Evaluation of Thermal and Water Stress on Vegetation from Satellite Imagery

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Abstract: To evaluate the thermal and water stress of vegetation canopy in Southern Québec, leaf water status was evaluated from vegetation indices derived from SPOT VEGETATION images and surface temperature from NOAA AVHRR images. This study was conducted by investigating vegetation conditions for two different periods, from June to August, 1999 and 2000.

The vegetation indices were integrated for the evaluating vegetation conditions as a new index, normalized moisture index (NMI). A trapezoid was defined by the NMI and surface temperature, and the thermal and water status of the vegetation canopy was determined according to separate small sections within the trapezoid.

Keywords: VEGETATION, AVHRR, vegetation indices, surface temperature, thermal and water stress

1. Introduction

Forest fires involve significant economic damage by destroying trees and by weakening the perennial nature of certain ecosystems. In Canada, the Canadian forest fire weather index (FWI) system evaluates forest water condition and fire danger using meteorological station data sets [9]. However, the spatial resolution of the stations is several tens to hundreds of kilometers, and measurements represent geographic spots rather than regions.

For the above application, imagery from the advanced very high resolution radiometer (AVHRR) in NOAA series has been widely employed because of its spatial (about 1 km) and temporal (two images per day) resolution. Vegetation stress from drought was evaluated using NDVI and thermal infrared bands [6]. The negative relationship between surface temperature and NDVI was applied to evaluate surface water status [8].

In the monitoring of vegetation moisture, short-wave infrared (SWIR, 1.60 µm), which is not included in AVHRR but is in SPOT VEGETATION, is more sensitive to water content than NIR or red bands, while NIR is almost independent of the variation in water content [3]. VEGETATION (VGT) on board the satellite SPOT 4 seems to be an optimum tool, compared to the other sensors available, for deriving vegetation indices. The SPOT VGT provides better spectral separation of forest classes than does NOAA AVHRR because of finer band widths and the SWIR band [1].

The objective of this study is to investigate the potential of VGT for evaluating water status on the boreal forest cover. Secondly, we wish to evaluate thermal and water risk over time and space using vegetation indices from the optical bands of VGT and surface temperatures from the thermal bands of AVHRR.

2. Study area and materials

In this study, we investigated water status of the vegetation canopy in a study area between latitudes 45°N and 50°N, and longitudes 76°W to 67°W in Southern Québec province. There is a large boreal region in the north, broadleaf forest in the south, and an agricultural region, mostly around Montréal city and along the river (Fig. 1). Considering the level of fire activity, a two-year comparison, and the satellite data availability, a study period from June to August of 1999 and 2000 was chosen.

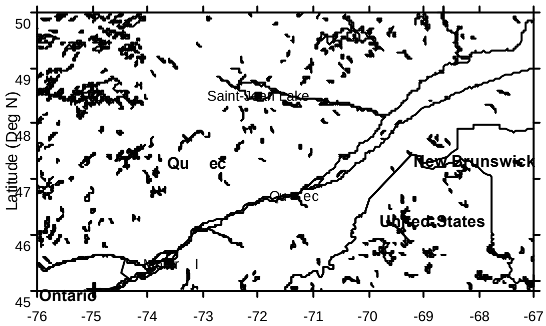

Fig. 1. Location of the study area in Southern Québec.

Meteorological parameters were measured at 45 meteorological stations spread throughout the study area. The parameters measured at the stations were air temperature, wind speed and direction, humidity, and precipitation with six components of the FWI system at midday. The FWI system consists of three fuel water codes: fine fuel water code (FFMC), duff water code (DMC) and drought code (DC), and three fire behavior indices: initial spread index (ISI), buildup index (BUI) and fire weather index (FWI).

NOAA-14 AVHRR images were selected for retrieving surface temperatures. The imagery for the study area was imaged at around 3 pm Eastern Canadian time. The NOAA-14 AVHRR images were collected for the period from June to August, 1999 and 2000.

Vegetation indices were derived from optical band images of VGT on SPOT 4. In this work, S1 (daily synthesis) and S10 (10-day synthesis) at 1 km resolution for VGT products were employed in obtaining vegetation indices.

4. Retrieval parameters

It was clearly proved that NDVI was superior to the other indices, or that there was only very small improvement when using the other indices. [2, 7]. The normalized vegetation water index (NDWI) using SWIR and NIR were suitable indices for evaluating vegetation water status [5]. Thus the NDVI and NDWI derived from VGT were employed for evaluating water content of the vegetation canopy as follows:

$$NDVI = (NIR-RED)/(NIR+RED) \quad (1)$$
$$NDWI = (NIR-SWIR)/(NIR+SWIR) \quad (2)$$

where RED is channel 2 (0.61-0.68 μm), NIR is channel 3 (0.78-0.89 μm), and SWIR is channel 4 (1.58-1.75 μm) of VGT.

Here the split-window algorithm of [4] was employed, since the algorithm was optimized for the mid-latitude region where our test area is located. The equation of the split-window algorithm is:

$$T_s = T_4 + [1.29 + 0.28(T_4 - T_5)] \times (T_4 - T_5) + 45(1 - e_4) - 40\Delta e \quad (3)$$

where T_s is surface temperature, T_4 and T_5 are brightness temperatures of channel 4 and channel 5 of AVHRR, and ε_4 and $\Delta\varepsilon$ are the emissivity of channel 4 and the emissivity difference between channel 4 and 5.

