CREATING A WILDFIRE MODEL FROM REMOTE SENSING OF BOREAL FORESTS IN NORTHERN ONTARIO

by

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A major research paper
presented to Ryerson University

in partial fulfilment of the requirements for the degree of
Master of Spatial Analysis
in the Program of Spatial Analysis

Toronto, Ontario, Canada

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Abstract

Ontario's boreal forests cover 41,171,000 hectares. Forest fires in the boreal forest are the main natural disturbance and 2011 was a very active year. In Northern Ontario 632,533 hectares were burned compared to 14,823 hectares in 2010 and 20,656 hectares in 2009. The overall objective of this research project is to investigate the extent of the burn areas utilizing remote sensing. Remote sensing provides a cost effective method for monitoring forest disturbance such as forest fires in vast remote areas, and can contribute insight to policy and management objectives. An analysis using remote sensing techniques was undertaken to examine the extent of several forest fires that occurred during 2011 in Northern Ontario. Landsat 5 Thematic Mapper images were acquired for study areas near Wabakimi Provincial Park and Pickle Lake with the time period being from 2009-2011 for both fire study areas. The post-fire image acquisition dates were as close as possible to fire extinguishment to minimize temporal distortions. The analysis utilized the Normalized Difference Vegetation Index (NDVI), Principal Component Analysis (PCA), Tasselled Cap Transformation (TCT), Normalized Burn Ratio (NBR), unsupervised classification and image differencing operations. Favourable conditions for wildfires such as dry conditions, thunderstorms, strong winds and large amounts of fuel were the main factors contributing to the 2011 fire season and they influenced fire behaviour and progression in the study areas. A total of 586 square kilometres (17% of the study area) and 450 square kilometres (18% of the second study area) were burned as a result of the fires.

Acknowledgements

I would like to thank my research advisor Dr. Wayne Forsythe for his guidance and advice and for allowing me to pursue such an interesting topic in the area of remote sensing and GIS. My gratitude also goes to my family and friends for their support and encouragement during my years at Ryerson University.

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List of Acronyms

dNBR – difference Normalized Burn Ratio

ETM+ – Enhanced Thematic Mapper plus

GIS – Geographic Information System

L1 T/G – Level 1 systematic and terrain corrected data product

NBR – Normalized Burn Ratio

NDVI – Normalized Difference Vegetation Index

NIR – Near Infrared

OMNR – Ontario Ministry of Natural Resources

PCA – Principal Component Analysis

PCIDSK – PCI Geomatics Database File

SWIR – Short Wave Infrared

TCT – Tasselled Cap Transformation

TM – Thematic Mapper

UTM – Universal Transverse Mercator

USGS – United States Geologic Survey

WGS – World Geodetic System

WRS 2 – Worldwide Reference System

CHAPTER 1: INTRODUCTION

1.1 Fire and Ontario's Boreal Forest

Ontario's boreal forests cover 41,171,000 hectares. Forest fires in the boreal forest are the main natural disturbance and 2011 was a very active year (Bergeron et al., 2001). In Northern Ontario 632,533 hectares were burned compared to 14,823 hectares in 2010 and 20,656 hectares in 2009. The boreal zone in Ontario covers 34.6% of the province and is situated between the Great Lakes and St. Lawrence zone and the northern boreal zone. The forested portion of Ontario's boreal zone is licensed under the Crown Forest Sustainability Act (CFSA) (OMNR, 2004). Historically, Ontario's boreal forest zone experiences anywhere between 200 and 2,300 fires per year, which accounts for 51% of all forest fire occurrences in the province. An average of 61,300 hectares of forest is burned per year. Substantial areas of spruce budworm-damaged forest stands are now present in the boreal zone, creating a volatile fuel in close proximity to valuable forests and communities (OMNR, 2004).

Disturbances periodically change the influence of edaphic factors on spatial patterns of vegetation in boreal regions (Schroeder and Perera, 2002). Fire is known as the dominant natural disturbance in the boreal forest, determining the age distribution and spatial age mosaic of the forested landscape (Bridge et al., 2005, Johnson, 1992, Weir et al., 2000). Crown fires are a major disturbance agent in boreal forests, and cause an abrupt change to existing spatial vegetation patterns by destroying overstory vegetation.

1.2 Fire Management in Ontario

The managed forest area of Ontario totals 45,000,000 hectares, and is dominated by boreal forests, which are approximately 30,000,000 hectares (Schroeder and Perera, 2002). Ontario is divided into six fire management zones based on common management objectives, land use, fire load, and forest ecology. The six zones are: Hudson Bay Zone, Northern Boreal Zone, Boreal Zone, Great Lakes/St. Lawrence Zone, Parks Zone, and the Southern Ontario Zone (OMNR, 2004). Figure 1-1 illustrates the various fire management zones in Ontario. The economy of the Boreal Zone is closely linked to the harvest and processing of natural resources and the protection of wood supply is a priority for stakeholders. Therefore fire suppression is active in this zone. Fire suppression efforts can be effective in protecting lives, personal property, and infrastructure. Furthermore, educational campaigns may have reduced the number of human-caused fires. However, research has shown that large fires and large-area burned years are strongly associated with the development of persistent blocking high pressure weather systems, conditions that usually consist of long periods of hot, dry weather that lead to severe drying of fuels (Johnson 1992, Johnson and Wow-chuck 1993, Johnson et al., 1995, Stocks and Street 1983, Stocks and Flannigan 1987). Usually fires that start in these conditions are the large fires which are difficult to control and can account for almost all of the annual area burned. In this study much of the total area burned in 2011 was due to a few large fires which were difficult for fire crews to control. While some areas may have been controlled from fire management teams, other areas may have quickly gone out of control due to favourable weather conditions (OMNR, 2012).

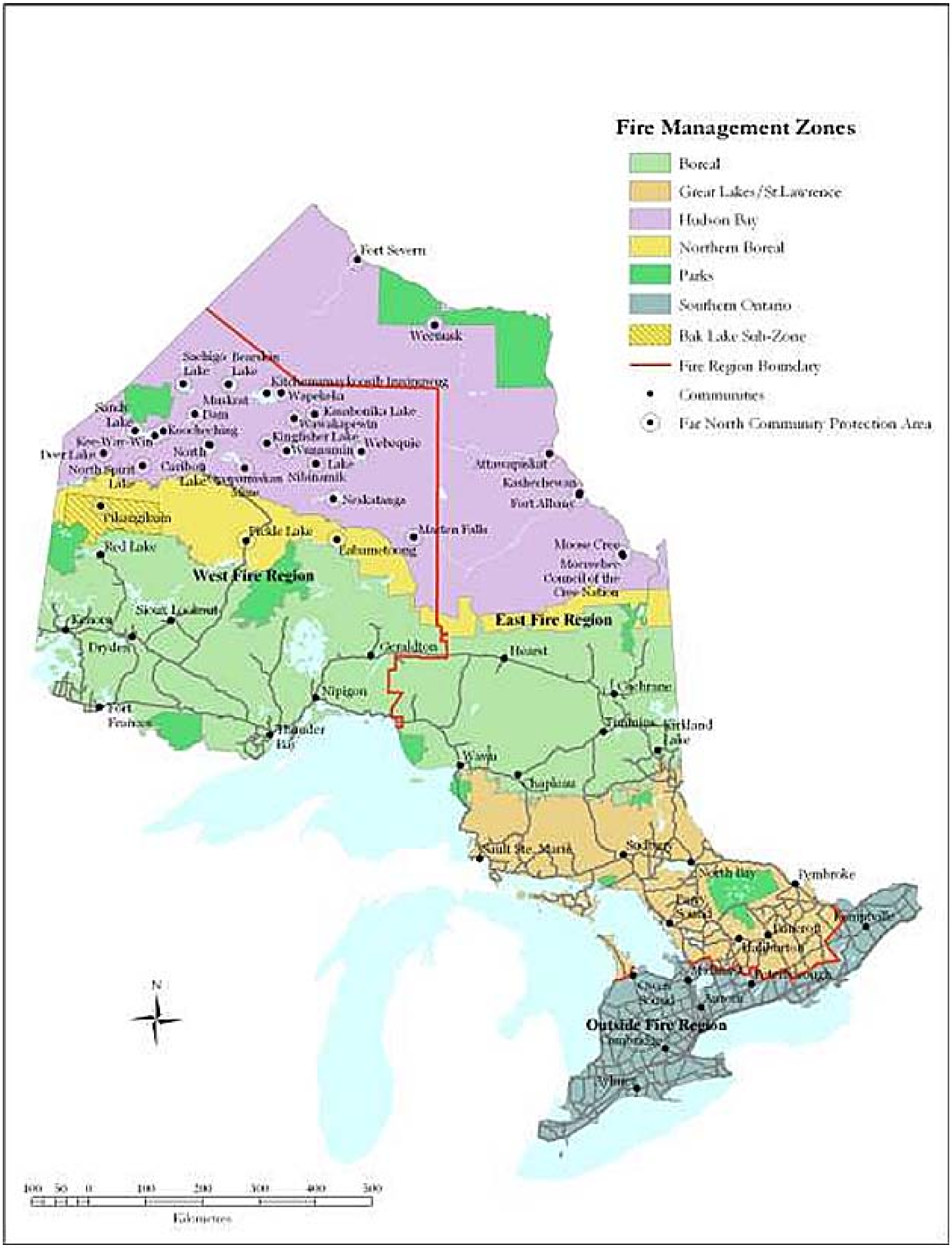

Figure 1-1: Fire Management Zones in Ontario retrieved from Ontario Ministry of Natural Resources Fire Management Zones (OMNR, 2004).

1.3 Remote Sensing of Wildfires

Traditional methods for detecting burn severity have concentrated on evaluating post-fire Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM+) scenes for vegetation regeneration using Normalized Difference Vegetation Index (NDVI) values (Wagtendonk et al., 2004). Change detection for ecosystem monitoring generally assumes overall phenological conditions to be comparable and as change caused in an ecosystem due to the result of fire can be categorized as abrupt, Landsat imagery is useful in classifying this change (Coppin et al, 2004). The Landsat program, run by the United States Geological Survey (USGS), is known as one of the longest and most comprehensive sources of remote sensing data used for earth observation, and is freely available to the public (Cohen and Goward, 2004). The Landsat TM and ETM+ sensors cover a wide range in the electromagnetic spectrum that includes parts of the visible, near infrared, and short wave infrared wavelengths. In terms of the revisit period, Landsat has a moderate temporal resolution of around 16 days for many locations around the world (Cohen and Goward, 2004). In terms of wildfires, while the 16 day revisit period is not the most effective in real-time wildfire management, Landsat imagery does provide useful data for change detection.

This study is focused on the detection of wildfires during the 2011 summer season. While there are several studies focused on the detection of wildfires, in terms of Landsat data, wildfires are usually easily spotted due to their size and localized land cover change within the image (Coppin et al, 2004).

1.4 Problem Statement

The overall objective of this research project is to investigate and recreate the extent of the burn areas utilizing change detection. An analysis using remote sensing techniques shall try and recreate the extent of several forest fires that occurred during 2011 in Northern Ontario. Landsat 5 Thematic Mapper images were acquired for study areas near the Wabakimi Provincial Park area. The post-fire image acquisition dates were as close as possible to fire extinguishment to minimize temporal distortions. The analysis shall make use of the Normalized Difference Vegetation Index (NDVI), Principal Component Analysis (PCA), the Normalized Burn Ratio (NBR), and the Tasselled Cap Transformation (TCT). In order to determine the land cover for the acquired images, unsupervised classification will be performed. In order to illustrate the extent of the burn area, band differencing and raster arithmetic will be utilized.

Specific research objectives include:

1) Utilizing NDVI, PCA, NBR and TCT to obtain vegetation information from the original Landsat imagery and to assist in land cover classification.

2) Classifying the Landsat images using unsupervised classification to determine the land cover characteristics for each image and study area.

3) Utilizing band differencing operations to extract the extent of the burn scars.

4) Statistical Analysis of land classes and burn scars and related meteorological data will be used to determine actual fire extent.

1.5 Study Area

The study sites, located in Northern Ontario, Canada are situated north and west of Wabakimi Provincial Park. Wabakimi Provincial Park is located approximately 265km north of Thunder Bay, Ontario. The fire known as SLK35 was located around 50km NNW of Wabakimi Provincial Park and the SLK 61, SLK 64, RED 84 fires were located about 200km west of the park. The study areas are characterized by moderate topography with elevations ranging from 209 to 516 metres above mean sea level for the SLK35 area. The SLK 61, SLK 64, RED 84 area is characterized with a higher elevation of 277 to 567 metres above sea level. The vegetation is characterized as mainly coniferous trees ranging from Jack Pine to Black Spruce to Trembling Aspen (Ontario Parks, 2006). As northern Ontario is known for its relatively short fire cycles, the forest mosaic is mainly composed of pure or mixed, even-aged stands at different stages of recovery following fire.

