A MULTI-METHOD ASSESSMENT OF THE TEMPORAL DYNAMICS OF TREED BOGS IN NOVA SCOTIA, CANADA

by

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List of Abbreviations Used

BP	Before present
BW	Black and white
CHM	Canopy height model
DEM	Digital elevation model (e.g. elevation of the ground)
DTM	Digital terrain model
DSM	Digital surface model (e.g. elevation of the vegetation canopy)
GCP	Ground control point
GIS	Geographic information system
GPS	Global positioning system
GSD	Ground sampling distance
KIA	The Kappa index of agreement
LiDAR	Light detection and ranging
OBIA	Object-based imagery analysis
RGB	Red green blue
UAV	Unmanned aerial vehicle
UTM	Universal Transverse Mercator coordinate system
NAD	North American Datum

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Abstract

Peat bogs make important contributions to carbon storage, fresh water supply and biodiversity maintenance. However, some studies have detected a notable shrinking of peat bogs and predicted an accelerating rate of tree establishment. Given the impact of altered structure and function of peat bogs, this study aimed at revealing the processes that influence tree establishment and the temporal-spatial changes in bogs over 70 years in Nova Scotia. Two bogs in Kejimkujik National Park were studied. Positions, species, height and mortality of trees were measured and analyzed by spatial point pattern analysis to understand spatial interactions among individuals and the underlying establishment processes. In addition, a time series of aerial photos (1928 to 2011) and UAV imagery (2017) were assembled to detect long-term tree crown dynamics in two bogs. Results indicated that well-established treed areas had comparatively larger and more distinct clumps of trees as well as more dead trees than the open bog areas. Intra- and interspecific spatial interactions varied by tree species and study site, suggesting that the two study areas did not always change in the same way. During the past years, trees have been encroaching in the two peat bogs but this study also found that encroachment rates are decreasing. Local topographic heterogeneity, drainage-blocking and competition between trees may have facilitated the successful seedling establishment and tree expansion in the two bogs.

Chapter 1 Introduction

1.1 Background

In the Canadian Wetland Classification System, wetlands are classified into five types: bogs, fens, swamps, marshes and shallow waters, of which bogs and fens are categorized as peatlands that feature partially decayed vegetation or organic matter (National Wetlands Working Group, 1997; University of Leicester, 2018). In Canada, peatlands cover approximately 113.6 million hectares, representing over 90% of Canadian wetlands and around 13% of Canada's land area (Peat Moss Associations in Canada, 2018).

Bogs receive most of their moisture and nutrients from precipitation (rainfall and snow etc.) rather than from runoff or groundwater, like fens (Gorham, 1957). Except for *Sphagnum* moss, a common form of peat, vegetation usually found in bogs includes sedges, shrubs, and carnivorous plants (National Wetlands Working Group, 1997). Forested wetlands are wetlands that are characterized by woody vegetation and they serve as an important part of the broad coastal landscape of the Atlantic provinces (Atlantic Ecosystems Initiatives, 2017). However, they have often been overlooked or misclassified by either forest management or wetland management, due to their more complex vegetation structure (Nova Scotia Department of Envrionment, 2011). As a type of forested wetlands, treed bogs represent bog areas that are dominated by stunted trees like black spruce with a moss and shrub understory (Ducks Unlimited Canada, 2018). Specific criteria for treed bogs regarding the proportion of tree cover (25%-60% suggested by Ducks Unlimited Canada) and average tree height (taller than 3 m or 6 m) are still under discussion (Ducks Unlimited, 2015; Atlantic Ecosystems Initiatives, 2017; Northern

Prairie Wildlife Research Center, 2018). Therefore in this paper, ‘treed bogs’ will generally refer to bog land with a dominance of tree cover (⩾25%) and any individual trees of any size in the bog are identified as ‘trees’.

Bogs play a really important role in ecosystem services and climate change. It takes hundreds or thousands of years for a bog to develop from a lake or a moss covered dry land with accumulated peat, which is a product of submerged plants debris that cannot be decomposed by microbes (Keddy, 2010; National Geographic, 2018). Due to the deep peat deposits, bogs have been recognized as the largest and the most efficient carbon sink, containing about 30% of the carbon in the world, which could reduce carbon release in a natural way and help moderate climate change accordingly (International Peatland Society, 2008). In addition, because of their unique characteristics, bogs also provide important habitat for many insects, amphibians and birds, especially for some species at risk, like the hairy canary fly and sandhill cranes (National Geographic, 2018). Raccoons and woodland caribou are common mammals that prefer to settle in bogs. Since bogs store a large amount of precipitation, they also purify water and prevent flooding (Ducks Unlimited Canada, 2018).

From an economic and industrial point of view, peat from bogs has been regarded as a crucial fuel for cooking and heating, even though it comes with the price of destorying the wetland ecosystems (Lappalainen & International Peat Society, 1996). Unlike other countries, Canada harvests *Sphagnum* peat moss mainly for horticultural purposes. Bogs are delicate and special ecosystems that should be conserved and restored properly, at both local and national scales.

1.2 Problem Statement

Identifying and understanding bog dynamics could create effective overviews on the status of the biodiversity and carbon sequestration in bogs (Lindsay, Birnie, & Clough, 2014), which is also the first step to plan bog restoration and protection projects. There have been many studies focusing on bog monitoring and conservation throughout Euroapean countries and some areas in North America (European Commission, 2018). An assessment of the fluxes of greenhouse gases in and out of bogs in a context of climate change and hydrological variations seems to be a constant topic in bog dynamics: researchers have measured carbon dioxide exchange, as well as gross photosynthesis, ecosystem respiration and net ecosystem exchange, along an environmental gradient or with manipulated experiemnts of temperature, atmospheric conditions, water table and N deposition, or compared with natual and disturbed sites (Laine et al., 2009; Trettin et al., 2011; Winden et al., 2012; Munir et al., 2015). As for future projections, bog modeling is recognized as a feasible way to investigate long-term dynamics of vegetation, drainage, soil, landform and carbon cycling in peat bogs, though many studies had to control some independent variables as constants to ensure unique correlations (Laine et al., 2009; Talbot, 2009; Pearson et al., 2015).

Investigating plant communities in peat bogs can also reveal vualuable information regarding bog functions and maybe some hints about the local climate (Petras, 2014; Robroek et al., 2017). For example, greater carbon fixation followed an increase in plant biomass in bogs, but carbon storage in the form of peat decreased because a water table drop always seemed to accompany vegetation increases (Talbot, 2009). Yet a particular vegetation pattern, like the alternate arrangement of wet- and dry-adapted plant communities, is very likely to increase peat accumulation in bogs (Loisel & Yu, 2013).

Other studies on peat bog vegetation suggest that changes in species composition might be an indicator for some early environmental changes, like the loss of indicator species for low temperature and high humidity (Graf et al., 2010; Petras, 2014).

With this background and the context of global warming, a worry is that higher temperatures and lower humidity are likely to encourage the invasion of woody species into bogs (Macdonald, 2009; Bu et al., 2011). Encroaching trees will also change the vegetation structure and hydrology in bogs (Macdonald, 2009). This could be a big threat to the biodiversity and ecosystem functioning of bog habitats. Some ecologists in Nova Scotia observed some shrinking or even loss of peat bogs (M. Smith, personal communication, March 14, 2017); however, specific and long-term wetlands dynamics are still understudied in Nova Scotia and more related research is needed.

1.3 Ecological Applications of Spatial Pattern and Remote Sensing

This study used several spatial-temporal methods and techniques to answer the above questions. There is a long history using spatial pattern to gain insights into ecological processes (Watt 1947), but it was not until the mid-1980s that scientists realized the importance of spatial relationships between organisms (Dale 2000). Today, the study of spatial structure is one of the most rapidly growing disciplines, effectively joining forces with the traditional field of plant ecology. The causes and consequences of dynamic ecosystems connect spatial characteristics of plant individuals and ecological activities, such as establishment, growth, competition, reproduction or senescence. Giving credit to spatial point pattern analysis, underlying processes can be uncovered through descriptive characterization and hypothesis testing (Wiegand 2014).

The invention of aircraft in the earily 20th century allowed people to observe the world from a global perspective; the development of digital information technology in the later 1980s enhanced people's understanding of imagery data (Campbell & Wynne, 2011). This remote sensing has been a useful tool in every field of sciencific and social development, including geographical and ecological research. Some commonly used remote sensing instruments include high spatial resolution, hyperspectral, thermal infrared, small-satellite constellation, and LIDAR sensors; popular techniques are image classification, vegetation index, inversion algorithms, data fusion, and the integration of remote sensing and geographic information systems (Wang et al., 2010). As a result, ecological issues like large scale species or habitat identification, distribution modeling and landscape change detection that cannot be addressed through traditional field-based methods, can find powerful approaches to help overcome difficulties (Kerr & Ostrovsky, 2003).

1.4 Purpose of Study

The project *Biodiversity and ecosystem functioning of forested wetlands across Atlantic Canada* funded by The Atlantic Ecosystems Initiatives took a multifarious approach to increase knowledge about forested wetlands and enhance capacity for conservation of this habitat across the Atlantic provinces and its biodiversity under threat from anthropogenic and climate changes (Atlantic Ecosystems Initiatives, 2017).

I detected the spatio-temporal changes of treed bogs over more than half a century and also investigated whether and how trees established and expanded into peat bogs in Nova Scotia. Specifically, I asked the following research questions:

1) How did tree cover change in the study bogs over 70 years?
2) What are the spatial patterns of tree communities in bogs?
3) How do spatial patterns of trees relate to tree encroachment patterns?
4) What factors have contributed to the dynamics of trees in bogs?

