APPLYING GEOGRAPHIC INFORMATION SYSTEMS AND REMOTE SENSING TO FOREST FIRE MONITORING, MAPPING, AND MODELING IN CANADA

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ABSTRACT

The Fire Monitoring, Mapping and Modelling System (Fire M3) is an initiative of the Canada Centre for Remote Sensing (CCRS) and the Canadian Forest Service (CFS), both agencies of Natural Resources Canada. The goals of Fire M3 are to use low-resolution satellite imagery to monitor actively burning fires on a daily basis; to estimate annual area burned; and to model fire behavior, biomass consumption, and carbon emissions from fires. Same-day fire products are made available on the Fire M3 web site and have been used for a variety of purposes including national reporting and climate change research. The daily operation of the system during the forest fire season involves 1) satellite image reception in Saskatchewan and Quebec; 2) production of geocoded, Canada-wide composite images at CCRS; 3) application of CCRS fire, smoke, and burned-area detection algorithms to produce raw fire products; 4) production of final daily fire products at CFS, including weather-based fire behavior modeling; and 5) dissemination of daily fire products on the Fire M3 web site within 12 hours of satellite reception.

keywords: boreal forest, Canada, fire monitoring, fire mapping, Geographic Information System, hotspots, remote sensing.

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INTRODUCTION

Approximately 10% of the world's forests occur in Canada. The 4 million km^2 of forest covers 40% of the country and is dominated by boreal forest types. Each year wildfires have significant ecological and economic impacts on Canada's forests, with an average of 9,000 fires burning over 20,000 km^2 annually across Canada (Stocks 1991, Weber and Stocks 1998, Amiro et al. 2001). While few of these fires grow larger than 2 km^2 in area, these larger fires account for almost all of the annual area burned. The sizes of these larger fires make them particularly well-suited to monitoring and mapping with low-resolution (image pixel size approximately 1 km^2) satellite sensors. Considering the area and remoteness of Canada's boreal forest, remote sensing is also a cost-effective means of providing a timely, synoptic view of forest fire activity in Canada.

The boreal forest covers 17% of the earth's surface, but accounts for more than 30% of its carbon storage (Kasischke 2000). Carbon storage is directly modified by fire by the release of carbon (CO_2, CH_4, CO) into the atmosphere during the combustion of forest and ground vegetation. Shifts in stand age distribution and increased ground layer decomposition rates following fire also indirectly influence the amount and rate of carbon storage. To assess these ecological and carbon budget impacts, a fundamental parameter that must be measured is the total burned area. This requires a method to map the spatial distribution of burned forest over vast, remote areas in an accurate, consistent, and timely manner.

Recognizing the potential economic and scientific benefits of satellite technology, Natural Resources Canada developed the Fire Monitoring, Mapping and Modelling System (Fire M3). The goals of Fire M3 are to use low-resolution satellite imagery to monitor actively burning fires on a daily basis; to estimate annual area burned; and to model fire behavior, biomass consumption, and carbon emissions from fires. Fire M3 products have been used in national reporting, climate change research, and delivery of current and historical fire information to industries and the public. In some cases, these products have also been used by fire management agencies to identify fires in remote areas. This paper provides an overview of the Fire M3 system and products, and summarizes project development over the past year.

SYSTEM ARCHITECTURE

Monitoring

Fire M3 uses a fire-detection algorithm developed by the Canada Centre for Remote Sensing (CCRS) (Li et al. 1997, 2000*a*; Fraser et al. 2000*a*) to recognize active fires in Advanced Very High Resolution Radiometer (AVHRR) satellite data. The algorithm performed well when compared with end-of-season fire maps produced by fire management agencies (Li et al. 2000*b*). Using the algorithm, CCRS and the Canadian Forest Service (CFS) developed a system to automatically identify and map fires in Canada on a daily basis. The system was demonstrated and tested in 1998; daily operation began in 1999.

For the identification of actively burning fires, Fire M3 acquires visible and infrared satellite imagery from the AVHRR sensor on board the U.S. National Oceanic and Atmospheric Administration (NOAA) satellite series, which make four afternoon passes per day across Canada. These data are received from two satellite receiving stations located at Prince Albert, Saskatchewan, and Mont Joli, Quebec. Daily processing of the images at CCRS is automated using the GeoComp-n system (Robertson et al. 1992; developed by PCI Geomatics, Richmond Hill, ON) and includes geocoding and compositing. *Geocoding* determines the precise location and orientation of the image on the earth's surface. This is done using a set of images of easily identifiable features of known location, which are then matched to those features visible on the incoming image. *Compositing* combines individual images to produce a single image covering all of Canada. Where two images overlap, the pixels with the least amount of cloud are automatically selected.