Jack Pine is known as an early to mid-successional species that almost exclusively originates after fire (Ontario Parks, 2006). While Jack Pines are well adapted to fire and usually mature at around 70 to 80 years, as they age their vigour declines which predisposes them to another fire. Jack Pine needles are highly flammable and readily burn if crowns are too close to the ground. Jack Pine trees rarely survive crown fires, and younger stands tend to be more susceptible to crown fires than older stands where the crowns are often thinner and higher from the ground (Ontario Parks, 2006). With the propensity for fires in Ontario’s boreal zone, Jack Pine provide fuel for wildfires as well as setting up the next generation of Jack Pine for germination after the fire.

Black Spruce is a shade-tolerant, long-lived species that is capable of vegetative reproduction through layering. Black Spruce is well adapted to regeneration following fire due to early and frequent seed production however it is easily killed by both surface and crown fires because of its thin bark and shallow roots (Ontario Parks, 2006). Overall fire is more frequent and has greater severity in coniferous forests compared to the less flammable deciduous forests (Ontario Parks, 2006). Recreational and resource-based tourism properties are generally isolated in the boreal zone but are often important values at risk in the event of an escaped fire. Forest access roads are the only ground access to many areas of the zone and effective fire management depends more heavily on aircraft than in the fire management zones located further south (Ontario Parks, 2006). Population and infrastructure within the boreal zone occur largely along Highways 11 and 17. Railways, highways, pipelines, and hydroelectric corridors are important economic links throughout the area, which may be disrupted by escaped fires (OMNR, 2004). Figure 1-2 displays the study area of the fire sites. The western section represents the SLK 61, SLK 64, RED 84 fires while the eastern section represents the SLK35 fire area. While the SLK 61, SLK 64, RED 84 fires are not in any parks zone, the SLK35 fire is right at the edge of Wabakimi Provincial Park.

This study site was chosen due to the high number of severe fires in the area as well as the proximity to several provincial parks with Wabakimi Provincial Park being the closest. In addition, several First Nations groups are located within the area. As the fires in the area impact human life (the community of Pickle Lake being in close proximity), vegetation, and Ontario's economy (lumber industry), the area around Wabakimi

Provincial Park was deemed suitable to explore the extent of the fires as several large fires were in the vicinity.

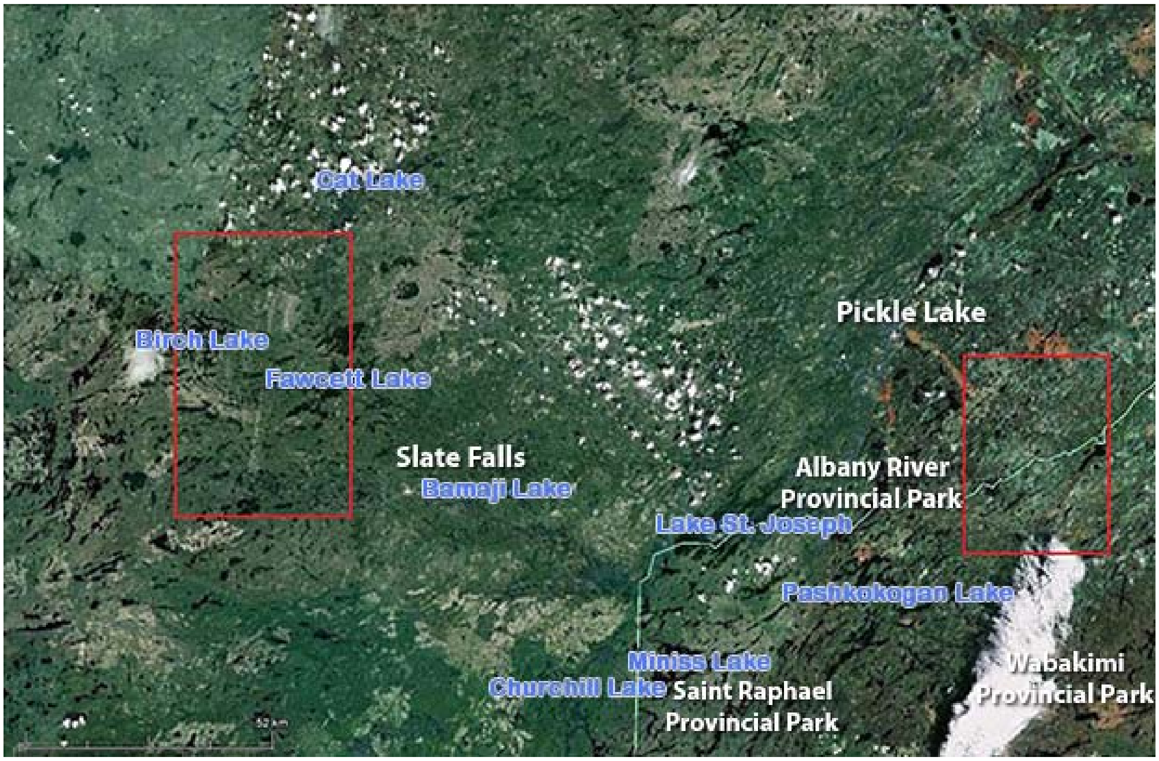

Figure 1-2: Fire Sites. The western section is the SLK 61, SLK 64, RED 84 fires. The eastern section is the SLK35 fire. Data source: Google Maps (2009)

1.6 Structure of the Paper

The paper is comprised of four additional chapters to directly address the research objectives of this study. The following chapter provides a review of literature relating to fires in boreal forest settings: (i) boreal forests; (ii) fire behaviour; and, (iii) remote sensing techniques. In Chapter 3, the data sources and various techniques utilized to determine and recreate fire extent are discussed. Chapter 4 discusses the results from the image classifications and image differencing and showcases the true fire extent. Finally, in Chapter 5, conclusions are drawn and future directions along with limitations and recommendations are presented.

CHAPTER 2: LITERATURE REVIEW

2.1 North American Boreal Forests and Remote Sensing

Forest fires in boreal forest settings are an uncommon occurrence and North American boreal forests are usually characterized with short fire cycles (Bergeron et al., 2001). Boreal forests in North America are usually characterized as close canopied forests which usually consist of conifers except in the southern boreal where aspen tend to become more common (Johnson et al., 2001). While forest fires are a natural part of the forest ecosystem and are important to the life cycle of indigenous habitats, damage done by forest fires is quite expensive. Natural resources burned as well as the threat to public safety (i.e. evacuations, burned homes) can be quite devastating. Other than fire prevention, early detection and suppression of fires is the most common way of minimizing damage and casualties. Whereas real time detection is needed for timely response to potential disasters, Landsat imagery provides good coverage of areas with its 30 metre resolution sensor. Damage done from forest fires is a suitable target for remote sensing due to the obvious change in land cover as the fire chars the ground, burns tree canopies and alters soil colour (White et al., 1996). Okanagan Mountain Park in British Columbia experienced a large wildfire in 2003 which caused extensive damage to the park and surrounding area. The park consists of over 10,000 hectares of a rugged landscape. The main type of forest cover is spruce-fir and other vegetation consists of grasslands. Due to the severity of the fire, around 45,000 residents had to be evacuated from the City of Kelowna and it is estimated that 239 homes were burned (Hefeeda and Bagheri, 2008). In the aftermath of the forest fire, about 25,912 hectares were scorched with many trees in the park being burned and $33.8 million in damages accumulated (Hefeeda and Bagheri, 2008).

2.2 Fire Behaviour

Fire behaviour can be described as how a fire acts in a given situation. Fire behaviour can be further broken down into several sub-categories. These categories are: kind or type, frequency, extent, seasonality, magnitude, and synergy (Johnson 1992, Ryan 2002).

Johnson (1992) describes ground fires as fires which propagate from fuel which rests on the forest floor. This includes, saplings, shrubs, dry wood which litters the forest floor. Crown fires on the other hand are those which spread on both the surface of the forest fuels and the tree crowns. Johnson (1992) includes a simple thermal model of fire rate of spread which he describes as shown below:

$$\frac{\text{Heat from the flaming front}}{\text{Heat required for fuel ignition}} \qquad (1)$$

The area within a fire's perimeter is often used to describe the extent of a fire, but the actual area burned, patch size, and burn mosaic should also be considered (Eberhardt and Woodward, 1987, Ryan, 2002, Turner and Romme, 1994, Turner et al., 1997). Heterogeneity in vegetation structure and microenvironment leads to heterogeneity in fire behaviour and effects that can increase the heterogeneity of post-fire vegetation whereas homogeneous environments lead to larger, more uniform fires (Ryan, 2002). In coniferous forests that constantly see repeated fires, post-fire trees such as Jack Pine may colonize and turn an area homogeneous. When fuels, weather, and terrain are relatively uniform within a region, a large portion of the area will be receptive to ignition and burnout at one time (DeLong, 1998, Ryan, 2002). Therefore, the literature strongly supports that dry continental air masses, strong persistence patterns such as blocking high-pressure ridges, and the strong wind events associated with passing of dry cold fronts create conditions suitable for rapid wildfire growth and extended severe fire weather (Flannigan and Wotton, 2001, Johnson, 1992, Johnson and Wowchuk, 1993, Ryan, 2002).

Fire frequency describes the number of fires in a given period of time. Fire frequencies vary from a few decades to several centuries depending on location in terms of boreal forest areas (Ryan, 2002). However, the minimum requirements for fires to occur are available dry fuel and a source of ignition which were mentioned earlier. In addition to the availability of dry fuel, natural barriers such as avalanche paths, lakes, rivers, and barren ground reduce the likelihood of fire spreading into an area (Ryan, 2002). With these factors two different sites in the same area can experience very different fires. Ryan (2002) goes on to describe that a boreal forest exhibits a pattern of periodic small fires with infrequent large fires that are associated with high wind and drought.

Fire intensity or magnitude refers to how intense or severe a fire is. However the literature is split on this definition and currently there is no universally accepted definition on fire magnitude (Ryan, 2002, White and Pickett, 1985). It is recognized in the literature that the amount of available fuel, weather conditions, and terrain steepness have a dominant effect on a fire's energy release characteristics and fire suppression capabilities (Johnson, 1992, Ryan, 2002). Literature suggests though that wind is perhaps the largest factor in boreal forests. Wind causes the most spatial and temporal variation as fires frequently pulsate between intense surface fires and crown fires with only modest changes in wind speed (Finney, 1998, Ryan, 2002, Scott, 1998, Scott and Reinhardt 2001, Van Wagner, 1993). Taking into account terrain when discussing fire magnitude, terrain can usually be a barrier to fire spread. A barrier can either keep a fire contained in a local area or flank it back with reduced severity and intensity. In referring to slope, the heading portion of the fire burns with the wind or upslope. The backing fire burns into the wind or down slope. The flanking fire burns perpendicular to the wind's axis (Ryan, 2002). Generally, the greater the wind speed or slope, the greater the difference between the intensity of the heading fire and backing fire.

Finally, seasonality directly affects fire behaviour. Seasonality is important because of direct changes in fuel moisture that affect flammability. Large boreal forest fires are commonly associated with drought and thus when relative humidity is low, wind speed is high, and fire fuels are abundant, crown or ground fires are bound to happen (Ryan, 2002). The springtime tends to see more crown fires as the ground level is still around freezing and thus not suitable for combustion but the summer usually sees higher intensity fires.

2.3 Change Analysis

When conducting a change analysis in determining fire extent, anniversary dates or windows are often used in imagery as it helps minimize discrepancies in seasonal vegetation fluxes and sun angle differences (Coppin and Bauer, 1996). When determining the optimal selection of the season for multitemporal forest cover change detection, data acquisition remains a topic of contention in the pertinent literature (Cohen and Goward, 2004, Coppin and Bauer, 1996, Verbyla et al., 2008). Coppin and Bauer (1996) state that the mapping of forest cutovers in pure or predominantly coniferous stands was optimal with early spring imagery, summer data did better for cutovers in deciduous stands.

Landsat imagery provides particularly good coverage in mapping fairly large areas with its TM sensor and land cover can usually be distinguished. Landsat data are popular for forest classification for such things as timber volume, wildlife habitat, succession stage, forest fragmentation and many others (Cohen and Goward, 2004). Classifications from Landsat data have been used to model many things such as bird habitats in mixed cover, cover density, fire risk assessment and crops in agricultural land (Cohen and Goward, 2004). Miller and Yool (2002) utilized Landsat TM and ETM+ data to map forest post-fire canopy consumption in several overstory types and to map burn severity. They found that Landsat data were well suited in mapping burn severity.

