential index as a function of relative greenness calculated on the basis of NDVI or VARI or NDWI [30],[31]. The use of VARI and NDWI reveals better with compare to that of NDVI;
- fire occurrence and drought monitoring using NDWI's (calculated from infrared and short wave infrared reflectance-values centered at 1.24, 1.64, and 2.13 μm) [32], [33] and normalized multiband drought index (NMDI) [34]-[36]. Among these indices, NMDI demonstrates better in describing seasonal moisture variations in the vegetation thus drought conditions as well.

In general, the above mentioned remote sensing-derived indices are used in monitoring the fire danger conditions as they have been evaluated against the fire danger conditions during the same period/time. It is worthwhile to mention that a limited number of remote sensing-based studies have been conducted in forecasting fire danger and/or pre-fire forest conditions. For example: (i) Vidal and Devaux-Ros [37] calculates water deficit index (WDI) by combining NDVI and the difference between $T_S$ and $T_a$; and shows its effectiveness in predicting the onset of fires; and (ii) $T_S$ increases at the locations prior to the fire occurrence [38], [39], among others.

The overall objective of this paper is to evaluate the potential of several MODIS-based variables/indices (calculated one period or 8-days prior to the fire occurrence) in forecasting fire danger conditions in Alberta. The variables/indices of interest include: (i) $T_S$; (ii) NMDI; and (iii) temperature-vegetation wetness index (TVWI: a measure of surface wetness conditions; [40], [41]) calculated on the basis of exploiting relation between $T_S$ and NDVI, which is similar to the formulation of WDI [37]. The specific objectives are to evaluate the:

i. capability of the individual variables of $T_S$, NMDI, and TVWI in forecasting fire danger conditions; and
ii. potential of combining all the three variables in forecasting the fire danger conditions, and finally generate the fire danger maps for the individual periods of interest.

## 2. Study are and data requirements

### 2.1. General description of the study area

Fig. 1 shows the extent of the study area with a land cover map at 1 km spatial resolution derived from annual composite of 2004 MODIS images (i.e., MOD12Q1 v.004), which falls in the northern portion of the Canadian province of Alberta. Geographically, it is in between 53–60 °N latitude and 110–120 °W longitude and dominant by boreal forest. In terms of land covers, we observed nine categories (i.e., water, shrubs, broadleaf crops, savannah, broadleaf forest, needle leaf forest, unvegetated, grasses/ cereal crops) (see Fig. 1 for more detail). Among the categories, 73.98% of the study area is covered by broadleaf and needle leaf forests. In general, the study area is characterized by cold (i.e., mean annual temperature varies between -3.6 °C and +2.3 °C) and relatively dry (i.e., mean annual precipitation varies between 376.8 mm and 632.40 mm) climatic conditions [7].

**Fig. 1**

2.2. Data requirements and its pre-processing

In this study, we used MODIS-based 8-day composites of $T_S$ images at 1 km resolution (i.e., MOD11A2 v.005); and surface reflectance images at 500 m resolution [i.e., MOD09A1 v.005; acquired over the spectral bands of red: 620-670 nm, near infrared (NIR): 841–876 nm, shortwave infrared (SWIR): 1628- 1652 nm), and SWIR: 2105- 2155 nm among others]. Both of the datasets were freely available from the Land Processes Distributed Active Archive Center [48]. The surface reflectance images were used to calculate NMDI-maps (see section 2.2.1). We also used the surface reflectance and $T_S$ images to generate TVWI-maps (see section 2.2.2). All of these data were acquired during the fire seasons (i.e., April-October) of 2006-2008, which fell in between 97-297 day of year (DOY). Note that there were some data gaps due to cloud contaminations and also the values of $T_S$, NDMI, and TVWI would change due to past fire events. Thus, we excluded these pixels from further analysis.

Apart from the satellite data, we also acquired historical wildfire database that describe fire incidents/occurrences in the study area during the fire seasons of 2006-2008. The database was freely available from Alberta Sustainable Resource Development (SRD) [49]. In total, there were 3204 no. of fire occurrences during 2006-2008 period over the forested areas in the study area. However, we considered those fires that burned an area of at least equal or greater than 1 hectare (i.e., 100 m x 100m ) as smaller fires might not be observable using the spatial resolution of the employed MODIS data (i.e., 500 m x 500 m). The resultant no. of such fire occurrences were found to be 406 in total.

### 2.2.1. Generating normalized multi-band drought index (NMDI)-maps

We calculated the 8-day composites of NMDI-maps at 500 m resolution using the following expression [35]:

$$NMDI = \frac{\rho_{860nm} - (\rho_{1640nm} - \rho_{2130nm})}{\rho_{860nm} + (\rho_{1640nm} - \rho_{2130nm})} \quad (1)$$

where $\rho$ is the surface reflectance-values for the corresponding NIR band (centered at 860 nm) and SWIR bands (centered at 1640 and 2130 nm). The NMDI-values may vary in the range 0 (i.e., indicating the driest conditions) to 1 (i.e., the wettest conditions).

