9547

Monitoring Vegetation Greenness Using Satellite Data: A Forest Fire Management Perspective

T.J. Lynham and B.G. Pierce

1997

NODA·EDNO

**CANADA
ONTARIO**

Northern Ontario
Development Agreement

Entente de développement
du nord de l'Ontario

Forestry • Foresterie

ABSTRACT

Changes in forest health, such as those caused by severe winter weather, insects, diseases, or anthropogenic influences, can make vegetation more susceptible to forest fire. These changes are often related to low amounts of chlorophyll in the plants. Chlorophyll reflects strongly in the near-infrared portion of the electromagnetic spectrum and can be monitored by sensors on earth-orbiting satellites. The spring green-up process can be observed using various sensors that monitor chlorophyll reflection in the near-infrared. By monitoring the greenness of vegetation, it may be possible to provide fire management agencies with timely information on changing forest hazard conditions. Techniques for monitoring vegetation greenness have become more common since the launch of the LANDSAT satellite program in 1972. Today the LANDSAT Multispectral Scanner (MSS) and the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) series of satellites are the primary sources of remotely sensed data for forestry. Both provide near-infrared data.

Analysis of 1-km resolution satellite data shows that greenness can be monitored throughout the growing season in Ontario by using the Normalized Difference Vegetation Index (NDVI) calculated from AVHRR data. A series of 20 composite images of Ontario permits visual tracking of the onset of green-up during the spring and early summer, and of the decrease in greenness in the late summer and early fall. Analysis of data for several sample sites across the forest regions of Ontario shows a distinct seasonal trend in greenness. Cloud contamination, image compositing artifacts, and the lack of ground sample data prevent the AVHRR NDVI product tested in this study from being useful for monitoring forest fire hazard.

A second analysis, based on NDVI calculated from 50-m resolution LANDSAT satellite data, indicates that changes in greenness over a 20-year period in the Sudbury Basin of Ontario can also be monitored to demonstrate the effect of anthropogenic activities. As recently as the early 1970s, the Sudbury Basin was sparsely vegetated because of plant stress and mortality resulting from sulphur dioxide pollution. With respect to revegetation, which can be monitored as increased greenness, the area has shown a vast improvement over the last 20 years. Most likely this is the result of huge reductions in local sulphur dioxide emissions, new smoke stack scrubbing

technology, and the construction of the Sudbury "super stack" chimney, which alleviates acute local pollution problems by dispersing emissions over a wider geographic area.

A simple regression equation, which is dependent on a fuel moisture parameter (derived from simple weather observations), was used to model human-caused forest fire occurrence in the Sudbury area. Predictions from the model suggest that, based on measured weather alone, fire managers should have expected to face twice the actual number of fires since 1982. Thus, there is an observed 50 percent decrease in the annual number of forest fires in the Sudbury District. This can be partly attributed to revegetation of the area.

RÉSUMÉ

Des changements dans l'état de santé des forêts, comme ceux causés par les conditions hivernales, les insectes, les maladies et les activités humaines, peuvent rendre la végétation plus vulnérable aux incendies. Ces changements correspondent souvent à des teneurs réduites des plantes en chlorophylle. La chlorophylle reflète fortement le rayonnement dans la zone du proche infrarouge du spectre électromagnétique et peut être mesurée à l'aide de capteurs à bord de satellites en orbite autour de la terre. Le verdissement printanier peut ainsi être observé. La mesure de la verdeur de la végétation pourrait permettre d'informer rapidement les organismes de lutte contre les incendies des changements influant sur le danger d'incendie. Les techniques de surveillance de la verdeur sont devenues plus courantes depuis le lancement du programme LANDSAT en 1972. Aujourd'hui, les scanneurs multibandes (MSS) de LANDSAT et les radiomètres perfectionnés à très haute résolution (AVHRR) qui équipent les séries de satellites de la National Oceanic and Atmospheric Administration (NOAA) sont les principales sources de données de télédétection utilisées en foresterie. Ces deux techniques fournissent des données dans le proche infrarouge.

D'après l'analyse des données satellitaires à 1 km de résolution, la verdeur peut être suivie pendant tout la saison de croissance en Ontario en utilisant l'indice de végétation par différence normalisée (NDVI) calculé à partir des données obtenues par AVHRR. Une série de 20 images composites de l'Ontario permettent de suivre le verdissement au printemps et au début de l'été puis la diminution de la verdeur à la fin de l'été et au début de l'automne. L'analyse des données pour plusieurs stations échantillons dans les régions forestières de l'Ontario révèle une nette tendance saisonnière quant à la verdeur. La contamination par les nuages, les artéfacts de composition des images et l'insuffisance des données d'échantillonnage empêchent toutefois l'utilisation du tandem AVHRR-NDVI testé dans cette étude pour la surveillance du danger d'incendie.

Une deuxième analyse portant sur le NDVI calculé à partir des données à résolution de 50 m de LANDSAT indique que les changements de la verdeur sur une période de 20 ans dans le bassin de Sudbury (Ontario) permettent de suivre les effets des activités anthropiques. Au début des années 70, la végétation du bassin de Sudbury était clairsemée sous l'effet de la pollution par le dioxyde de soufre qui stressait et tuait les plantes. Au cours des 20 dernières années, d'après l'augmentation de la verdeur qui peut être mesurée, la région s'est beaucoup revégétalisée grâce fort probablement aux réductions considérables des émissions locales de dioxyde de soufre, à la nouvelle technologie employée pour l'épuration des fumées et à la construction à Sudbury d'une supercheminée qui atténue les problèmes locaux aigus de pollution en dispersant les émissions au-dessus d'un territoire plus vaste.

Une équation de régression simple reposant sur un paramètre d'humidité des combustibles (dérivé de simples observations météorologiques) a été utilisée pour modéliser les incendies forestiers causés par l'homme dans la région de Sudbury. D'après les prévisions fournies par le modèle et reposant seulement sur les conditions météorologiques mesurées, les gestionnaires des incendies forestiers auraient pu s'attendre à deux fois plus d'incendies qu'il s'en est produit depuis 1982. Donc, il y aurait eu une diminution de 50% du nombre annuel d'incendies forestiers dans le district de Sudbury qui pourrait être partiellement attribuable à la revégétalisation de la région.

TABLE OF CONTENTS

MONITORING VEGETATION GREENNESS USING SATELLITE DATA: A FOREST FIRE MANAGEMENT PERSPECTIVE

INTRODUCTION

Except for leafless aspen (*Populus* spp.) fuels and seasonal fluctuations in the foliar moisture content of coniferous tree crowns, fire behavior prediction in Canada does not deal with seasonal changes in forest fire hazard. Forest fire hazard is defined by the Canadian Committee on Forest Fire Management (Merrill and Alexander 1987) as "a general term to describe the potential fire behavior, without regard to the state of weather-influenced fuel moisture content". Seasonal changes in fuel conditions can be brought on by variations in the weather or by other natural occurrences, such as defoliation or tree mortality. The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) assumes that predictions are made for average summer fuel conditions when forest stands are green and healthy.

A significant problem facing Ontario fire managers in the early spring is the assessment of changing fire hazard during the period of time between snow melt and the flushing of vegetation (typically referred to as "green-up"). High winds and dry, fine forest fuels often accompany this interval, which can result in many intense, fast moving forest fires.

Changes in forest health (brought on by severe winter weather, insects, disease, or anthropogenic influences) can affect the susceptibility of the forest to fire. Changes in forest health are often accompanied by a change in the overall amount of chlorophyll present in the plants. A reduction in the amount of chlorophyll, without removing the vegetation, usually means an increase in fire hazard.

Chlorophyll reflects in the near-infrared portion of the electro-magnetic spectrum. Several earth-orbiting satellites carry sensors that are sensitive to this portion of the spectrum. By monitoring the greenness of vegetation it may be possible to provide fire management agencies with information on changes in forest fire hazard. This information is especially critical to the fire management planning process in the spring or during periods of extreme drought.

Fire management programs could benefit directly from the evaluation of satellite-based forest greenness information. This would include monitoring changes in forest fire hazard prior to spring green-up, during widespread insect defoliation, and during prolonged drought. Changes owing to anthropogenic actions, such as pollution, would also be monitored.

Awareness of changes in forest fire hazard over a vast forest region, such as northern Ontario, is critical because the changes significantly affect fire behavior. Managers could take precautionary action, such as prepositioning fire fighting resources close to an area of concern, in order to minimize any losses that might result from a fire. Prepositioning of resources gives managers a huge advantage in controlling fire losses because the fire can be reached during its incipient phase, and before it has reached its maximum potential rate of spread. A single, large campaign fire can cost several millions of dollars to extinguish. In fact, 3 percent of the fires in Ontario account for 97 percent of the area burned (Stocks 1991). For the 20-year period from 1965 to 1984, Ontario averaged about 1 500 fires per year (Lynham 1987), but changes in forest condition could cause a shift in this average. Effective satellite monitoring could help the fire program by allowing managers to predict and prepare for these changes.

Changes in greenness of the forest, attributable to insect, disease, or anthropogenic sources, can be monitored and modeled to explain the direction and cause of the changes over time. Large forest areas that undergo long-term anthropogenic changes may require increased or decreased levels of fire protection.

This study monitors general seasonal variation in greenness throughout the 1993 growing season in Ontario using 1-km resolution National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) 10-day composites. A series of 20 composite images are used to track the onset of green-up in the spring, followed by peak greenness in the summer, and ending with a decrease in greenness in the late summer and early fall. Data for several sample sites located across Ontario's major forest regions (Boreal and Great Lakes–St. Lawrence) are analyzed to report on the seasonal trends in greenness. AVHRR data were acquired from the processing facility at the Manitoba Remote Sensing Centre (MRSC), which supplies georeferenced and calibrated AVHRR data from single dates as well as from 10-day composites.

A second aspect of the study monitors annual variation in greenness by studying four phenologically coincident scenes of the Sudbury Basin of Ontario. Results were taken over two decades using 50-m resolution LANDSAT data. Since 1970, the Sudbury Basin has been recovering from sulphur dioxide pollution caused by the local mining industry. Temporal LANDSAT data are analyzed to demonstrate the changes in peak summer greenness that have

occurred in this area. Data from 1974 imagery are compared with that from more recent dates (1976, 1980, and 1991). LANDSAT Multispectral Scanner (MSS) data were acquired from Radarsat International, the Canadian distributor of LANDSAT data. Sulphur dioxide emissions data collected by the Ontario Ministry of Energy and Environment (MOEE) from 1960 to 1993 and fire occurrence data retained by the Ontario Ministry of Natural Resources (OMNR) are also included to examine the relationship between sulphur emissions, changes in peak summer greenness, and the annual forest fire occurrence pattern over the last 20 years. Nonlinear regression techniques are used to model annual forest fire occurrence in the Sudbury District.

The boreal forest of northern Ontario is vast, sparsely populated by humans, and naturally prone to forest fires. It is almost impossible to acquire greenness information for an area the size of northern Ontario except from a satellite platform. Such information would permit fire managers to assess the changes in fire hazard.

Since the launch of the LANDSAT satellite program in 1972, several investigators have been developing techniques for monitoring vegetation greenness. Rouse et al. (1973) analyzed MSS data and developed a vegetation index (VI) and a transformed vegetation index (TVI) to assess rangeland and wheat crops on the Great Plains of the United States. The difference (Band 7 - Band 5) of radiance values, normalized over the sum (Band 7 + Band 5) of radiance values was first called the vegetation index. Rouse et al. (1974) concluded that the VI and TVI calculated from LANDSAT data could be used to monitor rangelands and wheat crops, and the close relationship between green biomass and TVI made it possible to follow the development of biomass.

Johnson (1976) successfully used Band 6 LANDSAT data in place of Band 7 to monitor green biomass. Banner and Lynham (1981) attempted to use a temporal vegetation index difference to map cutovers from LANDSAT using the difference equation from Rouse et al. (1973). This application worked only on sites that had not been revegetated.

Most work for monitoring biomass from satellite data has progressed along the same track, that is, production of a normalized difference vegetation index (NDVI) using a near-infrared band (0.8–1.1 μm) and a red band (.6–.7 μm) (Equation 1).

$$NDVI = \frac{NIR-R}{NIR+R} \qquad [1]$$

where:

NDVI = normalized Difference Vegetation Index
NIR · = near-infrared; and
R = red wavelength of the visual part of the electromagnetic spectrum

Healthy vegetation has approximately 10 percent reflectance in the visual red region of the electromagnetic spectrum, but about 70 percent reflectance in the near-infrared region (Avery and Berlin 1992). NDVI is used to capture the difference between the chlorophyll absorption minimum in the red spectrum and the peak in the near-infrared spectrum. This difference measures the amount and condition of green biomass. As damage begins to occur in green vegetation, a drop in the response in the near-infrared region occurs. When vegetation is dead, the reflectance in the visual red region increases while the reflectance in the near-infrared region is significantly reduced.