Image radiometry is used to help identify change. Several methods of radiometric analysis include band differencing, NDVI differencing, and image ratioing. In identifying the burn scar left behind from a forest fire in the 1988 Red Bench fire, Landsat TM data were utilized to detect areas of burn severity and vegetation regeneration. It was found that there were noticeable changes of reflectance in the visible and infrared (IR) spectrum (White et al., 1996). Miller and Yool (2002) state that multi-temporal change detection of remotely sensed data is a common method for determining how biophysical systems change through time. In their analysis, they use multi-temporal images along with a change detection algorithm to determine fire extent. Cohen and Goward (2004) also state that other than wildfires Landsat data are used to detect a variety of other change such as tree mortality, insect damage or logging.

2.4 Normalized Difference Vegetation Index (NDVI)

NDVI is utilized to help with the classification of changes due to fire (Miller and Yool, 2002). NDVI values range from -1 to +1 and measure the amount of biomass in an area. Darker pixels represent areas of little to no biomass and lighter pixels represent areas with a considerable amount of biomass. NDVI is calculated as shown below in Equation 2 with Landsat TM Band 4 being Near Infrared (NIR) and Landsat TM band 3 being the red band:

$$\frac{(\text{Band } 4 - \text{Band } 3)}{(\text{Band } 4 + \text{Band } 3)} \quad (2)$$

While NDVI is associated with vegetation greenness and photosynthetic activity, it can be used to detect decreases in vegetation due to fire (Fraser et al., 2000). The main drawback to NDVI is the tendency for commission error in burn assessment. NDVI decreases are usually caused by cases unrelated to fire such as drought, timber harvesting, or cloud contamination (Fraser et al., 2000).

2.5 Tasselled Cap Transformation (TCT)

A tasselled cap transformation can also be used along with NDVI to help with the identification of vegetation. As the tasselled cap measures brightness, greenness, and wetness, the greenness band can be used to help with the identification of vegetation in areas. These three components of the tasselled cap transformation account for most of the variance in an image scene and provide a reduction in data volume with minimal information loss (Jin and Sader, 2005). The TCT has been demonstrated in the literature as effective for vegetation mapping and temporal land cover change detection (Cohen and Goward, 2004; Healey et al., 2005).

2.6 Principal Component Analysis (PCA)

Principal component analysis (PCA) is frequently used to generate new transformed and uncorrelated data from multispectral satellite imagery (Brewer et al., 2005, Lilles and Kiefer, 1987). If based on multiple dates of imagery, such analysis can simplify change detection by isolating important spectral indicators of landscape change within fewer bands. Therefore abrupt change such as those caused by wildfires would easily be able to be identified by principal component analysis (Brewer et al., 2005). Salvador and Pons (1996) state that PCA is useful in identifying areas under dynamic change. Dong et al. (2006) go further and say that PCA is useful in simplifying the factors in fire mapping and zoning and therefore can make forest fire zoning relatively straightforward. Thus

PCA is another viable technique to use when creating classifications of fire areas as it will allow for easy visual investigation of the fire area.

2.7 Normalized Burn Ratio (NBR) and Difference Normalized Burn Ratio (dNBR)

PCA in fire mapping is utilized to help with the classification of features as it can provide helpful information in burn scar delineation. Miller and Yool (2002) however state that single date and multitemporal Kauth–Thomas transforms were found to produce more accurate maps of vegetation mortality due to fire than PCA. Miller and Yool (2002) go on to discuss about several band ratios with a band 7/band 4 ratio being the most noticeable for fire applications. Differencing the band 7/band 4 ratios was found to produce the best representation of fire severity based upon visual inspection and field knowledge (Miller and Yool, 2002). They go on to describe the new index called the normalized burn ratio (NBR) and it is formulated much like NDVI except Landsat TM Band 7 is used in placed of the red band. They state that the NBR was found to produce the best representation of fire severity based upon visual inspection and field knowledge (Miller and Yool, 2002). Equation 3 below shows the calculation of NBR:

$$\frac{(\text{Band } 4 - \text{Band } 7)}{(\text{Band } 4 + \text{Band } 7)} \qquad (3)$$

Therefore the NBR could be more useful in recreating fire extent whereas band 4 or band 3 differencing would show change in vegetation. A study by Key (2006) supports the use of NBR and the subsequent difference Normalized Burn Index (dNBR). One advantage of dNBR over the post-fire NBR alone was it tended to isolate the burn from unburned surroundings (where the difference is near zero), while the NBR alone retained values that occurred naturally in both burned and unburned areas (Key, 2006). Another study conducted in 2008 in Canada's Western boreal forests notes the use of band 7/4 ratios. dNBR is explored along with Composite Burn Index (CBI) and found a non-linear model worked in assessing the relationship (Hall et al., 2008). NBR and dNBR may be a viable alternative to simple band 4 or band 3 differencing.

Verbyla et al. (2008) utilized NBR and dNBR is analyzing burn severity in the Alaskan boreal region on on estimating fire severity from landsat TM/ETM+ data. While NBR is calculated using the equation above, the dNBR is calculated using the equation below:

$$dNBR = NBRprefire - NBRpostfire \qquad (4)$$

NBR can theoretically range from +1 to −1 and negative values are assumed to represent burned pixels, with fire severity increasing as NBR values become more negative (Verbyla et al., 2008). Likewise, dNBR can theoretically range from +2 to −2 and positive values are assumed to represent burned pixels, with fire severity increasing as dNBR values become more positive (Verbyla et al., 2008).

Verbyla et al., (2008) found that when dNBR was computed for unburned pixels as August NBR minus September NBR, over 90% of the pixels had positive values and could be falsely interpreted as being burned. When dNBR was computed for unburned pixels as July NBR minus August NBR, 62% of the pixels had positive values. Thus seasonal changes in NBR may result from a combination of changes in leaf area, vegetation senescence, and changes in solar elevation (Verbyla et al., 2008). Overall, the changes in NBR could add significant noise to fire severity estimates from dNBR. Verbyla et al., (2008) advise caution in the use of dNBR or any remotely sensed reflectance-based index that is sensitive to solar elevation and plant phenology to monitor trends in fire severity either in time or across regions. Verbyla et al., (2008) suggest there should be fire severity field data to assess the appropriate remotely sensed threshold value that really corresponds to severity levels estimated from remote sensing. Despite the caution, compared to NDVI or PCA, NBR and dNBR are suitable for determining the extent of the fire as well as measuring severity to investigate which areas were more severely burned (Verbyla et al., 2008).

CHAPTER 3: METHODOLOGY

3.1 Overview

A substantial portion of the development of this analysis was based on image classification and differencing. A multi-step process was undertaken to create the final classification images which represents true fire extent for both study sites. This process namely consisted of image selection, image subsetting, classification, differencing, and modeling which are shown in Figure 3-1.

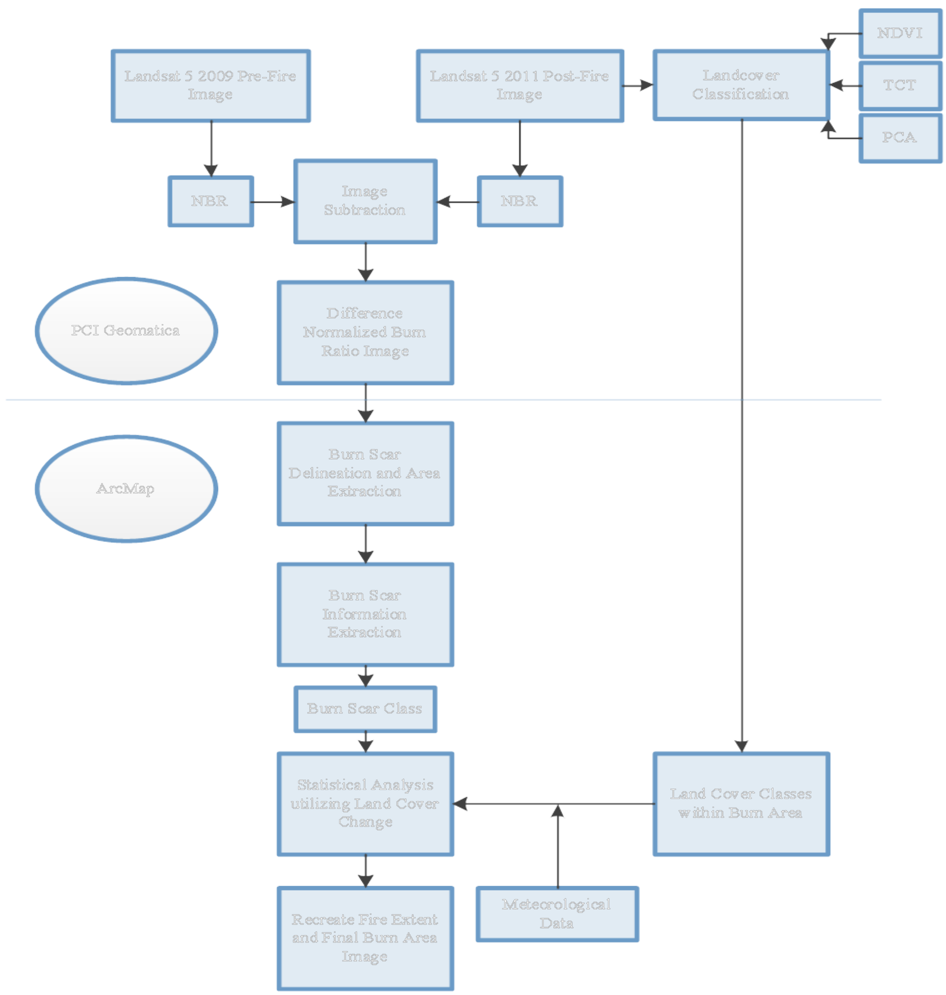

Figure 3-1: Overview of Methodology

3.2 Data

The primary raster data source for this study is the USGS Earth Explorer Landsat data archive that is freely available to the public for download at http://earthexplorer.usgs.gov. Landsat 5 TM level 1 systematic and terrain corrected (L1T/G) image data were acquired for the study site residing in path 26 row 24 for the SLK35 fire and path 27 row 24 for the SLK 61, SLK 64, RED 84 fires. For future reference the SLK 61, SLK 64 and RED 84 fires shall be known as the South Bay fires. Bands 1 – 5, and 7 for the TM sensors of Landsat 5 have a spatial resolution of 30m with each pixel covering 900 m^2. Images were narrowed down to the months of July, August and September to minimize temporal distortions and the fires in question burned in late July and were not put out until late July/early August. When inspecting burn images, care was taken to capturing near anniversary growing season conditions at the nearest possible annual temporal interval. This required visual inspection of atmospheric conditions in each image scene for the distribution and size of cloud cover or haze. While images were chosen that had less than 10% cloud cover, many images did in fact have cloud cover present. Fortunately, the images chosen were mostly free of cloud cover over the burn areas and thus the burn areas could be subset. Care had to be taken, however, not to include any cloud cover in the subset images so that clouds would not be an issue for classification. The final list of four mostly cloud-free images that were selected for analysis is presented in Table 3-1 along with their dates. Finally, meteorological data for Pickle Lake, Ontario were collected from the weather network (http://www.theweathernetwork.com/) and weather underground (http://www.wunderground.com/) websites as it was the nearest area to the fires in question.

Table 3-1: Landsat Images

Image Date	Sensor
August 29, 2009 (SLK35)	Landsat 5 TM
September 21, 2009 (South Bay Fires)	Landsat 5 TM
August 03, 2011 (SLK35)	Landsat 5 TM
September 27, 2011 (South Bay Fires)	Landsat 5 TM

Cloud cover did prove to be a challenge as many burn areas were shrouded by clouds and deemed unfit to be used in the analysis. While the South Bay fires were only less than a week apart in terms of temporal distortions, cloud cover inhibited the amount of available imagery for the SLK35 fire. The SLK35 2011 fire image had a 26 day period when compared to the 2009 image which introduces some temporal distortions as by late August vegetation may have changed since the beginning of August. The time step for both sets of images is two years as 2010 images were not available on the Earth Explorer website. The 2010 images would have been preferred to capture the "pre-wildfire state" of the study areas as they would have been the closest representation to the area before the wildfires burned in 2011 and altered the land cover.

3.3 Image Preprocessing

The Landsat visible and infrared image bands 1 - 5 and 7 for each acquisition date were assembled sequentially into PCIDSK database files and georeferenced in UTM Zone 16 North, WGS 1984 for the SLK35 fire and UTM Zone 15 North, WGS 1984 for the South Bay fires. Each image was processed at a pixel resolution of 30 metres for analysis. Each image was then further inspected to ensure that cloud cover was not present over the burn areas in question. The Landsat images were then subset to capture the burn areas of the respective fires as well as reduce the image file size for further processing. The resulting subset image for the SLK35 fire is 1799 pixels by 2039 lines covering an area of 3301 square kilometres. The resulting subset image for the South Bay fires is 1419 pixels by 1941 lines covering an area of 2478 square kilometres.

