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A Model to Assess Fire Danger using NOAA-AVHRR Images

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Abstract

In Canada, daily forest fire danger ratings are generated by the Canadian Forest Fire Danger Rating System (CFFDRS), based on estimates of fire weather indices (FWI). To evaluate the potential of NOAA-AVHRR images, an experiment was conducted in 1994 using test sites consisting of jack pine, black spruce and white spruce stands located in the MacKenzie river basin, Northwest Territories, Canada. FWI codes and indices were compared to ratios between actual and potential evapotranspirations (AET/PET). AET was computed from the difference between NOAA-AVHRR surface temperatures and maximum air temperatures, using the energy budget equation. PET was computed using both the CFFDRS method and the Penman-Monteith equation. In the model, the aerodynamic resistance and the soil heat flux were computed using NOAA-AVHRR NDVI images. AET values were similar to those found in the literature. AET/PET well correlated to FWI in most of the cases. Our study also shows that the Penman-Monteith equation is better than the CFFDRS method for computing PET.

Résumé

Cette étude a pour but d'évaluer le potentiel des images optiques et thermiques de NOAA-AVHRR pour gérer le danger d'incendies de forêts. Au Canada, le danger d'incendies de forêts est calculé par la Méthode canadienne d'évaluation des dangers d'incendie de forêts (MCÉDIF), à partir d'estimations des indices du système indice forêt-météo (IFM). Pour évaluer le potentiel des images NOAA-AVHRR, une expérimentation a eu lieu en 1994 sur des peuplements de pin gris et d'épinette blanche et noire situés dans le bassin du fleuve MacKenzie, Territoires du Nord-Ouest, Canada. Les indices IFM ont été comparés aux rapports entre l'évapotranspiration réelle et potentielle (ETR/ETP). ETR a été calculé avec l'équation de bilan énergétique à partir de la différence entre les températures de surface NOAA-AVHRR et les températures maximales de l'air. ETP a été calculé avec la méthode de la MCÉDIF et l'équation Penman-Monteith. Dans le modèle, la résistance aérodynamique et le flux de chaleur du sol sont calculés à partir d'images NDVI de NOAA-AVHRR. Les estimations de ETR sont proches de celles de la littérature. Le rapport ETR/ETP est bien corrélé à l'indice IFM dans la plupart des cas. Notre étude aussi montre que la méthode Penman-Monteith équation est meilleure que la méthode MCÉDIF pour calculer ETP.

1. Introduction

Boreal forests cover about 11% of the Earth's terrestrial surface and are to be considered in global climate and water balance analysis. They experienced short growing season, very cold and long winters, permafrost, short and warm summers and low annual precipitations. Summers are also characterized by longer days and high solar irradiances and air dryness which make the forests experiencing high evaporative demand and which can lead to desert or semidesert conditions in the afternoon (McCaughey *et al.*, 1997; Baldocchi *et al.*, 2000; Eugster *et al.*, 2000). Thereby, boreal forests are subjected to large fires.

Wildfire dangers depend on various factors, among others fuel moisture. In Canada, daily fire danger ratings are generated using a semi-empirical modular system known as the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.*, 1989). It combines, through simulated indices, weather, fuel, topography and ignition parameters. One of the CFFDRS subsystems, the Fire Weather Index (FWI) system, provides numerical ratings of relative mid-afternoon fire potentials, based solely on weather data recorded daily at noon LST (e.g., Canadian Forest Service (CFS), 1987; Stocks *et al.*, 1989). The FWI system has the limitation of not being able to consider variations in environmental conditions at finer spatial scales, but only produces estimates for large geographic regions. This is because it does not account for the difference in forest types and is dependent on weather records from widely dispersed stations. Information derived from satellite systems offers the potential to address these limitations. CFFDRS parameters that can be potentially monitored using satellite data include fuel type, fuel moisture and plant phenology. In previous studies reviewed in Chuvieco and Martin (1994) and in Leblon (2001), fuel moisture has been estimated through empirical relationships from both NOAA-AVHRR normalized difference vegetation index (NDVI) and thermal infrared imagery.

Our study presents an analytical model to estimate daily actual evapotranspiration (AET) during the 1994 fire season over 18 coniferous stands located in the

Northwest Territories, Canada, using NDVI and thermal infrared (T_S) NOAA-AVHRR images as well as ancillary data, i.e., tree height (z_h), air temperature (T_a), net radiation (Q_n) and canopy resistance (r_c) (Fig. 1).