Although LANDSAT was the primary source of satellite data during the 1970s for investigations into biomass monitoring, several other platforms have since come into use. Ahern and Horler (1986) provided a review of the outlook for future satellite sensors for use in forestry applications. In their assessment they noted that the MSS and the AVHRR were the primary sources of remotely sensed data for forestry. Since then, the LANDSAT Thematic Mapper (TM) has surpassed the MSS. Meanwhile the French satellite, Système Probatoire d'Observation de la Terre (SPOT), is also being sold internationally for its earth remote sensing capabilities. One of the advantages of LANDSAT over SPOT is that LANDSAT data have been available since 1972. SPOT data were not available until 1986, when SPOT-1 was launched.

Ahern and Horler (1986) pointed out that AVHRR data has a resolution (1.1 km at nadir) that is too low for large-scale, intensive forestry management, but it is attractive for the global monitoring of forests because of its 2 400-km swath. AVHRR has the longest planned data availability, provides daily coverage, and includes the two reflective wavelengths required for calculating NDVI. LANDSAT MSS has a much higher resolution (50 m) than AVHRR, and a swath of 185 km. MSS is better suited for examining management problems that are local in nature and not dependent on real-time imagery, because it is sometimes difficult to acquire cloud-free images at a given time. As the scope of this paper is both small scale and large scale, both types of imagery have been analyzed.

Several recent papers have examined the use of the NDVI data taken from the AVHRR sensor on board the NOAA satellites. Eidenshink et al. (1989) and Burgan et al. (1991) have demonstrated the utility of NDVI calculated from AVHRR for assessing vegetation greenness over the rangelands of the western United States. More recently, Burgan and Hartford (1993) summarized the current United States Department of Agriculture (USDA) Forest Service research on using AVHRR data to produce greenness and relative greenness maps for the conterminous United States.

Beaubien (1993) used a different technique, namely, single date, geocorrected AVHRR data, to enhance land cover in the province of Quebec. Rather than using NDVI, linear combinations of the red and infrared bands were used to generate a color enhanced image for the purpose of separating the forest into several cover types. Although this research was not designed to address the issue of greenness, Beaubien's technique could be used to examine how cover types appear to change as greenness changes over the growing season. Beaubien (1994) further extended this technique for use with LANDSAT data.

In the context of global change, Cihlar et al. (1989) integrated AVHRR satellite imagery with map data and a geographic information system (GIS) to permit the analysis of environmental trends in vegetation development and change.

MATERIALS AND METHODS

Advanced Very High Resolution Radiometer Satellite Series

NOAA operates two types of weather satellites. The Geostationary Operational Environmental Satellite (GOES) series remain in a geosynchronous orbit, and appear stationary relative to a fixed point on the equator. GOES is particularly useful for monitoring continental cloud and frontal patterns.

Another series of satellites, the NOAA, are in near-polar (9° off the poles), sun-synchronous orbits at an altitude of 833 km. Each one scans a 2 400-km swath of the earth twice a day. The sun-synchronous orbit ensures that the satellites keep pace with the sun's westward progress (Lillesand and Kiefer 1987). Even-numbered satellites cross the equator at 7:30 am and 7:30 pm local time, whereas the odd-numbered satellites cross the equator at 2:30 am and 2:30 pm local time (Avery and Berlin 1992). The scanner on board the NOAA series of satellites is the AVHRR. NOAA-6, 8, and 10 have AVHRR systems that record in four spectral bands; the AVHRR systems on the NOAA-7, 9, and 11 satellites consist of five spectral bands (Lillesand and Kiefer 1987). Table 1 lists the spectral bands of AVHRR and their principal applications.

LANDSAT Data

The first in the LANDSAT series of satellites, LANDSAT 1, was launched in 1972. Other satellites (LANDSAT 2, 3, 4, and 5) have followed but the only one functioning at this time is LANDSAT 5, which was launched in 1984. The launch of LANDSAT 6 in 1994 was unsuccessful and the satellite was lost. LANDSAT 7 is not scheduled for launch until 1997. This leaves a potential gap in LANDSAT data if LANDSAT 5 were to fail. The satellites follow repetitive, sun-synchronous, near-polar orbits similar to those of the NOAA satellites (Harper 1983).

LANDSAT 1, 2, and 3 had the same basic specifications. The main sensor was the MSS, which used an across track scanning mirror to collect data in four spectral bands

Table 1. Characteristics of the NOAA Advanced Very High Resolution Radiometer.

Band number	Wavelength (μm)		Primary uses
	NOAA 6,8,10	NOAA 7,9,11	
1	0.58–0.68	0.58–0.68	Daytime cloud and surface mapping, snow and ice extent
2	0.72–1.10	0.72–1.10	Surface water delineation, snow and ice extent
3	3.55–3.93	3.55–3.93	Hot target (e.g., forest fire) detection, nighttime cloud mapping
4	10.50–11.50	10.30–11.30	Cloud and surface temperature determination, day or night cloud mapping
5	Channel 4 repeat	11.50–12.50	Cloud and surface temperature determination, day or night cloud mapping, water vapor correction

Source: (Avery and Berlin 1992)

(green 0.5–0.6 μm, red 0.6–0.7 μm, near-infrared 0.7–0.8 μm, and near-infrared 0.8–1.1 μm). Each sweep of the detector simultaneously imaged six lines per band. An entire 185-km by 185-km scene was imaged in 25 seconds (Avery and Berlin 1992). LANDSAT 1, 2, and 3 also carried the Return Beam Vidicon (RBV) that used three cameras to instantaneously image an entire 185-km by 185-km scene. The images were stored on a photosensitive surface in three color layers (green, red, and near-infrared), and then scanned in raster form by an electron beam to produce a video signal (Lillesand and Kiefer 1987). Data from the MSS scanner became the preferred data stream because it provided the first multispectral digital data of the earth, and because the RBV was plagued with technical malfunctions (Lillesand and Kiefer 1987). The satellites had a swath of 185 km and made 14 evenly spaced orbits per day. Thus, it took 18 days to obtain complete coverage of the earth.

LANDSAT 4 and 5 were designed to carry an MSS similar to the scanners on the earlier satellites as well as the TM, an improved version of the MSS that images in seven wavelengths instead of four. The RBV was not included. The resolution of data provided by the MSS on the first five satellites was about 80 m. By contrast, TM provides data at a 30-m resolution.

Radarsat International (RSI), which handles the commercial sale and distribution of LANDSAT data products in Canada, provided a complete list of cloud-free satellite images for the Sudbury Basin. Four geocorrected images (8 July 1974, 15 July 1976, 3 July 1980, and 11 August 1991) were selected to capture the temporal effect. Unlike the GEOcoding and COMPositing (GEOCOMP) data, which were distributed with an NDVI data channel, the LANDSAT data do not come with an NDVI channel. It must be calculated from Band 5 (red 0.6–0.7 μm) and Band 7 (near infrared 0.8–1.1 μm) using the standard NDVI equation listed in Equation 1.

Geocoding and Compositing of AVHRR Data

The GEOCOMP system is a turnkey computer system that applies a geocorrection and creates a mosaic of processed AVHRR satellite data at the MRSC. The design specification for the system was set by the Canada Centre for Remote Sensing (CCRS) and it was built by MacDonald Detwiller & Associates (MDA), Vancouver, British Columbia. The system was designed to produce nearly cloud-free composite images of Canada from daily coverage taken by the AVHRR sensor for research and applications in global change and environmental monitoring.[1] The system began operating in 1992 and produced the first geocoded 10-day composites of the Canadian land mass in 1993. Twenty 10-day composites in 1993 covered the period from 11 April to 31 October. There were three composites per month; in months that contain 31 days, the extra day was added to the last composite of the month. Image data sets are also available for subscenes of the Canadian land mass. A user can specify the coordinates of a particular scene of interest, but predefined composites of the Canadian provinces and territories are provided as subsets of the national composite.

The following excerpt from the *User Guide for GEOCOMP Products*[2] describes the history of GEOCOMP as well as the basics for producing composites.

"GEOCOMP's heritage includes the Multi-Observational Satellite Image Correction System (MOSAICS) of CCRS and MDA, which was built to produce geocoded images of high resolution satellite data. MOSAICS featured advanced orbit modelling procedures, control point location using image chips, and a variety of resampling algorithms which together facilitate achieving high spatial accuracy of the individual registered images. For GEOCOMP, modifications were made to handle AVHRR data, and to develop a library of image chips for control point location based on LANDSAT and MOS images. (The 'COMP' subsystem was constructed by modifying MDA's in-house image analysis system called Meridian.) GEOCOMP thus operates in two steps. First, individual images are registered and resampled to co-register with one another and with the baseline map. Second, the images are composited to find the most cloud-free pixel for the period of interest. In the actual operation, the new image is passed through the compositing module and each 'new' pixel is retained only if it is 'more cloud-free' than the pixel already in the composite. The composite is thus gradually improved over the period as more cloud-free pixels are obtained. The requirement for high throughput was handled in GEOCOMP by giving the operator an option to divide the orbit into smaller scenes (thus reducing the number of empty pixels after geometric correction). This division into smaller scenes sometimes leads to artificial edges in the composite. Robertson et al. (1992) describe the design and characteristics of GEOCOMP. Buffam[3] provides detailed documentation of the GEOCOMP products from the user viewpoint."

[1] Cihlar, J.; Huang, F. User guide for GEOCOMP products. NBIOME Internal Press, Canada Centre for Remote Sensing, Ottawa, ON. (In press)

[2] Ibid.

[3] Buffam, A., 1994. GEOCOMP user manual. Canada Centre for Remote Sensing, Ottawa, ON. Internal Report.

GEOCOMP processes Optical Channels 1 and 2 of the AVHRR data and converts them from raw digital signal levels into apparent radiance at the sensor. The apparent sensor radiances are calibrated using a gain and offset, and the results are stored as 10-bit calibrated digital numbers on the image product generated by GEOCOMP (Teillet and Holben 1994). At this point the NDVI is calculated from the calibrated digital numbers and used to select the most cloud-free pixels for the compositing process. The gains and offsets used in the commercial GEOCOMP product for 1993 were incorrect. While this error had little or no impact on the 1993 compositing process, this NDVI was only useful for selecting the cloud-free pixels and not for other biospheric studies.[4]

To derive an NDVI product that could be used in biospheric work, calibrated digital signals (in units of radiance) had to be converted to reflectance. Because the 1993 calibration coefficients were incorrect, CCRS developed a procedure to decalibrate the data and then recalibrate it using the correct calibration coefficients. An atmospheric correction (Rahman and Dedieu 1994) was then applied and a true NDVI was calculated.

Analysis of the GEOCOMP AVHRR Data

Analysis was performed on a SPARC-10 Model 30 workstation built by Sun Microsystems using image analysis software from PCI Inc. of Richmond Hill, Ontario. The twenty 10-day composite scenes covering the 1993 growing season in Ontario were analyzed for greenness as represented by the NDVI. All the data received from the MRSC covered the same geographic extent and were geometrically registered by the geocoding performed during the GEOCOMP processing stage. Working with the same geographic region permitted certain pieces of the analysis to be performed once and to be applied to all the composites. An example of this is development of a water mask (discussed later) to highlight waterways in Ontario.

The projection definition for the data is the Lambert Conformal Conic, with a first parallel of 49°, a second parallel of 77°, a longitude of true origin of -95°, and a latitude of true origin of 0°. This information was needed to register the vector outline of the province along with the outline of the Ontario district boundaries and to ensure that they were in the same projection as the images.

As each 10-day composite was acquired on 8-mm tape, the image analysis software was used to load the data into a 20-channel database. This was set up to archive each of the 20 sequential AVHRR NDVI composites. Raw NDVI is a single pseudo-band, which is represented visually by gray tones. Bright areas on a raw NDVI represent a higher chlorophyll response and hence a greater degree of vegetation development. To assist in visual interpretation of NDVI images, the USDA Forest Service devised a pseudo-color table that remaps the entire range of raw NDVI gray tone values into representative colors. Pseudo-coloring is carried out by mapping each input NDVI gray level into three output levels, one for each of red, green, and blue. The new output is then passed through the video display color guns and the image appears in pseudo-color on the display. This process is analogous to slicing a gray-scale image into a desired number of levels and then assigning a solid color to each range of gray values. The Pseudo-Color Table (PCT) chosen for remapping the Ontario NDVI response was selected so that the color values rendered an image which was green for the high NDVI values, yellow for the intermediate values, and brown or red for the very low NDVI values. This was done to give a representative visual impression of the degree of greenness. The range of NDVI values for each pseudo-color was adapted from Burgan and Hartford (1993) and is presented in Table 2. The pseudo-color assignments are listed in Table 3.

