INVESTIGATING FOREST DISTURBANCE USING LANDSAT DATA IN THE NAGAGAMISIS CENTRAL PLATEAU, ONTARIO, CANADA

by

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Abstract

The Nagagamisis Central Plateau located in northern Ontario, Canada is an area of distinct natural and cultural significance in the Boreal shield ecosystem. The importance of this land was officially recognized in 1957 through the establishment of Nagagamisis Provincial Park Reserve. Since its inception, the park has experienced significant expansion and is currently under development as one of Ontario Parks 'Signature Sites'. Since the 1980's, timber harvest activity has led to widespread forest disturbance just outside of the park boundaries. Remote sensing provides a cost effective method for monitoring forest disturbance in vast remote areas, and can contribute insight to policy and management objectives. This research is focused on the detection of stand level forest disturbances associated with timber harvest occurring near Nagagamisis Provincial Park. The image time series data selected for this project is Landsat TM and ETM+; spanning a twenty-five year period from 1984 to 2009. The Tasselled Cap Transformation and Normalized Difference Moisture Index are derived for use in unsupervised image classification to determine the land cover for each image scene in the time series. Image band differencing and raster arithmetic are performed to create disturbance maps illustrating the size and spatial distribution of stand level forest disturbances between image dates. A total area of 1649 square kilometres or 26.1% of the study area has experienced stand level disturbance over the twenty-five year study period.

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List of Acronyms

AMSL – Above Mean Sea Level

ETM+ – Enhanced Thematic Mapper plus

FMU – Forest Management Unit

GIS – Geographic Information System

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

NDMI – Normalized Difference Moisture Index

NDVI – Normalized Difference Vegetation Index

NIR – Near Infrared

OLL – Ontario Living Legacy land use planning strategy

OMNR – Ontario Ministry of Natural Resources

PCIDSK – PCI Geomatics Database File

SFL – Sustainable Forest License

SWIR – Short Wave Infrared

TCT – Tasselled Cap Transformation

TM – Thematic Mapper

UTM – Universal Transverse Mercator

USGS – United States Geologic Survey

WRS 2 – Worldwide Reference System

CHAPTER 1: INTRODUCTION

1.1 Forest Disturbance in Canada's Boreal

The Boreal forest occupies a total area of 300 million hectares within Canada (Brant, 2009). The Boreal forest is a dynamic ecosystem that changes continually as a function of natural (succession, fire and insects) and anthropogenic disturbance events (land use change and timber harvest) that can have significant ecological effects (Schroeder et al., 2011; Wulder et al., 2010).

Cyclical forest fires regimes are a primary cause of stand level disturbance in the Canadian Boreal ecosystem (Schroeder et al., 2011; Kasischke and Turetsky, 2006; Weber and Flannigan, 1997; Heinselman, 1983). Anthropogenic resource extraction activities such as timber harvest have also had a large physical impact on the Boreal ecosystem in recent history (Wulder and Franklin, 2007; Schroeder and Perera, 2002). The size, frequency and intensity of fire regimes and timber harvest vary widely in terms of amount of tree mortality, vegetation and biomass loss within a disturbed area (Schroeder and Perera, 2002). Both fire and timber harvest disturbances impart significant and unique ecological effects on the forest landscape (Schroeder et al., 2011).

Across Canada, roughly one quarter of the Boreal ecosystem is managed by commercial timber harvest operations under public land lease agreements. In Ontario, a total area of 300,000 square kilometres of Boreal forest is managed and harvested under Sustainable Forest Licence (SFL) agreements (Schroeder and Perera, 2002). SFL agreements between the Ontario government and private timber harvest companies involve a formal proposal of harvest strategies and silviculture activity within geographic areas known as forest management units (FMU) (OMNR, 2011). These areas are subject to regular audits to ensure the contractors are fulfilling these agreements. Over the period of 1975 to 1993, there has been a 125% increase in the amount of Boreal forest harvested annually in Canada (Schroeder et al., 2011; Environment Canada, 2008). Between 1951 – 1960, the total clearcut area in Ontario was 5,000 square kilometres and increased to more than 20,000 square kilometres between 1981 and 1990 (Perera and Baldwin, 2000).

1.2 History of Timber Harvest in Canada

Boreal hardwood and softwood trees have economic value and undergo processing to become an array of construction materials and paper products. In the time leading up to WWII, loggers used axes, handsaws and horse drawn sleighs to pull logs to the riverbanks as was the standard logging practice in Canada (Weetman, 1983). From here the wood was driven downstream to mills for processing. This type of timber harvest selected only the best trees for harvest, left many standing trees throughout the harvested area and limited harvest to areas adjacent to waterways (Weetman, 1983). These practices of selective logging and the lack of heavy machinery resulted in less impact on the forest ecosystem than modern commercial harvesting methods. With large-scale commercial operations and the development of more efficient machinery, logging practices became an almost complete removal of all standing trees within large harvest areas (Weetman, 1983). This clearcut harvesting method results in changes to the land surface over broad spatial extents, which has a greater overall effect on the forest ecosystem (Sader et al., 2003). It is estimated that 88% of forests harvested in Canada between 1920 and 1996 were removed using clearcut harvesting methods (Schroeder et al., 2011). After harvest, lands are left to regenerate from natural seeding, silviculture management and tree planting.

In response to public concern in the 1960's regarding forestry practices and the need to protect natural areas, government legislation and forest management practices were implemented. These improved practices included more tree planting after harvest and modification of machinery to minimize the impact on the land, which allowed for increased chances of forest regeneration after harvest (Weetman, 1983). In addition to lower impact logging practices, tracts of land were put aside in order to preserve natural, mature forest stands for the purpose of better understanding forest ecosystem dynamics, natural and cultural heritage (Weetman, 1983).

1.3 Significance of Protected Lands

In Ontario, there is a long history of preservation and protection efforts for areas of significant natural and cultural heritage dating back to 1893 with the establishment of Algonquin Provincial Park. Following this, the passing of the Provincial Parks Act in 1913 led to the establishment of more than 150 Provincial Parks by 1983 (Ontario Parks, 2004). These protected areas contribute to maintaining a healthy ecosystem, protecting wildlife habitat and enhancing scientific understanding of forest ecosystems (Ontario Parks, 2004). Since the Provincial Parks Act, many land-use planning initiatives have been undertaken across the province to strengthen Ontario's protected area network of parks, conservation reserves and wilderness areas. These initiatives have been integrated into provincial policy through implementation of the Lands for Life (1997) and the Ontario Living Legacy (1999) land-use planning strategies. The purpose of these strategies is to guide the management and planning of land-use on crown land including the expansion of the protected area network (OMNR, 2002). In 2005, the protected area network consisted of a total area of more than 8 million hectares in Ontario (OMNR, 2004). Under the Ontario Living Legacy (OLL), nine flagship areas referred to as 'signature sites' are to be developed as showcases of Ontario's natural and cultural heritage (Ontario Parks, 2004). One such signature area is the Nagagamisis Central Plateau, which is located within the study site chosen for this project.

1.4 Nagagamisis Central Plateau

The Nagagamisis Central Plateau located in northern Ontario, Canada is an area of distinct natural and cultural significance in the Boreal shield ecosystem. It is located 30 km north of Hornepayne and 130 km southwest of Hearst, Ontario (Figure 1-1). The park's Cree aboriginal name Nagagamisis, means "lake with fine, sandy shores" (Ontario Parks, 2010). There are two large water bodies in the park, Lake Nagagami is located in the western portion of the park and Lake Nagagamisis to the east is a slender water body that has its long axis in the east - west direction. This area is home to unique glacial features including the Arnott Moraine and rare kettle, esker and kame features (OMNR, 2002a). This area also has a human history and cultural heritage dating back thousands of years (OMNR, 2002a). The importance of this land was officially recognized in 1957 through the establishment of Nagagamisis Provincial Park Reserve. Since its inception, the park has experienced significant expansion and is currently under development as one of Ontario Parks 'Signature Sites'. The present park consists of four distinct components: the Nagagamisis Provincial Park established in 1957, the Nagagami Lake Provincial Park established in 1985 under the Ontario Provincial Parks Act. Under the OLL, a park expansion of 32,680 hectares in 2003 resulted in the joining of the two parks to encompass Lake Nagagami, Lake Nagagamisis, the Foch - Nagagami River, surrounding topographic features and forest stands (Ontario Parks, 2003). The addition and creation of an enhanced management zone expanded the park to the north and south and includes lands in 13 geographic Townships. The addition included areas that have previously been subject to clearcut timber harvest activity. Timber harvest activity has been a prevalent agent of disturbance in the forestlands surrounding Nagagamisis Provincial Park Reserve. The challenge remains to protect areas of natural and cultural significance while maintaining the economic stability of the surrounding communities that are dependent on forestry and maintaining sustainable forest resources (Ekstrom, 2007).

1.5 Remote Sensing of Forest Disturbance

The use of satellite based remotely sensed data has been identified as an accurate and cost effective method for monitoring land cover changes on the earth surface (Cohen and Goward, 2004; Lunetta et al., 2004). Remote sensing provides an effective method for monitoring forest change in vast remote areas and can contribute insight to policy and management objectives (Coppin and Bauer, 1996; Sader et al., 2003). Periodic forest cover disturbance monitoring is necessary for assessment of sustainable forest management strategies and is useful for monitoring environmentally significant areas (Popatov et al., 2011). The Landsat program, run by the United States Geological Survey (USGS), is the longest running source of remote sensing data used for earth observation, and is freely available (Cohen and Goward, 2004). The 30 metre spatial resolution of the Landsat TM and ETM+ sensors provides adequate resolution to resolve both natural and anthropogenic stand level disturbances that occur within forest ecosystems (Schroeder et al., 2011).

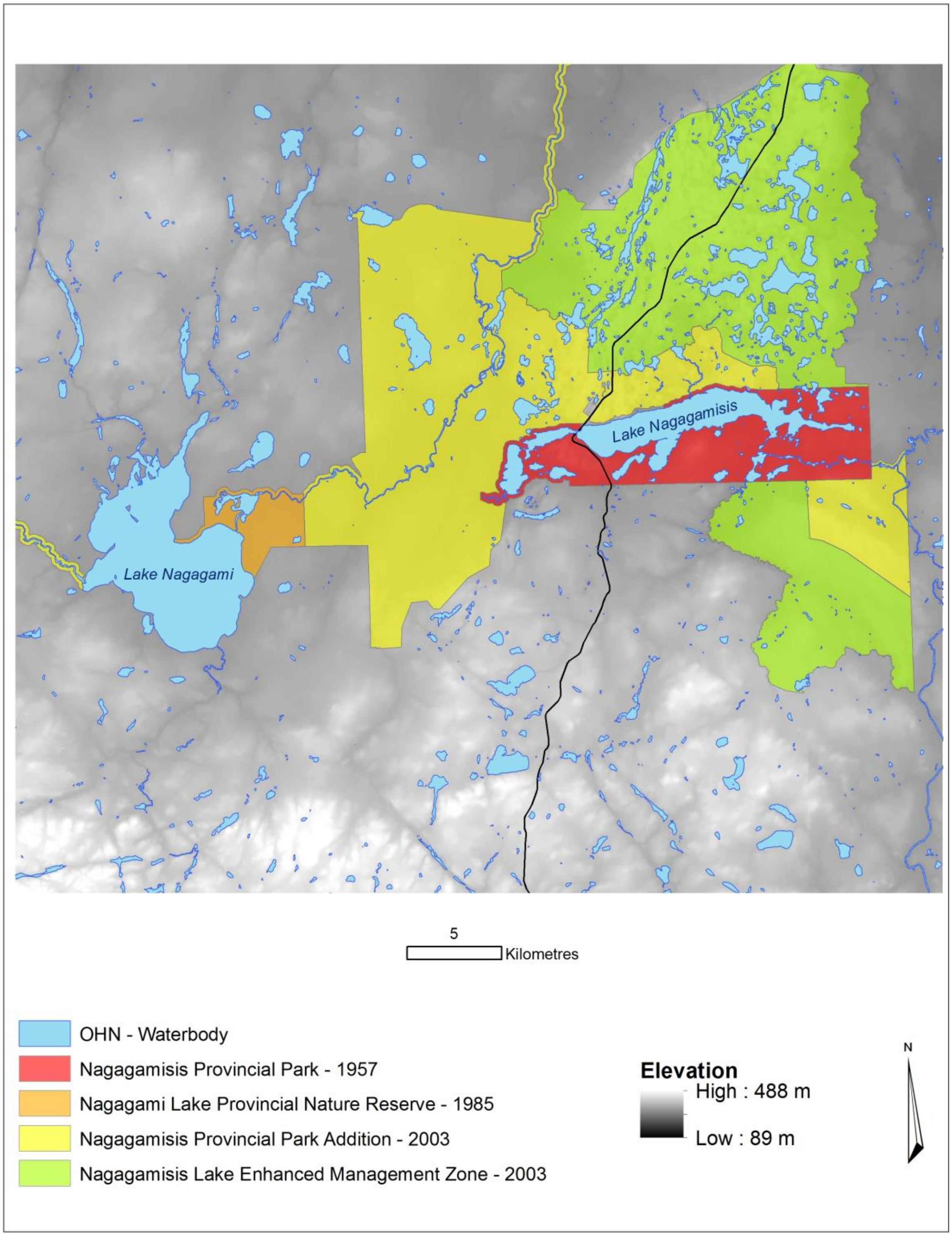

Figure 1-1: Nagagamisis Central Plateau Signature Site

The TM and ETM+ sensors provide a wide spectral resolution, which extends through the visible, near infrared, and short wave infrared portions of the electromagnetic spectrum. Landsat also provides a moderate temporal resolution with a revisit period of 16 days for most locations on Earth (Cohen and Goward, 2004). In the literature, Landsat data have been used for many forest classification and change detection applications such as: forest fragmentation, insect infestation, fire regime monitoring, timber volume estimation, forest succession and more (Gluck and Rempel, 1996; Cohen et al., 2001; Cohen and Goward, 2004, Schroeder et al., 2011).