In Nova Scotia, peatlands occupy more than three-quarters of 360,462 hectares of freshwater wetlands or about 5% of Nova Scotia (Nova Scotia Department of Envrionment, 2011). Most peatlands in Nova Scotia are bogs (Province of Nova Scotia, 2011). Some bogs are found in the Kejimkuji National Park, which is located about 60 km from the Atlantic Ocean and the Bay of Fundy in eastern Canada. The park receives 1,399 millimetres (55 in) of precipitation per year with 7.4°C annual average temperature (Environment Canada, 2011). Bogs comprise nearly half of the wetland area, and about 3% of the park land (Parks Canada, 1976). My two studied sites were Mud Lake Bog (44°20'54.18"N, 65°11'16.82"W) and North Cranberry Lake Bog (44°20'6.98"N, 65°14'31.15"W). The former is about 6.3 ha while the latter is much bigger at around 30 ha. Many species and communities have been documented at the site including *Sphagnum* moss, waist-high shrubs like leather-leaf *Rhodora*, and pitcher plants. Larch, red maple and black spruce also survive around the bog edges.

This thesis includes four chapters, of which chapter two and three are presented as independent studies. Chapter one introduces the research and project background, general purpose and approach of the study. Chapter two focuses on the detection of treed bogs dynamics over 70-90 years, addressing on research questions 1) and 4); chapter three provides a way to understand the process of tree encroachment into bogs, answering my research questions 2), 3) and 4). Chapter four synthesises key findings from the study as a whole and provides suggestions for future research.

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Chapter 2 Detection of Tree Dynamics in Bogs Using Sequential Aerial Photography and UAV Imagery

2.1 Introduction

Bogs are sensitive systems that change as a result of various types of disturbances, like agriculture, grazing, burning, mining, drainage and clear-cutting. This change is due to the nature of bogs – getting most moisture from precipitation (Gorham, 1957), which means any change in climate would affect the hydrology of bog and eventually change the growth and distribution of plants and animals in bogs (Bogology, 2013), though sometimes bog ecosystems have their own resistance and resilience to maintain a stable hydrology level (Scherer & Lorscheitter, 2014). Either human induced disturbances or natural fluctuations can influence bog dynamics, by affecting bog hydrology, soil and topography conditions together, finally leading to notable changes in landscapes and plant communities. For instance, during the last 5000 years, severe fire events changed a dry hummock bog community into a wet hollow community in central east Estonia, resulting in a shifts from *Sphagnum* to *C. vulgaris* dominated habitats (Sillasoo et al., 2011). In southern Québec, tree expansion in an agriculture landscape was facilitated by the drying of a bog surface rather than nutrient enrichment (Pellerin et al., 2016); a decrease in cotton-grass and an increase in the ericaceous shrub cover was observed on an abandoned bog site, 14 years after mining (Lavoie et al., 2005). Natural perturbations can also contribute to vegetation changes in bogs; over the long term, vegetation development in bogs has been prompted by high atmospheric depositions and climate variations (Hájková et al., 2011). Forest patches in bogs on the highlands of southern Brazil developed and then contracted during the last millennia under humidity and temperature changes (Scherer & Lorscheitter, 2014). Therefore, it is critical for resource and environmental management to have accurate and cost-effective estimations of the spatio–temporal pattern of bog vegetation and understand the driving forces of bog dynamics. Those valuable results and ideas could provide insight into the implications of climate change.

In Nova Scotia, peatlands occupy more than three-quarters of 360,462 hectares of freshwater wetlands or about 5% of Nova Scotia (Nova Scotia Department of Envrionment, 2011). Most peatlands in Nova Scotia are bogs, covered by *Sphagnum* moss and ericaceous shrubs with a dense growth of black spruce and larch, both of which have invaded the drier edges of bogs (Parks Canada, 1976; Province of Nova Scotia, 2011). Gradually, larch has been outcompeted due to its shade intolerance, whereas spruce grow slowly but has persisted for a longer time since they often drop seeds from lower limbs, which get buried in *Sphagnum* moss and prepare to sprout. Eventually, trees took over the bogs, becoming a mature though slow-growing forest. Park scientists have recognized the importance of micro-dynamics of peat bogs and noticed how some bogs are shrinking, causing habitat loss (Parks Canada, 2010).

Vegetation dynamics in bogs are usually subtle and cumulative so it may take time for them to be detected. Thus, studies focusing on long time periods are essential to monitor and capture vegetation changes. However, due to logistical and monetary constraints, long term studies are difficult to perform if using traditional field-based approaches. To overcome these difficulties, people have adopted paleoecological analyses (Foster & Zebryk 1993), repeated sampling of permanent plots (Taverna et al. 2005), vegetation modeling (Talbot, 2009; Pearson et al., 2015), space-for-time substitution (Pellerin et al. 2008) and time-series remotely sensed data. Of the above, aerial photograph interpretation, a basic kind of remote sensing application, has been commonly recognized as an achievable, efficient and cost effective method of documenting change.

The process of deriving the information from air photos to identify the various cultural and natural features is called imagery interpretation (Natural Resources Canada, 2018). With different purposes or using different types of images, there are many interpretation elements or factors used by people to understand a feature: location, size, shape, shadow, tone/color, texture, pattern, height/depth, site/association and time (Olson, 1960). Some traditional land cover classification or vegetation identification studies mainly use the tone and color information to determine features on the earth, because different objects reflect different proportions of energy in the blue, green, red, and infrared portions of the electro-magnetic spectrum. However, when it comes to spectral attributes are similar, more variables need to be included, such as shape, texture, neighbourhood (association), and more importantly, a temporal consideration of a series of photographs that can determine the historical change of an area.

Compared to satellite imagery, aerial photographs can date back earlier since satellite images only became available in the 1960s (Roush et al., 2017). A quantitative analysis of repeat aerial photography showed tree cover increases at an alpine treeline ecotone in United States since the early 20th century (Roush et al., 2017).; spatial patterns of forest encroachment between 1935 and 1996 in Valles Caldera grassland, New Mexico have been compared from orthorectified aerial photos, indicating a grassland decline and possible relationships between tree invasion and slope and elevation (Coop & Givnish, 2007). Multiple interpretation methods have also been applied to digital aerial photos such as point-based approaches focusing on individual tree positions and coverage-based tree crowns (Uuttera et al., 1998).

Given the significance and advantages of aerial photography, I used a time series of digitized air photos and analyzed them with a crown delineation technique. My primary objective was to identify the long-term (72-89 years) tree crown dynamics of two forested bogs at Kejimkujik National Park, Canada, and also to explore possible effects of topographic heterogeneity on stand dynamics. My specific goals include:

1) to determine the dynamics of tree cover over time;
2) to follow the spatial pattern of tree encroachment over time and
3) to detect if topography (elevation) is a driving force of tree encroachment.

2.2 Methodology

Study Area

The study was conducted in Kejimkujik National Park, Nova Scotia. The area has a cool humid temperate climate, resulting from the combination of the dry continental and the moist Atlantic air masses (Forest Management Institute, 1974). From 1971 to 2000, summers were warm with a July average temperature of 18.4 °C and an average 103.6 mm of annual precipitation (Environment Canada, 2018). Bogs comprise nearly half of the wetland area in the park, and about 3% of the park land. Most of the bogs are the result of the retreat of glacial ice and vegetation establishing in shallow lakes and ponds that once characterized the landscape (Parks Canada, 1976).

The two study sites were Mud Lake bog (44°20'54.18"N, 65°11'16.82"W) and North Cranberry Lake bog (44°20'6.98"N, 65°14'31.15"W) (Fig. 3-1), which are dominated by spongy mats of *Sphagnum* moss, waist-high shrubs like leather-leaf and *Rhodora*, and pitcher plants. Eastern larch (*Larix laricina*), red maple (*Acer rubrum*) and black spruce (*Picea mariana*) also survive mostly on raised hummocks around the bog's edge. Mud Lake bog covers an area of approx. 6.3 ha, whereas North Cranberry Lake (NCL) bog covers about 30 ha.