Table 2. NDVI category and greenness rating.

Class	NDVI range	Greenness rating
1	>0.66	High
2	0.60–0.66	
3	0.53–0.59	
4	0.48–0.52	
5	0.41–0.47	
6	0.34–0.40	
7	0.26–0.33	
8	0.16–0.25	
9	0.11–0.15	
10	0.05–0.10	
11	<0.05	Low

Table 3. Combinations for the pseudo-color table.

Class number	Red value	Green value	Blue value
1	0	69	0
2	0	97	0
3	15	130	8
4	64	166	33
5	122	212	69
6	194	255	110
7	255	210	0
8	207	112	61
9	150	26	0
10	191	0	0
11	255	255	255

[4] Cihlar, J.; Huang, F. User guide for GEOCOMP products. NBIOME Internal Press, Canada Centre for Remote Sensing, Ottawa, ON. (In press)

The general calculation of NDVI (Equation 1) results in a range of values from -1 to 1. Raw NDVI for AVHRR data is calculated in Equation 2, where the response value of a given (x,y) pixel pair from each source channel (NIR or R) is input to the formula.

$$NDVI = \frac{NIR(NOAAband2) - R(NOAAband1)}{NIR+R} \quad [2]$$

NDVI data from the GEOCOMP process have been manipulated to avoid storing the values as floating point numbers. Accuracy is preserved in an integer channel by converting (Equation 3) the raw floating point NDVI values (which range from -1 to +1) to an integer value (which ranges from 0 to 20 000). Most image display systems automatically scale input data into an 8-bit video display that ranges from 0 to 255 gray levels. To eliminate the effects of outliers in the data distribution, only data from the GEOCOMP NDVI channel in the range of 10 000 to 16 600 were scaled into the 8-bit video channel. This range corresponds to a baseline NDVI of 0 to 0.66. Negative NDVI values represent clouds, snow, water, and other nonvegetated surfaces (Burgan and Hartford 1993). Values higher than 0.66 were not encountered in a preliminary analysis of Ontario NDVI.

$$NDVI_{GEOCOMP} = (NDVI_{RAW}+1)*10\ 000 \quad [3]$$

The USDA Forest Service chose pseudo-color values to match each of the categories above. Category 1 can be thought of as representing a state of maximum greenness, while Category 10 represents no development at all. Category 11 represents cloud cover, bare earth, and other nonvegetated response. A subjective color scheme was then used to represent the relative development indicated by each category. The PCT for each of the 11 categories above is shown in Table 3. The combination of red, green, and blue values produces the final color.

Eight sample sites were selected to examine the annual trends in NDVI across Ontario. Each site consisted of a block of 20 pixels by 20 pixels (about 20 km by 20 km). An average NDVI was calculated for each site and the result was plotted against the composite period. An average NDVI calculated over the growing season was also determined for each of the eight sites.

Water Mask

Water is an important feature used in interpreting a map product, but it is not a feature of interest in the calculation of NDVI. To assist analysis of the pseudo-colored map images and to avoid confusion between water and other areas of low NDVI, a water mask was generated from an unsupervised classification using the K-means clustering

(KCLUS) routine, an iterative algorithm for assigning pixels with similar means to a selected number of classes. Once the classification converges it is possible to visually select the water class because it is distinct from other classes. The water mask was then converted to a standard blue bit map and superimposed over the Ontario subarea of each 10-day composite.

The unsupervised classification of the AVHHR data was based on the Band 1 (red) and Band 2 (near-infrared) data. For the classification of the LANDSAT data, Band 4 (green), Band 5 (red), and Band 7 (near-infrared) were used.

Ontario Provincial and District Vector Boundary

The provincial and district boundaries used on the Ontario greenness maps were acquired from the OMNR as a vector data file. This file used the same projection definition as did the GEOCOMP data product and was imported as a vector segment to be associated with each composite image. The district outlines are based on the new boundaries introduced by the OMNR in 1992. The fire occurrence data used in the fire model were based solely on the Sudbury District boundary defined prior to reorganization in 1992, because the data were coded according to those same older boundaries.

Sulphur Dioxide Emissions Data

Sulphur dioxide is one of the world's most common atmospheric pollutants. It is also a main ingredient in the production of acid precipitation (Dobrin and Potvin 1992). In Sudbury, there are two principal sources of sulphur dioxide emissions: INCO Ltd. and Falconbridge Ltd. The MOEE has maintained records on sulphur dioxide emissions from both of these sources.

Forest Fire Report Data, Weather Data, and the Fire Occurrence Prediction Model

The OMNR has paper and microfiche fire report records for the province dating back to 1917. Computer-coded records dating 1976 to 1994 were provided by the OMNR's Aviation, Flood and Fire Management Branch (AFFMB) in Sault Ste. Marie. The Canadian Forest Service, Great Lakes Forestry Centre, has coded a subset of the original Ontario fire report data for the years 1965 to 1975. These two data sets were combined to obtain a continuous source of fire occurrence data (1965 to 1994) for analysis in this study. The OMNR also maintains a computerized fire–weather database that has operated from 1963 and is updated each year. Both the fire and the fire–weather files share a district identifier that specifies the district from which the data were collected. When predicting fire occurrence it is just as important to know which days have

zero fire occurrence as which days are fire days (a day that has one or more fires). Since the fire occurrence file only contains information about fire days, the fire occurrence data were merged with the fire weather data to produce a file that contained a record for every day of the fire season. The merged record retained key fields such as district identification, date, associated fire weather indexes, and the number of fires for the day.

An important component of the fire weather indexes is the Fine Fuel Moisture Code (FFMC), a numerical representation of the moisture content of litter and other cured fine fuels in a forest stand (Van Wagner 1987). Cunningham and Martell (1973) suggested that fire occurrence could be modeled as a function of the FFMC, although they did not explicitly model the relationship. Simard and Main (1982) reported that the FFMC model was better than other litter models at predicting the moisture content of fine fuels in pine slash. Martell et al. (1987, 1989) used the FFMC to develop models for predicting daily human-caused forest fire occurrence in Ontario.

A model was developed to predict forest fire occurrence as a function of the daily FFMC. This model was an exponential function based on nonlinear regression with FFMC as the independent variable and expected daily fire occurrence as the dependent variable. The regression model is shown in the form of Equation 4. Data from 1965 to 1981 were used in the regression to obtain estimates for the regression coefficients β_0 and β_1.

$$\lambda = \beta_0 \cdot e^{\beta_1 \cdot FFMC} \qquad [4]$$

where:

λ = daily occurrence;
FFMC = the Fine Fuel Moisture Code;
e = the Euler number; and
β_0 and β_1 are regression coefficients.

The statistical procedure NLIN from the SAS Institute Inc. (1985) was used for fitting the regression model. Partial derivatives (Equations 5 and 6) of the model equation were required to optimize the NLIN procedure. The regression coefficients were then used to make predictions of annual human-caused fire occurrence rates in the Sudbury District, for the years 1982 to 1993. The expected number of fires per year is the sum of the expected number of fires per day as predicted by the model.

$$\delta\beta_1/\delta\lambda = \beta_0 \cdot \beta_0 \cdot e^{\beta_1 \cdot FFMC} \qquad [5]$$

$$\delta\beta_0/\delta\lambda = e^{\beta_1 \cdot FFMC} \qquad [6]$$

RESULTS AND DISCUSSION

GEOCOMP NDVI Composite Images of Ontario

Figures 1 to 20 are the greenness maps of the 10-day composites that were produced for Ontario during 1993. A sequential viewing of the images demonstrates that the AVHRR NDVI product has captured the lack of greennness in April (Figs. 1, 2). This is followed by a wave of increasing greenness that starts southeast of the Great Lakes in May (Figs. 3, 4, and 5), continues to increase through June (Figs. 6, 7, and 8), and peaks across the province in July (Figs. 9, 10, 11). By August (Figs. 12, 13, and 14) senescence has started south of Hudson Bay. A steep decline in greenness continues through late September (Figs. 15, 16, and 17), and trails off to a very low level of greenness in October (Figs. 18, 19 and 20)–one that is even lower than the initial level of greenness seen in April.

Greenness in the region, as indicated in the bottom left corners of Figures 1–9, shows a tendency to lag behind the greenness of surrounding areas. This area covers the southern part of the state of Minnesota and most of the state of Iowa. The area lags behind in greenness because it is one of the primary corn growing regions in the United States. Crops such as corn develop from bare soil and only generate enough biomass and leaf area to obscure the underlying soil when they are close to maturity. Corn in this region matures in mid to late July. In late July (Fig. 11) the area appears just as green as the whole area west of Lake Michigan and cannot be distinguished from known forested zones. By early October (Fig. 18) the area again shows less greenness than does the surrounding area, probably due to senescence and curing of the corn stalks. Later in October (Fig. 20) some of the area even appears devoid of greenness, which may occur after the stalks have been cut back and only stubble remains in the fields.

Cloud contamination was a major problem with many of the 1993 composite images, particularly those shot in the spring. The first good cloud-free image of Ontario occurred in late June (Fig. 8). It shows the advanced greenness of the forest around the Great Lakes and in eastern Ontario as well as the lag in greenness in the agricultural lands of southwestern Ontario. The predominantly boreal forest of northwestern Ontario has a lower level of greenness than does the eastern boreal forest. This may be an indication of the openness of the western boreal forest, which contains rock outcrops, and a high incidence of disturbance such as pollution, insect, disease, or fire damage. A 1993 survey on insect and disease conditions in Ontario (Howse and Applejohn 1994) indicates that there was major tree mortality in northwestern Ontario (Fig. 21) due to spruce budworm (*Choristoneura fumiferana* Clem.) infestation.
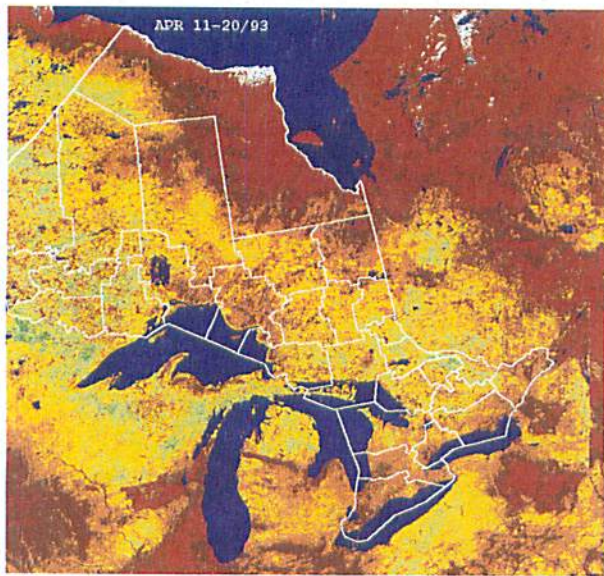
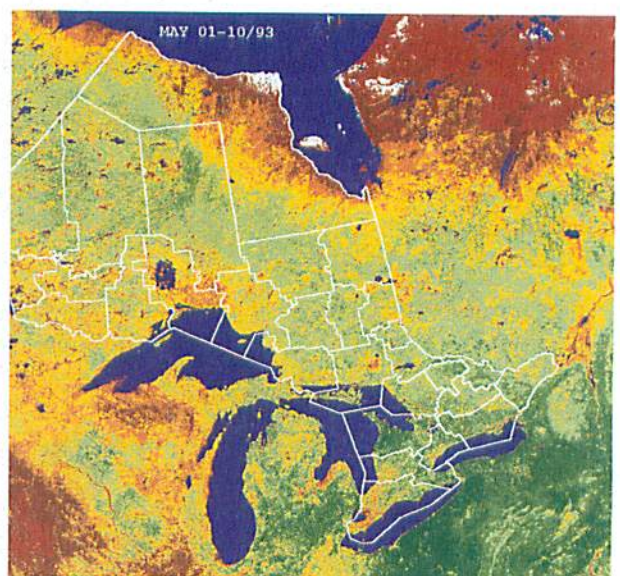*Figure 1. NDVI greenness map of Ontario for composite period 11–20 April 1993.*

