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Mapping fire scars in global boreal forests using imaging radar data

L. L. BOURGEAU-CHAVEZ, E. S. KASISCHKE, S. BRUNZELL, J. P. MUDD

Earth Sciences Group, Environmental Research Institute of Michigan, PO Box 134001, Ann Arbor, MI 48113–4001 USA

and M. TUKMAN

Pacific Meridian Resources, 660 J. Street, Suite 200, Sacramento, California 95814 USA

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Abstract. This study is an extension of earlier research which demonstrated the utility of ERS SAR data for detection and monitoring of fire-disturbed boreal forests of Alaska. Fire scars were mappable in Alaska due to the ecological changes that occur post-burn including increased soil moisture. High soil moisture caused a characteristic enhanced backscatter signal to be received by the ERS sensor from burned forests. Since regional ecological differences in the global boreal biome may have an effect on post-fire ecosystem changes, it may also affect how fire scars appear in C-band SAR imagery. In the current study we evaluate the use of C-band SAR data to detect, map and monitor boreal fire scars globally. Study sites include four regions of Canada and an area in central Russia. Fire boundaries were mapped from SAR data without *a priori* knowledge of fire scar locations. SAR-derived maps were validated with fire service records and field checks. Based on results from test areas in Northwest Territories, Ontario, south-eastern Quebec, and central Russia, C-band SAR data have high potential for use in detecting and mapping fire scars globally.

1. Introduction

Mapping and monitoring fire-disturbed sites (fire scars) is important for resource and land management as well as global change research. Atmospheric gas emissions due to biomass burning and the long term post-fire biogenic gas emissions from the scarred landscape have important implications for climate change (Justice and Korontzi 2000, Levine and Cofer 2000, Richter *et al.* 2000). Several techniques have been developed for using visible, infrared and thermal data to detect and map active fires and burn scars (Flannigan 1986, Cahoon *et al.* 1992, 1994, Kasischke and French 1995, Ahern *et al.* 2000, Michalek *et al.* 2000). The utility of Synthetic Aperture Radar (SAR) data for mapping fire scars has been more recently documented (Landry *et al.* 1995, Bourgeau-Chavez *et al.* 1997, Liew *et al.* 1999), but research shows SAR has unique capabilities that may compliment and enhance multi-spectral techniques for fire scar monitoring.

In 1991, the first European Remote Sensing Satellite (ERS) SAR images of Alaska

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revealed fire scars as 3–6 dB brighter than adjacent unburned forests (Kasischke *et al.* 1992). Burned areas were determined to be detectable in the Alaska SAR imagery due to the ecological changes that occur post-fire. These changes include removal of tree canopies, exposure of rough ground surfaces and increased ground moisture (Kasischke *et al.* 1994, Bourgeau-Chavez *et al.* 1997). Further research revealed that this phenomenon occurred only when the burned areas were wet such as in early spring, early autumn and after rain events (French *et al.* 1996, Bourgeau-Chavez *et al.* 1997). This enhanced brightness allowed Alaskan fire scars to be detected with moderate precision. Once detected, the burnt area can be mapped with high precision for several years after a fire. Increased ground moisture is the dominant factor causing the enhanced backscatter from burned forests (French *et al.* 1996, Bourgeau-Chavez *et al.* 1997). The increase in soil moisture post-fire is attributed to decreased surface albedo and melting of the permafrost layer as well as lowered evapotranspiration (Brown 1983, Dyrness and Norum 1983, Viereck 1983). However, in some cases soils have been observed to become drier postburn (Kershaw and Rouse 1971, Swanson 1996). The overall effects of fire on soil moisture are a function of fire severity, soil type and the presence or absence of permafrost. In different boreal regions, where permafrost may be absent or climatic conditions are more favorable for vegetation growth, enhanced backscatter may not occur. When rapid regeneration occurs after a fire, the duration of enhanced backscatter may be shortened because the new vegetation may attenuate the signal.

To determine the expandability of the SAR fire mapping procedure developed for Alaska to other boreal regions with varying ecological conditions, the current study was conducted using C- band SAR imagery (ERS and Radarsat) collected over four Canadian boreal regions and an area in central Russia. The overall goal was to develop a SAR technique for mapping and monitoring fire-disturbed boreal forests on a global basis. The objectives of this study were to:

1. determine if fire scars can be detected and mapped in the varying ecological conditions of boreal Canada and Russia as has been done in Alaska using C-band SAR imagery; if so,
2. determine if mapping fire scars with SAR imagery alone is feasible; and
3. identify any geophysical, ecological, or temporal conditions which may affect fire scar detection and area estimation in these ecologically different boreal regions.

To reach the goals of the current project,we conducted an in-depth study of SAR data collected over Canadian boreal regions. This analysis included a comparison of Canadian Fire Service (CFS) records to SAR-derived fire boundaries. We then evaluated ERS imagery collected over Central Russia for fire scar detection and mapping.

2. Background on fire mapping with SAR

One of the benefits of using SAR satellites for fire scar monitoring is that the microwave energy penetrates cloud cover. Concerns about cloud cover are always an issue when collecting visible data. Cloud problems were overcome to some extent with the technique of compositing several dates of the one-day-repeat AVHRR imagery. The compositing techniques have made AVHRR a more useful tool for detecting and mapping active fires and new fire scars on a regional basis. However, the coarse resolution of this sensor (1–4 km) results in moderate errors of estimated burn area. Also, because of the low resolution and spectral response of new vegetation, fire scar signatures fade rapidly, as soon as one year post-burn. A quantitative comparison of the detection and mapping of fire scars in Alaskan boreal forests using ERS SAR and a method using AVHRR NDVI 15-date composite 1 km data (French *et al.* 1994) was previously conducted (Bourgeau-Chavez *et al.* 1997). In the previous study, detection and mapping was conducted with *a priori* knowledge of fire scar locations. Burned areas were mapped by the Fire Service onto 1:250 000 scale maps using aircraft and field reconnaissance. These maps were used to select ERS imagery for analysis. Based on the 1990–1991 Alaska Fire Service (AFS) fire scar records, researchers found the ERS method of fire scar detection (54%) to be less accurate than the AVHRR method (70%). However, combining data from both sensors resulted in an improved capability of fire scar detection (81% accuracy). Furthermore, the estimation of area burned with ERS (96%) was much more precise than AVHRR (82%) when compared to Alaska Fire Service records.

When improved boundary mapping or longer viewing time is desirable, higher resolution visible data, such as Landsat TM or SPOT imagery is generally used. However, clouds remain an issue. SAR data from the ERS and Radarsat satellites are collected independent of cloud cover and daylight with a 14 day repeat cycle and resolution comparable to Landsat TM (30 m).

The ERS SAR sensor is a C-band, 5.6 cm wavelength imaging radar with vertical transmit and receive polarization (C-VV). It has a fixed antenna with an incidence angle of 23° to the swath centre. The ERS sensor has a resolution of 30 m and a footprint of 100 by 100 km. Two ERS sensors have been launched by ESA, ERS-1 in July 1991 and ERS-2 in April 1995, ERS-2 remains in operation.

The Radarsat satellite was launched in 1995 by the Canadian Space Agency. It is also a C- band system but is more sophisticated in that it operates in several modes with varying incidence angles, resolutions and footprints. The other difference is that it has horizontal transmit and receive polarization (C-HH). The Radarsat mode most similar to ERS is standard beam 1 (ST1) which has an incidence angle of 20°, resolution of 30 m and footprint of 100 by 100 km. ST1 data were used in this analysis.

Research and theoretical modeling have shown that the C-band data from SAR satellite sensors with steep incidence angles have potential to be used in conjunction with TM data for high accuracy mapping and fire scar monitoring (Bourgeau-Chavez *et al.* 1997, French *et al.* 1999). In fact, the two types of sensors compliment each other with SAR providing surface moisture information (Bourgeau-Chavez *et al.* 1997, 1999, French *et al.* 1996) and Landsat providing pre-burn vegetation type and density and post-fire vegetation regrowth patterns, temperature and burn severity information (Michalek *et al.* 2000). The Donnelly Flats fire scar presented in figure 1 burned 7600 ha in southeast Alaska in June of 1999. The Radarsat ST1 image (figure 1) was collected within days of the fire starting while the Landsat 7 image was collected one month later. It is apparent from these images that the burn extent may be mapped using either sensor, however, clouds and cloud shadows obstruct a portion of the fire in the Landsat 7 scene.

