ISPRS Journal of Photogrammetry and Remote Sensing 104 (2015) 224–236

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Review Article

Operational perspective of remote sensing-based forest fire danger forecasting systems

Ehsan H. Chowdhury, Quazi K. Hassan *

Department of Geomatics Engineering, Schulich School of Engineering, University of Calgary, 2500 University Dr NW, Calgary, Alberta T2N 1N4, Canada

ARTICLE INFO

Article history:
Available online 18 April 2014

Keywords:
Fire occurrence
Meteorological/environmental variables
System development
Spatial dynamics
Optical/thermal/radar imaging

ABSTRACT

Forest fire is a natural phenomenon in many ecosystems across the world. One of the most important components of forest fire management is the forecasting of fire danger conditions. Here, our aim was to critically analyse the following issues, (i) current operational forest fire danger forecasting systems and their limitations; (ii) remote sensing-based fire danger monitoring systems and usefulness in operational perspective; (iii) remote sensing-based fire danger forecasting systems and their functional implications; and (iv) synergy between operational forecasting systems and remote sensing-based methods. In general, the operational systems use point-based measurements of meteorological variables (e.g., temperature, wind speed and direction, relative humidity, precipitations, cloudiness, solar radiation, etc.) and generate danger maps upon employing interpolation techniques. Theoretically, it is possible to overcome the uncertainty associated with the interpolation techniques by using remote sensing data. During the last several decades, efforts were given to develop fire danger condition systems, which could be broadly classified into two major groups: fire danger monitoring and forecasting systems. Most of the monitoring systems focused on determining the danger during and/or after the period of image acquisition. A limited number of studies were conducted to forecast fire danger conditions, which could be adaptable. Synergy between the operational systems and remote sensing-based methods were investigated in the past but too much complex in nature. Thus, the elaborated understanding about these developments would be worthwhile to advance research in the area of fire danger in the context of making them operational.

1. Introduction

Forest fire is a natural phenomenon in many ecosystems across the world. It is considered as an ecological disturbance which is responsible for burning about 350 million hectares of forested land per annum on an average-basis (FAO, 2007). It has both negative and positive consequences on the ecosystem and impacts us in many ways (Bleken et al., 1997; Martell, 2011). In general, it is perceived as a threat (Amiro et al., 2009; Huesca et al., 2009; Sifakis et al., 2011), because the burning of forest causes: economic losses [e.g., average US$ 2.4 billion per annum between 2002 and 2011 period as a result of biomass burning (Chatenoux and Peduzzi, 2012)]; release of CO_2 into the atmosphere [e.g., the 1997 Indonesian wildfires have released about 13–40% of average annual global carbon emissions produced by the use of fossil fuels (Page et al., 2002)]; and health hazard due to smoke [e.g., inhalation of toxic gases from smoke worsen the heart and lung diseases, cough and breath, sore eyes, tears, etc. (Stefanidou et al., 2008)]. In addition, large fires can potentially kill the firefighters [e.g., in the United States 1144 firefighters killed during the 1994–2004 period (Kales et al., 2007)] and destroy human settlements [e.g., the 2011 Slave Lake fire in Alberta, Canada has destroyed 40% of the town that includes 454 dwellings, public library, town hall and office buildings costing CAD$ 700 million (CBC News, 2011; FTCWRC, 2012)]. However, forest fires have also many benefits, such as regulating fuel accumulations, regeneration of vegetation by removing fungi and microorganisms, disease and insect control, receive more energy through exposure to solar radiation, mineral soil exposure and nutrient release (Bond et al., 2005; Ruokolainen and Salo, 2009; Pausas and Paula, 2012). Besides these, recent concerns with climate change are forcing a high level of interest in quantifying its impact on forest fire regimes (Flannigan et al., 2009; Loehman et al., 2011). Thus developing an efficient forest fire management system is necessary to reduce the losses and enhance

* Corresponding author. Tel.: +1 403 210 9494.
E-mail address: qhassan@ucalgary.ca (Q.K. Hassan).

http://dx.doi.org/10.1016/j.isprsjprs.2014.03.011
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the benefits from wildfires (Stocks et al., 1989; de Groot et al., 2003; Leblon et al., 2012).

One of the most important components of integrated forest fire management is the forecasting of fire danger conditions (i.e., chance of fire occurrences). In general, the fire danger conditions are dynamic in both spatial and temporal dimensions (Vasilakos et al., 2009; Chuvieco et al., 2010; Saglam et al., 2008), and highly dependable on a set of factors. Those include: meteorological variables [e.g., temperature, wind speed and direction, relative humidity (RH), precipitation, etc.]; fuel conditions (e.g., live and dead fuel load, and fuel moisture content); topography (e.g., elevation, aspect, and slope); and sources of ignition such as human interferences (e.g., arson) or natural causes (e.g., lightning) (Jain et al., 1996; Chuvieco et al., 2004a; Adab et al., 2012). Among these factors, the topography is usually static in the temporal dimension, and influences the fire behavior (i.e., intensity and spreading after the ignition) to a large extent (Carlson and Burgan, 2003). As such, the fire danger conditions can be depicted as a function of meteorological variables and forest fuel conditions (also both of them are highly interrelated); while fire occurrences rely on the source of ignition (Wotton, 2009; Running and Coughlan, 1988; Malone et al., 2011).

It is interesting to mention that most of the operational forest fire danger forecasting systems across the world are primarily based on meteorological variables (Allgöwer et al., 2003; Abbott et al., 2007). Among the existing operational systems, the most prominent ones are the Canadian Fire Weather Index (FWI) System, US National Fire Danger Rating System (NFDRS), Australian McArthur Forest Fire Danger Rating System (FFDRS), and Russian Nesterov Index. These systems consist of the three following modules: (i) acquisition of meteorological variables at point locations over an area of interest; (ii) generate the surface maps for the variable of interest using geographic information system (GIS)-based interpolation techniques (e.g., inverse distance weighting, spline, kriging, etc.); and (iii) forecast the spatial dynamics of the fire danger conditions at landscape level. Note that various GIS-based interpolation techniques could potentially generate different map outputs using the same input variables (Chilès and Delfiner, 2012). In order to avoid these uncertainties, the remote sensing-based methods had shown usefulness due to their ability to view larger geographic extents in a timely manner. Thus, researchers had given significant efforts in incorporating remote sensing-derived variables in forest fire danger management activities (Aguado et al., 2003; Bajocco et al., 2010; Chuvieco et al., 2004b; Rahimzadeh-Bajgiran et al., 2012). Such attempts could be broadly categorized into two distinct groups: fire danger monitoring, and fire danger forecasting.

