INT. J. REMOTE SENSING, 2001, VOL. 22, NO. 14, 2839–2846

Monitoring fire danger of northern boreal forests with NOAA-AVHRR NDVI images

B. LEBLON

Remote Sensing and GIS Research Group, Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton, New Brunswick, E3B 6C2, Canada; e-mail: bleblon@unb.ca

M. ALEXANDER

Canadian Forest Service, Edmonton (Alberta), Canada

J. CHEN

Department of Geography, University of Toronto, Toronto (Ontario), Canada

and S. WHITE

Remote Sensing and GIS Research Group, Faculty of Forestry and Environmental Management, University of New Brunswick, Fredericton (New Brunswick), Canada

(*Received 25 July 2000; in final form 20 December 2000*)

Abstract. The objective of this study was to assess the potential of remote sensing from satellites for monitoring forest fire danger in northern Canadian boreal forests. In Canada, daily forest fire danger is rated by the Canadian Forest Fire Danger Rating System (CFFDRS). One of its components is the Fire Weather Index (FWI) system. FWI variables were computed from weather records of the 1994 fire season. They were correlated to NDVI and cumulative NDVI (ΣNDVI) data computed from NOAA-AVHRR red and near-infrared bands in the case of coniferous stands located in the Northwest Territories, Canada. NDVI and ΣNDVI data were more strongly correlated to FWI variables corresponding to slow-drying fuels, i.e. duff moisture code (DMC), drought code (DC) and buildup index (BUI), than to those related to fast-drying fuels, i.e. fine fuel moisture code (FFMC) and fire weather index (FWI). The correlations between spectral data and FWI variables were explained by the fact that both kinds of variables have a similar seasonal variation, but not by an eventual direct relationship between NDVI and fuel moisture conditions, since NDVI is more directly related to chlorophyllian activity of the vegetation than to droughtness conditions.

1. Introduction

Forests cover 42% of the Canadian lands and are subject to large fires that annually burn an average of around 2.3 million ha and cost more than 189 million Canadian dollars for fire suppression activities (Stocks 1991). In Canada, daily forest fire danger is rated by the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989). One of its subsystems, the Fire Weather Index (FWI) system,

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160110034663

rates relative mid-afternoon fire danger from noontime weather data. It considers one single forest type (i.e. a generalized pine forest), but three fuel layers: the fine surface litter, the loosely compact duff of moderate depth and the deep soil organic matter. Each layer has a different timelag, i.e. the time to lose about two-thirds of the free moisture at equilibrium, when the air temperature is 20° C and the relative humidity is 40%. The first layer is fast-drying with a timelag of 12 hours, while the second and the third layers are slow-drying, with a timelag of about 12 days and 25 days, respectively (Canadian Forest Service (CFS) 1987). Fuel moisture conditions of the first, second and third layers are rated through the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC) and the Drought Code (DC), respectively (CFS 1987). FFMC is linked with wind variance to form a rating index of five spread rate, the Initial Spread Index (ISI). DC and DMC are combined into a rating index of available fuel amount, the Buildup Index (BUI). ISI and BUI are combined into a rating index of frontal fire intensity, the Fire Weather Index, which is a general fire danger index.

