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FIRE DANGER ESTIMATION USING AVHRR IMAGES IN THE PRAIRIE PROVINCES OF CANADA

L. Domínguez(1), B.S. Lee(2) E. Chuvieco(1) and J. Cihlar(3)

(1) Departamento de Geografía, Universidad de Alcalá de Henares, Colegios 2, 28801 Alcalá de Henares, Spain.
(2) Canadian Forest Service, Northern Forestry Center, 5320 - 122 Street, Edmonton, Alberta, Canada T6H 3S5.
(3) Canada Center for Remote Sensing, 588 Booth Street, Ottawa, Ontario, Canada K1A 0E4.

SUMMARY

This paper presents some results on the estimation of fire danger from the analysis of AVHRR data on board the NOAA satellites. Multitemporal analysis of spectral vegetation indices and surface temperatures are correlated with the different indices of the Canadian Forest Fire Danger Rating System (CFFDRS). These indices were calculated from a set of 24 weather stations in the provinces of Saskatchewan and Manitoba. Correlations of these indices with satellite derived variables are presented. Determination coefficients for the specific periods are generally low, but multiple correlations including previous periods are higher. Temporal evolution of the different danger components for specific weather stations was also estimated from satellite information. The DC offered the highest values, with determination coefficients for some stations about 75 %. The FFMC and DMC presented less clear relationships.

INTRODUCTION

The most common approach to the estimation of vegetation stress from satellite data has been the analysis of spectral vegetation indices and, more specifically, multitemporal series of the Normalized Difference Vegetation Index (NDVI). NDVI provides a good indication of vegetation healthiness. Therefore, decreases in NDVI are related to reduction of plant vigour and greenness which are connected with vegetation moisture content.

These studies need to be based on sensors capable of offering very frequent coverage. The Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellites provide an excellent source for monitoring vegetation dynamism over large areas. Originally designed for meteorological observation, the AVHRR sensor has a coverage cycle of 12 hours with a pixel size of 1.1 x 1.1 km at nadir. At NOAA orbital height (about 800 km), this periodicity requires to have a very wide scan angle (± 55°), which causes a degradation in spatial resolution up to 2.5 x 7 km in the scene margins. Moreover, this observational geometry implies severe atmospheric and view angle distortions. However the general availability of these images and their low price explain the increasing use of these images for terrestrial applications, specially in global-change studies (Goward et al., 1991).

Several studies have shown strong correlations between AVHRR spectral vegetation indexes and critical physiological variables, such as green biomass Leaf Area Index (LAI), evapotranspiration, primary productivity, chlorophyll activity and Active Photosynthetically Absorbed Radiation by the plant (Cihlar et al., 1991; Asrar et al., 1989; Sellers, 1989). Most of these studies found significant statistical correlations between the NDVI and vegetation trends (Walsh, 1987; Kerr et al., 1989; Deblonde and Cihlar, 1993), but the specific correlations for single periods were more complicated to establish (Deblonde and Cihlar, 1993).

Several projects developed so far,have addressed the operational application of NDVI multitemporal profiles in fire danger estimation (Chuvieco and Martín, 1994). To avoid atmospheric disturbances, most of these studies have used weekly or biweekly maximum value composites. Good correlations have been found for areas of homogeneous herbaceous vegetation such as the grasslands in Australia (Paltridge and Barber, 1988) and the United States (Sadowski and Westover, 1986; Eidenshink et al., 1989 and 1990; Burgan and Hartford, 1993). However, very little experience is available on forested areas, where there are more complex interactions between the canopy and the understory components of the vegetation. Accumulated decrements of NDVI have been used in Spain to estimate fire danger in a forested area, but no quantitative correlations with field data were performed (López et al., 1991).

An alternative to the use of NDVI series for vegetation moisture estimation is to follow the thermal dynamics of the vegetation cover. Vegetation moisture stress can be measured as the ratio of actual and potential evapotranspiration (ET/PET). ET has proven to be linearly related to net radiation and to the difference between air and surface temperature (T_s - T_a). Over long term periods and at regional scales, correlation coefficients of $r=0.99$ have been measured between accumulated values of T_s - T_a and Σ ET - R_n (Seguin et al., 1991). As T_a can be obtained from weather stations and T_s from AVHRR thermal channels, this relationship might successfully be applied to fuel moisture estimation, complementing the analysis of NDVI time series.