This study is focused on the detection of disturbances associated with timber harvest activity that results in a near complete removal of all trees within an area. This removal of vegetation biomass is referred to in the literature as a stand level disturbance (Cohen et al., 2002). In this research, stand level disturbances can be described as areas larger than 900 square metres that can be detected and mapped using Landsat imagery (Cohen et al., 2002) The amount of forest land cover, size, and severity of disturbances has been used as an indicator of environmental condition such as habitat fragmentation and carbon flux within Canada (Lunetta et al., 2004; Cohen et al., 1996). The use of Landsat imagery has been shown in the literature to be an effective dataset for the detection of stand level disturbance as a result of timber harvest activity (Coppin and Bauer, 1994; Cohen et al., 1998; Cohen et al., 2002; Schroeder et al, 2011). Repeated land cover mapping of the same study site over a period of time allows for evaluation of changes in forest cover (Hall et al., 1991). Many studies make use of multiple image dates in order to detect changes in land cover through time (Coppin and Bauer, 1996; Schroeder et al., 2011). There are many different analytical methods presented in the literature yet, there is no consensus on the selection of methods that can be applied to all land cover applications with equal success and accuracy (Lunetta et al., 2004). In the comprehensive review of Coppin and Bauer (1994), many change detection techniques are tested and the authors conclude that image differencing and linear transformations perform better than other change detection methods (Wilson and Sader, 2002).

1.6 Vegetation Indices

The Thematic Mapper Tasselled Cap Transformation (TCT) (Crist and Cicone, 1984) reduces the six original Landsat reflectance bands 1-5 and 7 to three components representative of physical land surface characteristics known as brightness (TCT1), greenness (TCT2) and wetness (TCT3) (Kauth and Thomas, 1976). These three components 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; Franklin et al., 2001). In recent research, the TCT performed significantly better than the original Landsat bands for detecting change in a forested landscape (Healey et al., 2005). Forested lands that have recently been disturbed will exhibit a higher brightness, lower greenness and wetness values than undisturbed mature forest stands (Healey et al., 2005). Of particular interest is the wetness component for its sensitivity to plant and soil moisture, canopy structure and shadow (Crist and Cicone, 1984; Horler and Ahern, 1986; Cohen et al., 1995; Wilson and Sader, 2002).

The Normalized Difference Moisture Index (NDMI) is derived using Landsat bands four (NIR) and band five (SWIR) as shown in equation 1 (Goodwin et al., 2008). The NDMI algorithm is very similar to the Normalized Difference Vegetation Index (NDVI) that is commonly used in forest classification and to estimate characteristics such as leaf area, biomass, and canopy closure (Sader and Winne, 1992). In a direct comparison, NDMI has been shown to be a more accurate measure than widely used NDVI for detection of forest harvest activity (Wilson and Sader, 2002).

$$NDMI = [Band\ 4 - Band\ 5] / [Band\ 4 + Band\ 5] \quad (1)$$

1.7 Problem Statement and Research Objectives

The overall objective of this research project is to investigate the relationship and spatial patterns of stand level forest disturbance and expansion of provincial protected areas through time. This research uses a medium resolution image time series; spanning a twenty-five year period from 1984 to 2009. The detection of forest disturbance events on the land surface will be examined on an interval ranging from two to five years. This analysis makes use of Tasselled Cap Transformation (TCT) and Normalized Difference Moisture Index (NDMI) to extract additional spectral information from the original Landsat image bands. Unsupervised classification is then used to determine the land cover for each image scene. Image band differencing and raster arithmetic are then used to create disturbance maps that illustrate the size, spatial distribution and rate of stand level forest disturbances within the study site.

The four specific objectives of this research include:

1) Derive vegetation indices using the Normalized Difference Moisture Index (NDMI) and the Tasselled Cap Transformation (TCT) from the original Landsat image bands.
2) Classify images to determine land cover characteristics for each image date in the time series.
3) Conduct band differencing operations to detect areas that have experienced inter annual stand level disturbances on a roughly five-year.
4) Characterize the area, trend and spatial distribution of forest disturbance within the study site for the duration of the study period (1984 – 2009).

1.8 Study Area

The study site, located in northern Ontario, Canada centres around the community of Hornepayne on Highway 631. The site covers an area of 6,303 square kilometres located in the Ontario Shield Boreal eco zone and Lake Abitibi eco region (Figure 1-2). The climate of the Boreal region of Ontario is characterized by long cold winters, and cool to moderately warm summer seasons (Rowe, 1972). The site is characterized by moderate topography with elevations ranging from 89 to 488 metres above mean sea level. The land cover is dominated primarily by large tracts of mixed deciduous and Boreal forest consisting of coniferous trees (black spruce, white spruce, jack pine, balsam, European larch) and deciduous tree species (poplar, trembling aspen and white birch). This forested landscape is dotted with hundreds of lakes, peatlands and wetlands. The fluvial features within the site are a part of the Kenogami watershed, which drains north towards the

Hudson Bay lowlands. The surficial geology of the area is characterized by clay belt podzols in lowland area and glacial lacustrine deposits and outwash features such as eskers, kettle lakes, kames and erosional escarpments at higher elevations (Schroeder and Perara, 2002; OMNR, 2002a). The underlying bedrock is dominated by metamorphic and volcanic rock with some sedimentary deposits (OMNR, 2002b).

The communities in this part of Ontario are small, isolated population centres that rely heavily on the forest industry (Ekstrom, 2007). Hearst, Ontario is about twenty times more dependent on the forest industry than the Provincial average. There are no other primary industries in this area that employ such a significant number of people (Ekstrom, 2007). The dominant land use within the study site is large forest management units (FMU) zoned for commercial timber harvest. Portions of four FMUs are represented within the study site. Roughly half of the study site is located within the Nagagami FMU (3020 square kilometres) and the other half in the Hearst forest (2942 square kilometres) while smaller portions are located in the White River (193 square kilometres) and Big Pic forest (155 square kilometres) management units. There are several protected areas of natural and cultural significance located within the study site such as nature reserves and Provincial Parks protected as the Nagagamisis Central Plateau signature site that are of particular interest to this research.

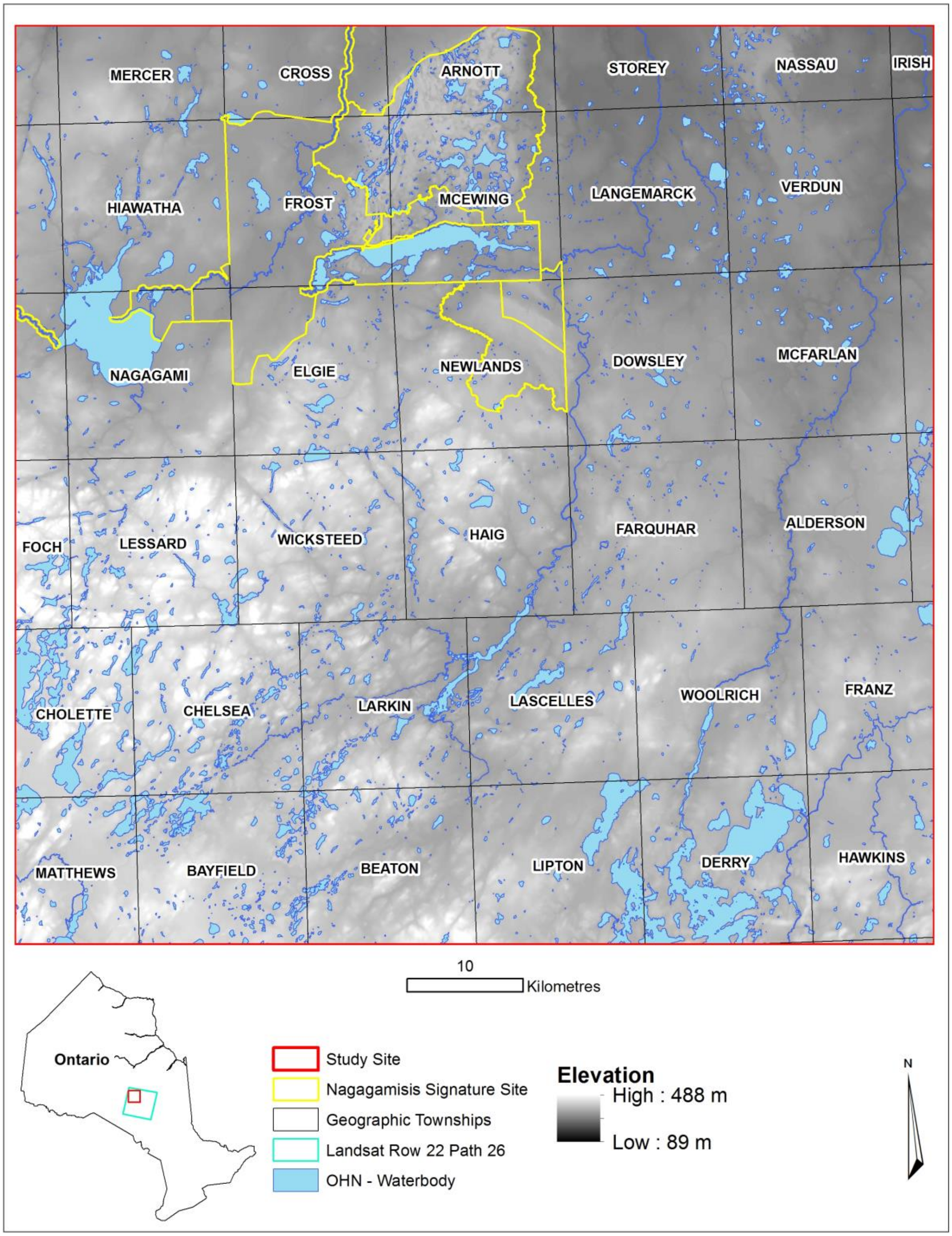

Figure 1-2: Study Site

CHAPTER 2: LITERATURE REVIEW AND METHODS

2.1 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://edcsns17.cr.usgs.gov/EarthExplorer/. Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) level 1 systematic and terrain corrected (L1T/G) image data were acquired for the study site residing in Path: 22, Row 26 WRS-2. The Landsat visible and infrared image bands 1 - 5 and 7 for both the TM and ETM+ sensors have compatible spatial resolution of 30 m and nearly identical spectral band resolution. Each image pixel covers a surface area of nine hundred square metres.

Over thirty, (May - September) images for the study period of 1984 to 2009 were acquired with a goal of capturing near anniversary growing season conditions at the nearest possible inter annual temporal interval. This required visual inspection of atmospheric conditions in each image scene for the distribution and size of cloud cover or haze. Only images that were cloud free over the study site were selected for use in the analysis. The final list of eight cloud-free image dates that were selected for analysis are presented in Table 2-1.

Table 2-1: Landsat Images

Image Date	Sensor
August 12, 1984	Landsat 5 TM
August 18, 1986	Landsat 5 TM
September 1, 1991	Landsat 5 TM
June 8, 1995	Landsat 5 TM
July 15, 2000	Landsat 7 ETM+
August 22, 2002	Landsat 7 ETM+
May 8, 2007	Landsat 5 TM
September 2, 2009	Landsat 5 TM

Frequent cloud cover at this latitude was a limiting factor in the image acquisition process. Cloud cover resulted in the use of images that span a five-month range and contain almost the entire phenological and foliage cycle of the deciduous trees in the study site. The dynamic atmospheric conditions also limited the study site to only a portion of the original 185 by 185 km image tile. These atmospheric conditions also limited the inter annual interval, resulting in two, four and five year time steps and not annual, anniversary image intervals. The time step for each selected image pair is presented in Table 2-2.

Table 2-2: Analysis Image Pairs and Time Step Duration

Image Pair	Length (years)
1984 - 1986	2
1986 - 1991	5
1991 - 1995	4
1995 - 2000	5
2000 - 2002	2
2002- 2007	5
2007 - 2009	2

2.2 Image Preprocessing

The Landsat L1T/G 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, NAD 1983 at a pixel resolution of 30 metres for processing and analysis. A visual investigation was carried out to ensure that all of the selected images were properly co-registered and correctly aligned prior to analysis. The full Landsat scenes contained in each PCIDSK file were then subset to isolate the specific study area that include the Nagagamisis Central Plateau signature site and surrounding commercial forest management units. Subsetting the imagery to the specific area of interest decreased the overall file size and increased the computational efficiency of processing and classification algorithms. The resulting subset image is 2646 pixels by 2647 lines covering an area of 6303 square kilometre.

Although radiometric correction of image time series datasets is recognized as an option for remote sensing projects, to account for variation in atmospheric and sun sensor geometry, no additional corrections were completed on the Level 1 data products used for this study. Radiometric differences do exist between analysis images, but the noises associated with temporal differences are minimal relative to the strong signal of stand level disturbance events (Cohen et al., 2002; Cohen et al., 2008). It was decided that the effort and time needed to atmospherically correct the imagery would not significantly affect the accuracy of the results (Cohen et al., 1998).

2.3 Image Band Differencing

Image band differencing involves the subtraction of pixels between two coregistered raster datasets to identify areas that have experienced change (Sader et al., 2003). Landsat band five short wave infrared (SWIR) difference images were produced for each inter annual image pair (Table 2-2). After experimenting with image band differencing using bands three, four and five, the band five (SWIR) differencing result was selected as the most appropriate for identifying areas of stand level forest disturbance. The SWIR channel is widely used in remote sensing for its sensitivity to vegetation structure, density, volume and leaf moisture content (Crist and Cicone, 1984; Horler and Ahern, 1986). The short wave infrared bands five and seven have been shown to contain more information about conifer and hardwood forests than any other Landsat bands (Horler and Ahern, 1986). In the context of the Boreal forest, band five has been effective for classification of clearcut harvest activity (Ranson et al., 2003).

The results of the band differencing operations for each time step of the analysis were saved as unsigned 8-bit raster datasets. When displayed in greyscale, these datasets are representative of changes to the forest cover between two image dates. Areas of forest that were disturbed prior to the beginning of each image time step appear in dark (black) tones that represent lower change values. While areas that were disturbed during each time step are shown in light (white) tones that represent higher change values. Areas that experienced no change during the time step are shown in shades of grey. These band difference images reveal the extent and spatial distribution of stand level forest disturbance and regeneration during each temporal image pair. Unsupervised classification methods were used to cluster the output band differencing raster datasets into three information classes. These classes were: regenerative change, disturbance change and no change.

Following a stand level disturbance, harvested areas experience a relatively quick regeneration of broadleaf pioneer species such as alder, poplar and other shrubs that appear as regenerative change in the difference images. The age of surrounding mature forest stands is 70 to 100 years (NRCAN, 2004). This research covers a time period of only 25 years, as such, the surface area of the regenerative change class continues to increase over the duration of the study. These areas differ from mature forest stands in both age structure and species composition. The true nature and composition of areas experiencing regeneration cannot be measured without in situ validation data. Since the focus of this work is on forest disturbance and not regeneration, these change areas are not included in the analysis. Alternatively, image classification is used to identify areas that remain disturbed at the later date of each image pair. The band differencing images are used only to identify areas that experience stand level disturbance between image pairs, as this is the primary focus of the study.