3.4 Unsupervised Classification

Unsupervised classification methods utilizing K-means were used to classify each image set. The K-means algorithm is a method commonly used to automatically partition a data set into k groups. The K-means classification groups all the pixels in the image into a specified number of classes where each class contains a cluster of pixels with similar spectral characteristics (measured in digital numbers) (Pope et al., 1994). This algorithm is appropriate for change detection when validation data sets of forest change (especially in the case of fire) are not available. K-means was run with the parameters of 50 output spectral clusters and 30 iterations. The low number of 50 output clusters was specified in order to allow the algorithm to group the image pixels into as many clusters as possible but in addition it was done to bypass software issues. Originally, 100 K-means classes were used but the software crashed when performing the classification. It was discovered that when more than 50 K-means classes were used, the software would crash. Sometimes specifying a lower number of output clusters leads to inaccurate results and poor classifications. In this research there were enough output classes to assign all the spectral signatures. These output clusters were then aggregated into five information classes, identifying pixels as water, evergreen forest, barren land, burn area or no data.

This aggregation was completed through visual comparison of the original Landsat images and secondary image sources to assign each spectral cluster to an information class. All fire was classified together regardless of its burn severity as there was no discrimination between amount of burn severity or burn type.

From the visible burn area and fire reports, the primary cause of the fires was dry conditions and lightning strikes. To confirm this, meteorological data were acquired from weather stations. These datasets included records of temperature, precipitation, humidity levels, and storm activity. As fire is one of the most significant agents of change in boreal forests, the large fires in the study areas were investigated to determine the source of ignition.

There were four fires in the study area during the analysis period with three of the fires in South Bay area (West of Wabakimi Provincial Park) and the other fire north of Wabakimi Provincial Park. These fires were all caused by lightning strikes. In all four instances, fire suppression was used in order to limit the growth and mitigate the damage caused by the fires as evidenced by the fire reports from the Canadian Interagency Forest Fire Centre (CIFFC, 2012).

The classification results presented in Chapter 4 provide snapshots of the size and distribution of the forest fires within each study site over the course of the study period. The inputs selected for the classification were chosen based on their ability to accurately classify vegetation and brightness and include the TCT. Upon utilizing NDVI, PCA, and TCT in the classification procedures, the TCT was found to provide the most favourable output spectral results. These transformed data and indices were computed for each image date and were included to increase the classification accuracy. The overall effect of each input on the classification accuracy is not known but when classifying the forest fires in each study area, the TCT most accurately delineated burn area. TCT clearly delineated the output spectral classes whereas NDVI and PCA had confusing spectral classes which were harder to aggregate into information classes. After visual inspection of the information classes, TCT was able to capture the burn area to a higher degree than NDVI or PCA. The inputs selected for use in each image classification are listed in Table 3-2.

Table 3-2: Input Bands

Input	Raster
1	Landsat band 1(blue)
2	Landsat band 2 (green)
3	Landsat band 3 (red)
4	Landsat band 4 (NIR)
5	Landsat band 5 (SWIR)
6	Landsat band 7 (MIR)
7	TCT Brightness
8	TCT Greenness
9	TCT Wetness

3.5 Accuracy Assessment

A post classification accuracy assessment was utilized to determine the quality of information derived from the data analysis and classification processes for each image. The aggregate classification for each fire site was evaluated to determine its classification accuracy. Due to data availability and time constraints, no ground truth or in situ validation datasets were available for assessment of the classification results. A reference image was visually interpreted and compared to the classification result to ensure that the classification was overall correct. The reference image used for the accuracy assessment was the Landsat TM image for each image date viewed as a true colour composite of bands 3, 2, and 1. A random sample of 300 reference points was generated for the reference image and was subsequently interpreted for each class of the aggregate classifications. The sample points were stratified proportionally to the number of pixels in each of the information classes. Based on the results of the accuracy assessment, a classification report and confusion matrix were generated for each image classification result. Foody (2002) describes the confusion or error matrix as the core of accuracy assessment. Therefore the confusion matrix and accuracy statistics has been established as a reliable method of accuracy assessment, even in times when in-situ data are not available to the user (Foody, 2002).

3.6 Band Differencing

For each of the four images, a NBR image was produced utilizing the NBR formula mentioned in Chapter 2. Burned pixels in the NBR images were assumed to be negative values. NBR is particularly sensitive to the changes in the amount of live green vegetation, moisture content, and some soil conditions which may occur after fire (Miller and Thode, 2007). With four NBR images produced, image subtraction was used to produce the dNBR images for each of the image sets (dNBR formula mentioned in Chapter 2). By analyzing the burned pixels in the post-fire images, factors that vary with topography such as vegetation and fire severity do not change substantially between the pre and post fire image dates (Verbyla et al., 2008). The only major topographic factor that changed was sun elevation. Fire severity in the dNBR image is modelled with burned pixels having more positive values. Burned pixels are easily distinguished from unchanged pixels in the image. The most burned pixels in the images have pixel values at or greater than one. Vegetation remains largely unchanged with pixel values near zero. Vegetation regrowth is indicated by negative values. The resultant dNBR images are presented in Chapter 4 with the burn area clearly delineated from the rest of the image.

3.7 GIS Analysis

After completion of the band differencing and image classification processes, the data were saved as PCIDSK files and then imported to a GIS environment for further analysis. The reclassified dNBR images were combined with the land cover classification results to produce extent maps for each fire area through raster calculations. An arithmetic multiplication operation was performed on each image pair in order to assign a land cover classification to areas of change identified in the dNBR images. This was achieved using the classification result for the most recent year of each time step and the corresponding dNBR image. The extent maps produced using this process identifies the extent of the fires as presented in Chapter 4.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 dNBR Images and Classification Results

The difference images and image classifications presented in this chapter provide a land cover map for the image dates chosen for this analysis. The classes presented in each land cover map are: water (blue), evergreen forest (green), barren land (grey), burn area (red), and no data (white). Classes were chosen and based on Anderson et al.'s (1976) classification system. The water class represents all areas within the study site that consist of water at the time of acquisition. The evergreen class is all forested areas in which the trees are predominantly those which remain green throughout the year. Both coniferous and broadleaved evergreens are included in this class. In most of the study area, the coniferous evergreens predominate and are thus labelled as evergreen forest (Anderson et al., 1976). The barren land class is land of limited ability to support life and in which less than one-third of the area has vegetation or other cover. In general, it is an area of thin soil, sand, or rocks. If there is any vegetation present on the Canadian Shield, it is more widely spaced and scrubby than that in the shrub and brush category in rangeland (Anderson et al., 1976). The burn area class is vegetation which has been disturbed by the wildfires and has seen significant change. It exhibits, based upon the Tasselled cap values, a high brightness but a low greenness and wetness. The dNBR images show the burned area as lighter hues with unchanged areas as more of a grey hue and other areas of change as darker hues. Figures 4-1, 4-2, 4-3 and 4-4 show the natural colour images for comparison purposes to the dNBR images.

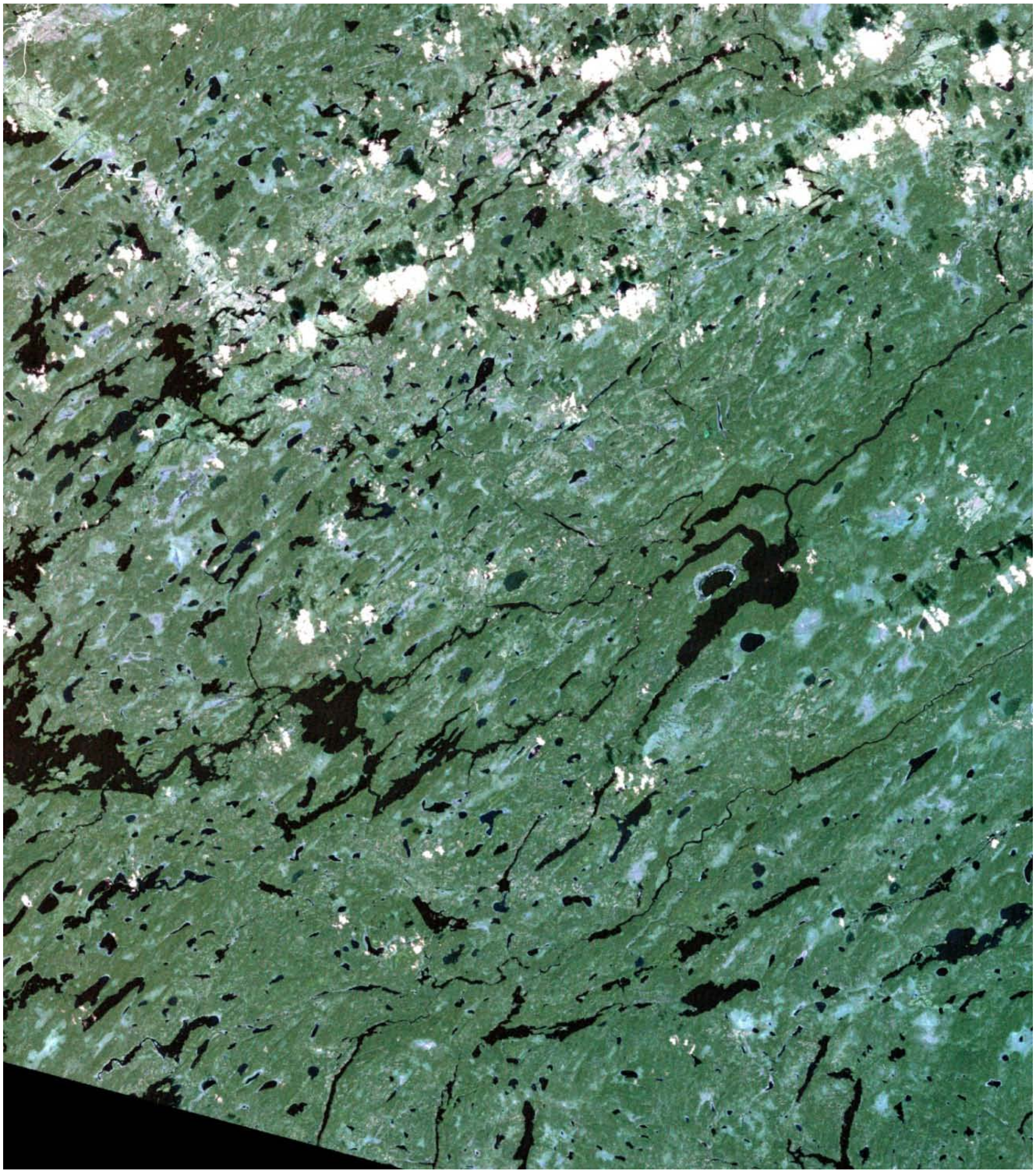

Figure 4-1: Bands 3, 2, 1 for the 2009 subset of the SLK35 fire with linear enhancement