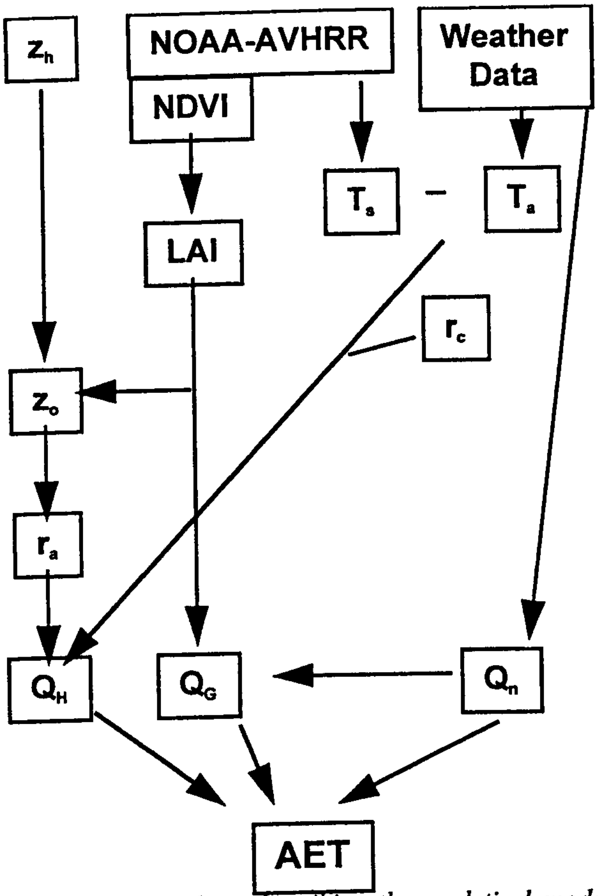


Figure 1. Flowchart describing the analytical model which computes AET from NOAA-AVHRR images and ancillary data (z_o = surface roughness, r_a = aerodynamic resistance)

Details of the model's equations can be found in Leblon et al. (2001a). NOAA-AVHRR is particularly suitable for such a computation, because it allows daily acquisitions of NDVI and thermal infrared images in the same time and over a huge area. AET estimations were then used to compute the ratio between actual and potential evapotranspiration (AET/PET). PET was computed using both the Penman-Monteith equation (PET_{PM}) and the CFFDRS method (PET_{CFFDRS}). For assessing the potential of AET/PET to be used as a fire danger index, AET/PET was related to FWI codes and indices computed from nearby weather stations. A similar study was already conducted over Mediterranean forests (Vidal *et al.*, 1994), but our study is different in that: (i) it is related to northern boreal forests, which experience a different fire-weather environment than Mediterranean forests; (ii) it uses NDVI images in the estimation of the aerodynamic resistance and of the soil heat flux (Fig. 1).

2. Materials

Our study area is located in the Mackenzie River basin, Northwest Territories, Canada (57°36' Lat. N. to 71°27' Lat. N. and 110°39' Long. W. to 135°18' Long. W.). Within the study area, stands were selected at six different sites (Table 1). There were two other stands located in Lone Mountain, but satellite images acquired on this site were noisy due to topographic effects. In each site, each stand is a 10 ha in size and is composed of pure or mixed stands of jack pine, white spruce and black spruce, depending on the site (Table 1).

Table 1. Geographical and biological characteristics of the studied sites.

Site (1)	Sp (2)	Lat. N.	Long. W.	dbh(3) (cm)	h(4) (m)	Density (Stem /ha)
Fs	jP	60°00	112°12	18.4	12.3	410
	bS	60°00	112°15	8.2	6.3	5857
	wS	60°03	112°13	14.8	11.3	1882
Hr	jP	60°30	116°14	18.7	12.9	622
	bS	60°30	116°14	18.7	11.6	975
	wS	60°33	116°07	17.3	12.3	2077
Sf	jP	61°52	121°28	19.6	12.0	1328
	wS	61°53	121°37	23.4	14.3	1470
	bS	61°56	121°33	14.8	10.5	2148
Lm	wS	62°11	123°20	28.8	10.7	n/a
	jP	62°11	123°20	21.5	4.7	n/a
Yk	wS	62°31	114°10	13.1	10.9	2120
	bS	62°31	114°10	10.5	10.9	2120
	jP	62°31	114°09	11.0	6.3	1554
Nw	bS	65°16	126°45	6.1	4.7	5546
	wS	65°17	126°52	12.9	11.4	8953
In	wS	68°18	133°31	6.0	8.3	1244
	bS	68°19	133°37	2.9	4.4	1004