In order to exclude areas of regenerative change, they were reclassified as areas of no change to focus on change events related to stand level disturbance within each image time step. The image classification results for each image pair were used to identify areas of past disturbance. The output result of these procedures was a binary raster consisting of classes of disturbance change and no change.

2.4 Vegetation Indices

Using the original six Landsat bands 1 - 5 and 7, the TM Tasselled Cap Transformation (Crist and Cicone, 1984) was performed on each image scene. Using Landsat bands 4 and

5, Normalized Difference Moisture Index (Wilson and Sader, 2002) was calculated for each image scene.

2.5 Unsupervised Classification

Unsupervised ISODATA classification methods were used to classify each image in the time series. The ISODATA algorithm is a multivariate classification method used to identify spectral groupings (clusters) among unknown image pixels and aggregate them into a specified number of classes (Lillesand et al., 2008). The ISODATA algorithm has been reported by Hame (1998) to be appropriate for change detection when validation data sets of forest change are not available. The ISODATA classification algorithm was run with the parameters of 255 output spectral clusters and 20 iterations. The maximum number of 255 output clusters was specified in order to allow the algorithm to cluster the image pixels into as many clusters as needed. The algorithm usually identified between thirty and thirty-five output clusters. Sometimes specifying a lower number of output clusters leads to inaccurate results and poor classifications. These output clusters were then aggregated into three information classes, identifying pixels as undisturbed / regenerated forest, disturbed forest or water. 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 disturbance events including fire, timber harvest and related bush roads will be classified together with no discrimination between change types.

It is quite obvious by the visible geometric patterns and road construction that the primary cause of stand level disturbance within the study site is timber harvest. To confirm this, validation data were acquired from the OMNR North –file geodatabase.

These datasets included records of disturbances caused by insect infestation and fire. As fire is one of the most significant agents of forest disturbance in this area, it was investigated as an alternative cause to timber harvest.

There were five fires in the study area during the analysis period. Three of these fires were caused by timber harvest operations, one was caused by a lightning strike and the fifth was listed as miscellaneous causes. In all five instances, fire suppression was used in order to limit the growth and mitigate the damage caused by the fires. This dataset confirms that timber harvest is the main cause of forest disturbance within the study site.

The classification results presented in Chapter 3.1 provide snapshots of the size and distribution of stand level forest disturbances within the study site at each image acquisition date over the course of the study period. The inputs selected for the classification have been chosen based on their ability to accurately classify vegetation and include the Tasselled Cap Transformation and Normalized Difference Moisture Index. These transformed data and indices have been 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 these indices have been proven effective for classification of forest vegetation and stand level disturbance events (Cohen and Goward, 2004; Wilson and Sader, 2002). The inputs selected for use in each image classification are listed in Table 2-3.

Table 2-3: Classification Input Datasets

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	NDMI
8	TCT Brightness
9	TCT Greenness
10	TCT Wetness

2.6 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 (Congalton and Green, 1999). The aggregate classification for each image date was evaluated to determine its 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. 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 stratified random sample of 300 reference points was generated for the reference image and interpreted for each class of the aggregate classifications. The sample points were stratified proportionally to the number of pixels in each of the three information classes. Based on the results of the accuracy assessment, error matrices and accuracy statistics were generated for each image classification result. This technique has been established as a reliable method of accuracy assessment when ground truth data are not available (Wilson and Sader, 2002).

2.7 GIS Analysis

After completion of the band differencing and image classification processes, the data were migrated to a GIS environment for further analysis. The reclassified band difference change images were combined with the land cover classification results to produce disturbance maps for each image time step through raster calculations. An arithmetic addition operation was performed on each image pair in order to assign a land cover classification to areas of change identified in the band five difference images. This was achieved using the classification result for the most recent year of each time step and the corresponding disturbance difference image. The disturbance maps produced using this process identifies areas that have experienced stand level disturbance during each temporal period and are presented in Chapter 3.2.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Image Classification and Accuracy Assessment

The image classifications presented below provide a land cover map for the seven image dates chosen for this analysis. The classes presented in each land cover map are: water (blue), undisturbed / regenerated forest (green) and disturbed forest (red).

The water class represents all areas within the study site that have a land cover of water at the time of acquisition. The undisturbed / regenerated forest class represents all forested lands including mature forest stands and cutovers more than five years old that have experienced regrowth. The overall health, tree species composition and age of old cutover stands cannot be validated due to a lack of in situ sampling but is classified as undisturbed / regenerated due to its spectral characteristics. Pioneer species are the first vegetation to colonize a cutover area after stand level disturbance. They are mainly deciduous plants with a high leaf area that cause the surface to appear as healthy vegetation exhibiting low brightness, high greenness and wetness values even though the age structure of the stand has been completely altered (Lunetta et al., 2004). The disturbed forest class, shown in red represents the amount of forested land that has experienced recent disturbance prior to the image acquisition date. The disturbed forest class represents areas that had been recently disturbed and exhibit a high brightness, low greenness and wetness TCT values. These areas had been disturbed in the recent past and experienced little to no vegetative regeneration.

The overall accuracy of the 1986 image classification in Figure 3-1 was 97.3% with a 95% confidence interval of 95.3% to 99.3%. The overall Kappa statistic was 0.916% with

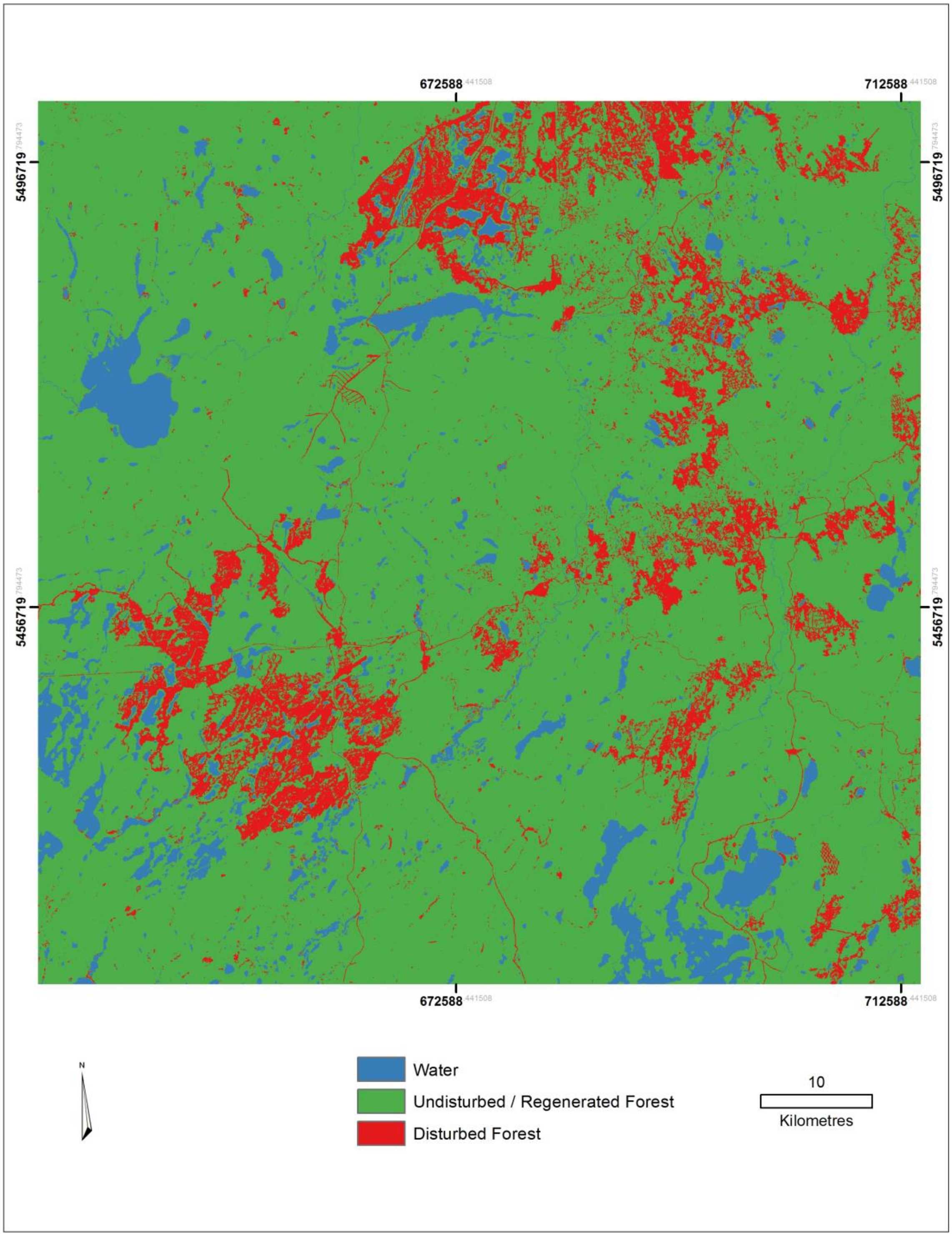

Figure 3-1: 1986, August 18 - Classification Result

a variance of 0.001%. Additional classification information is presented in the classification report (Table 3-1) and accuracy assessment matrix (Table 3-2).

Table 3-1: 1986 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	91.30%	77.62%, 104.99%	95.46%	84.48%, 106.43%	0.95
Undisturbed/ Regenerated Forest	98.77%	97.18%, 100.36%	97.97%	96.00%, 99.93%	0.89
Disturbed Forest	90.91%	79.59%, 102.23%	93.75%	83.80%, 103.70%	0.93

Table 3-2: 1986 Accuracy Assessment

			Reference Data		
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**21**	1	0	22
	Undisturbed/ Regenerated Forest	2	**241**	3	246
	Disturbed Forest	0	2	**30**	32
	Totals	23	244	33	300

The overall accuracy for the 1991 image classification shown in Figure 3-2 was 93.67% with a 95% confidence interval of 90.74% to 96.59%. The overall Kappa statistic was 0.756% with a variance of 0.004%. Additional classification information is presented in the classification report (Table 3-3) and accuracy assessment matrix (Table 3-4).

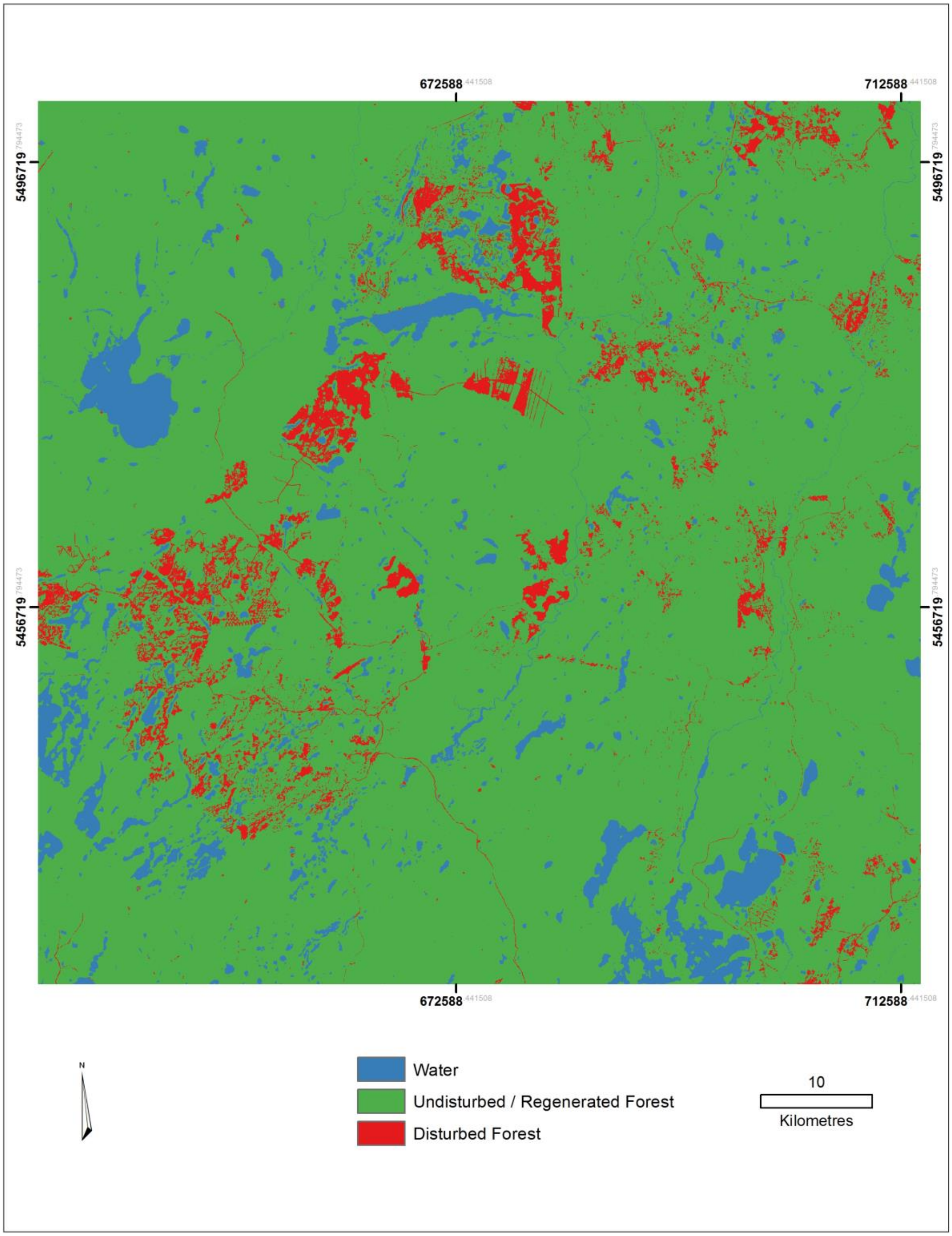

Figure 3-2: 1991, September 1 – Classification Result

Table 3-3: 1991 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	90.00%	74.35%, 105.65%	85.71%	68.37%, 103.10%	0.847
Undisturbed/ Regenerated Forest	98.80%	97.25%, 100.35%	93.92%	90.84%, 96.99%	0.635
Disturbed Forest	53.33%	33.81%, 72.85%	100.00%	96.88%, 103.13%	1.00

Table 3-4: 1991 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**18**	3	0	21
	Undisturbed/ Regenerated Forest	2	**247**	14	263
	Disturbed Forest	0	0	**16**	16
	Totals	20	250	30	300

The overall accuracy for the 1995 image classification shown in Figure 3-3 was 91.33% with a 95% confidence interval of 87.98% to 94.68%. The overall Kappa statistic was 0.677% with a variance of 0.005%. Additional classification information is presented in the classification report (Table 3-5) and accuracy assessment matrix (Table 3-6).