5. Analysis and results

The comparison of the two vegetation indices yields a strong positive correlation (Fig. 2). However, each index has additional information on vegetation canopy. It is thus necessary to use both indices for evaluating the vegetation canopy status. We suggested a new index that integrated the two vegetation indices as follows:

$$\text{Normalized Moisture Index (NMI)} = NDVI+NDWI \quad (4)$$

In this study, the precipitation events have significantly contributed to the increase of NMI. The values of the NMI and surface temperature were higher in June 1999 than in 2000. The surface temperature had approximately negative correlation with the NMI. It is obviously necessary to use surface temperature for evaluating vegetation status.

To explain vegetation status by water and thermal condition, we defined a trapezoid determined by the NMI and surface temperature. Denser and well-watered vegetation is found in the upper zone of the trapezoid, while sparse and deficiently watered vegetation is at the bottom. The left side of the trapezoid is an environment with lower temperature, and the right side is at a higher temperature. Therefore, minimum thermal and water stress may be found in the upper left section corner (section 1) of the trapezoid, while the maximum stress exists in the lower right corner (section 2). The lower left and upper right are section 3 and 4, respectively. Additionally, the four corner sections of the trapezoid are defined by lines delimited for the subsequent validation process (Fig. 3).

The monthly scattering plot for June was produced using the NMI and surface temperature from the whole collocated data sets superimposed on the trapezoid (Fig. 3). The vegetation of 1999 was denser and well-watered and at a higher temperature, while that of 2000 was sparser and deficiently watered and at a low temperature. In June 1999, the vegetation was perhaps exposed to thermal stress.

The Canadian Forest FWI system was employed for validation of our model. The DC reflected the water stress according to precipitation events by comparing with station data. The DMC and BUI were significantly correlated and so were the ISI and FWI. Therefore, the DC, BUI and FWI were employed as validation data to evaluate vegetation status defined by the NMI and surface temperature.

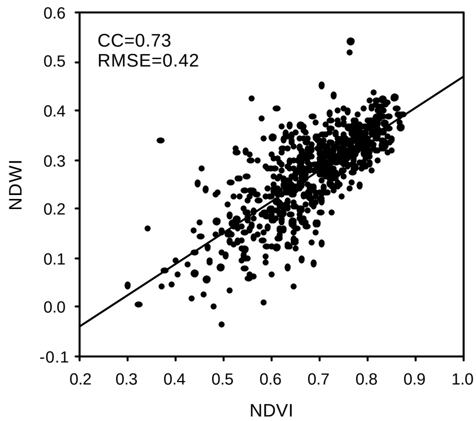

Fig. 2. Scatter plot of the NDVI and NDWI. CC is the correlation coefficient and RMSE is the root mean square error.

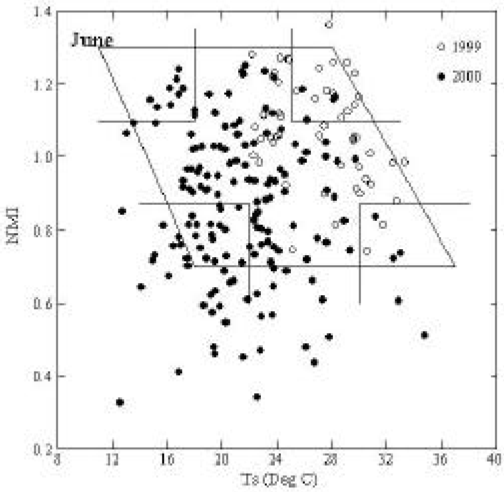

Fig. 3. Scatter plot of NMI and surface temperature with the trapezoid including the four sections.

The daily values of the DC, BUI and FWI were averaged monthly for the four sections of the trapezoid. The highest value of the average DC was found in section 2 and the second highest was in section 4. The highest BUI and FWI were also found in section 2 and almost of all the second were also found in section 2. Section 2, where the highest values were found, is the zone where the vegetation can be under maximum thermal and water stress as defined by our trapezoid. Also, section 4 was defined as an area where there can be thermal stress. Therefore the trapezoid has precisely evaluated water status of the vegetation in the study area. Section 3, where the vegetation may be under water stress, had lower DC. Thus it is clear that the thermal stress on the vegetation is more significant than water stress.

6. Conclusion

The vegetation status in terms of thermal and water stresses was evaluated using vegetation indices and surface temperature derived from satellite data. NDVI and NDWI were integrated into NMI, for monitoring the water status of vegetation as well as the vegetation density. The NMI and surface temperature were employed to define the trapezoid for evaluating vegetation status. The NMI revealed not only the density of vegetation but also the water content of vegetation by using the SWIR band. The trapezoid defined by the NMI and surface temperature allowed evaluation of the vegetation status in terms of thermal and water stresses. The dense forest region occupied the upper section of the trapezoid, but the agricultural or barren region was in the lower section, because the NMI included the NDVI classified regions according to vegetation density. Vegetation status defined by the trapezoid was reasonably well validated by comparison with the DC, BUI and FWI of the Canadian Forest FWI system. The average value of DC in the lower right section was much higher than the others. The upper right section obtained the second highest average values of DC. The highest values of the BUI and FWI were also found in the lower right section. Thus the trapezoid defined by NMI and surface temperature has reasonably evaluated the water status of the vegetation in Southern Québec. Additionally, the thermal stress had a more significant effect upon the vegetation status than did the water stress.

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