(1) Fs = Fort Smith, Hr = Hay River, Sf = Fort Simpson, Yk = Yellowknife, Lm = Lone Mountain, Nw = Norman Wells, In = Inuvik;(2)wS = white spruce, bS = black spruce, jP = jack pine, (3) dbh = mean diameter at breast height (cm); (4) h = mean tree height (m).

A better stand selection would consider the spatial and regional representativity of stands with regard first, to the area covered by each species in the study area and second, to the satellite coverage. However, because of limited research funds, our study was limited to the stands listed in Table 1. These stands were typical of the species found in the study area and were located on sites that were well distributed throughout the study area. The biological characteristics of each stand are also detailed in Table 1.

NDVI and surface temperature (T_S) data were extracted from 108 NOAA-11 AVHRR images acquired, from snowmelt to snowfall. The time of acquisition was between 22 and 24 UT, which means that the corresponding local time was afternoon. Each image belonged to GEOCOMP database and thus, was georeferenced following a Lambert conic conformal projection, in order that further geometrical corrections were not required (Robertson *et al.*, 1992). Each image has a ground spatial resolution of 1 km and is constituted of eight bands: two optical bands in the red and near-infrared, three thermal infrared bands and three bands giving, for each pixel, the sun zenith angle, the view zenith angle and the relative sun-sensor azimut angle. The images were corrected for illumination and atmospheric effects, following the method detailed in Gallant (1998). On each corrected NDVI image, a 3-by-3 pixel window was extracted for each stand based on its geographical coordinates (Table 1).

Weather stations located close to the stands provided daily weather data which are required to compute FWI codes and indices using the WeatherPro^{TM} package of Remsoft Inc. which is based in the CFFDRS equations (CFS, 1987). These data were also used to estimate PET_{CFFDRS} and PET_{PM}.(Fig. 1).

3. Results and Discussion

3.1. Determination of AET

AET was computed daily from the aerodynamic resistance (r_a), the canopy resistance (r_c) and the temperature difference between the surface and the air (T_s-T_a) (Fig. 1). r_a was computed from NDVI, tree height, wind speed, and reference height (Fig. 1). The computed mean r_a values ranged from 0.4-5.5 s. m^{-1}. Jarvis *et al.* (1976)'s review reported r_a values, ranging from 0.6-8.0 s. m^{-1} for various coniferous species. r_a values of 5 s. m^{-1} were reported over various coniferous stands (Kelliher *et al.*, 1993; Linacre, 1993) and over the old jack pine stand of the southern BOREAS site (SSA-OJP) in 1993 (Baldocchi and Vogel, 1996), but high r_a values (up to 15. s. m^{-1}) were reported over maritime pine, for Douglas-fir, for subarctic larch-black spruce (see the review of Kelliher *et al.*, 1993) and for the SSA-OJP stand in 1994 (Baldocchi *et al.*, 1997).

The r_c value used in our study (95 s. m^{-1}) was a median of values found in the literature for coniferous species. r_c was much high than r_a, in agreement with literature observations over rough surfaces, like forests (Lindroth, 1985a; Linacre, 1993; Kelliher *et al.*, 1993; Vidal *et al.*, 1994; Baldocchi and Vogel, 1996; Baldocchi *et al.*, 1997). According to the Jarvis-McNaughton theory on atmospheric coupling (McNaughton and Jarvis, 1983; Jarvis and McNaughton, 1986), smaller r_a and larger r_c should imply that AET is less coupled to available energy, but more strongly coupled to the vapor pressure deficit and to r_c (Baldocchi *et al.*, 1997, 2000; Eugster *et al.*, 2000). Large r_c values for boreal coniferous stands were explained by short-term factors, like partial stomatal closure due to soil and atmospheric moisture deficits (Kelliher *et al.*, 1993, 1997; Baldocchi *et al.*. 1997, 2000). Low soil water potentials cause stomatal closure through the release of abscisic acid from the roots (Kelliher *et al.*, 1993; Baldocchi *et al.* 1997, 2000), Long-term factors explaining large r_c values of boreal coniferous forests include low maximal stomatal conductance and low LAI (Lafleur, 1992; Lafleur and Rouse, 1995; Kelliher *et al.*, 1995; Baldocchi *et al.*, 1997, 2000), because of low site productivity due to climate, a short growing season and poor nutrient status (Baldocchi *et al.*, 1997, 2000). Low LAI also induces a more direct effect on evapotranspiration by limiting the cross-sectional area of the sapwood (Schultze *et al.*, 1987) and thus reducing xylem hydraulic conductivity (Baldocchi *et al.*, 1997, 2000).