The fire-detection algorithm is then applied to the single-day composite image to identify active wildland fires. *Hotspots* (pixels identified as containing fire) are recognizable in the mid-infrared channel because of the heat generated by the fire. However, other factors such as reflected sunlight can produce the same signal. Therefore, the algorithm is based on three infrared channels and consists of seven steps or filters: one to identify possible hotspots, four to filter out false hotspots due to factors such as warm surfaces and highly reflectant clouds, one to reject hotspots not in forested areas, and one to remove single-pixel fires. Smoke- and cloud-detection algorithms are also part of the daily processing stream. The data are then transmitted via the Internet to the Northern Forestry Centre in Edmonton, Alberta, for conversion into Geographic Information System (GIS) formats.

Mapping

The national fire-mapping component of Fire M3 uses a hybrid technique developed for annual, low-resolution mapping of burned forest canopy (Fraser et al. 2000*a*) based both on hotspot detection as described above, and on the Normalized Difference Vegetation Index (NDVI), a satellite image-derived measure of photosynthetically absorbed radiation. The method, called HANDS (Hotspot and NDVI Differencing Synergy), combines active fire monitoring with multi-temporal change detection. Change detection is accomplished by comparing pre- and post-fire season NDVI values derived from anniversary date composite imagery. The locations of actively burning fires, determined from the monitoring component of Fire M3, are used to derive a spatially adaptive, statistical threshold for differencing and separating burned areas. The NDVI values are computed from 30-day composites that are corrected for atmospheric distortion and reflectance variation due to viewing geometry (Cihlar et al. 1997). Thirty-day composites are used to ensure that the images are cloud free.

Fraser et al. (2000*b*) found that another index, similar to NDVI, provides superior separation of burned forest. This index uses imagery from another satellite, called SPOT (Système Probatoire d'Observation de la Terre). Launched in 1998, it carries a sensor designed specifically for monitoring vegetation. The index derived from SPOT imagery is also less susceptible to contamination by smoke. Therefore, the HANDS burned-area products from 1998 onwards use SPOT for change detection and AVHRR for hotspot detection.

Modeling

Fire weather and fire behavior potential at hotspot locations are estimated based on outputs from the Canadian Wildland Fire Information System (CWFIS) (Lee 1995). The CWFIS receives hourly and synoptic meteorological data via the Anik satellite from approximately 650 weather stations located across Canada. These data are used in the Spatial Fire Management System (Englefield et al. 2000) to produce daily fire danger maps and reports based on the Canadian Forest Fire Danger Rating System (Stocks et al. 1989).

PRODUCTS

Fire M3 products are available through a web site (http://fms.nofc.cfs.nrcan.gc.ca/firem3/). Products include 1) daily maps of hotspots, smoke and cloud cover, updated within 12 hours of image acquisition; 2) year-to-date hotspot maps; 3) yearly animated hotspot maps (1 frame per day); 4) charts of hotspot counts by day, month, and 10-day period (see examples in Figure 1); and 5) reports.

Reports include daily and year-to-date hotspot counts by ecozone (Wiken 1986). There are 15 ecozones in Canada, representing a very broad classification of physiographic and ecological similarities. A map of the ecozones can be found on the web site.

Maps are also available through a map server application that allows panning and zooming of hotspot maps. As the user zooms in, more detailed features such as towns, rivers, and roads become visible. The Identify tool enables users to retrieve the fire weather and fire behavior estimates calculated for each hotspot. Maps accessible through the map server include 1) hotspots, smoke, and cloud (Figure 2); 2) daily satellite composite images (at full resolution); and 3) annual HANDS burned areas.

The fire-detection algorithm has been applied to archived AVHRR imagery from 1994 onward, allowing for historical comparison and analysis (Figure 1d). The historical daily hotspot maps are also available through the map server application.