During the last several decades, remote sensing-based methods have been developed for monitoring the fire danger conditions. Most of these methods employed the remote sensing-derived environmental variables to assess the fire danger conditions during and/or after the fire events. As such, these methods would unable to forecast fire danger conditions; however, they might be useful in exploiting relationships between environmental variables and fire occurrences. In case of forecasting the fire danger conditions, some remote sensing-derived environmental variables had also been used, such as surface temperature (T_S) and normalized difference vegetation index (NDVI: an indicator of vegetation greenness) (Oldford et al., 2003); T_S, NDVI and water deficit index (WDI: soil and vegetation canopy water stress) (Vidal and Devaux-Ros, 1995); T_S condition prior to fire occurrence (Guangmeng and Mei, 2004); T_S, normalized multi-band drought index (NMDI: a measure of water content measurement in the vegetation canopy) and temperature–vegetation wetness index (TVWI: an indirect way of estimating soil water content) (Akther and Hassan, 2011a); and T_S, NMDI, and NDVI (Chowdhury and Hassan, 2013). Though these developments demonstrated their capabilities of forecasting fire danger conditions; however, further research would be required in enhancing both spatio-temporal resolutions, predicting the values in the event of cloud-contamination, and incorporating other remote sensing-derived meteorological variables (e.g., relative humidity, precipitation, etc.). In addition, these systems must be calibrated and validated prior to implementing over a new ecosystem of interest. Here, the goals of this paper were to review four major issues, such as (i) current operational forest fire danger forecasting systems and their limitations; (ii) remote sensing-based fire danger monitoring systems and effectiveness as an operational one; (iii) remote sensing-based fire danger forecasting systems and their functional implications; and (iv) synergy between operational forecasting systems and remote sensing-based methods.

2. Current operational Forest Fire Danger Rating Systems

Fire danger rating systems have been in operation in many countries around the world, especially in Canada, Australia, Russia and the United States (Stocks et al., 1989; Luke and McArthur, 1978; Deeming et al., 1978). The danger rating is a systematic process to estimate and integrate the variables of interest of the fire environment to quantify the potential of fire start, spread and impact in the form of fire danger (Merrill and Alexander, 1987; Sebastián-López et al., 2008; Albini, 1976; Rothermel et al., 1986; Deeming et al., 1972). These numerical ratings of fire potential are used in fire management both in wildfires and prescribed fires. The following sections describe the most prominent operational fire danger rating systems and their limitations.

2.1. Fire Weather Index (FWI) System in Canada

The FWI system has been widely used in Canada for fire danger forecasting since the 1980s, which is designed based on the characteristics of the Canadian forested ecosystems (CFS, 1984; van Wagner, 1987). It is the most established system, which are being implemented in many parts of the world, e.g., New Zealand (Alexander and Fogarty, 2002), Alaska (Alexander and Cole, 2001), Mexico (Lee et al., 2002), Argentina (Taylor, 2001), European countries (i.e., Sweden, Portugal, Spain) (Granstrom and Schimmel, 1998; San-Miguel-Ayanz et al., 2003a; Viegas et al., 1999), and eastern Asia (i.e., Indonesia, Malaysia) (de Groot et al., 2007). These wider adaptations have been possible as the FWI system solely uses four meteorological variables as input ones (i.e., temperature, wind speed, relative humidity at noon time; and accumulated precipitation during earlier 24-h). The FWI system produces six indices on the basis of a reference fuel type (e.g., mature pine stands for Canadian ecosystems) (van Wagner, 1987) (see Fig. 1 for details). These indices include: fine fuel moisture code (FFMC) calculated as a function of temperature, wind speed, relative humidity, and precipitation; duff moisture code (DMC) as a function of temperature, relative humidity, and precipitation; drought code (DC) as a function of temperature, and precipitation; initial spread index (ISI) as a function of FFMC and wind speed; buildup index (BUI) as a function of the DMC and DC; and fire weather index (FWI) as a function of ISI and BUI.

2.2. McArthur's Forest Fire Danger Rating System (FFDRS)

In Australia, a comprehensive Forest Fire Danger Rating System was formulated by McArthur (1958) using meteorological conditions to predict the fire spread rate on the basis of the amount of dead fuel burning and difficulty of suppressing them. The input variables of the FFDRS are: (i) Keetch–Byram Drought Index (KBDI:

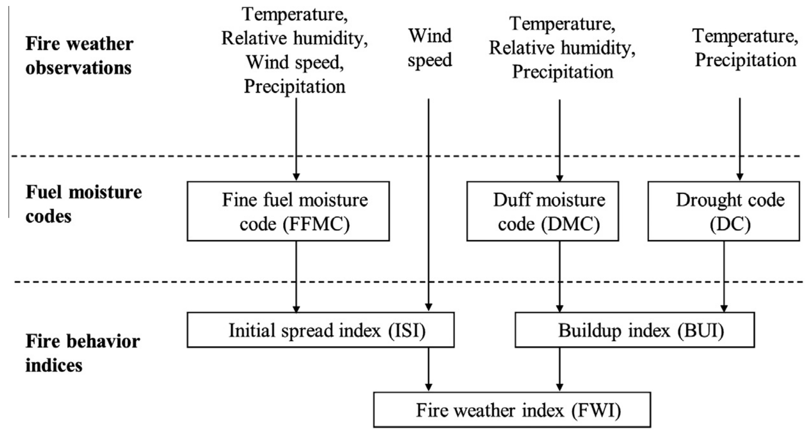

Fig. 1. Simplified schematic diagram of Forest Fire Weather Index System (adapted from van Wagner, 1987).

calculated as a function of average annual precipitation, 24-h precipitation, and maximum temperature)-based long-term seasonal soil dryness (Keetch and Byram, 1968); (ii) daily average temperature, 24-h accumulated precipitation, relative humidity and wind speed at 1500 h local time (McArthur, 1967). The FFDRS system consists of four sub-models (see Fig. 2): fine fuel availability or drought reason (calculated as a function of KBDI, precipitation, and days since precipitation); surface fine fuel moisture (SFFM: derived as a function of relative humidity, and temperature); rate of spread (RS: as a function of wind speed, fuel moisture, and fuel availability); and the difficulty of suppression (calculated as a function of RS, SFFM and wind speed). Note that several experimental fires were conducted using three distinct fuel models (e.g., grassland, eucalypt forest and pine tree) in the development of this system.

2.3. Russian Nesterov Index

The Nesterov Index is a simple Fire Danger Rating System developed by Nesterov in 1949 and widely used in the boreal forested regions of Russia. This index is computed based on daily observations of meteorological variables, such as dew point temperature, air temperature (T_a) at 1500 h local time; and the number of dry days since the last precipitation (see Fig. 3). The Nesterov's index considers the sum of all the preceding values in each day having precipitation less than 3 mm and the previous day's index. If the precipitation in a particular day is 3 mm or more, then the index is "zeroed" and a new index is computed based on the current day meteorological variables (Khan, 2012). Further changes of the Nesterov's index have been carried out by considering the forest fire drought indices or moisture indices PV-1 (i.e., related to moisture content of moss/top layer) and PV-2 (i.e., related to moisture content of duff layer) (Vonsky and Zhdanko, 1976).