However, at regional scales, like those of satellite images, feedback between the surface and the convective boundary layer reduces the sensitivity of maximal AET to r_c (Jacobs and De Bruin, 1992; McNaughton and Jarvis, 1991; Kelliher *et al.*, 1993; Dolman *et al.*, 1998). Also, r_c has been found to be largely insensitive to vapour pressure deficit in the case of the old jack pine at the northern BOREAS site, except for very low vapor pressure deficits (Moore *et al.*, 2000). The atmospheric coupling observed by Baldocchi *et al.* (1997, 2000) over the SSA-OJP stand can be explained by the fact that r_c is usually computed from AET (Moore *et al.*, 2000). Another explanation of the apparent discrepancy between both BOREAS sites is related to the forest floor contribution to the energy exchange. For boreal forests, particularly those located in the subarctic area, like in our stands at Inuvik, the openness of the canopy, the low LAI and the low leaf stomatal conductance make the forest floor and non-vascular plants (i.e., lichen) being an important source of AET (e.g., Lafleur 1992; Lafleur *et al.* 1992; Kelliher *et al.*, 1993; Lafleur and Rouse, 1995; Kelliher *et al.*, 1997; Baldocchi *et al.*, 1997, 2000; Eugster *et al.* 2000). For these forests, energy partitioning depends more on the available energy for evapotranspiration than for more closed forests (Lafleur and Rouse 1995), despite the low albedo of boreal forests which increases the available energy because of higher radiation absorption (McNaughey *et al.*, 1997; Baldocchi *et al.*, 1997, 2000; Eugster *et al.* 2000).

The resulting AET seasonal variation is smoother than the seasonal variation of T_s-T_a (Fig. 2). For each stand, AET fluctuated as the vapour pressure deficit and the soil moisture (Fig. 2), but according to a quadratic trend which is as follows: AET first increased, reached a plateau and then decreased over the summer and autumn (Fig. 2). A similar trend was already observed over various coniferous forests in Europe (Lindroth, 1985b, Cienciala *et al.*, 1998; Dolman *et al.*, 1998; Grelle *et al.*, 1999) and in Canada (Lafleur *et al.*, 1992, Baldocchi *et al.*, 1997, 2000).

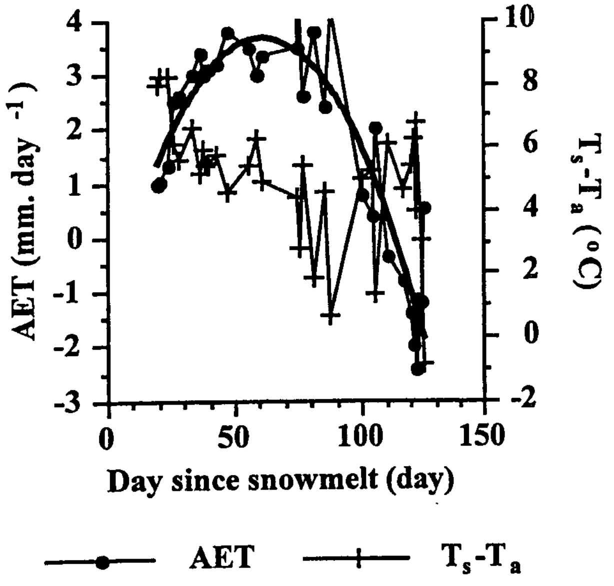


Figure 2. Seasonal variations of AET (mm. day^{-1}) and T_s-T_a (°C) for the black spruce stand in Fort Smith. The quadratic trend is represented by a solid line.

