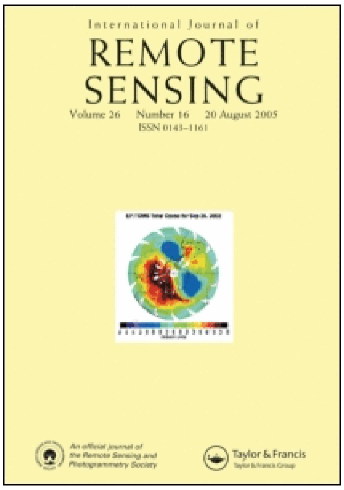

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Remote monitoring of spatial and temporal surface soil moisture in fire disturbed boreal forest ecosystems with ERS SAR imagery

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Due to the large volume of carbon currently stored in boreal regions and the high frequency of wildfire, the prospects of a warming climate would have important implications for the ecology of boreal forests which in turn would have significant feedbacks for carbon cycling, fire frequency, and global climate change. Since ecological studies and climate change models require routine information on surface soil moisture, the ability to remotely sense this variable is highly desirable. Toward this end research was conducted on developing methods for the retrieval of spatially and temporally varying patterns of soil moisture from recently burned boreal forest ecosystems of Alaska using C-band satellite radar data. To do this we focused on both individual date and temporal SAR datasets to develop techniques and algorithms which indicate how moisture varies across a recently burned boreal forest. For each of the methods developed we focused on reducing errors of SAR–derived soil moisture estimates due to confounding factors of variations in vegetative biomass and surface roughness. For the individual date soil moisture monitoring, we grouped test sites by a measurable biophysical variable, burn severity, and then developed algorithms relating moisture to SAR backscatter for each burn severity group. The algorithms developed had high coefficients of determination (0.56–0.82) and the moisture maps produced had high accuracy (3.61 rms error) based on the minimal validation conducted. For the seasonal soil moisture mapping we used principal component analysis to capture the time-variant feature of soil moisture and minimize the relatively time-invariant features that confound SAR backscatter. This resulted in good agreement between the drainage maps produced and our limited *in situ* observations and weather data. However, further validation, with larger sample sizes, is needed. While this study focuses on Alaska, research indicates that the techniques developed should be applicable to boreal forests worldwide.

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1. Introduction

Boreal forests cover 14.7 million km^2 or 11% of the earth's land surface (Bourgeau-Chavez *et al.* 2000a) and together with non-forested boreal ecosystems are a significant reservoir of carbon because of the development of deep organic soil layers (Kasischke *et al.* 2006). Forest floor decomposition is slow in the boreal biome due to the cold climate, and wildfire is the main mechanism of removal of the deep organic layers that develop. Wildfire burns approximately 8 million hectares of the global boreal forest each year (Kasischke *et al.* 1994) and general circulation models predict that a warming climate will increase the fire frequency and intensity in these high latitude ecosystems (Kasischke 2000, Raisanen 2001).

Due to the important role of boreal regions in our climate and hydrologic cycle, landscape scale soil moisture information is needed not only for ecological studies but for a wide array of models and estimates (climate change, biogeochemical cycling, hydrologic mapping). Further because of the large areas burned annually in boreal regions, landscape scale soil moisture information on recent burn scars has important implications not only for post-fire regeneration and post-fire net primary productivity, but also for the larger scale carbon cycling and climate change models.

Soil moisture information is not easily attained through ground-based studies at regional scales. However, satellite-based Synthetic Aperture Radar (SAR) imagery represents a promising method for prediction of landscape scale soil moisture information. Past empirical and theoretical studies have demonstrated the dependence of satellite based SAR C-band backscatter on soil moisture conditions in bare to low vegetated landscapes including rangeland, agricultural fields, and recently burned boreal forest fire scars (e.g. Dobson *et al.* 1992, Wooding *et al.* 1992, French *et al.* 1996, Ulaby *et al.* 1996, Moran *et al.* 2000). Newly burned boreal forest fire scars of Alaska, Canada and Russia appear brighter than adjacent unburned forest in the European Space Agency's ERS C-band imagery when the soil is wet (Kasischke *et al.* 1995, Bourgeau-Chavez *et al.* 1997, 2000a) and darker than the unburned forest when the soil is very dry. Thus, the dynamic range of backscatter from burned boreal sites is quite large (5–8 dB), compared to unburned forest (1–3dB) in the same wet to dry conditions.

The recently burned forests of Alaska have unique surface soil qualities which affect the relationship between backscattered C-band energy and soil moisture. Unburned Alaskan boreal forests are typically characterized by deep organic layers consisting of both undecomposed and decomposed material. Fire burns these layers to various depths, depending on the severity of the burn, and thus influencing the surface roughness, soil density, and water holding capacity of the remaining layers. The patterns of burn severity are then influential on the soil moisture patterns across the burned landscape and the patterns of forest regeneration and net primary productivity.

The focus of the research presented here was to develop methods for retrieval of spatially and temporally varying patterns of soil moisture from recently burned boreal forest ecosystems using C-band satellite radar data. To do this we focused on both individual date and temporal SAR datasets to develop techniques and algorithms which indicate how moisture varies across a recently burned boreal forest. Individual date soil moisture maps provide spatial information for a given point in time and may be correlated directly with *in situ* data for validation. A seasonal soil moisture index provides temporal information on the drainage patterns of a burned area and relative moisture classes. Together these techniques provide a novel remote sensing approach to monitoring the spatially varying hydrologic condition of recently burned boreal forests.

2. Background

Three single channel C-band SAR sensors have been in orbit since the early to mid-1990s; the European Space Agency's ERS-1 and 2, and the Canadian Space Agency's Radarsat satellites. In this research we focused on the ERS-2 SAR satellite which was launched into orbit in 1995 and remains in operation. The ERS-2 SAR sensor operates at 5.3 GHz (5.7 cm wavelength) with vertically polarized transmission and reception (VV-pol) and a central incidence angle of 23°. We focused on VV-polarization (ERS-2) because it is less sensitive than HH-polarization (Radarsat) to the orientation of plant leaves, which attenuate the signal from the soil surface (Ulaby *et al.* 1979).

Although the steep incidence angle mode of the ERS-2 satellite sensor is close to optimum sensor parameters required for soil moisture mapping (Ulaby *et al.* 1986), the backscatter relationships are hindered by confounding factors of surface roughness and vegetative structure and biomass. Multiple frequency, multiple polarization, or multiple incidence angle SAR could be used to remove surface roughness and vegetation effects (Oh *et al.* 1992, Dubois *et al.* 1995, Dobson and Ulaby 1998, Srivastava *et al.* 2003), but scientists have struggled with developing methods to overcome these issues with single-channel SARs. The repeat nature of the single channel orbiting satellite SARs make them invaluable for monitoring and worthwhile for developing methods to reduce or quantify the surface roughness and vegetative signals. In theory, *in situ* data of surface roughness, plant geometry and biomass could be used to extract soil moisture information from backscatter values across a landscape. However, this technique would be tedious and impractical over large areas. Many scientists have focused on bare soil areas for moisture extraction. Quesney *et al.* (2000) developed watershed-scale soil moisture algorithms for monitoring bare agricultural fields in France by averaging C-band backscatter over all bare fields and referencing a weighted average of *in situ* data measured in those fields. They assumed that the roughness effects at the watershed scale were constant over the agricultural year. This resulted in a backscatter to soil moisture correlation coefficient of 0.94 with model accuracy of $+/-$ 4.5%.

Other methods have been investigated that group sites based on vegetation type to reduce the error due to vegetative differences (Oldak *et al.* 2003); however biophysical parameters of stem height and density are also needed for this to work. In addition, the soil type can influence the dielectric properties of the soil, penetration depth of the microwave energy, plant growth structure, and thus the amount of backscatter.

Moran *et al.* (2000) and Shoshany *et al.* (2000) developed methods to remove surface roughness effects by referencing each SAR scene to a dry date SAR scene (when surface roughness is more dominant). This technique of referencing to a dry date allowed comparison of multiple sites in a simple linear algorithm with a coefficient of determination of 0.93 (Moran *et al.* 2000). However, for soil moisture values less than 20%, they found no significant change in backscatter relative to dry backscatter.

In recently burned Alaskan boreal forests, biomass typically changes very little over a season and it is generally low enough in recent burns to have negligible effects on the attenuation of the SAR soil moisture signal. Dobson *et al.* (1992) determined that at C-band vegetative biomass only becomes important as it reaches 1.0 kg/m^2 and then it only attenuates the signal by less than 0.2 dB. Biomass studies of Alaskan burned boreal forests also revealed that in the early stages of regeneration, when biomass levels are less than 1.0 kg/m^2, vegetation has little effect on C-band radar backscatter (Harrell *et al.* 1995). Further to this, Harrell *et al.* (1995) found that surface soil moisture conditions often have a stronger influence on C-band

SAR backscatter from burned and unburned forests than biomass (range 0.11 to 5.58 kg/m^2 black spruce biomass). Regeneration biomass measured in year four post-fire of burned sites in Alaska resulted in a range of biomass from 0.050–0.153 kg/m^2 (Bourgeau-Chavez *et al.* 1997). Biomass will be a greater influence on backscatter from severely burned sites which typically have greater revegetation than less severely burned sites.

Surface roughness also changes very slowly at recently burned boreal sites, allowing a localized homogeneous burned forest site to be monitored for soil moisture over several seasons with fairly high accuracy. The problem arises when comparing different test sites across the burn which may vary in type of exposed soil, surface roughness, and re-vegetation; three parameters that affect C-band microwave scattering. However, there is a single factor that influences the variability in all three of these biophysical parameters which can be estimated remotely, burn severity (Michalek *et al.* 2000, Key and Benson 2004). Fires burn the organic soils and influence the soil density and surface roughness that remains post-burn, as well as post-fire revegetation. By quantifying the severity of burn across the fire-disturbed landscape and then grouping test sites by this burn severity parameter in the analysis of SAR backscatter versus soil moisture, we were able to develop models to predict spatial variation in soil moisture on an individual date.

In contrast, for seasonal soil moisture indices we focused on time series analysis which can be used to filter out temporal autocorrelation such as surface roughness and biomass and leave the moisture variable for extraction. In this method sites are compared to themselves through time rather than to a mosaic of burn severity/cover types within a single-date scene.

3. Study areas

Alaska test sites were observed and measured near Delta Junction from 2000–2004, and near Anderson from 2003–2004. Empirical model development was based on data collected at two recent burn scars near Delta Junction, which are the prime focus of this study, the 1994 Hajdukovich Creek Burn (HC, a.k.a. Gerstle River Burn, GR) and the 1999 Donnelly Flats burn (DF, figure 1). Three sites were chosen in each Delta scar for field sampling in 2000. Additional Delta sites were chosen in subsequent years for validation and were not included in the model development.

The Anderson study sites (figure 2) were purely used for validation of the analyses conducted at Delta Junction and were not included in the model development. Two sites from the Anderson study area, one in the Anderson Clear Fire of 2003 and a second in a 1991 fire scar (Anderson Burned Spruce) were chosen for sampling in 2003–2004 (figure 2). All study areas and sites are described in detail below.

3.1 *Delta junction study sites*

Delta Junction is located 190 km southeast of Fairbanks on nearly level topographic relief with poor to moderately well-drained soils. Pre-burn vegetation at all sites was primarily black spruce (*Picea marianna*).