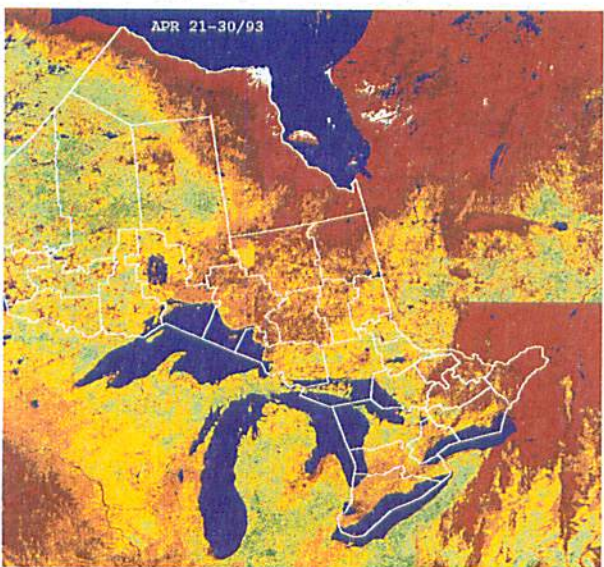*Figure 3. NDVI greenness map of Ontario for composite period 1–10 May 1993.*

Figure 2. NDVI greenness map of Ontario for composite period 21–30 April 1993.
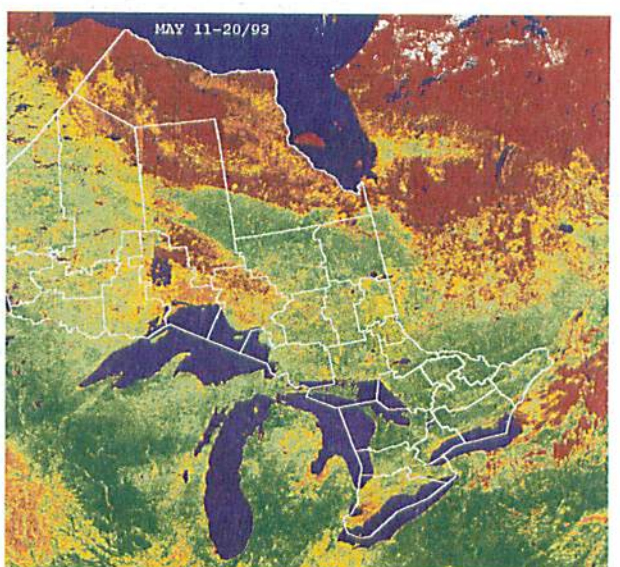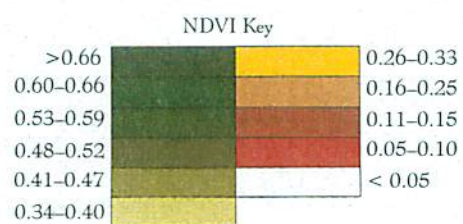

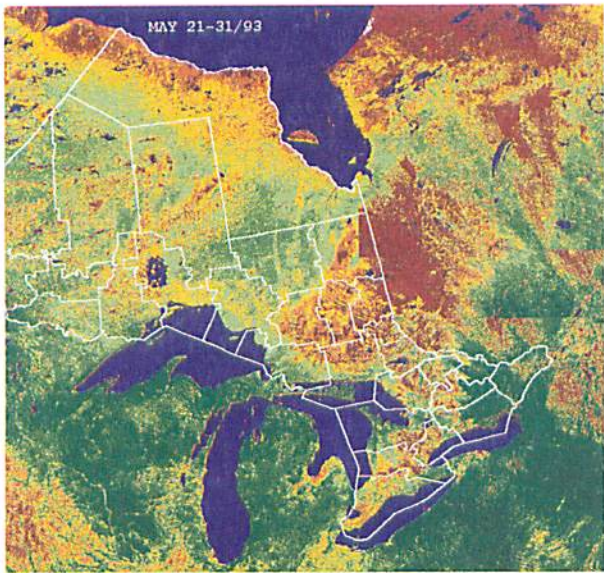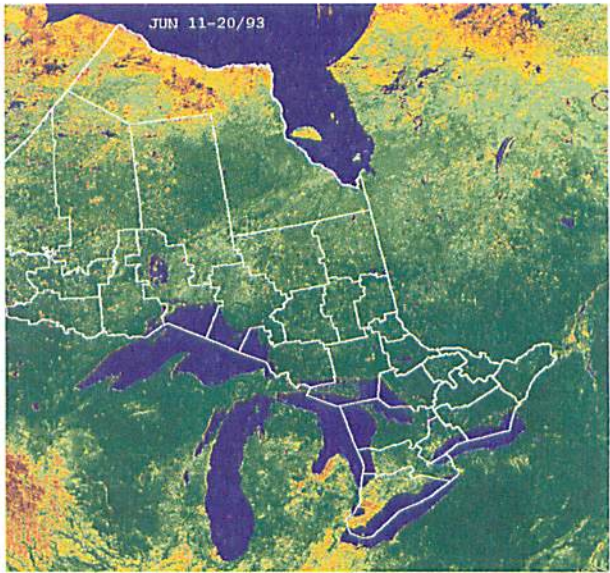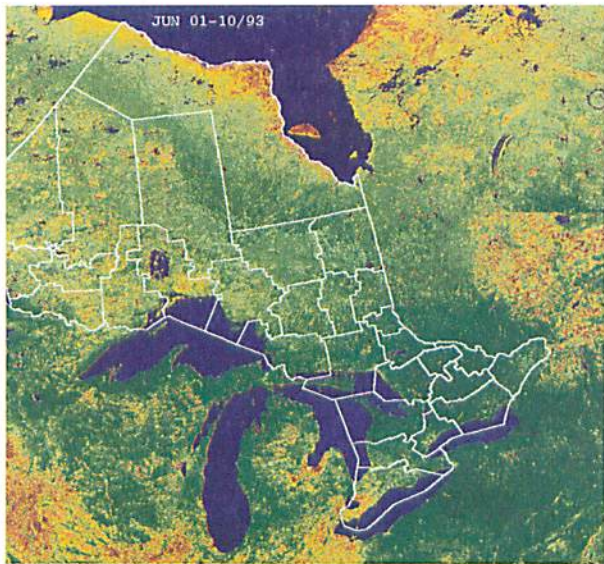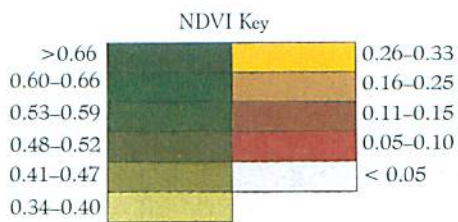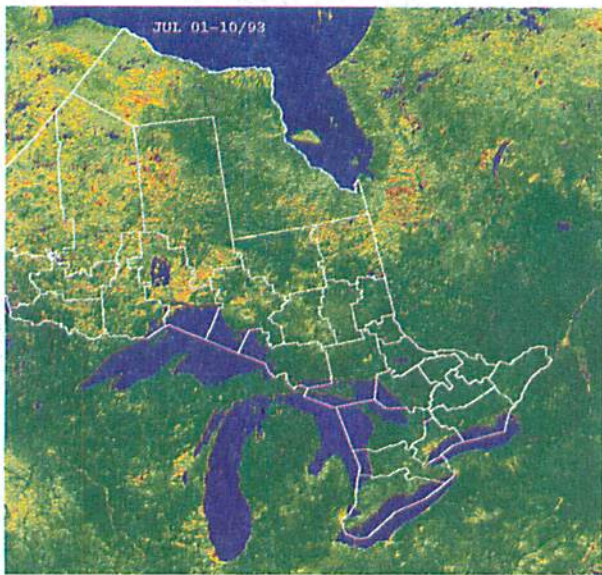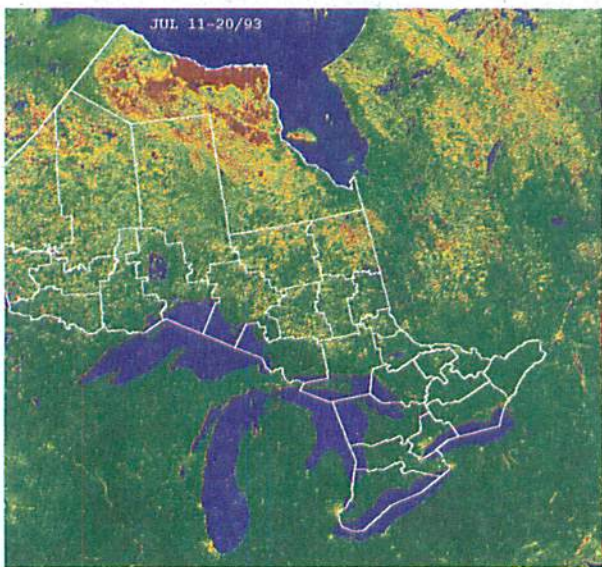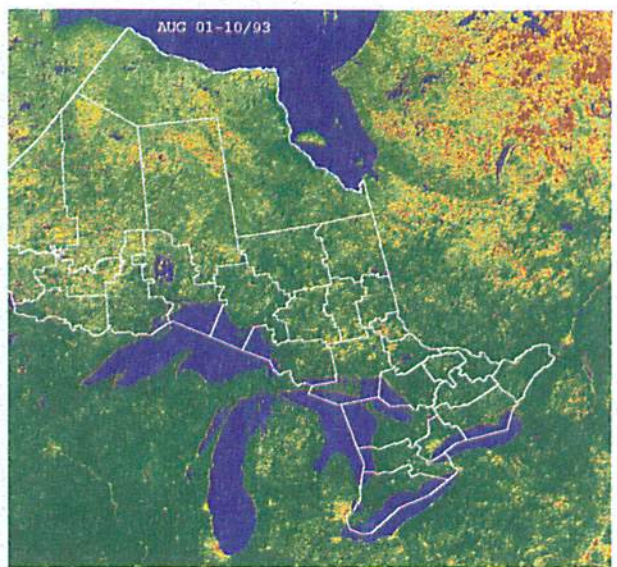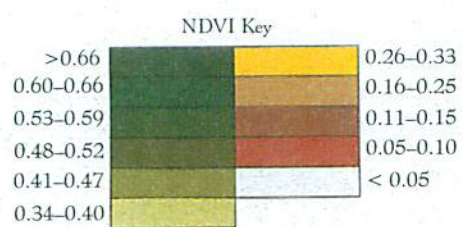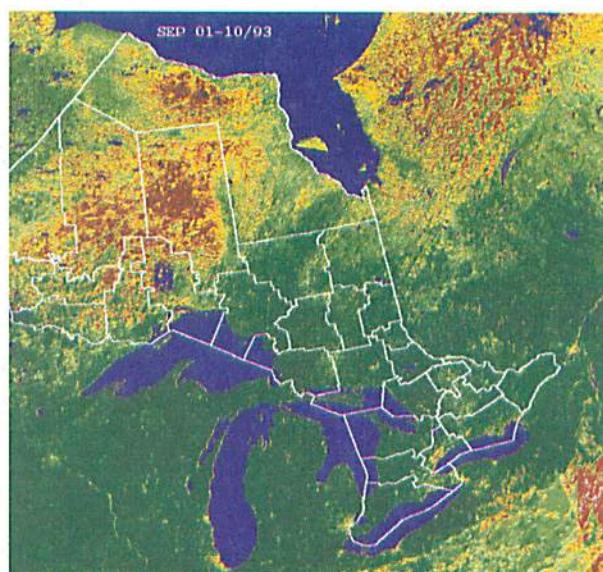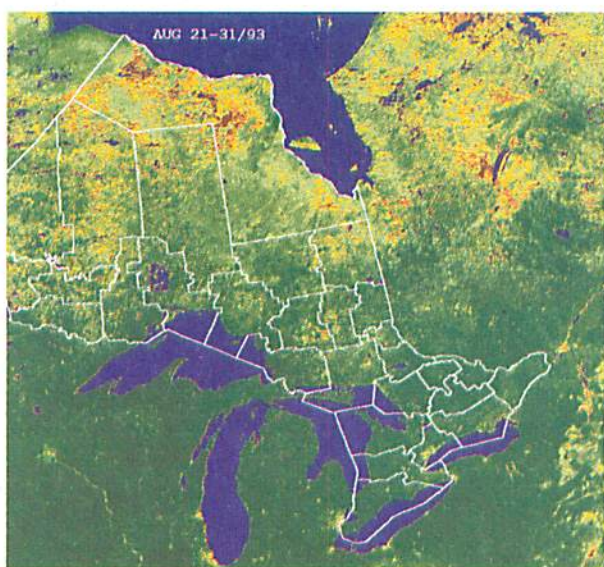*Figure 4. NDVI greenness map of Ontario for composite period 11–20 May 1993.*

NDVI Key

>0.66	0.26–0.33
0.60–0.66	0.16–0.25
0.53–0.59	0.11–0.15
0.48–0.52	0.05–0.10
0.41–0.47	< 0.05
0.34–0.40	

Figure 5. NDVI greenness map of Ontario for composite period 21–31 May 1993.