Although, clouds are not an issue with SAR data, the Alaska fire scar study (Bourgeau-Chavez *et al.* 1997) revealed three issues that are: (1) Mountains: fire scars were not visible in single date ERS imagery of steep mountains due to slope-induced radiometric effects of layover and radar shadowing. Compositing three dates of ERS imagery allows fire scars to be detected in mountains by cancelling out the

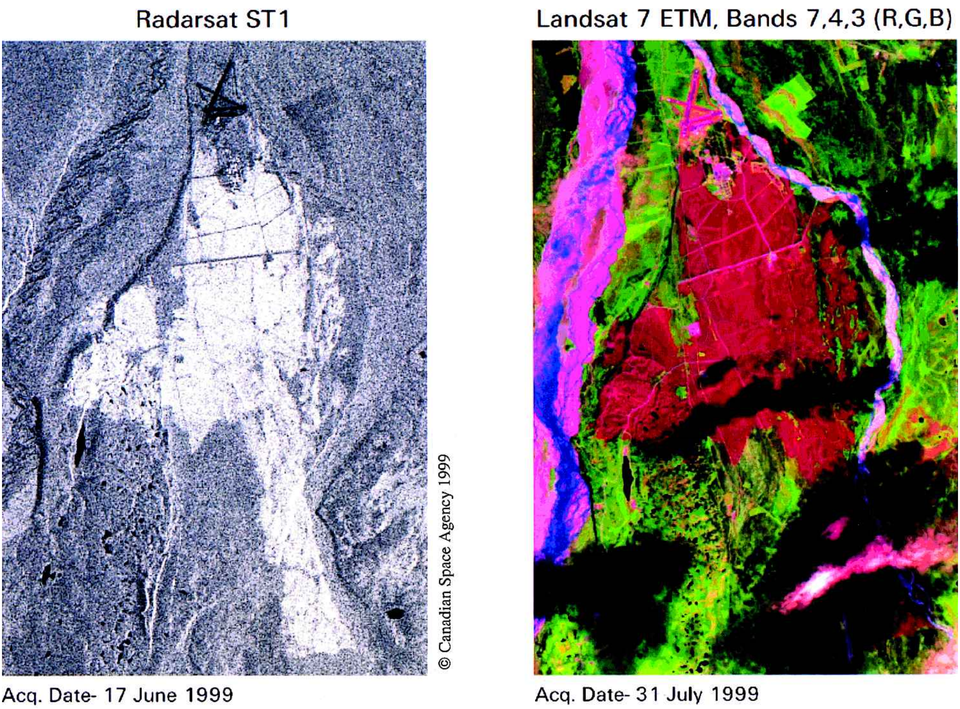

Figure 1. 1999 Donnelly Flats fire as it appears in Radarsat and Landsat Imagery. Fire scar boundaries are mappable from both sensors.

effects of local angles of incidence. Repeat ERS orbits have a slight shift in location causing the backscatter due to local angles of incidence to shift. (2) Wetlands: wetlands appear similar to fire scars and are often indistinguishable. Both have similar physiognomic conditions and both have wet soil conditions which causes enhanced backscatter. (3) Season: the enhanced brightness observed from fire scars is seasonal, with bright returns occurring only when the ground is wet (after rain events, after snow melt in spring and as ground water recharges in autumn). This change in brightness can change the shape of the fire scar.

Differences in factors such as regional climate, forest type or presence of permafrost may also have an effect on the characteristic SAR signature observed from burned areas. To investigate the effects of ecological variability in boreal regions on the ability to map fire scars with SAR, we evaluated data collected over several ecozones of Canada.

3. Ecology of Canada study areas

The North American boreal forest extends from Newfoundland to Alaska with the northern limit ranging from 68° N latitude in the Brooks Range of Alaska to 58° N latitude at the western edge of Hudson Bay (LaRoi 1967). The southern limit is less distinct and is highly dependent on precipitation and soil moisture (Hogg 1994, Fosberg *et al.* 1996). Local climatic conditions in boreal North America vary along gradients from north to south and east to west. From north to south, the temperatures generally increase. The climate ranges from dry with extreme annual temperature variations in the west to a relatively warmer, wetter, maritime climate of eastern Canada (Bonan and Shugart 1989). Fire is more frequent in drier regions of western Canada and Alaska where fire cycles average 50 to 100 years than in high moisture regions of eastern Canada where the fire cycle exceeds 200 years (Hienselman 1981). Variations in fire frequency are closely tied to variations in climate. Permafrost conditions also vary across the North American Boreal Forest, from continuous at the northern extremes to discontinuous throughout much of Alaska and Canada to permafrost free in the southern limits of the boreal forest. Generally from south to north there is a decline in the prominence of hardwoods, an increase in conifers and a decline in tree heights and stand densities (Rowe and Scotter 1973).

The varying ecological regions of Canada were mapped as ecozones by Wiken (1986) and the Alaska boreal forest was mapped as ecoregions by Gallant *et al.* (1995). These maps, which were both based on vegetation physiognomy, climate, physiography, soils, major wildlife populations and the distribution of water bodies, were merged by Bourgeau-Chavez *et al.* (2000) to obtain a map of the entire North American Boreal forest (figure 2).

To determine if fire scars can be detected and mapped in the ecologically varying boreal ecozones of Canada, three ERS study areas were chosen to capture the west to east differences. The study areas selected were in Northwest Territories (NWT), Ontario and Quebec (figure 2). To capture the ecological variation in the north–south direction, a sequence of three to eight adjacent north–south images were obtained from each study swath. Since all of the study swaths are in discontinuous permafrost zones and non-mountainous areas, a fourth location in southeastern Quebec covering

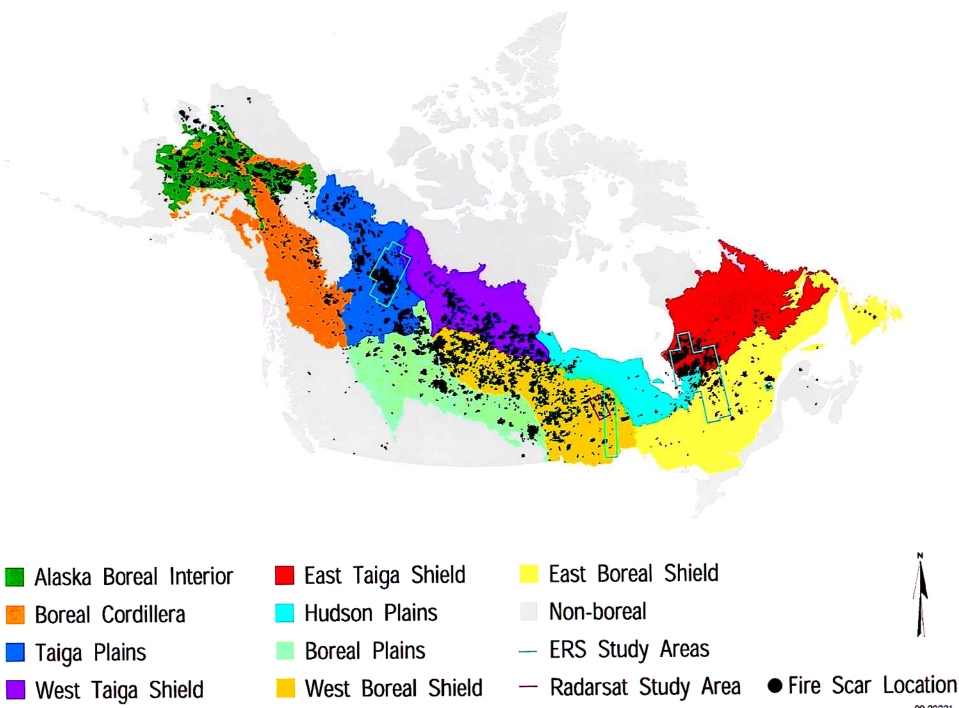

Figure 2. Site location map for Canada includes ecoregions (Bourgeau-Chavez *et al.* 2000) and fire scars from 1980 to 1997.

a single 1991 fire was included in the analysis because it is in a permafrost free zone and also in a mountainous area.

Each study area is described below, with ecozone descriptions based on a compilation of maps and ecosystem depictions from Rowe (1972), Wiken (1986), and Gallant *et al.* (1995).

3.1. *Northwest Territories study swath*

The NWT study area is located primarily in the Taiga Plains ecozone (figures 2 and 3). There are a large number of wetlands and organic soils in this region, second only to the Hudson Plains ecozone. Permafrost is extensive and perches water on the low-angled slopes resulting in extensive seasonally waterlogged soils. The climate is cold and semi-arid similar to Interior Alaska (table 1). Open canopied forests (taiga) dominate in the central portion of the Taiga Plains where our swath lies. The soils are thin, the climate unfavourable for forest growth and fire is frequent. A patchwork of wet areas intermixed with open dwarf stands dominated by black spruce typifies the landscape. White spruce occurs on well-drained sites with black spruce. Tamarack is increasingly associated with black spruce towards the north. Jack pine is common in the south-central area on sandy soils. The northeastern tip of our swath lies in the West Taiga Shield, but no fires occurred in this part of the study swath.