The FWI system does not account for the difference in forest cover types and relies on interpolated point-source weather records. Such a limitation can potentially be overcome by satellite remote sensing, which offers the advantage of large area coverages as well as data acquisition in remote areas on a regular basis and without destroying the studied resource. Over northern boreal forests, NDVI images, computed from red and near-infrared NOAA-AVHRR bands, have been used to map fire scars (e.g. Kasischke and French 1995, Fraser *et al.* 2000), to detect active fires (e.g. Li *et al.* 2000) and to estimate coniferous foliar moisture contents (FMC) (Leblon *et al.* unpublished data), but not to FWI variables. Elsewhere, these images have been related to FWI variables (Dominguez *et al.* 1994, Camia *et al.* 1999) and to fuel moisture variables (Paltridge and Barber 1988, Hartford and Burgan 1994, Burgan *et al.* 1998, Chuvieco *et al.* 1999). These studies assumed that droughtness was enough to decrease the vegetation greenness and therefore NDVI. Because changes in vegetation greenness likely occur on a long-term basis, cumulative NDVI (ΣNDVI) has been also related to simulated annual transpirations of US coniferous forests (Running and Nemani 1988), to computed evapotranspirations of Canadian ecosystems (Deblonde and Cihlar 1993), to fire potentials (Hartford and Burgan 1994, Illera *et al.* 1996) and to FMC of northern boreal forests (Leblon *et al.* unpublished data). Over Western Canada, FWI variables were better correlated to NDVI data, if previous compositing periods were considered (Dominguez *et al.* 1994).

This Letter presents preliminary results on the use of NDVI and ΣNDVI images to estimate FFMC, DMC, DC, BUI and FWI. ISI was not considered here, because it differs from FFMC only by wind-related variables, which cannot be estimated from NDVI images. The study used data acquired during the 1994 fire season over 18 coniferous stands located in northern Canada.

2. Materials and methods

2.1. *Study area*

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.). Forest stands located in this basin experienced a high fire occurrence between 1980 and 1989 and in 1994 (Leblon *et al.* unpublished data). Our study area falls within the Taiga Plains Ecozone. Within the study area, stands were selected at seven different sites (table 1). Each stand is a 10 ha of pure or mixed stands of jack

Table 1. Description of the studied sites classified from the Southern part to the Northern part of the study area (from Leblon *et al.* unpublished data).

Site name[1]	Snowmelt–Snowfall	Stand[2]	Lat. N.	Long. W.	Elev. (m)	Weather station Name and Number[3]	Lat. N.	Long. W.	Elev. (m)
FS	30/04–13/10	JP	50°00′36″	112°12′11″	185	FS(A)	60°01′	111°57′	205
		BS	60°00′54″	112°15′04″	185	2202200			
		WS	60°03′45″	112°13′06″	180				
HR	30/04–13/10	JP	60°30′28″	116°14′47″	275	HR(A)	60°50′	115°47′	166
		BS	60°30′31″	116°14′57″	275	2202400			
		WS	60°33′32″	116°07′51″	250				
SF	01/05–15/09	JP	61°52′05″	121°28′24″	130	SF(A)	61°45′	121°14′	169
		WS	61°53′04″	121°37′52″	130	2202101			
		BS	61°56′33″	121°33′53″	130				
LM	10/06–01/09	WS+JP	62°11′18″	123°20′05″	686	LOMO	62°11′	123°20′	686
YK	01/05–15/09	WS+BS	62°31′37″	114°10′52″	183	YK(A)	62°28′	114°27′	206
		JP	62°31′50″	114°09′15″	168	2204100			
NW	05/05–05/09	BS	65°16′27″	126°45′35″	69	NW(A)	65°17′	126°48′	74
		WS	65°17′27″	126°52′30″	61	2202800			
IN	15/05–20/09	WS	68°18′54″	133°31′01″	69	IN(A)	68°18′	133°29′	68
		BS	68°19′43″	133°37′39″	23	2202570			

(1) FS = Fort Smith, YK = Yellowknife, HR = Hay River, SF = Fort Simpson, LM = Lone Mountain, NW = Norman Wells, IN = Inuvik; (2) WS = white spruce, BS = black spruce, JP = jack pine; (3) Weather station located at the airport and operated by Environment Canada (except for Lone Mountain, where the weather station is located on the Lone Mountain tower and is operated by the Northwest Territories Department of Natural resources).

pine, white spruce and black spruce, depending on the site (table 1). In each stand, there were no overstory deciduous trees that could affect the seasonal variation of NDVI. 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 detailed in Leblon *et al.* (unpublished data).