OBJECTIVES

This paper presents preliminary results of a cooperative project being developed between the Canadian Forest Service, the Canada Centre for Remote Sensing and the University of Alcalá de Henares (Spain). The objective of our research was to test the feasibility of using NOAA-AVHRR information to estimate fire danger. For operational purposes fire danger was defined by the different components of the Canadian Forest Fire Danger Rating System (Van Wagner, 1987). We hypothesized that the use of satellite information could benefit the spatial interpolation of the different danger indices; if good correlations were measured between both sets of data. In a second phase, analysis of satellite data and weather variables will be performed on areas affected by large fires, in order to test the suitability of both approaches for predicting these events. We will also test the correlations of satellite data with fuel moisture measures obtained on the ground.

METHODS

Study area

The study area covers a rectangle of 1000 x 700 kilometres of the provinces of Saskatchewan and Manitoba in central Canada (figure 1). This area presents a flat topography (300 - 600 m.) with numerous postglacial lakes. Climate has continental features, with an average rainfall of 400 mm/year, concentrated mainly on summer. Temperatures range between -26 °C in January and 18 °C in July, with around 109 frostfree days. Soils are black and grey wooded. Vegetation is mainly related to climatic conditions. Two main vegetation types are presented: grasslands, at the Southwest, and the boreal forest. Grassland is formed by short grass species, such as blue grass, wheat grass and speargrass. The boreal forest includes conifer species, from which white and black spruce (*Picea glauca* and *Picea mariana*) are more widespread. Jack pine (*Pinus banksiana* Lamb) as well as aspen and balsam poplar (*Populus tremuloides* and *Populus balsamifera*) are also represented in the area.

AVHRR image processing

NOAA-AVHRR images include important geometric and radiometric distortions caused by its wide scan angle (± 55°). To reduce the latter problems it is generally recommended to use multitemporal composites of NDVI. The NDVI is defined by:

$$\mathrm{NDVI} = \frac{\rho_{IR} - \rho_R}{\rho_{IR} + \rho_R}$$

being ρ_{IR} and ρ_R, the reflectance measured by the sensor in the infrared and red bands, respectively. Although it has been shown that the NDVI is less affected by atmospheric disturbances and view angle effects than the original raw data (Holben, 1986), it does not solve all the problems derived from the AVHRR wide scan angle. The most widespread method to correct these distortions is the use of Maximum Value Composites (MVC: Holben, 1986), based on the fact that all the referred distortions always imply a reduction in the NDVI values. Consequently, by taking the maximum value of a series, it is assumed that noise effects will be eliminated. The MVC is generated by choosing the maximum NDVI value of a multitemporal series of AVHRR images, typically seven to nine. It reduces the effects of viewing geometry and atmospheric scattering, although it may be influenced by cloud contamination.

In this study we analyzed 10 MVC produced by the Manitoba Remote Sensing Center. They cover the 10-day periods between May, 1st and August 10th, 1993. The daily images were rectified and transformed to a Lambert Conic Conformal projection. After the correction was applied, NDVI was calculated for every AVHRR scene. The maximum value of the

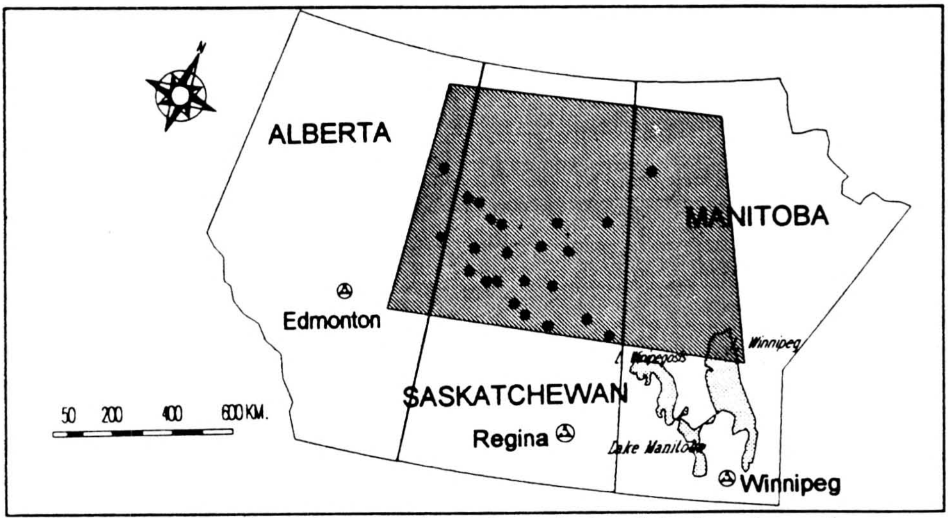

Figure 1: Location of the study area. Points refer to the location of weather stations