Low AET values occurred in spring and autumn. These values can be due to low available energy (Moore *et al.*, 2000), but also to occurrence of chilling and frost events (Baldocchi *et al.*, 1997, 2000). Low temperature reduces evapotranspiration, by reducing photosynthesis and stomatal conductance (Baldocchi *et al.*, 1997, 2000), but also more directly, by affecting the ratio between the slope of the vapour pressure curve and the psychrometric constant (Baldocchi *et al.*, 2000), both variables being related to evapotranspiration. However, these events are not enough to stop the forest evapotranspiration at the beginning of the spring (Baldocchi *et al.*, 1997).

At the end of the growing season, negative AET values occurred (Fig. 2). Negative AET values were also observed in winter over South France Mediterranean forests and were partially explained by condensation (Vidal *et al.*, 1994). These negative values illustrate the limits of the energy budget approach for computing AET. When these negative values are removed from the data set, the mean AET value over the season ranged from 1.6 mm per day for the 3 stands at Yellowknife to 3.3 mm per day for the white spruce stand at Fort Smith and the black spruce stand at Inuvik (Table 2).

Table 2. Comparison between mean AET and mean PET. PET_{CFFDRS} is computed with the CFFDRS method; PET_{PM} is computed with the Penman-Monteith equation (AET and PET in mm. day^{-1})

Site	Sp.	AET	PET_{CFFDRS}	PET_{PM}
Fs	bS	2.6	3.4	7.3
	wS	3.3	3.3	6.8
	jP	2.6	3.3	7.4
Hr	bS	1.8	3.3	6.0
	wS	1.9	3.3	5.8
	jP	1.8	3.3	6.0
Sf	bS	2.7	3.4	7.1
	wS	2.7	3.2	6.7
	jP	2.7	3.2	7.1
Yk	bS	1.6	3.0	6.4
	wS	1.6	3.0	6.4
	jP	1.6	3.1	6.7
Nw	bS	2.1	3.3	7.5
	wS	2.7	3.1	6.6
In	bS	3.3	3.4	6.4
	wS	2.8	3.4	6.0

(1) Fs = Fort Smith, Hr = Hay River, Sf = Fort Simpson, Yk = Yellowknife, Lm = Lone Mountain, Nw = Norman Wells, In = Inuvik;(2)wS = white spruce, bS = black spruce, jP = jack pine.

This range of AET variation is within the values observed in the literature (Leblon et al. 2001a). On average, AET for the jack pine stands (2.0 mm per day) tends to be less than for the spruce stands (2.2 mm per day for the black spruce and 2.4 mm per day for the white spruce). Such a species difference was already observed over the BOREAS sites and related to a difference in environmental growing conditions (Baldocchi *et al.*, 2000). Indeed, jack pine typically grow up on sandy upland sites, where humidity and soil moisture are limited, but black spruce stands are on wet organic soils, where evapotranspiration is less limited by soil moisture. In this last case, the limiting factors are soil temperature in spring and elevated atmospheric humidity deficits in summer (Jarvis *et al.*, 1997; Baldocchi *et al.*, 2000).

3.2. Determination of PET

Potential evapotranspiration (PET) was computed on a daily basis (mm. day^{-1}) using two different methods. They are the CFFDRS method (PET_{CFFDRS}) and the Penman-Monteith Method (PET_{PM}). PET should be greater than AET in most of the cases, since AET is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration, while PET is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration. AET greater than PET may occur only when the available energy is not limited and the canopy is sufficiently wet (Jarvis *et al.*, 1976).

PET_{CFFDRS} did not vary among sites (Table 2) and during the season. This result does not agree with the literature, since PET should vary during the summer and across latitudes (Eugster *et al.*, 2000). There are two possible explanations of the lack of summer and latitudinal variations of PET_{CFFDRS}. First, the CFFDRS method is a modification of the Thornthwaite method, which was designed for estimating PET on a monthly basis. A scaling daylength adjustment factor was used to scale PET on a daily basis, but the factor has a monthly value. Second, the Thornthwaite method was originally calibrated for crop canopies, but not for forest canopies. In addition to the lack of seasonal and latitudinal variations, PET_{CFFDRS} was lower than AET in many times (Table 2). Kolka and Wolf (1998) already found that theThornthwaite method is not suitable for computing PET of forests located in the Upper Great Lakes areas. Therefore, PET_{CFFDRS} will not be used to calculate the AET/PET ratio.