2.2. *Materials and methods*

NDVI data were extracted from 108 NOAA-11 AVHRR images acquired, from snowmelt to snowfall (table 1). The time of acquisition was late afternoon, which corresponded to the period of maximum fire potential. Each image was georeferenced to a Lambert Conic Conformal projection, with a ground spatial resolution of 1 km. The images were corrected for illumination and atmospheric effects, following the method detailed in Leblon *et al.* (unpublished data). On each corrected NDVI image, a 3-by-3 pixel window was extracted for each stand based on its geographical coordinates (table 1). Mean values of NDVI were then computed and were used to fit interpolating models that computed the NDVI on cloudy days. There was no statistically significant interpolating model for the stands located at the highest elevation, Lone Mountain, which experienced a high NDVI seasonal variability.

This site was therefore not considered in our study. Estimated daily NDVI data were then used to compute cumulative NDVI (ΣNDVI) values from the beginning of the fire season (table 1). Daily NDVI and ΣNDVI data were correlated to daily values of FWI variables, using the SAS correlation procedure. These variables were computed from daily records of dry-bulb air temperature, relative humidity, wind, and rainfall at the closest weather station using the WeatherPro™ package of Remsoft Inc., following the method detailed in CFS (1987).

3. Results and discussions

Pearson's correlation coefficients between NDVI and FWI variables are presented in table 2. Every significant correlation was positive, but the correlation was not significant in the most northerly sites, i.e. Inuvik and Norman Wells, as well as in the site experiencing excessive rainfall, i.e. Fort Simpson (Leblon *et al.* unpublished data). Correlations were significantly improved by using cumulative NDVI (ΣNDVI) data (table 3). For both NDVI and ΣNDVI, the correlation was better with variables corresponding to slow-drying fuels, like DMC, DC and BUI, than to variables related to fast-drying fuels, like FFMC and FWI (tables 2 and 3). Strong correlations have previously been observed between DC and 10-day composite NDVI data acquired over grasslands and forests (Dominguez *et al.* 1994, Camia *et al.* 1999).

Table 2. Pearson's correlation coefficients with NDVI[(1)].

Site[(2)]	Species[(3)]	FFMC	DMC	DC	BUI	FWI	n[(4)]
FS	BS	−0.105^{NS}	0.426*	0.289^{NS}	0.417*	0.120^{NS}	32
	WS	−0.109^{NS}	0.090^{NS}	0.427*	0.221^{NS}	0.147^{NS}	24
	JP	−0.184^{NS}	0.371^{NS}	0.410*	0.420*	0.038^{NS}	25
	Mean	−0.154^{NS}	0.277^{NS}	0.351*	0.334*	0.081^{NS}	36
HR	BS	−0.137^{NS}	0.506*	0.465**	0.585***	0.162^{NS}	33
	WS	−0.192^{NS}	0.479**	0.398*	0.528***	0.077^{NS}	37
	JP	−0.137^{NS}	0.506**	0.465**	0.585***	0.162^{NS}	33
	Mean	−0.126^{NS}	0.473**	0.475**	0.532***	0.173^{NS}	41
SF	BS	0.361^{NS}	−0.107^{NS}	−0.023^{NS}	−0.093^{NS}	0.204^{NS}	24
	WS	0.123^{NS}	−0.041^{NS}	−0.018^{NS}	−0.034^{NS}	0.007^{NS}	33
	JP	0.069^{NS}	−0.063^{NS}	0.033^{NS}	−0.047^{NS}	0.137^{NS}	34
	Mean	0.040^{NS}	−0.147^{NS}	−0.076^{NS}	−0.141^{NS}	−0.083^{NS}	37
YK	BS + WS	0.119^{NS}	0.644***	0.712***	0.669***	0.413**	41
	JP	0.114^{NS}	0.633***	0.719***	0.661***	0.402**	48
	Mean	0.095^{NS}	0.623***	0.731***	0.654***	0.391**	46
NW	BS	0.089^{NS}	0.237^{NS}	0.310^{NS}	0.232^{NS}	0.166^{NS}	20
	WS	−0.278^{NS}	0.361^{NS}	0.521*	0.364^{NS}	0.089^{NS}	15
	Mean	−0.162^{NS}	0.229^{NS}	0.314^{NS}	0.227^{NS}	0.072^{NS}	22
IN	BS	0.022^{NS}	0.137^{NS}	0.352^{NS}	0.165^{NS}	0.055^{NS}	17
	WS	0.092^{NS}	0.273^{NS}	0.476*	0.302^{NS}	0.208^{NS}	18
	Mean	0.078^{NS}	0.202^{NS}	0.458*	0.234^{NS}	0.157^{NS}	21
All	BS	−0.041^{NS}	0.391***	0.194*	0.358***	0.132^{NS}	167
	WS	−0.097^{NS}	0.266***	0.200**	0.259***	0.055^{NS}	168
	JP	−0.135^{NS}	0.267**	0.152^{NS}	0.246**	0.003^{NS}	140
	Mean	−0.081^{NS}	0.303***	0.178*	0.278***	0.058^{NS}	203