### 2.2.2. Generating temperature-vegetation wetness index (TVWI)-maps

In this study, we adopted the method of generating TVWI-maps at 500 m resolution described in earlier studies [40], [41]. It consisted of the following three steps [40], [41]: (i) NDVI images were produced as a function of red (620–670 nm) and NIR (841–876 nm) surface reflectance-values; (ii) $T_S$ images were transformed to potential surface temperature ($\theta_S$) at mean-sea-level using fundamental meteorological concepts of adiabatic lapse rate and a digital elevation model at 500 m resolution of the study area in the calculation of atmospheric pressure under neutrally-stratified atmospheric conditions [40]; and (iii) the scatterplots of $\theta_S$-NDVI during each 8-day were then interpreted on the basis of hydro-meteorological principles (see Fig. 2). The TVWI-values varied in between 0 (i.e., the driest locations) and 1 (i.e., the wettest locations).

**Fig. 2**

## 3. Methods

Fig. 3 illustrates the concept of forecasting forest fire danger as a function of MODIS-derived three variables (i.e., $T_S$, NMDI and TVWI). During each of the 8-day period, it required to calculate the study area-specific average-values over the forested areas [i.e., $\overline{T_S}(i)$, $\overline{NMDI}(i)$, and $\overline{TVWI}(i)$] for each of the variables; and their generalized patterns are also shown in Fig. 3. The values of both $\overline{T_S}(i)$ and $\overline{NMDI}(i)$ would start to increase from the onset of the fire season and reach to a maximum at height of the growing season before start to decrease again [36], [44]. On the other hand, the values of $\overline{TVWI}(i)$ would relatively high both at the onset and end of the fire season as the surface could be more wet due to relatively lower temperature regimes. In order to forecasting fire danger conditions during i+1 period, the instantaneous values of the variables at a given pixel during i period (i.e., $T_{S\,(i)}$/ $NMDI_{(i)}$ / $TVWI_{(i)}$) were compared with their respective average-values (i.e., $\overline{T_S}(i)$, $\overline{NMDI}(i)$, and $\overline{TVWI}(i)$). For example, the fire danger would be considerably high if the one or more of the following conditions would be existed:

- $T_{S\,(i)} \geq \overline{T_S}(i)$, as high temperature might favour the fire to initiate;
- $NMDI_{(i)} \leq \overline{NMDI}(i)$, as low moisture in the vegetation might support the fire occurrences; and

- $TVWI_{(i)} \leq \overline{TVWI}(i)$, as low values of surface wetness conditions might also support the fire to ignite.

**Fig. 3**

In order to evaluate the above mentioned concept, we considered the actual fire occurrences (i.e., 406 no. of fire) as representative cases of the fire danger conditions. Thus, for each of the fire locations (where the fires were occurred during i+1 period), we extracted the mean values of the variables of $T_S$, NMDI, and TVWI during i period over a window of 3x3 pixels. These were then evaluated both individually and also combinedly in understanding the fire danger conditions.

In terms of individual variables, we determined how many cases the values of a particular variable (i.e., value at i period for each of fire occurred during i+1 period) with compare to the study area-specific average during i period fell under the high or low fire danger categories (see Fig. 3 for more details). Both of the high and low danger categories, were further divided into six classes on the basis of study area-specific average and the standard deviation-values in the range of "average ± 3 standard deviation" at every standard deviation intervals for the variable of interest. The particular analysis was carried out to understand whether relatively warmer or less moist conditions would favour more fires to occur.

We also evaluated whether the combination of the three variables would enhance the capability of describing fire danger conditions with compare to the individual variables. It was formulated by integrating the outcomes of the individual variable (i.e., whether fire danger conditions were "high" or "low" as discussed in the above paragraph) for each of fire. This process led to have four fire danger classes; i.e., (i) very high: if all the three variables indicated that the fire danger would be high; (ii) high: if at least two of the three variables indicated that the fire danger would be high; (iii) moderate: if at least one of the three variables indicated that the fire danger would be high; and (iv) low: if all of the three variables indicated that the fire danger would be low. We then determined the "% of the cases" fell under each of the fire danger classes. Finally, we generated fire danger maps at 500 m resolution upon combining all of the three variables.

## 4. Results and Discussion

Fig. 4 shows the temporal dynamics of the study area-specific average values for the variable of $T_S$, NMDI, and TVWI during the fire seasons (i.e., in between 97-297 DOY) for the period 2006-2008. All of the variables revealed distinct patterns that coincided with the generalized pattern we assumed in developing the proposed method (see Fig. 3). Quadratic fits to the variables as a function of DOY were found to have strong relations (i.e., $T_S$: $r^2$ ~ 0.83-0.87, NMDI: $r^2$ ~ 0.72–0.77 during 121-273 DOY, and TVWI: $r^2$ ~ 0.70–0.79; see Table I for more details). Note that both at earlier and later part of the season (values are not shown in Fig. 4), the NMDI-values were relatively high. It would be associated with wetness resulted from snow melting earlier in the season and snow accumulation later on. A similar pattern was also observed in other vegetation wetness indices (e.g., NDWI) over boreal forested region [45].