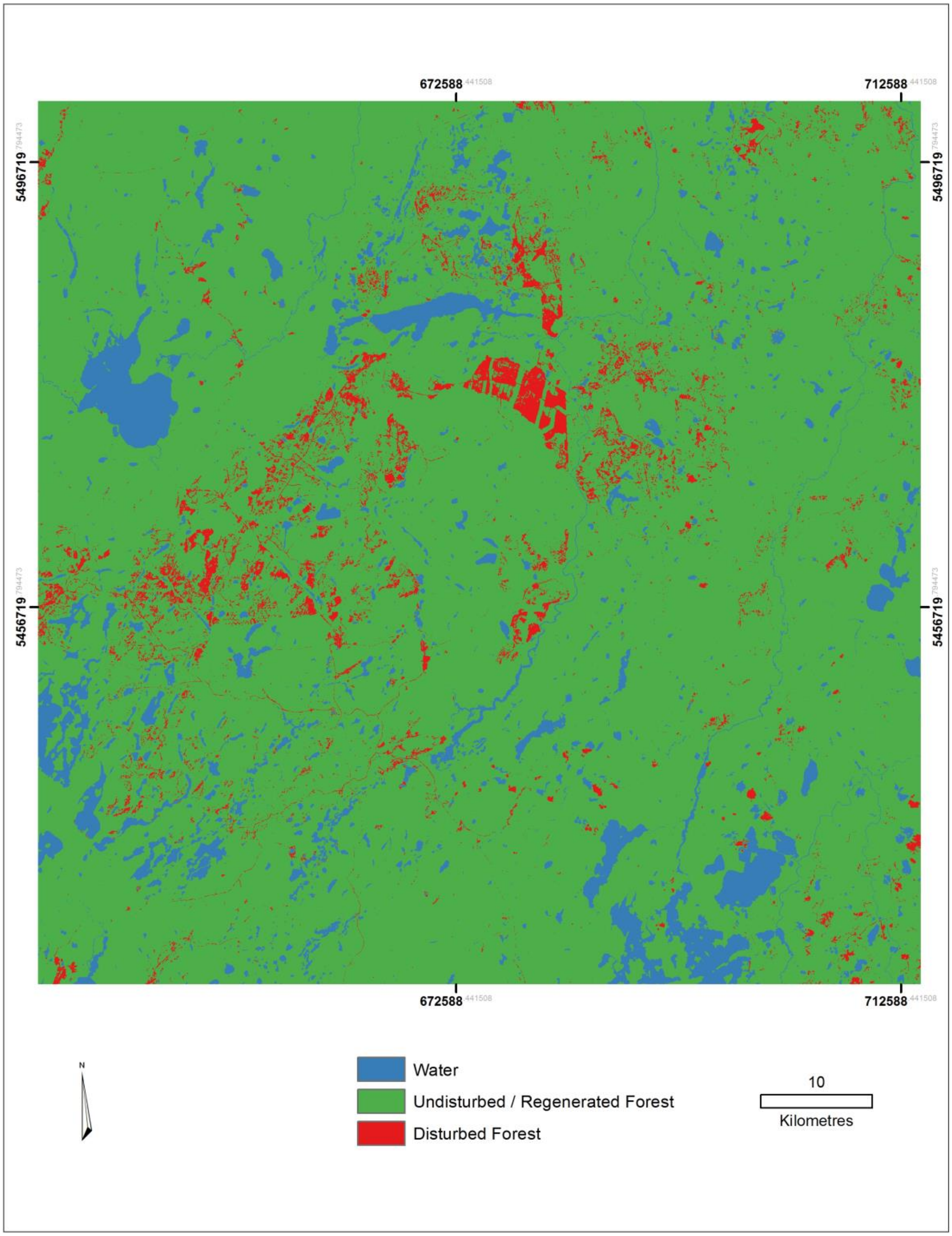

Figure 3-3: 1995, June 8 - Classification Result

Table 3-5: 1995 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	88.00%	73.26%, 102.74%	95.65%	85.14%, 106.16%	0.953
Undisturbed/ Regenerated Forest	99.18%	97.84%, 100.52%	90.98%	87.35%, 94.61%	0.517
Disturbed Forest	32.26%	14.19%, 50.33%	90.91%	69.38%, 112.44%	0.899

Table 3-6: 1995 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**22**	1	0	23
	Undisturbed/ Regenerated Forest	3	**242**	21	266
	Disturbed Forest	0	1	**10**	11
	Totals	25	244	31	300

The overall accuracy for the 2000 image classification shown in Figure 3-4 was 91.33% with a 95% confidence interval of 87.98% to 94.68%. The overall Kappa statistic was 0.718% with a variance of 0.004%. Additional classification information is presented in the classification report (Table 3-7) and accuracy assessment matrix (Table 3-8).

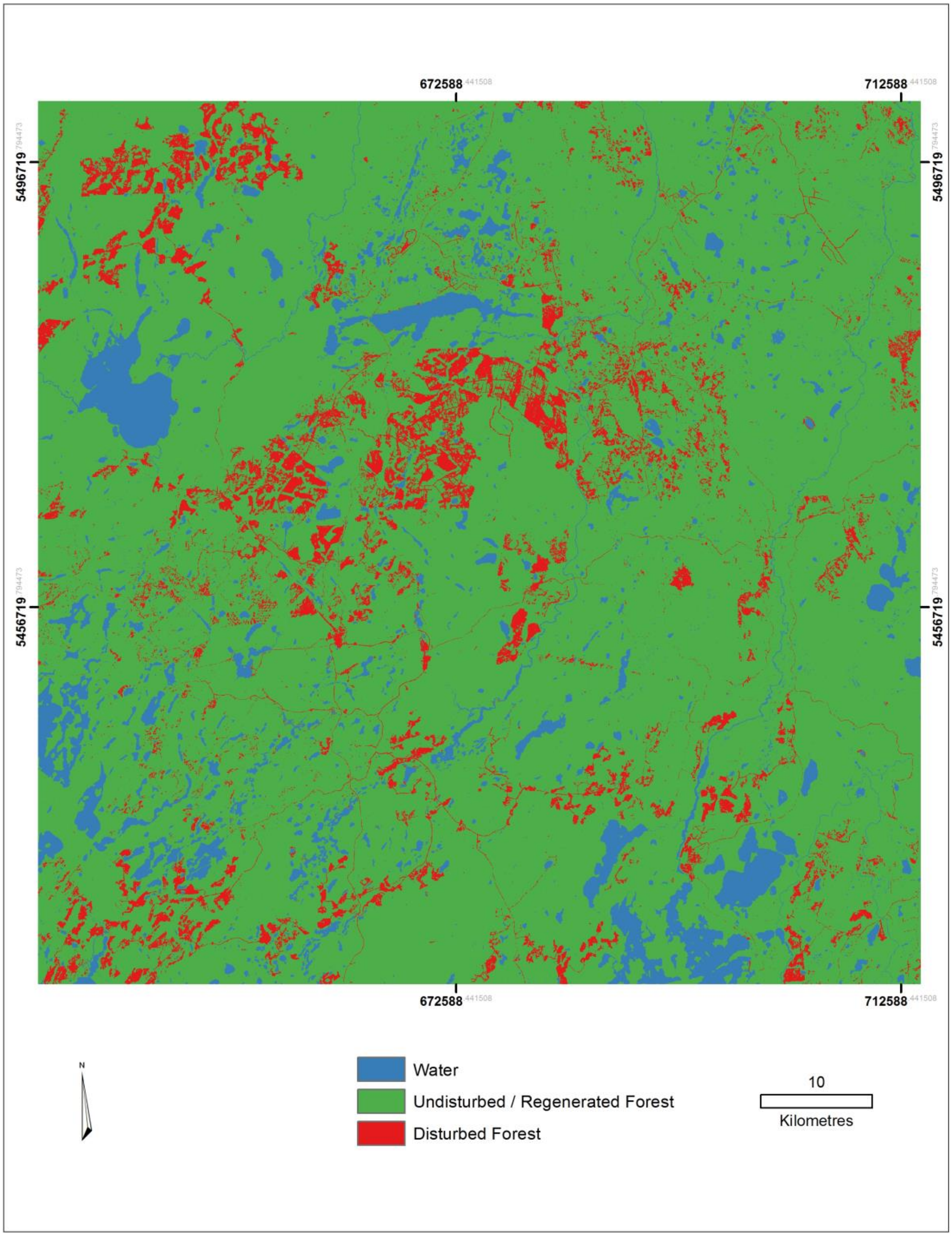

Figure 3-4: 2000, July 15 - Classification Result

Table 3-7: 2000 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	84.00%	67.63%, 100.37%	87.50%	72.19%, 102.82%	0.864
Undisturbed/ Regenerated Forest	97.50%	95.32%, 99.68%	92.13%	88.62%, 95.64%	0.606
Disturbed Forest	54.29%	36.35%, 72.22%	86.36%	69.75%, 102.98%	0.846

Table 3-8: 2000 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**21**	3	0	24
	Undisturbed/ Regenerated Forest	4	**234**	16	254
	Disturbed Forest	0	3	**19**	22
	Totals	25	240	35	300

The overall accuracy for the 2002 image classification shown in Figure 3-5 was 89.33% with a 95% confidence interval of 85.67% to 92.99%. The overall Kappa statistic was 0.700% with a variance of 0.007%. Additional classification information is presented in the classification report (Table 3-9) and accuracy assessment matrix (Table 3-10).

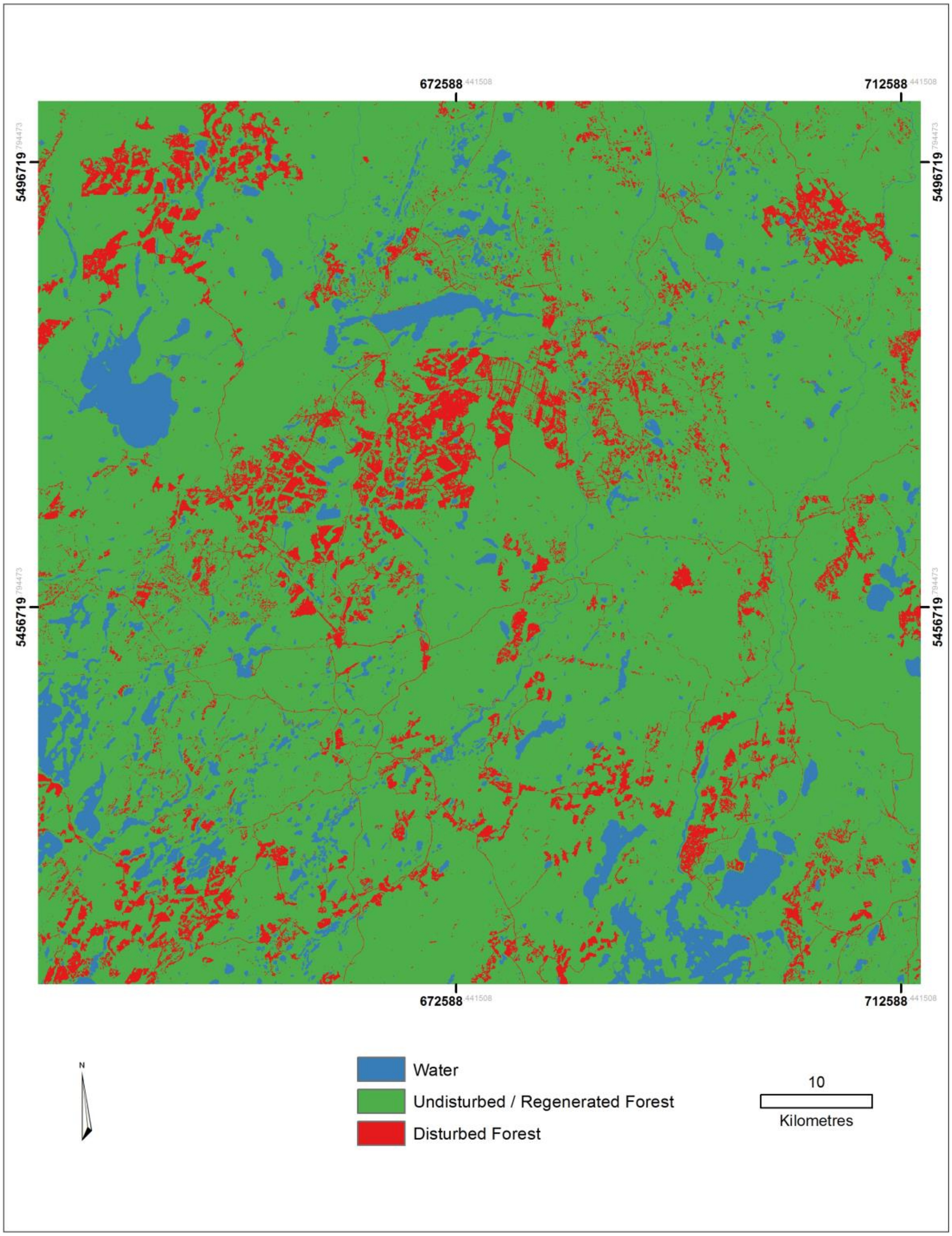

Figure 3-5: 2002, August 22 - Classification Result

Table 3-9: 2002 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	80.00%	62.32%, 97.68%	90.91%	76.62%, 105.20%	0.901
Undisturbed/ Regenerated Forest	98.22%	96.27%, 100.17%	88.76%	84.63%, 92.88%	0.551
Disturbed Forest	54.00%	39.19%, 68.82%	93.11%	82.16%, 104.05%	0.917

Table 3-10: 2002 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**20**	2	0	22
	Undisturbed/ Regenerated Forest	5	**221**	23	249
	Disturbed Forest	0	2	**27**	29
	Totals	25	225	50	300

The overall accuracy for the 2007 image classification shown in Figure 3-6 was 84.33% with a 95% confidence interval of 80.05% to 88.62%. The overall Kappa statistic was 0.627% with a variance of 1.558%. Additional classification information is presented in the classification report (Table 3-11) and accuracy assessment matrix (Table 3-12).