The HC 94 burn (Fire# A312) consumed 9077 hectares in the summer of 1994. Consumption of the trees and ground layers in this fire was highly variable. In some areas the deep organic soil layers (25 to 40 cm thick) were almost entirely consumed (severe burn), while in other areas they were only partially consumed (moderate to light burn). This variation in burn severity had a significant effect on revegetation of

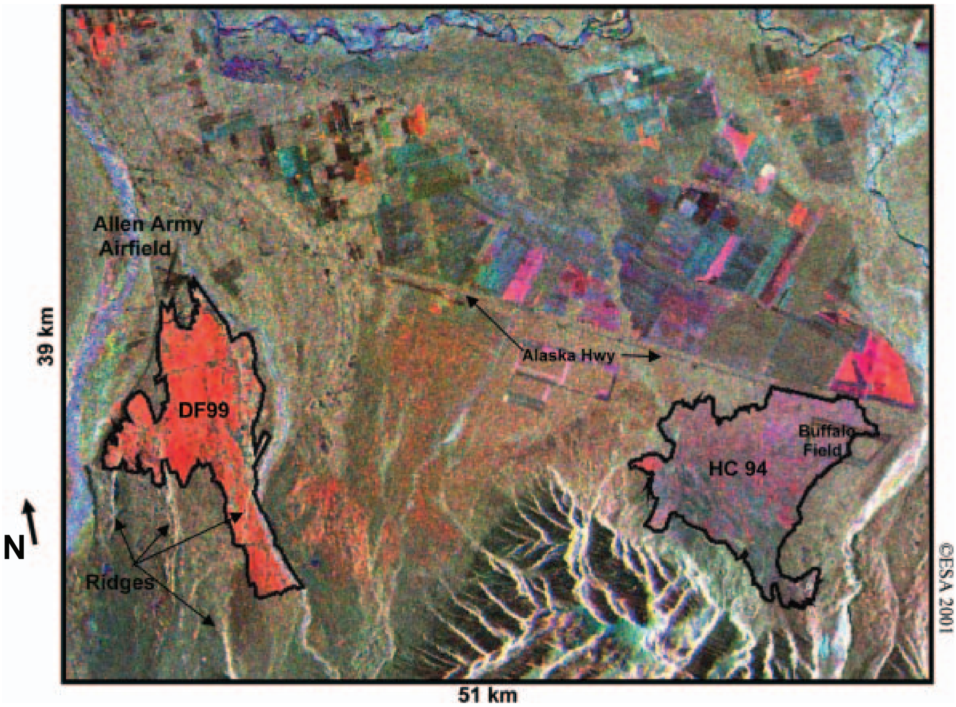


Figure 1. 9 ERS-2 multi-date composite of Delta Junction Alaska, showing the 1999 Donnelly Flats (DF99) burn area and the 1994 Hajdukovich Creek (HC94) burn. Red scene is from 6 July 2001, green is from 10 August 2001 and blue is from 29 August 2001.

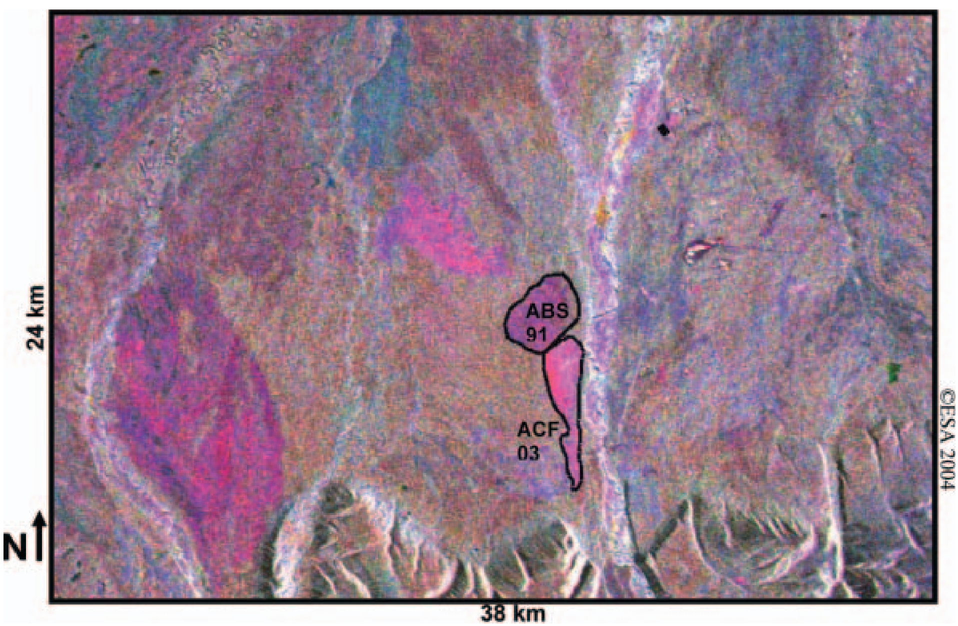


Figure 2. ERS-2 three date color composite of the Anderson Alaska study area showing the 1991 Anderson Burned Spruce (ABS) fire and the 2003 Anderson Clear fire (ACF). Red scene is from 23 July, green is from 4 July, and blue is from 14 May 2004.

the sites (figure 3). The severely burned areas had greater revegetation than the moderately burned sites (Durant *et al.* 1999). The fire killed nearly all overstory trees, but the degree of burn to the canopy was also variable. In 1998 new and resprouting vegetation covered 16 and 28% of the surface of moderately burned and severely burned areas, respectively (Durant *et al.* 1999). By 2003, severely burned site HC1 was dominated by small aspen and willow trees of 1–3 cm in diameter and 2–4 m in height (figure 4). Approximately 26% of the ground of HC1 was covered by live vegetation. Moderately burned HC2 (figure 4) had many willow clumps with 25–70% ground cover consisting of grass in dense areas and small willow and aspen on more bare areas. Site HC3 (figure 4) burned so severely that most of the pre-burn black spruce trees fell over and were regenerated by dense aspen and willow (0.5 to 2 m tall) with 85–95% of the ground covered. The entire HC burn is located on flat land with a gradual increase in elevation from 412 to 457 meters. There are mountains to the south with some ridges protruding north and we tried to avoid these areas in the analysis.

The DF fire (Fire# B-222) ignited just south of Delta Junction in June 1999 consuming 7579 hectares. DF is very well drained with a thin organic layer remaining over gravel very near the surface in the northern portion of the burn. Consumption of the trees and ground were less variable than at the HC 94 site, however, the northern portion of the 1999 burn had more of a severe ground burn than the southern portion. The southern portion had several inches of singed moss remaining. At the end of summer 2000 regrowth constituted almost 5% of the ground cover and was dominated by lupin (*Lupinus polyphyllus*), grass and willow (Durant *et al.* 1999). By 2003 moderately burned DF1 (figure 4) had 1.5–13 cm average organic soil remaining and was covered by knee-deep grasses and sedges (*Carex spp.*) and occasional aspen seedlings. Lightly burned site DF3 (figure 4), had 5.5–14 cm of organic soil, but also knee-deep grasses with blueberry (*Vaccinium uliginosum*), sedges and fireweed (*Epilobium angustifolium*). The DF site is generally

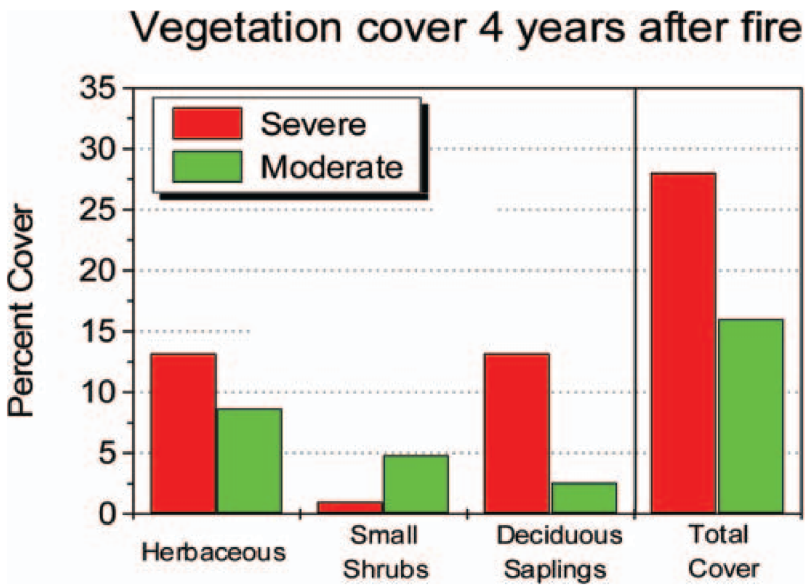


Figure 3. Bar chart of revegetation measured four years after the fire in severely versus moderately burned locations in the 1994 Hajdukovich Creek Burn (Durant et al. 1999).

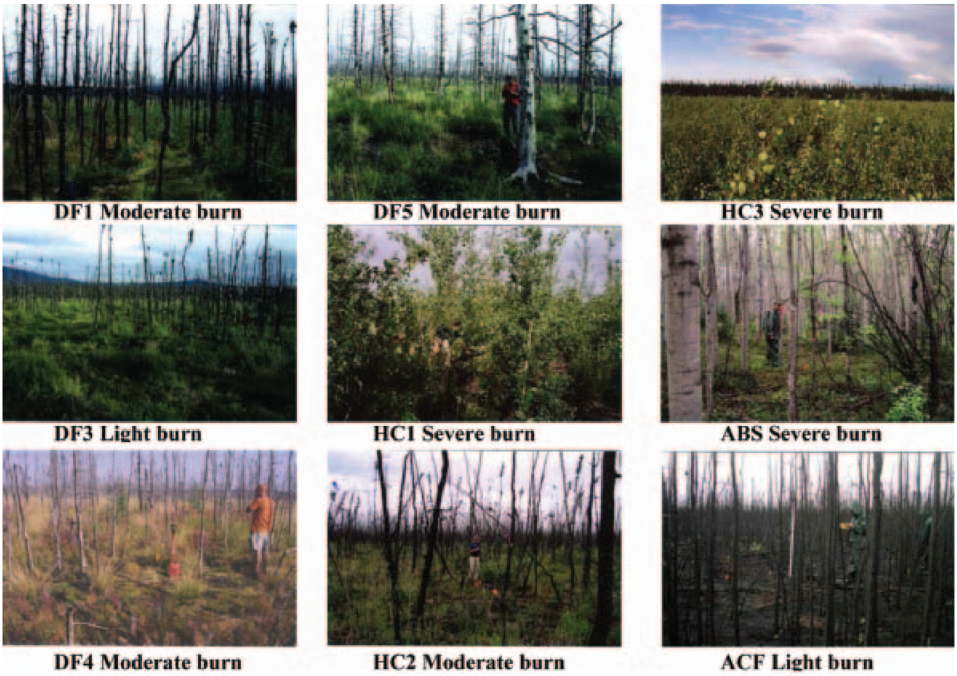


Figure 4. Photos of burned test sites and validation sites. Photos taken in 2003.

on flat land but contains some ridges (figure 1). Elevation gradually increases in the northern portion from 400–500 m and in the southern portion from 500–620 m, with a 15 m ridge seen as a linear feature within the burn (figure 1). This feature will always appear bright due to its orientation.

Table 1 presents biophysical parameters of the burned test sites as measured in 2003–2004. Both live and standing dead trees were sampled. DF2, a site measured only in 2000–2002 is similar to DF1, but it was not biophysically sampled in 2003. Sites DF4 and DF5 (figure 4) were sampled only in 2003–2004 and used as validation sites. Validation sites also included DF10 and 11 in 2001, and DF10-14 in 2002.