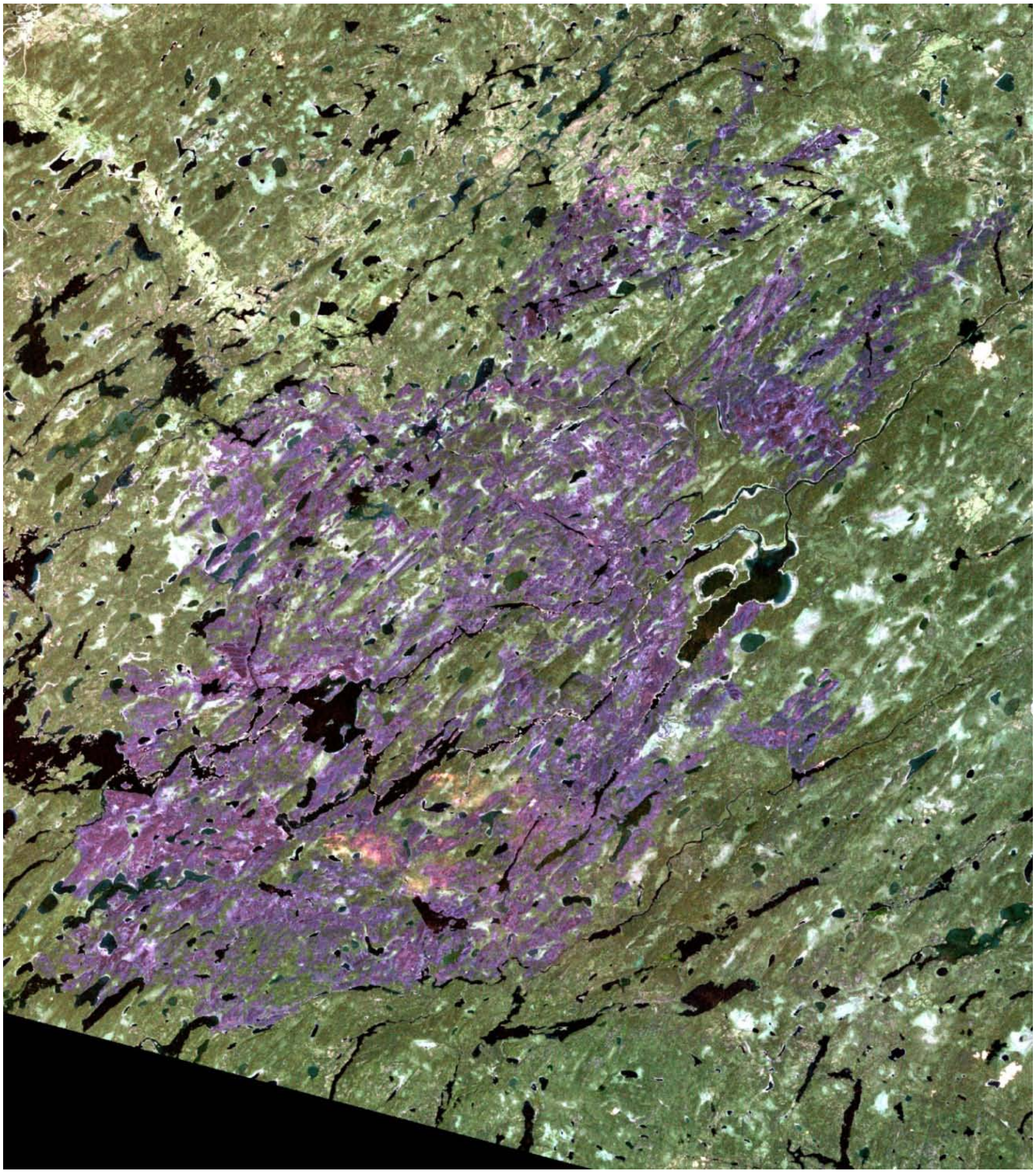

Figure 4-2: Bands 3, 2, 1 for the 2011 subset of the SLK35 fire with linear enhancement

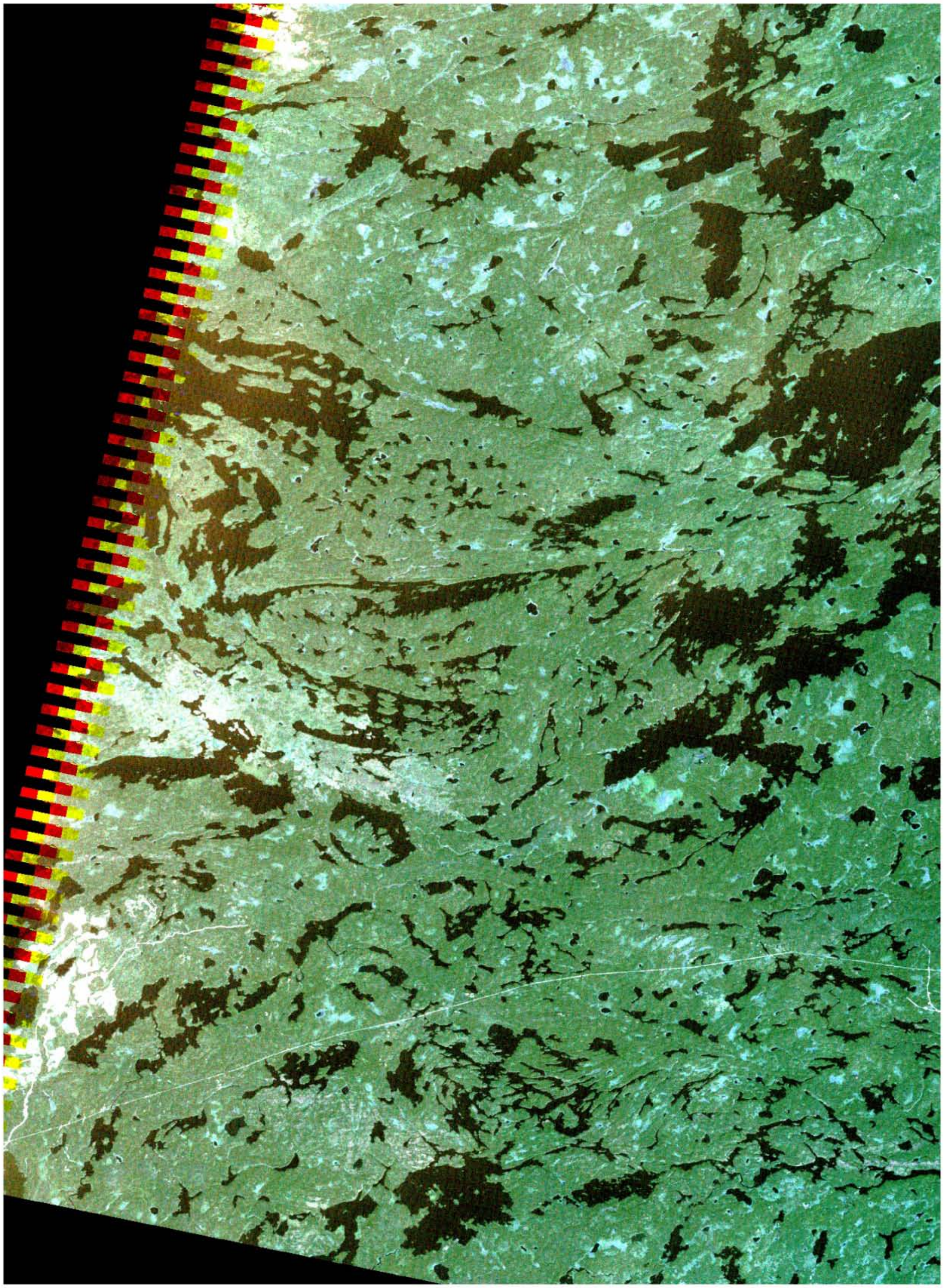

Figure 4-3: Bands 3, 2, 1 for the 2009 subset of the South Bay fires with linear enhancement

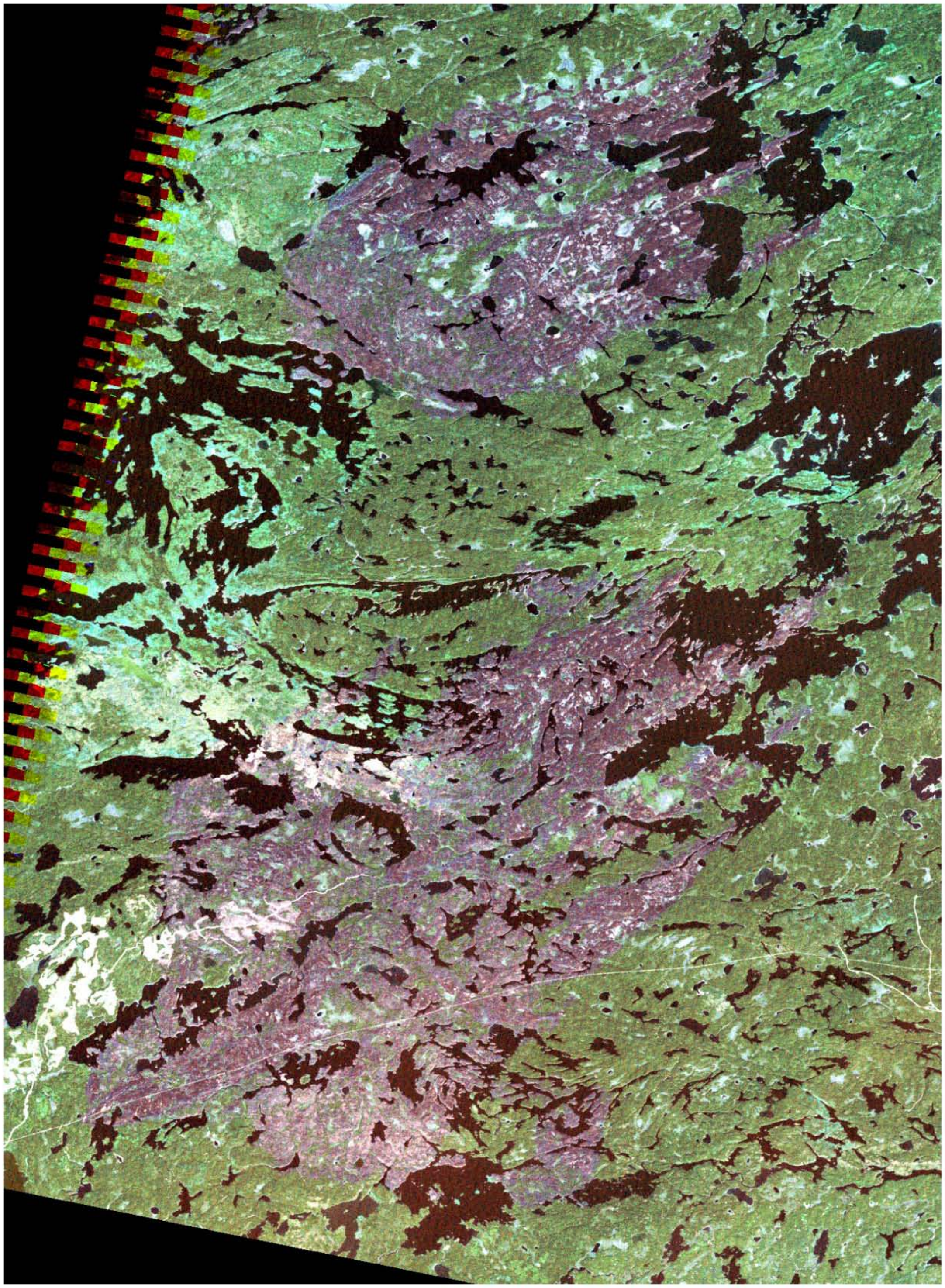

Figure 4-4: Bands 3, 2, 1 for the 2011 subset of the South Bay fires with linear enhancement

The values for the SLK35 dNBR image range from -0.25 to 1.01 with the higher positive values appearing in the burned area (values represented in Figure 4-5 shown below).

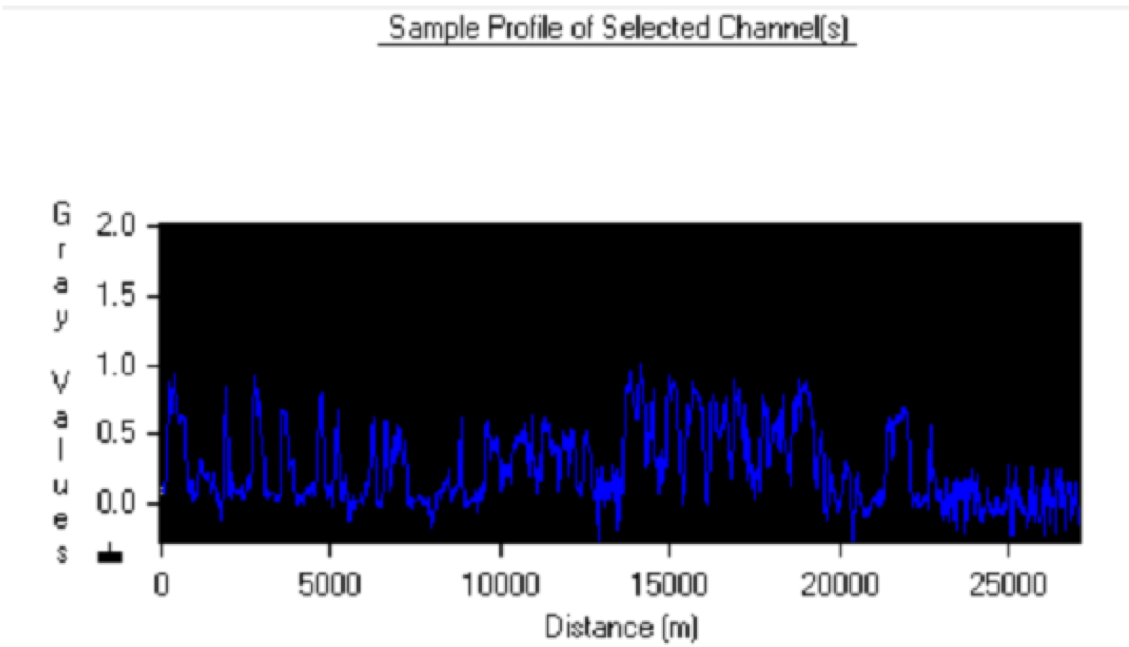

Figure 4-5: SLK35 Fire Spectral Profile

While most of the area is unchanged as shown in the image, the dNBR of the SLK35 fire indicates that the area burned was of low to low/medium severity. The NBR values range from -0.419 to 0.700 with negative values representing burned area. However the extremely dark areas are perhaps areas of noise created from the difference image due to cloud cover. As NBR ranges from -1 to 1, a low value of -0.419 suggests low to moderate burn severity. The prefire SLK35 South Bay image was subtracted from the post fire image to produce the dNBR image. The extremely dark areas in the dNBR image could be perhaps attributed to noise as small portions of cloud cover could be identified within the 2009 image. Due to this noise there are areas which show change within the vegetation and slightly over the burn area however this is incorrectly represented. Any impact the cloud cover had is minimal as the large majority of the burn area is cloud free and extent was still able to be mapped. As mentioned in Chapter 2, Verbyla et al. (2008) state that the changes in NBR could add significant noise to fire severity estimates from dNBR. Figure 4-6 shows the SLK35 difference image. The values range from -0.129 to 0.934 with the higher values appearing in the burned area (values represented in Figure 4-7).