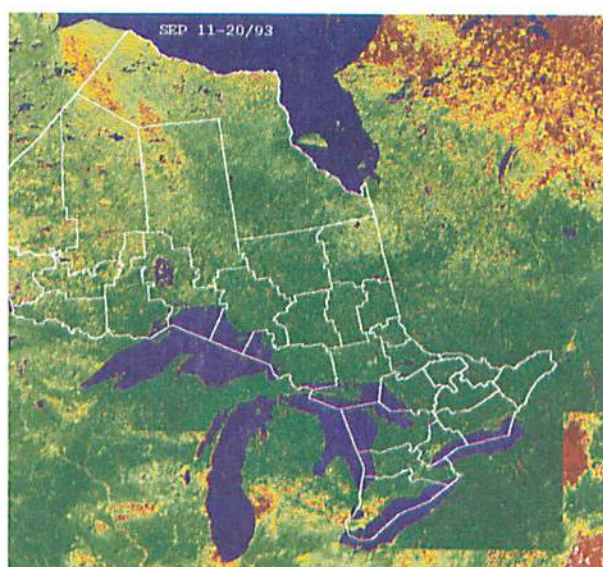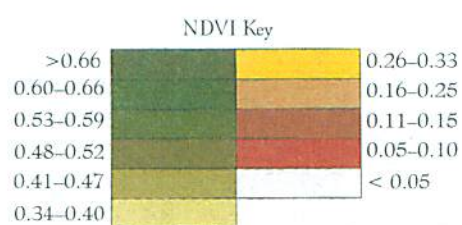*Figure 7. NDVI greenness map of Ontario for composite period 11–20 June 1993.*

Figure 6. NDVI greenness map of Ontario for composite period 1–10 June 1993.

Figure 8. NDVI greenness map of Ontario for composite period 21–30 June 1993.

NDVI Key

>0.66	0.26–0.33
0.60–0.66	0.16–0.25
0.53–0.59	0.11–0.15
0.48–0.52	0.05–0.10
0.41–0.47	< 0.05
0.34–0.40	

9

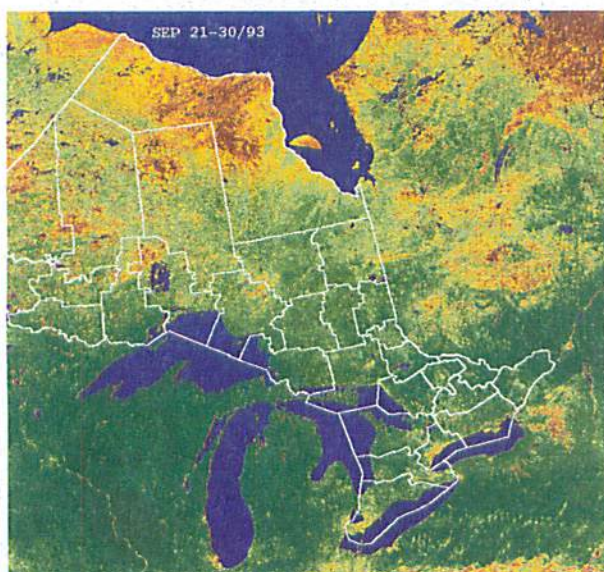*Figure 9. NDVI greenness map of Ontario for composite period 1–10 July 1993.*

Figure 11. NDVI greenness map of Ontario for composite period 21–31 July 1993.

Figure 10. NDVI greenness map of Ontario for composite period 11–20 July 1993.

Figure 12. NDVI greenness map of Ontario for composite period 1–10 August 1993.

NDVI Key

>0.66	0.26–0.33
0.60–0.66	0.16–0.25
0.53–0.59	0.11–0.15
0.48–0.52	0.05–0.10
0.41–0.47	< 0.05
0.34–0.40	

Figure 13. NDVI greenness map of Ontario for composite period 11–20 August 1993.

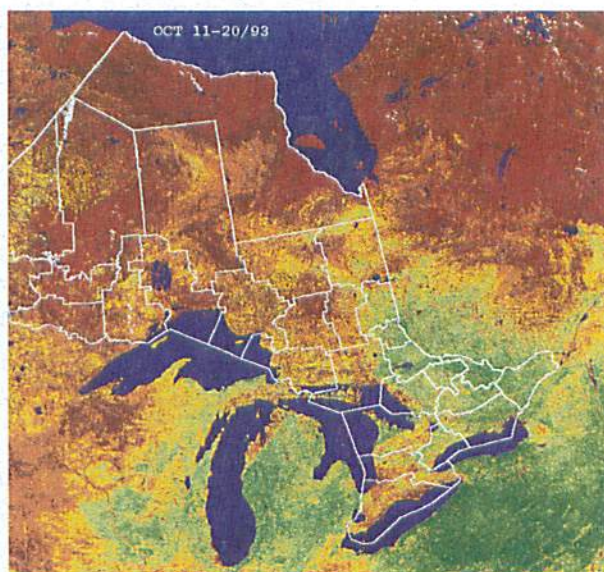Figure 15. NDVI greenness map of Ontario for composite period 1–10 September 1993.

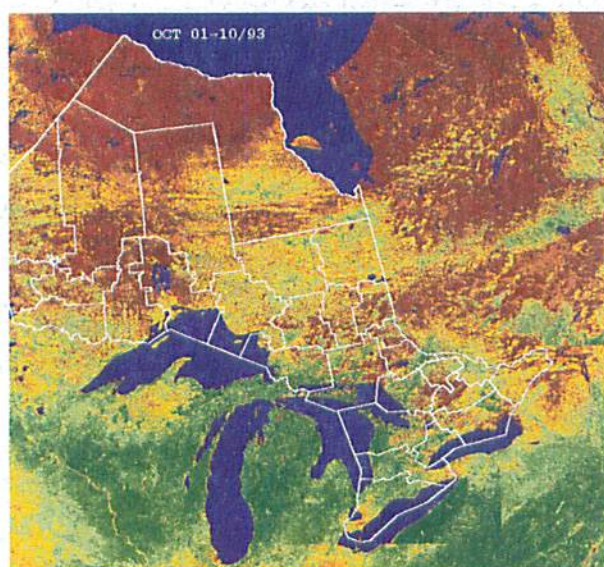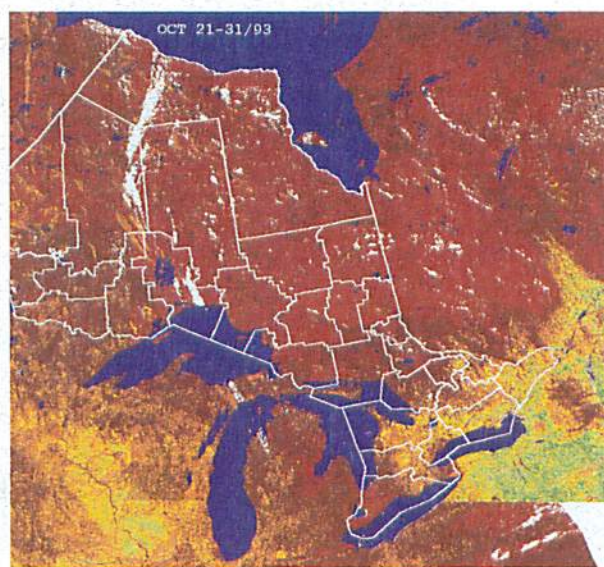Figure 14. NDVI greenness map of Ontario for composite period 21–31 August 1993.

Figure 16. NDVI greenness map of Ontario for composite period 11–20 September 1993.

NDVI Key

>0.66		0.26–0.33
0.60–0.66		0.16–0.25
0.53–0.59		0.11–0.15
0.48–0.52		0.05–0.10
0.41–0.47		< 0.05
0.34–0.40		

Figure 17. NDVI greenness map of Ontario for composite period 21–30 September 1993.

Figure 19. NDVI greenness map of Ontario for composite period 11–20 October 1993.

Figure 18. NDVI greenness map of Ontario for composite period 1–10 October 1993.
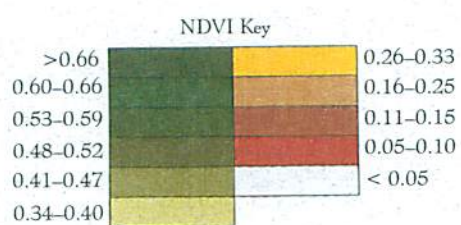

Figure 20. NDVI greenness map of Ontario for composite period 21–31 October 1993.
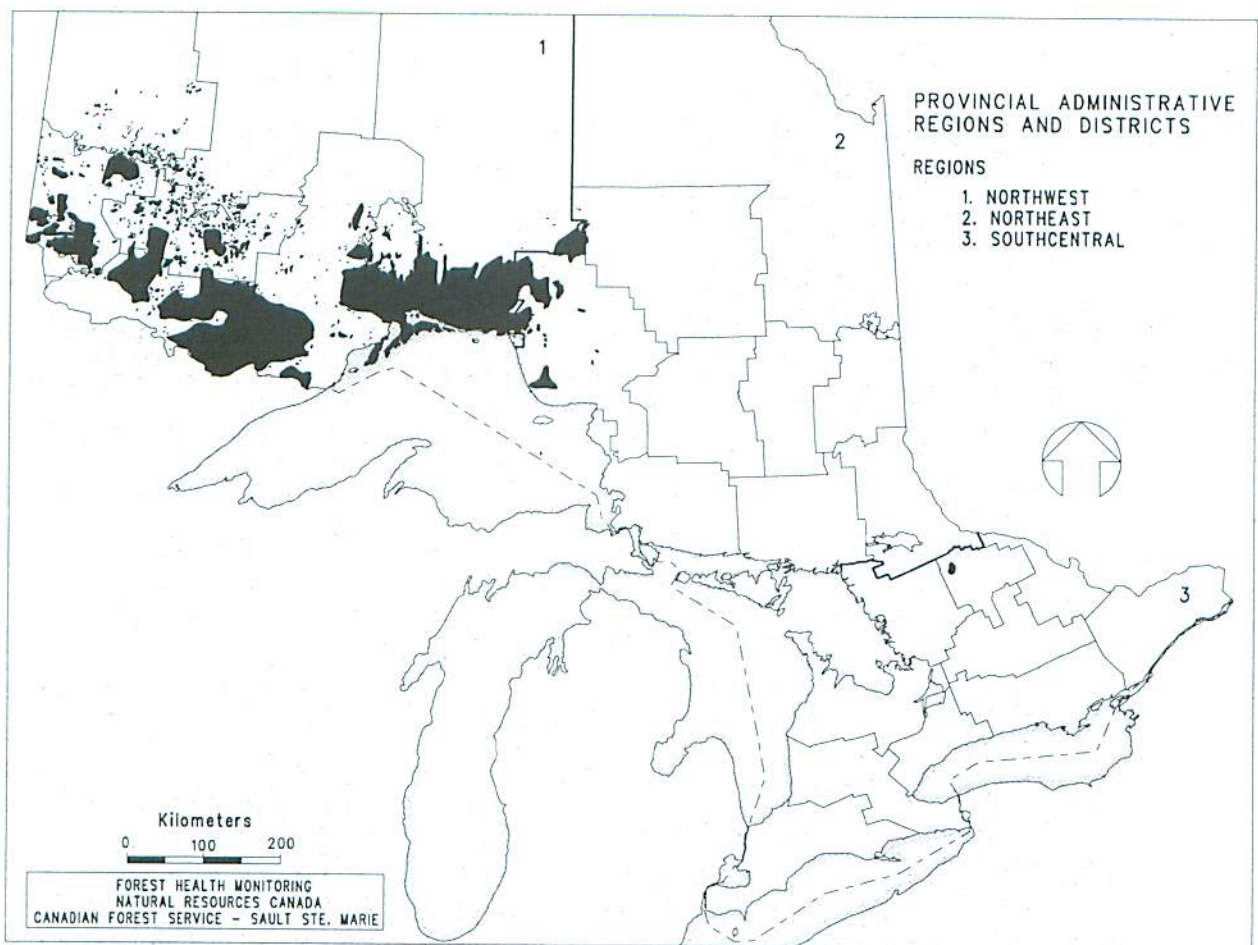
NDVI Key

>0.66		0.26–0.33
0.60–0.66		0.16–0.25
0.53–0.59		0.11–0.15
0.48–0.52		0.05–0.10
0.41–0.47		< 0.05
0.34–0.40		

12

PROVINCIAL ADMINISTRATIVE
REGIONS AND DISTRICTS

REGIONS
1. NORTHWEST
2. NORTHEAST
3. SOUTHCENTRAL

Kilometers
0   100   200

FOREST HEALTH MONITORING
NATURAL RESOURCES CANADA
CANADIAN FOREST SERVICE – SAULT STE. MARIE

Figure 21. Spruce budworm mortality in 1993.