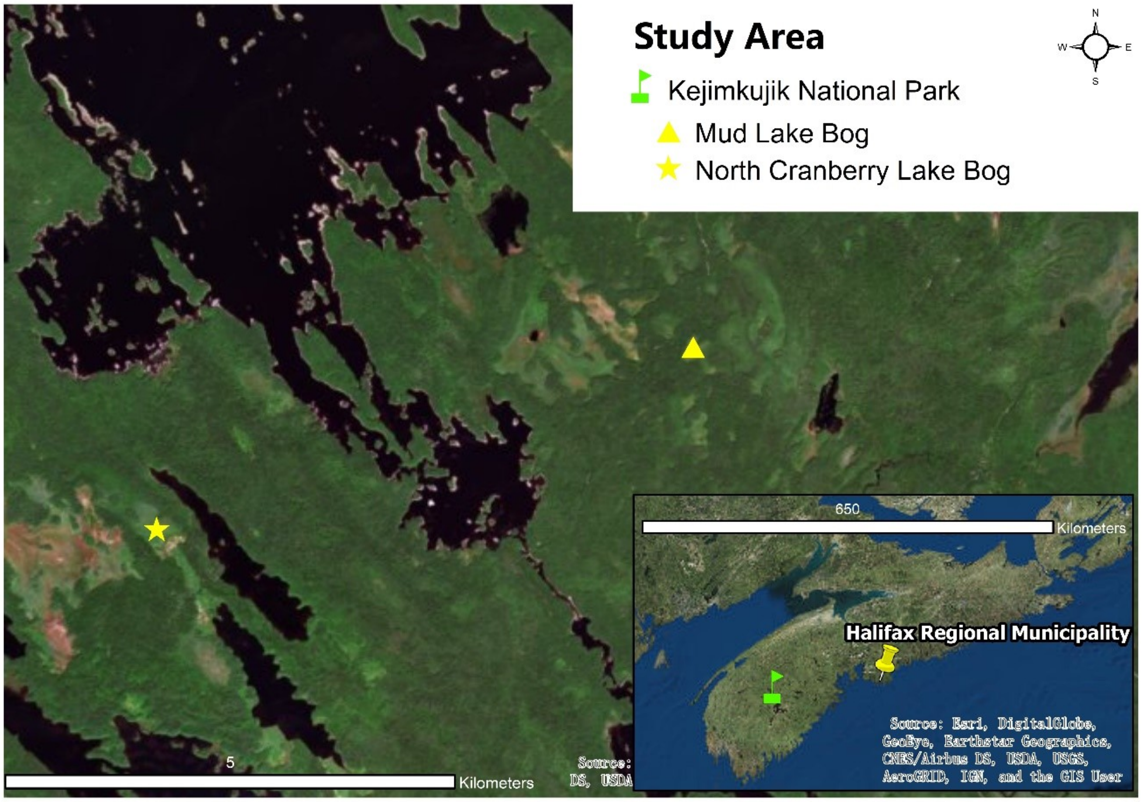

Figure 2-1. Location of two study sites: Mud Lake bog and North Cranberry Lake bog in Kejimkujik National Park (M. Smith, personal communication, March 14, 2017).

Acquisition of Imagery and Digital Models

All the digitized aerial images before 2017 were scanned from traditional film roll archives, published by Parks Canada and Province of Nova Scotia (Nova Scotia Geomatics Centre). Aerial photos captured in the earlier years are in black & white (panchromatic) though some of them are in scanned color, while recent images are in natural color. All of these digital aerial photos had very fine spatial resolution ranging from 0.02 m to 1.01 m and were saved as Tagged Image File Format (tiff) images (Table 2-1, 2-2). But it is worthy to note that the resolution listed in the tables are not the actual film resolution or camera system resolution which is affected by the camera lens, the film's emulsion and exposure time (Avery et al., 1992). Here the resolution is the smallest pixel size or effective resolution that is based on the scanning aperture and the scale of the original imagery (Nelson et al., 2000).

Table 2-1. Flight dates and digital image acquisition information for Mud Lake. NSGC: Nova Scotia Geomatics Centre

Year/Month/Day	**Color**	**Scale**	**Resolution (m)**	**Source**
1945	BW	1:15000	0.73	Parks Canada
1962/05/02	BW	1:17000	0.29	NSGC
1971	BW	1:15000	0.27	Parks Canada
1976/06/24	RGB	1:10000	0.15	NSGC
1986/07/23	RGB	1:10000	0.15	NSGC
1992/0717	RGB	1:10000	0.15	NSGC
2001/08/26	RGB	1:10000	0.45	NSGC
2010	RGB	1:15000	0.25	Parks Canada
2011/08/18	RGB	1:12500	0.18	NSGC
2017/07/26	RGB	1:9090	0.02	Drone Imagery

Table 2-2. Flight dates and digital image acquisition information for North Cranberry Lake. NSGC: Nova Scotia Geomatics Centre

Year/Month/Day	**Color**	**Scale**	**Resolution (m)**	**Source**
1928	BW	1:15000	1.01	Parks Canada
1945	BW	1:15000	0.20	Parks Canada
1965/06/17	BW	1:17000	0.23	NSGC
1976/06/05	RGB	1:10000	0.15	NSGC
1986/07/20	RGB	1:10000	0.15	NSGC
1992	RGB	1:10000	0.22	Parks Canada
2001/08/26	RGB	1:10000	0.46	NSGC
2010	RGB	1:15000	0.25	Parks Canada
2011/08/31	RGB	1:12500	0.18	NSGC
2017/07/26	RGB	1: 9090	0.02	Drone Imagery

Advances in the fields of UAV (unmanned aerial vehicle) technology has made it feasible to obtain very high-resolution imagery and 3D views of objects on earth (Anıl Can Birdal, 2017; Ayrey, 2015; Gatziolis et al., 2015). I took UAV images of Mud Lake Bog and North Cranberry Lake Bog on July 26, 2017. The UAV used for this study was a Phantom-4 Professional Dà-Jiāng Innovations (DJI) embedded with a GPS (Global Positioning System) receiver, a gimbal that allows a balanced movement for camera and lenses, an exclusive remote controller and a camera. The Phantom-4 Pro camera was equipped with a 1-inch 20-megapixel complementary metal-oxide semiconductor sensor and had a manually adjustable aperture from F2.8 to F11 (DJI, 2017). Flight missions were controlled by an autopilot Pix4Dcapture (Pix4D, 2017a), which allowed me to create flight plans prior to flight, including dimensions, path, altitude, overlap and camera angle for capturing objects with better quality. The flight height was set as 80 m and a side photographic overlap of 80% was chosen for optimal processing condition (Dandois et al et al., 2015). For Mud Lake bog, the flight lasted 8 minutes and covered 6.2 ha, whereas for North Cranberry Lake bog, two 16-minute flight missions were applied to a larger area of 27.1 ha. To ensure that images were taken from multiple angles, the flight paths were programmed as double grids (Pix4D, 2017c), in which two consecutive nadir rectangle missions were flown over the area with a near-vertical camera angle (80°).

The camera of the drone recorded objects using a series of photos taken in the double grids mission. By matching different photo perspectives of a single object, a point cloud of the study area can be generated by surface matching and triangulation. The images obtained from the UAV were processed and analyzed in Pix4Dmapper (Pix4D, 2017b) in a fully automatic mode, producing orthomosaic images, Digital Surface Models (DSMs), as well as Digital Terrain Models (DTMs) from point clouds. The photographing and modeling conditions are provided in a Pix4D Quality Report. The spatial resolution of drone imagery and DSMs was 0.02 m for both study sites. For the terrain information, I obtained 1 m-resolution digital elevation models (DEMs) from Parks Canada which were generated from airborne LiDAR data in 2010.

With digital images and models prepared, a methodology frame was developed to evaluate tree dynamics and encroachment (Fig. 2-2).

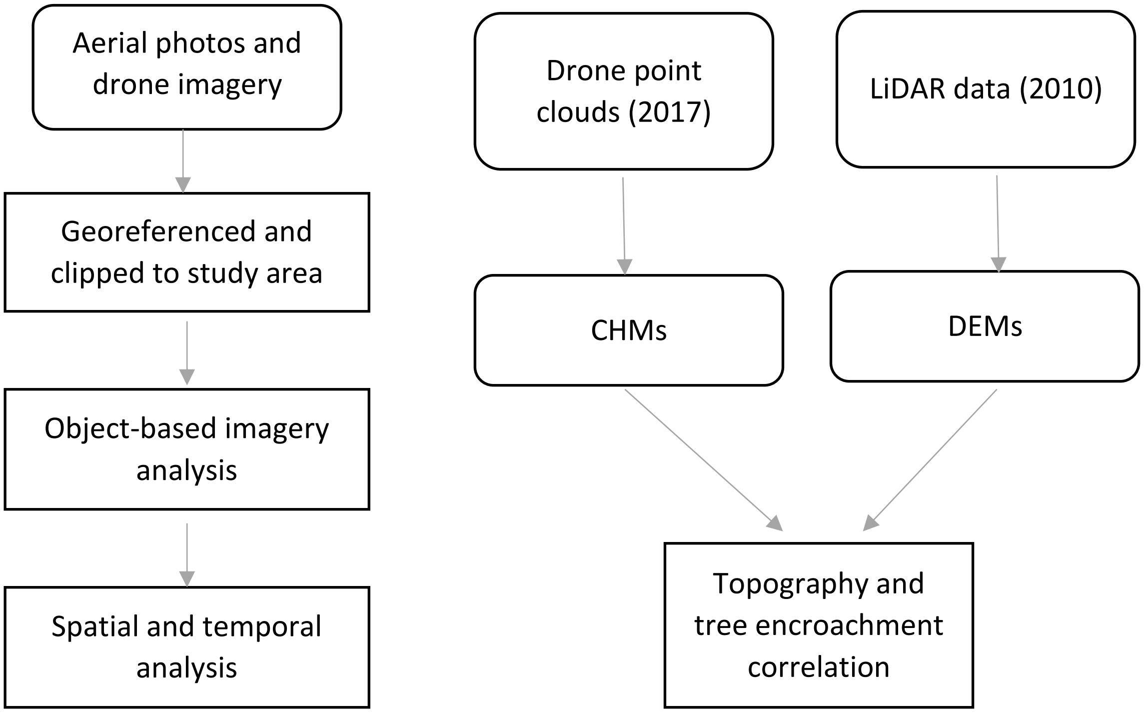

Figure 2-2. Schematic diagram of the overall methodology used in this study.

Data Preparation

All the images and digital models were then processed in ArcMap 10.5 (ESRI, 2016). Images and digital models were projected or transferred to the same map projection and coordinate system: NAD 1983 UTM Zone 20N. Photos were then georeferenced to be geographically consistent with each other: their geographic information was aligned with the aerial photo taken in 2010, which was selected as a reference for both study sites. Then, images were clipped to each individual bog area, excluding surrounding forests as 3.10 ha for Mud Lake bog and 14.95 ha for North Cranberry Lake bog. For a better imagery processing efficiency, images with cell size smaller than 0.25 m were resampled to 0.25 m, for later object-based imagery classification. Similarly, DEMs, DSMs and DTMs were also cropped to the corresponding study areas.