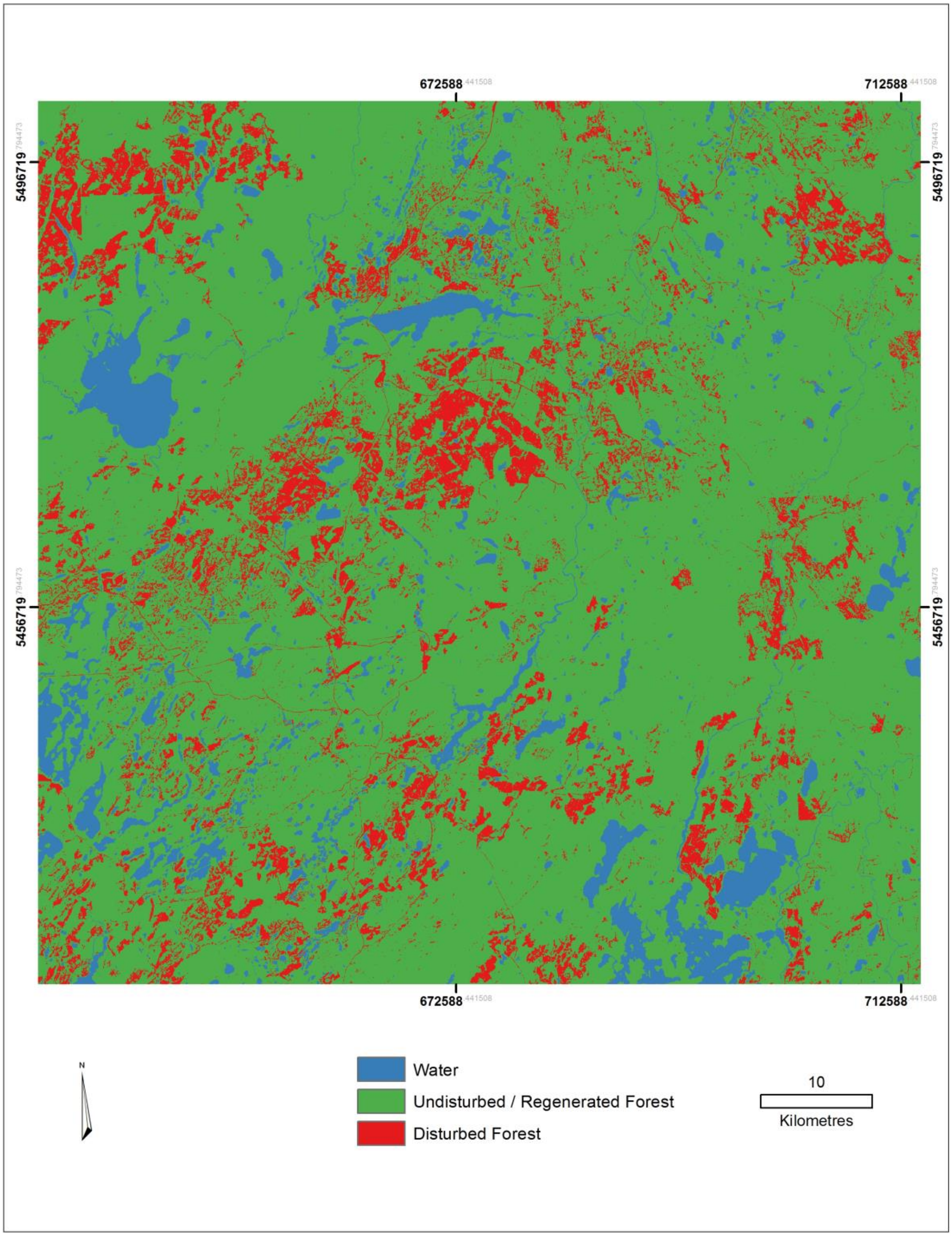

Figure 3-6: 2007, May 8 - Classification Result

Table 3-11: 2007 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	78.57%	61.59%, 95.56%	95.65%	85.14%, 106.16%	0.952
Undisturbed/ Regenerated Forest	98.03%	95.87% 100.19%	82.23%	77.21%, 87.25%	0.451
Disturbed Forest	46.38%	33.89%, 58.87%	91.43%	80.73%, 102.14%	0.889

Table 3-12: 2007 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**22**	1	0	23
	Undisturbed/ Regenerated Forest	6	**199**	37	242
	Disturbed Forest	0	3	**32**	35
	Totals	28	203	69	300

The overall accuracy for the 2009 image classification shown in Figure 3-7 was 85.00% with a 95% confidence interval of 80.79% to 89.21%. The overall Kappa statistic was 0.594% with a variance of 0.029%. Additional classification information is presented in the classification report (Table 3-13) and accuracy assessment matrix (Table 3-14).

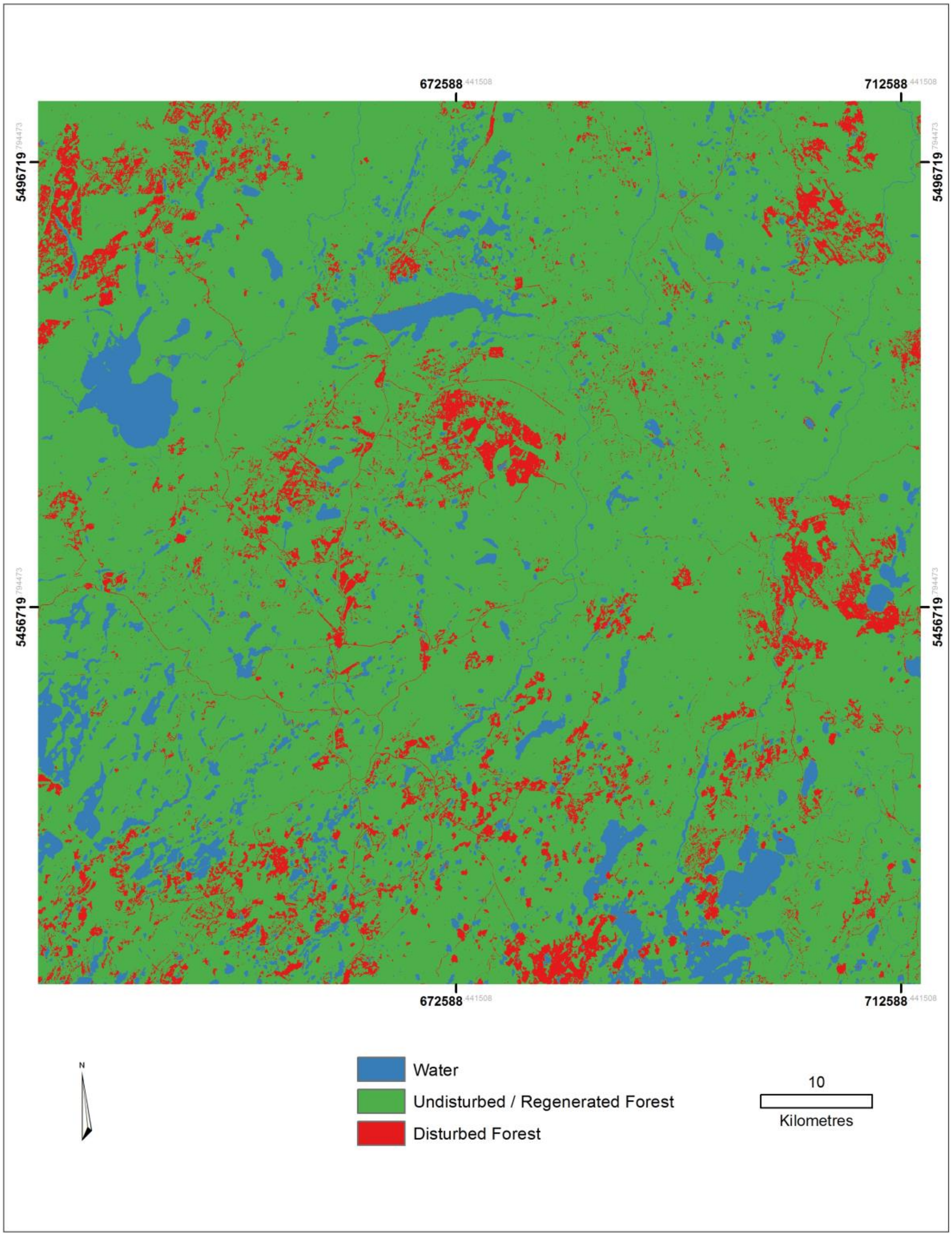

Figure 3-7: 2009, September 2 - Classification Result

Table 3-13: 2009 Classification Report

Class	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	77.78%	60.24%, 95.31%	87.50%	72.19%, 102.82%	0.863
Undisturbed/ Regenerated Forest	97.71%	95.49%, 99.92%	84.86%	80.23%, 89.49%	0.446
Disturbed Forest	38.18%	24.43%, 51.93%	84.00%	67.63%, 100.37%	0.804

Table 3-14: 2009 Accuracy Assessment

		Reference Data			
		Water	Undisturbed/ Regenerated Forest	Disturbed Forest	Totals
Classified Data	Water	**21**	1	2	24
	Undisturbed/ Regenerated Forest	6	**213**	32	251
	Disturbed Forest	0	4	**21**	25
	Totals	27	218	55	300

The results obtained through unsupervised classification were acceptable in terms of overall accuracy but a high degree of confusion between the disturbed and undisturbed / regenerated forest classes was sometimes a factor and varied greatly between image dates. This led to some classification results exhibiting low producer's accuracy values for the disturbed forest class. These low values could be the result of spectral similarity between undisturbed forest and areas that may have experienced partial harvest that did not remove all standing timber or, harvested areas that have experienced significant regeneration. There also seemed to be lower producer's accuracy in the early (May –

June) and late (September) growing season images. Furthermore, there is a possibility that increased complexity caused by harvest and regeneration within forest stands could have led to lower overall accuracy in the later image dates.

The classification results were not used in post classification ‘delta’ change detection; instead the band five difference images were used to determine areas of disturbance. Delta change detection involves the classification of two images followed by pixel based comparison between the two classification results (Coppin et al. 1994). It was not used because it is subject to the compounding of classification errors, which may lead to inaccurate results (Coppin et al. 1994). Image differencing has been identified by Coppin and Bauer (1996) to outperform other change detection techniques. Performing change detection using band differencing technique avoided compounding classification errors in the change detection process and subsequent statistical analysis. The present disturbance class shown in the change maps is a result of band differencing. The undisturbed / regenerated forest and past disturbance classes of the disturbance maps are a product of image classification and are thus affected by the accuracy of the classification results.

3.2 Disturbance Mapping

Change detection mapping of disturbance events involved the arithmetic addition of the land cover classification results presented above and the band five difference image for each temporal period. The change maps illustrate four land cover types for each temporal period examined in this research. In the four classes: blue areas represent water, green areas represent undisturbed / regenerated forest, beige areas represent past disturbance experienced prior to the time step of each map and red areas that represent present disturbance occurring during the time step shown in each change map.

The grid systems overlaid on the disturbance map results are geographic Townships boundaries. Disturbance patterns caused by timber harvest activity appear to coincide with these Townships as planning and management units. They have been included to aid in the description and interpretation of stand level forest disturbance events. A detailed index of the Township names is presented in Figure 1-2.

1984 – 1986

In the two year period from 1984 – 1986 shown in Figure 3-8, the present disturbance class reveals 113 square kilometres (1.8 % of the study site) of stand level disturbance. The disturbance during this period occurs in the southwest Townships of Lessard, Chelsea and Cholette. There are disturbances in the northeast of the study site in Dowsley and Verdun Township. There is also disturbance occurring along the north shore of Lake Nagagamisis in McEwing Township in areas located outside the park boundary. During this period, only a small strip of land is protected north of Lake Nagagamisis. Construction of bush roads is visible south of Lake Nagagami and Lake Nagagamisis to the west of highway 631in Elgie and Nagagami Townships.

The disturbance map also shows an area of 577 square kilometres (9.1% of the study area) in the past disturbance class occurring prior to the beginning of this time step in 1984. This disturbance is visible on the north shore of Lake Nagagamisis extending north into McEwing, Arnott and Storey Townships. A large past disturbance area is also visible to the southeast in Chelsea and Larkin Township. Other areas include Townships to the east including Farquhar and Woolrich. The combined total surface area of disturbed forest in 1986 is 689 square kilometres or 11% of the study area. The average annual

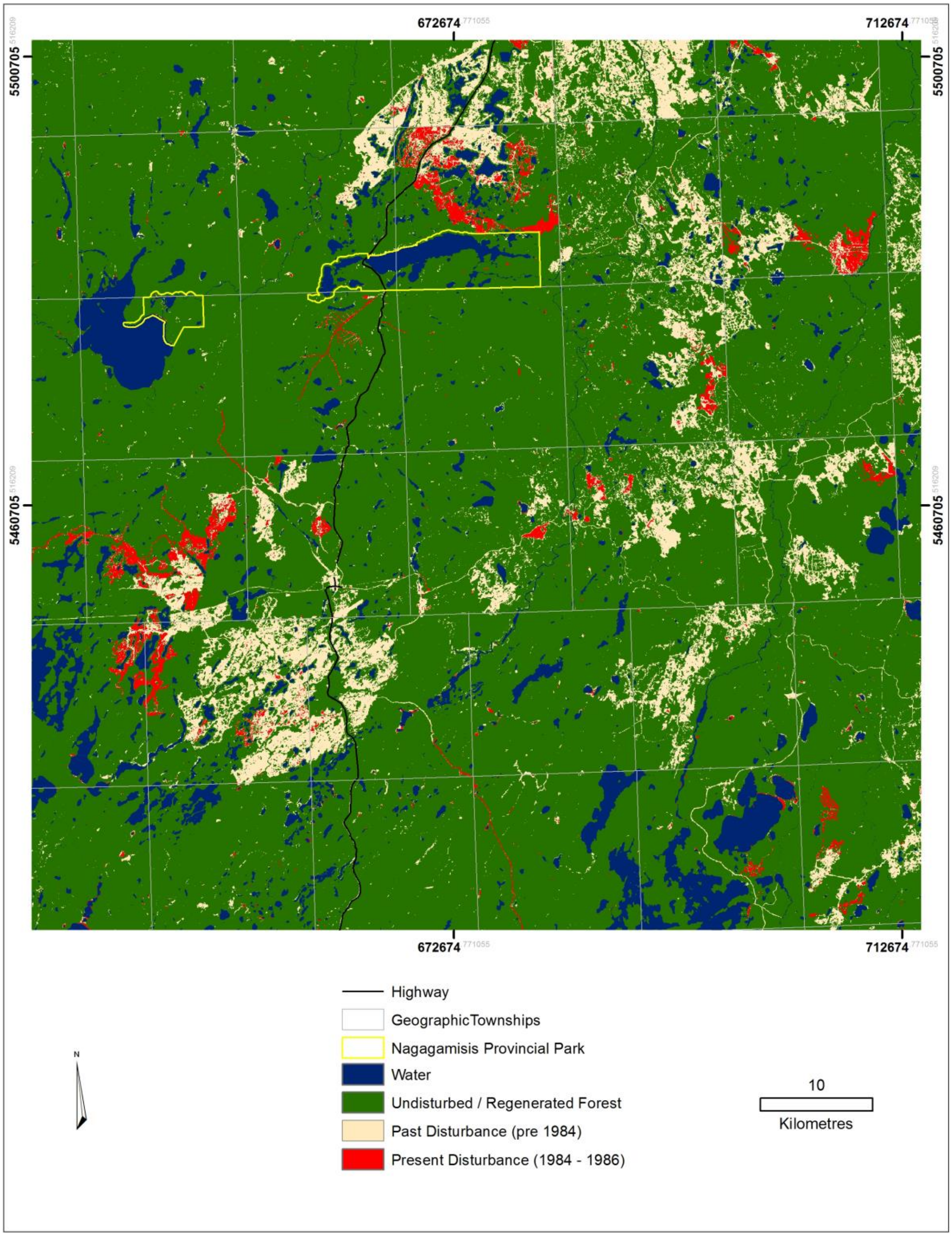

Figure 3-8: 1984 - 1986 Disturbance Map

disturbance for the 1984 – 1986 time step is 56 square kilometres or 0.90% of the study site.