[(1)]Significant at $\alpha = 0.001$ (***), at $\alpha = 0.01$ (**) and at $\alpha = 0.05$ (*); [(2)]FS = Fort Smith, YK = Yellowknife, HR = Hay River, SF = Fort Simpson, LM = Lone Mountain, NW = Norman Wells, IN = Inuvik, All = all sites; [(3)]WS = white spruce, BS = black spruce, JP = jack pine; Mean = Average spectral data among species; [(4)]n = Number of observations.

Table 3. Pearson's correlation coefficients with ΣNDVI[(1)].

Site[(2)]	Species[(3)]	FFMC	DMC	DC	BUI	FWI	n[(4)]
FS	BS	−0.115[NS]	0.501***	0.991***	0.724***	0.268[NS]	41
	WS	0.081[NS]	0.475**	0.990***	0.711***	0.199[NS]	35
	JP	0.101[NS]	0.524***	0.991***	0.736***	0.278[NS]	34
	Mean	0.091[NS]	0.499***	0.990***	0.726***	0.232[NS]	44
HR	BS	0.031[NS]	0.286[NS]	0.994***	0.475**	0.121[NS]	41
	WS	0.009[NS]	0.290[NS]	0.995***	0.481***	0.072[NS]	45
	JP	0.022[NS]	0.290[NS]	0.994***	0.480**	0.118[NS]	42
	Mean	−0.005[NS]	0.370**	0.992***	0.542***	0.108[NS]	49
SF	BS	0.222[NS]	0.734***	0.690***	0.741***	0.423*	36
	WS	0.233[NS]	0.718***	0.674***	0.721***	0.225[NS]	44
	JP	0.272[NS]	0.713***	0.656***	0.715***	0.290[NS]	44
	Mean	0.213[NS]	0.695***	0.634***	0.694***	0.125[NS]	46
TK	BS + WS	0.126[NS]	0.769***	0.952***	0.809***	0.618***	47
	JP	0.105[NS]	0.719***	0.944***	0.764***	0.568***	53
	Mean	0.086[NS]	0.712***	0.941***	0.756***	0.531***	51
NW	BS	−0.213[NS]	0.685***	0.954***	0.724***	0.049[NS]	29
	WS	−0.229[NS]	0.771***	0.970***	0.801***	0.095[NS]	27
	Mean	−0.210[NS]	0.705***	0.960***	0.742***	0.099[NS]	32
IN	BS	−0.461*	0.136[NS]	0.964***	0.187[NS]	−0.393*	28
	WS	−0.322[NS]	0.173[NS]	0.967***	0.224[NS]	−0.301[NS]	30
	Mean	−0.330[NS]	0.200[NS]	0.967***	0.249[NS]	−0.283[NS]	33
All	BS	−0.032[NS]	0.510***	0.768***	0.587***	0.195**	222
	WS	−0.027[NS]	0.486***	0.770***	0.565***	0.149*	228
	JP	0.098[NS]	0.529***	0.719***	0.610***	0.229**	173
	Mean	−0.019[NS]	0.499***	0.747***	0.571***	0.136*	255