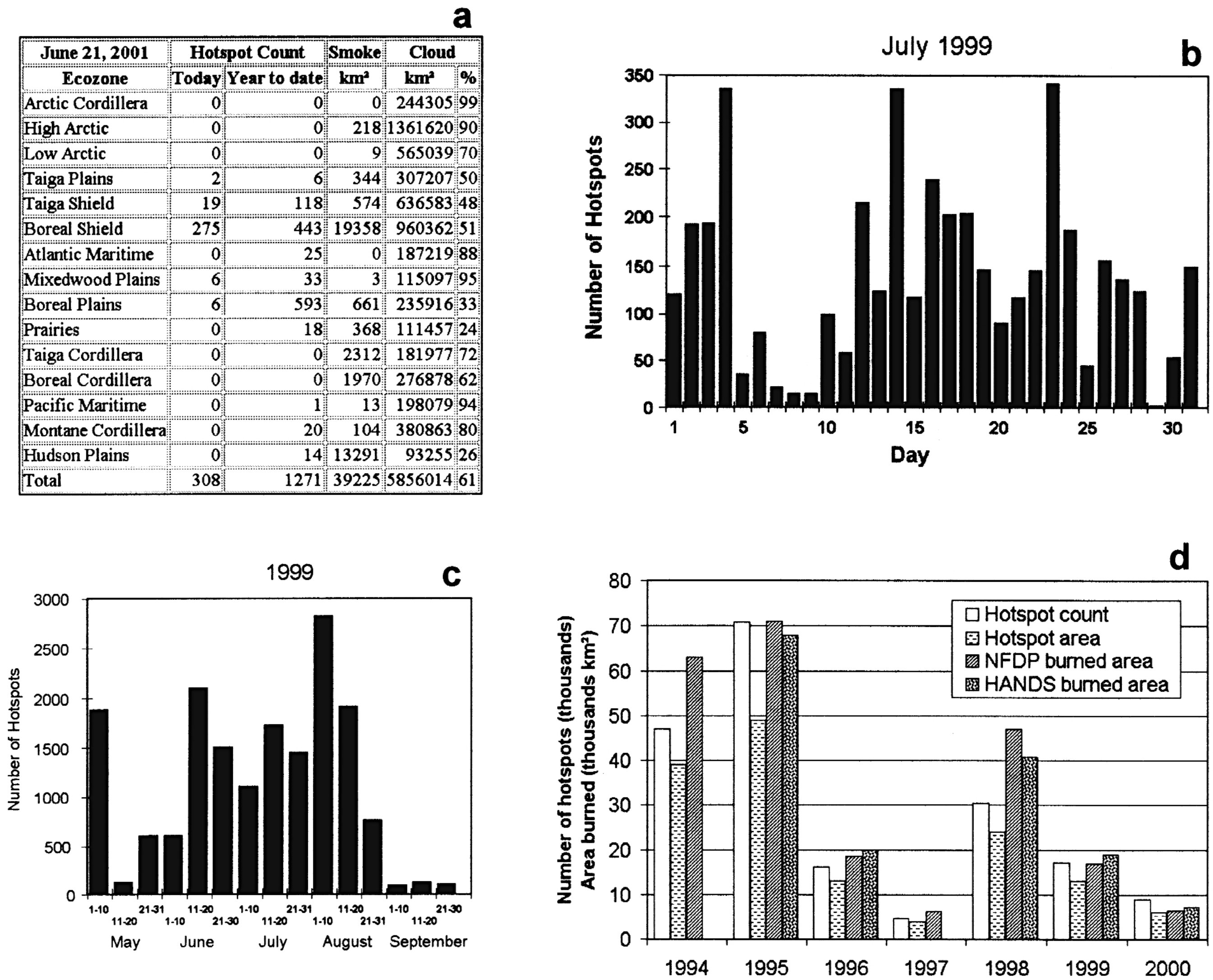
DISCUSSION

Fire M3's daily hotspot monitoring has generated significant interest from the public, government, and some industries. Interest from fire management agencies has been limited because their own fire detection networks are able to identify fires more quickly and accurately. These networks, which include fire towers, aerial patrols, and the public (through toll-free hotlines) are not limited by satellite overpass timing, satellite image resolution, or processing delays. However, satellite-based monitoring contributes toward a consistent daily national overview of fire and smoke in Canada. Unlike post-fire burn perimeter maps, hotspot monitoring also provides daily tracking of fire spread within individual multi-pixel fires. Because the fire regime in Canadian boreal forests is characterized by infrequent, large, intense, stand-replacing fires (Stocks 1991), the limitations on satellite-based monitoring are not as severe as they would be, for example, in areas dominated by surface fires burning below the forest canopy. However, such fires could still produce detectable smoke.

The hotspot identification algorithm has been tested for Russia and the United States, as well (Li et al. 2001). During 2000, the algorithm was used to generate daily fire products that contributed to the coordination of fire fighting efforts in the northwestern United States. It is expected that the algorithm and methodology would perform well in other areas with similar forest types, such as Scandinavia and Alaska.