2.4. National Fire Danger Rating System (NFDRS) in USA

The NFDRS operational system was first released for public use in 1972 in the United States. This system is a complex operational system that uses a set of user defined constants, several meteorological variables, fuel types, both live and dead fuel moisture, and generates output at different tiers of operation and illustrated in Fig. 4 (Burgan, 1988; Deeming et al., 1972; Bradshaw et al., 1983). It requires two sets of inputs, such as site description that includes fuel model, slope class, live fuel types, climate class, latitude, and average annual precipitation; and daily meteorological observations acquired at 1300 h. local time that includes dry bulb temperature, relative humidity, dew point, wind speed, wind direction, state of weather (illustrating information on stage of

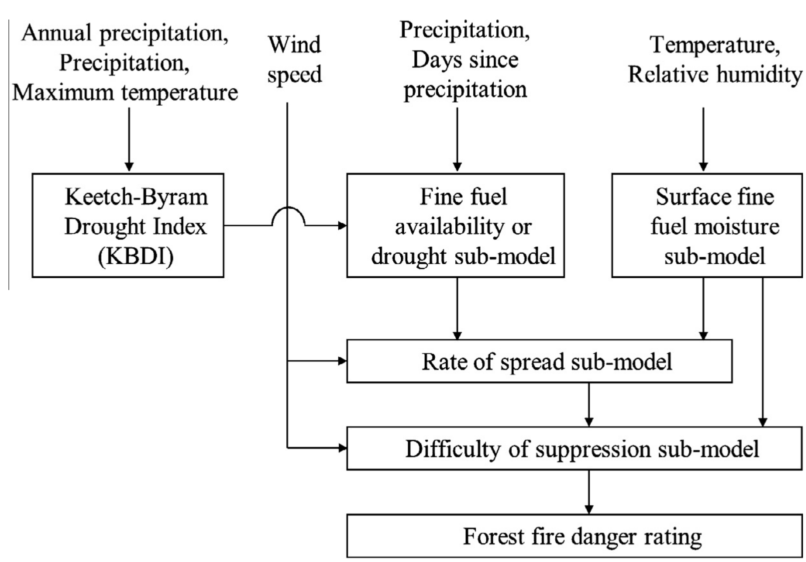

Fig. 2. Schematic diagram of McArthur's Forest Fire Danger Rating System (adapted from McArthur, 1967).

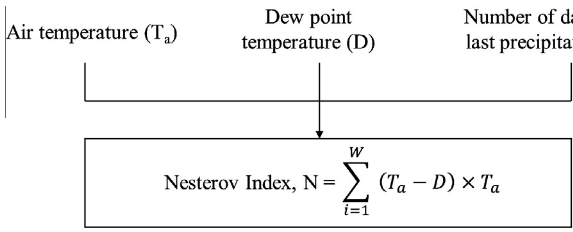

Fig. 3. Schematic diagram of the Russian Nesterov Index.

cloud, precipitation, fog, and thunderstorms/lightning), and solar radiation. In addition another index namely KBDI (Burgan, 1988; Andrews et al., 2005) are also used as an external response to the system. This system generates two tiers of outputs. Firstly, the intermediate outputs (that serve as pre-processor for the next day's processing) are the estimation of: (i) live fuel moisture for woody and herbaceous (i.e., expressed as percentage of the oven dry weight of the sample); and (ii) dead fuel moisture (i.e., moisture content of the dead organic fuels on the forest floor which consisted of 1-h, 10-h, 100-h and 1000-h time lag fuels derived as function of temperature, precipitation, cloudiness and relative humidity). Finally, the NFDRS provides four major fire behavior components and indices [calculated by using the Rothermel (1972) mathematical fire spread model], i.e., spread component (SC) is the predicted rate of spread (calculated as a function of wind speed, slope, fine fuel moisture, live woody fuel moisture); ignition component (IC) is the likelihood of a reportable fire from firebrand that needs suppression (calculated as function of fine fuel moisture and SC); energy release component (ERC) is the total energy released during flaming of a fire (calculated considering the dead and live fuel moisture); and burning index (BI) as function of SC and ERC, which is used as a fire danger indicator by most of the fire managers.

2.5. Limitations of the operational systems

All of the major operational systems described in the earlier sub-sections, in general, suffer from the following drawbacks, such as:

(1) All the operational systems are based on point-source meteorological data, located sparsely in a vast geographic extent. In general, the forecasting of danger conditions at or near meteorological stations resembles more accurate information compared to other parts of the landscape. In order to address this, it required installation of more meteorological stations (Hijmans et al., 2005; King and Furman, 1976), which would be quite expensive in terms of installation and maintenance, data collection and its processing.

(2) To delineate the spatial dynamics of the fire danger conditions the point-source observations of meteorological variables are used in the scope of all of the operational systems. In general, GIS based interpolation techniques are adopted to generate the surface maps of the variable of interest. It is worthwhile to emphasize that employment of different interpolation methods can produce different map outputs using the same input variables (Oldford et al., 2006; Leblon, 2005; Longley et al., 2010), thus forecasting of danger conditions over a large forested area limits the usability of the operational systems (Leblon et al., 2012).

(3) All the operational systems except the Russian Nesterov Index consider the dead fuel moisture as the danger indicator; however, the fire danger conditions may also depend on live fuel moisture conditions (Bajocco et al., 2010; De Angelis et al., 2012; Yebra et al., 2013). In fact, the live fuel moisture condition is a critical variable in defining fire danger conditions as it is closely related to the flammability of the live fuels and also propagation characteristics of fire.

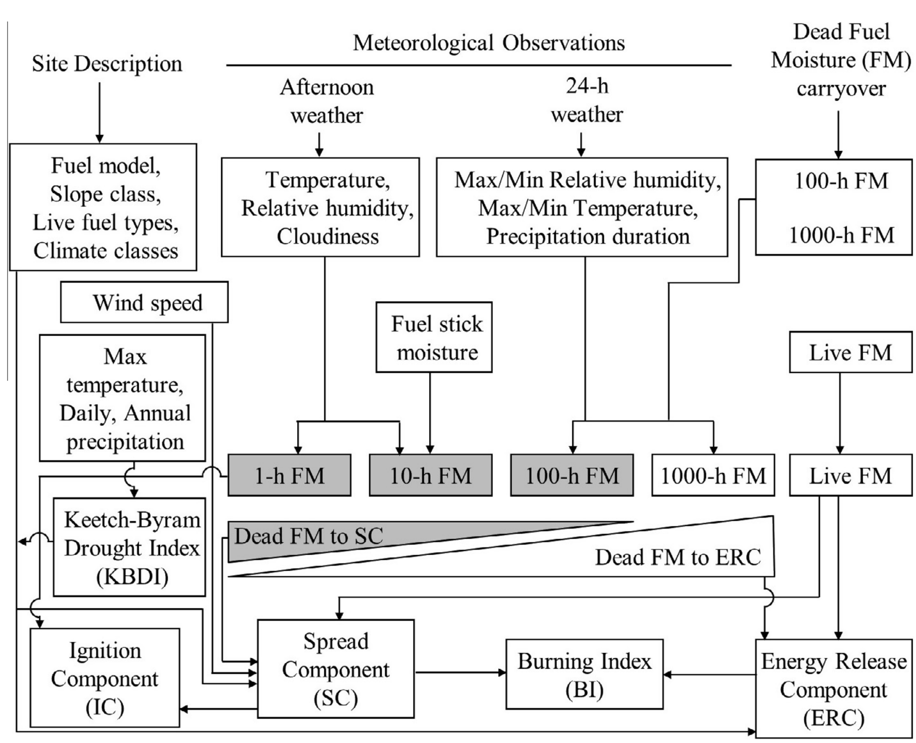

Fig. 4. Structure of the US National Fire Danger Rating System (adapted from Burgan, 1988).