1986 – 1991

In the five year period from 1986 – 1991 shown in Figure 3-9, the present disturbance class experienced 290 square kilometres (4.6 % of the study area) of stand level disturbance. The location of disturbances during this period occurs on the eastern edge of the Arnott Moraine in McEwing Township, and to the south and southwest of Lake Nagagamisis in Elgie and Newlands Townships. The area surrounding the bush road construction visible in the 1984 – 1986 map in Elgie Township, to the west of Highway 631 have now experienced stand level disturbance. Areas in the Eastern Townships of Foch, Lessard and Wicksteed experienced stand level disturbances. New road construction is visible in Nagagami and Hiawatha Townships. The map also shows an area 151 square kilometres of disturbance (2.4% of the study area) that occurred prior to 1986, a significant decrease from the past disturbance class in the 1894 – 1986 period. The total surface area of disturbed forest in 1991 was 441 square kilometres or 7% of the study site. The average annual disturbance for the 1986 – 1991 time step is 58 square kilometres or 0.92% of the study site.

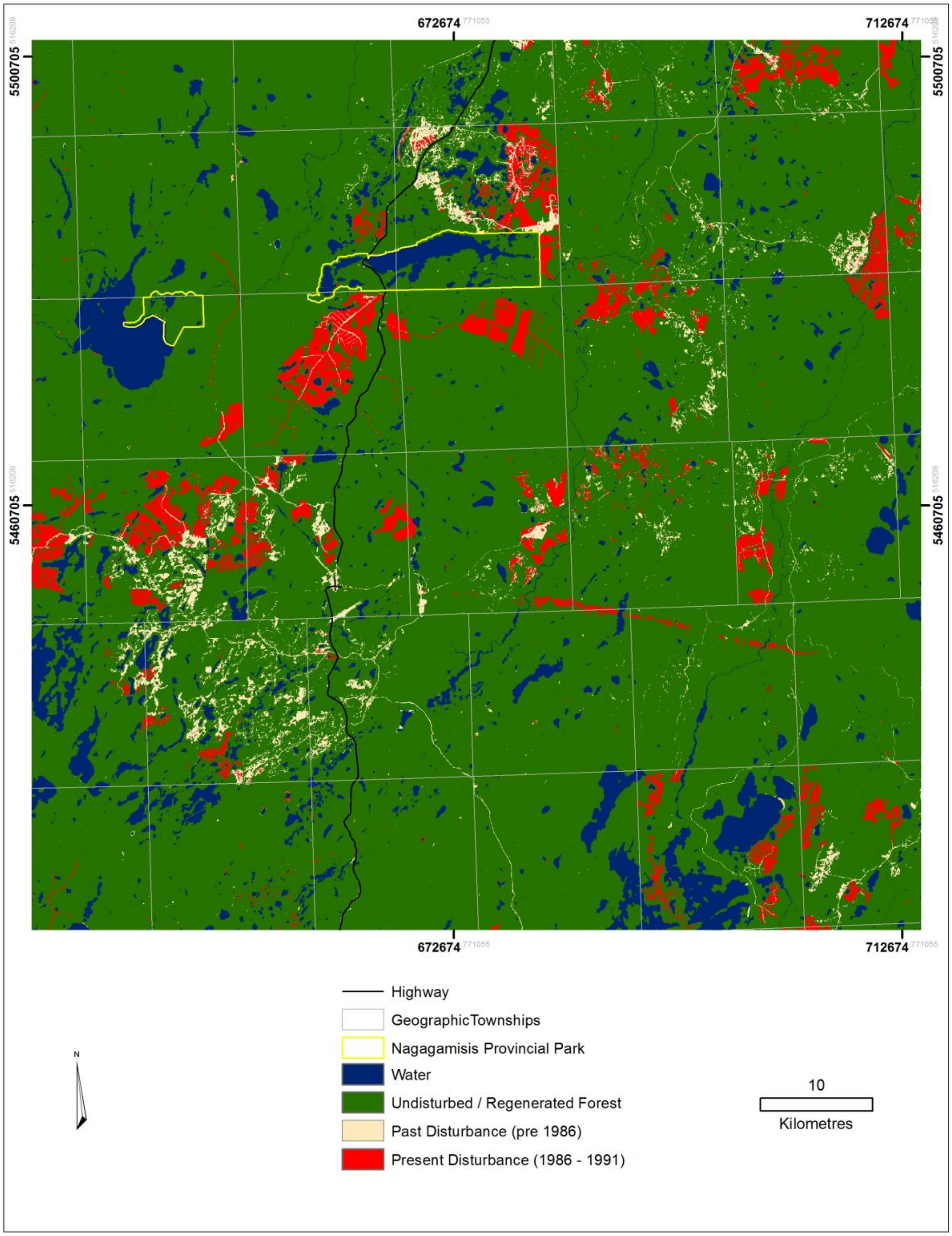

Figure 3-9: 1986 - 1991 Disturbance Map

1991 – 1995

In the four year period from 1991 – 1995 shown in Figure 3-10, an area of 286 square kilometres (4.5 % of the study area) experienced stand level disturbance. The disturbance occurs in large patches and was focused south of Lake Nagagami and Nagagamisis on both sides of Highway 631 in Elgie, Newlands, Dowsley, Wicksteed and Nagagami. There is new road construction occurring in Mercer and Hiawatha Township expanding disturbance in the northwest. Smaller patches of disturbance are also visible in the southern Townships. This map reveals a past disturbance area of 113 square kilometres were disturbed prior to 1991. The total surface area of disturbed forest in 1995 was 399 square kilometres or 6.3% of the study site. The average annual disturbance for the 1991 – 1995 time step is 72 square kilometres or 1.14% of the study site.

1995 – 2000

In the five year period from 1995 – 2000 shown in Figure 3-11, an area of 374 square kilometres (5.9% of the study site) experienced stand level disturbance. The disturbance during this period is spread out over the entire study area with large patches occurring in the northeast in Mercer, Cross and Hiawatha Townships and just south of Lake Nagagamisis in Newlands Township. There are also disturbances in the southern Townships of the study site but they are much smaller than those in the north. New road construction activity is visible in the north - eastern Township of Verdun. In addition to the disturbances during this period, an area of 225 square kilometres (3.6% of the study site) remains disturbed from prior periods. The total surface area of disturbed forest in 2000 was 599 square kilometres or 9.5% of the study site. The average annual

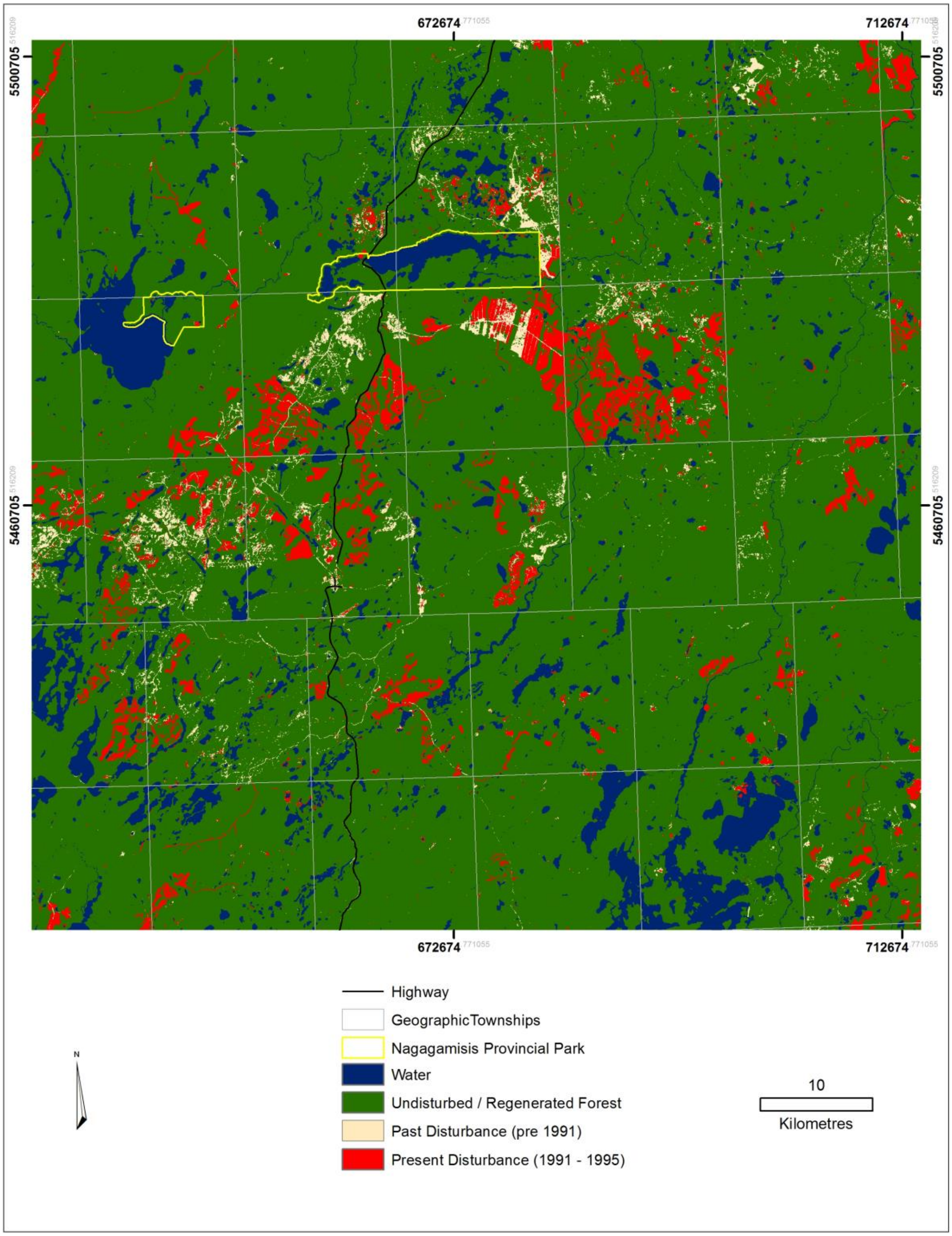

Figure 3-10: 1991 - 1995 Disturbance Map

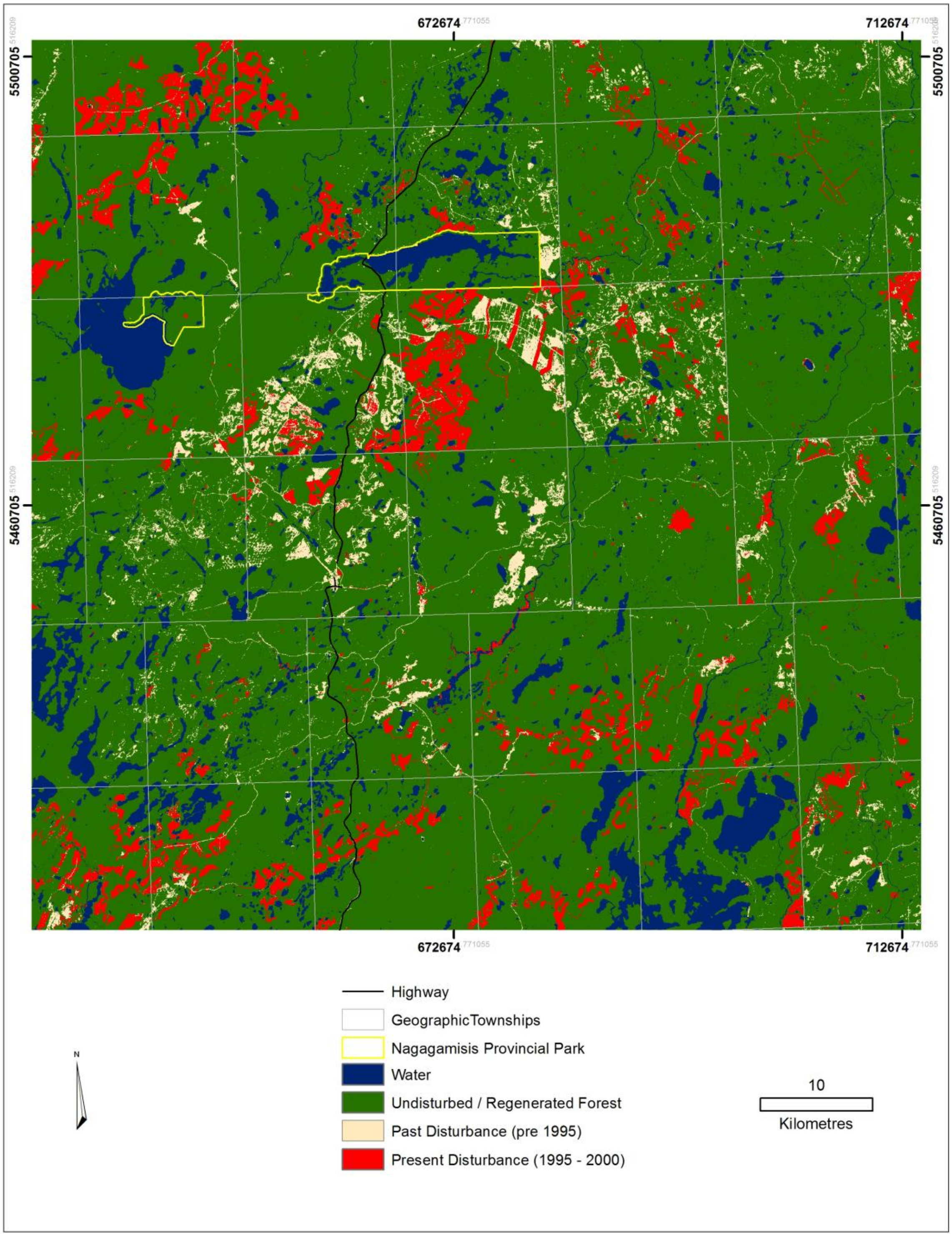

Figure 3-11: 1995 - 2000 Disturbance Map

disturbance for the 1995 – 2000 time step is 75 square kilometres or 1.19% of the study site.