NDVI for every 1 km. pixel of the whole country was selected for each 10 day period. Mosaics of the whole country were then generated. We finally extracted the study area from these mosaics.

Every 10 days data set included 10 bands following the GEOCOM format established by the MRSC: the original 5 bands of the AVHRR sensor, plus the NDVI, solar height, declination and azimuth angle, and acquisition day.

Spring and summer of 1993 were unusually cloudy in the study area. Consequently, in spite of using the MVC, we observed that not all the atmospheric disturbances had been removed. To reduce the effect of cloud contamination, a mask with the highest values of channels 1 and 2 was obtained (Saunders, 1986). Moreover, all the NDVI values below 0.1 were eliminated, assuming this value as a threshold for vegetated areas.

Several authors have noted that the absolute NDVI value may not provide a clear image of vegetation trends, because it is highly related to landscape structure and amount of vegetation cover (Eidenshink et al., 1990; Kogan, 1990). Therefore, to isolate the weather-related component from the temporal variability of every pixel it has been suggested the use of greenness images, which account for the relative variation of NDVI. Greenness images were generated from the formula proposed by Kogan (1990):

$$GR = \left(\frac{NDVI_o - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right) * 100$$

where GR is relative percent green, ND_o is the observed NDVI for an specific pixel, and ND_{min} and ND_{max} are the minimum and maximum NDVI values of that pixel for the whole study period.

Surface temperatures were calculated using a three step approach. First, brightness temperatures were obtained from channels 4 and 5 radiances according to the following formula (Kidwell, 1991):

$$T_b = \frac{1.439 * 10^{-5} * \lambda}{\ln \left(1 + \frac{1.191 * \lambda^3}{L}\right)}$$

where T_b means brightness temperature, λ central wavelength of that band and L, the radiance value for that band.

Secondly, the emissivity correction was introduced in order to derive radiant temperatures:

$$T_{ra} = T_b * \epsilon$$

where T_{ra} and T_b are radiant and brightness temperatures, respectively, and ϵ is the emissivity of a vegetation cover, which we assumed to be 0.96 as an average (Chen and Zhang, 1989).

Finally, to eliminate the effect of atmospheric emittance, we applied the split window approach. Routinely used to derive sea surface temperatures, the split window is a multichannel method which assumes the atmospheric disturbances are proportional to the difference between temperatures measured in two thermal channels. From the different sets of coefficients derived for land temperatures, we used the values proposed by McClain et al (1985), which provided the best results in estimating surface temperature over grasslands (Cooper and Asrar, 1989):

$$T_s = a\, T_4 + b\, (T_4 - T_5) - c$$

where T_s is surface temperature, T_4 and T_5 are radiant temperatures of channels 4 and 5 of AVHRR; and a, b and c are the split window coefficients proposed by McClain ($a = 1.035$, $b = 3.046$ and $c = 283.934$).

Fire weather index data

Components of the Canadian Forest Fire Weather Index (FWI) System, were calculated for a set of 24 weather stations distributed over the study area (figure 1) for correlation with satellite-derived variables.

The FWI is the weather subsystem of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner, 1987). The CCFDRS also includes three additional sub-systems, the Canadian Forest Fire Behavior Prediction (FBP) System, the Canadian Forest Fire Occurrence Prediction (FOP) System, and the Accessory Fuel Moisture (AFM) System. FBP is a system which can be used to predict quantitative fire behavior, while the FOP and AFM systems are still under development.

The Fire Weather Index (FWI) is computed from several intermediate components (figure 2): the Buildup Index (BUI) and the Initial Spread Index (ISI). The former is more related with long term danger conditions (weeks) and the latter refers to short term changes (days).