(4) Apart from the Russian Nesterov Index system, a limited number of fuel types have been considered in the scope of all of the operational systems. These fuel-specific parameters (e.g., ignition temperature of woody material, rates of combustion, and extinction of moisture from vegetation, etc.) are determined by laboratory-based experiments (Wilson, 1985, 1990; Byram, 1963; Nelson, 1984). Thus, the characteristics of additional fuel types are required to be determined in the event of implementing these systems over other ecosystems.
(5) In the framework of both Australian FFDRS and US NFDRS systems, KBDI has been used as a proxy of soil water content. The calculation of KBDI can be improved by incorporating the duration and intensity of precipitation (San-Miguel-Ayanz et al., 2003b).
(6) In general, the fire danger rating systems are fairly complex from an operational point of view and need complex data inputs in most of the instances (Lawler, 2004).

3. Remote sensing-based fire danger monitoring

Remote sensing-based fire danger monitoring is the act of delineating danger conditions at the current time. It consists of the following four stages: acquisition of the remote sensing data of interest; calculation of remote sensing-derived variables/indices relevant to danger conditions; establishment of the relation between remote sensing-derived variables and danger-related indicators; and generation of the danger map. In terms of remote sensing-derived variables, these can be broadly grouped into several categories, e.g., vegetation greenness; meteorological variables; surface wetness conditions calculated by exploiting the relations between T_S and vegetation indices; and vegetation wetness condition, which are described in the following sub-sections.

3.1. Vegetation greenness

Among the various vegetation greenness-related indices, the commonly used ones are: NDVI (i.e., calculated as function of surface reflectance of red [0.60–0.70 μm] and near infrared (NIR) [0.70–0.90 μm] spectral bands) (Rouse et al., 1973); soil adjusted vegetation index (SAVI: calculated as a function of red and NIR spectral bands) (Huete, 1988); global environmental monitoring index (GEMI: function of red and NIR spectral bands) (Pinty and Verstraete, 1992); relative greenness (RG: function of seasonal dynamics of NDVI or visible atmospherically resistant index (VARI: function of blue, green [0.50–0.60 μm] and red spectral bands) (Burgan and Hartford, 1993; Kogan, 1990; Gitelson et al., 2002); and enhanced vegetation index [EVI: function of blue [0.40–0.50 μm], red and NIR spectral bands (Huete et al., 2002)]. Table 1 summarizes some of the example cases of these vegetation greenness indices in monitoring the fire danger conditions reported in the literature.

3.2. Meteorological variables

Remote sensing-based meteorological variables (e.g., T_S, T_a, and RH) were used in monitoring fire danger conditions. For example: (i) AVHRR 10-day composite of T_S images were used in the boreal forests of northern Alberta and southern Northwest Territories, Canada (Leblon et al., 2007). The individual compositing period and cumulative T_S were correlated with the DC values of the Canadian FWI system. It was found that the cumulative T_S performed better than the individual T_S (i.e., r^2 value in the range of 0.32–0.76); (ii) dead fuel moisture content was estimated using Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI) remote sensing data in the Iberian Peninsula of Spain (Nieto et al., 2010). In this study, two meteorological variables, such as the T_a (calculated by exploiting T_S and NDVI scatterplot) and RH (as a function of vapor pressure and precipitable water content) were derived. These were combined to calculate the equivalent moisture content of vegetation and observed promising results (i.e., mean errors ranging from 1.9% to 2.7%); (iii) the dead fuel moisture codes of the FWI system (i.e., DC and DMC) were modeled using 10-day composite of AVHRR T_S images over the boreal forests in northern Alberta and the southern Northwest Territories of Canada (Oldford et al., 2006). The T_S was revealed good correlation with the DMC during the spring season (i.e., r^2 value of 0.34); and (iv) AVHRR-derived monthly composite of T_S were used to determine the fire risk indicator over the temperate forest in Central Mexico. During the period of November–February, the maximum and minimum values of T_S values were computed and then generated the difference between them. These differences were evaluated against the actual fire occurrences and found that ~60% of the fires took place when they were between 8 and 15 °C (Manzo-Delgado et al., 2004).

3.3. Surface wetness conditions

For the last two decades, the relationship between vegetation index (VI) and T_S variables were exploited for estimating the surface wetness conditions. In the literature, several studies had demonstrated the effectiveness of T_S–VI in monitoring fire danger conditions, e.g., (i) 10-day composite of AVHRR-derived NDVI and T_S images were used to calculate the slope between them that acted as a fire danger indicator (i.e., decrease in slope was related to increases in water stress) over the Mediterranean forest in east Spain (Illera et al., 1996). The derived slopes were found to detect approximately 68% of the fire events while the slopes were having a decreasing trend; (ii) 10-day composite of AVHRR-derived NDVI/T_S ratio, RG and accumulated sunshine hours (meteorological data) were integrated and found good agreement with the DC values of the Canadian FWI system (i.e., r^2 value of 0.79) over the Mediterranean forest in south Spain (Aguado et al., 2003); (iii) 8-day composite of AVHRR-derived NDVI and T_S in conjunction with the day of year were employed for estimating the fuel moisture content as part of fire danger rating over the Mediterranean grasslands and shrubs in Spain (Chuvieco et al., 2004c). The model showed good agreements with the ground-based estimates of fuel moisture content (FMC) (i.e., r^2 values greater than 0.8 for both grass and shrubs); and (iv) MODIS-derived 8-day composite of T_S and 16-day composite of EVI data were used to develop a disturbance index (DI) over a broad range of bioclimatic regions in the western United States (Mildrexler et al., 2007). The DI values were generated using the annual maximum T_S/EVI ratios to multi-year mean values. Under normal conditions (i.e., absence of disturbance) the DI value would be ~1.0 and in case of wildfire, it would be >1.0 (i.e., T_S would increase and EVI would decrease for the current year compared to multi-year mean value). Comparison of the DI values (>1.64) against MODIS active fire data and other fire perimeter maps found close correspondence.

3.4. Vegetation wetness condition

Several indices representing vegetation wetness conditions [i.e., calculated as a function of NIR and shortwave infrared (SWIR) spectral bands] were implemented to determine the fuel moisture content as an indicator of fire danger. The commonly used indices include: NMDI, normalized difference water index (NWDI), simple relation water index (SRWI), normalized difference infrared index (NDII), global vegetation moisture index (GVMI), canopy water content (CWC), water index (WI), and moisture stress index

Table 1
Example of remote sensing-based vegetation greenness indices used in fire danger monitoring studies.