**Fig. 4**

**Table I**

Fig. 5 illustrates the comparison between the fire specific values of the variables and their respectively study area-specific averages during i period while the fires were occurred in the following period. We found reasonable amounts of fires fell under the high fire danger category [i.e., 60.59% when $T_S(i) \geq \overline{T_S}(i)$ ; 72.41% when $NMDI_{(i)} \leq \overline{NMDI}(i)$ ; and 54.19% when $TVWI_{(i)} \leq \overline{TVWI}(i)$ ] during the period 2006-2008. In general, our finding about $T_S$ in predicting fire danger provided better quantification in comparison to other studies. For example: (i) Oldford et al. [38] demonstrated qualitatively for 18 no. of fire events (i.e., occurred only during the month of July in 1994 over Canadian northern boreal forests) that the average $T_S$-values were having positive incremental trends as the date of fire occurrences approached ; and (ii) Guangmeng and Mei [39]) also reported similar findings as [38] on the basis of analyzing 12 no. of fires, that occurred during April and May in 2003 in Northeast China**.** On the other hand, it was not possible to compare performance for the both NMDI and TVWI, as their implementation in predicting danger conditions were so far not found in the literature. The discrepancies associated with high danger categories for each of the variables and fire category [i.e., 39.41% when $T_S(i) \geq \overline{T_S}(i)$; 27.59% when $NMDI_{(i)} \leq \overline{NMDI}(i)$; and 45.81% when $TVWI(i) \leq \overline{TVWI}(i)$ ] might be attributed due to one or more of the other influencing factors, such as, precipitation, wind speed, topography, fuel cover types, etc. [20], [38], [46], [47], which were not included in this study.

We further analyzed the fire danger classes upon categorizing on the basis of study area-specific average and the standard deviation-values. However, it didn't reveal clear association with the states of the variables (in terms of deviating from the study area-specific average values) and the number of fire occurrences. For example, most of the fires were found to be within "average ± 1 standard deviation" category, which indicated either more warmer or less surface/vegetation wet/moist conditions didn't favour the fires to initiate. Similar situations (e.g., drier condition didn't correspond with high number of fire occurrences) were also reported elsewhere (e.g., [48]).

**Fig. 5**

Upon combining the three individual variables in predicting fire danger conditions, we found that the predictability was enhanced to a greater extent (see Table II for more details). On an average, we found that 91.63% of the fires fell in the categories of very high, high, and moderate fire danger classes during the period 2006-2008. It would be associated with the fact that the combination of weather and fuel conditions should predict the danger conditions better in comparison to individual ones. A relatively small number of cases (i.e., 8.37% of the fires) were found to be in the low danger class (i.e., none of the variables were in favour of fire occurrences), which might be associated with other influencing factors mentioned earlier.

**Table II**

Fig. 6 shows an example fire danger mapping at 500 m spatial resolution for the period 25 June-02 July, 2008 produced by combining all of three variables of $T_S$, NMDI, and TVWI from the previous period June 17-June 24 2008. Over the entire study area, we observed that approximately ~47% of areas fell under "very high" to "high" danger categories. Further analysis of the high danger category (i.e., ~32% of the entire study area) revealed that the combinations of either $T_S$ and TVWI, or $T_S$ and NMDI produced high amount danger conditions (i.e., ~13% for both $T_S$ and TVWI, and $T_S$ and NMDI of the entire study area). On the other hand, the combination of NMDI and TVWI were able to capture ~5% of the entire study area. These observations might be related to fact that the two combinations (i.e., $T_S$ and TVWI; and $T_S$ and NMDI) were representing both the weather and fuel condition, the remaining combination of NMDI and TVWI were representing primarily fuel conditions. In case of moderate danger class (where at least one of the variable indicated the high fire danger condition), NMDI was the dominant variable (i.e., ~12% of the entire study area). It might be the case as NMDI would be directly related to the fuel moisture conditions (i.e., one of the most critical factors for the fire initiation) [23]. It would be worthwhile to note that fires would only occur over the moderate-to-very high danger classes if there would be a source of ignition.

**Fig. 6**

### 4.1. Further considerations

Despite the effectiveness of our proposed method of combining the variables of $T_S$, NMDI, and TVWI in predicting fire danger conditions; we need to consider the following issues in order to potentially enhance its capability:

- Other important weather variables, in particular to precipitation and relative humidity are quite often used in the framework of danger mapping systems [16]; so thus it would be worthwhile to investigate.
- The incorporation of lightning data during i+1 period with our fire danger map from the i period could be interesting to investigate in determining the degree of agreements of our danger map with the fire occurrences.

- Vegetation phenological stages (i.e., the influence of climatic variables on the plant developmental phases) would be worthwhile to incorporate, as they plays important role in supporting fire incidents [49];
- The current temporal scale (i.e., 8-day) remains a bit challenging from operational point of view. As in practice fire danger maps are operationally produced at daily-level as a function of weather variables acquired at point-locations across the landscape. Thus, it requires to develop methods to forecasting at much finer temporal scales (e.g., 2-4 days of intervals).
- The dynamics of fire occurrences significantly differ from ecosystem-to-ecosystem [29]. Thus we strongly recommend to evaluate the proposed methods prior to implementing in other the ecosystems rather than boreal ones.