DTMs represent the height of the ground level and DSMs capture the top of natural and built features on the Earth's surface. Canopy Height Models (CHMs) are the heights of objects above the ground. Therefore, I derived CHMs by taking the difference between the ground elevation (DTMs) and the top of trees (DSMs) (Fig. 2-3). In ArcMap 10.5, this was achieved through "Minus" tool in *Raster Calculator* toolset, to subtract DTMs from the DSMs.

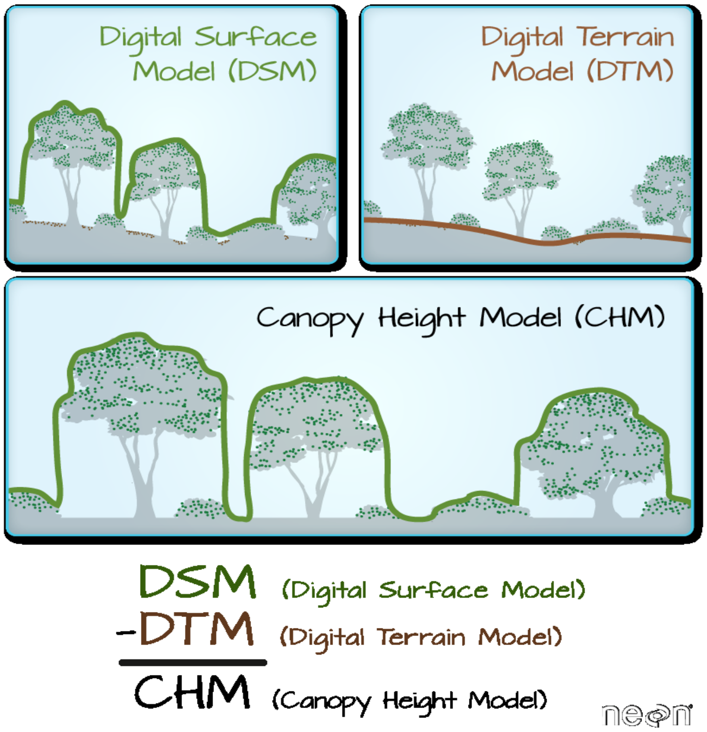

Figure 2-3. How CHMs are generated from DSMs and DTMs. Graphic: Colin Williams, NEON

Data Processing

Object-based imagery analysis (OBIA)

With high spatial resolution images, object-based image analysis (OBIA) is preferable since it can find more textual, topological and semantic information than spectral information in the images (Baatz & Schäpe, 2000). Before detecting dynamics of tree cover in bogs, the first step was to extract tree crown in bogs. Objects on the earth have different patterns of reflectance and absorption over different wavelengths. For example, healthy plants usually have a high reflectance in the near-infrared between 0.7 and 1.3 µm (National Learning Network for Remote Sensing, 1999). Unfortunately, in this study the images do not contain any near-infrared information or even RGB bands that could help identify trees. Additionally, it was difficult to detect differences between tree clusters and bog areas from their spectral information because both woody plants and herbaceous plants reflect most of the visible green light. Therefore, instead of single pixels, clusters of pixels known as objects are classified in OBIA. Tree crown delineation was conducted through object-based classification using the Trimble's eCognition 9.02 software (Trimble Geospatial, 2015). Aerial photos were classified into four polygon categories: bog, tree crown, water bodies and shadow, making it possible to calculate canopy cover change.

The processing of OBIA was carried out in two steps. The first step was the multiresolution segmentation with proper parameters, breaking down imagery to objects. This was controlled by setting the segmentation scale, shape vs. spectral and compactness vs. smoothness parameters. The scale parameters were set to 5, 10 or 15 for different digital images, due to the differences in their spatial resolution and geometry. This was determined empirically through visual inspection of the results, mainly the size and complexity of the segmented objects, comparing against known reference areas, like tree crowns. Since many images were panchromatic and because of the difficulty of distinguishing tree crown and bog land in color images, I put more emphasis on the shape of segments than on spectral information in the OBIA, using a shape parameter of 0.7 and compactness parameter of 0.5 for all digital images.

In the second step, I collected a set of training areas for the four classes “tree crown”, “bog land”, “shadow” and “water” and conducted a supervised classification using the k-nearest neighbors algorithm (Altman, 1992). Statistics of texture and shape features were mainly used to classify objects in the image. The classification process classified all objects in the entire image into the four categories based on the selected samples and defined statistics. The classification was refined by editing classified objects manually to other classes, improving the classification accuracy. Final classifications were then exported as discrete raster datasets for each image, which are suitable for further processing in geographic information systems.

Accuracy assessment

An accuracy assessment was conducted to evaluate how close the OBIA land cover classification to the actual classification on-ground at the study area (Aquino, 2015). After OBIA, 15-20 objects within each land cover class were randomly created as validation samples, since they were visually determined as the correct land cover, respectively. Then, a confusion matrix was generated by comparing the validated class samples to the OBIA classification results (Appendix A and B).

Classification accuracy and kappa coefficients were used to assess the OBIA performance. In the error matrix table, producer's accuracy was the number of reference samples classified correctly divided by the total number of reference samples selected for that class, indicating the probability that a certain land cover on the ground is classified as such from the image. On the other hand, user's accuracy represented the accuracy from the point of view of a map user, stating how accurate the classified land cover on the map could be recognized on the ground. This was calculating by taking the number of correct classified samples for a particular class and dividing it by the total number of samples that identified as this class. Combined with all classes, overall accuracy referred to the proportion of correctly classified samples in the total number of validated samples. The Kappa index of agreement (KIA) is a statistical index measuring inter-rater agreement for qualitative items (Cohen, 1960). It essentially evaluates the performance of the classification compared to random assignment. KIA ranges from -1 to 1: a value of 0 indicates a random classification; negative values indicated poor levels of agreement; values close to 1 imply very good level of agreement.

Spatial and temporal analysis

In order to determine changes in land cover between years, land cover maps for each year at both study sites were generated from the classifications of bogs and tree encroachment rates were calculated. Analyses were mostly implemented in ArcMap 10.5 (ESRI, 2016) (Fig. 2-4).

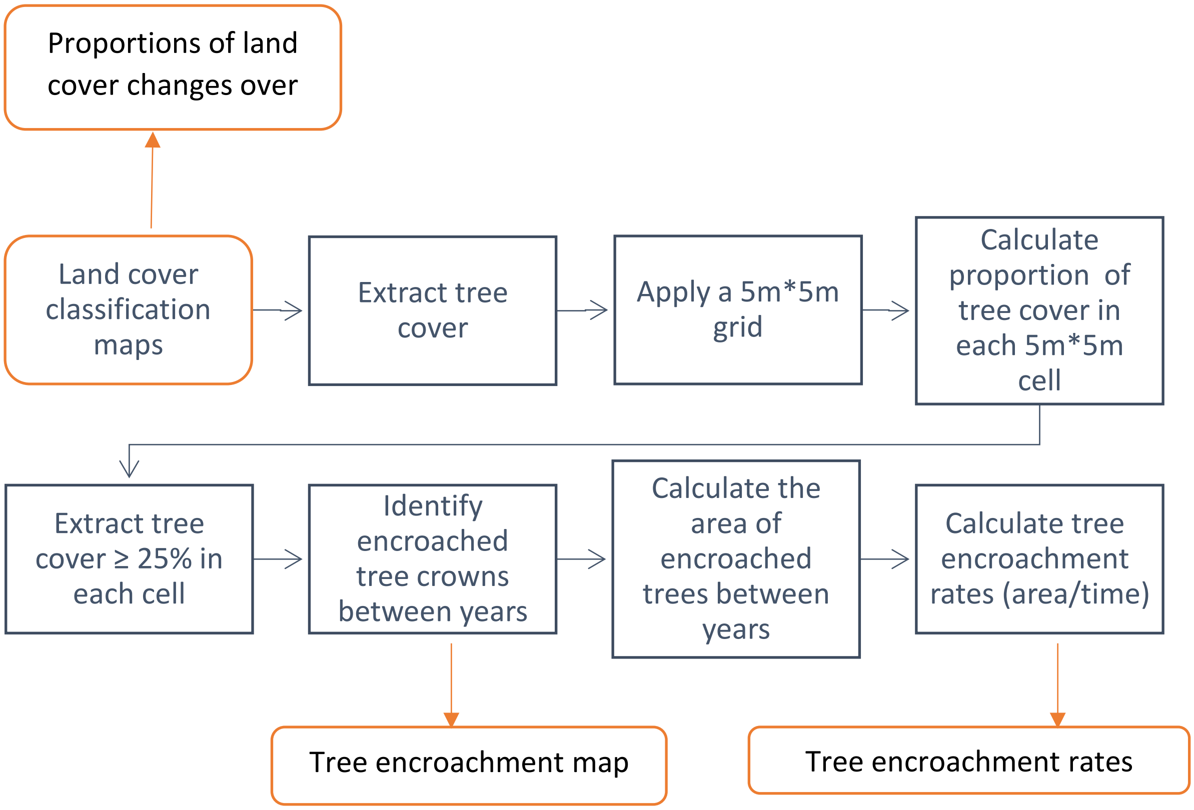

Figure 2-4. Flowchart illustrating the main steps and outputs for spatial and temporal analysis. Elements in squares are processes and circular frames are the outputs.