Indices	Sensor	Method	Locations	Reference
NDVI	Advanced Very High Resolution Radiometer (AVHRR)	Estimated the dead fuel moisture indices (DMC, DC and BUI) of the Canadian FWI system over Canadian boreal forested ecosystems. In these cases, AVHRR-derived 10-day composites of NDVI were used. In all these studies, the correlations were reasonable (i.e., r^2 values in the range of 0.03–0.65)	Northwest Territories, Canada	Leblon et al. (2001)
			Northern Alberta and southern Northwest Territories, Canada	Leblon et al. (2007)
			Saskatchewan and Manitoba, Canada	Dominguez et al. (1994)
	AVHRR	Developed a dynamic fire risk index as a function of NDVI and a set of static variables (that include proximity to road, slope, altitude, and type of vegetation cover). In general, the decrements in NDVI-values in the temporal dimension had an influence on the increment of the fire risk	Mediterranean forests of Tenerife Island, Spain	Hernandez-Leal et al. (2006)
	SPOT-VEG	Calculated monthly-composite of NDVI and correlated with the fire frequencies determined by Moderate Resolution Imaging Spectroradiometer (MODIS)-based hotspot data; and found a reasonable accuracy (i.e., r^2 value of 0.34)	Mazandaran forest, northern Iran.	Ardakani et al. (2011)
	MODIS	Commissioned 16-day composite of NDVI data during 2001–2006 fire seasons. The differences of indices for every 16 days were fitted to the fire frequencies; and found no relationship	Forested regions of Galicia and Asturias, Spain	Bisquert et al. (2014)
RG	MODIS	Calculated as a function of 16-day composite of MODIS-derived NDVI and VARI. They observed that VARI-based RG had a strong relationship with the observed live fuel moisture (i.e., average r^2 value of 0.73) over evergreen shrubs. They also evaluated VARI-based RG values in calculating FPI and then compared with the MODIS-based active fire products. These comparisons revealed reasonable correlation (i.e., r^2 value of 0.27)	Southern California, USA	Schneider et al. (2008)
	AVHRR	Calculated from 10-day composite of NDVI and determined dead fuel moisture codes (i.e., DMC and DC) of the Canadian FWI system; and revealed good relationships (i.e., r^2 value in the range of 0.43–0.50)	Boreal forests of Saskatchewan and Manitoba, Canada	Dominguez et al. (1994)
			Northern boreal forests of Alberta and southern Northwest Territories, Canada	Oldford et al. (2006)
EVI	MODIS	Used 16-day composite of EVI with day of year to quantify fire activity. These models were able to differentiate the various fire danger levels having about 5% estimation errors	Mediterranean forests, north-west Spain	Bisquert et al. (2011)
		Employed the difference between two consecutive 16-day composite of EVI; and compared with the fire frequency during 2001–2006 fire seasons. It revealed that these differences were having good correlations (i.e., r^2 values in between 0.62 and 0.84)	Forested regions of Galicia and Asturias, Spain	Bisquert et al. (2014)
SAVI, VARI, GEMI	MODIS	Used 8-day composite of surface reflectance to calculate the vegetation indices and compared with fire frequencies during 2001–2006; and found good correlations for SAVI and GEMI (i.e., r^2 values in between 0.60 and 0.81)	Forested regions of Galicia and Asturias, Spain	Bisquert et al. (2014)

(MSI). Some of the example cases by use of these indices are summarized in Table 2.

3.5. Fire danger monitoring using SAR images

In addition to optical and thermal remote sensing data for monitoring forest fire danger conditions, a number of studies had been carried out to assess the possibilities of using Synthetic Aperture Radar (SAR). The SAR was used due to its ability to capture images independently from daylight, cloud coverage and weather conditions. In particular to forest coverage, the backscatter energy received by the sensors depends on the moisture conditions of the forest floor, canopy and precipitation events which could be utilized for describing the fire danger conditions. Some such studies using SAR images are as follows: (i) ERS-1 SAR data were used to assess the dead fuel moisture conditions over the northern boreal forest in Northwest Territories, Canada (Leblon et al., 2002); and good relationships were found between the radar backscatter and FWI codes (i.e., r^2 values in between 0.30 and 0.40 for DMC, DC and BUI); (ii) ERS-1 and ERS-2 SAR-derived backscatter values were used to calculate the DC values of the FWI system over boreal forests of Alaska, USA (Bourgeau-Chavez et al., 2007); and found to have reasonable agreements (i.e., r^2 values ~0.64); and (iii) Radarsat-1 images were used to extract the backscatter values over the northern boreal forest in south-central of Northwest Territories, Canada (Abbott et al., 2007); and the comparison of radar backscatter values were found to have a strong relationship with the FWI codes (i.e., r^2 values in between 0.68 and 0.83, 0.77 and 0.82, 0.72 and 0.86, and 0.62 and 0.85 for DMC, DC, BUI and FWI respectively).

3.6. Limitations of remote sensing-based monitoring systems

The review of the remote sensing-based monitoring systems revealed that the accuracies of the environmental variables as a fire danger indicator have shown a wide range of r^2 values. As fire occurrences depend on both meteorological and biophysical variables, thus, the use of single variable might not able to show the fire danger conditions appropriately due to the following reasons:

(1) Vegetation greenness-related variables are slow responding ones, which reflects long-term conditions (i.e., does not change over short period even though drought persists in vegetation) (Leblon et al., 2001; Vicente-Serrano et al., 2012) and relates to several other variables, such as sunlight; temperature; soil moisture; and inter and intra species competition.
(2) The precisions observed using the meteorological variable T_S found to be varied considerably due to several reasons, e.g., the sensor signals might be saturated due to high temperature difference between fires and earth's surface (Realmuto et al., 2011); low spatial resolution of T_S might

Table 2
Example of remote sensing-based vegetation wetness indices used in fire danger monitoring.

Indices	Sensor	Method	Locations	Reference
NDWI	MODIS	Established relations between FMC and: (i) 8-day composite of NDWI (Stow et al., 2005); and (ii) 10-day composite of NWDI (Dennison et al., 2005). The agreements were reasonable in both of the cases, such as r^2 value of: (i) 0.50 in case of Stow et al. (2005); and (ii) between 0.39 and 0.80 for Dennison et al. (2005)	Chaparral shrublands in California, USA	Stow et al. (2005) and Dennison et al. (2005)
NDWI, NDII, GVMI, MSI, SRWI	MODIS	Used 8-day composite for the index of interest and compared with the FMC and equivalent water thickness (EWT); and found good agreements in most of the cases (i.e., r^2 values in the range of 0–0.81)	Savanna forests in Senegal, West Africa	Sow et al. (2013)
NMDI, NDWI	MODIS	Employed daily NMDI and NDWI-values in detecting forest fires. The performance was evaluated against the MODIS-based active fire spots during the fire occurrences and observed that NMDI performed better (i.e., matched with over 75% of the fire instances)	Southern Georgia, USA and mixed forests in southern Greece.	Wang et al. (2008)
GVMI, NDVI	MODIS	Employed 8-day composite to calculate the vegetation water content (VWC) using the empirical relationship of GVMI and EWT. In addition, monthly composite of NDVI were also compared with the VWC. Both of the indices indicated that their lowest values were coincided with the fire occurrences during the period of spring fires (March to May)	Inner Mongolia plateau and Song Liao plain.	Jiang et al. (2012)
NDWI, CWC	MODIS	Compared 8-day composite of these indices with the FMC; and found to have reasonable relations (i.e., r^2 values in the range of 0.26–0.44).	Northern Utah, USA	Qi et al. (2012)
NDII6, NDII7, NDWI	MODIS	Used 16-day composite and compared with the FMC. Multiple regressions was performed during the period of 2000–2006 and found good relationships (i.e., r^2 values in the range of 0.64–0.70).	Chaparral shrublands in California, USA	Peterson et al. (2008)
NDII6, NDII7, WI, NDWI, EWT	Airborne Visible Infrared Imaging Spectrometer (AVIRIS), MODIS	Employed both AVIRIS and MODIS-derived indices during the period 1994–2004 with the FMC; and found that the AVIRIS-derived indices were better correlated (i.e., r^2 values in between 0.72 and 0.85) than the MODIS-derived ones (i.e., r^2 values in between 0.55 and 0.61)	Shrublands in California, USA	Roberts et al. (2006)