## 5. Concluding remarks

In the scope of this paper, we demonstrated a MODIS-based simple protocol for forecasting forest fire danger conditions and its implementation over boreal forest-dominant regions in Alberta. It employed 8-day composite of variables/indices (i.e., $T_S$/NMDI/TVWI) during i period to forecast fire danger during i+1 period. The results showed that the individual variables of $T_S$, NMDI and TVWI could be used to predict the fire danger reasonably where NMDI had the best capabilities. The integration of these three variables revealed that the forecasting might be enhanced, i.e., ~91.63% of the fires fell in the "very high" to "moderate" fire danger classes during the period 2006-2008. Despite the agreements, we suggest that the proposed methods should be evaluated prior to implementing in other ecosystems across the world except for the similar boreal forested regions like our study area.

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## List of Figure Captions

Fig. 1. Location of the province of Alberta in Canada (a); and the extent of the study area described using MODIS-based land cover map.

Fig. 2. Scatterplots of $\theta_S$-NDVI and their interpretation on the basis of hydro-meteorological principles describing the concept of the TVWI methods.

Fig. 3. Conceptual diagram of forecasting forest fire danger as a function of MODIS-derived variables (i.e., $T_S$ NMDI and TVWI).

Fig. 4. The temporal dynamics of the study area-specific average values for the variable of (a) $T_S$, (b) NMDI and (c) TVWI during the fire seasons (i.e., in between 97-297 DOY) for the period 2006-2008.

Fig. 5. Frequency distribution of the fires in relation to the fire specific values of the variables (i.e., $T_{S,}$ NMDI and TVWI) and their respectively study area-specific averages during i period while the fires were occurred in the following period on the basis of the "study area-specific average ± 3 standard deviation" values.

Fig. 6. An example fire danger mapping at 500 m spatial resolution for the period 25 June-02 July, 2008 produced by combining all of three variables of $T_S$, NMDI, and TVWI from the previous period June 17-June 24 2008.