Different values were given to the four classes (above) using the "Reclassify" tool: 0-water, 1-bog land, 2-tree crown and 3-shadow. Tree crowns were extracted to an individual layer through "Select by attributes" for the value "2". Next, I applied a fishnet mask with 5 m× 5 m cells over the entire tree cover maps for each bog site (Fig. 2-5). Tree dynamics could therefore be investigated within each 5 m × 5 m cell, at a relatively fine scale but greater than a pixel level. Tree crowns covering more than 25% of each 5 m × 5 m cell were defined as “treed bogs” because I used a threshold of 25% tree cover to distinguish treed area from the open bog in each year (Ducks Unlimited, 2015). Next, layers of treed bog area in the different years were all combined into one layer by "Union" tool.

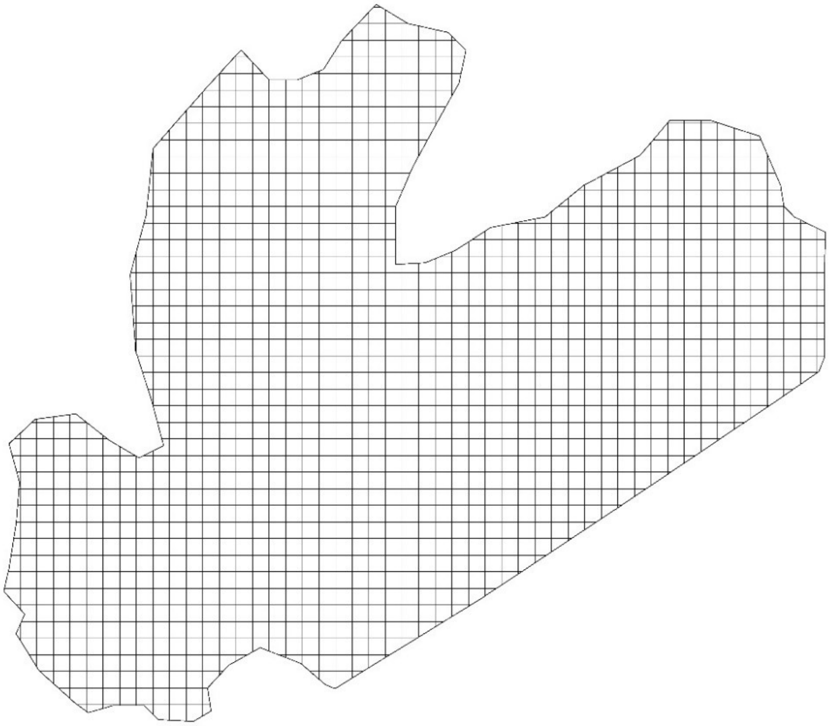

Figure 2-5. A Fishnet mask on Mud Lake Bog with 5m× 5m cells

When comparing a particular feature in a time series of images, image noise is always an issue causing biases in classification, like the random variation of brightness or spectral information in images (Rohankar, 2013). In order to reduce such interference, here I assumed that trees detected from later year images had already established for a while, meaning the encroachment of trees into open bog was always a progressive process. Therefore, to understand the process of where and when trees started to encroach into the open bogs, tree crowns were only accepted and kept in the first year they appeared. This was also achieved through the "Select by attributes" tool in ArcMap 10.5 by providing a SQL query expression to select tree crowns that newly occurred in that year. Finally, the tree encroachment map was generated, showing where and when trees were established. Accordingly, tree encroachment rates were calculated, which were defined as average annual tree encroachment area: area of new tree encroachment divided by the number of years. With these outputs, spatial and temporal dynamics of tree encroachment in bogs were evaluated visually and quantitatively.

DEMs and CHMs

To evaluate the correlation between topography and tree encroachment, first I resampled DEMs (1.00 m) and CHMs (0.02 m) to the same 0.02 m cell size, then I created 100 and 250 random points over the Mud Lake bog and North Cranberry Lake bog, respectively, according to their cover area. Each point was assigned two cell values of elevation and tree height at the random location, by using the tool of "Extract Multi Values to Points" in ArcMap 10.5. Next, I tested the linear correlation between the values in DEMs and CHMs for each bog.

Moreover, I tried another method to detect any possible influence of microtopography on tree growth or tree invasion. I classified values in Digital Elevation Models (DEMs) obtained from LiDAR in 2010 into three equal categories, representing low elevations (class 1), medium elevations (class 2) and higher elevations (class 3) in each bog (Fig. 2-12). Canopy Height Models (CHMs) were then evaluated and classified tree height values into three categories: 0-2 m, 2-10 m and more than 10 m (Fig. 2-13). This is also based on the description of wetland classification regarding the vegetation height (Ducks Unlimited, 2015). Last, I calculated the mean, maximum, median and standard deviation of canopy height values that belonging to each elevation class.

2.3 Results

Accuracy assessment

The confusion matrix in Appendix A and Appendix B represented the OBIA accuracy assessment for each image. The results showed little difference between study sites and they had decent classification accuracy in general: the overall accuracy for all images ranged from 74.37% to 92.33% and the kappa coefficient ranged from 0.61 to 0.88, except for the earliest image in each study site. Land cover maps of Mud Lake bog 1945 and North Cranberry Lake bog 1928 exhibited higher degree of error rates, with only about 63% overall accuracy and 0.44 kappa coefficient.

From the view of different land cover types, the producer's accuracy of shadow varied among years for both studied bogs. The identification of bog land and tree crown had stable performance in the Mud Lake bog. However, in the North Cranberry Lake bog, tree crown tended to have more accurate classification while bog land had higher omission errors during the recent years.

Spatio-temporal bog dynamics

A general visual assessment of the land cover maps (Fig. 2-6) reveals a trend of "greening", as more and more new woody vegetation established in the eastern and southern portions of Mud Lake bog. The central and northern regions displayed open or low-density tree cover for over 70 years. Between 1945 and 1992, a small patch of lake was identified in the Mud Lake bog, which gradually shrank through time and eventually dried up.

On the earliest air photo in 1945, more than 85% of the study region was bog land with only 0.31 ha tree crown scattered over the bog (Fig. 2-8a). Tree coverage increased to over one hectare (36% of the area) in the following 26 years, but then decreased as bog recovered by 7 % to about two hectares. Since 1986, tree encroachment has been ongoing in Mud Lake bog with tree cover increasing by almost a third to cover over half of the study area by 2017, whereas, only 25% of the area has stayed as open bog. Water coverage declined from 0.02 ha in 1945 to only 0.005 ha in 1992 and totally converted to bog by 2001. Shadow can be seen as a type of technical error in the aerial interpretation because objects on the ground block light source so information in this area is lost in the dark. The amount of shadow on images seemed to increase over years as trees grew.

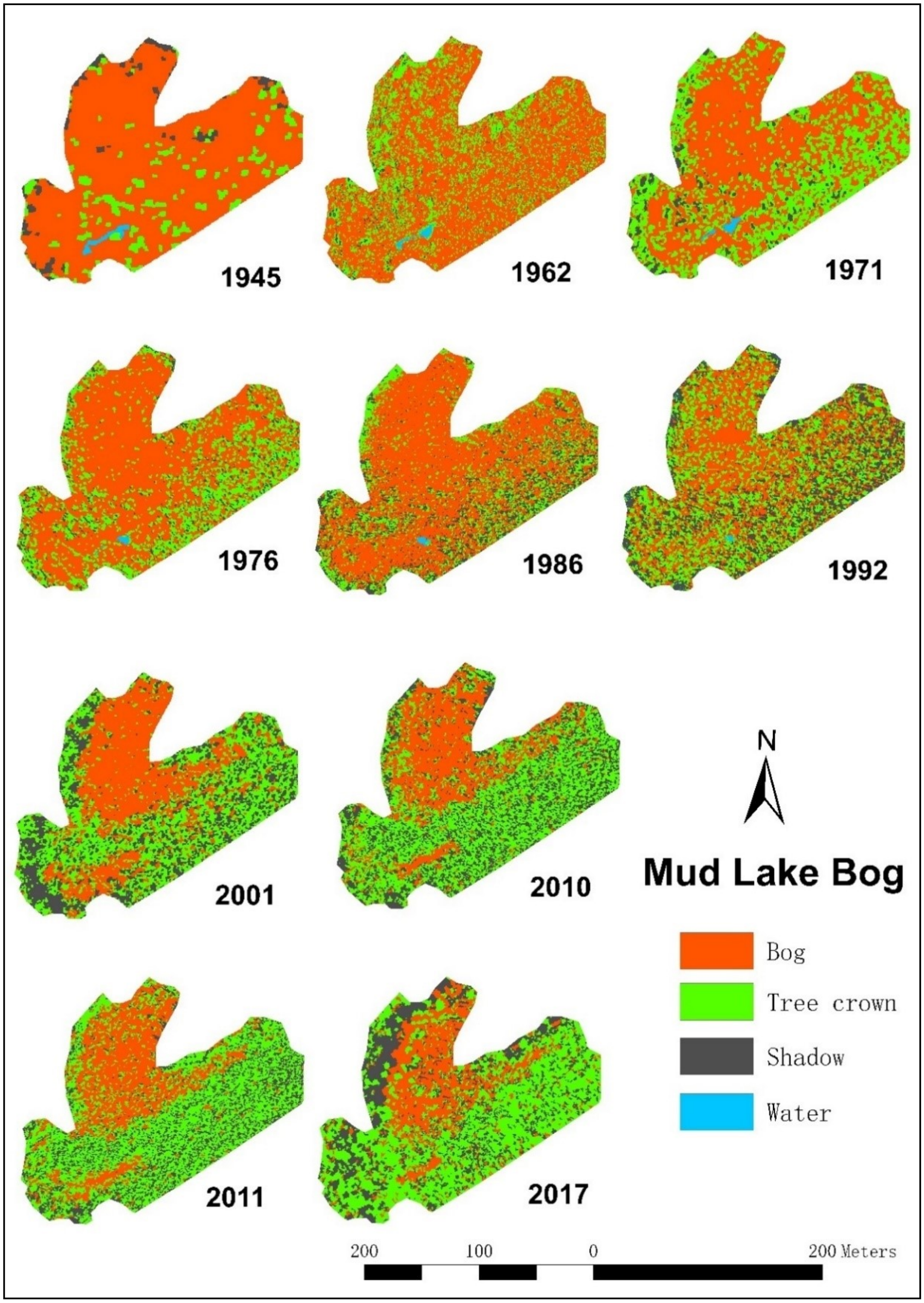

Figure 2-6. Land cover changes generated from object-based classification for Mud Lake bog from 1945 to 2017