3.2. *Ontario study swath*

Our Ontario study swath is located primarily in the West Boreal Shield (figures 2 and 4). The northeastern tip extends into the Hudson Plains ecozone which is dominated by wetlands. In the northern portion of our Ontario Swath, glaciation was intense. The landscape is dominated by irregular relief with rocky ridges separating poorly drained depressions and many narrow lakes. The climatic conditions are less severe than the NWT study area (table 1) and thus allow reasonable tree growth and development of closed canopy forests. However, fire frequency is greater than in other regions (table 1). Black spruce is the predominant species on upland thin soils where it is associated with jack pine. Frequent fires have encouraged the spread of jack pine. On lowland, poorly drained areas black spruce again dominates and is associated with tamarack.

The southern portion of our Ontario swath ranges from a relatively level plateau-type to rolling topography to more rugged terrain. Glaciation covered much of the plateau-like region with calcareous drift. Extremely variable forests exist in this region from mixed types with lush shrub understory to floristically poor single dominant conifer forests. Black spruce occurs on shallow swamp land as well as on uplands. Mixtures of black spruce and jack pine are common on the uplands with white birch and trembling aspen associates. Warmer, more productive sites such as till uplands, deep valley soils and riverine and lacustrine areas support mixed forests of trembling aspen, white spruce, balsam fir, black spruce, balsam poplar and white birch with a well developed shrub understory. Some of the low areas have eastern white cedar associated with black spruce or tamarack. The dominance of deciduous species (white birch, trembling aspen and balsam poplar) increases southward. Bogs, muskegs and rock barrens are common.

3.3. *Quebec study swath*

Our Quebec study area extends from the southern portion of the East Taiga Shield into the north central portion of the East Boreal Shield and the eastern

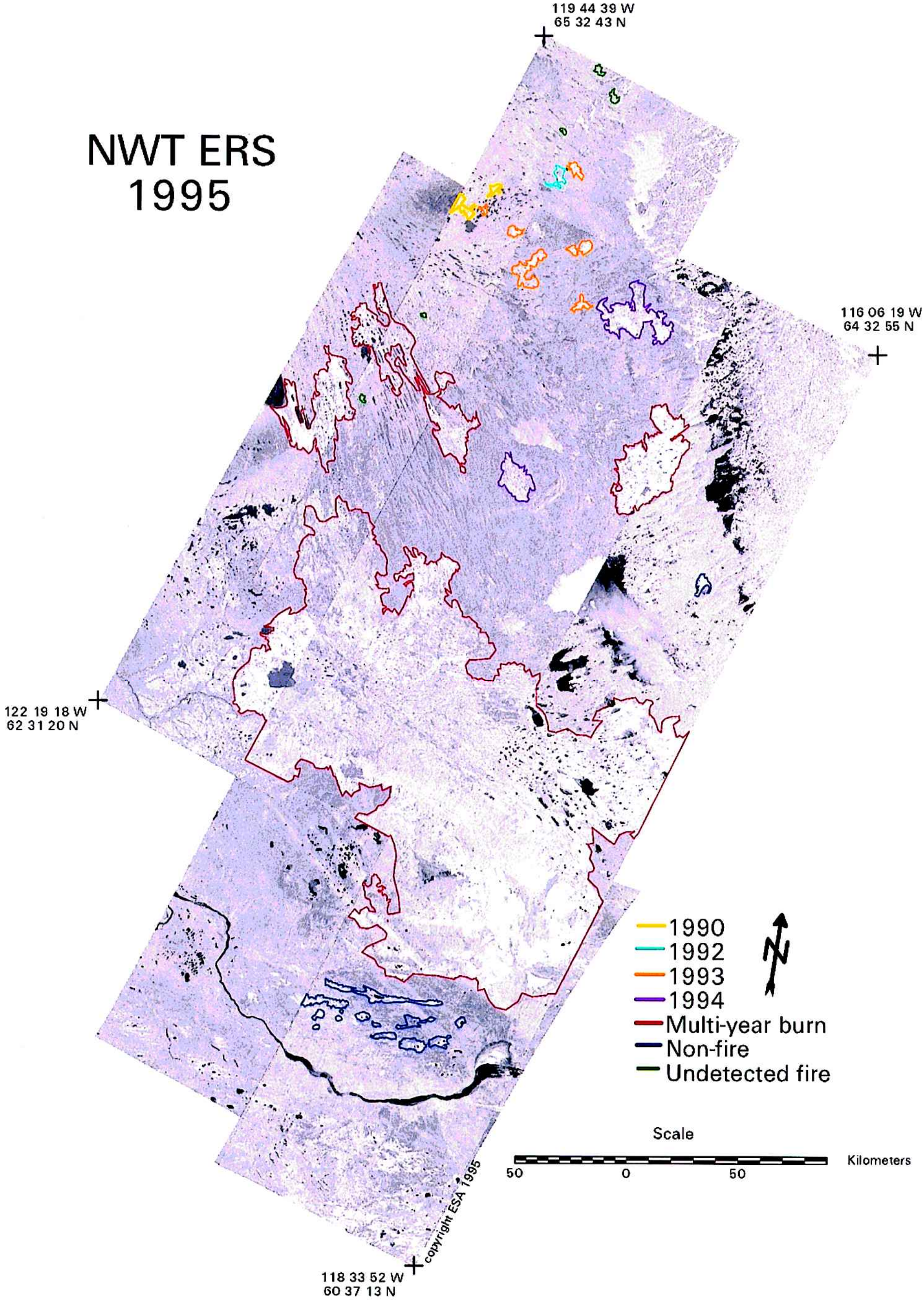

Figure 3. Mosaic of 17 ERS images from our NWT swath. Data are from 2 May, 5 July, 8 July, 31 August, 13 September and 16 September 1995.

portion of Hudson Plains (figures 2 and 5). Permafrost is common in this part of the East Taiga Shield. The topography is flat and rolling on acidic Precambrian rock. This area consists of a patchwork of lakes, rivers, bogs, swamps and muskeg

Table 1. Average climate and fire information for the study areas based on ecozone.

Boreal ecozone	Mean annual temperature (°C)	Mean annual precipitation (cm)	Fire cycle (years)
NWT/Taiga Plains	−10 to −1	20 to 50	179
Ontario/West Boreal Shield	−2 to 1.5	43 to 76	91
N. Quebec/East Taiga Shield	−5 to −1	50 to 80	324
S. Quebec/East Boreal Shield	−1 to 2	81 to 135	905
Hudson Plains	−4 to −2	40 to 80	506
Alaska Boreal Interior	−3.5	17 to 55	184

with upland forest and barrens. The forests have the characteristic open park-like form consisting of black spruce with lichen groundcover. Closed forest stands are rare but occur on midslopes and on shallow peatlands. Balsam fir is associated with black spruce and white spruce on upland well drained sites. Tamarack tends to frame the lakes and dominates the calcareous substrates, while jack pine appears in the southwest. Trembling aspen, balsam poplar and white birch are infrequent. The climate is more favourable and the fire cycle is longer than in NWT or Ontario (table 1). In the northern East Boreal Shield the terrain is nearly flat to rolling hills to mountainous. Although, no mountains exist in our study swath. Upland sites are dominated by balsam fir. Black spruce dominates on thin soils and on lowlands. White spruce occurs throughout the northern range. White birch is a common associate of the balsam fir and spruce. Trembling aspen and jack pine are secondary associates, occurring where fire is more frequent. In the Hudson Plains, the climate is similar to the Boreal Plains and Boreal Shield ecozones. However, the high water table, underlying permafrost and low relief result in a colder and wetter environment. Black spruce and Tamarack dominate this ecozone.

3.4. *Quebec Northshore fire*

The Northshore fire is located in the East Boreal Shield (figures 2 and 6). This site is an area absent of permafrost. The climate of the East Boreal Shield is characterized by more precipitation, longer growing seasons and less temperature extremes than our other test areas. Therefore, the climate is more favorable for forest growth. The southern portion of the East Boreal Shield is characterized by nearly level topography with occasional hills and ridges. The region is in the clay belt which is characterized by endless stretches of black spruce over lowland flats and gently rising uplands. Tamarack is scarcely found in this region. A spruce and eastern white cedar mix is more common. Better drained sites such as upland till sites and alluvium sites are dominated by hardwood and mixed stands of trembling aspen, balsam poplar, balsam fir, white spruce and black spruce. Jack pine occurs on dry sites and is associated with white birch. The dry sites with the poorest, rocky soils are dominated by jack pine mixed with black spruce. The fire cycle is long. The average fire size is small. The forests are generally closed crown.

The four study areas chosen for this analysis are quite varied, ranging from severe to more favourable climates, from high to low fire frequency, from lowlands to rocky ridges and low mountains, from discontinuous to permafrost free, from floristically poor to floristically richer and from open to closed canopy forests. The range of conditions represented by our test areas allow a thorough investigation of fire mapping abilities with SAR imagery in boreal Canada.