2000 – 2002

The two year period from 2000 – 2002 presented in Figure 3-12, an area of 122 square kilometres (1.9% of the study area) experienced stand level disturbance. The disturbance during this period is spread out over the entire study site and is occurring in smaller patches in Hiawatha, Elgie, Newlands, Bayfield, Larkin, Woolrich and Derry Townships. There is one large patch to the northeast in Verdun where road construction was visible in the previous time step. In addition to the disturbances during this period, an area of 515 square kilometres (8.2% of the study site) remains in the past disturbance class. The total surface area of disturbed forest in 2002 was 637 square kilometres or 10.1% of the study site. The average annual disturbance for the 2000 – 2002 time step is 61 square kilometres or 0.96% of the study site.

2002 – 2007

In the five year period from 2002 – 2007 presented in Figure 3-13, an area of 302 square kilometres (4.8% of the study site) experienced stand level disturbance. The disturbance during this period is spread out over the entire area with concentrations north of Lake Nagagami in Downer and Frances Townships, south of Lake Nagagamisis in Elgie and Newlands and to the east of the study site in Alderson Township. Disturbance is also visible in the southern Townships of Larkin, Lascelles, Franz, Lipton, Beaton and Bayfield. In addition to the disturbances during this period, an area of 526 square

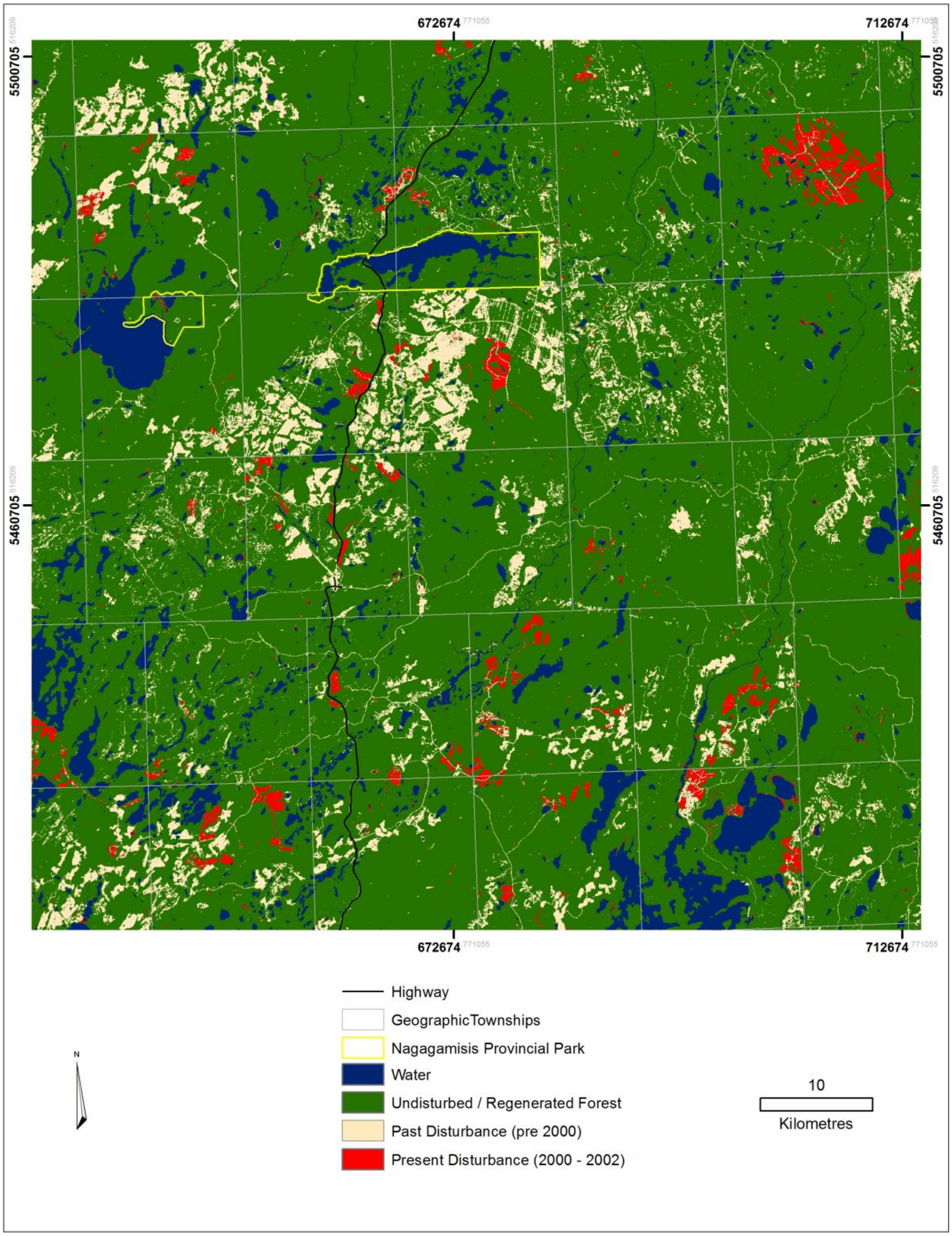

Figure 3-12: 2000 - 2002 Disturbance Map

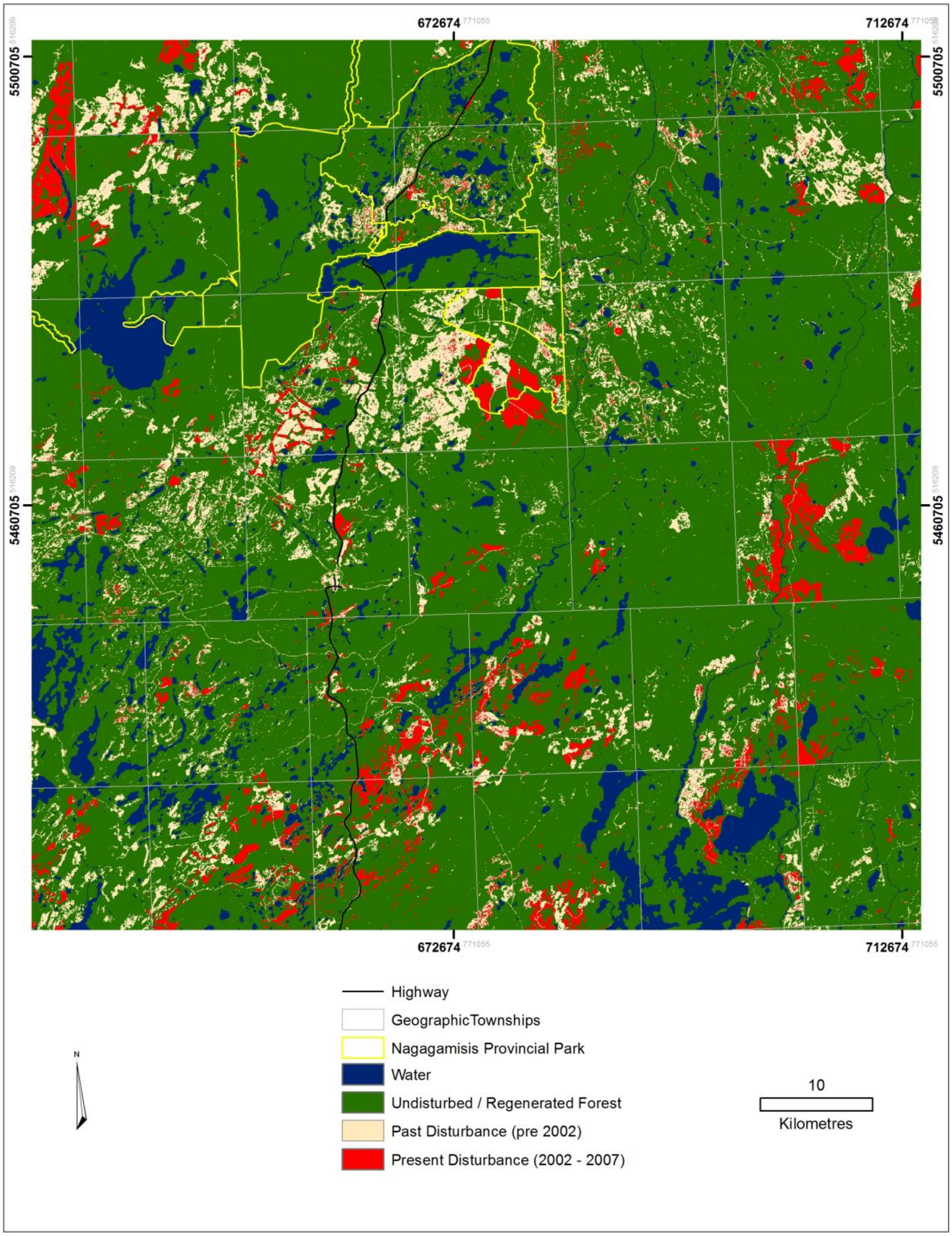

Figure 3-13: 2002 - 2007 Disturbance Map

kilometres (8.4% of the study site) remains disturbed in the past disturbance class. The total surface area of disturbed forest in 2007 was 828 square kilometres or 13.1% of the study site. The average annual disturbance for the 2002 – 2007 time step is 60 square kilometres or 0.96% of the study site.

2007 – 2009

In the two year period from 2007 – 2009 presented in Figure 3-14, a total area of 75 square kilometres (1.2% of the study site) experienced stand level disturbance. Disturbance during this period is concentrated in the southern portion of the study site with a larger patch in Alderson Township. Some small disturbances are occurring within the enhanced management area north of Lake Nagagamisis in McEwing Township. In addition to the disturbances during this period, an area of 435 square kilometres (6.9% of the study site) remains in the past disturbance class. The total surface area of disturbed forest in 2009 was 510 square kilometres or 8.1% of the study site. The average annual disturbance for the 2007 – 2009 time step is 37 square kilometres or 0.61% of the study site.

Over the course of the twenty-five year study period, from 1984 to 2009, stand level forest disturbance was experienced throughout the study site. Based on the results of the image differencing operations, a total area of 1649 square kilometres or 26.1% of the study site experienced stand level disturbance. The spatial distribution and size of the disturbance events that occurred during the study period are presented in the cumulative disturbance map (Figure 3-15). The divergent colour ramp chosen to symbolize disturbance events ranges from a dark red that represents the most recent disturbance period (2007 – 2009) to a dark green that represents the oldest disturbance period (1984 – 1986).