[(1)]Significant at $\alpha = 0.001$ (***), at $\alpha = 0.01$ (**) and at $\alpha = 0.05$ (*); [(2)]FS = Fort Smith, YK = Yellowknife, HR = Hay River, SF = Fort Simpson, LM = Lone Mountain, NW = Norman Wells, IN = Inuvik, All = all sites; [(3)]WS = white spruce, BS = black spruce, JP = jack pine; Mean = Average spectral data among species; [(4)]n = Number of observations.

However, in these previous studies, the correlations were negative. In both studies, NDVI data were acquired not only on forests, but also on grasslands, for which droughtness strongly reduces vegetation greenness and thus NDVI, while in the same time, it increases FWI variables. In our case, NDVI images were acquired solely on coniferous stands, for which NDVI did not decrease throughout the season. Rather, as already observed over boreal forests (Goward *et al*. 1985, Kasischke and French 1997), NDVI increases until mid-summer and then decreases. Such a seasonal trend is explained by Kasischke and French (1997) as a function of understory deciduous phenology in relationship with spring and fall temperatures as well as with the first snowfall. Thereby, the seasonal variation of NDVI did not reflect possible droughtness increasing throughout the season, as shown by the seasonal trends of the FWI variables.

The positive relationship between DMC, DC or BUI and ΣNDVI can be explained by the fact that both types of variable increase throughout the fire season, at a similar rate, as shown in figure 1 for DC and the stands located at Hay River. Both increases are explained differently: DMC, DC and BUI increase with the droughtness, while ΣNDVI increases with vegetation growth, like NDVI. ΣNDVI's computed over the growing season were already linearly related to green biomass accumulation of North American ecosystems (Goward *et al*. 1985). The present

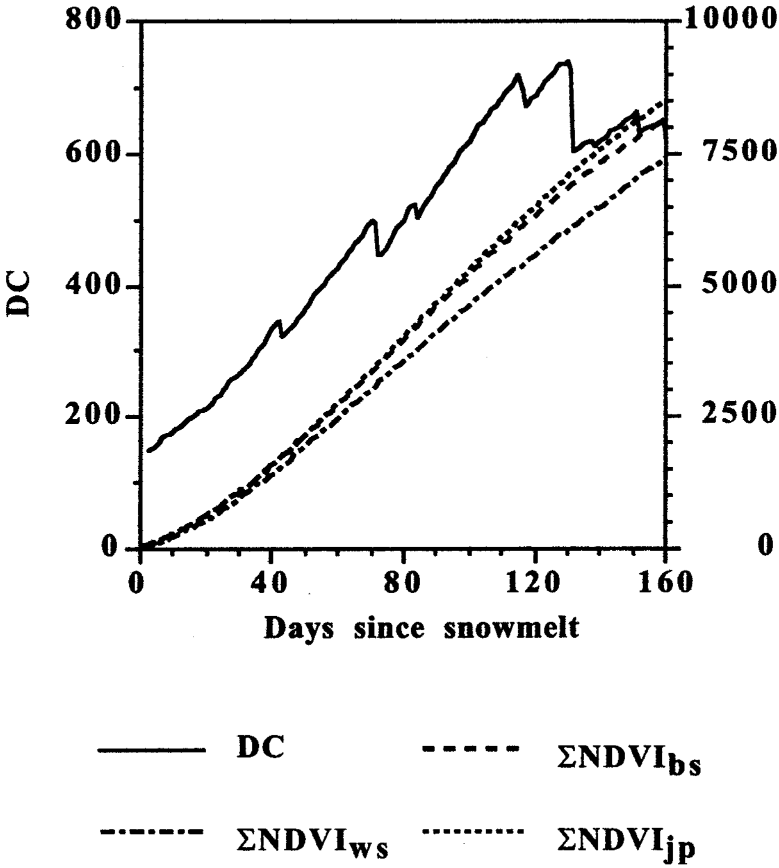

Figure 1. An example of seasonal variation for DC and ΣNDVI for the three stands of Hay River (bs: black spruce, ws: white spruce and jp: jack pine).