Annual burned area totals for Canada (Figure 1d) indicate that HANDS provides estimates similar to those provided by the National Forestry Database Program (NFDP) (http://nfdp.ccfm.org/). The NFDP data are derived from Canadian fire management agencies, which rely on conventional (ground or air-based) mapping techniques. Fire management in Canada is handled by the provinces, territories, and national parks, each of which has different methods and capabilities for fire mapping. The national data are only complete after the last province reports, and the data quality varies among provinces. A comparison of HANDS results with agency fire maps for 1995 and 1996 (Fraser at al. 2000*a*) indicates that although the algorithm missed many fires smaller than 10 km^2, there was good correspondence for larger fires, which account for the vast majority of the area burned. There were also some fires identified by the algorithm that were missed by the agencies. The HANDS method therefore provides timely and consistent national burned-area products that can complement existing conventional burned area surveys.

The modeling component of Fire M3 is based on the outputs of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), part of the Canadian Forest Fire Danger Rating System. The FBP System produces estimates of fuel consumption based on fuel moisture, fuel load, and crown fraction burned; these factors in turn depend on weather, fuel type, and terrain information. Such fuel consumption estimates can be used to calculate total fuel consumption in Canada. This simple



June 21, 2001	Hotspot Count		Smoke	Cloud	
Ecozone	Today	Year to date	km²	km²	%
Arctic Cordillera	0	0	0	244305	99
High Arctic	0	0	218	1361620	90
Low Arctic	0	0	9	565039	70
Taiga Plains	2	6	344	307207	50
Taiga Shield	19	118	574	636583	48
Boreal Shield	275	443	19358	960362	51
Atlantic Maritime	0	25	0	187219	88
Mixedwood Plains	6	33	3	115097	95
Boreal Plains	6	593	661	235916	33
Prairies	0	18	368	111457	24
Taiga Cordillera	0	0	2312	181977	72
Boreal Cordillera	0	0	1970	276878	62
Pacific Maritime	0	1	13	198079	94
Montane Cordillera	0	20	104	380863	80
Hudson Plains	0	14	13291	93255	26
Total	308	1271	39225	5856014	61

Figure 1. Canadian Fire Monitoring, Mapping and Modelling System (Fire M3) sample outputs. (a) Hotspot count, smoke, and cloud areas by ecozone for 21 June 2001. (b) Hotspot count by day for July 1999. (c) Hotspot count by 10-day period for the 1999 fire season. (d) Hotspot count and burned area by year. The hotspot count differs from the hotspot area because of pixels that are hot on more than 1 day. The burned-area data were obtained from the National Forestry Database Program (NFDP), based on conventional burn mapping techniques, and Fire M3's HANDS (Hotspot and NDVI [Normalized Difference Vegetation Index] Differencing Synergy) method. HANDS estimates were not available for 1994 and 1997.

approach has various drawbacks, including the assumption that each hotspot represents a full 1 km² of burned area; however, this methodology could be used to provide both daily and annual emissions estimates. Preliminary emissions estimates from Fire M3 are similar to those calculated by Amiro et al. (2001), who used the FBP System to estimate atmospheric carbon emission in Canada for 1959–1995 based on provincial fire perimeters, daily weather, modeled fire progression, and a modeled fire end date.

Changes in 2001

In 2000, the increasingly late time of AVHRR image acquisition by the NOAA-14 satellite over Canada required the insertion of an additional filter to remove false hotspots caused by sun glint from sub-pixel water bodies. In 2001, NOAA-14 satellite drift and later overpass time caused further degradation in image quality, precipitating a switch to NOAA-16. However, the primary fire detection channel (channel 3a, mid-infrared) on NOAA-16 is switched off during the day in favor of a new shortwave infrared channel (channel 3b). The new daytime channel is less sensitive to active fires (Fraser et al. 2000*b*), though it is effective for smoke detection.