3.2 *Anderson study sites*

Anderson Alaska is located 128 km southwest of Fairbanks in a lowland region underlain by discontinuous permafrost on level topography. The Anderson Clear fire (ACF, a.k.a. Rex Bridge fire# B197) burned mostly black spruce, but also some aspen in the spring of 2003. The burn severity of this site ranged from lightly burned singed moss to severely burned with exposed mineral soil. Organic soil depth ranged from 4–18 cm at this site. In 2003 revegetation was low with less than 6% ground cover (figure 4). The second fire scar site in Anderson was burned in 1991 (Big Rex fire# B278) and consumed 624 hectares of primarily black spruce ecosystems. This site is referred to as the Anderson Burned Spruce (ABS) in our study. Regrowth at this site is of low density with willow clumps 2–3 m high scattered throughout. In 2003, vegetation covered 78% of the ground with primarily grasses and lesser amounts of labrador tea (*Ledum palustre*) and fireweed (figure 4). This site was more severely burned than ACF. Due to the small sizes of these burn scars, only one site

Table 1. List of biophysical parameters for the burned test sites sampled in 2003 and 2004 at Delta and Anderson Alaska. Top soil layers were variable across a test site, regenerating moss at these sites was between 0.5 and 1.0 cm depth, all layers exposed are listed.

Site	ABS	ACF	DF1	DF3	DF4	DF5	HC1	HC2	HC3
Major pre-burn species (>50%)	Black Spruce	Black Spruce	Black Spruce	Black Spruce	Black Spruce	Black Spruce	Black Spruce	Black Spruce	Black Spruce
Secondary pre-burn species (>20%)							Aspen		
Pre-burn density (# trees/ha)	14500	32233	2360	3420	3500	1010	6920	4490	60
Average pre-burn diameter (cm)	3.57	3.04	8.49	8.20	5.99	11.86	1.84	6.75	9.83
Average pre-burn height (m)	3.41	2.86	3.88	3.81	3.26	5.00	2.91	4.24	4.08
Total pre-burn biomass ($kg\,m^{-2}$)	1.13	1.84	1.76	2.18	0.97	2.85	0.27	1.93	0.05
Percent live tree biomass (%)	1	0	0	0	0	0	49	4	0
Average canopy closure (%)	7	4	5	5	5	4	27	8	13
Average ground cover (%)	78	6	55	54	37	50	26	56	77
Year of burn	1991	2003	1999	1999	1999	1999	1994	1994	1994
Burn severity	Severe	Low	Moderate	Low	Moderate	Moderate	Severe	Moderate	Severe
Depth to mineral	2–10 cm	4–18 cm	1.5–13 cm	5.5–14 cm	4–13 cm	3.5–9.5 cm	3–10.5 cm	8– 21 cm	4– 5 cm
Mineral soil type	Clay loam	Clay loam	Clay loam	Silty clay loam	Clay loam	Clay loam	Clay loam	Silty Cclay loam	Silt loam
Measured bulk density 12 cm depth sample ($g\,cm^{-3}$)	0.379	0.074	0.533	0.343	0.727	0.433	0.623	0.259	0.426
Top soil layers	Regen moss/ upper duff	Burned moss/ upper duff	Regen moss/ lower duff	Regen moss/ dead moss/ lower duff	Regen moss/ dead moss/ upper duff	Regen moss/ upper duff	Regen moss/ dead moss/ upper duff	Regen moss/ upper duff	Regen moss/ dead moss/ upper duff

per fire was sampled at the Anderson locations (table 1). These sites were used for validation of the Delta SAR moisture algorithms.

4. Field methods

Field sampling is essential to understanding the SAR signatures and developing models to monitor fuel moisture on the ground. Direct measurements of soil moisture, biophysical parameters and burn severity information were collected at all test sites.

Each of the test sites was chosen to represent a four hectare area of homogenous pre- and post-burn ecosystem type. Optimally the sites were set up in 200×200 m areas with two parallel transects 100 m apart and each 50 m from the ends. Five 10×10 sample plots were randomly selected along each of the 200 m long transects with a 25 m buffer at each end. Site characterization measurements included pre-burn cover type, density of trees, diameter (basal for black spruce, dbh for other species), tree height, groundcover, and depth of organic soil. Groundcover was visually estimated as percent cover within each 10×10 m plot by species.

We used methods defined by Dyrness and Norum (1983) and Viereck *et al* (1979) to measure burn severity in the field. Unburned Alaska black spruce forests are typically underlain by deep organic soil layers characterized by horizons of live moss, dead moss, somewhat decomposed moss (upper duff), and well-decomposed moss (lower duff) over a mineral soil. When a fire sweeps through these ecosystems, the organic soil layers are typically burned to various depths. Thus in our burned sites, the top 6 cm layers are sometimes singed moss, other times they are well-decomposed duff, and in other cases bare mineral soil. Thus, the degree of ground burn to a site to a large extent determines the composition of the exposed soil surface. The burn classes range from 1 to 5 and are described as:

(1) unburned moss
(2) singed moss
(3) light burn, moss layer burned down to humus with no moss regrowth
(4) moderate burn, surface burned almost to mineral soil with some moss regrowth
(5) severe burn, mineral soil exposed

Sampling of soil moisture was timed to coincide within 24 hours with radar satellite overpasses. The moisture was measured using a water content reflectometer, Campbell Scientific Hydrosense (CS620) instrument. Five samples were measured at each plot in the top 6 cm of the soil surface. Since the probes are 12 cm long, they were inserted at a 60° angle for 6 cm depths. Five samples were also collected at each plot with the probe in the vertical position. This was especially important for dry periods since radar penetration has been found to be greater than a wavelength (5.7 cm) when the organic medium is dry; this is especially true for the low bulk density organic soils of Alaska. A total of 50 samples at each depth were collected on each observation date at a given test site. Note that while moisture was optimally recorded at 6 cm and 12 cm depths, in some cases records of 12 cm depths were not made due to frozen soil or rocks in the 6–12 cm depth. Also, in 2002, only 12 cm measurements were collected and only at the DF study area.

The mean of these samples per depth per site was then calculated and converted to percent volumetric moisture using algorithms which we developed specifically for the Alaskan organic soils. The Hydrosense instrument has a built-in calibration algorithm for a loam mineral soil which is not applicable to organic soils. This type of water content reflectometer was designed and tested for use in agricultural mineral soils and works best in loams with bulk densities $\leqslant 1.55\,g\,cm^{-3}$. In the organic soils of Alaska, we have measured bulk densities of 0.032 to $0.727\,g\,cm^{-3}$ for our test sites (table 1). In 2003–2004 soil samples of known volume were harvested from each test site for development of site specific calibration algorithms. Details about the accuracy of the Hydrosense probe and the calibration to the organic soils of Alaska are provided in Garwood *et al* (2006).

5. Individual date soil moisture mapping: SAR methods and analyses

Five years of SAR data were used in the development of the algorithms (or models) relating backscatter to soil moisture for individual date soil moisture mapping. In analyzing the multiple years of ERS-2 SAR data we discovered a decreasing trend in the data over time which needed to be removed through a normalization process. Note that the seasonal soil moisture principal component analysis presented in §6 was performed prior to the discovery of the trend in the SAR data. This should not be a problem because analyses of data within a season are minimally affected by the decreasing trend. However, caution should be taken in comparing between years.

5.1 *Normalization of ERS-2 SAR imagery*

The ERS-2 sensor has shown excellent quality and radiometric calibration over the first nine years of the mission (Meadows *et al.* 2004). However, there has been a decrease in the SAR transmitter pulse power of 0.66 dB per year until 2000 and 0.82 dB until February 2003 resulting in an increase in the noise equivalent radar cross-section. The gain was then increased by 3 dB in February 2003 and the noise equivalent radar cross-section was estimated at −23.3 dB in early 2004 (Meadows *et al.* 2004). The loss in gain in the processing of the ERS-2 SAR imagery may be accounted for by use of the replica pulse power. 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, our data were processed by the Alaska Satellite Facility (ASF) which does not use the pulse replica power in calibration. Therefore it was necessary for us to normalize our data post-processing using the published pulse replica power information (Meadows *et al.* 2004). ASF references all data to 1998 measurements, so we also conducted the correction with reference to 1998 pulse replica power measurements. Note that this loss in power is characteristic of ERS-2 but not ERS-1, which was stable throughout its lifespan.

5.2 *Individual date soil moisture mapping procedure*

Using the burn severity assessments conducted in the field (table 1), the DF and HC test sites with similar burn severity categories were grouped for analysis. This resulted in four sites in the moderate burn category including sites 1 and 2 from DF and sites 2 and 4 from HC; two sites in the severe burn category including sites 1 and 3 from the HC burn; and one site in the low burn severity category, site 3 from DF. Our soil moisture *in situ* data were then used to investigate the relationship between soil moisture and ERS-2 SAR backscatter within these groups. *In situ* moisture collected at the sites within each burn severity group on the various dates and years were analyzed together. All dates of data collection that had rainfall recorded (either by the local weather station or by the field crew) were not included in the model development, unless the moisture values were above 30% which would indicate that the sites were wet prior to the current rain event. This eliminated problems with backscatter being elevated due to moisture on the vegetation and litter layer which are not indicative of the soil moisture.

The individual date model development procedure consisted of parametric methods including Pearson correlation and linear and polynomial regression development. All regression models were considered good if they had a coefficient of determination greater than 0.55, low standard error, and were significant with a p-value less than 0.05. The simplest model was sought, therefore in choosing a polynomial model over a linear model, the coefficient of determination had to increase by more than 5% and standard error decrease by at least 5% or the polynomial model was abandoned. All regression algorithms were tested for the assumptions of the model including normality and homogeneity.

Once the models were developed and tested, they were applied to several SAR scenes for mapping soil moisture condition across the burn scar. To do this we first segmented the entire DF burn into burn severity classes using Landsat mapping techniques developed by Michalek *et al* (2000). The Michalek *et al.* (2000) method uses the first six channels of Landsat to create maps of burn severity to the ground layer as defined by Dyrness and Norum (1983). The DF site was thus segmented into three classes; light, moderate and severe (figure 5). These maps were checked with *in situ* measured burn severity described above. Once the SAR scenes were segmented, we applied the SAR-soil moisture algorithms to the image pixel values to create maps of soil moisture. The resulting moisture maps were then validated with *in situ* data not used in the development of the maps or algorithms.

5.3 *Algorithm development of soil moisture condition based on ERS-2 SAR backscatter*

By segmenting the sites into burn severity groups and then analyzing the relationships between 6–12 cm *in situ* soil moisture within these groups and ERS backscatter, we developed fairly strong correlations (table 2). All Pearson correlations were greater than 0.74. The 6 cm soil moisture correlations with SAR were better than 12 cm for all burn severity groups (table 2). Also note that the 6 cm measurements were strongly correlated to the 12 cm for the severe and moderate burn categories ($r=0.87$ and 0.94, respectively). This is probably because at the moderate and severely burned sites the vertically inserted probe is entering the mineral soil at both 6 and 12 cm depths, but for the low burn severity sites, the 6 cm probe is entirely in organic soil while the 12 cm probe is crossing over the mineral soil layer boundary, in many cases. We therefore focus on presenting 6 cm moisture measurements in the regression section, except for the low burn severity analysis.

5.3.1 Moderate burn severity moisture model development. The simple linear regression model developed for 6 cm *in situ* moisture collected at the moderate burn sites of HC and DF versus ERS-2 backscatter (figure 6) resulted in a strong relationship with a coefficient of determination of 0.82 and a significant sample size ($n=36$). Another moderately burned test site located in Donnelly Flats (DF4) and monitored in 2003–2004 was used for validation (overlaid square points of figure 6). These points fall within the bounds of the modelled data and present a tighter fit around the regression than the modelled data.