While most of the area appears unchanged as shown in the image, the dNBR of the South Bay fires indicate that the area burned was of low to low/medium severity. The difference values are smaller than the SLK35 image which indicates that the fires may have been slightly less severe or there may have been less fuel in the area to burn. The NBR values range from -0.421 to 0.686 with negative values representing burned area. As NBR ranges from -1 to 1, a low value of -0.421 suggests low to moderate burn severity. The prefire NBR South Bay image was subtracted from the post fire image to produce the dNBR image. Like the SLK35 image, the South Bay dNBR has mostly no change except for the burn area. Figure 4-8 shows the values for the South Bay difference image. Figure 4-9 shows the classification results for the SLK35 fire.

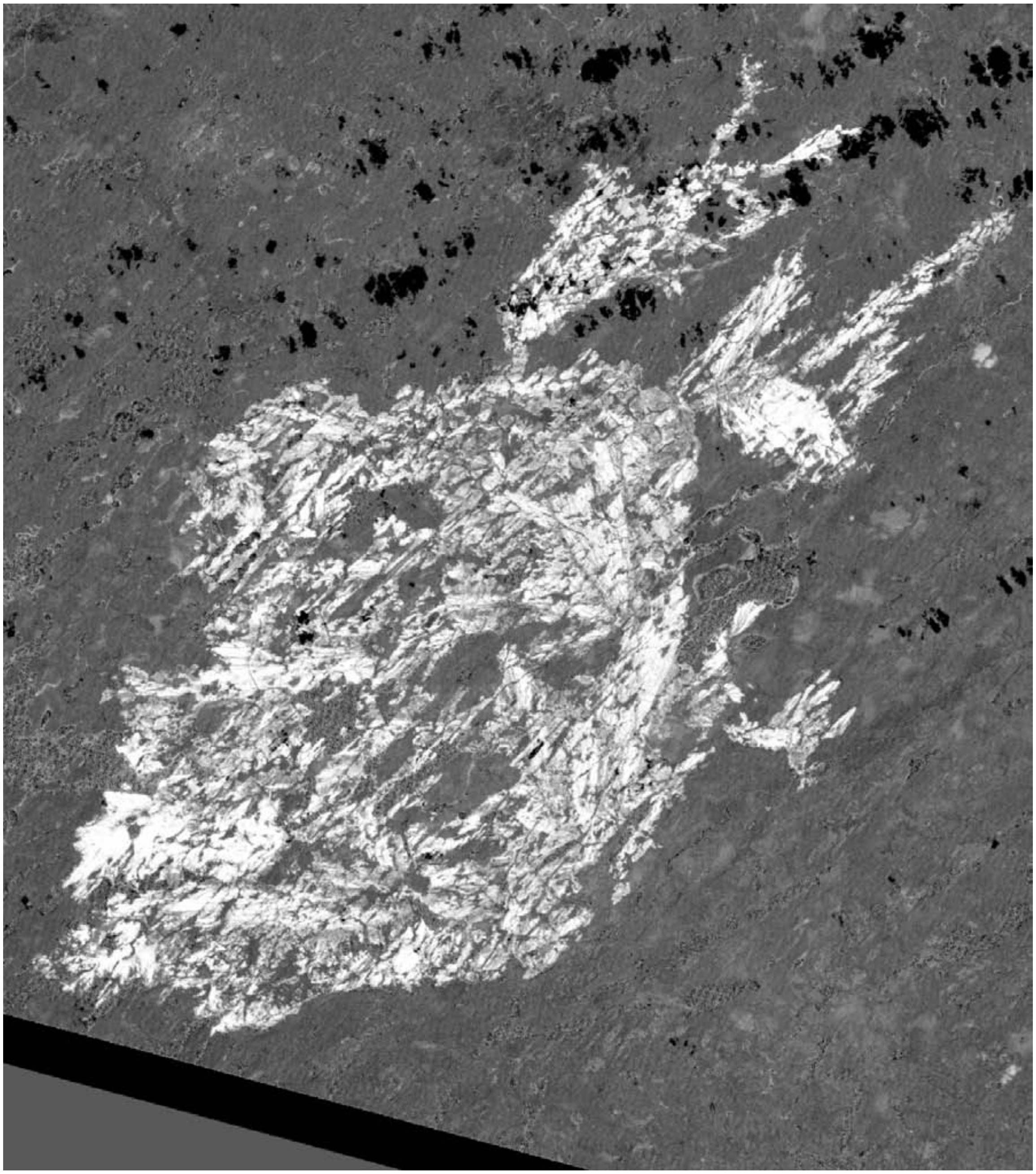

Figure 4-6: SLK35 fire difference normalized burn ratio (dNBR) with burned area appearing white (values near or greater than 1), unchanged area appearing grey (values near 0) and regrowth as negative values (darker areas lower than 0).

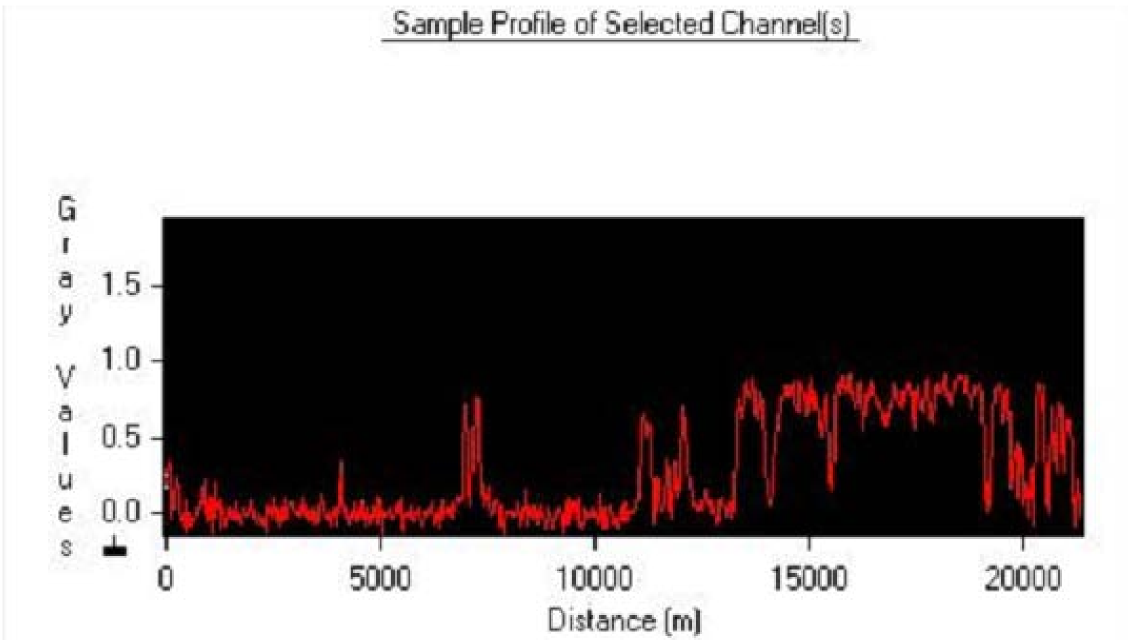

Figure 4-7: South Bay Fires Spectral Profile

The overall accuracy for the 2011 SLK35 image classification shown in Figure 4-9 was 95.667% with a 95% confidence interval of 93.196% to 98.137%. The overall Kappa statistic was 0.926% with a variance of 0%. Additional classification information is presented in the classification report (Table 4-1) and confusion matrix (Table 4-2).

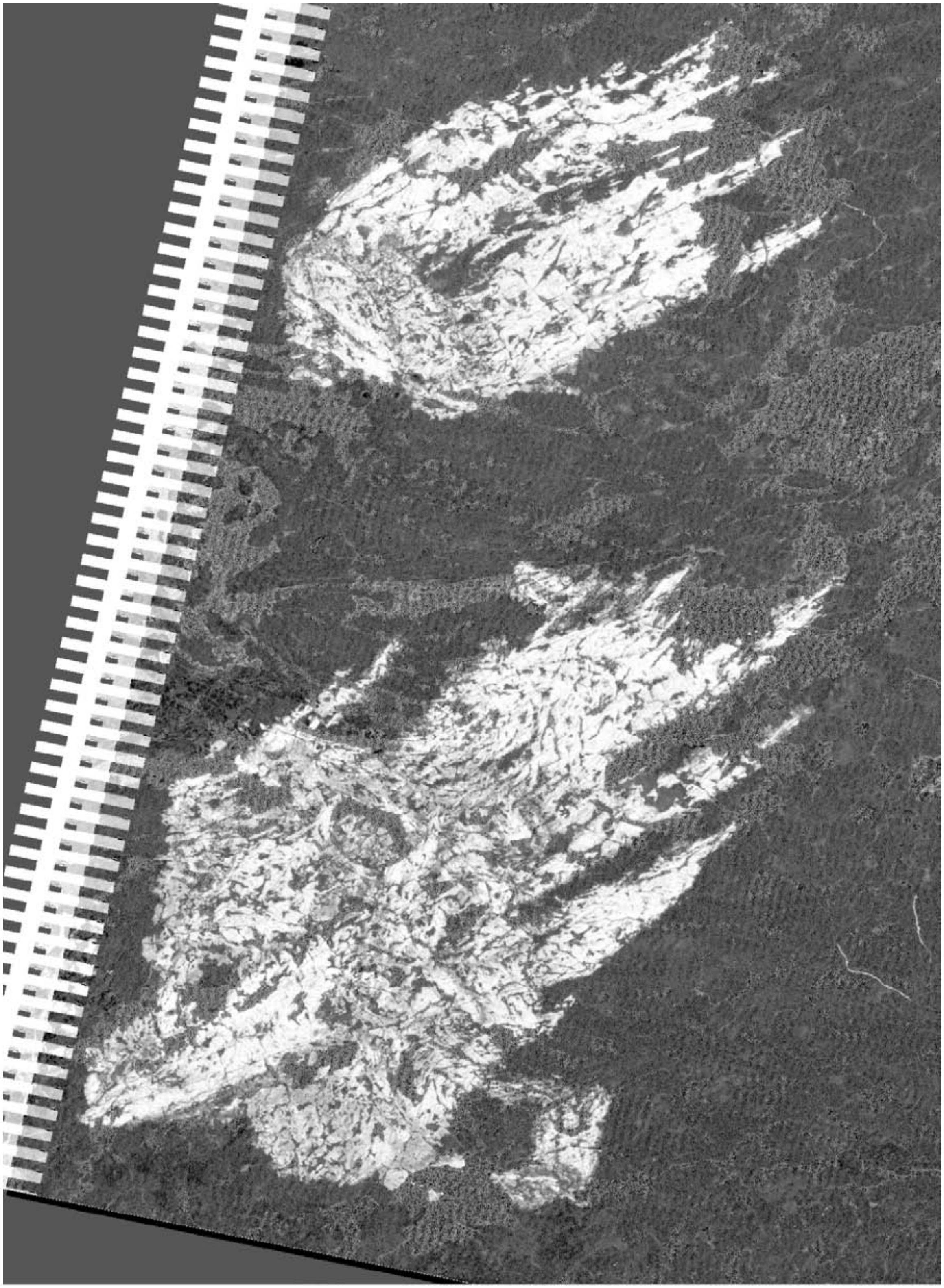

Figure 4-8: South Bay fires difference normalized burn ratio (dNBR) with burned area appearing white (values near or greater than 1), unchanged area appearing grey (values near 0) and regrowth as negative values (darker areas lower than 0).