North Cranberry Lake bog is three times larger than Mud Lake bog, covering 14.95 ha. A preliminary review of a time series of aerial photo classifications (Fig. 2-7) indicated that there were two different land cover change processes occurring in the North Cranberry Lake bog. Before 1965, the northern portion of the study area had been generally open except for a patch of forest. In the northern portion, tree cover expanded between 1965 and 1976 then declined by 1986 and increased again from 1992 to 2017. In contrast, the southern portion of bog showed the opposite trend: it had comparatively dense tree cover between 1928 and 1965, but after 1976 it experienced a considerable tree loss, ending up with a few small tree patches in 2017.

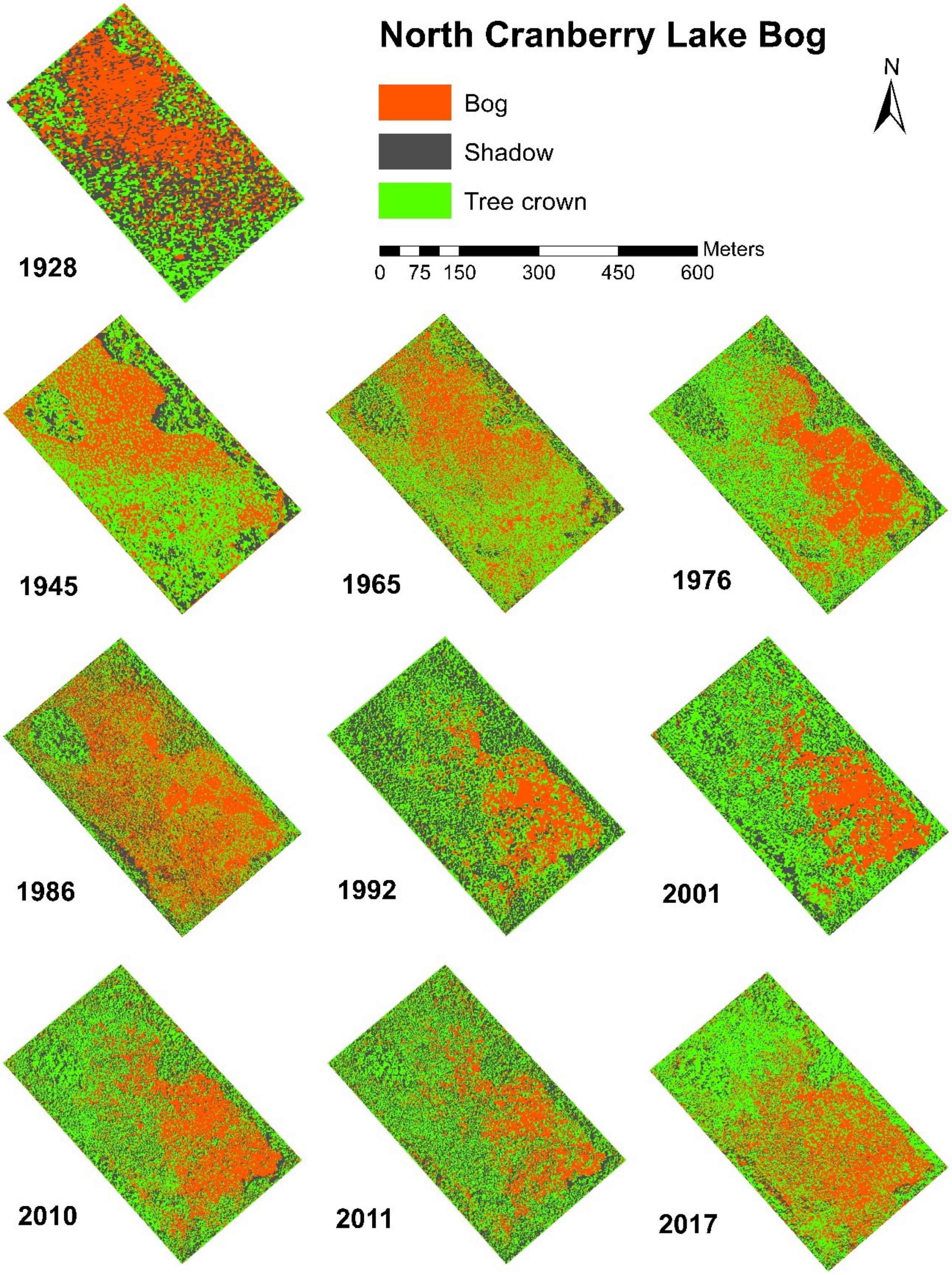

Figure 2-7. Land cover changes from object-based classification of North Cranberry Lake bog from 1928 to 2017

In 1928, only 3.90 ha of trees were delineated in the North Cranberry Lake bog with the rest bog land (36%) and shadow (38%). The trend of tree encroachment over the 89 years was not always on the rise (Fig. 2-8b). After a notable tree expansion between 1928 and 1945, tree coverage reached 6.99 ha then changed little in the next three decades. Tree cover clearly degenerated in the North Cranberry Lake bog by 17% from 1976 to 1986. In following 31 years, trees encroached in the bog with a total growth of 19%. In 2017, more than half of the study area was covered by trees. Bog land also fluctuated during the 89 years. In 1928 bog land comprised 36% of the total area and increased slightly by 1965. After that, bog land lost 1 ha in 1976 but gained area later in 1986 to reach its largest value of 6.78 ha. However, a marked decrease was found between 1986 and 1992 to the smallest bog land area of 3.06 ha. This figure had been basically unchanged until 2011 when the proportion of bog land expanded and kept going up to 34% (5.12 ha) in 2017. Compared to Mud Lake bog, more errors of shadow were identified in the North Cranberry Lake bog aerial photo classification, ranging from 13% to 38%. The error rate increased from 1945 to 1992 then went down in the recent years.

Figure 2-8. The proportion of land cover changes in (a) Mud Lake bog over 72 years and (b) North Cranberry Lake bog over 89 years

Tree encroachment

Trees tended to establish in the outer area around the Mud Lake bog, from the southern and eastern regions in 1945, then gradually encroached into the heart of bog later (Fig. 2-9). By 1962, many trees had started to encroach into the northern and central parts of the bog with an annual tree encroachment rate of 0.019 ha per year (Fig. 2-11). 1962 to 1972 was the fastest time for tree encroachment in the Mud Lake bog, at 0.080 ha per year, during which time most trees were found in the southern and eastern parts of the bog. In the next five years, trees were still expanding into the bog at a comparatively high rate. In contrast, tree establishment was slowest between 1976 and 1986 in the eastern part of bog, followed by a minor increase from 1986 to 1992 over the entire bog. After that, trees invaded with a slowing or unchanged pace until 2017, ending at 0.016 ha per year. Trees established in new areas between 1992 and 2001 mostly in the southern and northeastern portions of the bog and more gradually in the central part by 2017; however, this still left the central-northern part of the bog with considerable amount of open area.