LEGEND
1 Sault Ste. Marie
2 North Bay
3 London/Chatham
4 Kapuskasing
5 Lower Severn River
6 Pickle Crow
7 Ignace/Steep Rock L.
8 Lower Albany River

N
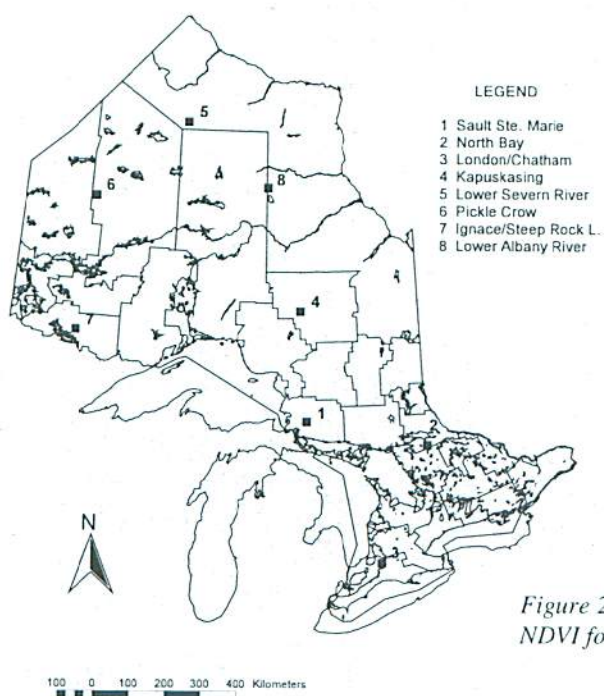
*Figure 22. Sample sites for monitoring annual changes in
NDVI for Ontario.*

100   0   100   200   300   400 Kilometers

13
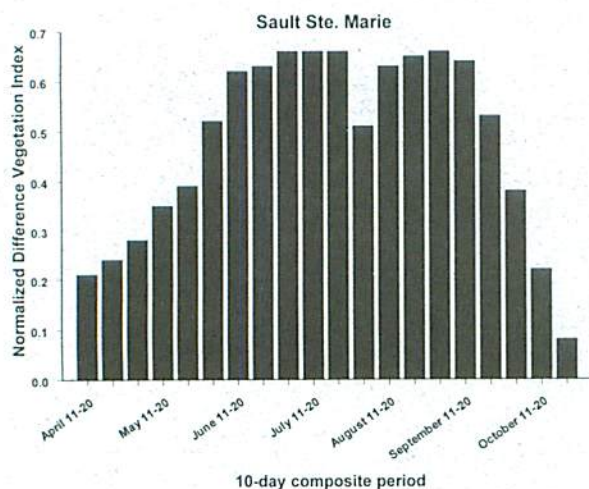
Figure 23. Average NDVI by composite period for Sault Ste. Marie.
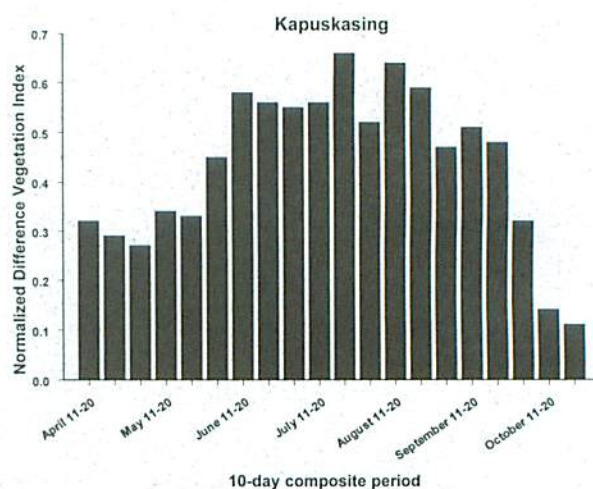
Figure 26. Average NDVI by composite period for Kapuskasing.
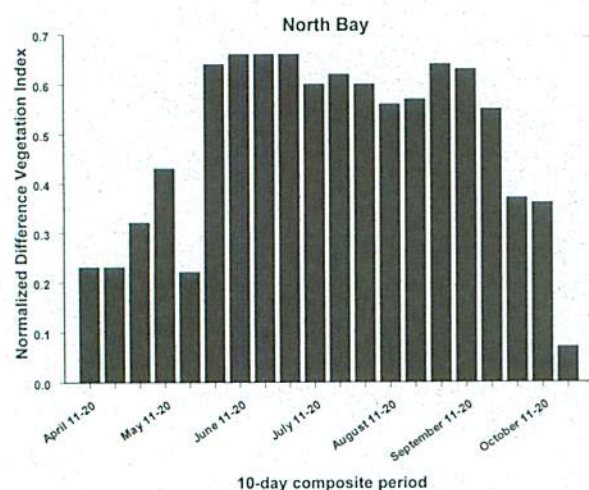

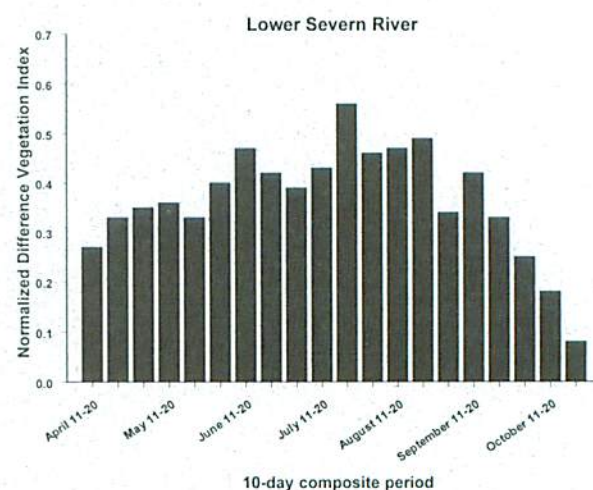Figure 24. Average NDVI by composite period for North Bay.

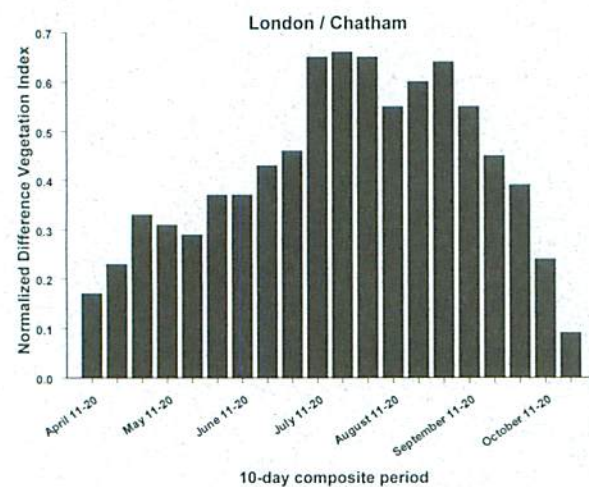Figure 27. Average NDVI by composite period for Lower Severn River.

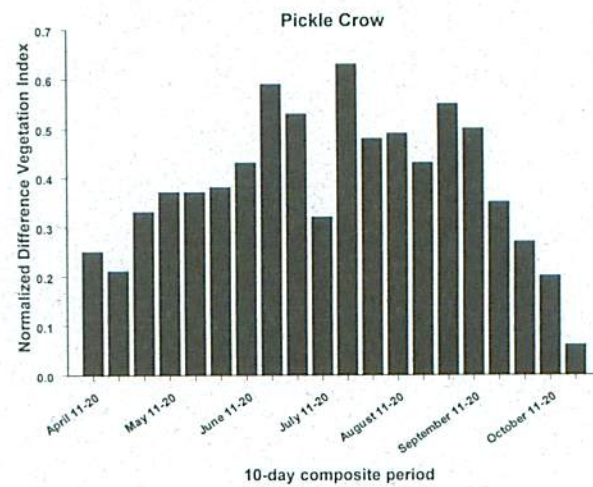Figure 25. Average NDVI by composite period for London/ Chatham.

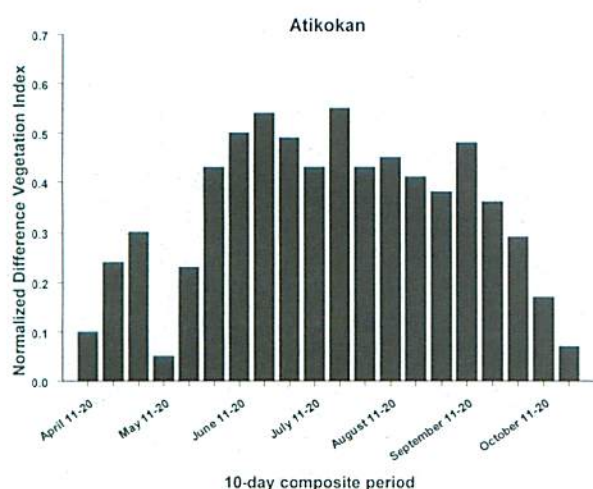Figure 28. Average NDVI by composite period for Pickle Crow.

14

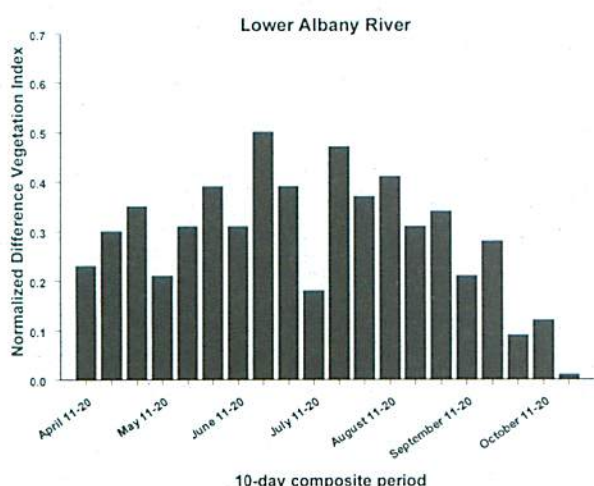Figure 29. Average NDVI by composite period for Atikokan.

Figure 30. Average NDVI by composite period for Lower Albany River.

Differences in greenness in northwestern Ontario, as seen between Figure 15 and Figure 16, are largely a result of cloud contamination. When cloud cover is solid, as in Figure 15, the NDVI values are very low and the cloud is easily recognized as red patches. However, thin cloud contamination may result in only slightly lower NDVI values. This will make it difficult to detect as cloud because the area still appears green. However, it will be a lighter shade of green, and thus give a false impression of lower greenness.

Many of the figures show abrupt changes in greenness along straight lines that run north–south or east–west. These straight demarcations are especially evident in Figures 2, 5, 16, 18, and 20. The reduction in greenness on the Ontario–Quebec border from Figure 4 to Figure 5 is not real, but is a result of cloud contamination. Contamination of the composite product is the result of a lack of cloud-free images to use in the compositing process. The lines are the edges of cloud-free scenes from 1 day that could not be combined with adjacent cloud-free passes on any other day of the 10-day composite period. This problem is more prevalent in the spring and fall because clouds are more common then.

The eight sample sites (Fig. 22) that were selected to examine the annual trends in NDVI across Ontario are charted in Figs. 23 to 30. The bar charts show that there is a consistent, gradual increase in NDVI during the spring. Greenness peaks in July and August before dropping off in September and October. The rate of decrease in NDVI after August is steeper than the rate of increase in the spring. Since the effect occurs across the entire province, it is probably from physiology. NDVI values for the 1–10 August composite (Fig. 23) and for the 11–20 July composite (Fig. 28) show sudden dips compared to the periods before and after. In both cases the lower average NDVI values are a result of cloud obscuration. Despite the problems with cloud contamination, the charts show that around Sault Ste. Marie (Fig. 23) and North Bay (Fig. 24) NDVI peaks at higher values than at other sites and also remains high for a longer time. Both of these sites are in the heart of the Great Lakes–St. Lawrence Forest Region and have a large hardwood component (maple [*Acer* spp.], birch [*Betula* spp.], oak [*Quercus* spp.], and poplar [*Populus*, spp.]), which probably results in higher NDVI values.