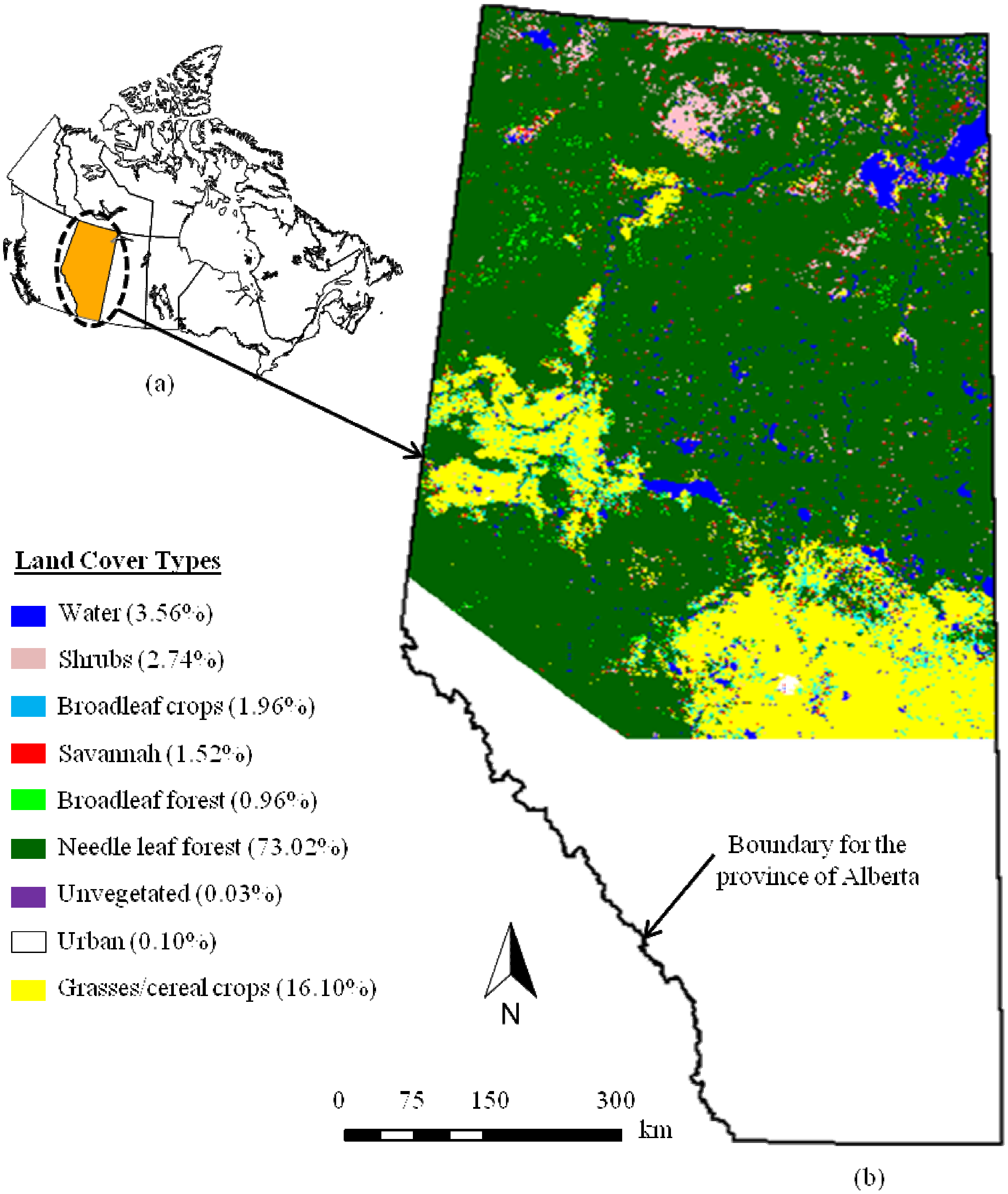

(a)
Land Cover Types
Water (3.56%)
Shrubs (2.74%)
Broadleaf crops (1.96%)
Savannah (1.52%)
Broadleaf forest (0.96%)
Needle leaf forest (73.02%)
Unvegetated (0.03%)
Urban (0.10%)
Grasses/cereal crops (16.10%)
N
Boundary for the province of Alberta
0 75 150 300
km
(b)

Fig. 1.

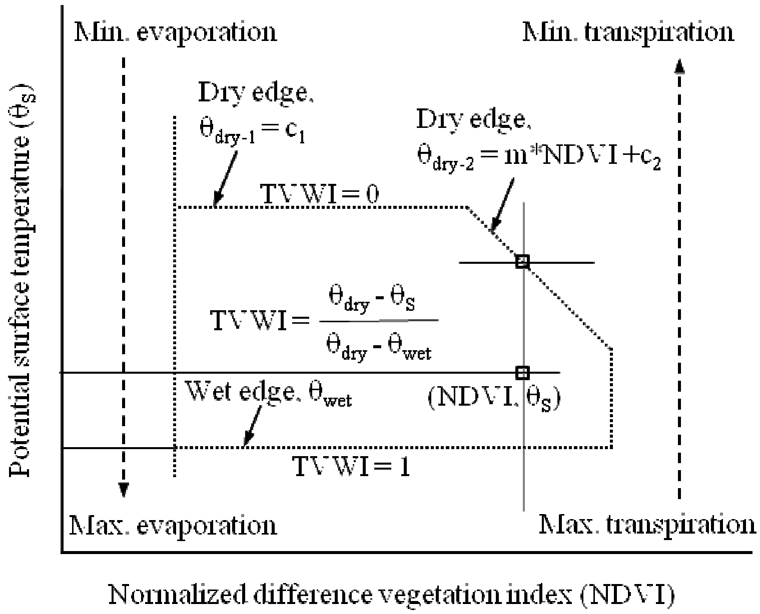
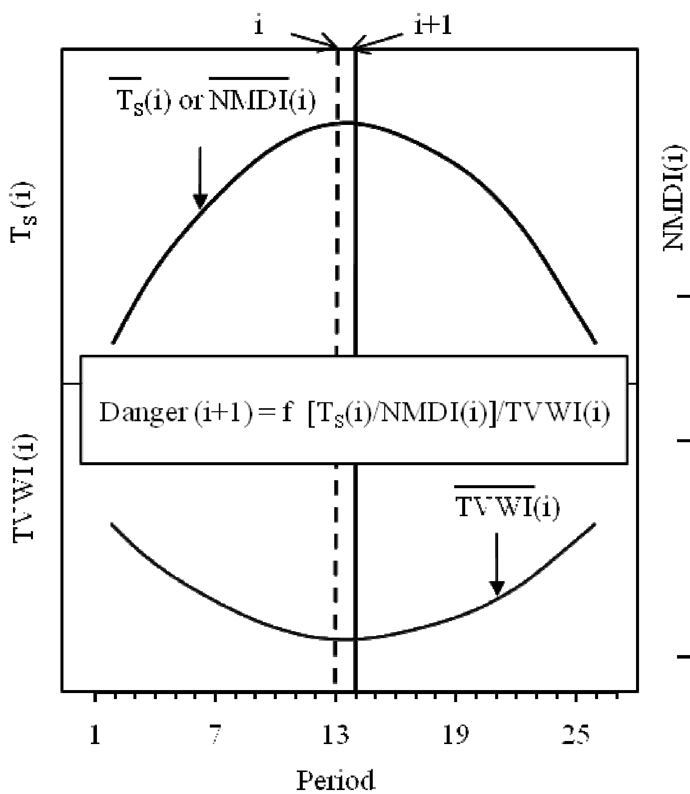

Min. evaporation
Min. transpiration
Dry edge,
θdry-1 = c1
Dry edge,
θdry-2 = m*NDVI + c2
TVWI = 0
TVWI = (θdry - θS) / (θdry - θwet)
Wet edge, θwet
(NDVI, θS)
TVWI = 1
Max. evaporation
Max. transpiration
Potential surface temperature (θS)
Normalized difference vegetation index (NDVI)

Fig. 2.




| Variable | Danger (i+1) | |
|---|---|---|
| | **High** | **Low** |
| $T_S(i)$ | $\geq \overline{T_S}(i)$ | $< \overline{T_S}(i)$ |
| NMDI(i) | $\leq \overline{NMDI}(i)$ | $> \overline{NMDI}(i)$ |
| TVWI(i) | $\leq \overline{TVWI}(i)$ | $> \overline{TVWI}(i)$ |

$T_S(i)$/ NMDI(i)/TVWI(i) are the value of the respective variable for each of the pixels during i^th^ period

$\overline{T_S}(i)$/ $\overline{NMDI}(i)$/$\overline{TVWI}(i)$ are the average of the respective variable for all of the pixels during i^th^ period

Fig. 3.