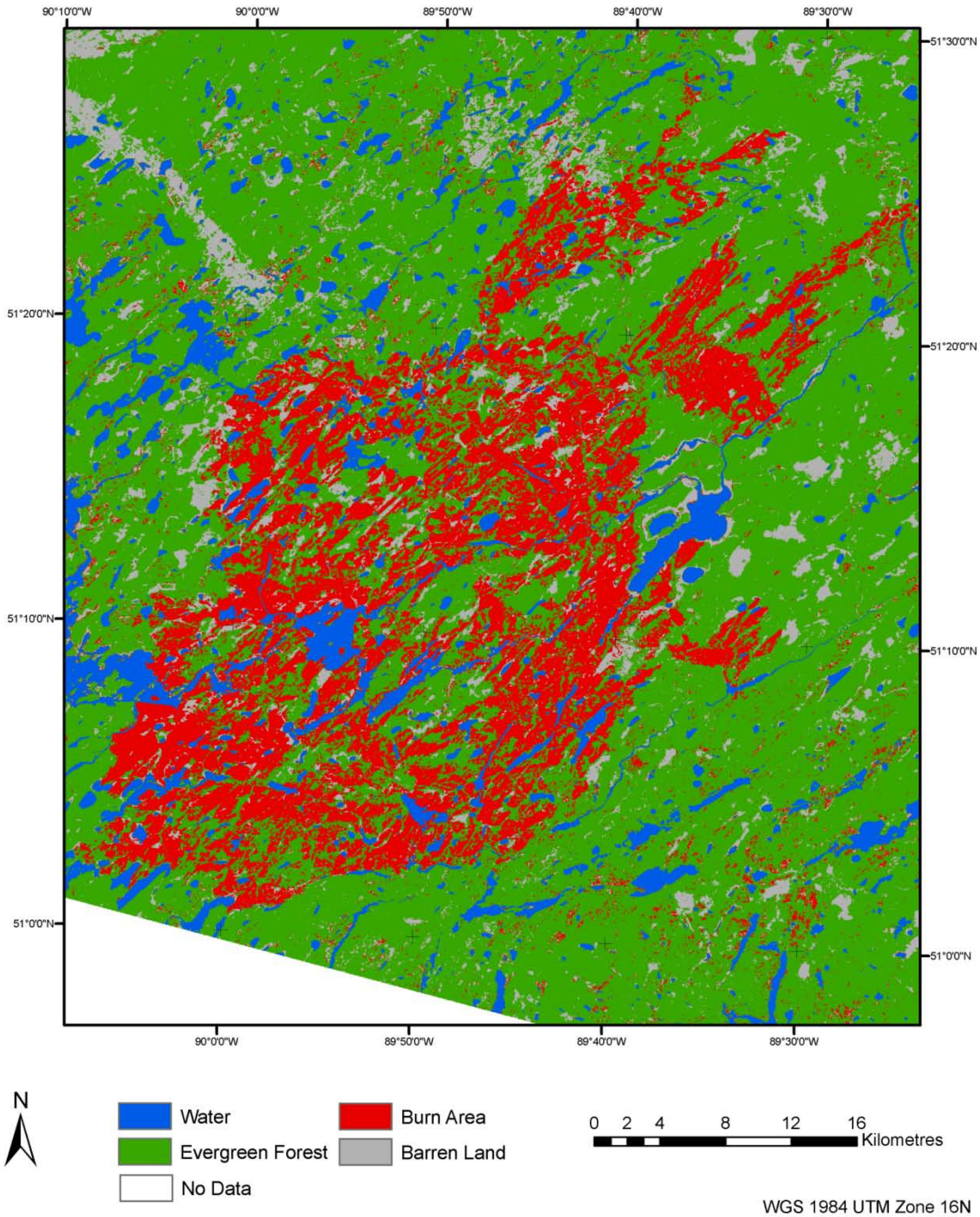

Figure 4-9: SLK35 Fire Classification Results

Table 4-1: 2011 SLK35 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	100.000%	98.000% 102.000%	100.000%	98.000% 102.000%	1.0000
Evergreen Forest	98.315%	96.143% 100.487%	95.628%	92.393% 98.864%	0.8925
Burn Area	89.063%	80.635% 97.490%	95.000%	88.652% 101.348%	0.9364
Barren Land	84.211%	65.183% 103.238%	88.889%	71.593% 106.185%	0.8814
No Data	100.000%	96.429% 103.571%	100.000%	96.429% 103.571%	1.0000

Table 4-2: 2011 SLK35 Confusion Matrix

Classified Data	Water	Evergreen Forest	Burn Area	Barren Land	No Data	Totals
Water	25	0	0	0	0	25
Evergreen Forest	0	175	6	2	0	183
Burn Area	0	2	57	1	0	60
Barren Land	0	1	1	16	0	18
No Data	0	0	0	0	14	14
Totals	25	178	64	19	14	300

Burn area has a producer's accuracy of 89.063% and is considered acceptable for this study. Burn area and barren land had some minor confusion with each other. Figure 4-10 shows the classification results for the South Bay Fires.

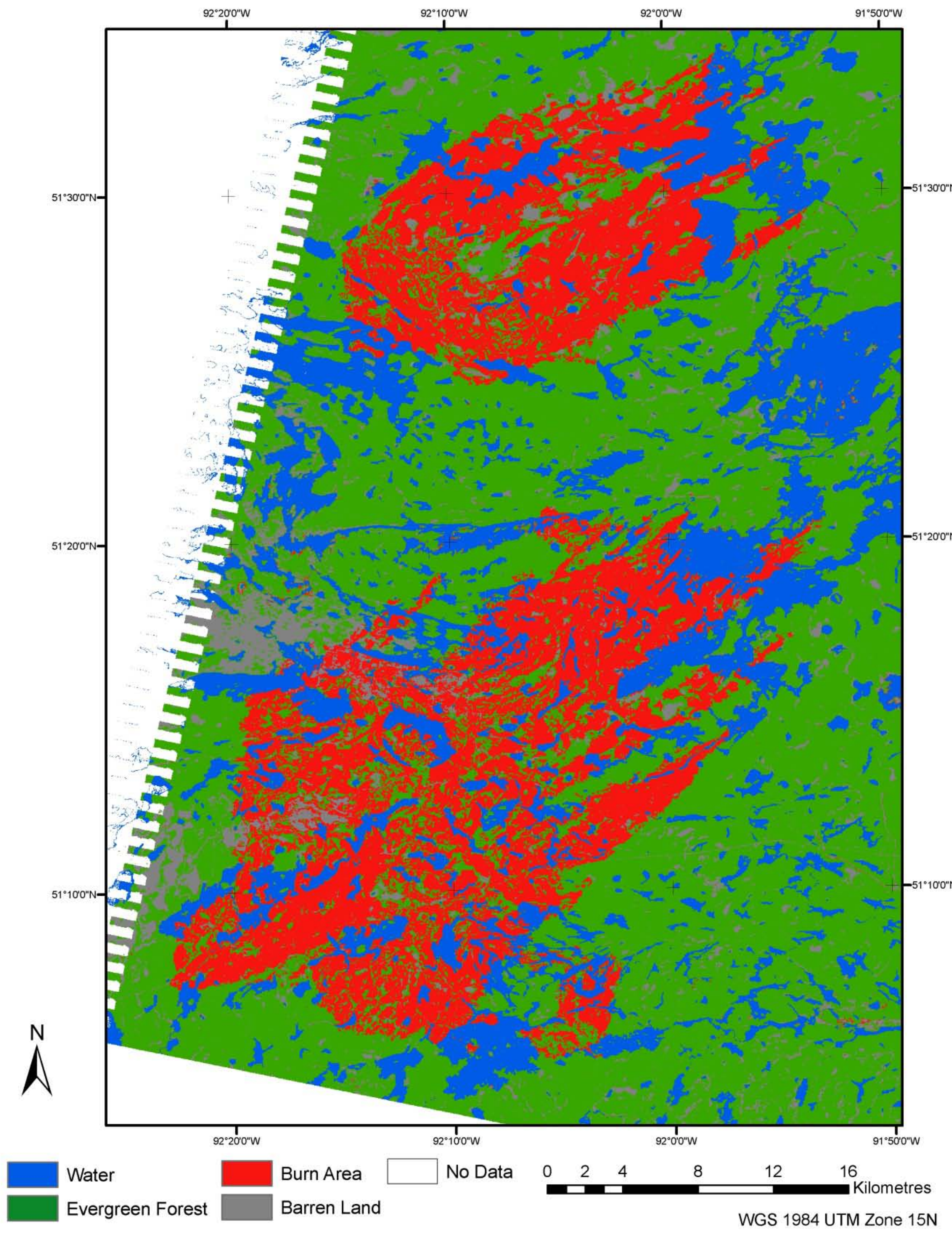

Figure 4-10: South Bay Fires Classification Results

The overall accuracy for the 2011 South Bay image classification shown in Figure 4-10 was 93% with a 95% confidence interval of 89.95% to 96.05%. The overall Kappa statistic was 0.896% with a variance of 0%. Additional classification information is presented in the classification report (Table 4-3) and confusion matrix (Table 4-4).

Table 4-3: 2011 South Bay Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	97.959%	92.980% 102.939%	97.959%	92.980% 102.939%	0.9756
Evergreen Forest	94.667%	90.737% 98.596%	94.667%	90.737% 98.596%	0.8933
Burn Area	87.500%	77.945% 97.055%	92.453%	84.398% 100.508%	0.9072
Barren Land	93.939%	84.283% 103.596%	86.111%	73.425% 98.797%	0.8439
No Data	75.000%	46.333% 103.667%	75.000%	46.333% 103.667%	0.7396

Table 4-4: 2011 South Bay Confusion Matrix

Classified Data	Water	Evergreen Forest	Burn Area	Barren Land	No Data	Totals
Water	48	0	0	1	0	49
Evergreen Forest	1	142	7	0	0	150
Burn Area	0	0	49	1	3	53
Barren Land	0	5	0	31	0	36
No Data	0	3	0	0	9	12
Totals	49	150	56	33	12	300

Even though burn area has a producer's accuracy of 87.5% (and is lower than the SLK35 fire), it is still considered acceptable for this study. The results obtained through unsupervised classification were acceptable in terms of overall accuracy and there was some minor confusion in the error matrix. This led to some minor misclassifications of barren land and the burn area. These misclassifications could be the result of spectral similarity between the barren land class and areas that may have experienced partial burning and have a higher brightness. There also seemed to be lower producer's accuracy for the no data class in the South Bay classification report. This is due to the zipperline showcasing the edge of the image but it was classified as no data. The high kappa statistics however were good as that indicated good model performance.

4.2 Final Fire Extents

Performing change detection using band differencing techniques avoided compounding classification errors in the change detection process and subsequent statistical analysis. Change detection mapping of the burn areas involved the arithmetic multiplication of the land cover classification results presented above and the dNBR image for each temporal period to determine change and no change. The burn area class in the figures below is a result of the difference image being multiplied with the classification results. The burn area classes of the true fire extent maps are a product of image classification and are thus affected by the accuracy of the classification results. The actual burn area was calculated in regards to the subset image to discover the true extent of the fire area.

Figure 4-11 on the next page begins with the actual burn extent of the SLK35 fire.