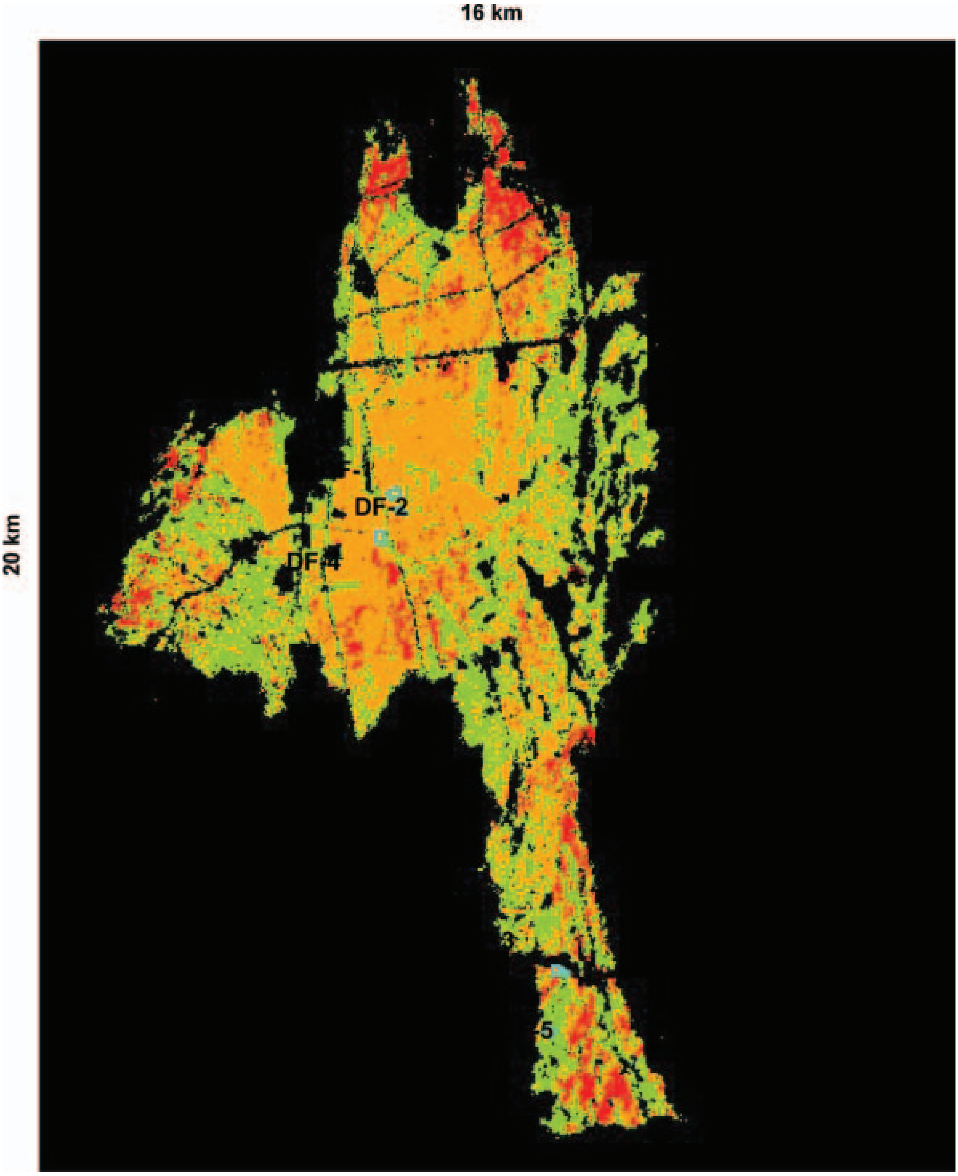


Figure 5. Landsat-derived burn severity map of the Donnelly Flats 1999 burn (from David Williams and Eric Kasischke UMd, 2001). Red=severe burn (>80% mineral soil exposed); orange=moderate burn severity (>15% <80% mineral soil exposed); green=low burn severity (<=15% mineral soil exposed). DF-1 to DF-5 are plotted with cyan boxes for reference.

5.3.2 Severe burn severity moisture model development. For the severely burned HC sites (HC 1 & 3, figure 7), a simple linear model was developed for SAR backscatter versus soil moisture with a coefficient of determination of 0.59 and a significant sample size (n=32). Data were collected between 2000–2001 and 2003–2004. No *in situ* data were collected for HC sites in 2002. Moisture at the severe burn sites in 2000–2001 ranged from 22–62% in the upper 6 cm. In 2003 it ranged from 15–26%, and in 2004, one of the driest summers on record, moisture ranged from

Table 2. Pearson correlation coefficients for the 6 and 12 cm *in situ* moisture measurements of the various burn severity categories versus ERS SAR Backscatter. Note that sample size varies by depth in some cases and all rain dates are included.

	Severe burn (2000–2001) *n=34*		Moderate burn (2000–2001 & 2003–2004) *n=42 (49)*		Low burn severity *n=12 (14)*	
	6 cm	12 cm	6 cm	12 cm	6 cm	12 cm
ERS backscatter	0.77	0.74	0.87	(0.81)	0.83	(0.79)
6 cm		0.87		0.94		0.78

7–31% (with 31% occurring in May). Due to the cold climate and often permafrost conditions, boreal soils are often waterlogged beneath the surface. These moisture ranges are comparable to values reported by Jandt *et al.* (2005) and Ferguson *et al.* (2003). To validate the model, we have plotted data from another severely burned test site near Anderson Alaska (ABS). These data were collected in 2003–2004, and ranged from 12–42% moisture. The validation data fall within the bounds of the modelled data. Also presented are the data from all severely burned test sites that were eliminated from the original plot due to recorded rain, either by the local weather station or by the field crew. The data collected on rain dates for the most part land within the bounds of the modelled data. However, the triangle that is an outlier is from 23 July 2004 when 0.63 inches of rain were recorded at Anderson. The other dates had light rain which did not affect the backscatter at these sites. Note that the slope of the severe burn algorithm is much flatter than the moderate burn curve. The range in backscatter is also smaller (7 dB) versus the moderate burn site (>9 dB). The severely burned sites have greater revegetation post-burn which is likely attenuating more of the signal from the soil surface.

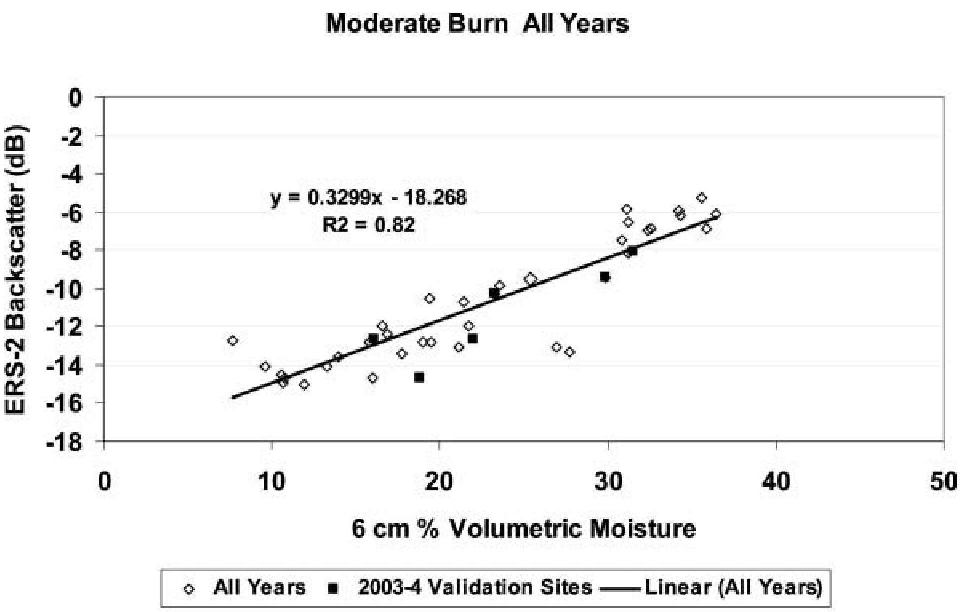


Figure 6. Plot of moderate burn backscatter from Hajdukovich Creek and Donnelly Flats moderate burn sites for years 2000, 2001, 2003, and 2004 with linear fit. 2003–4 validation sites are overlaid for comparison.

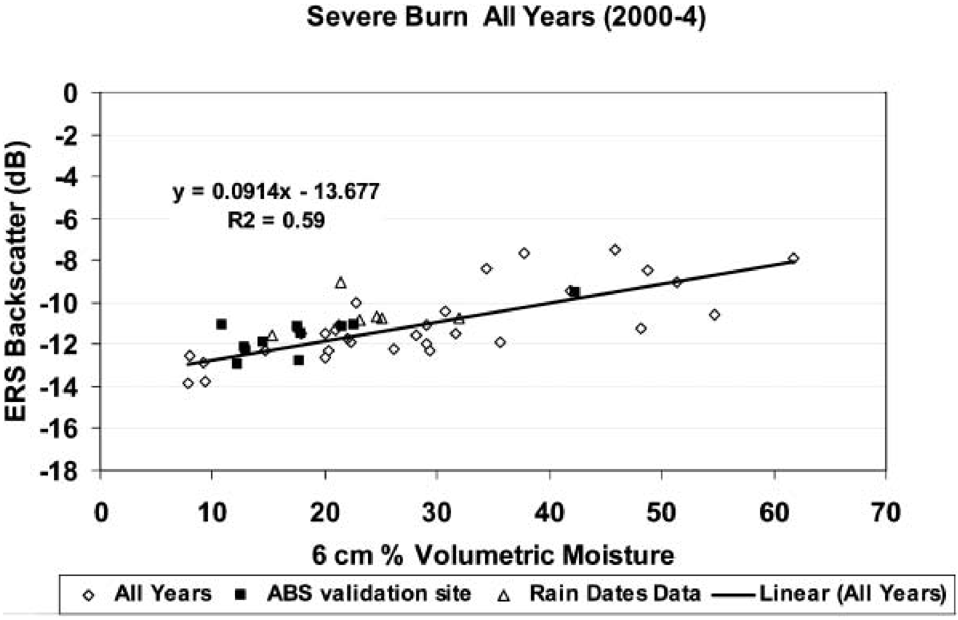
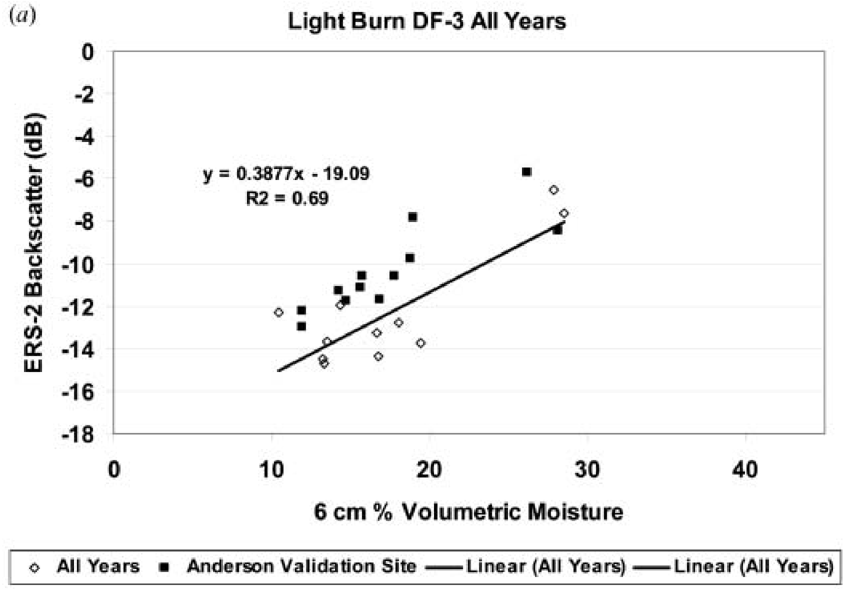


Figure 7. Plot of ERS-2 backscatter versus *in situ* moisture collected at the two severely burned sites of HC (HC1&3), with 2003–4 Anderson burned spruce (ABS) as validation. Data from rain dates are also overlaid.