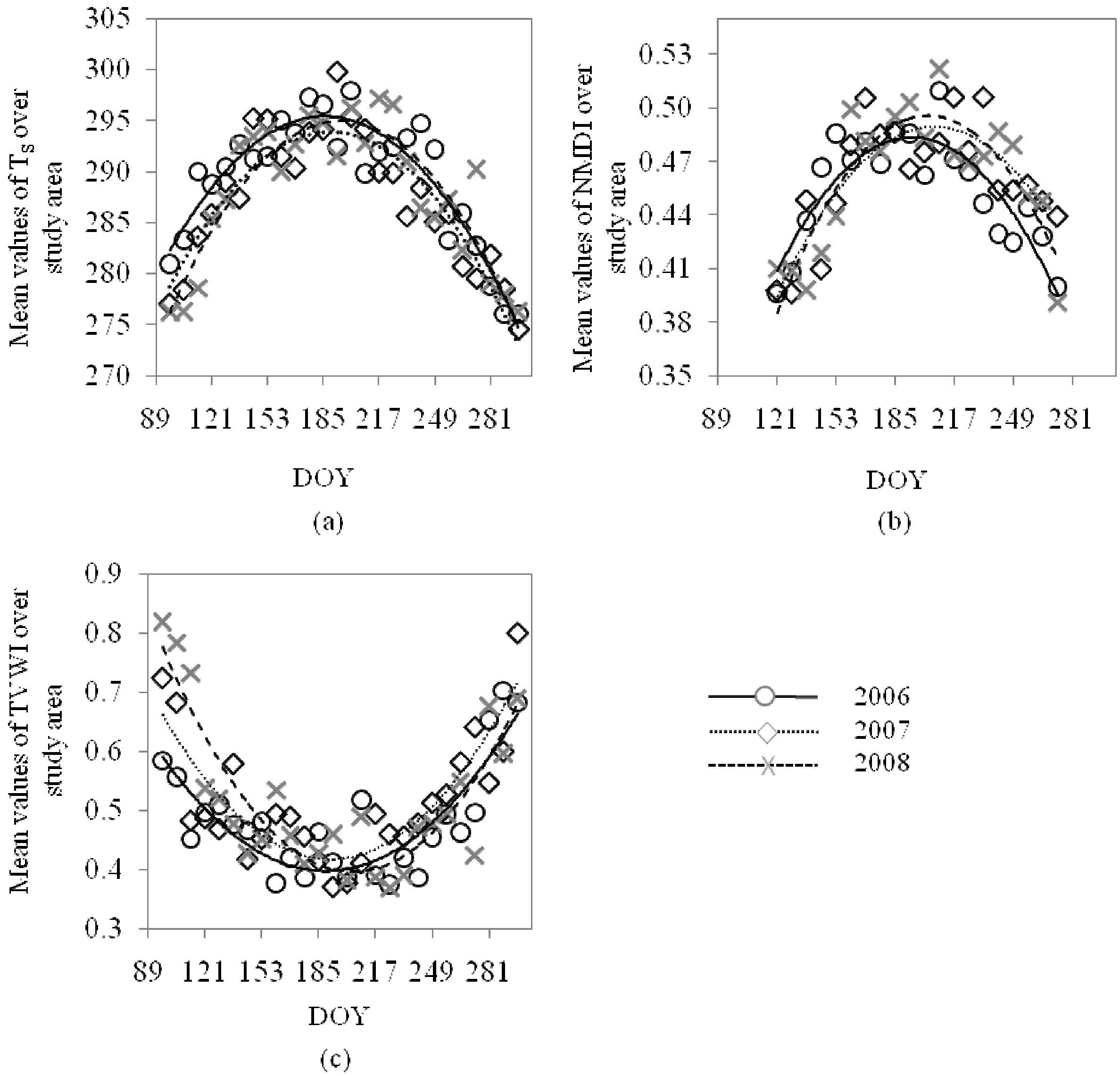

Mean values of $T_S$ over study area
305
300
295
290
285
280
275
270
89 121 153 185 217 249 281
DOY
(a)
Mean values of NMDI over study area
0.53
0.50
0.47
0.44
0.41
0.38
0.35
89 121 153 185 217 249 281
DOY
(b)
Mean values of TVWI over study area
0.9
0.8
0.7
0.6
0.5
0.4
0.3
89 121 153 185 217 249 281
DOY
(c)
2006
2007
2008

Fig. 4.