lessen the circumstantial information (Leblon et al., 2007); fires manifest a diurnal cycle (Zhang et al., 2011; Beck et al., 2001) which might be biased due to observation in fixed time by the sensors; and heterogeneous properties of the emissivity of the land surface.

(3) Combination of T_S–VI would not be suitable over topographically variable terrains (Carlson, 2007). It is the case as T_S is often lower in high elevation areas compared to low-lying areas within the same geographical region. As such, employment of non-elevation corrected T_S images could incorrectly delineate that surface wetness conditions in upland areas are wetter than in low-lying areas (Hassan et al., 2007; Akther and Hassan, 2011b).

(4) Application of vegetation wetness condition using NIR and SWIR spectral bands have several limitations, such as vegetation moisture estimation is an approximation method (both field and remote sensing); difficult to measure EWT at field level (Chuvieco et al., 2003); relationship between FMC/EWT and vegetation moisture are species-specific (thus understanding of biophysical properties of species mixtures would be useful); and SWIR generally affected by other factors (e.g., vegetation canopy, illumination and viewing positions, and soil characteristics), etc. Also issues like quantification the error-levels of the remote sensing-derived FMC values and their implementation in the scope of operational fire danger forecasting systems pose enormous challenges (Yebra et al., 2013).

(5) SAR usually provides higher resolution images, but has an inherent problem of speckles which look as a grainy texture due to random constructive and destructive interference from the multiple scattering. Other problems that are noticeable includes, e.g., right angle surfaces causes double bounce reflection; volume scattering may occur when the radar beam penetrates the top most surface; and the brightness of the image increase due to high moisture content of the target surface (Moreira et al., 2013). Moreover, the radar operates under commercial mode and the revisits time period is quite long (i.e., ERS-1/2 repeat cycle is around 35 days compared to Radarsat-1/2 almost 24 days coverage) (Joyce et al., 2009; Leblon et al., 2012) which limits capturing the temporal dynamics of the moisture conditions. On the contrary, some of the optical and thermal remote sensing images (e.g., AVHRR, MODIS, Landsat, etc.) are completely free for public uses and also the temporal resolution of these images are relatively higher, e.g., AVHRR and MODIS at daily and Landsat at 16-days.

In addition to the above mentioned limitations of the remote sensing-based fire danger monitoring methods, in principle, have suffered much from the operational perspective. Because fire danger condition cannot be monitored as it portrays futuristic events (i.e., the occurrences of the fire events have not been materialized). However, the fire occurrences could be monitored using the current time variables and helpful in assessing the forest fire related disaster. Moreover, MODIS-based fire detection data are available at a daily temporal scale which is well accepted, fully operational and used by the fire managers for monitoring purposes. So, the remote sensing-based methods developed during the past several decades mostly suffer from the forecasting capabilities, and not considered as operational ones.

4. Remote sensing-based fire danger forecasting systems

In addition to the above remote sensing-based monitoring techniques described in Section 3, it would be worthwhile to note that a limited number of studies had found in the literature on the use of remote sensing in forecasting forest fire danger conditions. In these cases, the remote sensing-based indicators were calculated prior to the fire occurrences and then compared with the actual fire occurrences for validation purposes. Some of such example studies are briefly described in Table 3.

In order to evaluate the performance of the systems described in the scope of Akther and Hassan (2011a) and Chowdhury and Hassan (2013), we applied them to forecast the danger conditions during the catastrophic fires in 2011 taken place between 9 and 16 May period, in particular to Slave Lake [that incurred an estimated economic loss of $700 million (FTCWRC, 2012)] and Fort McMurray regional fires [responsible for burning of 595,000 ha of muskeg and bush (Treenotic, 2011)] in Alberta (see Fig. 5). In these danger maps, the input variables (i.e., T_S, NMDI and TVWI in Fig. 5a; and T_S, NMDI and NDVI in Fig. 5b) were acquired during 1–8 May 2011. Both of the methods demonstrated their excellent abilities to forecast these fires (i.e., 100% and >88% of the fire spots fell under "very high" to "high" danger categories for Slake Lake and Fort McMurray regional fires; see Table 4 for details).

It would be worthwhile to note that remote sensing-based forecasting systems would be more robust upon incorporating other critical variables, such as incident solar radiation, precipitation, relative humidity, and wind speed; human induce fire ignition sources and lightning frequency; spatially dynamic but temporally static variables, these are elevation, aspect, slope, proximity to roads, and vicinity to settlements; impact of long weekend that relates with movement of people in particular to forested areas and its relation; phenological stages of the vegetation (i.e., impact of climate on vegetation development phases); enhancement of both spatial and temporal resolutions (i.e., FFDFS); and evaluation of the systems in other ecosystems.

5. Synergy between operational forecasting systems and remote sensing-based methods

The synergy between the operational fire danger forecasting systems and remote sensing-based methods are rarely found in the literature due to the variation in temporal (i.e., daily to hourly

Table 3
Brief description of some remote sensing-based fire danger forecasting systems.