results suggest that red and near-infrared-based vegetation indices, like NDVI and ΣNDVI, are better indicators of chlorophyllian activity of vegetation rather than indicators of actual droughtness. Thermal infrared AVHRR bands are possible better droughtness indicators than the red and near-infrared ones, because they are related to the surface temperature which is analytically related to actual evapotranspirations (see the review of Leblon 2000). Another spectral variable which can possibly be related to droughtness conditions is the radar backscatter as computed from SAR imagery, because of its relationship with fuel dielectric constant and thus with fuel moisture content (see the review of Leblon 2000). FWI variables have already been related to NOAA-AVHRR surface temperatures acquired over Western Canada (Dominguez *et al.* 1994) and to ERS-1 SAR radar backscatters acquired over Alaskan boreal forests (Bourgeau-Chavez *et al.* 1999) and over the stands considered in this study (Leblon *et al.* unpublished data).

4. Conclusions

FWI indices were computed from weather data recorded during the 1994 fire season and correlated to NDVI and cumulative NDVI (ΣNDVI) data calculated from NOAA-AVHRR images acquired over coniferous stands located in the

Northwest Territories, Canada. NDVI and ΣNDVI data were better related to FWI variables corresponding to slow-drying fuels, i.e. duff moisture code (DMC), drought code (DC) and buildup index (BUI), than to those related to fast-drying fuels, i.e. the fuel moisture code (FFMC) and fire weather index (FWI). The positive correlations of NDVI or ΣNDVI with FWI variables were explained by the fact that both kinds of variables increased throughout the fire season, because of vegetation growth for NDVI and ΣNDVI and because of droughtness increasing for FWI variables. This may confirm that NDVI is a better indicator of chlorophyllian activity of vegetation, rather than that of droughtness, at least in the case of conifer boreal forests. Such preliminary results should be validated for other fire seasons, since they were acquired in 1994 which was observed to be particularly hot and dry (Leblon *et al.* unpublished data). Other spectral NOAA-AVHRR variables more closely related to vegetation droughtness should also be studied, such as the surface temperature computed from thermal infrared images. Further studies will be carried out to investigate the use of NOAA-AVHRR thermal infrared data to estimate FWI variables.

The operational use of NDVI and thermal infrared NOAA-AVHRR images can be limited because images cannot be acquired during cloudy conditions, as shown in Leblon *et al.* (unpublished data). This limitation requires interpolating models to estimate missing data. These models still have an empirical nature and need to be adjusted in each case. One alternative is to use SAR images as complementary source of data, because SAR images are always clear, independently of weather conditions. For the stands considered in this study, ERS-1 radar backscatter has been already related to NDVI and to FWI variables (Leblon *et al.* unpublished data).

Acknowledgments

The authors thank Robert Fraser, Canada Centre of Remote Sensing, Ottawa for his careful review of the manuscript. This study was funded by the Canadian Interagency Forest Fire Committee and by the Natural Science and Engineering Research Council. NOAA-AVHRR images were provided under the EODS program, thanks to J. Cihlar and J. Chen, Canada Centre of Remote Sensing, Ottawa. Weather data were obtained from Marty Alexander, Canadian Forest Service, Edmonton and Rick Lanoville, Government of Northwest Territories, Fort Smith.

References

Bourgeau-Chavez, L., Kasischke, E. S., and Rutherford, M. D., 1999, Evaluation of ERS SAR data for prediction of fire danger in a boreal region. *International Journal of Wildland Fire*, in press.