The London/Chatham chart (Fig. 25) shows a slower increase in NDVI in the spring than does any of the other sites. This may be from the dominance of agricultural crops that usually do not form a continuous green cover until July or August. On the other hand, forest vegetation flushes in May or June.
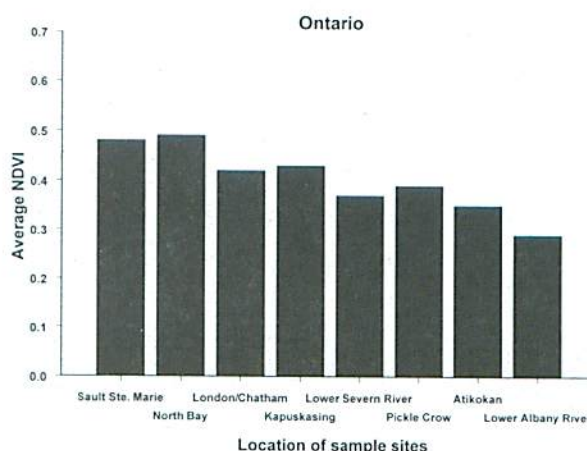

Figure 31. Average annual NDVI for Ontario sample sites.

15

Average annual NDVI (Fig. 31) is highest in the Sault Ste. Marie and North Bay sites and decreases northward to the Albany River site. Coniferous trees, mixed with a component of birch and poplar, dominate the northern Ontario forest. In central Ontario the forest has a vast, diverse hardwood component that probably results in higher annual average NDVI values.

Overall, the series of NDVI composite images presented in this report can be used as a tool to monitor the general progress of green-up and senescence in Ontario.

LANDSAT NDVI, Forest Fire Occurrence, and Anthropogenic Pollution in Sudbury

The four pseudo-colored NDVI images for the Sudbury Basin were acquired in July for 1974, 1976, and 1980 and in August for 1991. This period of the summer is typically the time of peak greenness in healthy vegetation. The lake at the center of each image is Lake Wanapitei, and the city of Sudbury is located about 30 km southwest of the lake.

Pseudo-colored NDVI images for the Sudbury Basin show similar patterns of greenness in 1974 (Fig. 32) and 1976 (Fig. 33). The two white zones around the city of Sudbury indicate that the area is devoid of vegetation. The western zone is an area occupied by the INCO Ltd. Copper Cliff smelter, and the eastern zone surrounds the INCO Ltd. smelter in Coniston to the south and the Falconbridge Ltd. smelter in Falconbridge to the north. The Coniston smelter was closed prior to the spring of 1972 and the Copper Cliff smelter was replaced by a 381-m "super stack" in August 1972. These zones of low greenness, adjacent to the Sudbury smelters, show up clearly on the 1-km resolution AVHRR composites for 1993 (Figs. 6–17). The general impression from the 1974 and 1976 LANDSAT scenes (Figs. 32 and 33) is that the whole basin area is low in greenness, considering that the images were taken in July when greenness should be at a maximum. The 1976 image (Fig. 33) also contains several linear pockets of cumulus cloud that obscure parts of the image. These cloud patches are located east, north, and northeast of Sudbury. They appear white with red fringes and are not to be confused with the white, unvegetated zones around Sudbury.

In the 1980 imagery (Fig. 34) there is a stark increase in the overall greenness of the Sudbury basin, but the zones of low or nil vegetation cover around the smelters are still prominent although reduced somewhat in size. The major improvement in greenness occurred east and south of the city. The slower return to peak summer greenness north and northwest of Sudbury may be because the prevailing winds in the area are from the south. Therefore, remaining sulphur dioxide emissions, even though reduced, would be most likely to affect the area north of the city. But there

is a broad area immediately north of the city that has increased significantly in greenness. As well, there is an east–west zone across the top of the image that indicates lower greenness than either the 1974 or 1976 scenes. Both of these changes may be the result of the super stack, which injects contaminants high enough into the atmosphere that nearby areas receive lower amounts of pollution and areas farther away experience an increased deposition of contaminants.

The outstanding feature of the 1991 NDVI pseudo-color image (Fig. 35) is that, except for the city zone, most of the basin appears to reach peak greenness levels that would normally be expected for the time of year (i.e., early August). The 1991 image does not show the feature of reduced greenness across the north that was evident in the 1980 image. Possibly, this is a result of the significant reduction in sulphur dioxide emission levels starting in 1978. Combined sulphur dioxide emissions data (Fig. 36) from the main Copper Cliff and Falconbridge smelters started to drop dramatically in 1978. Several events contributed to about a 50 percent reduction in emissions in the 1980s compared to the early 1970s. The first event was a strike at INCO Ltd. It started in 1978 and continued into 1979 (Negusanti and McIlveen 1990). The second was action taken to limit the sulphur dioxide emissions at both the Copper Cliff and Falconbridge smelters. The Copper Cliff smelter was limited to 3 265 tonnes/day (1 200 ktonnes/year) in 1978, followed by a reduction to 2 268 tonnes/day (830 ktonnes/year) in 1980, and a further reduction to 1 770 tonnes/day (650 ktonnes/year) after 1982. The Falconbridge smelter was limited to 422 tonnes/day (154 ktonnes/year) in 1979 (Negusanti and McIlveen 1990). Even though INCO Ltd. could have legally emitted 1 200 ktonnes/year, they and Falconbridge together produced only 684 ktonnes (Fig. 35); about one-half of the allowable limit for 1978. The difference is most likely a result of the 1978 strike. A similar pattern can be seen in 1979 as the strike pushed emissions below 500 ktonnes/year. In 1980, after the strike, combined emissions from both smelters rose to almost 1 000 ktonnes/year. By 1980 the Copper Cliff super stack had been operating for 8 years. This, combined with the huge reductions in sulphur dioxide emissions, may help to explain the apparent improvement in greenness by 1991.

Forested areas that were killed by sulphur dioxide pollution have not returned to mature forests. In fact, most of them support early successional vegetation such as grasses and shrubs, and young poplar, birch, and pine (*Pinus* spp.). These would provide a strong enough reflectance in the near-infrared to result in high NDVI values in the composites. Nonetheless, most types of broad vegetation coverage will reduce the fire hazard.
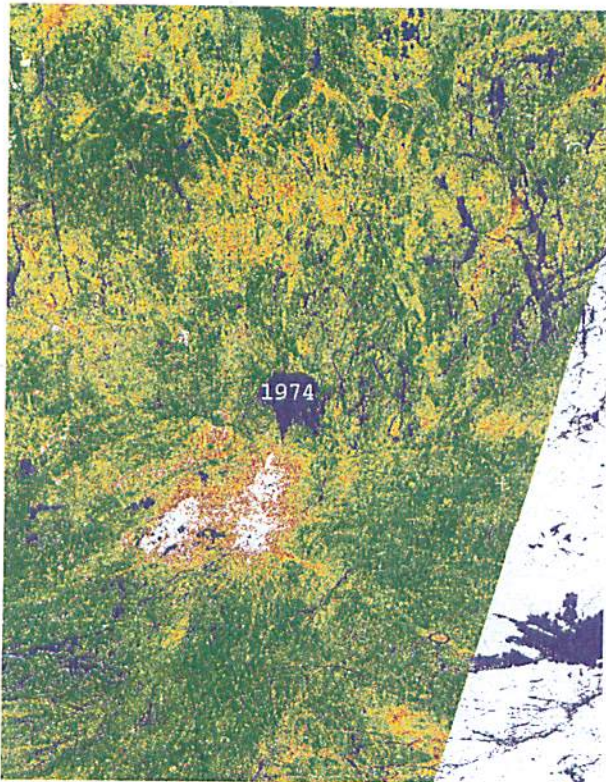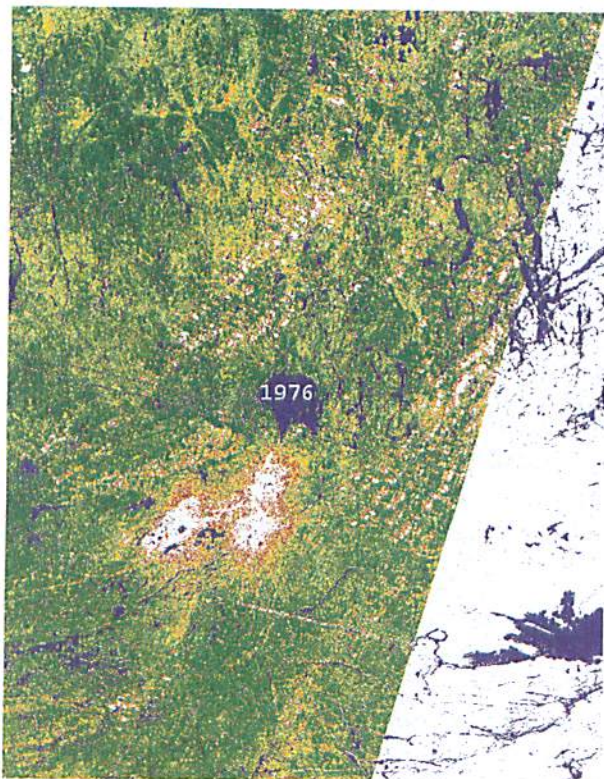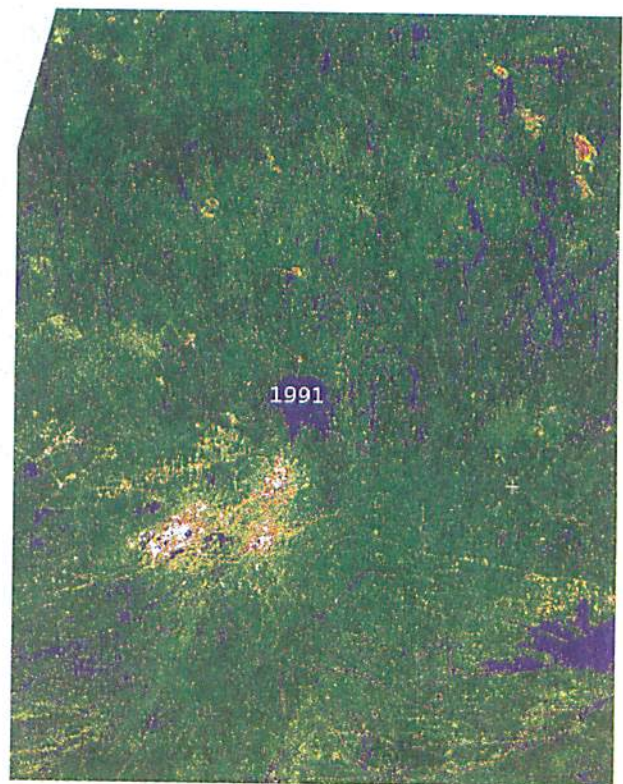
Figure 32. NDVI greenness map of the Sudbury Basin for the summer of 1974.
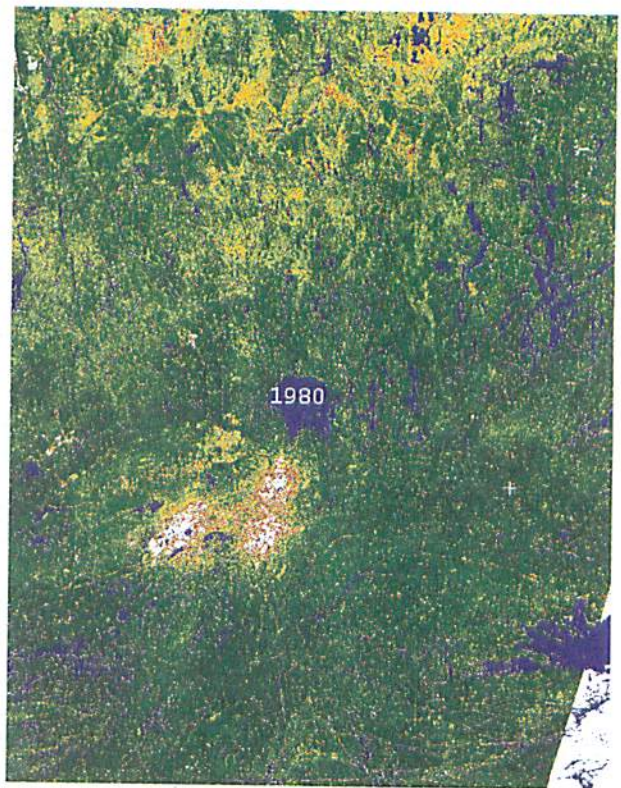
Figure 34. NDVI greenness map of the Sudbury Basin for the summer of 1980.