In this project, since we were dealing with 10-days composites of satellite information, only the long term danger conditions were considered. Consequently, the Duff Moisture Code (DMC), Drought Code (DC) and Buildup Index (BUI) were computed for the 24 weather stations we had available. Calculation of the Fine Fuel Moisture Code (FFMC) were also included in order to test the effect of daily changes in the maximum values of NDVI for the 10 days periods.

All these indices were calculated with daily data, but average values of 10 days periods were also calculated for the correlations with satellite data.

RESULTS

Single correlations between the FFMC, DMC, DC and BUI on one side, and NDVI, Greenness and Surface temperature, on the other, were computed for every 10 day period where satellite images were available. As a preliminary finding, we have observed no clear trend in the correlations between FWI codes and satellite data. Pearson r correlation coefficients between the FFMC and NDVI range from 0.0189 (May 1-10) to 0.429 (May 11-20). For the DC most of the correlations are negative as expected, with the highest value of -0.56 (July 1-10). In both the FFMC and the DC, no clear timelag was shown. The DMC showed lower correlations with a maximum of -0.36 for the same period of July 1-10. The BUI presented the highest correlation for the beginning of July as well, with a value of -0.558.

Greenness measures also did not exhibit good correlations. Although these experiences should be extended to periods with less cloud cover, the preliminary conclusions of these correlations show a lack of spatial association between the FWI codes and the satellite-derived variables.

Given that the NDVI is related to the temporal dynamics of the vegetation cover, we calculated multitemporal regressions between each FWI component and the satellite variables for all the previous periods. For instance, for the last period, August 1-10, the FFMC, DC, DMC and BUI were estimated from the NDVI of that period plus the 9 previous periods. We repeated the procedure with the Greenness values (GR), surface temperatures (ST) and a ratio of NDVI and surface temperature (NDVI/ST). As expected, the multiple R squared was

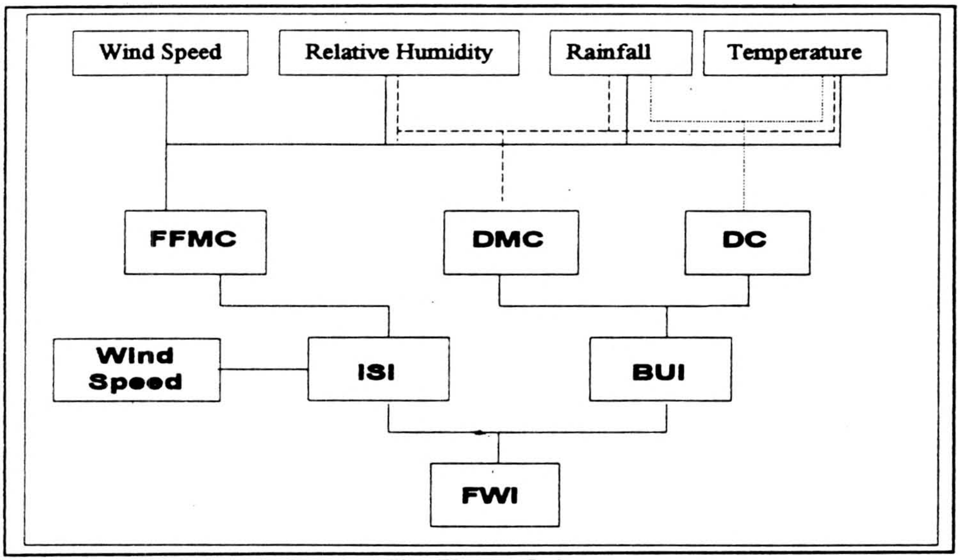

Figure 2: Structure of the Canadian Fire Weather Index

generally higher when more previous periods were available. Since we analyzed only 10 periods of satellite images (from May 1-10 to August 1-10), the number of independent variables decreased from the last period, when 10 independent variables were available, to May 11-20, which had only 2 independent variables. R^2 values for the estimation of the FFMC in the last period are 0.696 using the NDVI/ST, 0.526 for the ST and 0.441 for the GR. The DMC showed also good correlations for the last period ($R^2=0.716$ with the ST, 0.653 for the NDVI and 0.559 for the NDVI/ST), decreasing to the middle of June, were only GR provides a good estimation ($R^2=0.43$). The DC show good correlations only with NDVI and GR (R^2 over 0.5 for 5 out of the 10 periods).