The second method used to compute PET is the Penman-Monteith method. It is considered as a reference method. In each case, PET_{PM} was higher than PET_{CFFDRS} (Table 2). PET_{PM} was also more variable among the sites (Table 2) and over the season. When the seasonal variation of PET_{PM} was compared with the AET computed from the energy budget equation, PET_{PM} was greater than AET for each case (Table 2). PET_{PM} will be used to calculate the AET/PET ratio.

3.3. Definition of a AET/PET-based fire danger index

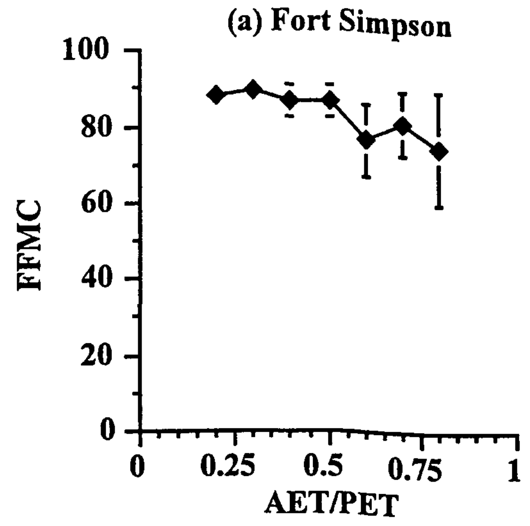
Over the season, the AET/PET ratio fluctuated in response to wetting and drying cycles, but according to a negative linear trend. Such a negative trend was already observed with the AET/Q_n ratio over the SSA-OJP stand (Baldocchi *et al.*, 1997, 2000; Eugster *et al.* 2000). This trend was explained by a strong control of surface and soil moisture over evapotranspiration (Baldocchi *et al.*, 1997, 2000; Eugster *et al.* 2000). In order to assess the relevance of AET/PET as fire potential indicator, correlations between the ratio and each FWI code and index were computed for each stand, each species, each site and for all the cases (Table 3).

Table 3. Pearson's correlation coefficients (1) between AET/PET and FWI codes and indices

(2)	(3)	FFMC	DMC	DC	FWI	(4)
Fs	bS	-0.55	-0.30	-0.37	-0.56	26
	wS	-0.12	-0.33	-0.30	-0.47	18
	jP	-0.52	-0.16	-0.09	-0.36	19
	M	-0.44	-0.26	-0.35	-0.45	30
Hr	bS	-0.35	-0.10	-0.03	-0.37	25
	wS	-0.33	-0.15	-0.08	-0.46	25
	jP	-0.35	-0.10	-0.03	-0.37	25
	M	-0.26	-0.09	-0.08	-0.27	28
Sf	bS	-0.49	-0.28	0.01	-0.45	17
	wS	-0.60	-0.34	-0.02	-0.40	25
	jP	-0.55	-0.37	-0.12	-0.36	25
	M	-0.53	-0.21	-0.06	-0.34	25
Yk	bS	0.02	0.12	0.11	0.16	30
	wS	0.02	0.13	0.12	0.17	30
	jP	0.16	-0.10	-0.20	0.09	37
	M	0.14	0.10	0.00	0.17	34
Nw	bS	-0.52	-0.27	-0.09	-0.38	16
	wS	-0.44	-0.08	0.27	-0.26	11
	M	-0.59	-0.30	-0.11	-0.47	17
In	bS	-0.15	-0.92	-0.75	-0.41	12
	wS	-0.59	-0.88	-0.78	-0.59	13
	M	-0.31	-0.90	-0.82	-0.49	16
All	bS	-0.40	-0.20	-0.24	-0.37	126
	wS	-0.38	-0.20	-0.30	-0.36	122
	JP	-0.41	-0.14	-0.21	-0.30	106
	M	-0.39	-0.20	-0.29	-0.36	150

(1) The coefficients significant at α = 0.05 are underlined; (2) Fs = Fort Smith, Yk = Yellowknife, Hr = Hay River, Sf = Fort Simpson, Nw = Norman Wells, In = Inuvik; All = all sites; (3) wS = white spruce, bS = black spruce, jP = jack pine; Mean = average ratio among species; (4) number of observations.

Correlations for the individual stands were computed from the raw data, whereas correlations per site and on for all the cases were computed from the mean ratio values for each site, since FWI indices and codes did not differ from one species to another at the same site. FFMC and FWI were most correlated with the ratio, except in Inuvik, where DC, DMC, and the BUI were the most correlated (Table 3). The difference at Inuvik may be related to the more sparse forest canopy occurring at this site, which makes satellite signals sensitive not only to the surface level, but also to the forest floor level. At the other sites, the ratio seems to be mostly sensitive to the moisture content of the litter and other fine fuels (FFMC).