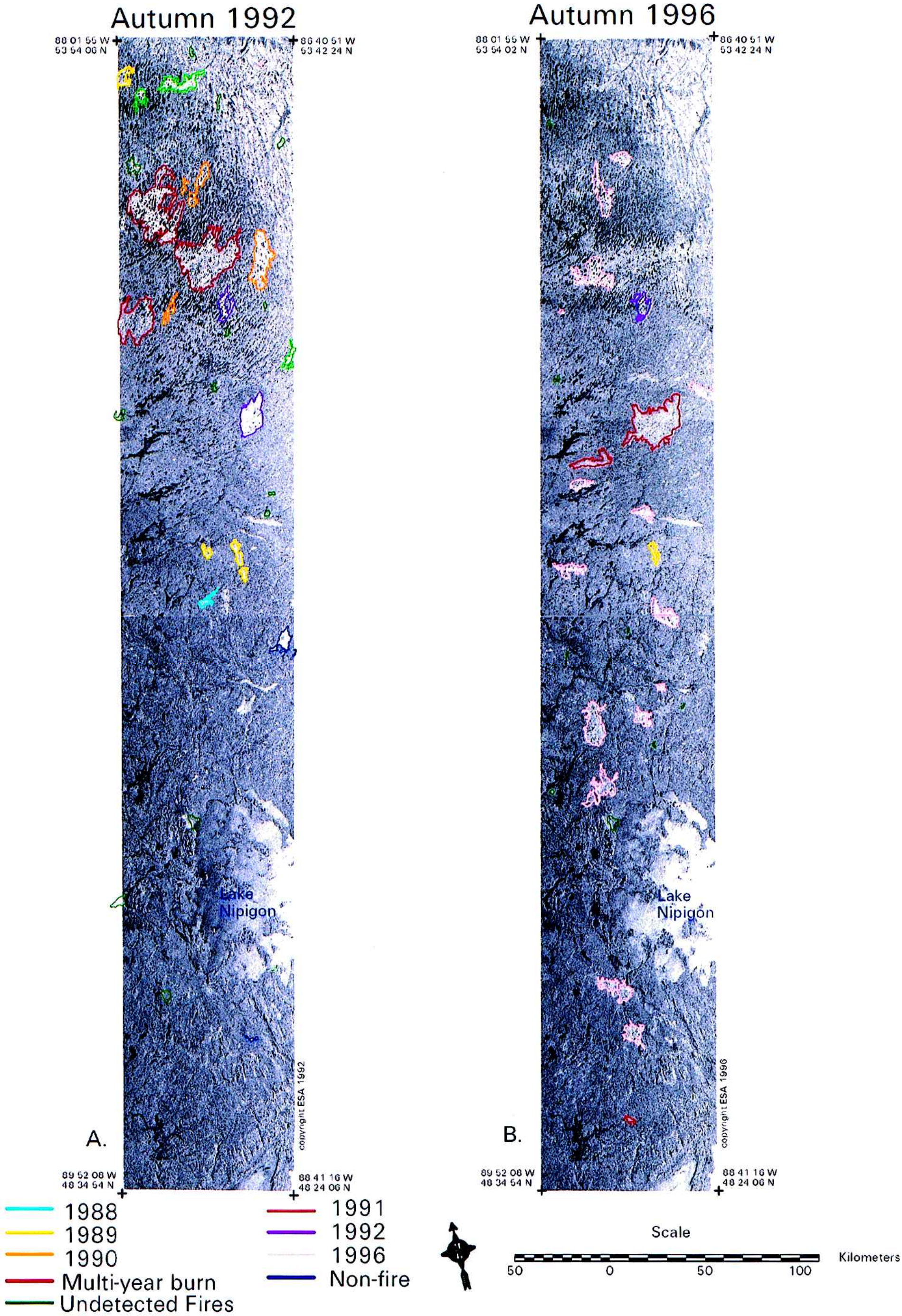

Figure 4. Mosaicked ERS imagery of our Ontario swath from: (a) 10 August and 14 September 92; (b) 8 August and 12 September 1996.

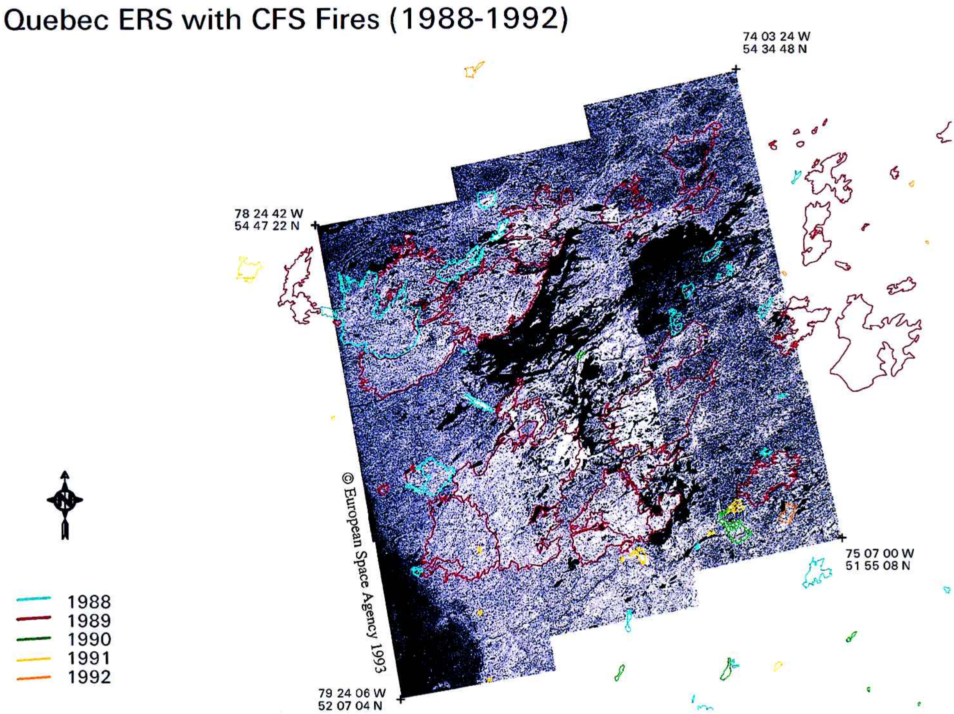

Figure 5. Mosaic of 9 ERS images from our Quebec study area from 9, 12 and 15 May 1993.

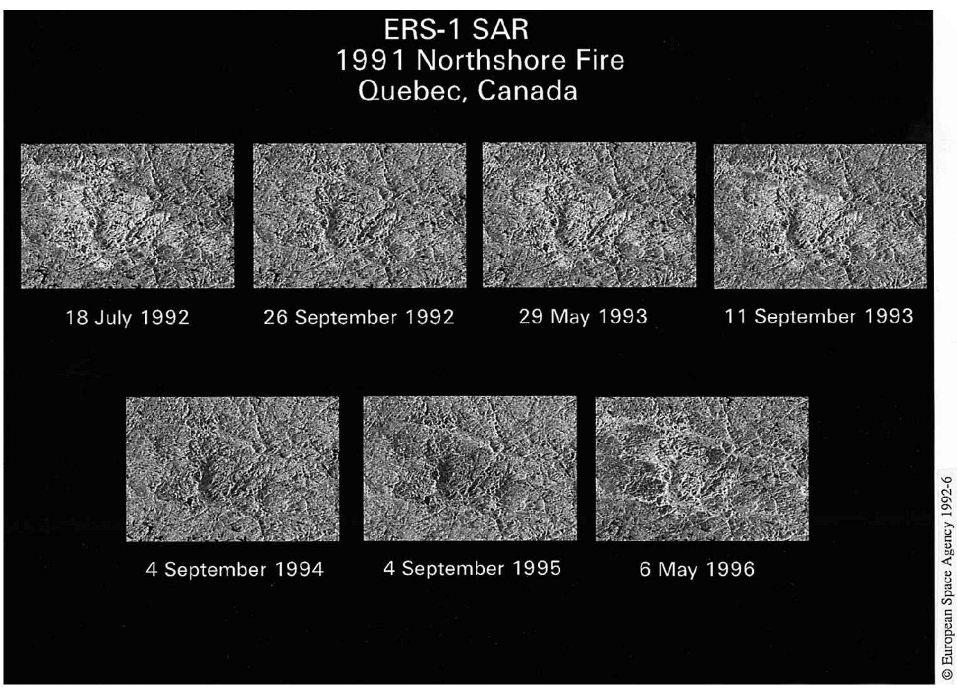

Figure 6. Time series of ERS imagery for the 1991 Northshore fire.