5.3.3 Low burn severity moisture model development. For the low burn severity site (DF3) the sample size was smaller (12), but a simple linear regression fit the data well (R^2=0.70). A 2003–2004 test site near Anderson (ACF) that was also lightly burned was used as a validation site (figure 8(*a*)). The ACF site shows slightly higher backscatter for each 6 cm moisture level than DF3. This may be due to the thicker singed moss/upper duff layer at the Anderson site and thus deeper penetration by the SAR. Although, theoretically the penetration depth of a medium is a single wavelength (5.7 cm for C-band), the moss is very light and airy and the SAR likely penetrates it more than a wavelength when it is dry. In fact we found SAR penetration of dry singed moss/upper duff to be greater than 12 cm in a laboratory experiment where we placed a 12 cm deep sample from DF3 in a chamber with perfect absorbers and illuminated it with C-band microwave energy (Bourgeau-Chavez *et al.* 2000b). Therefore our 6 cm moisture samples at the Anderson ACF site would not be as well correlated to the SAR backscatter because the singed moss and upper duff is often deeper than 6 cm. When data from the 12 cm probes were related to ERS-2 SAR backscatter it resulted in a regression (figure 8(*b*)) with a slightly lower coefficient of determination (0.62) than the 6 cm plot, but a smaller bias between the Donnelly Flats and Anderson data. This indicates that the SAR may be penetrating deeper than 6 cm into the low bulk density singed moss and upper duff of the ACF site.

5.3.4 ERS-2 SAR soil moisture mapping and validation. The regression analyses and validation with independent sampling sites demonstrate that there are strong correlations between patterns of soil moisture in recently burned boreal forests of Alaska and ERS-2 SAR backscatter when the burned areas are segmented by burn severity. In all cases simple linear regressions were the best fit to the data with fairly



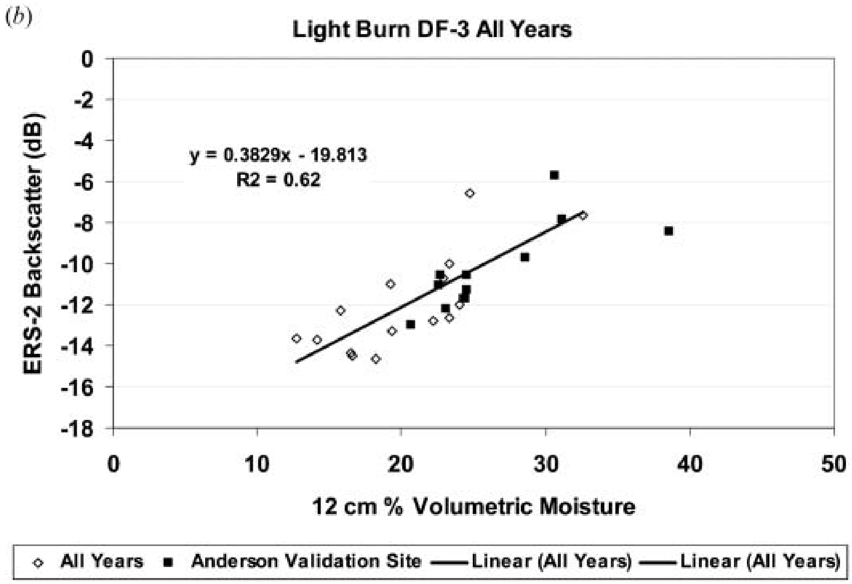


Figure 8. (*a*) Plot of 6 cm depth and (*b*) 12 cm depth volumetric soil moisture versus ERS SAR backscatter in dB at the low burn severity DF3 site. Data from the 2003–4 low burn severity Anderson site (ACF) were overlaid for validation.

high coefficients of determination, low standard errors and p-values less than 0.05. Higher order regressions did not significantly improve the models and they were therefore not reported.

The relationships developed between ERS-2 backscatter and soil moisture allow the use of SAR to monitor variation in soil moisture at a given site over time, but also indicate that moisture sensing between burned sites is possible if the sites are categorized by burn severity.

The next step was to map spatially varying soil moisture patterns across the burn scar using the empirically-derived regression model algorithms. The algorithms were therefore inverted (table 3) and then applied to four dates of ERS-2 imagery from 2002 (data not used in the algorithm development) over the DF burn scar. These images represent both wet and dry conditions and *in situ* data were available from two of the image dates for validation, although only 12 cm depths were measured in 2002.

The SAR data were first filtered to reduce speckle using a 5×5 averaging window. Next the image data were segmented by burn severity class based on Landsat-derived burn severity maps, and converted to dB. Finally the corresponding 12 cm moisture prediction algorithms of table 3 were applied to the SAR segmented data. Figure 9 shows the four moisture prediction maps created through this method.

For validation of these maps, 12 cm *in situ* data collected on 24 June and 14 August 2002 were compared to map values of predicted moisture (table 4). The difference between the predicted and *in situ* moisture ranges from +4.79 to −7.54, with a mean of −1.94. Overall the comparison to *in situ* data showed a fairly good agreement between predicted and actual measurements, with a low rms error (3.61 volumetric soil moisture). Optimally a more strict validation exercise would be conducted since these two images (22.9–32.9%) do not represent the full range of moisture conditions. However, due to time and budget constraints such an exercise was not feasible.

This analysis and validation demonstrates the ability to remotely map soil moisture across a burned boreal forest on an individual date when the site is segmented by burn severity. This capability has many applications from inputs to ecological models to monitoring moisture patterns for fire danger prediction (Bourgeau-Chavez *et al.* 2005a, 2005b). However, to thoroughly understand the moisture dynamics of a site, one needs to also observe how the site responds to drying and rainfall throughout a growing season and not just on an individual date. Observation of a time-series of data provides a better indication of drainage characteristics of a site, i.e. poorly-drained versus well-drained conditions, than observing one or two dates of data.

6. Seasonal soil moisture index maps

A recently burned boreal forest often exhibits an initial increase in ground moisture post-burn. However, as the depth to the permafrost layer increases and vegetation

Table 3. Inverted simple linear regression models for soil moisture prediction and statistics for the Delta Junction soil sampling sites, grouped by burn severity. R^2=coefficient of determination, SE=standard error, m=slope, b=intercept. Note that rain dates have been removed.

Model	Sample size	*p-value*	R^2	SE	m	b
Severe burn 6 cm	28	<0.0005	0.59	9.25	6.4327	99.807
Severe burn 12 cm	31	<0.0005	0.56	9.128	5.9324	95.093
Moderate burn 6 cm	32	<0.0005	0.82	3.84	2.4724	49.344
Moderate burn 12 cm	38	<0.0005	0.69	4.9	2.3076	49.23
Low burn 6 cm	12	0.001	0.69	3.434	1.7854	39.461
Low burn 12 cm	14	0.0008	0.62	3.312	1.6244	39.843

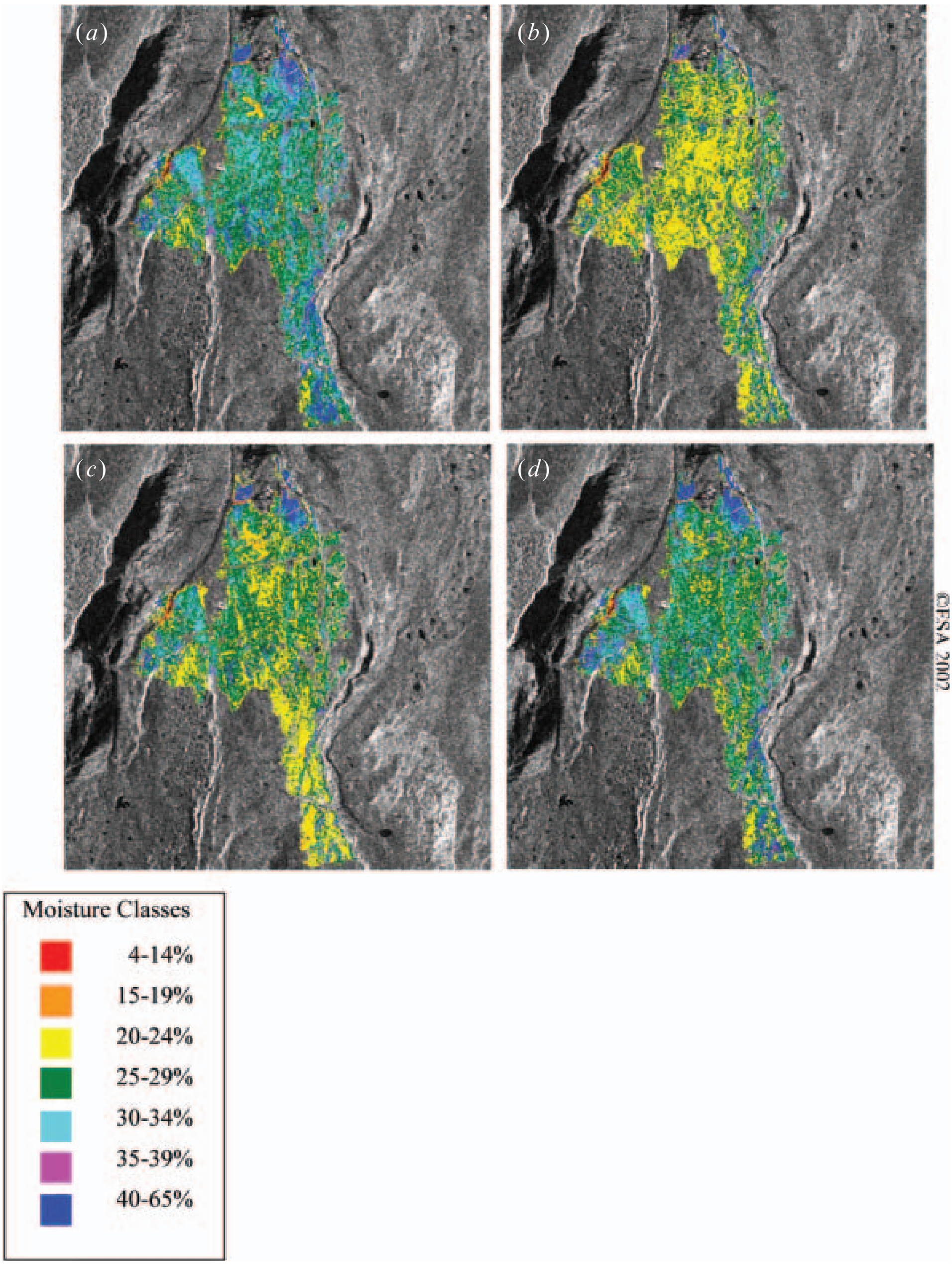


Figure 9. Individual date patterns of 12 cm soil moisture maps for the Donnelly Flats 1999 burn. Data are from 2002: (*a*) 17 May; (*b*) 24 June; (*c*) 26 July; and (*d*) 14 August.

regrows (causing increased transpiration) the moisture patterns change. To observe these changes, we assumed that the large dynamic range in ERS SAR backscatter from a burn scar over a season was dominated by variation in soil moisture and that we could retrieve that information by reviewing a time-series of images through principal component analysis (PCA). One advantage of using PCA is that the PC-loadings can be tied to *in situ* data. The loading of each input image with each

Table 4. Comparison of *in situ* data collected on 24 June and 14 August 2002 to predicted soil moisture at those sites in Figure 14.