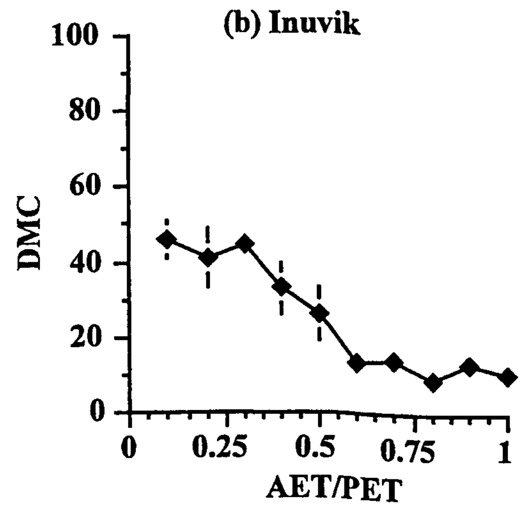


Figure 3. Relationships between the AET/PET ratio and FWI codes and indices for (a) FFMC at Fort Simpson, and (b) DMC at Inuvik. Error bars represent 1 standard deviation around the mean. The trend is indicated by a solid line.

In order to define a fire danger index based on the AET/PET ratio, AET/PET values were categorized into classes ranging from 0.0 to 1.0 by steps of 0.1, as in Vidal *et al.* (1994). For each class of AET/PET, a mean value for each FWI index and code was estimated. The error around the mean was also computed through the corresponding standard deviation. These categorized ratios were plotted against mean FWI index or code (Fig. 3). AET/PET increases when the FWI index or code decreases, because an increase in AET/PET means less droughtness, which yields to lower FWI indices or codes. For FFMC, such a trend is found in Fort Simpson (Fig. 3a) and Norman Wells, but not in Yellowknife and Inuvik. For DMC, DC and BUI, the trend is found in Fort Smith and Inuvik (Fig. 3b), but not at the other sites. A similar trend is also found when pooling all together the mean values for the different sites (Fig. 4).

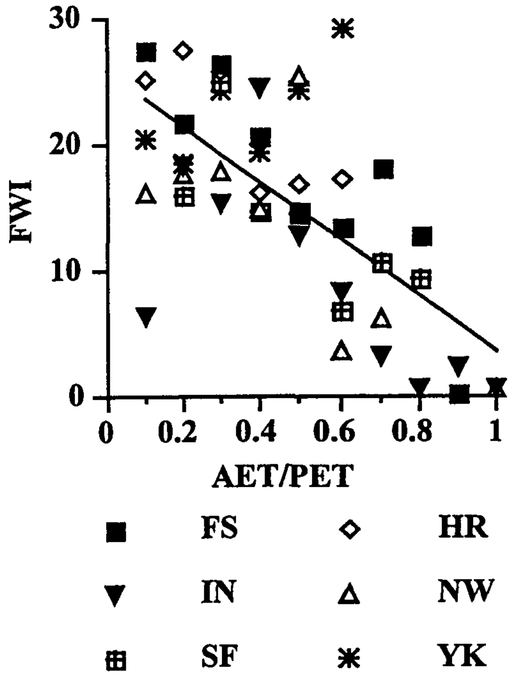


Figure 4. Relationships between the AET/PET ratio and FWI for all the sites together. Each site is marked by a different symbol. The trend is indicated by a solid line.

Fire danger monitoring based on the AET/PET ratio is advantageous, because first it uses a ratio which is analytically derived from NOAA-AVHRR images. Second, the ratio is computed at the time of satellite overpass, but it can be used at another daytime, because AET measured over BOREAS stands were shown to vary little during the day, i.e., between 10 and 18 hours (McNaughey *et al.*, 1997; Jarvis *et al.*, 1997; Baldocchi *et al.*, 1997, 2000; Eugster *et al.*, 2000). However, the ratio cannot be computed under cloud sky conditions. Also, there is some variability around the trend (Fig. 3 and 4), which means that droughtness as indicated by AET/PET is not the only fire danger factor to be considered. For example, another important factor that should be considered is the wind, which is taken into account in the AET/PET ratio, only indirectly, through the computation of r_a.