4. Fire scar detection and mapping in Canada

4.1. *Canada fire scar mapping procedure*

The approach used to map fire scars in Canada using ERS data was similar to that used for the 1997 Alaska study (Bourgeau-Chavez et al. 1997). The only difference was that for the present study we did not have *a priori* knowledge of fire scar locations and dates of burn. Thus, the areas we mapped in Canada were merely potential fire scars which needed to be verified with the Canadian Fire Service (CFS) database. The CFS fire location database was obtained in digital format after the ERS fire scar mapping was complete.

The procedure used for mapping fire scars in Canada consisted of four basic steps: (1) SAR data acquisition; (2) visual evaluation and rating of the data for fire scar mapping; (3) selection of the best rated images to be georeferenced and mosaicked; and (4) digitization of potential fire scar boundaries.

ERS data were ordered from the 1992 to 1996 growing seasons, with most of the data being ordered from the spring and autumn time frames because these were the times determined to be best for viewing fire scars using ERS imagery in Alaska (Bourgeau-Chavez *et al.* 1997). Data were ordered over regions which were known to have high fire occurrence based on discussions with CFS. We obtained a total of 157 ERS images from the three swath study areas.

The second step was to visually evaluate the imagery for fire scar mapping. Each image was given a rating of 1 to 5 for fire scar visibility, with 1 meaning no scars visible and 5 indicating a strong brightness contrast between potential fire scars and unburned forest. Using this system, imagery needed to have at least a rating of 3 for fire scars to be digitizable.

The third step was to select the best rated images of the three study areas for digitizing, mosaic these images and georeference them. ERS data from 1995 were selected to examine potential fire scars in the Northwest Territories (figure 3), 1992 and 1996 ERS data were selected over Ontario (figure 4), and 1993 ERS data were selected over Quebec (figure 5). Multiple images were mosaicked together, often from multiple dates, to get a complete study area for digitizing fire boundaries. All images were calibrated, however, radiometric correction of adjacent orbits was not necessary for detection and delineation of potential fire scars. Nine images of Quebec, 17 images of the NWT study area, and 6 images for each year (92 and 96) from Ontario were mosaicked. Imagery used for digitizing were from 10 August and 14 September of 1992 for the 1992 Ontario swath and from 8 August and 12 September 1996 for the 1996 Ontario swath. Quebec imagery were from 9, 12 and 15 May 1993 (figure 5). Data from 2 May, 5 July, 8 July, 31 August, 13 September and 16 September 1995 were used in the NWT study. For NWT, some areas only had a single image date available for our mosaic, and in some cases fires were less visible or not visible compared to other portions of the mosaic. These images were included in the mosaic to make it complete. The mosaicked image swaths were then imported into a geographic information system (GIS) and georeferenced.

The final step was to digitize the boundaries of the potential fire scars. This was done on the computer screen in a GIS. The SAR data have a pixel spacing of 12.5 m and resolution of 30 m. In most cases the best delineation of a fire scar boundary was not at a 1:1 scale but 1:2 or 1:3. In all cases the scars were digitized at a resolution of 50 m or better. The boundaries of all bright areas, which were larger than 10 pixels and which were not obviously wetlands or lakes on windy days, were digitized as potential fire scars in the Ontario and NWT image mosaics. Limited data were available over our Quebec study area (four image dates) and the contrast between potential fire scars and unburned forest was not as great as it was in the NWT or Ontario swaths. No Quebec image was given a rating higher than three for digitizing. Also, what appeared to be wetlands were confused with potential burn boundaries. Therefore, we chose not to digitize potential fire boundaries from the Quebec swath.

Next, the Canadian Fire Service (CFS) boundaries were obtained in GIS polygon format from 1980 to 1995 for NWT and Ontario, and through 1997 for Quebec. Additional point locations for 1996 fires in Ontario were also available. These points included attribute data containing burn area estimates. The CFS methods of mapping fire scars were based primarily on aircraft/helicopter reconnaissance, air photo interpretation and for NWT on Landsat interpretation (personal communication, Brian Stocks). An estimated 95% of the fire boundaries were mapped at a 1:250 000 scale. These are similar to the methods used by the Alaska Fire Service.

The CFS locations and burn areas were compared to those boundaries digitized from ERS data. Since only the fire start point locations were available for Ontario 1996 fires, actual ERS boundaries could not be assessed but estimated areas were compared.

4.2. *Results of Canada fire scar analysis*

A total of 78 potential fire scars were digitized from the NWT and Ontario (92 and 96) swaths. Fifty-seven of these boundaries represented actual fire scars. The 21 mismapped potential fire boundaries were all small areas representing 1.6% of the total area mapped with ERS. A comparison of these mis-mapped boundaries to topographic maps indicate that most of the incorrectly mapped areas are wetlands, but a few were small lakes. Wind causes the lakes to have rough surfaces and thus enhanced backscatter. Note, there were some small fire scars within our Canadian images, which were interpreted as wetlands and therefore not digitized. Further statistics are provided below by study area.

4.2.1. *1992 Ontario swath detection statistics*

Of the 27 potential fires digitized from 1992 ERS data of Ontario, 20 were actual fires. The mis-mapped fires represent 3% of the total area mapped using ERS. Of the 20 actual fires digitized from 1992 ERS data, two were on the image edge with most of these fires burning outside of the image swath. Thus our statistical analysis was conducted on the 18 complete boundaries. In comparing these 18 fire boundaries to CFS data for the 5 years prior to the image dates and the year the imagery were collected our fires actually represented 23 individual fires, some of which burned together and were not distinguishable (table 2).

Based on CFS records, 38 fires burned within our study swath between 87 and 92. Our 23 detected fires represent 61% of the individual fires which burned (table 2). However, these 23 fires represent a large portion (92%) of the area mapped by CFS. Since most of the fire scars undetected were from older fires, we reran the statistics for fires occurring 2 years prior to the image collection year and the year of image collection (years 1990 to 1992). This resulted in 71% detection of fire scars with those detected fire scars representing 96% of the total area mapped by CFS. Thus, we found greater accuracy in fire scar mapping with ERS within two years of the burn for the Ontario 1992 swath.

Table 2. ERS fire detection statistics for the 1992 ERS Ontario image swath. CFS fire statistics are used for comparison.

Year	Fires detected using ERS	CFS area of fires detected	Fires undetected using ERS	CFS area of fires undetected	Fires detected using ERS (%)	CFS area of fires detected (%)
1987	1	1399	0	0	100	100
1988	1	1153	4	5927	20	16
1989	6	20 484	5	6209	55	77
1990	8	104 768	3	2229	73	98
1991	4	70 169	2	2918	67	96
1992	3	42 337	1	2820	75	94
Total	23	240 308	15	20 102	61	92

4.2.2. *1996 Ontario swath detection statistics*

For the 1996 Ontario image swath, we mapped 20 potential fires, 1 of which was a seven-year old (1989) fire. There were no false alarms. The fire boundaries mapped in the 1996 ERS imagery represented 24 actual fires (table 3: note it does not include the 1989 fire), many of which burned together. We detected 23 out of 55 fires (51% detection) that burned between 1991 and 1996. These detected fires represent 61% of the burn area mapped by CFS. Statistics for the two years prior to image collection and the year of collection (years 1994–1996) show 62% detection of the fires representing 94% of the burn area as mapped by CFS. For the 1996 Ontario image swath, we did substantially better mapping fires within 2 years of the burn.

4.2.3. *1995 Northwest Territories detection statistics*

Using the 1995 NWT imagery we mapped 31 potential fire boundaries. Of these 31 boundaries 17 represented burn areas, the other 14 boundaries were false alarms. The 14 false alarms represent only 2% of the total area mapped with ERS and they were all wetlands. The 17 ERS mapped boundaries corresponded to 32 burns mapped by CFS from 1989 to 1995 (table 4). We were unable to detect 6 fires with ERS (not including 2 large 1995 fires which burned in areas of our ERS swath which had image dates prior to the 2 fires burning (May and July). For the 7 years of fires (1989 to 1995) we detected 84% of the fires representing 99% of the area burned as mapped by CFS. Statistics for years 1993 to 1995 show detection of 95% of the fires representing 99.98% of the area burned. Although statistics show better detection

Table 3. ERS fire detection and CFS area statistics for the 1996 ERS Ontario Image swath. Note that one 1989 fire was also detected.

Year	Fires detected using ERS	CFS area of fires detected	Fires undetected using ERS	CFS area of fires undetected	Fires detected using ERS (%)	CFS area of fires detected (%)
1991	0	0	6	74 086	0	0
1992	2	26 207	2	18 950	50	58
1993	0	0	1	412	0	0
1994	2	17 877	1	547	67	97
1995	2	7747	5	1052	29	88
1996	17	110 034	7	7521	71	94
Total	23	161 864	22	102 567	51	61

Table 4. ERS fire detection statistics based on CFS fire locations and areas for 1995 NWT Image Swath.

Year	Fires detected using ERS	CFS area of fires detected	Fires undetected using ERS	CFS area of fires undetected	Fires detected using ERS (%)	CFS area of fires detected (%)
1989	6	20 840	4	4387	60	83
1990	3	34 224	1	376	75	99
1991	2	6255	0	0	100	100
1992	1	744	0	0	100	100
1993	9	36 244	1	481	90	99
1994	9	884 752	0	0	100	100
1995	2	1 153 219	0*	0*	100*	100*
Total	32	2 136 278	6*	5245*	84*	99.8*

* *Note*: these numbers do not include 2 large 1995 fires within the swath area because our ERS data from 1995 were collected prior to the 2 fires.

within 2 years of the burns, as was the case for Ontario, detection was very high for NWT (84%) up to 6 years post burn.

4.3. *Fire scar detection: comparison of 1997 Alaska study to the Canada study*

For comparison of our study to the fire scar study conducted on 1992 Alaska ERS imagery of 1990 and 1991 fires (the 2 years prior to image collection not including the year of image collection (Bourgeau-Chavez *et al.* 1997)), we ran statistics on fires detected from 1990 and 1991 for the 1992 Ontario swath, for 1994 and 1995 fires for the 1996 Ontario swath, and for 1993 and 1994 fires for the 1995 NWT swath. For the Alaska study, 54% of the fires were detected with ERS representing 68% of the total burn area mapped by ASF in the years 1990 and 1991 (table 5). Using AVHRR data, 70% of the fires were detected representing 93% of the burn area mapped by ASF. For the Canada study, 71% of the 1990–1991 fire scars were detected in the 1992 Ontario swath with those fires representing 97% of the total burn area mapped by CFS (table 5); 40% of the 1994–1995 fires were detected in the 1996 Ontario swath and those fires represented 94% of the total burn area mapped by CFS; and 95% of fires were detected in the 1995 NWT swath representing 99.9% of the total CFS area burned.

A ratio of the sensor mapped burn areas to fire service records was calculated for fires detected by each sensor (table 5). These results show ERS estimates

Table 5. Statistics for the 2 years prior to image collection dates (for ERS). For Ontario 1992–1990 and 1991 fire detection, Ontario 1996–1994 and 1995 fire detection, NWT 1996–1994 and 1995 fire detection, Alaska 1992–1990 and 1991 fire detection.

Region/years(s)/sensor	Detection of individual fires (%)	CFS or AFS area burned represented by those fires detected (%)	Sensor area/forest service area for sensor detected fires
Ontario 92 ERS	71	97	0.98
Ontario 96 ERS	40	94	1.05
NWT 95 ERS	95	99.9	1.06
Alaska 92 ERS	54	68	0.94
Alaska 90–92 AVHRR	70	93	0.82

(94–106%) as improved over AVHRR (82%). Furthermore, although our ERS mapping procedure for Canada was conducted blindly, statistics show fire scar detection was better in Canada than in Alaska. One reason that we may have had difficulty in detecting some fires in our Alaska test area (the interior) versus our Canada test areas could be the fact that the Alaska test area contains many more mountainous regions. Although, a multi-temporal image compositing procedure was developed to overcome the detectability problem in mountains, the process is time consuming and was not implemented across the state due to program constraints.

4.4. *Accuracy of ERS area estimates for the Canadian study sites*

For a detailed analysis of area estimates, we compared each fire boundary mapped using ERS to the corresponding CFS boundary. The ERS versus CFS area estimates are presented in tables 6, 7, and 8, for the Ontario 1992, Ontario 1996, and NWT swaths, respectively. For the 1992 Ontario swath we mapped 241 791 ha with ERS which was 101% of the CFS mapped area (table 6). This estimate had an rms error of 1676 ha (7%). The 1996 Ontario Swath comparison to CFS boundaries (table 7) resulted in an overall ERS area of 169 828 hectares compared to the CFS area of 164 834. The ERS area was 103% of the CFS area. Our estimates had an rms error of 2648 ha (32%). For the 1995 NWT swath we mapped 2 574 284 ha which was

Table 6. 1996 Ontario Swath ERS fire boundary to CFS fire boundary comparison. Rms error = 2648 or 32%. Note that the 1996 fire boundaries are based on area estimates reported by CFS and not digitized boundaries. Areas for all other years are based on digitized boundaries.

Polygon number	Fire name(s)	Years burned	ERS area	CFS area	ERS/CFS
1	NIP19	1996	3887	4100	0.95
2	NIP66	1996	10 602	8020	1.32
3	NIP82	1996	14 995	24 000	0.62
4	GER18	1992	7268	4951	1.47
5	NIP81	1996	326	600	0.54
6	NIP68	1996	6360	8650	0.74
7	GER17, GER26, NIP33	1992, 1994, 1995	43 815	40 094	1.09
8	GER62, NIP35	1994, 1995	8021	6786	1.18
9	NIP22	1996	3277	2800	1.17
10	NIP43	1996	3983	4000	1.00
11	GER36	1989	2429	2970	0.82
12	NIP37	1996	5521	5175	1.07
13&14	NIP76	1996	8340	8364	1.00
15	THU83	1996	1051	881	1.19
16	THU65	1996	16 388	15 967	1.03
17	THU36	1996	4282	3645	1.17
18	THU74	1996	11 762	6833	1.72
19	THU38	1996	9722	8900	1.09
20	NIP63, NIP46	1996	6891	7300	0.94
21	THU45	1996	912	800	1.14
Summary			169 828	164 834	1.03

Table 7. 1992 Ontario ERS Swath fire boundaries compared to CFS records. Rms error of 1676 or 7%.

Fire number	Fire name(s)	Years burned	ERS area	CFS area	ERS/CFS
1	GER80	1989	4926	6104	0.81
2	GER26	1991	10 300	9265	1.11
3	GER84	1991	3394	3560	0.95
4	GER44, noname	1990, 1990	7206	6320	1.14
5	GER35	1990	1324	1324	1.00
6	GER33, GER50	1990, 1991	57 572	60 738	0.95
8	GER29/37	1990	21 408	21 792	0.98
9	GER21, GER28/45	1987, 1990	59 937	55 434	1.08
11	GER93/94, GER39, GER14	1989, 1990, 1992	30 121	29 865	1.01
12	GER18	1992	6486	4951	1.31
13	GER38	1990	2654	4838	0.55
14	GER63	1991	3147	2094	1.50
15	GER17	1992	18 571	21 256	0.87
16	GER36	1989	3229	2970	1.09
17	GER34	1989	1640	1805	0.91
18	GER35	1989	1544	1081	1.43
19	GER21	1988	1962	1153	1.70
20	GER27	1989	6369	5760	1.11
Summary			241 791	240 308	1.01

Table 8. NWT 1996 swath ERS boundaries compared to CFS fire boundaries. RMS error of 82 401 ha or 35%.

Polygon number	Years burned	ERS area	CFS area	ERS/CFS
2	1993	2586	1762	1.47
3	1992	3255	744	4.38
4	1990	1367	267	5.12
5	1990	3786	4378	0.86
6	1993	764	252	3.03
7	1995	2322	1338	1.74
8	1993	2099	1686	1.24
9	1993	3952	3291	1.20
10	1993	10 185	3017	3.38
11	1994	39 298	37 642	1.04
12	1993, 1994	61615	22 612	2.72
13	1993	2315	1997	1.16
14	1993, 1994	82 185	81 157	1.01
15	1991, 1994	43 755	34 592	1.26
16	1989, 1994	90 280	54 613	1.65
17	1994	19 632	17 422	1.13
18	1989, 1990, 1991, 1993, 1994, 1995	2 204 888	1 869 506	1.18
Summary		2 574 284	2 136 278	1.21

121% of the CFS mapped area of 2 136 278 ha (table 7). Our estimates had an rms error of 82 401 ha or 35%. These compare to the Alaska study (Bourgeau-Chavez *et al.*, 1997) of 40 fires resulting in 978 373 ha mapped using ERS which was 96% of the 1 022 348 ha mapped by AFS with an rms error of 7666 (20%). Using AVHRR 82% of the AFS area was mapped (839 300 ha) with an rms error of 10 138 ha (34%).

Some of the variability in area estimates can be explained by the timing of the image collection date or aircraft reconnaissance relative to the stage of the fire. If the fire was still burning when it was mapped, then the mapped area would have been underestimated, either by our ERS method or by fire service methods. The largest difference between ERS and CFS area estimates (121%) was with the NWT comparison. When the CFS boundaries for NWT are visually compared to ERS, Landsat TM or AVHRR imagery collected 1–2 years post-burn, it is apparent that more area burned than was mapped in the records we obtained from CFS. Some fires must have continued to burn after the boundaries were mapped by CFS.

There may also be problems in mapping fires with ERS which are adjacent to wetlands. In some cases wetlands adjacent to fire scars may be mapped as part of the fire. The season in which the ERS imagery were collected could also affect the area mapped since fire scar appearance does vary with season.

4.5. *Temporal variations in regional imagery of Canada*

Seasonal imagery from several individual fire scars were obtained over several years to determine how temporal conditions affect fire scar visibility. For comparison, seasonal imagery of four fires in Alaska are included in the analysis. In Alaska, imagery were obtained of fires known as the 1990 Tok fire, the 1994 Hajdukovich Creek fire, the 1990 Bettles fire and the 1990 Kotzebue Sound tundra fire. In Canada, imagery of the 1991 Northshore fire in Quebec, 1996 fires of Ontario, and 1994 and 1995 Horn Plateau fires in NWT were obtained. In all cases, visibility of fire scars varied temporally. With the scars being bright after snowmelt in the spring, fading as the ground dries out and becoming bright again during rainfall events. The fire scars completely fade during dry periods and in some cases become darker than surrounding unburned vegetation. This assessment is based on coincident weather data for some of the test areas (weather data were not available for all sites) and also based on our intense studies of Alaska fires and how their appearance has varied with rainfall patterns (Bourgeau-Chavez *et al.* 1997).

A time series of images of the 1991 Northshore fire in southeastern Quebec is shown in figure 6. This fire occurred in a hilly area. It is noticeable from this figure that the fire scar visibility and apparent shape of the scar varies with season. Rain occurred the days of the ERS overpasses on 18 July 1992, 29 May 1993 and 11 September 1993. Images from these dates show the scar as brighter than surrounding unburned forest. Heavy rain occurred from mid April to 2 May 1996 and on the ERS collection date of 6 May 1996, the fire scar appears bright. Little to no rain occurred in the weeks prior to the 26 September 1992, 4 September 1994 and 4 September 1995 image collection dates and the fire scar is barely noticeable or not noticeable at all on these dates. This fire is visible in this low hills region for 5 years post-burn. 1997 and 1998 Radarsat imagery from May, June and July show the bright signature to have dissipated while new fires have become apparent.

While fire scar visibility in Alaska was determined to be best in spring just after snowmelt and second best in early autumn, for our Ontario sites the data we obtained show fire scars better in early autumn than spring. This may be due to different weather patterns in Ontario, or it may be due to chance rain events and data availability. The NWT and Quebec data showed similar seasonal trends of fire scar visibility to that of Alaska.

4.6. *Geophysical and ecological conditions that may influence fire scar detection and mapping in Canada*

Although fire scar mapping with SAR data in NWT and Ontario proved feasible, the SAR data obtained over our Quebec study swath area were insufficient for detection and mapping. Fire scars were noticeable in the ERS imagery once the Quebec CFS burn boundaries were overlaid (figure 5). However, it would be difficult to map fires blindly in Quebec using the ERS data available due to the low contrast in burned versus unburned forests. This low contrast may be due to the type of fires which occurred in this area (high versus low severity) and thus the rate of regrowth (in combination with favorable climate conditions). Or it may be due to less of an increase in ground moisture post-burn. Since few fire scars burned in the 1990–1992 period and our SAR data are from 1992 and 1993, we cannot form any conclusions about the ability or inability to map fires in the Quebec swath study area. The problem could simply be due to lack of timely data and decreased viewing time in this more favorable climate.

In the southern most portion of the ERS Quebec study swath, wetlands are prevalent and confuse our detection of fire scars even further. This lower portion of the Quebec image mosaic (figure 5) is in the Hudson Plains ecozone and northern portion of the East Boreal Shield. Although, we did not have sufficient Quebec data to try compositing several dates of imagery to increase differentiation of wetlands from fire scars, we were able to try this technique in other wetland areas.

Much of the zone where fires occur in Canada is interspersed with wetlands, but some areas caused more difficulties than others in SAR interpretation. The top of the Ontario swath is in the Hudson Plains Ecozone and is dominated by wetlands. Three dates of imagery (06 July, 10 August and 14 September 1992) from this area were composited in an attempt to better differentiate wetlands from fire scars (figure 7). The grayscale imagery shows how similar the fire scars appear in brightness to the wetlands (located in the upper right corner). The three date ERS image shows the wetlands (light green) can be well differentiated from the fire scars (pinkish) and the unburned upland forest (dark green) and lakes/ponds (blue). This compositing technique was less successful in a three date composite of Radarsat imagery collected over Ontario (Radarsat Ontario study area figure 2). The Radarsat images of Ontario contain a significant number of wetlands in the lower portion of the scene (figure 8). Thus, three images were composited from wet and dry conditions to help distinguish wetlands from fire scars (figure 8). This resulted in making the fire scars outside wetland areas better distinguished, but made discriminating wetlands from fire scars (both appear blue and cyan) more difficult. The difference between this Radarsat composite and the Hudson Plains Ontario ERS composite is that for the latter, wetlands were relatively unchanged in the three images while the fire scars changed in brightness between dates. For the Radarsat composite, both the fire scars and wetlands change in image brightness on the three dates. The wetlands of the Radarsat composite seem to be seasonally flooded and thus strongly affected by precipitation patterns as are the fire scars. In a case such as this, optical data, such as Landsat TM, is needed for distinguishing fire scars from wetlands (figure 8).

5. Fire scar detection in Russia

The overall goal of this project was to determine if boreal fire scars can be mapped on a global basis using SAR satellite data. Using a data grant for a small number of ERS scenes collected over central Russia, we conducted a pilot study to

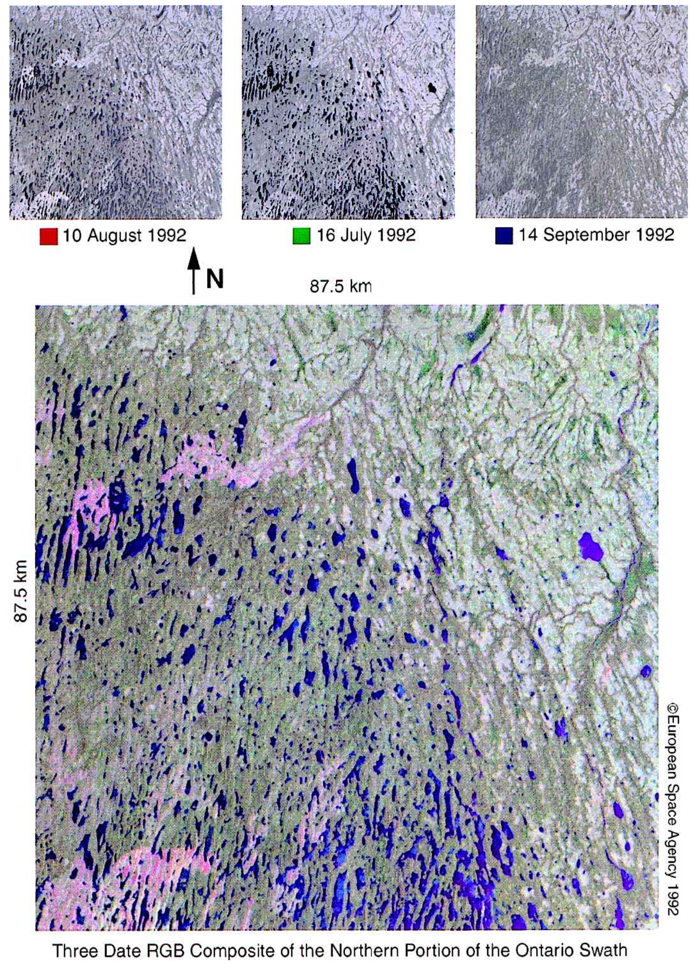

Figure 7. Three date RGB ERS image composite of the Northern portion of the Ontario swath.

determine if fire scars can be mapped with C-band SAR data in Russia as they are in Canada and Alaska.