Reference	Method	Limitations
Vidal and Devaux-Ros (1995)	Calculated water stress in vegetation as a fire risk indicator over the Les Maures Mediterranean forest in southern France. In this study, Landsat TM-derived NDVI and T_S images were used during dry periods of 1990 and 1992 as well as the T_a maps generated from point-source measurements available at weather stations. The scatter-plots between NDVI and T_S–T_a interpreted to calculate the WDI. These plots were having trapezoid shapes and defined by dry (i.e., line of highest temperature to NDVI that represents an insufficient amount of water for evapotranspiration) and wet edges (i.e., representing the lowest temperature line to NDVI and have enough amount water for evapotranspiration) (Akther and Hassan, 2011a; Hassan and Bourque, 2009). The comparison between the real fire occurrences data and pre-fire WDI found that location where WDI $\geqslant$0.6 coincided with 100% of the fires	The major issue was the limited use of satellite data (i.e., only three images). Thus, the authors intended to extend the scope of validation, which was not materialized (Vidal, personal communication)
Guangmeng and Mei (2004)	Used MODIS-derived T_S images to evaluate the forest fire risk over the evergreen and deciduous forested region in northeast China during the period of April-May of 2003. The T_S was evaluated over 20 $\times$ 20 pixels around the fire site and found an increasing trend at least 3-days before fire occurrence	The study did not quantify the rate of increment of the T_S values.
Oldford et al. (2003)	Employed AVHRR-derived T_S and NDVI images for mapping the pre-fire forest conditions during 11-day period preceding to fire occurrences over the northern boreal forests in Northwest Territories, Canada. The temporal trends of both of the variables revealed that the T_S-values were increasing at least 3-days earlier than the fire occurrences, while NDVI did not show clear indications. In addition, T_S values compared against the FWI code derived from meteorological variables; and revealed a good relationship for burned (i.e., r^2 value of 0.55) and unburned (i.e., r^2 value of 0.65) forested areas	The T_S alone might not be sufficient enough for forecasting danger conditions as such danger depends on so many other biophysical variables
Akther and Hassan (2011a)	Commissioned MODIS-derived variables (i.e., T_S, NMDI and TVWI at 8-day temporal scale) to forecast the forest fire danger conditions over the boreal forested region of Alberta during 2006–2008. The fire danger forecasting system was formulated by integrating all the three variables. For example: during $i+1$ period the fire danger conditions would be determined upon comparing the instantaneous values of the variable of interest and their study area-specific average values during i period. The danger would be high if: (i) T_S values would be higher or equal (i.e., high temperature might favor fire ignition); or (ii) NMDI or TVWI values less or equal (i.e., low vegetation moisture and/or surface wetness might sustenance fire); in comparison to the study area-specific average values. As such, four fire danger classes were possible, such as (i) very high - all variables designated as high danger; (ii) high – at least two variables designated as high; (iii) moderate – at least one variable label as high; and (iv) low – all variables indicated low danger category. The comparison of the above mentioned fire danger categories with the real wildfire data (available from Alberta Government) revealed that ~91.6% of the fires fell under the "very high" to "moderate" categories	Despite having reasonable agreements, two specific shortcomings could be noted, such as (i) data gaps due cloud contamination in the input variables were excluded; and (ii) computation of TVWI was relatively complex and highly dependent on the skills of the professionals involved
Chowdhury and Hassan (2013)	Provided two improvements in order to address the limitations described in Akther and Hassan (2011a), such as (i) a gap-filling algorithm for the input variables (i.e., T_S, NMDI and NDVI); and (ii) use of NDVI instead of TVWI, which not only lessen the complexity in calculation but also remove the redundancy in the input variables. The enhanced system evaluated against the MODIS fire spot data during the 2011 fire season. For example: a comparison between the fire danger categories and MODIS-derived fire spots revealed that 98.2% of fire spots fell under "very high" to "moderate" danger classes	The temporal resolution (i.e., 8-day) of these maps would be considerable in the event of mid-term forecasting; however, daily-scale forecasting would be ideal from the operational point of view

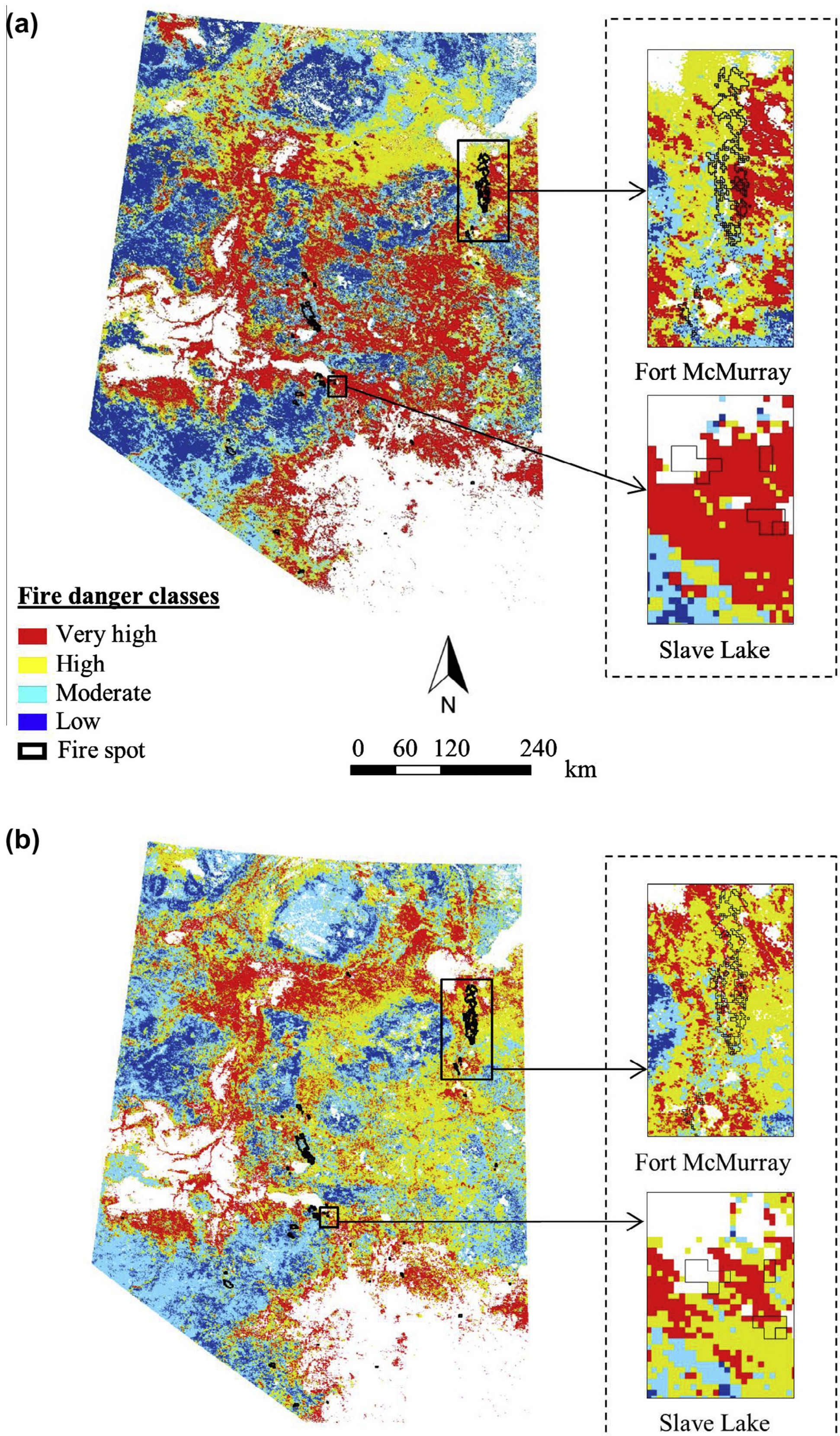

Fig. 5. Fire danger map for the period 9–16 May 2011 generated by combining (a) T_S, NMDI, and TVWI; (b) T_S, NMDI, and NDVI (after Chowdhury and Hassan, 2013) variables acquired during the prior 8-day period (i.e., 1–8 May 2011).