Since channel 3a would only be available at night, a

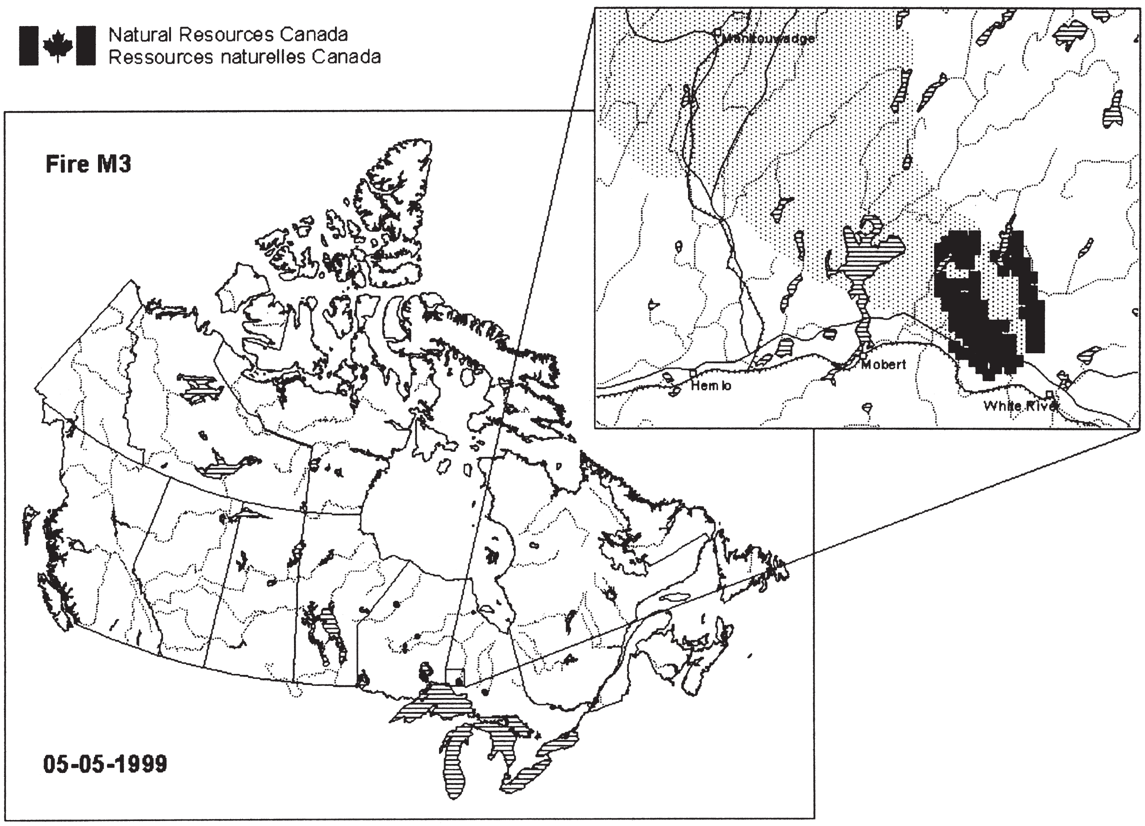


Figure 2. Sample maps from the Internet map server on the Fire Monitoring, Mapping and Modelling System (Fire M3) web site showing Canada-wide hotspots for 5 May 1999. The inset shows the zoom capability of the map server for fires in Ontario on the same day. The elliptical shape of an actively burning fire (black) can be seen clearly along with its associated smoke plume (gray).

new algorithm was developed specifically for nighttime detection (Abuelgasim and Fraser 2002). The algorithm consists of two threshold tests based on channels 3a and 4, along with a filter to remove hotspots not in forested areas. The GeoComp-n processing chain also had to be revised, including precision geocoding of night imagery using the heat signature from water bodies. During the fire season, hotspots identified from night imagery were available on the web site the following morning. Quality control and refinement of the algorithm was done on the fly based on fires observed during the 2001 fire season. The final algorithm was used to reprocess all the 2001 composites retroactively at the end of the fire season.

The major advantage of night detection is that it avoids the false hotspots associated with sun glint. The disadvantage is that it misses fires that are less active at night due to lower temperatures and calmer winds. It is difficult to assess how the NOAA-16 night products compare with the previous NOAA-14 day products. Only 5,600 km^2 burned in Canada during 2001, mostly attributable to some large early fires in Alberta, northern Manitoba, and Saskatchewan. NOAA-16 identified most of these, but missed several large fires in the Northwest Territories due to the fact that the 3a/3b switch occurred near the 60th parallel in late June and early July. By the end of July, the switch had moved far enough north to provide almost complete coverage of Canadian forests.

Small fires (<1 km^2 burned area or 1 AVHRR pixel) without obvious smoke were also largely missed. For example, Ontario had over 1,500 fires during 2001, but Fire M3 identified very few of them. However, the total burned area in Ontario was only 107 km^2, for an average final fire size of less than 0.1 km^2. The area actively burning at time of overpass would normally be even smaller. The limited success in detecting small fires at night may be due to the diurnal cycle of fire intensity. But it is likely that NOAA-14 would not have detected most of these small fires either, since NOAA-14 hotspots were almost always accompanied by a visible smoke plume and few smoke plumes were visible in Ontario during 2001.

These changes can be expected to reduce the completeness of the hotspot maps, as well as the burned area maps produced using the HANDS method. It is hoped that both the monitoring and mapping products of Fire M3 will be improved in 2002 using data from the Moderate Resolution Imaging Spectroradiometer (MODIS), which contains channels designed specifically for fire monitoring (Kaufman et al. 1998). MODIS was launched by the U.S. National Aeronautics and Space Administration in December 1999 and is already being used to monitor forest fires in the United States.

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