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Review Article

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

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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

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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: