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Assessing spatial and temporal variations in surface soil moisture in fire-disturbed black spruce forests in Interior Alaska using spaceborne synthetic aperture radar imagery — Implications for post-fire tree recruitment

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Abstract

Recent studies [Bourgeau-Chavez, L.L., Kasischke, E.S., Riordan, K., Brunzell, S.M., Nolan, M., Hyer, E.J., Slawski, J.J., Medvecz, M., Walters, T., and Ames, S. (in press). Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery. *Int. J. Rem. Sens.*] demonstrated that ERS SAR imagery can be used to estimate surface soil moisture in recently burned black spruce forests in interior Alaska. We used this relationship to analyze the intra- and inter-annual variations surface soil moisture in two burned black spruce forests in Alaska. The results of this study showed distinct seasonal and longer-term trends in soil moisture in the two sites, with the site that burned in 1994 having higher soil moisture than the site that burned in 1999. The differences in soil moisture between the sites were related to landscape-scale variations in soil drainage and seasonal permafrost thawing. Finally, we found that the 1999 site had dramatically lower levels of tree recruitment (both aspen and black spruce) than the 1994 site as a result of the lower soil moisture levels. These results show that the ERS SAR and similar systems can be used to monitor a site characteristic that is important to understanding changes in the ecosystem community structure that result from variations in climate and the fire regime in the boreal region.

Keywords: ERS SAR; Boreal forest; Fires; Soil moisture; Tree regeneration

1. Introduction

The 2004 and 2005 Alaskan fire seasons represented this state's highest and third highest burned area since 1950 (2.71 and 1.78×10^6 ha, respectively), with most of the fire-affected areas located in the interior boreal forest region. Alaska's burned area during the decade between 1996 and 2005 (7.58×10^6 ha) represents 1/3 of the total burned area recorded since 1950. The burned area recorded over the past decade is equivalent to 17% of the boreal forest region in Interior Alaska, while that in 2004 and 2005 represents 10%. The increased fire activity in Alaska is consistent with the longer-term trends throughout the entire North American boreal forest region, where the average annual burned area has nearly tripled, from an average of 1.11×10^6 ha during the 1960s to 3.04×10^6 ha during the 2000s, most likely as the result of climate warming (Gillett et al., 2004; Kasischke & Turetsky, 2006).

The terrestrial ecosystems of the boreal region are a significant reservoir of carbon because of the development of deep organic layers in peatlands occupying poorly-drained sites and the presence of permafrost under many forests (Gorham, 1991; Harden et al., 2000; Kasischke & Stocks, 2000). In addition, variations in the consumption of surface organic layers during fires in permafrost forests directly affects the patterns of post-fire successions (Landhaeusser & Wein, 1993; Johnstone & Kasischke, 2005; Johnstone & Chapin, 2006) and post-fire soil respiration (Bergner et al., 2004). Monitoring and understanding

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the impacts of climate change and the recent increases in burned area on these ecosystems presents an important challenge to the scientific community (Kasischke et al., 1995a; Turetsky et al., 2002, 2004).

Because of the remote location of the boreal forest and the large extent of fires that are common to this region, satellite-remote sensing systems are becoming an increasingly important tool for monitoring this biome's land surface. Using coarse resolution (8 by 8 km) data from the AVHRR system, numerous scientists have noted an overall increase in vegetation greenness in the boreal region during the 1980s and 1990s (Myneni et al., 1997; Tucker et al., 2001; Zhou et al., 2001). While the observed increases in vegetation greenness are consistent with the warming that has occurred in this region (Lucht et al., 2002), other sources have been found, including earlier melting of snow (Dye & Tucker, 2003) and regeneration of vegetation following fires (Kasischke & French, 1997; Hicke et al., 2003). In addition, inter-annual variations in NDVI greenness have shown to be correlated with large-scale atmospheric circulation, such as the Arctic Oscillation (Vicente-Serrano et al., 2006). Throughout the Russian boreal forest, satellite observations provide the only means for reliable burned area information (Sukhinin et al., 2004). Satellite imagery have been also been demonstrated to be useful for mapping relative patterns of damage resulting from fires (Michalek et al., 2000; Isaev et al., 2002; Epting et al., 2005).

French et al. (1996) and Bourgeau-Chavez et al. (2007) showed that the backscatter measurements collected by space-borne synthetic aperture radar (SAR) systems can be used to estimate soil moisture in recently burned forests, a capability that may prove to be important in understanding patterns of post-fire vegetation recovery in boreal forests. Here we present the results of a study with the goal of using ERS-1 and ERS-2 C-band (5.7 cm wavelength) SAR data to: (1) analyze the spatial and temporal variations patterns of soil moisture in recently disturbed black spruce forests; (2) relate these patterns to variations in climate and site characteristics; and (3) explore the relations between soil moisture patterns and post-fire tree recruitment.

2. Background

Research has shown that changes to boreal forest ecosystems caused by fires result in unique signatures on spaceborne imaging radar imagery collected over Alaska, Canada, and Russia (Kasischke et al., 1992, 1994; Bourgeau-Chavez et al., 1997; 2002; French et al., 1999). Burn-scar signatures were much more apparent on C-band (5.7 cm wavelength) imagery collected by the ERS-1 synthetic aperture radar (SAR) than on L-band (24 cm wavelength) SAR imagery collected by the JERS-1 SAR (Bourgeau-Chavez et al., 1997). Burn-scar signatures have been detected on both VV (ERS-1/2) and HH (Radarsat) polarization imagery, but the strength of the signature on HH-polarized imagery diminishes as incidence angle increases (French et al., 1999).

A study of ERS-1 SAR imagery collected over a 100 × 600 km area in east-central Alaska by Bourgeau-Chavez et al. (1997) showed that burn-related signatures were not present for all fires. The study site contained a number of recent (within 2 years) and older burn scars (up to 13 years old). For the 103 fire events that occurred within two years previous to the SAR data collections, Bourgeau-Chavez et al. (1997) were able to identify unique signatures in only 56 events, whereas 70 of these events were detected on visible/near infrared spectrum imagery collected by the Advanced Very High Resolution Radiometer (AVHRR) system. Detection of burn-scar signatures from fires occurring in mountainous terrains was difficult. Bourgeau-Chavez et al. (1997) found, however, that (1) burned area estimates for the 103 fire events could be significantly improved by combining the information provided by both sensors, (2) early-spring ERS SAR imagery was better for detection of burn scars, and (3) older burn scars were less detectable than ones that were less than a few years old.

These initial studies demonstrated that factors controlling the presence/absence of burn-scar signatures on satellite SAR imagery are complex. Fire significantly alters the composition and characteristics of vegetation, which in turn, alters the scattering of the microwave electromagnetic energy being transmitted/received by satellite and airborne SAR systems. While the loss of living biomass as a result of fire results in a decrease in radar backscatter, the loss of branches and foliage and the desiccation of tree boles reduce canopy attenuation and make it possible to directly sense variations in soil moisture from direct backscatter from the ground surface (Kasischke et al., 1995b; French et al., 1996; Bourgeau-Chavez et al., 2007). In boreal forests, increases in soil moisture occur immediately after snowmelt in the spring and after periods of significant rainfall, which in turn, result in radar image intensities that can be 3 to 5 dB higher (during the first several years after a fire) than those found in adjacent unburned forests (Kasischke et al., 1994). Because of seasonal variations in soil moisture, there are seasonal patterns in ERS radar backscatter over burn scars as well (Bourgeau-Chavez et al., 1997). In burn-scars that were 2 to 5 years old, French et al. (1996) found a significant, positive linear correlation between moisture in the top 10 cm of the soil surface and ERS radar backscatter.

A number of studies have explored using of spaceborne SARs for monitoring variations in soil moisture in vegetated surfaces via direct observations and theoretical microwave scattering models. While there is a general consensus that in the absence of vegetation and when surface roughness remains constant, SARs can be used to estimate soil moisture (French et al., 1996; Shoshony et al., 2000; Moran et al., 2000; Oldak et al., 2003), the degree to which biomass limits soil moisture detection by SARs is less clear. Studies in agricultural areas note that the sensitivity of SAR to variations in soil moisture ceases in areas of high crop or grassland biomass; however, these studies do not report the exact levels of biomass when the sensitivity to variations in soil moisture sensitivity ceases (Moran et al., 2000; Oldak et al., 2003). Kasischke et al. (2003) showed a strong linear correlation between ERS SAR backscatter and soil moisture in Florida marl prairie sites where aboveground biomass averaged 320 g m^{-2} (range of 200 to 420 m^{-2}). In this study, the range of ERS backscatter under the observed biomass conditions and moisture conditions (7 dB) was greater than predicted by a theoretical microwave scattering model (MIMICS) (2.5 dB). In sites where shrubs are clumped and not evenly distributed across a landscape, enough open space exists whereby increases in biomass may not be limiting to SAR detection of variations in soil moisture. Using a theoretical microwave scattering model, Wang et al. (2000) showed that increases in clumped shrub biomass: (a) did not result in significant increases in ERS C-band SAR backscatter for biomass increases from 0 to 300 g m^{-2}; and (b) the increases in biomass did not affect the sensitivity of the ERS SAR to variations in soil moisture. The conditions being modeling by Wang et al. (2000) simulated those found in burned black spruce forests in Alaska, where much of the initial vegetation regrowth occurs in willow clumps.

Bourgeau-Chavez et al. (2007) studied soil moisture/SAR backscatter relationships using ERS SAR data collected between 2000 and 2004 in sites established in burns (that occurred in 1994 and 1999) in Interior Alaska. This study found positive linear correlations between backscatter and soil moisture in sites where vegetation biomass ranged between 50 and 300 g m^{-2}, and the majority of this biomass occurred in willow clumps or aspen seedlings that were unevenly distributed across the site. In this study, the slope of the relationship between backscatter and soil moisture varied as a function of the depth of the organic/mineral soil profile remaining after the fire. Using independent sites for validation, Bourgeau-Chavez et al. (2007) demonstrated an rms error for radar-predicted soil volumetric moisture of backscatter of 3.6% absolute, which was within ±7.6% (relative) of the *in situ* observations. Since the sites studied by Bourgeau-Chavez et al. (2007) had low levels of biomass, and that much of this biomass occurred in willow clumps, the sensitivity of the ERS SAR backscatter to variations in soil moisture is consistent with the findings of Wang et al. (2000) and Kasischke et al. (2003).

Recent research has shown that the depth of the ground-layer organic mat remaining after fire in Alaskan black spruce forests is highly variable. This variation exists between different fire events as well as within single events (Kasischke et al., 2000a,b; Michalek et al., 2000; Kasischke & Johnstone, 2005). In turn, the variations in organic layer depth after fire influence post-fire patterns of surface soil temperature and moisture, which control patterns of secondary succession (Kasischke et al., 2000c, Johnstone & Kasischke, 2005; Johnstone & Chapin, 2006) and soil respiration (O'Neill et al., 2002, 2003, 2006; Bergner et al., 2004). Thus, the ability to monitor post-fire patterns of soil moisture in boreal forests provides an important tool for studying an environmental characteristic that controls a range of ecosystem processes.

3. Methods

Seasonal and inter-annual variations in ERS radar backscatter and SAR-predicted soil moisture from two burned forests in Interior Alaska were analyzed for this study. The ERS SAR data collected during this study spanned a time period of 5 to 10 years after the fire event. The two fires were located on different landscape features, which in turn, influenced pre-fire forest type, permafrost development, and mineral soil moisture. One fire event burned during two distinct time periods, resulting in variations in the depth of the surface organic layer remaining after the fire. The other fire event burned over several different landscape features, which in turn controlled forest type, permafrost development, soil moisture, and depth of organic soil after the fire.

In this study, we examined variations in SAR backscatter/soil moisture as a function of time during the growing season, time since the burn, depth of remaining organic soil, and site drainage characteristics. In addition, we collected and obtained data on recruitment of tree seedlings as a function of burn depth in the two fire events to investigate how soil moisture affects post-fire tree regeneration.

3.1. Study region and test sites

The sites used in this study were in the Delta Junction region of Alaska, in recently burned black spruce forests located on a relatively flat plain between the Alaska Range and the Tanana River (Fig. 1). This region contained four recent burns (1956, 1987, 1994, and 1999) as well as mature stands that originated from fires that occurred between 1700 and 1915 (Nettleton-Hollingsworth, 2004; Kasischke & Johnstone, 2005). The presence of the Alaska and Richardson Highways and secondary roads and trails facilitated access to the study sites. The sites used in this study have also been used in a range of scientific research (French et al., 1996, 1999; Kasischke & French, 1997; Michalek et al., 2000; Wang et al., 2000; Rahn et al., 2002; O'Neill et al., 2003; Chambers & Chapin, 2003; Chambers et al., 2005; Bergner et al., 2004; Hyer & Goetz, 2004; Treseder et al., 2004; Johnstone, 2005; Johnstone & Kasischke, 2005; Kasischke & Johnstone, 2005; Liu et al., 2005).

For this study, we focused on the 1994 and 1999 fire events (Fig. 1). Analysis of Landsat imagery collected in 1986 shows that both of these fires burned primarily in black spruce forests that are common in interior Alaska. The first event burned in a 9077 ha fire located ~50 km east of Delta Junction during June–August of 1994 near Hajdukovich Creek (referred to as the HC94 burn). This fire started at the base of the Alaskan range in June and initially burned until mid-July (area a in Fig. 1). The fire became active again in the middle of August, and burned until early September (area b Fig. 1) (Michalek et al., 2000). The center of the second fire event was located 15 km south of Delta Junction near Donnelly Flats (referred to as the DF99 burn) and burned 7579 ha between 11 and 18 June 1999.

The topography of the HC94 burn event is flat (slope <1%), with elevations of 480 m near the base of the Alaska Range that gradually slopes 370 m at the northern most portion of the HC04 burn near the Alaska Highway. The topography of the DF99 burn event is more complex, as its geomorphology was affected by a glacial end moraine located to the northeast of the study region. Overall, this area slopes gently from an elevation of 560 m at the southern edge to 410 m at the northern edge. The center part of the DF99 burn (area A in Fig. 1) is a flat to gently

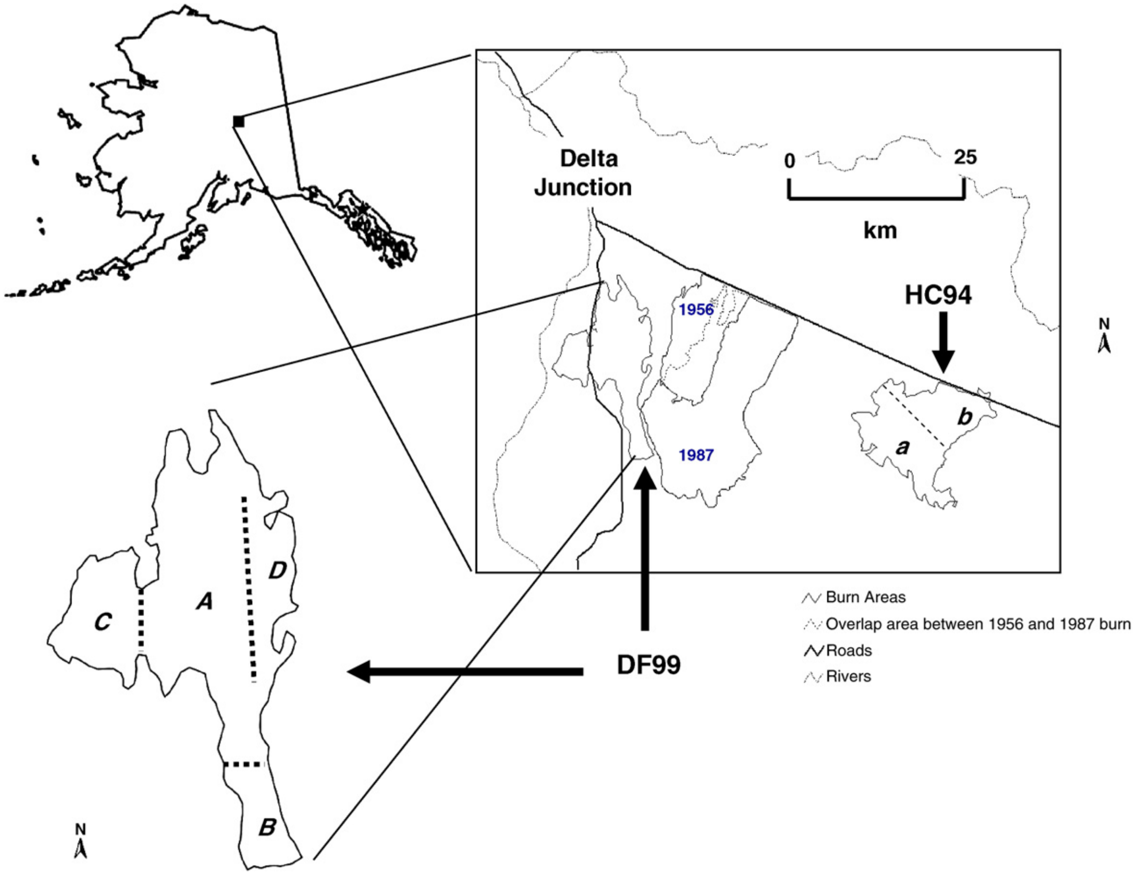

Fig. 1. Location of burned areas in the region used in this research. The individual study sites were located within the 1994 Hajdukovich Creek (HC94) and 1999 Donnelly Flats (DF99) fire events.

rolling till plain. There is a 10 to 15 m tall escarpment between the areas marked A and B, with the latter being lower in elevation and consisting of a flat plain. Area *C* contains a series of kames and kettle ponds and lakes. Finally, area D gently slopes downward to the east to a poorly-drained floodplain adjacent to Jarvis Creek.

Schoephorster (1973) mapped and described the soils of the entire study region, which are part of the Volkmar–Nenana–Richardson Association, and described as nearly level to moderately sloping, well-drained silt loams over gravel or sand located on outwash plains or terraces. They were formed from several sources, including: (a) outwash from the retreating glaciers that were present during the Pleistocene, most likely the Donnelly Glaciation; (b) outwash from streams originating in the Alaska Range; and (c) airborne deposition of silt (loess) from the 500 to 2000 m wide Gerstle and Big Delta River floodplains (the Gerstle River is located immediately to the east of the HC94 burn, while the Big Delta River lies 2 km to the west of the DF99 burn). Because of the presence of permafrost in the upper 1 to 2 m of the soil profile in mature black spruce stands in this region, soils in these stands were classified as Gelisols.

The nearest climate station was in Big Delta, located approximately 30 km to the west of the center of the study region. Average annual temperature at this station was −2.2 °C, with the coldest month being January (−19.6 °C) and the warmest July (15.6 °C). The average annual precipitation was 29.2 cm, with three quarters of this amount occurring during the growing season (May to September). Maximum snow depth in February averaged 25 cm. While the average growing-season (May to August) precipitation was 17% below the long-term average of 22.2 cm for the 10 years of this study (1995–2004), only 4 of 10 years experienced below average precipitation. The average growing season temperature was 0.9 °C lower than the long-term average, with only 2 years experiencing above average temperatures.

The two sites experienced important differences in local microclimate. The DF99 site is located at the end of a broad valley. As a result of this location, this area experienced periodic high wind events originating in the Isabel Pass of the Alaskan Range that resulted in higher rates of surface evaporation and increased rates of plant transpiration. All other factors being equal, we would expect these winds to cause lower soil moisture in the DF99 sites compared to the HC94 sites.

3.2. Field observations

Our research focused on study sites located within two different regions in each burn (areas a and b in the HC94 burn and areas A and B within the DF99 burn in Fig. 1) as well as unburned stands adjacent to or within the boundaries of the two burns. To minimize the effects of variations on topography on

ERS SAR backscatter, sites were selected where the slope <1%. The unburned stands in this study were classified into one of three different black spruce forest communities by Kasischke and Johnstone (2005) based on the categories defined by Nettleton-Hollingsworth (2004). Characteristics from specific burned and unburned forest stands (collected by a number of researchers) were compiled for this study, as follows:

(a) Measurements of the organic layer depth in 19 sites in the HC94 burn and 9 sites in the DF99 burn were from Kasischke and Johnstone (2005).
(b) Canopy tree characteristics (stem density, average diameter, year of previous burn) of unburned black spruce stands adjacent to or within the burned (8 for the HC94 burn and 6 for the DF99 burn) were from Kasischke and Johnstone (2005).
(c) Depth of the silt layer above gravel in the mineral soil for 19 burned stands in the HC94 burn and 6 unburned stands adjacent to or with the DF99 burn were from (Kasischke & Johnstone, 2005).
(d) Data to estimate pre-fire black spruce stand density from 5 burned stands in the DF99 burn (3 in area A and 2 in area B) were collected in the summer of 2005 using a modified version of the approach developed by Johnstone and Kasischke (2005) (3 sample transects were used instead of 5).
(e) Data to estimate tree seedling recruitment data (for aspen and black spruce) as well as willow biomass data for the HC94 burn were from Johnstone and Kasischke (2005). These data were collected during the fall of 2002 and summer of 2003.
(f) Data to estimate tree seedling recruitment data in 5 burned stands in the DF99 burn (3 in area A and 2 in area B) were collected in the summer of 2005 using a modified version of the approach developed by Johnstone and Kasischke (2005) (3 sample transects were used instead of 5).
(g) Permafrost depth and mineral soil moisture data in the unburned stands adjacent to the HC94 and DF99 burns were from data collected in late August 2003 by Kasischke and Johnstone (2005).

In addition to the above data collected from the two study areas, we also used end-of-season depth-to-permafrost data collected and archived through the Bonanza Creek Experimental Forest (BCEF) Long Term Ecological Research site. After a June 1983 forest fire that occurred within the BCEF boundaries, a study was initiated on the effects of fire on the depth to permafrost at the end of the growing season. Using a metal probe, the depth to permafrost has been measured in late September/early October at ten points along transects located within the burn and in an unburned stand adjacent to the burn annually since 1983. The depth of the organic layer in the unburned area averaged 19.1 ± 0.3 cm (mean ± standard error), compared to 7.1 cm ± 0.1 cm in the burned area. For this study, we used depth to permafrost data collected from 1983 to 1996 (L. Viereck, unpublished data available through the BCEF LTER data archive).

3.3. Analysis of ERS SAR data

As a result of previous research (French et al., 1999; Wang et al., 2000), we began requesting ERS SAR image collections over the HC94 burn in the spring of 1995. Research involving ERS SAR at the DF99 site began in the summer of 2000. We requested image acquisitions from the Alaska SAR Facility (ASF) on all dates that the ERS-1 and ERS-2 SARs were able to view the study sites between May and September of each year. In some cases, conflicting data requests precluded data collection. In two years, data were requested and collected during mid-April. We were able to compile an archive of ERS SAR imagery for the HC94 burn area covering the period of 1995 to 2004, with the exceptions of 1998 (when no imagery was collected) and 1999 (imagery was available for only part of this year). We obtained ERS SAR imagery for the DF99 burn scar for the period of 2000 to 2004. These collections resulted in 70 ERS SAR images, with an average of 8 observations per year for the HC94 burn and 7 observations per year for the DF99 burn.

The data used in this study were collected by the ERS-1 SAR for 1995–1997 and by the ERS-2 SAR for 1998–2004 and acquired through a direct downlink maintained by the ASF, where the data were processed and calibrated. The ERS-1 sensors have been found to be quite stable, and the uncertainties associated with calibration are on the order of ±0.2 dB relative and ±1.0 dB absolute (Meadows et al., 2004). The calibration procedures used by ASF include geometric and sensor corrections (range falloff, adjustments for variations in the antenna gain pattern, and adjustments for system gain). Absolute calibration of the ERS SAR data used within-scene, precision calibration targets. The ERS-2 SAR has not been stable, with Meadows et al. (2004) reporting a known loss of gain over time. Although information concerning the change in gain over time is provided in the replica pulse power and should be accounted for during calibration at the processing facility, ASF did not use the pulse replica power in calibration. In our study, we normalized our ERS-2 SAR data during post-processing using published pulse replica power information (Meadows et al., 2004). Finally, the ERS SAR data were geo-referenced within a geographic information system using reference points that were identified within each image.

Using road intersections as ground-control points, the different ERS SAR images were georeferenced using a second order polynomial georectification with bilinear interpolation to 12.5 by 12.5 m pixels. In the HC94 burned area, we extracted ERS backscatter values from 200 by 200 m areas (16 by 16 pixels) centered on the locations of test sites where field data were collected for ecological studies (Johnstone & Kasischke, 2005; Kasischke & Johnstone, 2005). Given the 25 m (range) by 22 m (azimuth) ground resolution of the ERS SAR, the sample area resulted in a 90% confidence interval of ±1.3 dB (Ulaby et al., 1982). We extracted an average backscatter value for a large (1000 by 1000 m or 80 by 80 pixels) patch of unburned black spruce adjacent to the HC94 burn. In the DF99 burn, we extracted radar backscatter from 1000 by 1000 m areas located in areas A and B, which encompassed sites used for collection of soil moisture (see Bourgeau-Chavez et al., 2007) and from an unburned forest stand just to the south of area A. This sample area resulted in a 90% confidence interval of ±0.30 dB.

3.4. Relating ERS radar backscatter to soil moisture

During the summers of 2001 to 2004, studies were conducted to relate ERS radar backscatter levels to volumetric soil moisture measurements using field data collected within the HC94 and DF99 burns. Details of the field sampling approach used in this study can be found in Bourgeau-Chavez et al. (2007). In summary, in the Bourgeau-Chavez et al. (2007) study, volumetric moisture was measured in the top 6 cm of the ground surface (either the remaining surface organic layer, mineral soil, or a combination of the two) was measured with a Campbell Scientific Hydrosense (CS620) instrument that measures soil moisture using time-delay reflectrometry. Measurements were obtained at various test sites on the same day as the ERS SAR imagery. Forty soil moisture measurements were collected at 8 permanent grid locations within each site by inserting the 12 cm long probes at a 45% angle into the surface in order to measure the top 6 cm of the surface profile. Five soil moisture measurements were collected at random distances and directions at each grid point. The manufacturer's coefficients were used to estimate the moisture where the ground layer was mineral soil. For sites that contained surface organic matter, the Hydrosense measurements were calibrated by collecting samples of surface organic matter and varying the moisture content under laboratory conditions (L. Bourgeau-Chavez, unpublished data). In the field, data were collected in sites with shallow (<2.5 cm), moderate (2.5 to 7.5 cm) and deep (>7.5 cm) layers of surface organic matter. The results showed that both the range and median volumetric soil moistures derived from the field samples decreased as the depth of the organic layer increased (Table 1). Finally, Bourgeau-Chavez et al. (2007) found significant statistical correlations between ERS SAR backscatter and volumetric soil moisture, and generated equations to estimate soil moisture for three surface organic layer ranges based upon using ERS and field data collected on several different dates (Table 1). The equations in Table 1 were used to estimate soil moisture for different years based on average ERS backscatter values.

Table 1
The range in volumetric soil moisture content observed in the HC94 and DF99 study sites, and regression equation coefficients for estimating volumetric soil moisture content (VMC), where VMC $=a\sigma+b$, with σ being the ERS backscatter

Organic layer depth range (cm)	Volumetric soil moisture content (%)			Regression equation			
	Minimum	Maximum	Median	a	b	r^2	s.e.
<2.5 cm	8	61	28	6.4327	99.802	0.59	3.43
2.5 to 7.5 cm	8	38	22	2.4624	49.344	0.82	9.25
>7.5 cm	10	28	16	1.7854	39.461	0.69	3.84

All r^2 values were significant at $p<0.001$. Equations and data are from Bourgeau-Chavez et al. (in press).

4. Results and discussion

The ERS SAR imagery in Fig. 2 illustrates the levels of spatial and temporal variations that occur in radar backscatter over burned forests during the first year after a fire. In Section 4.1, we conclude that variations in biomass associated with vegetation regrowth have a relative small impact on the ERS SAR backscatter in our study sites. In Section 4.2, we present and analyze the seasonal and inter-annual trends in radar backscatter, which are then used in Section 4.3 to analyze variations in soil moisture in the two study sites. Finally, in Section 4.4, we relate the patterns of SAR observed soil moisture to post-fire tree recruitment in the two study sites.

4.1. Effects of variations in post-fire vegetation characteristics on ERS radar backscatter

The vegetation regrowth occurring in the black spruce forest stands in the study sites would be expected to affect ERS SAR backscatter in two ways if all other site characteristics (such as soil moisture) remain constant. First, over a number of years, there would be a small increase in average ERS SAR backscatter as a result of increased direct and multi-path scattering from woody and non-woody biomass. Second, over the course of a growing season, we would expect the seasonal variations in herbaceous biomass to decrease backscatter because this biomass attenuates the radar backscatter that results from direct scattering from the soil surface as well as direct and multi-path scattering from the stems of shrubs and trees (see, e.g., Fig. 2 in Kasischke et al., 2003).

Overall, the levels of woody plant biomass in the HC94 stands during the ninth year after the fire (2003) were low, less than 300 g m^{-2} with the levels of aspen, spruce biomass, and total biomass varying as a function the depth of the organic layer remaining after the fire (Fig. 3, Table 2). While the biomass estimates in Table 2 do not include all the aboveground biomass present at a site, previous studies showed that non-willow, understory vegetation in black spruce mature black spruce stands was about 1/3 of the total (Kasischke et al., 2000a). Overall, the non-willow and aspen biomass in our sites was low, and we estimate the total biomass in the unburned stands was at most 400 g m^{-2}. The data of Johnstone and Kasischke (2005) showed that the willow and aspen foliage was 22% of the total. Using these data, we estimate the maximum seasonal level in non-woody biomass in the HC94 stands ranged between 50 g m^{-2} in stands with deeper organic layers (>2.5 cm) to 100 g m^{-2} in stands with shallow organic layers (<2.5 cm). While we did not measure biomass levels in the DF99 burns, our field observations showed that willow was absent from the shallower organic layer sites and present in very low levels in the deep organic layer sites. Regrowth of shrubs and other vegetation were generally low in these sites as well. Given the low level of tree recruitment in these sites compared to the HC94 sites (Table 2), we estimate total biomass in all DF99 sites was <50 g m^{-2}, with non-woody biomass <20 g m^{-2}.

Previous studies by Harrell et al. (1995) investigated the relationship between aboveground woody biomass and ERS-1

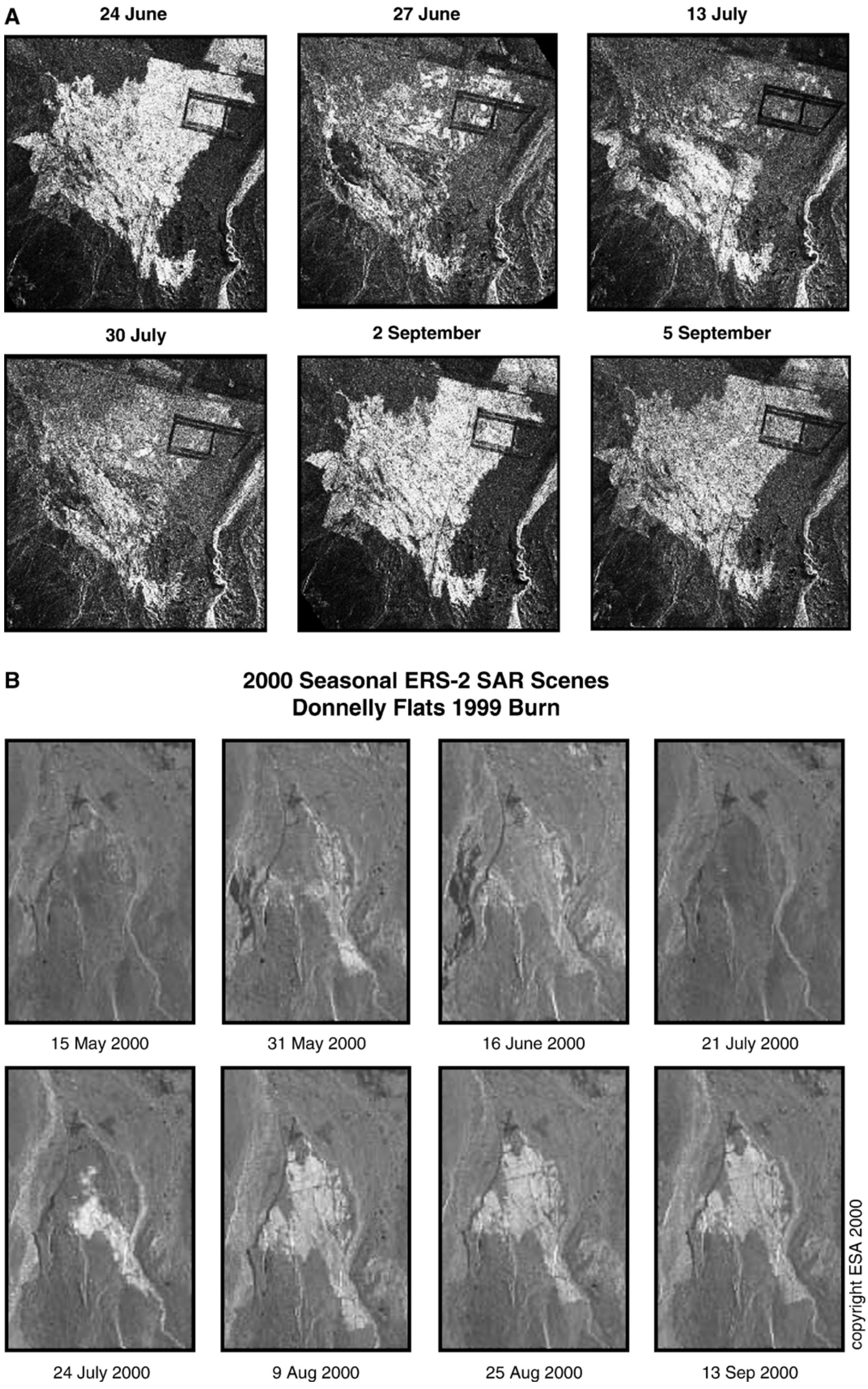

Fig. 2. ERS-1 and ERS-2 SAR imagery collected over the (A) HC94 and (B) DF99 fire events during the first year after the fires took place (e.g., 1995 for the HC94 fire and 2000 for the DF99 fire).

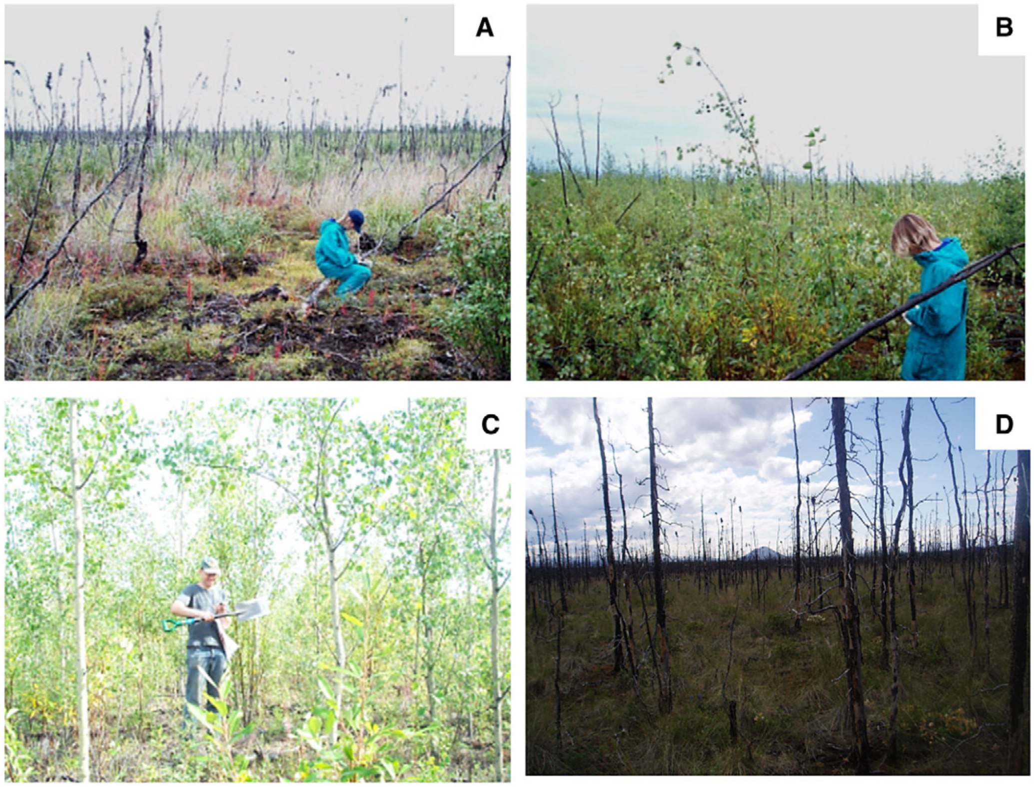

Fig. 3. Photographs of vegetation regrowth in sites dominated by black spruce prior to the fire. (A) 2003 photograph in the HC94 burn in an area with a 15 cm deep organic layer; (B) 2003 photograph in the HC94 burn in an area with a 4 cm deep organic layer; (C) 2003 photograph in the HC94 burn in an area with a 1 cm deep organic layer; and (D) 2005 photograph in the DF99 burn in an area with a 1 cm deep organic layer. While the levels of biomass may appear to be substantial in these surface photography (particularly in sites c and d), in fact the canopies were open with substantial gaps of low levels of herbaceous vegetation and shrubs between individual trees.

C-band backscatter in black spruce forest stands near Delta Junction, including a site that was recently burned and included low levels of biomass. Fig. 6 in Harrell et al. (1995) shows a plot of ERS-1 backscatter versus aboveground biomass based on data collected on 19 April 1992 when the aboveground vegetation was thawed (air temperature = 7 °C) and there was a 50 cm deep snowpack covering the ground in the region. Thus, these data were collected when the influence of variations in surface moisture were minimal. For this date, the Harrell et al. (1995) data showed backscatter varied linearly as a function of biomass, with a variation of 3.1 dB for plots where the biomass ranged between 0.0 and 5400 g m^{-2}. This results in a sensitivity of 0.6 dB per 1000 g m^{-2} of biomass for the forests in the Delta Junction region. The maximum biomass of 400 g m^{-2} observed in the HC94 and DF99 would result in an ERS-1 backscatter difference of 0.24 dB when compared to a plot with no vegetation.

Kasischke et al. (2003) used the MIMICS theoretical microwave scattering model (Ulaby et al., 1990) to examine the influence of variations in non-woody biomass on ERS-1 backscatter from sites with variable soil moisture. Over the soil moisture ranges observed in HC94 and DF99 (0.1 to 0.6 cm^3 cm^{-3}), the growth of foliage and other non-woody biomass over the course of a growing season would reduce ERS backscatter by ~0.9 dB for 100 g m^{-2} of foliage, and half this amount for 50 g m^{-2} of foliage. Based on these model

Table 2
Average post-fire tree recruitment, biomass, and recruitment levels in stands within the HC94 and DF99 burns

Burn	Number of Sites	Organic layer depth		Aspen seedlings		Spruce seedlings		Total biomass[a] (g m^{-2})	Pre-burn spruce density (stems m^{-2})	Spruce recruitment (% of pre-burn)
		Range (cm)	Average (cm)	Density (stems m^{-2})	Biomass (g m^{-2})	Density (stems m^{-2})	Biomass (g m^{-2})			
HC94	7	<2.5	1.4	2.16	191.8	0.47	1.3	262.7	1.1	43
	7	2.5 to 7.5	5.1	3.99	42.9	1.7	1.4	154.9	1.11	153.4
	5	>7.5	13.1	1.96	10	4.04	6.9	135.4	1.09	370.1
DF99	3	2.5 to 7.5	2.5	0.06		0.09			0.58	15.2
	2	>7.5	10.8	0.03		0.09			0.69	12.6

The HC94 sites were sampled 9 years after the burn, while the DF99 burns were sampled 6 years after the burn.
[a] Includes aspen, black spruce, willow total biomass.

estimates, if soil moisture were constant across all sites, we would expect the ERS backscatter during the growing season to be approximately 0.5 dB lower in those HC94 sites with high biomass (e.g., sites with organic soils less than 2.5 cm in Table 2) compared to those sites with low biomass (sites with organic soils >2.5 cm in Table 2).

Fig. 4 presents the seasonal variation in ERS SAR backscatter for low (sites where the surface organic layer was >2.5 cm) and high biomass (surface organic layer <2.5 cm) sites in the HC94 burn in 2003. Leaf flushing begins in interior Alaska during the first week of May, with leaf foliage fully grown by late May. Based on this pattern, one would expect a 0.5 to 0.9 dB drop in ERS backscatter between early May and early June for the two sites due to seasonal foliage growth, which is less than the 1.3 dB (low biomass plots) to 1.4 dB (high biomass plots) observed in the 2003 ERS data. If seasonal biomass growth were the primary cause of the decrease in ERS SAR backscatter, we would expect a larger drop in the high biomass plots compared to the low biomass plots. Overall, the low biomass plots have a significantly higher ERS SAR backscatter compared to the high biomass plots (paired two-sample t-test, $P<0.03$), with the differences being more pronounced in the middle of the summer, which is consistent with the model predictions if soil moisture were the same at each site. Alternatively, one might argue that the soil moisture would be lower in the higher biomass plots because the higher foliage levels result in a more rapid depletion of soil water via evapotranspiration.

The average growing season (June to August) ERS backscatter for low and high biomass sites in the HC94 fire over the period of 1995 to 2004 show that substantial differences in backscatter between the low and high biomass plots occurred primarily during 2003 and 2004 (Fig. 5). As with the 2003 data, the average ERS SAR backscatter between the high and low biomass plots were significantly different in 2004 (paired two-sample t-test, $P<0.03$). The ERS SAR backscatter from the higher biomass plots was 0.7 dB lower than the low biomass plots for these two years, which is consistent with the predictions of the MIMICS model. For all other years except 1995, there was no significant difference (paired two-sample t-test, $P=0.10$) in the backscatter between the high and low biomass plots, supporting the hypotheses that differences made little difference in microwave scattering from the vegetated surfaces.

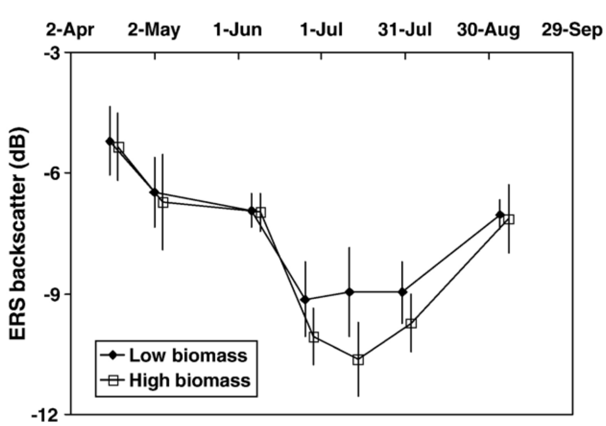

Fig. 4. Seasonal variations in ERS SAR backscatter for the 2003 growing season for plots with low and high biomass. The error bars represent ±1 standard deviation of the mean backscatter from the individual plots used to generate the average.

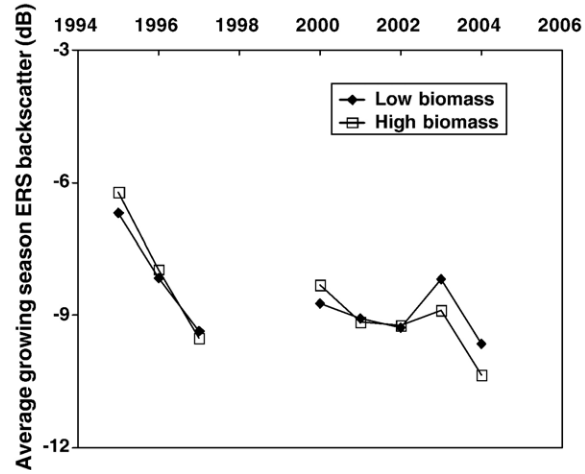

Fig. 5. Average ERS SAR backscatter during the growing season (June, July, August) for high and low biomass plots in the HC94 burn plotted as a function of year after the burn.

In summary, we conclude that variations in biomass in the HC94 plots had relatively small impact (on the order of 0.5 dB or less) on variations in ERS backscatter between different growing seasons or during a single growing season. Since the biomass levels in the DF99 burn were substantially lower than in the HC94 plots, the influence of variations in biomass on ERS backscatter in these data are even less substantial.

4.2. Sources of variations ERS radar backscatter

Seasonal profiles of average ERS SAR backscatter for burned and unburned sites are presented in Fig. 6 for the HC94 and DF99 fire events. For both sites, the ERS SAR backscatter values were significantly higher in the spring shortly after snowmelt than in remaining of the growing season (2.1 dB in the HC94 sites and 2.6 dB; two-sample t-test assuming unequal variances, $P<0.01$). ERS SAR backscatter decreased during June and often into July, until the sites received enough precipitation to raise soil moisture, which resulted in increased ERS radar backscatter late in the growing season (July and August).

4.2.1. Freeze–thaw effects

ERS SAR backscatter values from 12 April 2002 were extremely low because of the sub-freezing temperatures present on that date (Fig. 6). The sharp increase in ERS SAR backscatter between 12 April and 2 May 2002 is consistent with transitions observed in boreal regions that occur when the vegetation goes from a frozen to thawed state (Way et al., 1990; Rignot & Way, 1994). The 12 April 2002 ERS SAR backscatter measurements were excluded from additional analyses.

4.2.2. Organic layer depth

As discussed previously in Section 4.1, variations in organic layer depth in the HC94 sites resulted in differences in vegetation cover, which in turn, had small effects on ERS SAR backscatter primarily during years 9 and 10 after the fire. We found that there were small differences (1 dB or less) in ERS SAR backscatter as a function of depth of the remaining organic soil (Fig. 7), primarily in the HC94 sites. In the DF99 sites, the difference in backscatter between the sites with moderate and

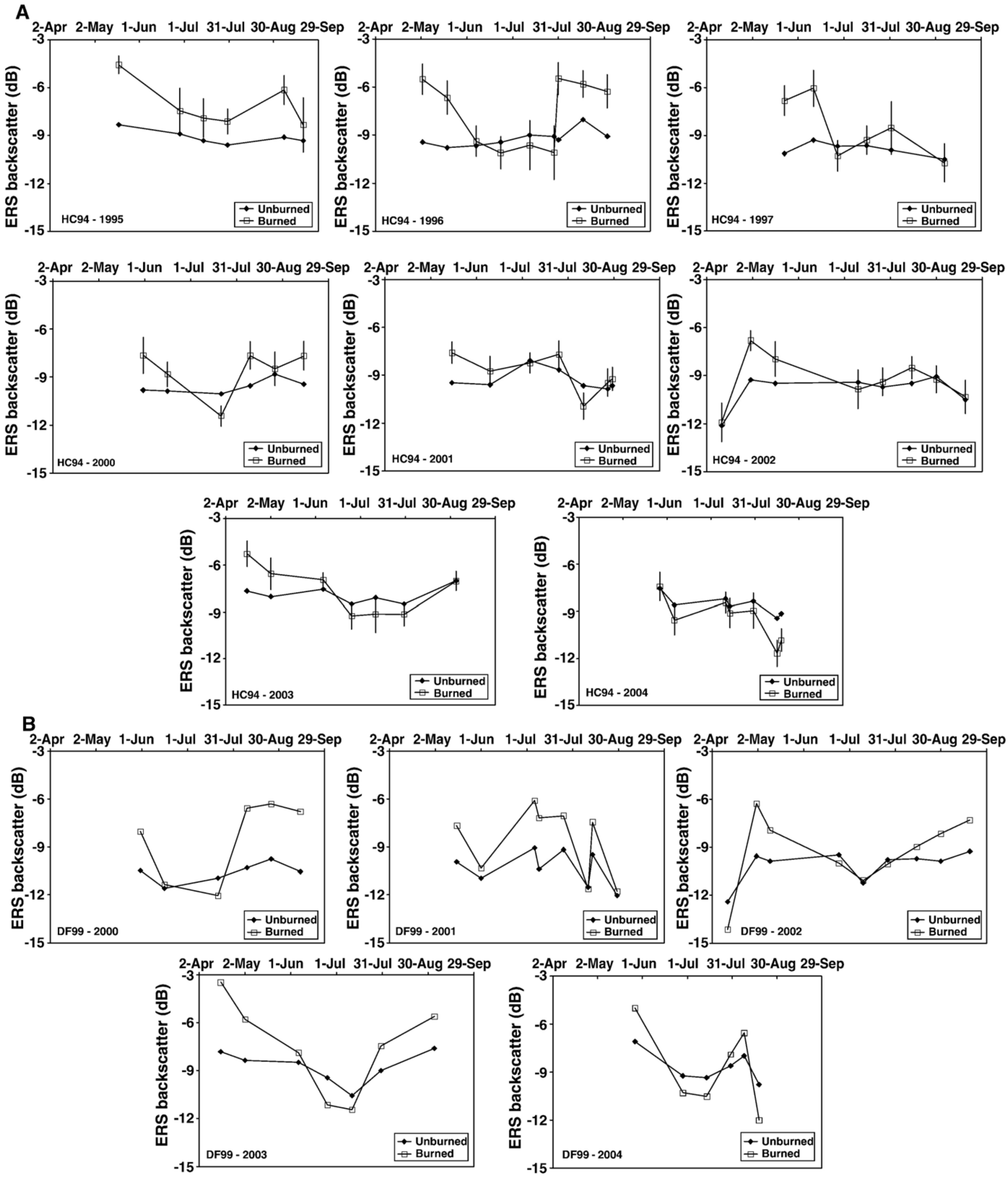

Fig. 6. Seasonal plots of average ERS-1 and ERS-2 SAR backscatter for the (A) HC94 and (B) DF99 fire events for all years when data were available for both burned and unburned stands of black spruce. The error bars for the HC94 burned plots represent ±1 standard deviation of the mean backscatter from the individual plots used to generate the average. For the remaining points, the uncertainties are ±0.30 dB, which are too small to present on the graph.

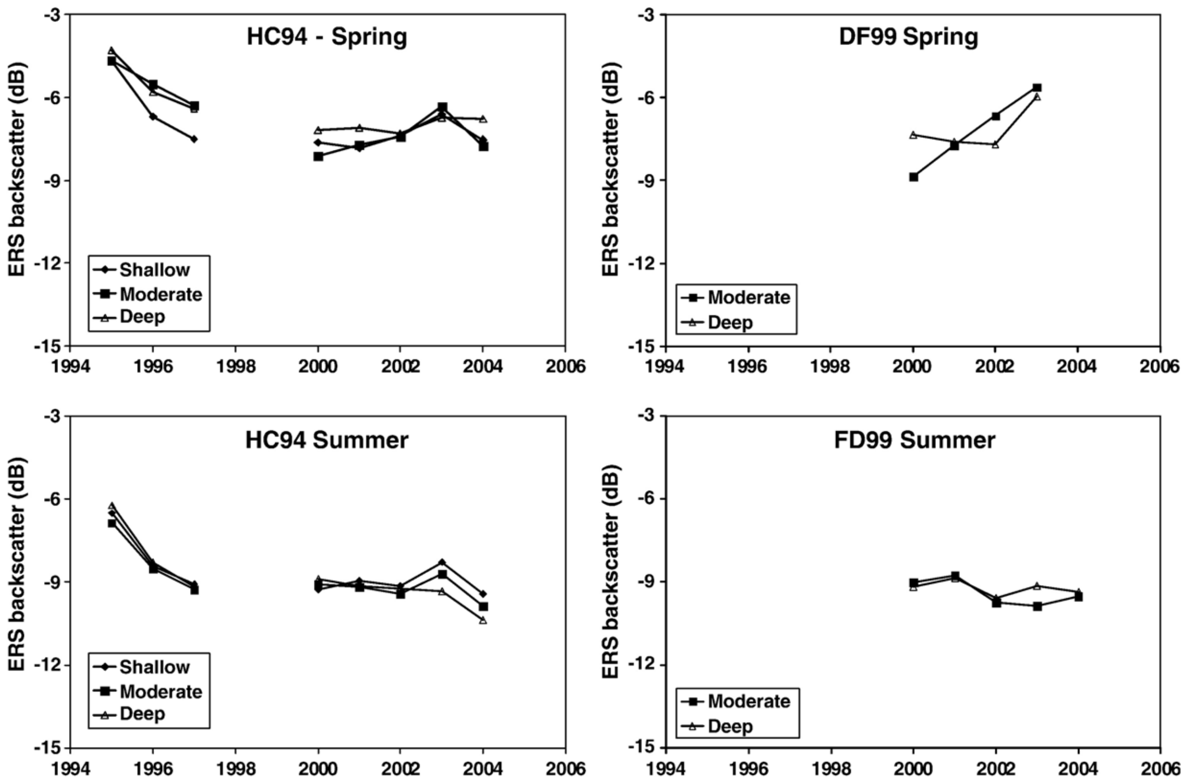

Fig. 7. Average ERS SAR backscatter from burned sites with different organic layer depths plotted as a function of time since the burn.

deep organic layers were not significantly different across all years of the study, both in the spring and summer observations (paired two-sample *t*-test, $P=0.10$). In the HC94 sites, there were no statistically significant differences between the sites with shallow, moderate and deep organic layers, even during the summer observations in 2003 and 2004 (ANOVA, spring observations, all years: $F=0.17$; $P=0.84$; summer observations, all years: $F=0.39$; $P=0.68$; summer observations, 2003 and 2004: $F=1.05$; $P=0.36$).

The sites with the shallowest surface organic layer had a slightly lower ERS SAR backscatter during the first 3 years after the fire during the spring, while the sites with the deepest surface organic layer had the highest backscatter during years 6 to 9 after the fire. During the summer, differences did not exist until years 9 and 10 after the fire, when the sites with the deepest surface organic layers had the lowest backscatter, and the sites with shallowest surface organic layers had the highest backscatter.

4.2.3. Unburned versus burned stands

As found previously by Bourgeau-Chavez et al. (1997), the contrast between burned and unburned stands was greatest in the springtime because of the high soil moisture, but the overall contrast between the burned and unburned sites decreased over time (Figs. 6 and 8). By the tenth year after the HC94 fire, the unburned stands had a higher average ERS SAR backscatter value than the burned stands (Fig. 8).

The ERS backscatter for the unburned forests adjacent to the HC94 burn were an average of 0.74 dB higher than for the unburned stands adjacent to the DF99 burn (Fig. 9) (paired two-sample *t*-test, $P<0.001$). The difference between the unburned stands was greater in the summer (0.85 dB, paired two-sample *t*-test, $P<0.001$) than in the spring (0.24 dB, paired two-sample *t*-test, $P<0.09$). We attribute these differences to one of two factors: (a) the higher biomass present in the HC94 stands (because of higher stand densities) (e.g., Harrell et al., 1995); or (b) the higher moisture levels of the surface organic layers owing to the fact that the HC94 black spruce stands had permafrost whereas the stands used for the DF99 analysis did not.

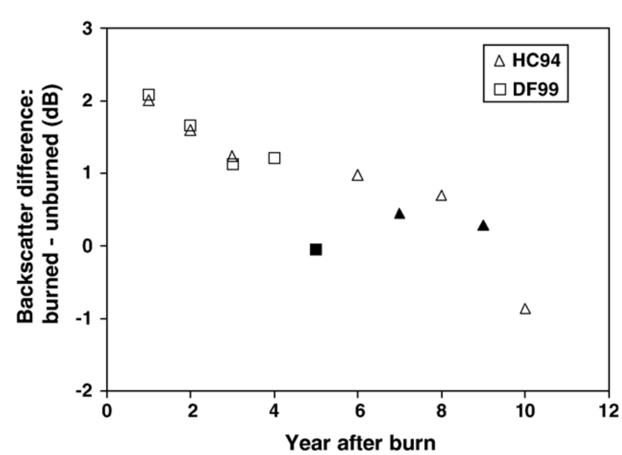

Fig. 8. Difference in ERS SAR backscatter between burned and unburned stands for the HC94 and DF99 fires plotted as a function of time since the burn. The open boxes and triangles represent those years where the differences were significantly different (paired *t*-test, $P<0.10$).

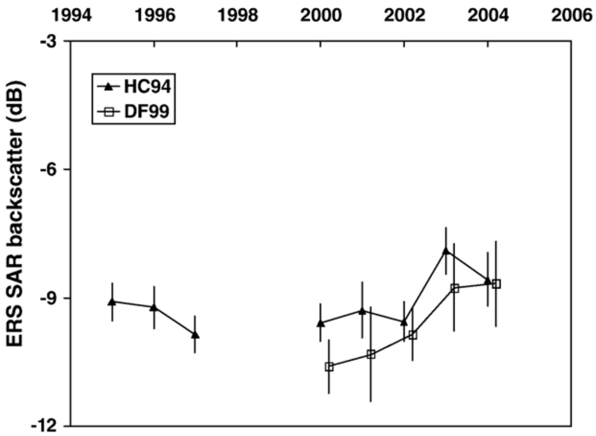

Fig. 9. Average ERS SAR backscatter for the unburned stands adjacent to the HC94 and DF99 fires for the different years of the study. The error bars represent ±1 standard deviation of the mean backscatter from the different dates of imagery used to generate the average.

The increases in average backscatter in 2003 and 2004 were significantly different from previous years in both the HC94 (ANOVA, $F=9.85$, $P<0.0001$) and DF99 sites (ANOVA, $F=6.39$, $P<0.001$). In the DF99 sites, the average ERS backscatter were significantly higher in both 2003 and 2004 compared to 2000 and 2001 (Tukey HSD test, $P<0.05$), where in the HC94 sites, the average ERS backscatter in 2003 was greater in all years but 2004, where average ERS backscatter 2004 was greater than in 1997, 2000, and 2002 (Tukey HSD test, $P<0.05$).

While the overall magnitude of the ERS backscatter declined over time for burned sites in the HC94 and DF99 study areas, the seasonal range in observed backscatter did not (Fig. 10). In contrast, the magnitude and seasonal range for the unburned stands remained constant. The seasonal ERS backscatter range was higher in the burned stands compared to the unburned stands for both sites (paired two-sample t-test, $P<0.05$). The higher seasonal range in the burned versus unburned sites is likely due to the removal of live vegetation by fire, which results in the direct backscatter from the ground surface being the primary source of detected signals from the burned sites, which in turn is driven by variations in soil moisture.

The average seasonal range in ERS SAR backscatter signatures greater in the DF99 burned sites than in the HC94 burned sites (10). This higher range was the result of the DF99 sites having lower ERS SAR backscatter values during the summer time than the HC94 sites (Fig. 10).

There was higher variability in the backscatter signatures for the unburned DF99 stands region compared to unburned HC94 stands (Fig. 10; paired two-sample t-test, $P<0.05$). This higher variability may be related to the fact that the DF99 unburned stands had lower stand densities and therefore had more exposed ground surface. Because of this larger exposed ground area, variations in surface organic layer moisture due to precipitation may have more influence on the backscatter signatures from the DF99 unburned stand.

During the first three years after the fire occurred, the average ERS backscatter values were higher in the HC94 burned stands than in the DF99 sites during both spring (e.g., May) and summer (June through August) (Fig. 10). This result shows that the surface soil moisture was higher for the first several years following the fire in the HC94 sites. As discussed below (Section 4.4), soil moisture influences patterns of tree recruitment and post-fire succession.

Inter-annual variations in ERS SAR backscatter in the burned sites were complex. During 1995 to 1997, springtime backscatter decreased (for the HC94 sites), while during the 2000 to 2003 period, it increased (for both the HC94 and DF99 sites) (Fig. 11). These variations are most likely related to the timing of the melting of the snowpack during the spring, the amount of moisture that resulted from this melting, and the degree of permafrost remaining at the site. There were no discernible patterns in inter-annual variations in the summertime backscatter measurements, except for a decrease in the HC94 sites during 1995 to 1997.

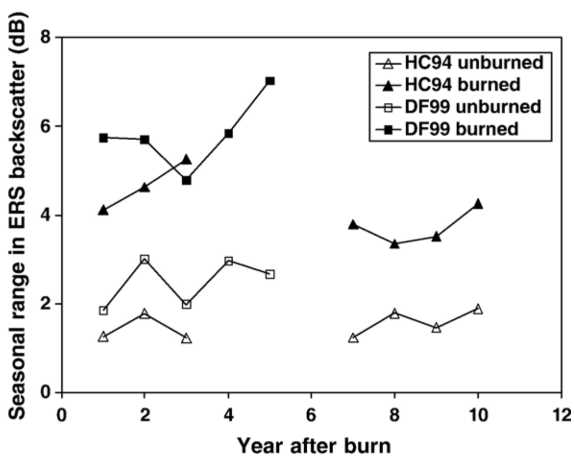

Fig. 10. Seasonal range in average ERS SAR backscatter for the burned and unburned stands in the HC94 and DF99 fire events plotted as a function of year after the burn.

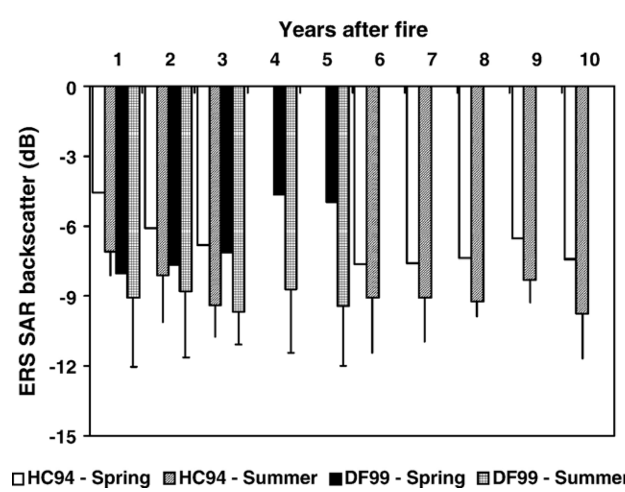

Fig. 11. Trends in average ERS-1 and ERS-2 SAR backscatter from burned sites for the spring and summer periods in the HC94 and DF99 fire events as a function of year after the burn. The error bar for the summer periods represents the minimum backscatter observed during that year.

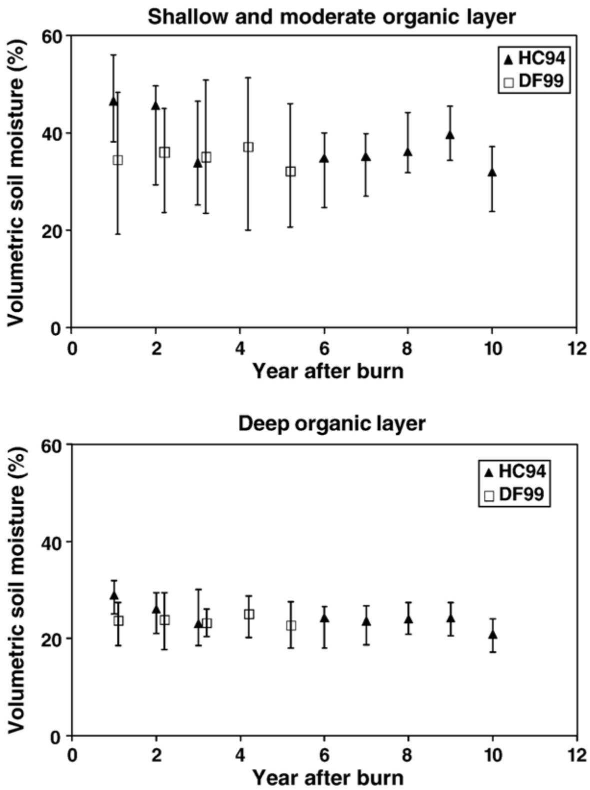

Fig. 12. Trends in average SAR-derived volumetric soil moisture based on the equations presented in Table 1 for burned sites in the HC94 and DF99 burn events. Error bars represent the minimum and maximum soil moisture estimates for each year.

4.3. Variations in soil moisture

While Bourgeau-Chavez et al. (2007) used sites within area A of the DF99 fire to develop soil moisture equations for areas with moderately-deep organic layers, field surveys show that a significant portion of this area had shallow organic layers as well (Kasischke & Johnstone, 2005). To estimate soil moisture using the ERS backscatter measurements for area A, we assumed that half this site was covered by shallow organic layers and half by moderate organic layers.

As would be expected from the trends in ERS backscatter, we found that the average soil moisture during the growing season were significantly higher ($P<0.10$, two-sample t-test assuming unequal variances) during the first two years following the fire in the HC94 sites than in the DF99 sites (Fig. 12). The HC94 sites with shallow to moderate depths of organic soils had an average soil moistures that were 10% higher than in similar DF99 sites, where the soil moisture in the sites with deeper organic layers were an average of 3% higher in the HC94 sites. In addition, the DF99 sites experienced the lower soil moisture levels during the first three growing seasons. Compared with the HC94 sites, the DF99 sites experienced minimum soil moistures that were 8% lower in the shallow/moderate organic layer sites and 3% lower in the deep organic layers. Because of low sample numbers ($n=3$), these differences were not significantly different ($P=0.10$, paired, two-sample means t-test). Finally, the HC94 sites all experienced a decrease in soil moisture during the first three years after the fire, after which soil moisture appeared to show slight inter-annual fluctuations.

4.4. Effects of depth of burning and soil moisture on post-fire tree recruitment

Field data show that prior to the fire, the HC94 site was occupied by dry non-acidic black spruce forests or wet non-acidic black spruce forests with deep (25 cm) organic layers lying on top of shallow permafrost (Table 3). The unburned forests of area B of the DF99 site were similar to those found in the HC94 site. In contrast, Area A of the DF99 site contained elevational acidic black spruce woodlands that were on sites with shallower silt layers, deeper permafrost, and drier soils (Table 3).