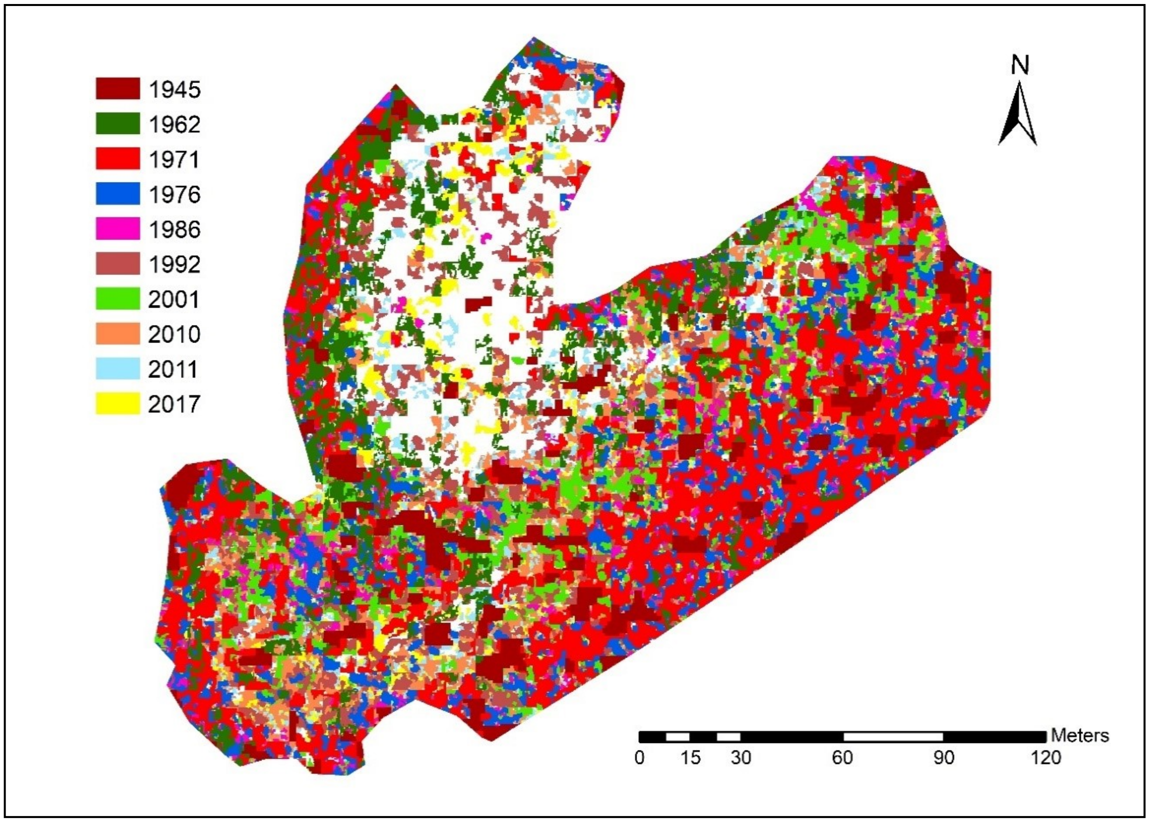

Figure 2-9. Timing of trees encroachment into Mud Lake bog in 5m ×5m cells. Area with different colors represent trees newly found in imagery by that year. For example, yellow area represent tree covers that established and grew up between 2011 and 2017. Blank area is considered as open bog, with less than 25% tree cover.

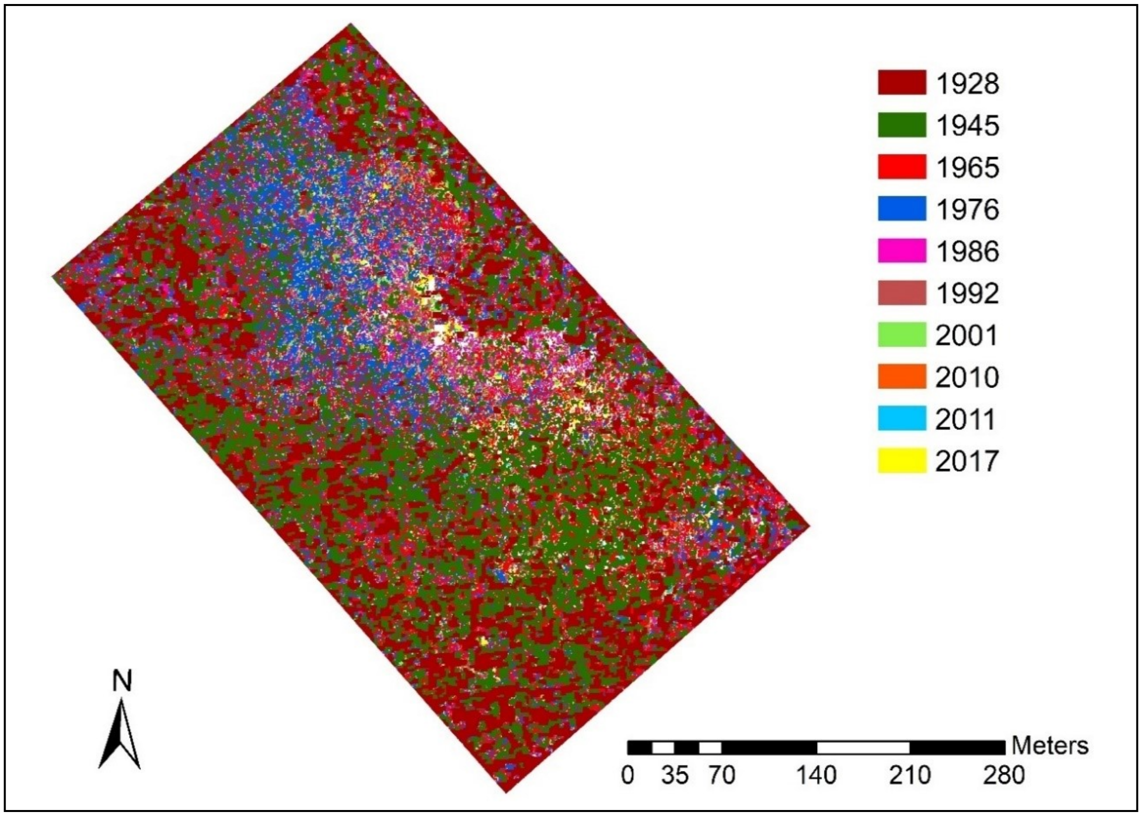

Figure 2-10. Timing of trees encroachment into North Cranberry Lake bog in 5m ×5m cells. Area with different colors represent trees that newly found by that year. For example, yellow area represent tree covers that established and grew up between 2011 and 2017. Blank area is considered as open bog, with less than 25% tree cover.

North Cranberry Lake bog had a somewhat different pattern and distribution of tree encroachment than Mud Lake bog, but in general the rate of tree encroachment also decreased over time. In 1928, it had nearly 4 ha of trees in the study region and only the central and northern parts had scarce tree cover (Fig. 2-10). Most tree encroachment occurred between 1928 and 1945 at a rate of more than 0.280 ha per year (Fig. 2-11), during which time trees were evenly established but with larger patches in the southern area. Similarly, from 1945 to 1965, invaded trees were evenly distributed across the North Cranberry Lake bog though they developed at a much slower rate of 0.122 ha per year. Since 1965, the density and distribution of newly settled trees varied in the bog: northern and central portions tended to have a higher density of recruited trees, whereas the southeastern parts of bog saw few new trees and the rest of the bog had a comparatively lower density of trees. This kind of tree encroachment distribution lasted for a while until 2001. Afterwards, there were no large number of new trees established in the northern bog, but the central-southeastern area found more seedlings clusters. Except for the time periods 1965-1976, 1986-1992 and 2010-2011, the tree invasion rate in North Cranberry Lake bog decreased over time to a low of 0.022 ha per year.

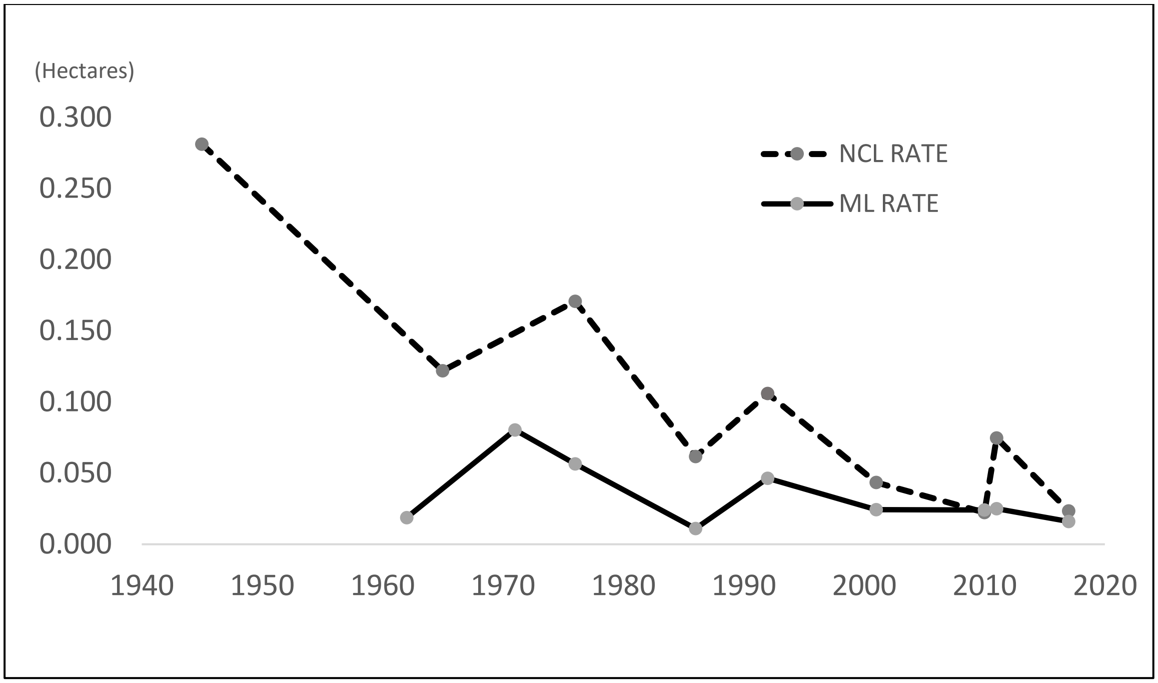

Figure 2-11. Average tree encroachment rate in two studied bogs (ha/year). Each point represents average rate from the previous recorded year to the current year. For example, the figure for the North Cranberry Lake bog in 1945 means the average tree encroachment rate between 1928 and 1945 was 0.281 ha per year.

Variation of tree height with elevation

The topography in the Mud Lake bog was very flat, ranging from 93.23 m to 94.43 m (Fig. 2-12a). Most of the higher terrain (class 3) was found around the southeastern area; the low terrain (class 1) was located at some edges of the bog; most of Mud Lake bog was on the medium-high ground (class 2). By contrast, the North Cranberry Lake bog had a relatively wider range of elevations of up to 5 m (Fig. 2-12b). The higher classes of elevations were under forest patches, usually in the north-central regions and at the edges of bog. Lower landforms were spread across the North Cranberry Lake bog, especially in the southern open area.