4. Conclusions

In Canada, daily fire danger for the major forest types is operationally predicted by the Canadian Forest Fire Danger Rating System (CFFDRS). The CFFDRS system has the limitation of not dealing with variable environmental conditions at fine scale. Our study presents a model that computes actual evapotranspirations (AET) from thermal infrared NOAA-AVHRR images and synoptic air temperature data, using a energy budget approach. AET is then used together with potential evapotranspiration estimates (PET) in order to define the ratio between actual and potential evapotranspiration (AET/PET). The model was fitted with ground-based, weather and images data acquired during the 1994 fire season over 18 stands located in the MacKenzie River basin, Northwest Territories. Two methods for estimating PET were tested: (i) the CFFDRS method (PET_{CFFDRS}), and (ii) the Penman-Monteith equation (PET_{PM}). Both AET and PET_{PM} estimations require the determination of the soil heat flux and of the aerodynamic resistance (r_a). Both variables were computed from NOAA-AVHRR NDVI images. Such a method has the advantage of explicitly considering the effect of ground cover over the soil heat flux and over r_a. The computed AET's were within the range of variation observed in the literature. PET_{PM} was shown to give more reliable estimates than PET_{CFFDRS}.

The potential of the AET/PET ratio as fire danger index was assessed by comparing the ratio to FWI indices and codes. Good relationships were found with fast-drying fuel codes (FFMC) in Fort Simpson and Norman Wells, but with slow-drying fuel codes and indices (DMC, DC and BUI) in Fort Smith and Inuvik and with FWI in Fort Smith, Hay River, Fort Simpson and Norman Wells. The potential of the AET/PET ratio as fire danger index was assessed by comparing ratio values to FWI codes and indices. There is now the need to assess if this ratio can effectively be used to map fire danger potentials by comparing AET/PET maps to actual fire maps. This work will be done in a further study.

Our study also shows that this ratio has negative values at the end of the growing season, which illustrates one of the limitations of the developed method for fire danger monitoring. Other limitations include: (i) the impossibility of using the method during cloudy days. Among all the possible strategies for increasing image availability reviewed in Bussières and Goïta (1997), one of the most promising is the use of radar images which are acquired whatever the weather conditions. For the studied stands, Leblon *et al.* (2001b) already found good relationships between ERS-1 SAR radar backscatters and FWI codes. Further study is needed to develop a method which uses both NOAA-AVHRR and ERS-1 images to estimate moisture-related variables, like in Moran *et al.* (1997); (ii) the impossibility of using the method over rough terrain, like in Lone Mountain, unless the satellite images have been corrected for topographic effects, with methods such as those of Teillet *et al.* (1982); (iii) the need to test the method for other years, because 1994 was shown to be particularly hot and dry in northwest Canada (McCaughey *et al.*, 1997; Baldocchi *et al.*, 1997; Gallant, 1998); (iv) the use of a constant value for the albedo, whereas this variable was already estimated from NOAA-AVHRR near-infrared images (Granger 1997) and from LANDSAT-TM optical bands (Baastiansen *et al.*, 1998; Baastiansen, 2000). This will be addressed in a further study; (v) the use of a constant value for the canopy surface resistance (r_C), although r_C depend on many variables, like LAI, vapour pressure deficit, etc... (e.g., Lindroth, 1985a; McNaughton and Jarvis, 1991; Kelliher *et al.*, 1995; Cienciala *et al.*, 1998; Grelle *et al.*, 1999). Also, northern boreal forests are not only made of trees, but other components should be considered when computing r_C, like shrubs, lichen, moss, etc... Eventually, NDVI should be used in this computation, because it is an integrated measurement over the forest; (vi) the need of *a priori* knowledge of the canopy height. Further research is needed to develop a method for estimating tree height from remote sensing, for example from radar images, like in Riom and LeToan (1981) or in Dobson *et al.* (1995); (vii) the lack of comparison with flux measurements , although our estimated results compare well with literature results. This comparison will be done in a further study using BOREAS data. Finally, further studies are also needed to validate more spatially-explicit models, like the SEBAL model (Baastiansen *et al.*, 1998; Baastiansen, 2000) and to test more spatially-accurate satellite images, like those provided by the MODIS, because spatial resolution of NOAA-AVHRR images is too coarse, despite their advantage of being theoretically available four times a day over the study area.

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