Johnstone and Kasischke (2005) showed that post-fire variations in the depth of the organic layer in the HC94 affected tree recruitment and growth. As a result of the removal of a

Table 3
Summary of characteristics of the mature black spruce forest stands that were adjacent to or within the perimeters of the HC94 and DF99 burns

Burn [a]	Forest community type [b]	Burned/ Unburned	Burn year	Stem density (stems ha^{-1})	Basal diameter (cm)	Depth of silt above gravel (cm)	Organic layer depth (cm)	Permafrost depth [c] (cm)	Mineral soil moisture (%)
HC94	Wet non-acidic black spruce	Unburned	1760	4866	6.6	n/a	25.1	22.4	47.8
HC94	Dry non-acidic black spruce	Unburned	1855	8439	6.7	n/a	24.9	40.7	33.8
HC94-a		Burned (July)	1860	6931	6.2	26.7	9.9	n/a	n/a
HC94-b		Burned (August)	1865	9031	5.2	33.2	2.1	n/a	n/a
DF99	Dry non-acidic black spruce	Unburned	1875	3508	7.9	25.0	17.8	43.8	45.6
DF99-A		Burned	n/a	6870	n/a	n/a	10.4	n/a	n/a
DF99	Elevational acidic black spruce woodland	Unburned	1915	4512	8.2	13.9	10.8	164.0	17.3
DF99-B		Burned	n/a	5833	n/a	n/a	2.5	n/a	n/a

[a] The letters following the different burns (HC94 and DF99) represent specific regions used in this study (see Fig. 1).
[b] Forest community types in the study region are after Kasischke and Johnstone (2005) based on Nettleton-Hollingsworth (2004).
[c] Depth below surface of mineral soil.

substantial amount of the organic soil profile during fires which exposed either mineral soil or dense humic organic soil, wind-borne aspen (*Populus tremuloides*) seeds were able to germinate and grow on those sites that burned during the later part of the growing season in the HC94 burn. In the HC94 burn, black spruce recruitment and growth were positively correlated to the depth of the organic layer remaining after the fire, while aspen recruitment and growth was negatively correlated to organic layer depth (Fig. 3A–C, Table 3). The sites with the shallowest organic layer remaining after the fire not only had substantial invasion and growth of aspen (Fig. 3C), but that the recruitment of black spruce seedlings was <50% of pre-burn stand density. Johnstone et al. (2004) showed that net recruitment in burned boreal forests stops after 10 years, indicating that the composition of the forest community in the deeply burned HC94 fires will likely change dramatically from those found prior to the fires.

In contrast to the HC94 sites, there was virtually no recruitment of aspen in the burned DF99 sites in either area (Fig. 3D, Table 2). This was somewhat surprising since patches of mineral soil were exposed in parts of area A by the 1999 fire, and similar sites in the HC94 burn experienced recruitment and substantial growth of aspen (Fig. 3C). In addition, recruitment of black spruce seedlings was extremely low in both areas A and B, being less than 20% of the pre-burn stand density. These low recruitment levels indicate that a much more stands of black spruce forests are likely to develop in the burned areas of the DF99 event than were present prior to the fire.

One of the impacts that fire has on black forests is to cause an increase in soil temperature and decrease in soil moisture for the first several decades after a fire, especially sites with permafrost (Viereck, 1983). The warming occurs because of a decrease in the insulation capacity of the surface organic layer combined with increases in direct solar insolation (Bonan, 1989). The post-fire warming of the ground layer in sites with permafrost eventually leads to deeper active layers, which lowers soil moisture because of increased drainage. However, the BCEF data showed that the process of ground temperature warming and permafrost thawing is gradual (Fig. 13). Because of this gradual warming, sites that had permafrost prior to the fire will still experience impeded drainage from the presence of permafrost for several years after the fire, which may be the cause of the high soil moistures observed in the HC94 site for the first several years after the fire compared to latter years (Fig. 12). The lack of permafrost in the shallow organic layer sites in the DF99 sites may be one of the reasons these sites had much lower soil moisture during the first several years after a fire compared to HC94 sites.

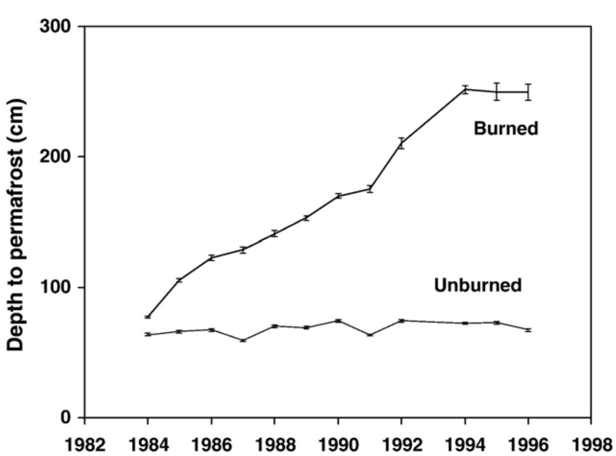

Fig. 13. Plot of the end of the season average depth to permafrost obtained from burned and unburned stands from the 1983 Rosie Creek fire near Fairbanks, Alaska. Error bars represent ±1 standard error (data provided courtesy of L. Viereck of the University of Alaska, Fairbanks).

5. Conclusions

In this study, we showed that the backscatter measurements obtained from the ERS-1 and ERS-2 SAR systems are sensitive to seasonal and inter-annual variations in near-surface soil moisture in the burned black spruce forests of interior Alaska. While inter-annual variations biomass will increase ERS SAR backscatter (on the order of 0.3 dB), and seasonal growth of foliage and herbaceous biomass will cause a decrease (on the order of 0.5 dB), the observed variations in ERS SAR backscatter (5 to 7 dB) are much larger than would be expected from the variations in biomass. The linear correlations found between ERS SAR backscatter and measured soil moisture support our conclusion that the ERS SAR can be used to monitor seasonal variations in soil moisture in the recovering burned stands in Interior Alaska.

Soil moisture variations in these forests are climatically related to springtime snow melt and seasonal precipitation patterns, with differences across the landscape being due to mineral soil texture and permafrost thaw dynamics, both of which affect soil drainage. While the SAR soil-moisture sensitivity was visually most evident in the SAR imagery collected during the first several years after a fire (Fig. 8), we found that the ERS SAR data could be used to observe seasonal variations in soil moisture in imagery collected 10 years after the fire (Fig. 6A). Recent studies by Bourgeau-Chavez et al. (in press) showing the variations in SAR backscatter observed in the two sites used for this study resulted from differences in soil moisture, which allowed us to analyze the soil moisture trends within and between the sites (Fig. 12).

The ERS SAR backscatter trends were distinctly different between the two study sites for the first three years following the fire. The HC94 site had higher backscatter levels than DF99 in both spring and summer during the first two years after fire (Fig. 11), indicating higher levels of soil moisture at the HC94 sites (Fig. 12). Decreases in spring and summer backscatter in the HC94 sites suggest a distinct decline in soil moisture during the first three years following the fire (Fig. 12). Seasonal variations in backscatter were greater at the DF99 sites because backscatter decreased to very low levels during the summer (Fig. 10). This means that the DF99 site experienced much lower soil moisture levels than the HC94 sites during the growing season.

These variations in backscatter measurements are consistent with differences in site characteristics likely to influence soil moisture. The absence of permafrost in the area A of the DF99 burn, along with the shallower silt layers, would lead to more well-drained soil conditions in this site, and the higher winds at this site would also result in drier soils. While fire results in the thawing of permafrost in black spruce forests, it takes several growing seasons for this melting to occur (Fig. 13). Thus, we would expect soil moisture to be higher in burned sites where permafrost reduces soil drainage, as was observed in the HC94 sites. The decrease in soil moisture during the first 3 years following fire in the HC94 sites is consistent with a progressive increase in active layer depth and soil drainage in the years after fire (Fig. 13).

We also observed a slight increase in backscatter in the spring in the DF99 sites during the first four years following the fire, while summer backscatter levels remained constant, indicating an increase in spring but not summer soil moisture following fire in the DF99 burn. This pattern cannot be explained through site drainage/permafrost dynamics. However, there was also an increase in spring backscatter in the HC94 sites during the same time periods (e.g., years 6 to 9 in Fig. 11), indicating these changes may be due to variations in levels of snowmelt occurring in the spring just prior to the time of the ERS SAR data collections.

The measured levels of tree recruitment between the sites are consistent with the differences in soil moisture estimated from the ERS SAR data. In the study region, aspen seed dispersal typically begins during the second week of June, so the residual soil moisture remaining after snowmelt and soil moisture during the remaining summer affect seed germination and seedling survival. Aspen seedlings were able to germinate and grow within the severely-burned areas (e.g., areas with low levels of organic soils) of the HC94 burn because adequate soil moisture was present during both the spring and summer growing periods. In contrast, low aspen recruitment at severely-burned sites in the DF99 burn is likely the result of lower summer soil moisture, which not only lessens rates of seed germination, but also leads to moisture-related stress and mortality in seedlings that do germinate. Lower levels of black spruce recruitment in the DF99 compared to HC94 sites is probably also associated with increased moisture stress in the DF99 burn.

As noted earlier, recent warming trends in the boreal forest region have resulted not only in increased fire activity, but increased levels of net primary production. Models predict that over the longer term, climate warming in the Alaskan boreal forest is likely to result in decreases in black spruce forests and increases in deciduous forests, with the level of invasion and growth of deciduous tree species being determined by available soil moisture (Bonan & Korzuhin, 1989). The results from our research support these modeling studies and show that spaceborne SARs present a unique means to monitor variations in surface moisture in burned sites at multiple-temporal scales. When combined with satellite-derived maps of pre-fire vegetation cover and burn severity, the SAR observations of soil moisture can be used to assess the potential for changes in forest cover in the boreal region.

Acknowledgements

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