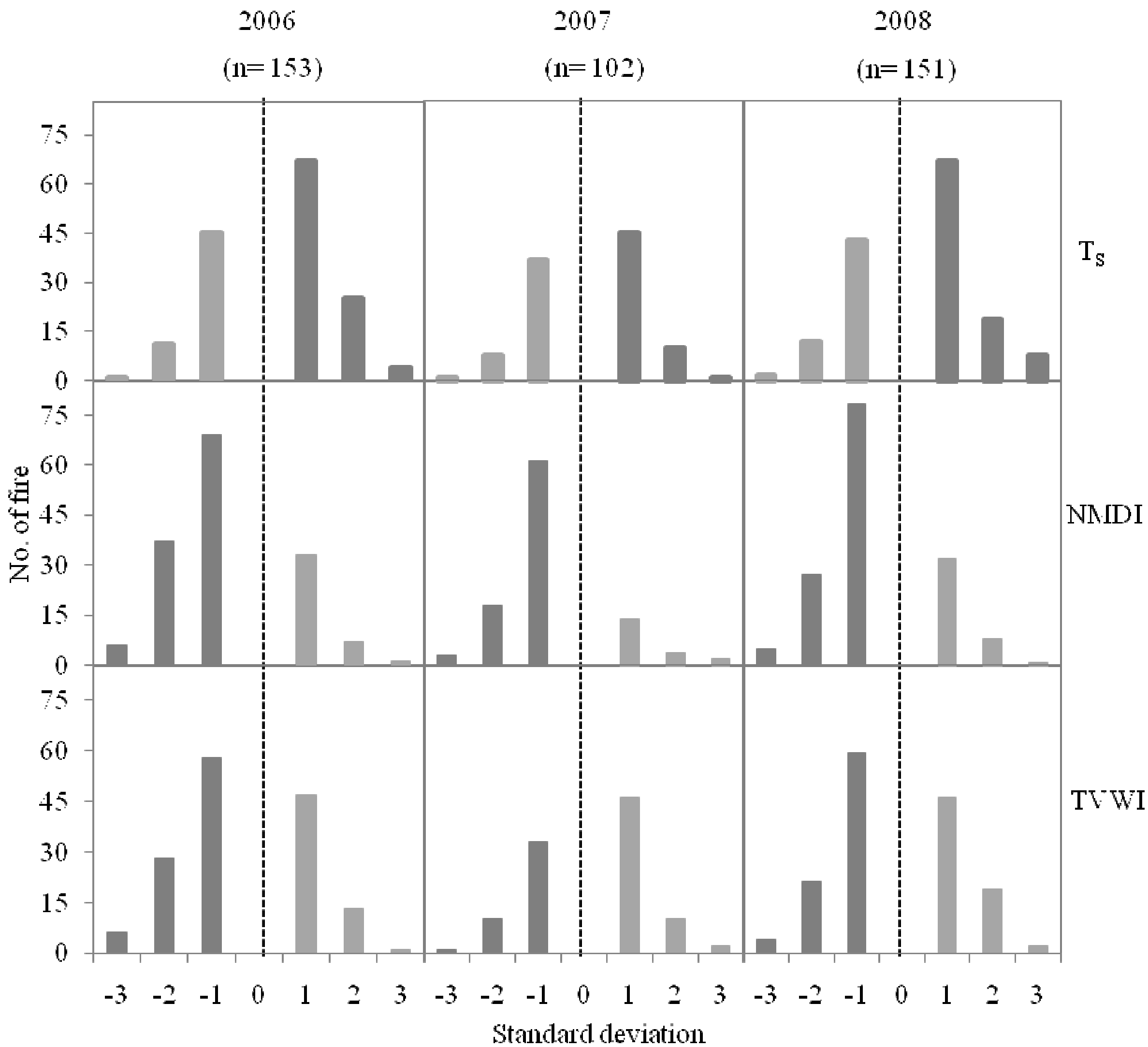

2006
(n= 153)
2007
(n= 102)
2008
(n= 151)
75
60
45
30
15
0
$T_S$
NMDI
TVWI
No. of fire
-3 -2 -1 0 1 2 3
Standard deviation

Fig. 5.