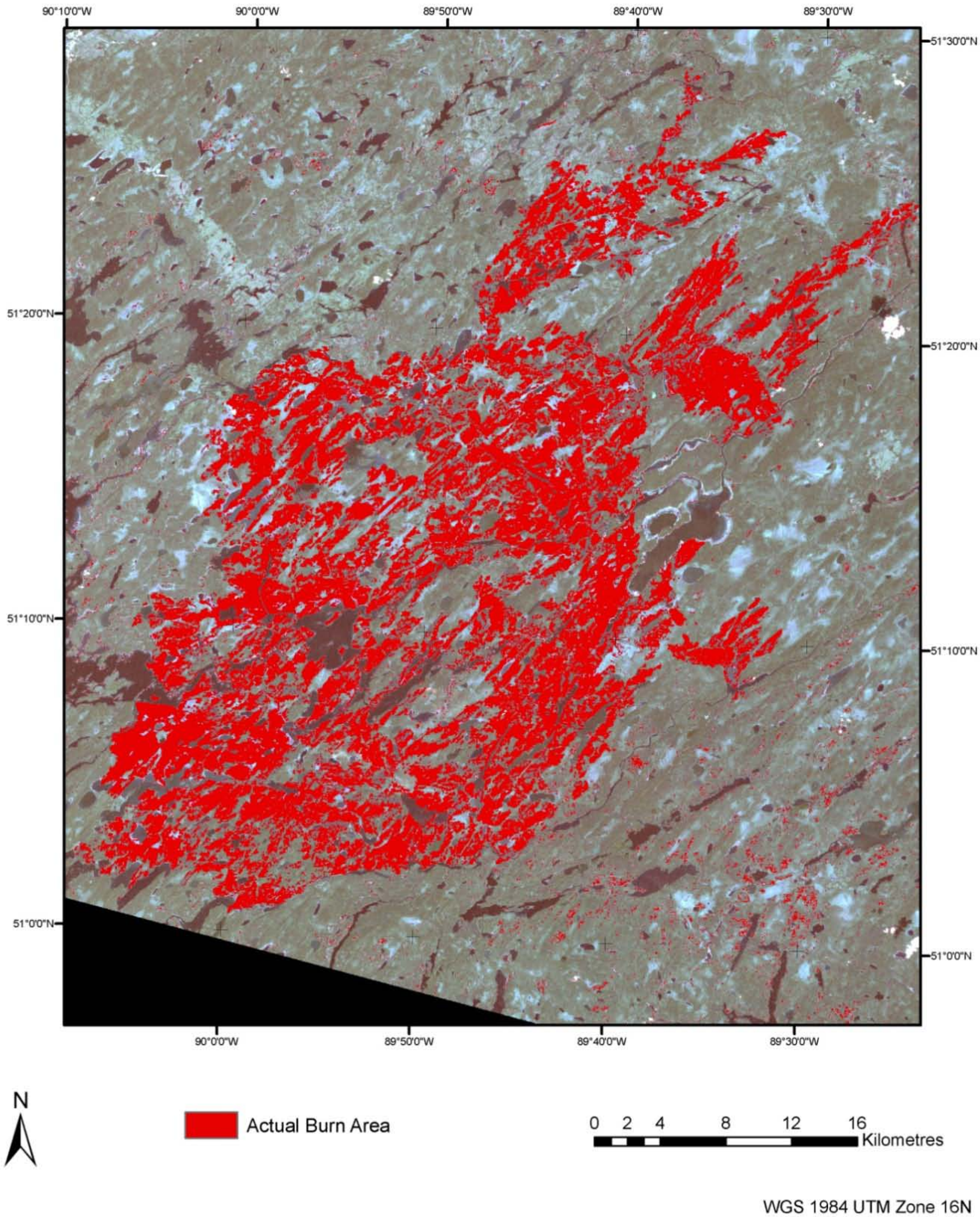

Figure 4-11: SLK35 Fire Actual Burn Extent

SLK35 True Fire Extent 2009-2011

In the two year period from 2009 – 2011 shown in Figure 4-11, the SLK35 burn area class (shown in red) experienced 586 square kilometres (17% of the study area) of extent. Out of the 632,533 hectares burned in 2011, the SLK35 fire accounts for 9% of the total area burned in 2011. While small lakes and barren land from the Canadian Shield acted as a barrier to impede the progress of the SLK35 fire, ultimately fire suppression crews were needed to keep it under control. Some areas around the small lakes and barren land displayed limited burning and some other areas around water bodies appear to be unburned. Meteorological data from the month of July shows that mid July had several thunderstorms which could have started the fire by a lightning strike. Winds during the month of July as well were quite strong reaching as high as 64km/h. With strong winds fueling the fire, it progressed in a fair distance even able to bypass several terrain features. From the shape of the burn area, the fire progressed towards the north east and looks to be largely wind driven with winds coming out from the north west and south west.

Meteorological data had shown the mean high temperature in July to be 26 °C. Regardless of having several thunderstorms, consistent daytime highs of over 26 °C from mid-July dried out much of the vegetation in the area turning it into fuel for when the fire was burning into the area. The NDVI images further strengthen this notion as they show large amounts of light grey areas which indicate vegetation under some level of stress.

Figure 4-12 shows the actual burn extent of the South Bay fires.

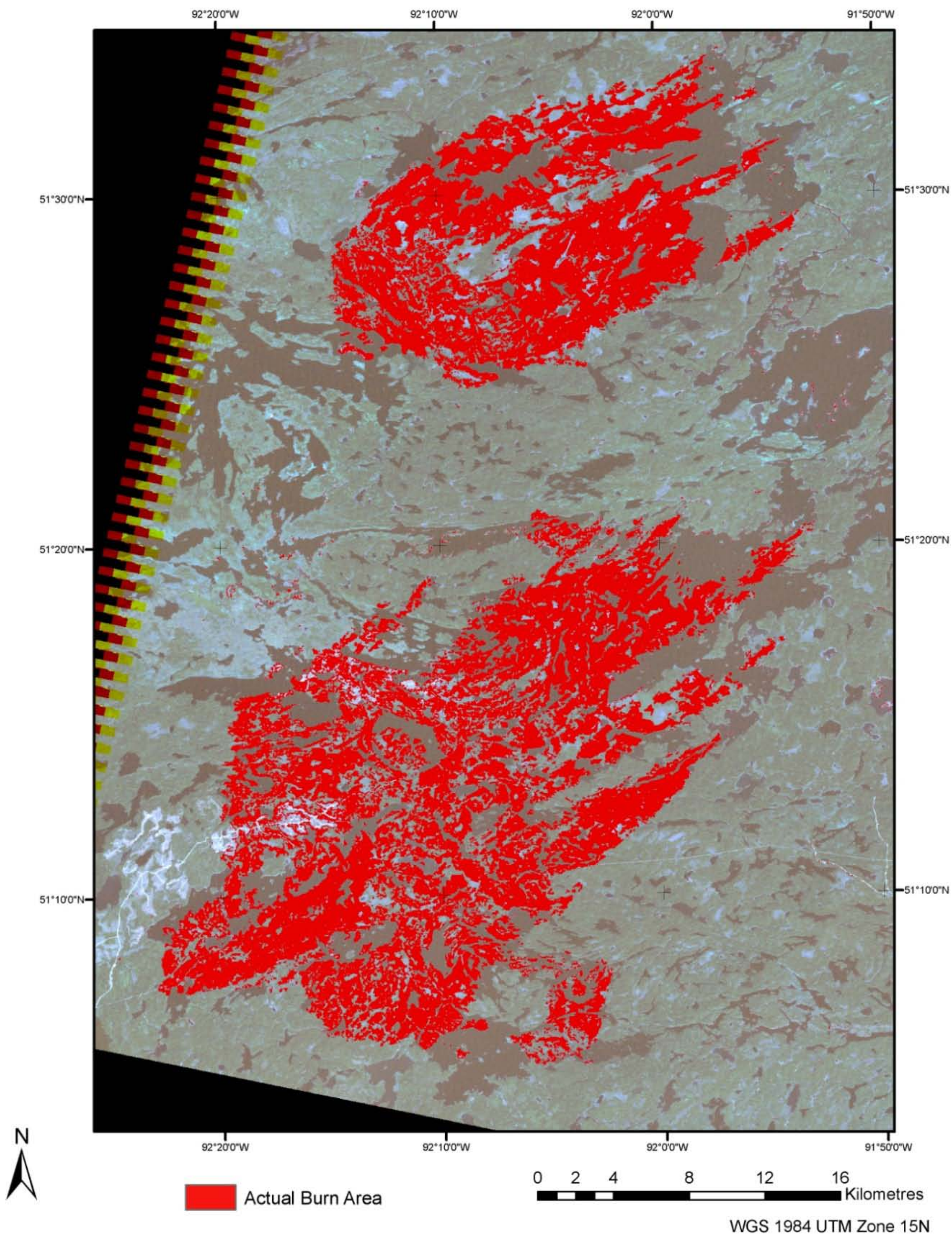

Figure 4-12: South Bay Fires Actual Burn Extent

South Bay True Fires Extent 2009-2011

In the two year period from 2009 – 2011 shown in Figure 4-12, the South Bay burn area class experienced 450 square kilometres (18 % of the study area) of extent. Out of the 632,533 hectares burned in 2011, the South Bay fires (shown in red) account for 7% of total area burned in 2011. In conjunction with the SLK35 fire, these burn areas account for 16% of the total burned area in 2011. These finding support the statement that most of the burned area in 2011 was caused by several large fires.

Meteorological data from July appears useful here as the study areas are close by and near each other. Thunderstorms that would affect one area would also most likely affect the other and thus the South Bay fires are subject to the same weather conditions as the SLK35 fires. Strong winds evident in Figure 4-12 along with fairly high temperatures caused several large fires. Even though the SLK35 fire has a larger extent by comparison, these fires are still notable in that they managed to burn nearly as much as the SLK35 fire. In addition, the NDVI image showed that the vegetation in the area was that of a light grey which could indicate that it was under some stress due to dry conditions. In terms of terrain, there are plenty of small lakes and some barren land by the Canadian Shield which helped serve as a natural barrier against the fire and limited some extent as some areas around water bodies appear to be unburned. Both areas show areas of barren land (more barren land in the SLK35 image), which could impede the progression of the fires. The amount of vegetation in both images far exceeded the amount of barren land which provided abundant fuel for the fires.

Overall, the meteorological data shows that July of 2011 was a fairly stormy and hot month and that the fires burn direction was largely influenced by the wind. Strong winds blowing from the south west and north west were prevalent during the second half of July. Winds from the south west were recorded for 13 out of 17 days from the period of July 15 to August 1. Winds from the north west were recorded for 13 out of 17 days of the same time period. Winds from the north east and south east were present on several days but not to the extent of the prevailing winds during the same time period. The fires were located on higher ground in both study areas at above 500m. With the winds blowing largely from the south west, the fires progressed towards lower elevations. Regardless of fire's tendency to burn uphill, elevation did not matter much in the cases of the SLK35 and South Bay Fires. The main barrier to the fires was the abundance of lakes in both study areas. While no one was harmed from these fires, approximately 1,036 square kilometres of vegetation were burned. In addition, there are many more burn areas in the boreal region according to fire reports from CIFFC, however, Landsat images for those fire sites had considerable cloud cover when visually inspected. As these fires were quite close to park areas, tourists within the area would have to take caution from these fires. The proximity of the SLK35 fire may have also put the residents of Pickle Lake at risk if the winds had blown it towards the North West. The South Bay Fires burned on some rural roads which put in danger people driving in the area. With such a large area burned however, the lumber industry in Northern Ontario felt some impact as many trees were burned and based upon the severity maps, they were perhaps crown fires. Fire management teams were ill equipped to handle many large fires of the magnitude shown in this study. Dry weather with thunderstorms and strong winds, just like what was said in the literature were the cause of the 2011 forest fire season.

CHAPTER 5: CONCLUSIONS

The combination of remote sensing techniques utilized in this study has proven to be an effective method for mapping wildfire extent in a boreal forest setting. The image classification methods made use of the original Landsat bands and TCT to produce results with overall classification accuracies ranging between 93% - 95.667%. The dNBR images proved to be an accurate representation of changes to the vegetation and land cover after the forest fires affected the study site.

The results of this study estimate the total area of forest disturbance caused by fire over the study period of 2009-2011 to be 586 square kilometres (17% of the study area) for the SLK35 area. The South Bay area experienced 450 square kilometres (18 % of the study area) of fire disturbance. Both areas showed considerable burn extent and were some of the larger and more notable fires of 2011. Favourable conditions for wildfires such as dry conditions, thunderstorms, strong winds and lots of fuel were the main factors of the 2011 fire season. Sub factors included not enough fire management crews to handle the overwhelming amount of fires compared to 2009 and 2010.

While the ecological role of fire as an agent of disturbance for the maintenance of ecosystems and critical habitat is required in boreal forests, Ontario should have more fire management staff ready in the case that fire favourable conditions appear again. All fires having the potential to negatively impact values and/or cause social disruption should receive full response and sustained action until extinguished.

By measuring the extent of several fires within the study site, and integrating change detection methods it was possible to monitor and display and recreate fire extent for the 2011 fire period. Forest fires have been identified as a prominent cause of disturbances within the study site. dNBR has shown to be a reliable technique in modelling forest fires in boreal forests. This research will contribute to understanding of the evolution of fire management within the boreal forest zone. It further establishes the dynamic of fire within the boreal zone and how to effectively map the extent of it utilizing TCT, NBR and dNBR.

5.1 Limitations

The extent of this study was limited by several factors including atmospheric conditions, time constraints, and software issues which only resulted in the creation of 50 K-means classes, and resources. The dynamic atmospheric conditions of the study site and frequent cloud cover during the desired season acquisition window limited the number of images and burn area that could be acquired and utilized. This limitation led to the use of imagery that was almost a month apart and was not close to anniversary dates between images. Ideally, imagery would have been collected on an annual basis with minimal cloud cover, on the same day each year to minimize radiometric and phenological differences. Time and resource constraints limited the study by not allowing for any in-situ sampling or validation data to be collected and used for classification or accuracy assessment. Quality in-situ validation data would have allowed for the classification of tree types as well as improved classification results. Finally, software issues limited the number of K-means classes that could be utilized during the unsupervised classification.

Any more than K-means 50 classes and the software would crash, otherwise 100 K-means classes would have been used for more a more accurate classification.

In future work, the use of NBR as an input band in addition with the TCT may improve classification results for the study areas. In addition, difference images such as band 4 differencing can be compared to that of dNBR. Finally, natural barriers to fire spread can be examined to see how effective they are at mitigating fire progression and limiting fire extent.

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