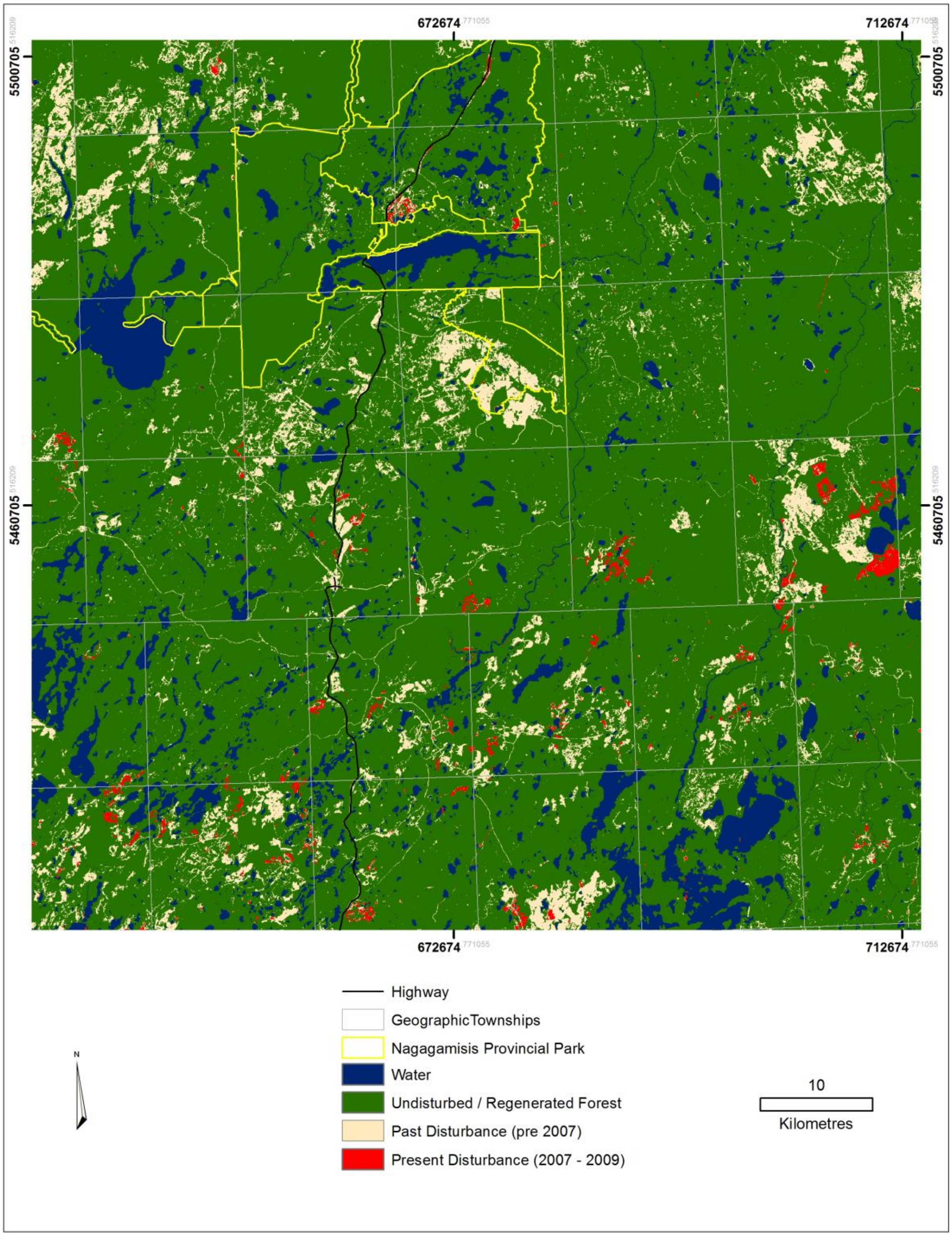

Figure 3-14: 2007 - 2009 Disturbance Map

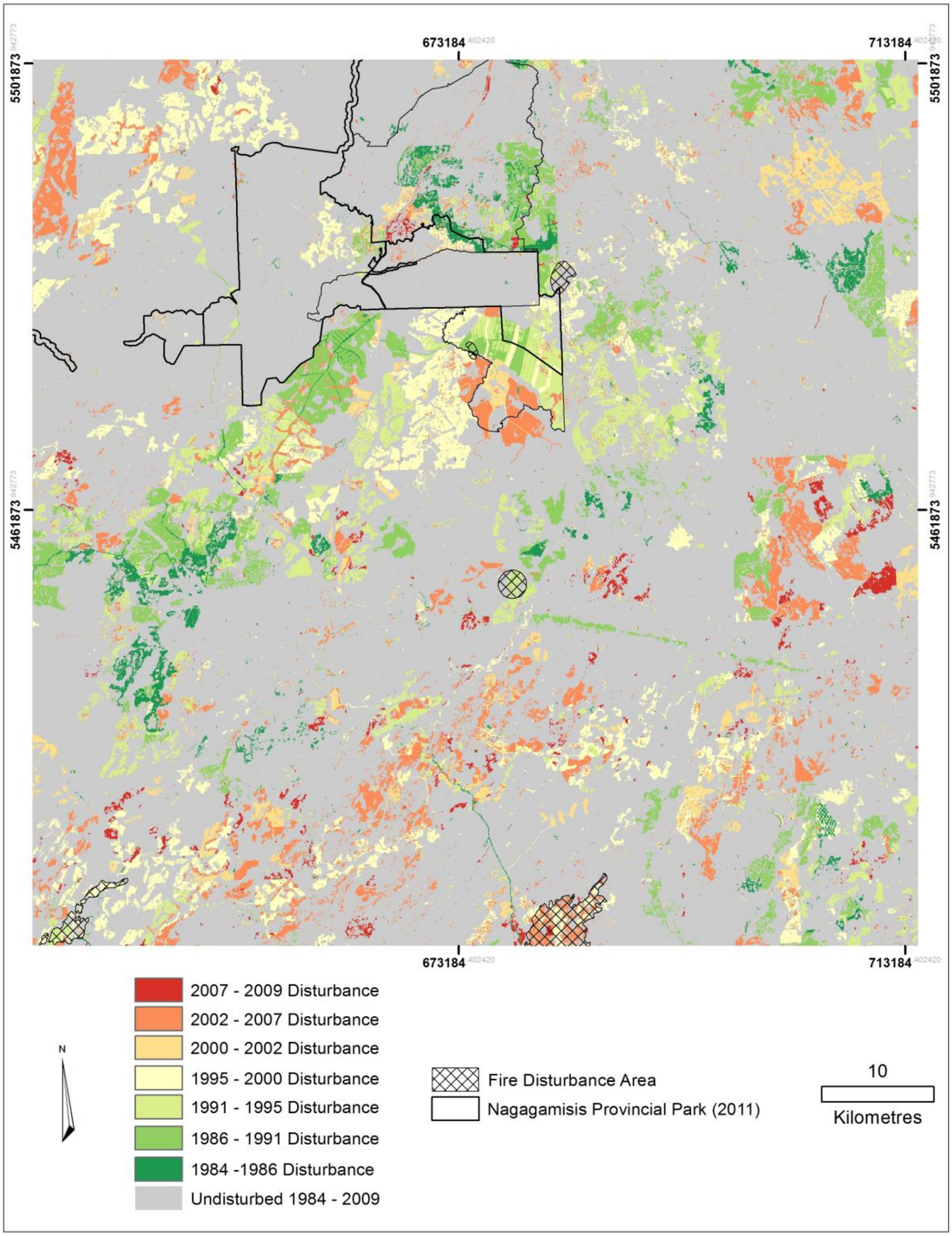

Figure 3-15: Cumulative Disturbance Map 1984 – 2009

This colour scheme does not imply the health condition or level of regeneration within disturbed areas, only the time period in which the disturbance event occurred. This map reveals a large amount of disturbance has occurred south of the Nagagamisis Central Plateau in Elgie, Newlands, Dowsley and Lessard Townships that spans almost the entire duration of the study period. There are also more recent disturbance events visible in the northwest corner of the study site in Frances, Downer and Mercer Townships. The overall patch size of disturbance events varies throughout the study site. There seems to be a pattern of larger patch sizes in the north and smaller patches in the southern portion of the study site.

Trends of the stand level disturbance events were examined and visualized using time series graphs of average annual disturbance spanning the entire duration of the study period. Figure 3-16 represents the average annual disturbance as an area in square kilometres for each temporal period of the study. Figure 3-17 represents the average annual disturbance as a per cent of the total study area for each temporal period of the study.

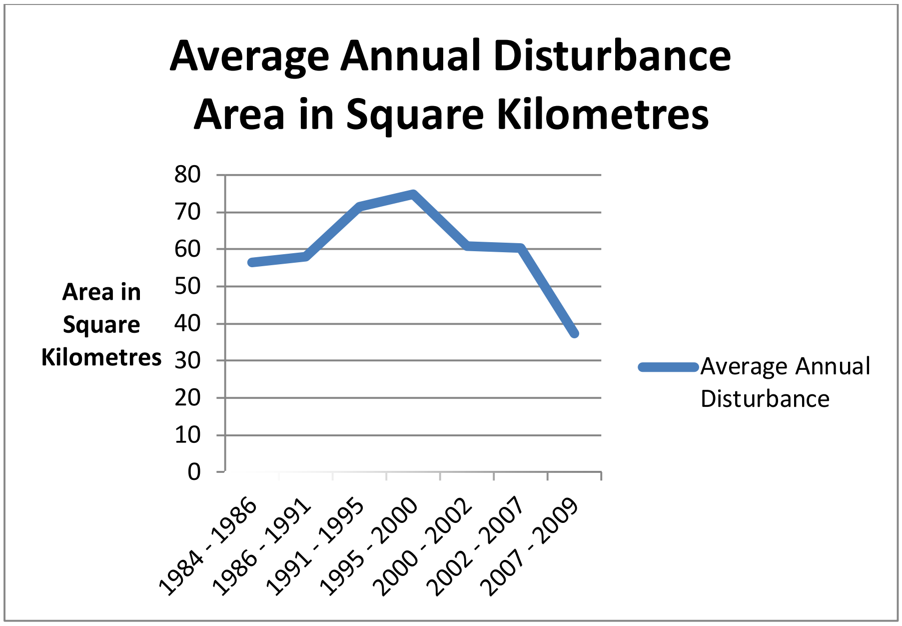

Figure 3-16: Average Annual Disturbance (Area in Square Kilometres)

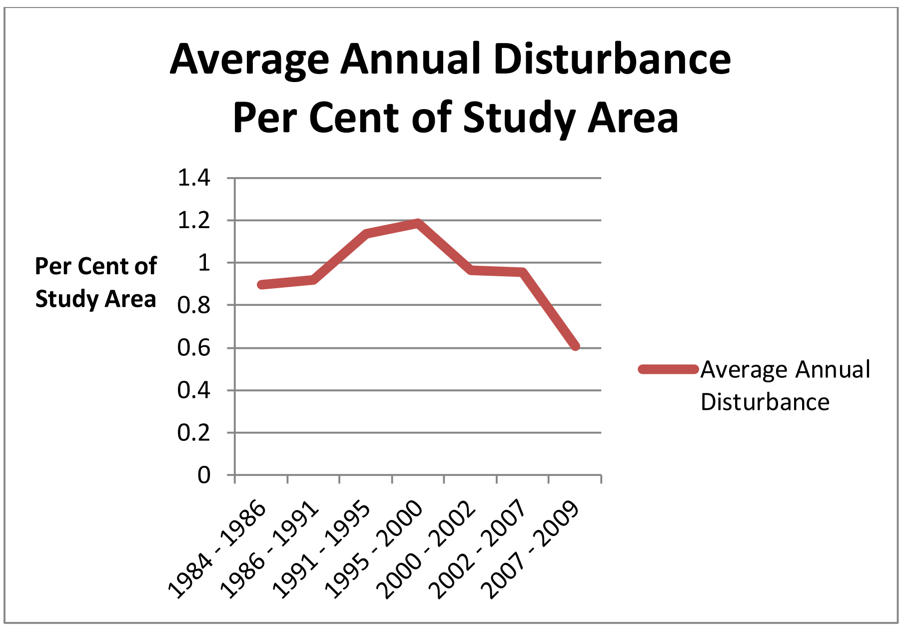

Figure 3-17: Average Annual Disturbance (Per Cent of Study Area)

The 1984 - 1986 period experienced an annual average disturbance area of 56 square kilometres or 0.9 % of the study area. From 1986 to 1991, the annual average disturbance area increased slightly to 58 square kilometres or 0.9% of the study site. In the 1991 – 1995 period, there was an increase in disturbance area to 72 square kilometres or 1.1% of the study area. The average annual disturbance area increased between 1995 – 2000 to a peak of 75 square kilometres or 1.2% of the study area. From 2000 to 2002, the average annual disturbance area decreased to 61 square kilometres or 1.0% of the study area. During the 2002 – 2007 period, the average annual disturbance area was 60 square kilometres or 1.0% of the study area. In the 2007 – 2009 period, the average annual disturbance area was 37 square kilometres or 0.6% of the study area.

These data indicate a stable average annual disturbance of roughly 0.9% between 1984 and 1991 followed by an increase in average annual disturbance to just over 1.1% between 1991 and 1995. Disturbance remains stable at this level between 1995 and 2000 followed by a decrease in average annual disturbance between 2000 and 2002. Between 2002 and 2007 the average annual disturbance stabilizes at roughly 1.0%, levels similar to those experienced in 1984 – 1991. The average annual disturbance fell significantly between 2007 and 2009 to a minimum of 0.6% at the end of the study period. The overall trend observed in these data indicates that the observed annual average disturbance values are stable at roughly 1.0% for the period of 1984 to 2007 and then begin to decline.

With regard to the Nagagamisis Central Plateau park lands, disturbance events have been abundant in the areas just outside of park boundaries. Large areas on all sides on the park lands experienced stand level disturbances during the 1984 – 2009 study period. Over the course of the study period, the Nagagamisis Provincial Park has grown from 81 square kilometres in 1957 to more than 600 square kilometres today. The evolution and expansion of the park boundaries over time seems to occur after areas have experienced disturbances. In the case of the enhanced management zone, much of this area had been disturbed by timber harvest in the 1970's and 1980's. This area has since been replanted and is developing into a thriving young forest (ONMR, 2002a). The continued effort to preserve areas of natural and cultural heritage over the course of the study period demonstrates a strong commitment by the government and resident of Ontario. The expansion of Nagagamisis Central Plateau Signature site will ensure the protection of these natural and cultural significant lands for future generations to enjoy.

CHAPTER 4: CONCLUSIONS

The combination of remote sensing techniques and data used to undertake this research have proven to be an effective method for mapping and monitoring forested lands after stand level disturbance events. The image classification methods made use of the original Landsat bands and vegetation indices: TCT and NDMI to produce results with overall classification accuracies ranging between 97.3% - 84.3%. The band five difference images proved to be an accurate representation of changes to the vegetation and land cover after stand level forest disturbances within the study site.

The results of this research estimate the total area of forest disturbance over the study period of 1984 – 2009 to be 1649 square kilometres or 26.1% of the study site. The rates of disturbance were very consistent over the duration of the study period, around 1% of the study site per year. Large areas of disturbance seem to be concentrated in areas that are very close to the Nagagamisis Central Plateau Provincial Park at each stage in its expansion. It is clear from the disturbance maps that protected areas are required to ensure preservation of significant cultural and historical locations. The land use planning strategy implemented through the Lands for Life and Ontario Living Legacy have contributed significantly to the protected area network within the study site increasing the total area of protected lands from 80 square kilometres in 1957 to more than 600 square kilometres today. This expansion has provided enhance recreational activity and the preservation of natural and cultural heritage of the Nagagamisis Central Plateau Signature Site. Further investigation and planning will be required for guiding the land use of the enhanced management area for additional benefits.

By measuring stand level forest disturbance within the study site, and integrating change detection methods it was possible to monitor stand level forest disturbance of the course of a 25 year period from 1986 - 2009. Timber harvest activity has been identified as a prominent cause of disturbances within the study site. This research will contribute to understanding of the evolution of the Nagagamisis Central Plateau signature site within the surrounding forest management units. It establishes the rate and spatial distribution of stand level disturbance of forested lands within the study site.

4.1 Limitations

The scope of this study was limited by several factors including: atmospheric conditions, time and resources. The dynamic atmospheric conditions of the study site and common mid-latitude cyclonic activity led to frequent cloud cover during the desired growing season acquisition window. This limitation led to the use of imagery that spanned the entire growing season and was not always close to anniversary dates between images. In an ideal world, imagery would have been collected on an annual basis, 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 and measurement of forest regeneration and stand composition after stand level disturbance events.

In future work, the use of patch indices may be useful to determine if there have been any significant changes to timber harvest practices over the course of the study period.

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