A third set of correlations related every FWI component with the satellite variables for that period and the value of the same component for the precedent period. Multiple Correlations with the DC are above 0.95 for 8 periods, which offers a clear image on the slow temporal variability of this index. On the other hand, the DMC showed less temporal correlation, since only 4 periods offered R squared values above 0.7. The BUI also showed poor multiple correlations, with only two periods with R squared above 0.65.

Finally, we estimated the temporal series of the FWI components for all 10-days periods in every station using the NDVI, GR, ST and NDVI/ST as independent variables. In other words, for every station a multiple regression was computed to estimate the evolution of the FFMC, DMC and DC from the evolution of satellite-derived variables. The DC was again the variable which more frequently presented good correlations with satellite variables. In 10 out of 24 weather stations temporal evolution of the DC was estimated with r-squared values above 0.6. For most of these weather stations the NDVI, GR and ST were selected as significant variables at 0.9 probability level. In the case of the FFMC and DMC, only 4 and 3 weather stations, respectively, could be predicted with reasonably error. Figure 3 shows observed and predicted temporal trends of the DC for the weather station of Fort McMurray, located in a boreal forest area in Alberta. In this case, computed r-squared was 0.89. Independent variables were NDVI, GR, NDVI/ST and ST.

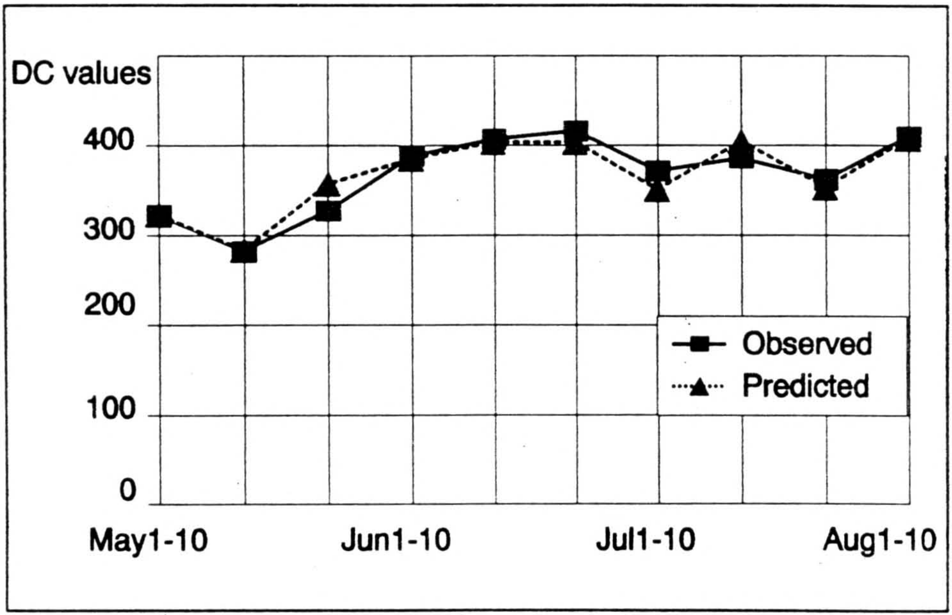

Figure 3: Temporal trend of the Duff Moisture Code in Fort McMurray. Observed and predicted values by satellite data

DISCUSION

More effort should be devoted in trying to understand the relationships between the components of the Canadian Fire Weather Index and satellite derived information. Spatial correlations between the FWI components and satellite-derived variables for every single period do not reveal a clear pattern, although negative correlations are dominant as one could expect. The DC exhibits higher correlations, which is reasonable according to its interval of recurrence. Taking into account satellite data for the previous periods improves the estimation, although no systematic trends can be inferred.

Several reasons may explain the difficulties in establishing a general framework to explain the relationships between satellite variables and FWI components: (i) the importance of cloud cover for the period analyzed, (ii) the deficiency in understanding the contribution of the understory component to the satellite signal in boreal forest, and (iii) lack of data on fuel moisture.

With respect to temporal trends, our preliminary results show that satellite derived variables may be used to estimate temporal trends of danger values, for specific weather stations. A longer series of data, beginning in March instead of May, would notably help to improve the establishing of these temporal profiles.

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