Burgan, R. E., Klaver, R. W., and Klaver, J. M., 1998, Fuel models and fire potential from satellite and surface observations. *International Journal of Wildland Fire*, **8**, 159–170.

Camia, A., Bovio, G., Aguado, I., and Stach, N., 1999, Meteorological fire danger indices and remote sensing. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, edited by E. Chuvieco (Berlin: Springer-Verlag), pp. 39–59.

Canadian Forest Service (CFS), 1987, Canadian Forest Fire Danger Rating System—User's Guide. Fire Danger Group of the Canadian Forest Service, Ottawa, Ontario, Three-ring binder (unnumbered publication).

Chuvieco, E., Deshayes, M., Stach, N., Cocero, D., and Riano, D., 1999, Short-term fire risk: foliage moisture content estimation from satellite data. In *Remote Sensing of Large Wildfires in the European Mediterranean Basin*, edited by E. Chuvieco (Berlin: Springer-Verlag), pp. 17–38.

Deblonde, G., and Cihlar, J., 1993, A multilayer analysis of the relationship between surface environmental variables and NDVI over the Canadian landmass. *Remote Sensing Reviews*, **7**, 151–177.

Domingeuz, L., Lee, B. S., Chuvieco, E., and Cihlar, J., 1994, Fire danger estimation using AVHRR images in the Prairie provinces of Canada. *Proceedings of the 2nd International Conference on Forest Fire Research, Coimbra, Portugal, November 1994*, **2**, pp. 679–690.

Fraser, R. H., Li, Z., and Cihlar, J., 2000, Hotspot and NDVI differencing synergy (HANDS): a new technique for burned area mapping over boreal forests. *Remote Sensing of Environment*, **74**, 362–376.

Goward, S. N., Tucker, C. J., and Dye, D. G., 1985, North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer. *Vegetatio*, **64**, 3–14.

Hartford, R. A., and Burgan, R. E., 1994, Vegetation condition and fire occurrence: a remote sensing connection. *Proceedings of the Interior West Fire Council Meeting and Symposium, Coeur d'Alene, ID, 1–3 November 1994*.

Illera, P., Fernandez, A., and Delgado, J. A., 1996, Temporal evolution of the NDVI as an indicator of forest fire danger. *International Journal of Remote Sensing*, **17**, 1093–1105.

Kasischke, E., and French, N. H., 1995, Locating and estimating the areal extent of wildfires in Alaskan boreal forests using multiple-season AVHRR NDVI composite data. *Remote Sensing of Environment*, **51**, 263–275.

Kasischke, E., and French, N. H., 1997, Constraints on using AVHRR composite index imagery to study patterns of vegetation cover in boreal forests. *International Journal of Remote Sensing*, **18**, 2403–2426.

Leblon, B., 2000, Forest fire hazard monitoring using remote sensing: a review. *Remote Sensing Reviews*, **20**, 1–57.

Li, Z., Nadon, S., Stocks, B., and Cihlar, J., 2000, Satellite detection of Canadian boreal forest fires: development and application of the algorithm. *International Journal of Remote Sensing*, **16**, 3071–3082.

Paltridge, G. W., and Barber, J., 1988, Monitoring grassland dryness and fire potential in Australia with NOAA-AVHRR data. *Remote Sensing of Environment*, **25**, 381–394.

Running, S. W., and Nemani, R. R., 1988, Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Remote Sensing of Environment*, **24**, 347–367.

Stocks, B. J., 1991, The extent and impact of forest fires in northern circumpolar countries. In *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine (Cambridge: MIT Press), pp. 197–202.

Stocks, B. J., Lawson, B. D., Alexander, M. E., Van Wagner, C. E., McAlpine, R. S., Lynham, T. J., and Dubé, D. E., 1989, The Canadian Forest Fire Danger Rating System: an overview. *The Forestry Chronicle*, **65**, 450–457.