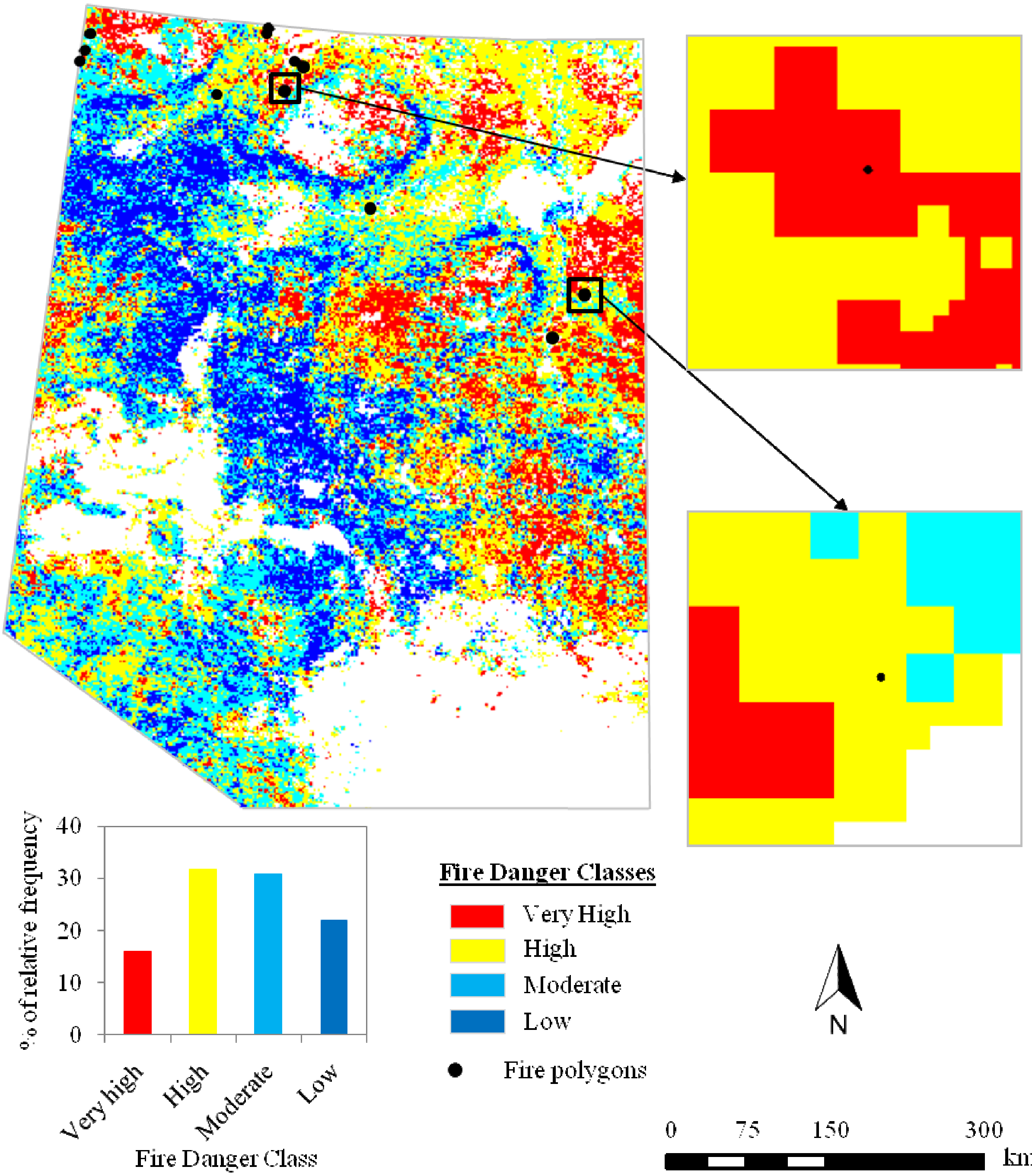

% of relative frequency
40
30
20
10
0
Very high
High
Moderate
Low
Fire Danger Class
Fire Danger Classes
Very High
High
Moderate
Low
Fire polygons
N
0
75
150
300
km

Fig. 6.

**Tables**

TABLE I

Description of the quadratic fits ($y = a_1x^2 + a_2x + a_3$) to the variables of $T_S$ / NMDI / TVWI as a function of DOY during the period 2006-2008.

| Variables | Year | $a_1$ | $a_2$ | $a_3$ | $r^2$ |
|---|---|---|---|---|---|
| **$T_S$** | 2006 | -0.001 | 0.758 | 220.9 | 0.87 |
| | 2007 | -0.001 | 0.619 | 237.8 | 0.85 |
| | 2008 | -0.001 | 0.676 | 229.9 | 0.83 |
| **NMDI** | 2006 | -1.00E-05 | 0.005 | -0.046 | 0.77 |
| | 2007 | -1.00E-05 | 0.005 | -0.065 | 0.72 |
| | 2008 | -2.00E-05 | 0.006 | -0.18 | 0.77 |
| **TVWI** | 2006 | 2.00E-05 | -0.008 | 1.211 | 0.72 |
| | 2007 | 3.00E-05 | -0.010 | 1.414 | 0.70 |
| | 2008 | 3.00E-05 | -0.013 | 1.775 | 0.79 |

TABLE II

% of data under each of the fire danger condition categories upon combining all of three variables (i.e. $T_S$ / NMDI/ TVWI; extracted over the fire pixels one period prior to the fire occurrences) during the period 2006-2008.

| ***Year*** | ***No. of the variables satisfying the fire danger condition*** | ***Fire danger classes*** | ***% of data*** |
|---|---|---|---|
| **2006** | All | Very High | 37.91 |
| | At least 2 | High | 28.10 |
| | At least 1 | Moderate | 26.14 |
| | None | Low | 7.84 |
| **2007** | All | Very High | 23.53 |
| | At least 2 | High | 38.24 |
| | At least 1 | Moderate | 31.37 |
| | None | Low | 6.86 |
| **2008** | All | Very High | 33.11 |
| | At least 2 | High | 34.44 |
| | At least 1 | Moderate | 22.52 |
| | None | Low | 9.93 |
| **2006-2008** | All | Very High | 32.51 |
| | At least 2 | High | 33.00 |
| | At least 1 | Moderate | 26.11 |
| | None | Low | 8.37 |

## **Brief Biography**

**M. Shammi Akther** received the B.Sc. degree in Civil Engineering from Rajshahi University of Engineering and Technology, Bangladesh in 2004. She is currently an M.Sc student in the Department of Geomatics Engineering at the University of Calgary. Her research focuses on the application of remote sensing-based techniques in understanding the dynamics of boreal forest.

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