Unfortunately, fire scars are not routinely mapped and recorded in Russia as they are in North America. Therefore, information on where fires occur in Russia is limited. Due to low knowledge of burn areas and data constraints, we focused our efforts on the Krasnayarsk region in central Russia where we have a coincident study. In our data archive, we had a Russian MSU-SK image that was collected over central Russia on 28 June 1997 and we knew it contained at least one recent fire (1996). The MSU-SK imagery is collected using a multi-spectral scanner onboard the Russian Resurs-O platform. The data are of moderate resolution (170 m in VIS) with spectral ranges of: 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–1.1 and 10.4–12.6 nm. The swath width is 600 km with a repeat cycle of 3–5 days. Using the MSU-SK data we conducted an unsupervised classification in ERDAS image using all channels to find potential fires. We then extracted the classes which distinguished this one 1996 fire

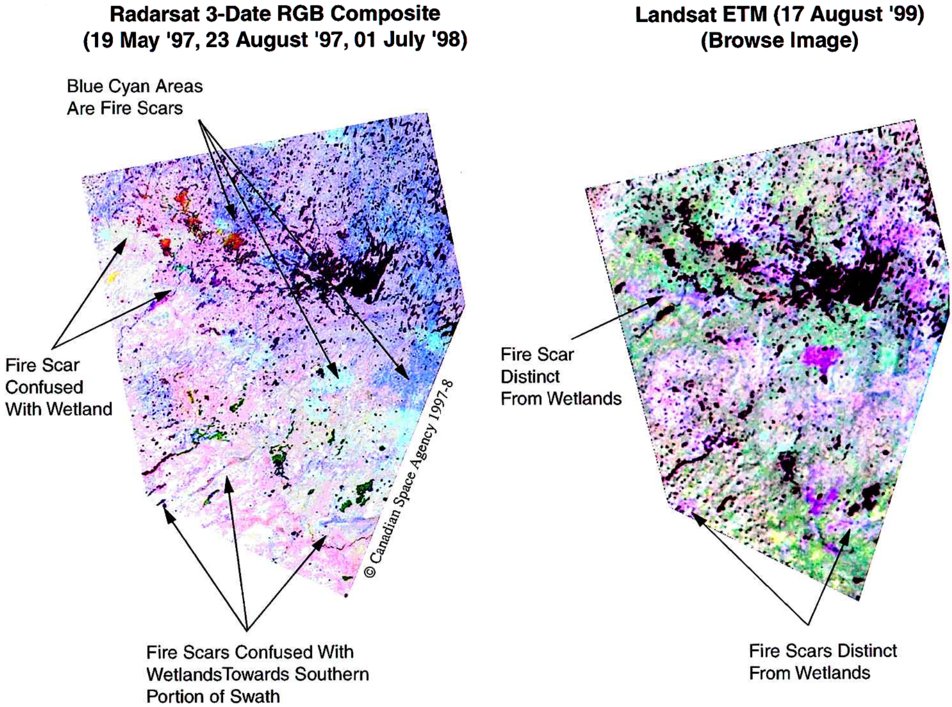

Figure 8. Three date RGB Radarsat image composite of North Ontario compared to Landsat TM imagery of the same area.

from other features. The result was overlaid on the greyscale image of band 3 (figure 9).

Using the potential fire scar classified MSU-SK image as reference, we obtained ERS data over a subset of the potential fire sites. The ERS imagery showed bright signatures in May 1998 corresponding to the potential fire areas identified in the MSU-SK imagery (figure 9) along with some other small regions which were potential fires not identified with the MSU-SK. The potential fire scar boundaries were digitized from the ERS imagery. We noticed that one area in the ERS image appeared to have been clearcut and may not be a burn scar (figure 9).

To verify the boundaries delineated on the ERS image, a Russian colleague (S. Kharuk, pers. comm.) conducted a field check. Our colleague confirmed the delineated sites as burn scars from 1996 and 1997. Also, the one site predicted as a cut site based on the signature observed in the ERS imagery, was determined to be a clearcut area that burned in 1996.

Additional imagery from the region supported observation of seasonal signatures of the 1996–1997 fires throughout the growing season. Data were acquired from June 1998, August 1999 and September 1999. The fire scars were detectable in June 1998 but not in the August or September 1999 imagery. The conditions may have been frozen during the September 1999 data collection which would explain the lack of fire scar brightness. No other data were available over this site but we hope to observe it again in the growing season of 2000.

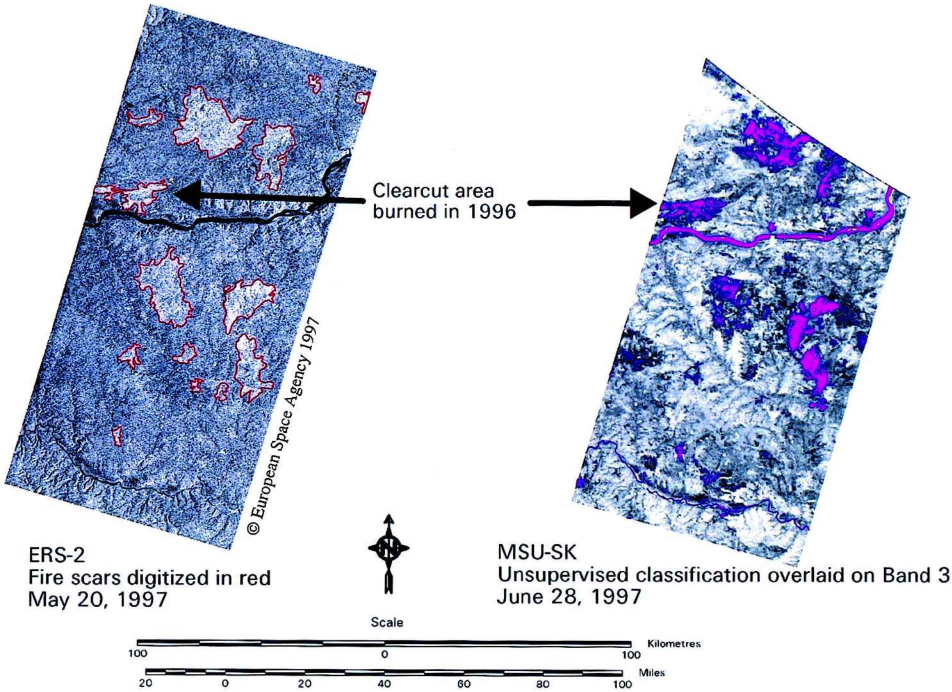

Figure 9. MSU-SK unsupervised classification of Krasnoyarsk Region Biryusa River Basin in Central Russia and ERS imagery of the same area with digitized fire boundaries.

6. Discussion and conclusions

In this study we have demonstrated that fire scars are mappable in a range of boreal ecosystems across the globe using C-band SAR imagery. However, further research is needed in some areas. For the Ontario and NWT study sites, we found that it is feasible to detect fire scars with SAR alone and no *a priori* knowledge of fire scar location (62 to 92% detectability of 94 to 99.98% of fires within 2 years of burn). Once detected, fire boundaries can be mapped using SAR data with high accuracy (overestimation of 1 to 3% for Ontario, 21% for NWT). Note for NWT current multi-spectral and SAR data indicate more area burned than was mapped in field records we obtained from CFS. While the statistics calculated for SAR-derived fire scar boundaries mapped over NWT and Ontario were favourable, our data availability for Quebec was limited and our analysis was inconclusive. Further evaluation of SAR data collected over our Quebec study swath is needed before any conclusions may be drawn.

We found the length of viewing time of fire scars with ERS or Radarsat data is between 3 and 7 years in Alaska and Canada. This time is comparable to that of Landsat TM and SPOT. Fire scar visibility appears to generally decrease in viewing time from western to eastern Canada with the Quebec swath having the shortest time for viewing fire scars, 3–4 years. The Northshore fire, in southeastern Quebec, was visible for at least 5 years post-burn. However, it is in an ecologically and topographically different region than the Quebec study swath.

Seasonal variations in fire scar visibility occur globally, with the best season for fire scar viewing being either spring or early autumn depending on the site. Most sites we have evaluated show spring after snowmelt as being the best time for viewing fire scars with SAR data, however, the data we had for Ontario, showed autumn as the best time with autumn imagery displaying the greatest contrast between fire scars and unburned forest.

The major problem encountered in mapping fires in Canada with SAR was distinguishing fires from wetlands. This is more of a problem when the landscape is dotted with wetlands as is true in parts of all three of our study areas. Multi-temporal SAR data sometimes allows better distinction between fire scars and wetlands. But a combination of SAR and multi-spectral data will likely be necessary in wetland regions for complete fire scar monitoring and mapping.

For boreal regions like Russia, which are not well mapped by fire service agencies, a method was described of using lower resolution optical data with a large footprint to find potential fire scars and following up with selective C-band SAR coverage. The C-band data may be used both to verify the potential fire scars and map them with greater precision. Further evaluation of SAR data over Russia is also needed since we were limited to two years of data over one geographic area.

Although a manual interpretation method was used in this study to map fire scars from SAR imagery, the technique can be automated. Image analysis techniques have been developed for edge detection and feature extraction which could be easily adapted for automated mapping of fire scars.

An improved method for fire scar mapping and monitoring might be to use a combination of SAR and multi-spectral data. The long viewing time with SAR and TM data allows for monitoring of fire scars over several years. Since global boreal forest mapping with ERS or Radarsat would be costly and time consuming, an improved method for fire scar mapping and monitoring would be to use multi-spectral data with a large footprint to detect fires and then use finer resolution SAR in combination with finer resolution multi-spectral data to map selected fire boundaries with great detail and to monitor ecologic condition over time.

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