Date	Site	Predicted moisture	*In situ* moisture	Difference	Difference^2
24-Jun-02	DF 1	25.18	24.92	0.26	0.07
24-Jun-02	DF 2	21.57	25.22	−3.65	13.33
24-Jun-02	DF 3	23.04	22.90	0.14	0.02
24-Jun-02	DF 10	23.25	26.28	−3.03	9.18
24-Jun-02	DF 11	23.25	27.90	−4.65	21.65
24-Jun-02	DF 12	21.82	24.24	−2.42	5.84
24-Jun-02	DF 13	21.26	28.80	−7.54	56.91
14-Aug-02	DF 1	30.91	29.94	0.97	0.95
14-Aug-02	DF 2	28.48	32.92	−4.44	19.71
14-Aug-02	DF 3	28.10	23.31	4.79	22.97
14-Aug-02	DF 10	27.29	33.15	−5.86	34.34
14-Aug-02	DF 11	28.74	31.13	−2.39	5.70
14-Aug-02	DF 12	27.47	27.28	0.19	0.04
14-Aug-02	DF 13	27.23	29.29	−2.06	4.25
14-Aug-02	DF 14	26.31	25.77	0.54	0.29
			Mean	−1.94	13.02
			rms error		3.61
			% rms error		13.1%

principal component was calculated after Jensen (1996) using the formula:

$$R_{kp} = \frac{a_{kp} * \sqrt{\lambda_p}}{\sqrt{Var_k}}, \qquad (1)$$

where a_{kp}=eigenvector for image date k and component p, λ_p=eigenvalue for component p, and Var_k=variance of image date k in the covariance matrix

A time-series of six to eight images from several growing seasons (May to September) were gathered for the two fire scars from Delta Junction Alaska. All of the images in a series were chosen from either ascending (overpasses at 23:00) or descending orbits (overpasses at 11:00) to minimize between-scene differences due to diurnal variation and scene orientation. The principal component analysis procedure was applied to each time-series of georectified image sets using Erdas Imagine software. The method we used to create seasonal soil moisture indices is based on the assumption that those areas that are wet (bright in the SAR) on some dates and quickly dry out (dark in the SAR on subsequent dates) would be more well-drained than sites that stay wetter and thus remain brighter in the SAR imagery through time. Rainfall and Fire Weather Index data, as well as *in situ* moisture were used for validation of these maps.

To create seasonal soil moisture index maps of our Delta burn scars, we reviewed SAR imagery of the HC 94 fire in year one post-burn (1995) and again in year six post-burn (2000). For comparison, we reviewed the DF 99 burn in each of the first three years after the burn (2000–2002).

We begin with a detailed description of the PCA process for the 1995 ERS-1 analysis of the HC burn, followed by a presentation of all products and validation. In all cases the second or third principal component was found to be highly correlated to soil moisture variation. Relative drainage conditions were mapped by level slicing the principal component image that was best correlated to soil moisture variation.

6.1 *1995 Hajdukovich Creek principal component analysis*

For the 1995 HC 94 PCA, a time series of six ERS-1 images from 1995 were used as input (figure 10). The burned area and surrounding unburned forest were included in the PCA input, but the mountains were eliminated due to errors in registration from different viewing angles (orthorectification was not applied). The first two principal component images (PC1 and PC2) derived from this series of input images are presented in figure 11. PC1 shows stable scene elements such as the river, the buffalo field (figure 1), topographic relief, roads, and burned versus unburned areas. The PC2 image can be used to map the exact outline of the fire and areas that did not burn within the outer boundaries. PC2 shows high variation across the burn scar, and low variability in the unburned surrounding forest. PC2 also has patterns within the burn that are similar to the Landsat-derived burn severity map, with low burn severity areas showing up bright on PC2 and severe burn severity areas generally showing up quite dark.

Ideally, we would compare the PC loadings (loading is the relationship of each input image to the new PC image) to *in situ* soil moisture data, but in 1995 we did not collect *in situ* soil moisture. Therefore, to determine which, if any, of the our PC images were related to soil moisture we used the rain data and fuel moisture codes calculated from a nearby weather station (Allen Army Airfield north of Donnelly Flats burn, see figure 1). The fuel codes are calculated from weather data using the Canadian Forest Fire Danger Rating System's Fire Weather Index (Van Wagner 1987). These codes provide an overall indication of moisture in the region based on a book-keeping of weather conditions. We chose to use these codes in lieu of *in situ* moisture because they provide a good indication of the overall fuel moisture of the landscape. We then used the fuel moisture codes in comparison to the loadings for each input image date.

For the 1995 HC data there was a strong relationship between loadings for PC2 and the fine fuel moisture code (FFMC, r=0.83), which is representative of moisture

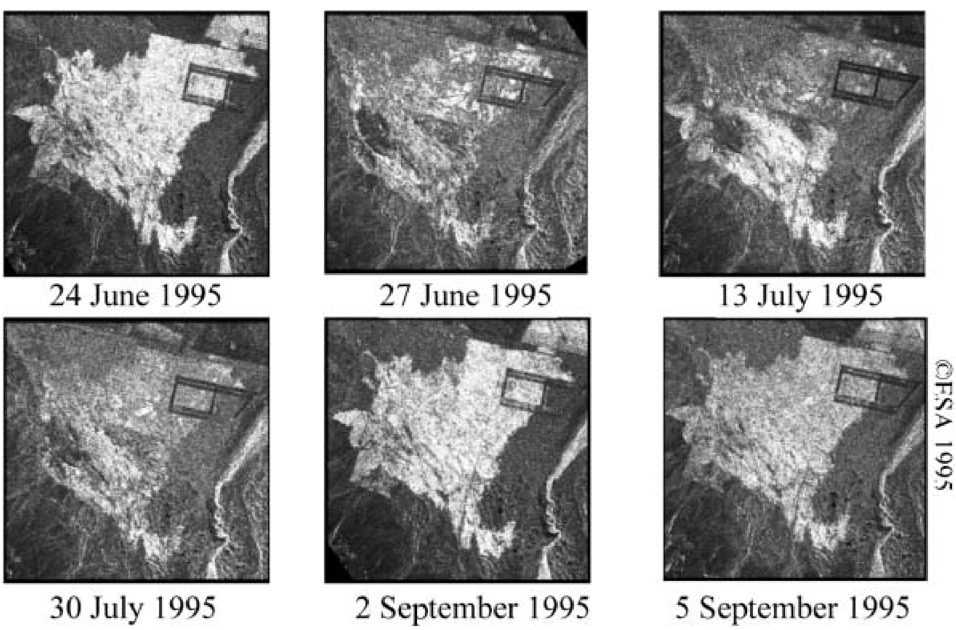


Figure 10. Six input calibrated ERS-1 Images for Principle Component Analysis of the Hajcukovich Creek 1994 Burn.

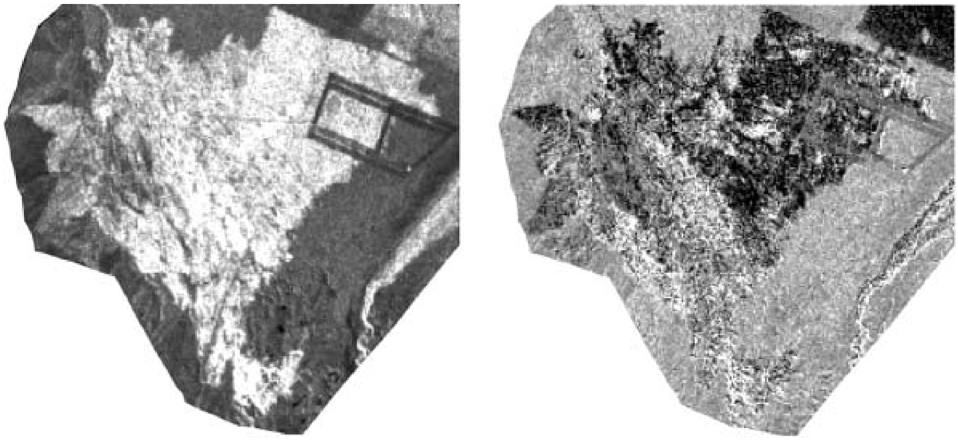


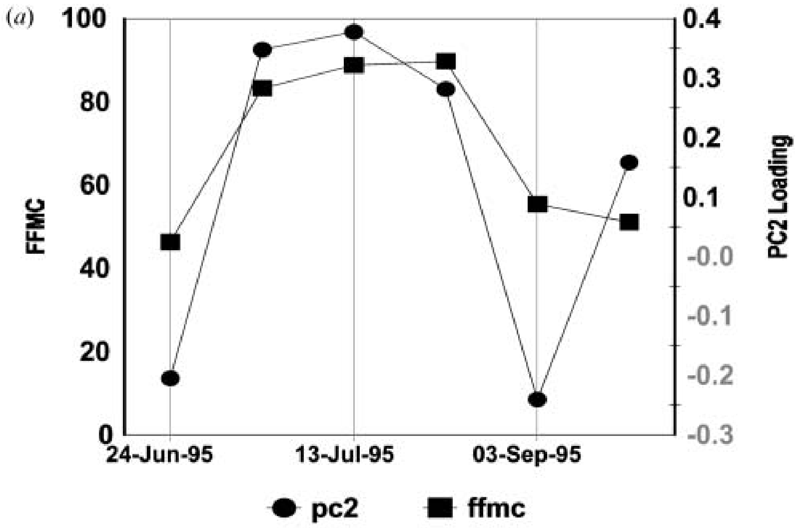
Figure 11. The first two Principal Component images (PC1 and PC2) from the input of six ERS images from 1995 collected over the Hajdukovich Creek burn.

in the top few cm of the ground litter layer in an unburned forest. A strong inverse relationship to rainfall ($r=-0.68$) also occurred for the 1995 HC dataset (figure 12).

Using PC2 to represent an index of seasonal soil moisture, we level sliced the image and then colour-coded it to represent four levels of relative soil moisture or drainage classes (figure 13). The burned area was extracted from the PC2 image using the burn boundary from the Alaska Fire Service database. This boundary was likely based on aircraft reconnaissance and includes some unburned areas, which show up "blue" or "wet" since the change in backscatter over time is low from non-burned sites just as temporal variation is low in wetter sites.