Table 4
Percentage of data under each fire danger categories using the combined input variables of T_S, NMDI, and TVWI; and T_S, NMDI, and NDVI in comparison to the fire spot.

Method: combination of input variables	Percentage of fire spots for					
	Slave Lake			Fort McMurray		
	Very high	High	Cumulative	Very high	High	Cumulative
T_S, NMDI, and TVWI	97.2	2.8	100	19.4	69.3	88.7
T_S, NMDI, and NDVI	33.3	66.7	100	19.3	74.7	92.0

observations of meteorological parameters and remote sensing-derived variables acquired depending on the revisit time of the satellites) and spatial (i.e., discrete objects in case of meteorological observations and continuous field of observations for remotely sensed data) dimensions of the both systems. However, the Wildland Fire Assessment System of US Forest Service integrates multi-temporal and multi-spatial observations to forecasts a series of environmental conditions that delineate fire prone areas (Burgan et al., 1997). It combines fuel models, meteorological observations, and remote sensing-derived variable (i.e., NDVI). The system has been generating FPI (i.e., synergy between NFDRS described in Section 2.4 and remotely sensed NDVI) on a daily basis since 1990s (Burgan et al., 1996, 1998; Preisler et al., 2009).

In the process of FPI development, there are three input variables (see Fig. 6). Those include: (i) 10-h dead fuel moisture conditions produced as a function of meteorological variables in the framework of NFDRS (see Fig. 4); (ii) RG-derived from AVHRR-based 7-day composite of NDVI at 1-km spatial resolution; and (iii) dead fuel moisture of extinction calculated as a function of 8-month composites of NDVI (Goward et al., 1990), land cover maps (Loveland et al., 1991), and ground-based information about fuel characteristics. Comparison between the FPI and standard NFDRS maps have revealed that FPI maps are showing better spatial variability (Burgan et al., 1998). In general, this synergy requires several input variables and also complex in nature. Thus, adopting this system in another ecosystem would require significant amount of effort.

6. Concluding remarks

In this paper, we reviewed the most prominent operational fire danger rating systems and their limitations; and effectiveness of remote sensing-based methods for monitoring and forecasting fire danger conditions and their implications in operational perspective. The operational fire danger rating systems are mainly based on the meteorological variables and easily obtainable from ground-based observations. However, these systems have several weaknesses, such as (i) fire danger ratings are derived from sparsely located point-source meteorological data; (ii) spatial dynamics of the variable of interest generated by employing interpolation methods, which are highly dependable on density of observation network, topography, and the type of interpolation method used; (iii) function of dead fuel moisture only; (iv) limited number of fuel types are used, as determination of fuel parameters are time-consuming, cost intensive, and dynamic over different climatic conditions; (iv) the parameters and relationships are determined empirically using field and laboratory experiments; and (v) complex rules in operational perspective. So thus, it is essential to investigate the fire danger ratings in each ecosystem independently, as it depends on the interactions between biotic and abiotic components. The changing climate conditions also urge of revisiting the parameters of the operational systems for making them more reliable and acceptable.

The fire danger conditions are the most important part in integrated fire management due to their wide applicability (e.g., pre-fire forest conditions, delineating prescribe burning area, reduce intensive survey operations, quick detection of fire starts and deployment of firefighting units, etc.). Over the last several decades, the remote sensing-based methods have been investigated for fire danger management activities. These methods are categorized into two major groups: fire danger monitoring and fire danger forecasting systems. In particular for monitoring the fire danger conditions, several environmental variables are derived from optical, thermal, and radar images, and explored individually and/or in combination. As the fire danger conditions define the likelihood of fire occurrence, these methods are found to be unsuccessful because they attempt to capture danger conditions during and/or after the fire occurrence. However, for monitoring the forest fire related disaster, MODIS-based fire detection data are available at a daily temporal scale which is under full operation and used by the fire managers for fire behaviour and suppression strategy.

The use of remote sensing-based methods for forecasting fire danger conditions are found in the literature though limited. Most

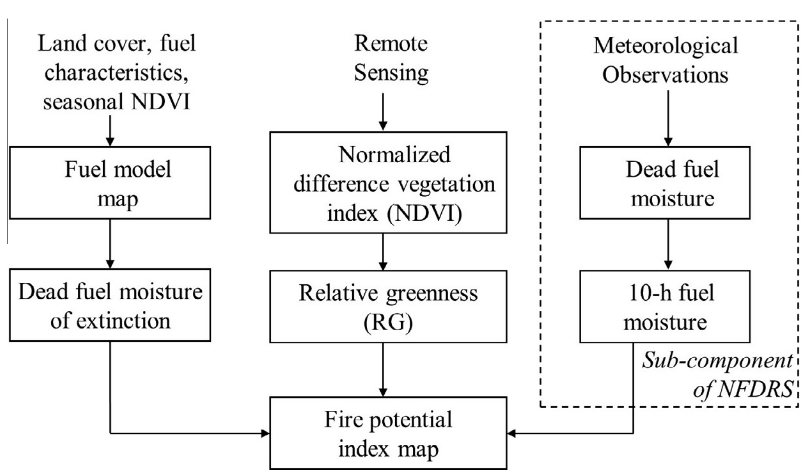

Fig. 6. The operational system to produce the fire potential map using remote sensing-derived variable and National Fire Danger Rating System (see Fig. 4) (adapted from Burgan et al., 1998).

of the fire danger forecasting systems are in the moderate range and coarse spatial resolution. An NDVI-based operational system was proposed by Burgan et al., 1998 to compute the fire potential maps, but it could not be considered as a fully remote sensing-based method as it combines satellite data, meteorological observations and fuel models (detail in Section 5). The methods illustrated above have the potential to functioning by incorporating some adjustments and improvements, such as enhancement of temporal resolution; acquisition of cloud free imagery by the sensors; development of enhanced gap-filling methods that would improve quality of optical and thermal images; and better understanding of the vegetation characteristics those are closely related to fire danger conditions. It is interesting to note that, the radar data has the potential to capture in the microwave spectral bands that penetrates cloud, canopy and interacts with the tree structure, and theoretically in any weather, but has greater limitations in temporal scale and operates under the commercial operating mode. The forthcoming satellites, such as National Polar-orbiting Operational Environmental Satellite System (NPOESS), RADARSAT constellations, SENTINEL, and future MODIS will enhance the forecasting methods due to the increase ability of the sensors, a constellation of satellites, and enhancement of the spectral resolution.

Acknowledgments

The study was funded by a Natural Sciences and Engineering Research Council of Canada Discovery Grant to Dr. Q. Hassan. We would like acknowledge Queen Elizabeth II scholarship to E. Chowdhury. We are indebted to NASA for providing the MODIS data at free of cost. In addition, we would like to acknowledge the anonymous reviewers for providing invaluable feedback.

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