Figure 33. NDVI greenness map of the Sudbury Basin for the summer of 1976.

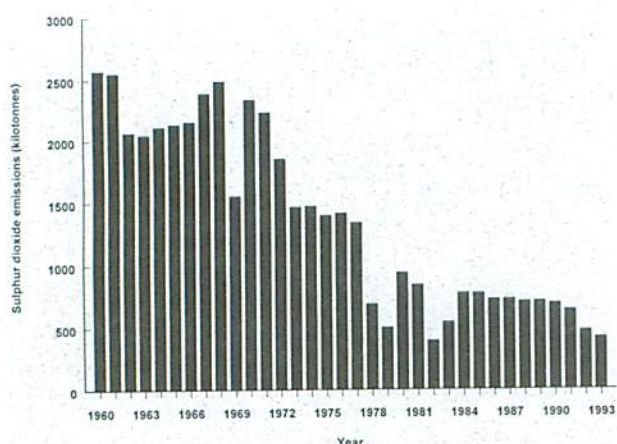*Figure 35. NDVI greenness map of the Sudbury Basin for the summer of 1991.*

17

Figure 36. Sulphur dioxide emissions from the Sudbury smelters for 1960 to 1993.

An issue that is of interest to fire managers is the discussion surrounding the changes in fire occurrence rates in the Sudbury District since the mid-1960s. Comparing the observed annual number of fires in Sudbury since 1981 to the number predicted by the model presented in this paper (Table 4) shows that observed fire occurrence is about 33–50 percent of what would be expected, based on predictions from the model. Exceptions were in 1982, when more fires occurred than predicted, and in 1983, when the observed and expected number of fires were about equal.

Table 4. Annual forest fire occurrence in Sudbury.

Year	Annual number of human-caused forest fires in the Sudbury District[a]	
	Observed	Expected
1982	207	146
1983	155	176
1984	63	139
1985	83	174
1986	70	169
1987	138	213
1988	126	254
1989	165	287
1990	85	236
1991	117	188
1992	62	210
1993	74	220

[a] The district is defined by the boundaries that were in place prior to reorganization in 1992.

Many possible factors affect annual fire occurrence rates in Ontario (Lynham 1987), but the magnitude of the decrease in the Sudbury area is larger than for any other part of the province. This difference is probably attributable to changes that have increased the overall greenness of the area over the last 20 years.

18

CONCLUSIONS AND RECOMMENDATIONS

NOAA AVHRR data can be used to develop relative greenness maps for the province of Ontario. Raw NDVI, which is a single pseudo-band represented by gray tones, can be remapped with a pseudo-color table to highlight chlorophyll-rich vegetation. The NDVI scale is relative, however, because it indicates areas that are greener than others. Thus, it cannot be used to quantify chlorophyll content without further study. Also, ground sampling will be required to relate particular levels of greenness to actual forest conditions.

The GEOCOMP product is not ready for operational use when the need is immediate (24–72 hours). Addition of high speed communication lines from the GEOCOMP facility at the MRSC in Winnipeg, Manitoba, could make this possible. There are also several important aspects of the GEOCOMP product that must be improved. The NDVI data should be calculated to permit biospheric analyses and an atmospheric correction should be an option for users. Development of an algorithm for generating a cloud mask that could be stored as an additional GEOCOMP pseudo-band would be useful for delineating cloud contamination in NDVI composites.

The GEOCOMP system was designed to produce nearly cloud-free composite images of large pieces of land by selecting the most cloud-free pixels from several daily images of the same land area. At present, the composites only provide a very general means of monitoring greenness (which is actually a measure of the amount of chlorophyll) without consistent local evaluation and verification. Most composite images contain artifacts, largely a result of cloud contamination. Imagery with such abnormalities is difficult to use operationally for monitoring forest fire hazard.

Most work that has been carried out for monitoring greenness or biomass from satellite platforms has relied on NDVI. This index is well suited to this application because it is the ratio of infrared to red bands of data. This ratio helps reduce some, but not all, atmospheric effects in the data. It also emphasizes areas of high chlorophyll. NDVI varies mainly in response to the amount of broadleaf vegetation as well as to vegetation density. Typically, pure broadleaf forests progress from almost no greenness in the early spring to maximum greenness in the summer. On the other hand, forests dominated by evergreens show a small amount of greenness in the spring that increases throughout the growing season as broadleaf vegetation joins the coniferous crowns. The evergreen forests do not reach the same maximum greenness achieved by the pure broadleaf forests; therefore, the highest values are usually concentrations of broadleaf vegetation.

Changes in vegetation greenness in the Sudbury Basin can be monitored from LANDSAT satellite data by employing a procedure similar to that used in the analysis of AVHRR data. The increases in greenness and the 50 percent reduction (since 1981) in the expected annual number of fires are partly related to reductions in acid precipitation. Reductions in sulphur dioxide emissions since 1978 and the commissioning of the Sudbury "super stack" have ameliorated the acute contamination problem in the Sudbury Basin.

Alternative sources of NOAA AVHRR data should be explored. The GEOCOMP product is attractive to some users because the final output is calibrated, geocoded, and composited. Users that prefer to start with raw data and process it according to their own needs can also choose to purchase the data from other commercial sources.

Although composites seem attractive for monitoring vegetation by reducing cloud cover, often more information can be extracted from selected, cloud-free, single-date images through enhancement or classification procedures (Beaubien 1993). Combined with weather data, satellite data could be used to monitor fire hazard.

ACKNOWLEDGMENTS

LITERATURE CITED

Ahern, A.J.; Horler, D.N.H. 1986. Outlook for future satellites and data use in forestry. Remote Sensing Reviews 2(1):215–253.

Avery, T.E.; Berlin, G.L. 1992. Fundamentals of remote sensing and airphoto interpretation. 5th ed. Maxwell Macmillan Canada, Inc., Don Mills, ON. 472 p.

Banner, A.V.; Lynham, T.J. 1981. Multitemporal analysis of LANDSAT data for forest cutover mapping: A trial of two procedures. p. 233–240 in W.G. Best and S. Westlake, eds. Proc. 7th Canadian Symposium on Remote Sensing. 8–11 September 1981, Winnipeg, Manitoba. Canadian Aeronautics and Space Institute, Ottawa, ON. 600 p.

Beaubien, J. 1993. Méthodolgie de classification des données AVHRR pour la surveillance du couvert végétal. p. 597–603 in P. Gagnon, ed. Proc. 16th Canadian Symposium on Remote Sensing, 7–10 June 1993, Sherbrooke, Quebéc. Canadian Remote Sensing Society, Ottawa, ON. 938 p.

Beaubien, J. 1994. Landsat TM satellite images of forests: From enhancement to classification. Canadian Journal of Remote Sensing 20(1):17–26.

Burgan, R.E.; Hartford, R.A.; Eidenshank, J.C.; Werth, L.F. 1991. Estimation of vegetation greenness and site moisture using AVHRR data. p. 17–24 in P.L. Andrews and D.F. Potts, eds. Proc. 11th Conference Fire and Forest Fire Meteorology. 16–19 April 1991, Missoula, Montana. Society of American Foresters, Bethesda, MD. 616 p.

Burgan, R.E.; Hartford, R.A. 1993. Monitoring vegetation greenness with satellite data. USDA For. Serv., Intermountain Res. Stn., Odgen, UT. GTR INT-297. 13 p.

Cihlar, J.; D'Iorio, M.; Mullins, D.; St-Laurent, L. 1989. Use of satellite data and GIS for environmental change studies. p. 933–943 in M.M. Allam, ed. Challenge for the 1990s. GIS Geographic Information Systems. Proc. National Conf. 27 February–3 March 1989, Ottawa, Ontario. Canadian Institute of Surveys and Mapping, Ottawa, ON. 1436 p.

Cunningham, A.A.; Martell, D.L. 1973. A stochastic model for the occurrence of man-caused forest fires. Can. J. For. Res. 3(2):282–287.

Dobrin, D.J.; Potvin, R. 1992. Air quality monitoring studies in the Sudbury area 1978 to 1988. Ontario Ministry of the Environment, Technical Assessment Section, Northeastern Region, Sudbury, Ontario. Queen's Printer for Ontario, Toronto, ON. 128 p.

Eidenshink, J.C.; Haas, R.H.; Zokaites, D.M.; Ohlen, D.O. 1989. Integration of remote sensing and GIS technology to monitor fire danger in the northern great plains. p. 944–956 *in* M.M. Allam, ed. Challenge for the 1990's. GIS Geographic Information Systems. Proc. National Conf. 27 February–3 March 1989, Ottawa, Ontario. Canadian Institute of Surveys and Mapping, Ottawa, ON. 1436 p.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian forest fire behavior prediction system. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, ON. Inf. Rep. ST-X-3. 63 p.

Harper, D. 1983. Eye in the sky: Introduction to remote sensing. 2nd. ed. Polyscience Publications Inc., Montreal, QC. 252 p.

Howse, G.M.; Applejohn, M.J. 1994. Forest insect and disease conditions in Ontario. Nat. Resour. Can., Canadian Forest Service–Ontario, Sault Ste. Marie, ON. Survey Bulletin, Fall 1993. 12 p.

Johnson, G.R. 1976. Remote estimation of herbaceous biomass. MSc. thesis, Colorado State University, Ft. Collins, CO. 120 p.

Lillesand, T.M.; Kiefer, R.W. 1987. Remote sensing and image interpretation. 2nd. ed. John Wiley and Sons, Inc. Toronto, ON. 721 p.

Lynham, T.J. 1987. An analysis of annual people-caused forest fire occurrence in Ontario. MScF thesis, University of Toronto, Faculty of Forestry, Toronto, ON. 100 p.

Martell, D.L.; Bevilacqua, E.; Stocks, B.J. 1989. Modelling seasonal variation in daily people-caused forest fire occurrence. Can. J. For. Res. 19:1555–1563.

Martell, D.L.; Otukol, S.; Stocks, B.J. 1987. A logistic model for predicting daily people-caused forest fire occurrence in Ontario. Can. J. For. Res. 17:394–401.

Merrill, D.F.; Alexander, M.E. 1987. Glossary of forest fire management terms. National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, ON. 15 p.

Negusanti, J.J.; McIlveen, W.D. 1990. Studies of the terrestrial environment in the Sudbury area 1978–1987. Ontario Ministry of the Environment, Northeastern Region, Sudbury, Ontario. Queen's Printer for Ontario, Toronto, ON. 69 p. + append.

Rahman, H.; Dedieu, G. 1994. SMAC: A simplified method for the atmospheric correction of satellite measurements in the solar spectrum. Int. J. Remote Sensing 15(1):123–143.

Robertson, B.; Erickson, A.; Friedel, J.; Guindon, B.; Fisher, T.; Brown, R.; Teillet, T.; D'Iorio, M.; Cihlar, J.; Sancz, A. 1992. GEOCOMP, a NOAA AVHRR geocoding and compositing system. p. 223–228 *in* L.W. Fritz and J.R. Lucas, eds. Proc. of the XVIIth Congress, ISPRS, Vol. XXIX, Part B2, Commission II. 1992. Washington, DC. Amer. Soc. for Photogrammetery and Rem. Sens., Bethesda, MD. 642 p.

Rouse, J.W.; Haas, R.H.; Schell, J.A.; Deering, D.W. 1973. Monitoring vegetation systems in the great plains with ERTS. p. 309–317 *in* S.C. Freden, E.P. Mercanti and M.A. Becker, eds. Third ERTS Symposium, Vol. 1, Section A. 10–14 December 1973, Washington, DC. National Aeronautics and Space Administration, Washington, DC. NASA SP-351. 976 p.

Rouse, J.W.; Haas, R.H.; Schell, J.A.; Deering, D.W.; Harlan, J.C. 1974. Monitoring the vernal advancement and retrogradation (greenwave effect) of natural vegetation. NASA/GSFC, Greenbelt, MD. Type III Final Report. 371 p.

SAS Institute Inc. 1985. SAS user's guide: Statistics. 5th ed. Cary, NC. 1290 p.

Simard, A.J.; Main, W.A. 1982. Comparing methods of predicting jack pine slash moisture. Can. J. For. Res. 12:793–802.

Stocks, B.J. 1991. The extent and impact of forest fires in northern circumpolar countries. p. 197–202 *in* J.S. Levine, ed. Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications. The MIT Press, Cambridge, MA. 569 p.

Teillet, P.M.; Holben, B.N. 1994. Towards operational radiometric calibration of NOAA AVHRR imagery in the visible and near-infrared channels. Canadian Journal of Remote Sensing 20:1–10.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, ON. For. Tech. Rep. 35. 37 p.