6.2 *1995 Hajdukovich Creek principal component analysis product validation*

Since *in situ* data collections at the HC site began in the 2000 season, *in situ* data do not exist for validating our soil moisture product created from 1995 PC2 imagery. Thus, we used a pseudo-validation method described by Verhoest *et al.* (1998). Verhoest *et al.* (1998) mapped soil moisture variation in the Zwalm catchment using 8 ERS images and compared their results to drainage maps with good agreement. They found the second PC to show strong resemblance to soil drainage maps. Note that soil drainage maps for Delta Junction were not available with high enough spatial resolution for comparison to our map. To test the accuracy of their maps, Verhoest *et al.* (1998) hypothesized that the positive PC2 values represented areas of high seasonal soil moisture and poor drainage and that the negative PC2 values represented areas of low seasonal soil moisture and better drainage. To test this they plotted the mean backscatter value from each input image that represented those areas in the PC2 image with positive (bright) PC values against mean backscatter from each input image that corresponded to those areas in the PC2 image with negative (dark) PC values. They also plotted rainfall patterns on the graph. When we do this it is apparent that backscatter observed in the input images that represent the positive PC2 values tend to stay brighter over time and react less strongly to rainfall and drying. The backscatter from each of the input images that is representative of the negative PC2 values reacts quickly to rainfall, with backscatter values becoming equal to or greater than that in the positive PC2 areas, but the backscatter quickly declines in non-rain conditions (figure 14). These patterns are



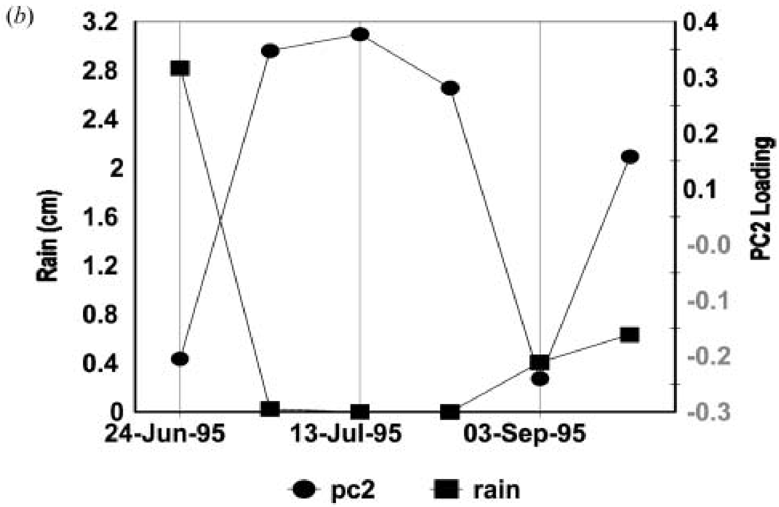


Figure 12. Summer of 1995 plot of PC2 and FFMC (*a*) by date and PC2 and rain (*b*) by date for the HC 94 burn ERS-1 dataset.

indicative of well- (negative PC2) versus more poorly-drained (positive PC2) conditions. Note that the opposite could also occur, with negative PC2 values representing well-drained sites and positive PC2 values poorly-drained sites. Knowing that dark areas of our PC2 image represent well-drained areas and bright (positive) areas of the PC2 image represent more poorly-drained conditions helps to verify our 1995 HC seasonal soil moisture map.

6.3 *2000 Hajdukovich Creek principal component analysis validation*

In 2000 *in situ* soil moisture sampling began, therefore our 2000 HC 94 map (figure 15) could be validated with actual soil moisture measurements. We used the three permanent field sites where *in situ* moisture was collected continuously with

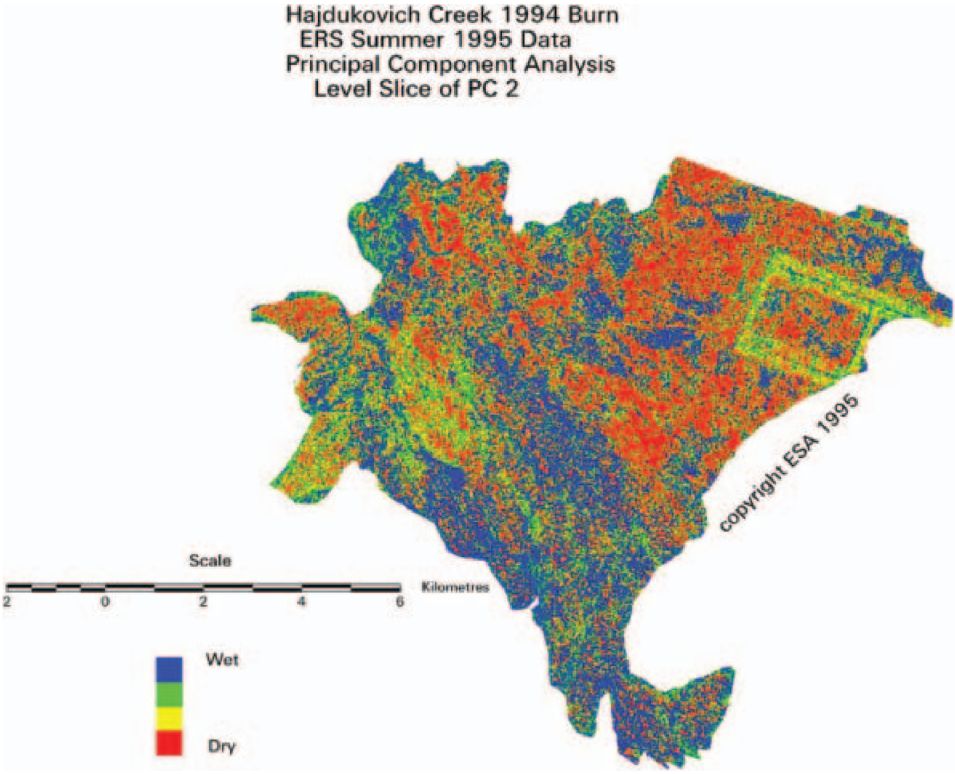


Figure 13. 1995 seasonal soil moisture index map for the HC 1994 burn site based on a time-series of six summer ERS-1 SAR images.

data loggers in the deeper soil layers as validation for this map (table 5). The permanent sites (PS) monitored in 2000 had 30 cm long Campbell Scientific CS615 probes inserted at various depths horizontally in a single location to monitor change in moisture over the season. These probes were installed in the spring and left in place all summer. However, as one probe stopped working in July, and two were not installed until 9 June, we used the data from June 9 to July 17 for all four probes in table 5. Also, at the time of this study the *in situ* moisture measurements collected with the CS615 probes were calibrated for mineral soil whether the samples were organic or mineral. We therefore used the deeper soil layers for validation because they represented mineral soil and were a better indicator of soil drainage conditions than the top layers. Post study, CS615 calibration to organic soils was completed by Garwood *et al.* (2006).

Based on our *in situ* data, the map appears to be fairly accurate. When comparing *in situ*, it is important to look not just at the volumetric soil moisture measurements but at the range and standard deviation of these measurements (table 5). Sites with a higher degree of variation will generally have better drainage than sites that have more constant soil moisture.

The driest site (red on the map of figure 15) is HCPS3. This site has a large range in volumetric soil moisture (11.3%) and a higher standard deviation (3.5) than site HCPS1 which has a similar mean *in situ* moisture (~43%) but a smaller range of moisture values (7). HCPS3 is a severely burned site with exposed mineral soil and

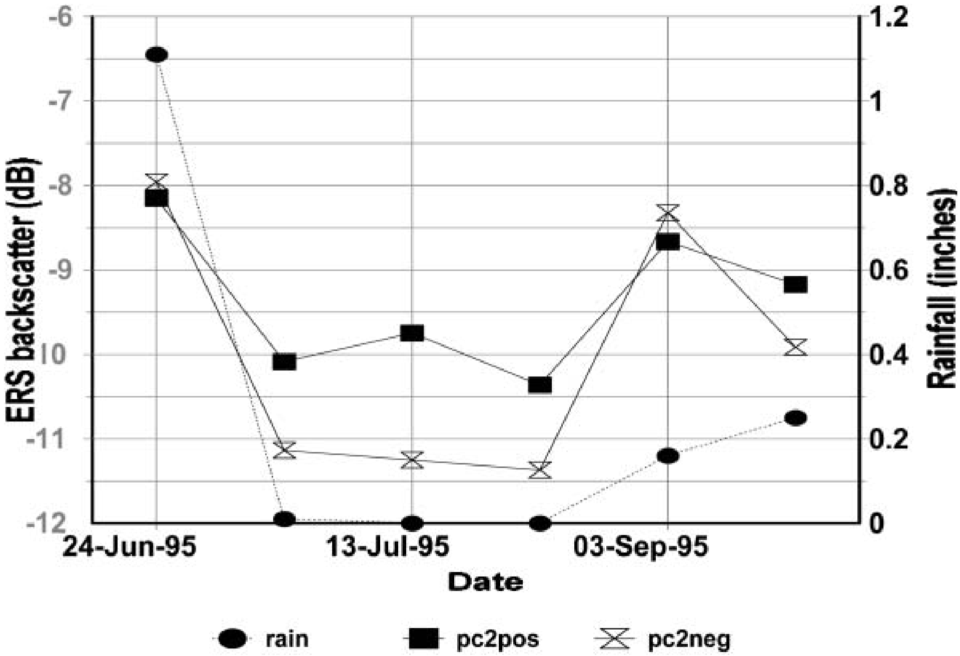


Figure 14. Plot of rainfall versus mean backscatter from areas of the HC fire scar with positive PC2 values (x) and backscatter from areas with negative PC2 values (boxes). Rainfall (y2 axis) is from day of overpass.

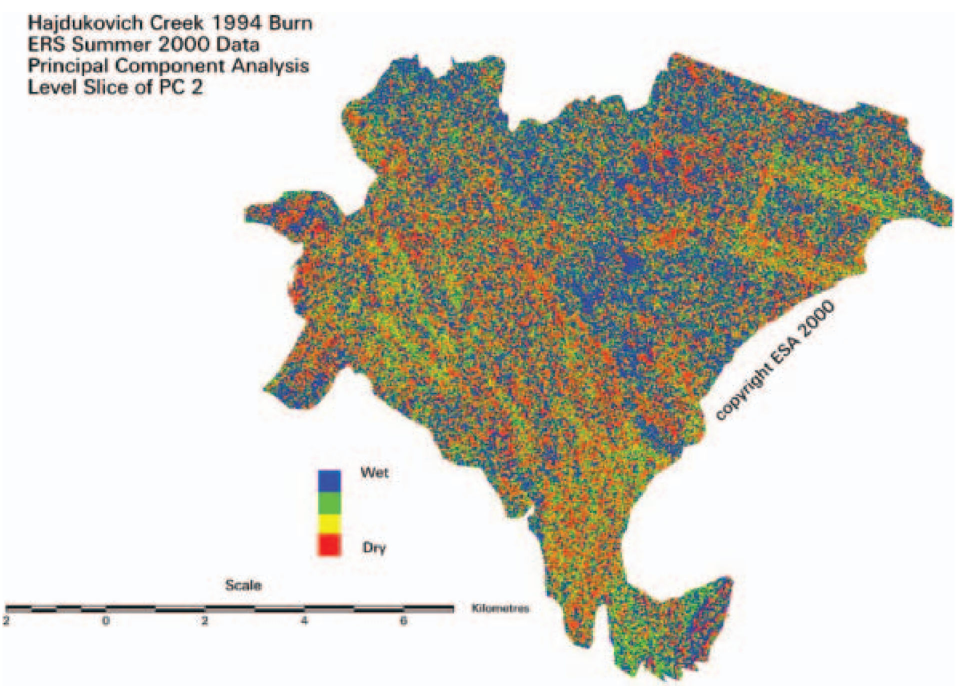


Figure 15. 2000 soil moisture index map derived from principal component analysis of six seasonal ERS-2 images of the 1994 Hajdukovick Creek burn.

Table 5. *In situ* volumetric soil moisture (VSM) and field observations compared to the appearance of the 3 sampling sites of the Hajdukovich Creek 1994 burn in 2000, and one site at Donnelly Flats. *VSM measured at 25 cm for PS1 and PS3 and 15 cm for PS2*.

Site	Appearance soil moisture index map	Map wetness	Burn severity	*In situ* VSM mineral	Range of VSM	Mean and standard deviation	Field observations
HC PS1	Yellow-multi	Moderately dry	Severe	40–47	7	43.3+/−1.5	Organic soil <2 cm
HC PS2	Red with some blue-green	Moderately Dry	Moderate	50–61	11.2	54+/−3.97	More than 5 cm of fibric soil
HC PS 3	Red	Dry	Severe	38.7–50	11.3	43.9+/−3.5	Mineral soil
DF PS1	Yellow-green-multi	Moderately wet	Moderate	54.5–57.6	3.1	56+/−0.8	Wetter site with singed moss

appears to be mapped correctly as a well-drained site. HCPS1 appears to also be mapped correctly as less well-drained with more stable moisture conditions.

If we extend the moisture observation period back to 15 May 2000, a week after the loggers at HCPS1 were installed, the mean increases only slightly from 43 to 45%, the range from 7 to 10 (39.8 to 49.9%) and standard deviation from 1.5 to 2.9. But if we observe moisture for site HCPS3 beginning on 15 May 2000, then the mean increases more substantially from 43 to 50%, the range greatly increases from 11 to 29 and the standard deviation from 3.5 to 8.5. Based on *in situ*, HCPS3 is a considerably better-drained site.

The last validation site of Hajdukovich Creek, HCPS2, was moderately burned with more organic soil remaining post-fire. This site appears blue-green with many red (dry) areas. It is the wettest of these three test sites based on the *in situ* data (mean of 54% moisture from June to July). The *in situ* is a point measurement, not distributed over four hectares as the water sites sampled with the Hydrosense were. The central GPS point of HCPS2 falls in one of the blue-green areas of the map. If we look at this site until September 16 (it was installed on 9 June so we cannot go back to 15 May), then the mean drops slightly to 50% but the standard deviation does not go up much (it increases to 4.2), and the range increases somewhat from 11.2 to 15.2. This site is less variable over time than HCPS3, with much higher moisture, and thus is more poorly drained.

6.4 *2000 Donnelly Flats principal component analysis validation*

The 2000 Donnelly Flats PCA was based on seven input ERS-2 SAR scenes from 15 May to 13 September (figure 16). This site is mostly flat land but contains some ridges of only 15 m, but they appear as bright linear features in the imagery (figure 1). The ridge within the burn should be ignored in the soil moisture map. *In situ* measurements occurred only from 8 June to September of 2000 for DFPS1 at 23 cm depth and there were no other permanent sites at Donnelly Flats. DFPS1 shows the lowest range in moisture and the lowest standard deviation as compared to the HC sites, demonstrating that it is a relatively wet site, as was noted by field observation. The permanent site measurements ended in 2000, so the trends in the 2001 and 2002 DF maps were compared to rainfall patterns for validation.

6.5 *2001–2002 Donnelly Flats principal component analysis validation*

The principal component analysis for 2001 was based on eight input ERS images from 16 May to 29 August 2001 (figure 16). In comparing the 2001 map to that of 2000, the 2001 map is less blue-green and more red-yellow. The overall drier conditions represented in the 2001 soil moisture index map were also observed in the cumulative rainfall plots from 2000 to 2002 (figure 17) from the Fort Greely weather station. However, in the 2001 map while many of the wet sites (blue in 2000) got a little drier (green-yellow), many of the dry sites (red in 2000) got a little moister (yellow). The increase in yellow sites may be due to the timing of the rainfall and/or the timing of our ERS-2 collections. Rainfall patterns were similar in 2000 and 2001 until mid-July 2001 when over 6 cm was received, while 2000 remained relatively dry until about 11 August 2000, when more than 6 cm of rain was received and the 2001 plot flattens out (figure 17). 2001 was a much drier year overall (13.97 cm of rain from May to 31 August) than 2000 (19.3 cm of rain from May to 31 August), and 2002 (20.57 cm of rain from May to 31 August) was slightly wetter than 2000. However, the pattern of rainfall in 2002 was steady over the season, while 2000 had a dry period from mid-July to 11 August.

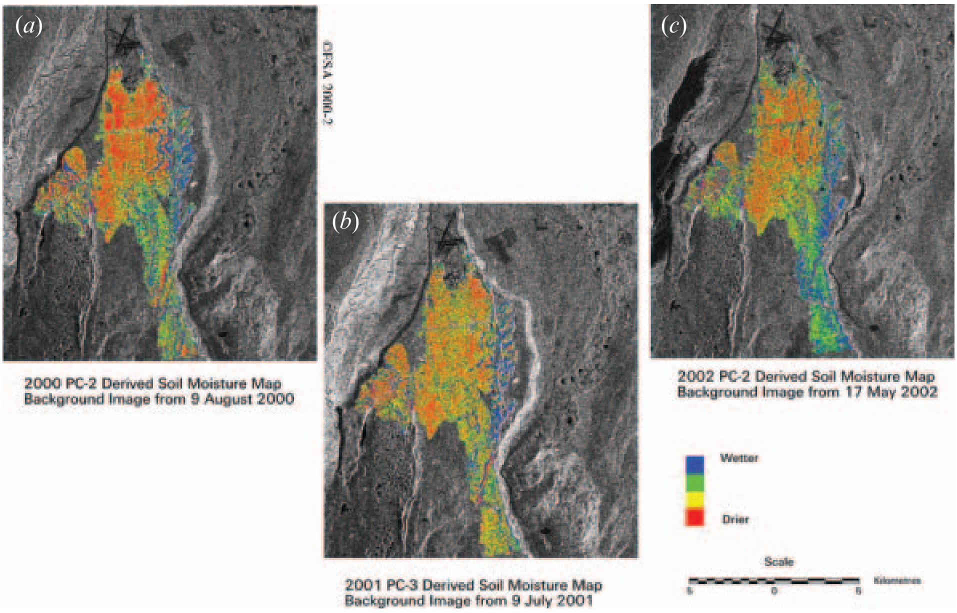


Figure 16. Seasonal soil moisture index map of the 1999 Donnelly Flats burn based on a principal component analysis of (*a*) seven scenes of 2000 ERS data; (*b*) eight scenes of 2001 ERS data; and (*c*) seven scenes of 2002 ERS data.

The 2002 map (figure 16) shows that the southern part of the burn and the northeastern burn along the edge of the stream remained wet throughout the season, while the northern and northwestern parts of the burn were quite dry. This 2002 map is a good representation of how the field crew described the overall site as far as drainage characteristics were concerned. Although there was more rain in 2002, the northern part of the burn does not show up wetter because of better drainage (figure 16). Note that these soil moisture index maps were created before discovering that the ERS-2 sensor was losing power over time. Therefore, these products were not normalized prior to creation and care should be taken in comparing between years, although trends are apparent.

7. Discussion and conclusions

The individual date soil moisture estimation procedure developed in this research was based on five years of summer (May to September 2000–2004) ERS-2 SAR imagery and modelled with coincident *in situ* samples of soil moisture. Due to the large dynamic range from the burn scars and the slow regeneration, we found that prediction of soil moisture from C-band SAR backscatter is possible through year 13 post-fire (1991 fire at Anderson) although biomass becomes more of an issue as the scars age. The technique produced good results for applying the developed models across a burned landscape to map the spatially varying patterns of soil moisture condition, with low rms error. It is a robust technique in that it was developed and validated using data from multiple burn scars in two different areas of interior Alaska. Furthermore, the developed technique allows the use of satellite-based optical/infrared remote sensing to group sites for soil moisture retrieval with satellite SAR imagery. This technique should therefore be applicable to new sites with minimal *in situ* data available.

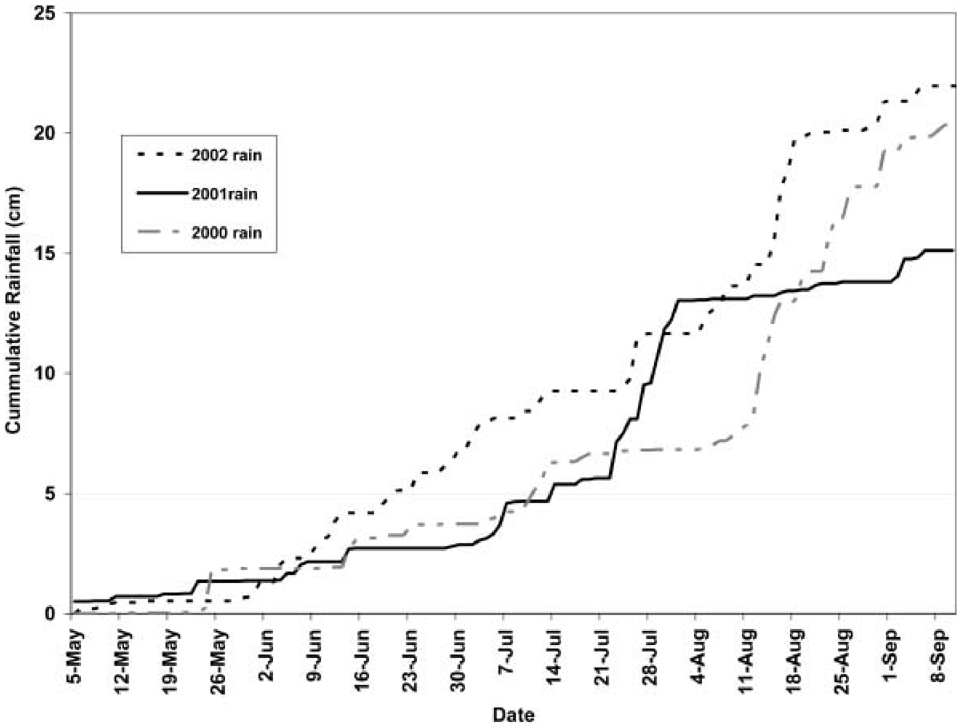


Figure 17. Cumulative rainfall from the Fort Greely Weather Station, north of Donnelly Flats, from the May to September fire seasons of 2000–2002.

The seasonal soil moisture index technique developed under this study provides information on the drainage of the burned sites which is a variable of interest in assessments of post-fire regeneration, NPP, and the need for remediation by foresters.

Validation of the seasonal soil moisture indices was positive, however, we had limited *in situ* data sets for seasonal validation and had to rely on weather data for much of the assessment. A more thorough *in situ*-based investigation is desirable for a full evaluation of these products. However, the PCA technique represents a potentially powerful tool for mapping soil drainage classes in recently burned boreal forests.

Since the time series analysis of the seasonal soil moisture index procedure allows assessment of the moisture of a particular point on the landscape through time without loss of spatial resolution and with minimal ancillary information about the biophysical characteristics, we are using this technique to evaluate the use of SAR data for an improved fuel moisture monitoring capability in burned and unburned forests for the wildfire managers of Alaska. The increased spatial resolution of a satellite SAR-derived fuel moisture monitoring method would enhance the current point-source weather based system (Bourgeau-Chavez *et al.* 2001b, 2005a, 2005b). Although C-band energy reflectance from forests is generally due to volume scattering from the canopy layer, canopy penetration does occur with steep incidence angles under sparse forest conditions, as are common in Alaska. Rignot *et al.* (1994) determined that the moisture status of the forest floor had a major influence on the temporal ERS backscatter response of a black spruce forest in Alaska. However, to reduce the confounding factor of forest biomass even further, an investigation of the longer wavelength L-band (23 cm) data from the recent launch of ALOS PALSAR is underway for inclusion in our landscape fuel moisture monitoring research.

The seasonal soil moisture index technique and the individual date soil moisture prediction approaches provide tools for a thorough assessment of hydrologic condition of burned forests of interior Alaska. Although the algorithms may have to be changed slightly for different boreal ecosystem types, the methods should be applicable to burned boreal forests worldwide that are underlain by deep organic layers. Previous research of the detection of burn scars with SAR revealed a global application for boreal forests (Bourgeau-Chavez *et al.* 2001a). The bright, high soil moisture signature post-burn, as well as the large dynamic range of backscatter over a season, was observed in Canada, Alaska and Russia.

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