The average tree canopy height in North Cranberry Lake bog (0.88 m) was twice that of the Mud lake bog (0.4 m). Trees shorter than 2 m were the majority in both bogs, comprising over more than 80% of the total area (Fig. 2-13). Trees 2 m - 10 m tall were scattered over the two bogs except the central part of the Mud Lake bog, and they were sparse in the southern region of North Cranberry Lake bog. Very few tall trees greater than 10 m were found at the southwestern corner in the Mud Lake bog. In North Cranberry Lake bog, there were several patches of trees over 10 m tall, but only at the edges of the bog.

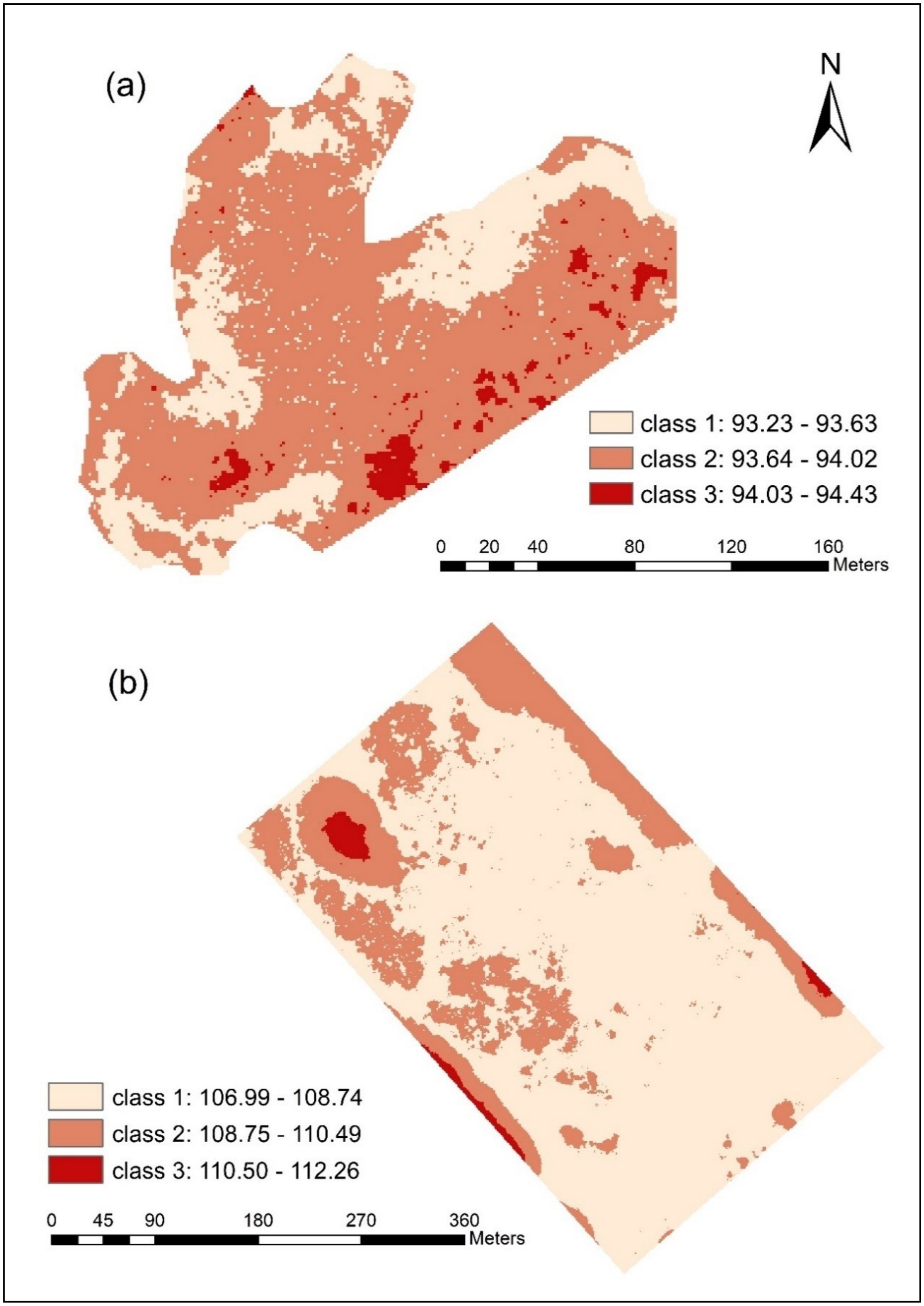

Figure 2-12. Three classes of digital elevation (m) in (a) Mud Lake bog and (b) North Cranberry Lake bog (2010). Elevation values were equally classified into three classes. DEMs derived from Parks Canada.

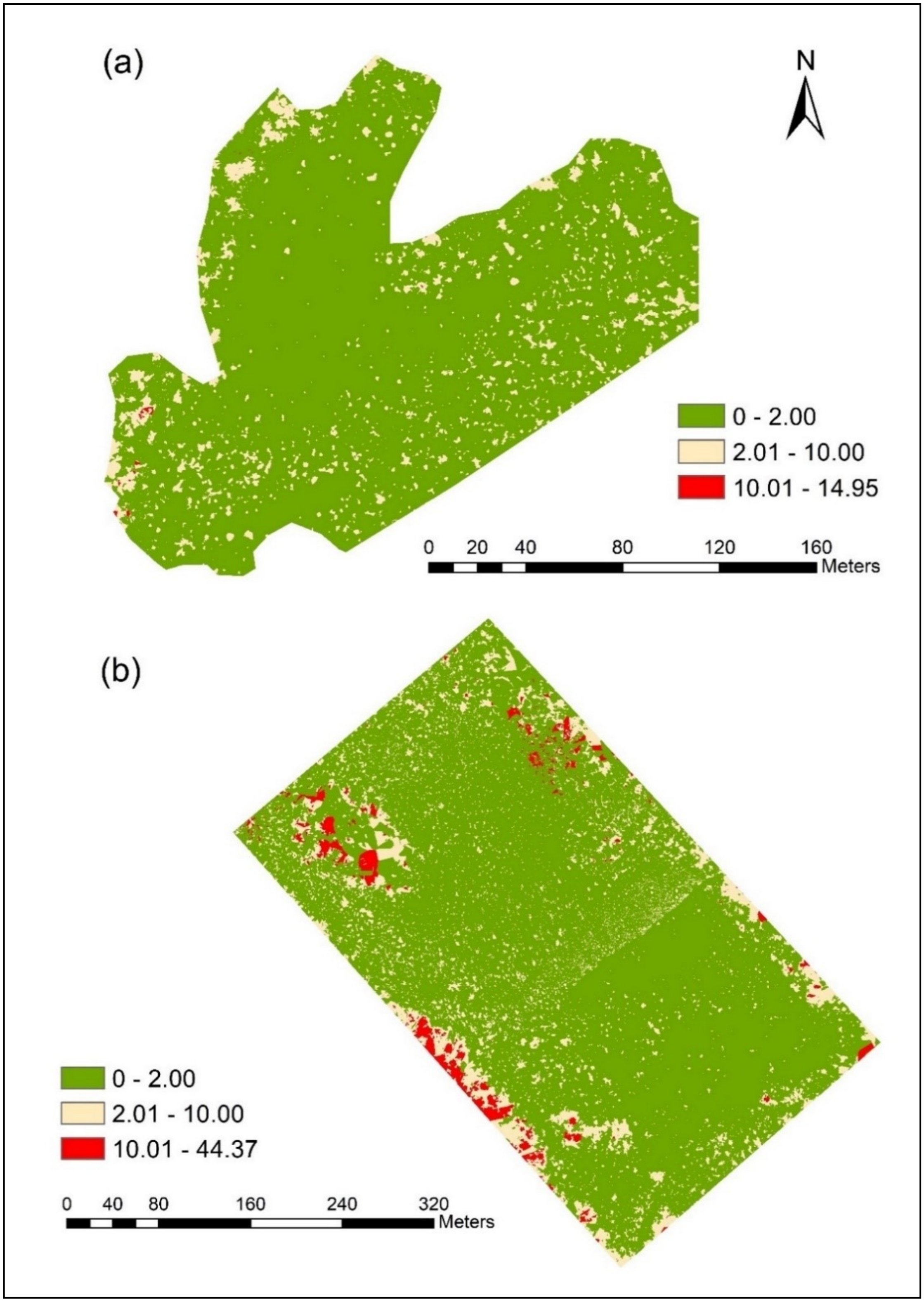

Figure 2-13. Canopy height models (m) of (a) Mud Lake bog and (b) North Cranberry Lake bog (2017). CHMs derived from 3D point clouds of UAV RGB images and were classified into 0-2 m, 2-10 m and more than 10 m tall (Ducks Unlimited, 2015).

Poor linear correlations were found between elevation and tree height in both bogs with correlation coefficient of 0.02 and 0.06 in Mud Lake bog and North Cranberry Lake bog, respectively (Fig. 2-14). However, some other correlations might be possible by comparing tree height between different elevations: in both of the bogs, trees rooted on higher elevations seem to be taller than others. This can be inferred from the canopy height statistics calculated for different elevation classes (Table. 2-3). Additionally, there was comparatively more variation in tree height in the medium and high elevation classes in the North Cranberry Lake bog.

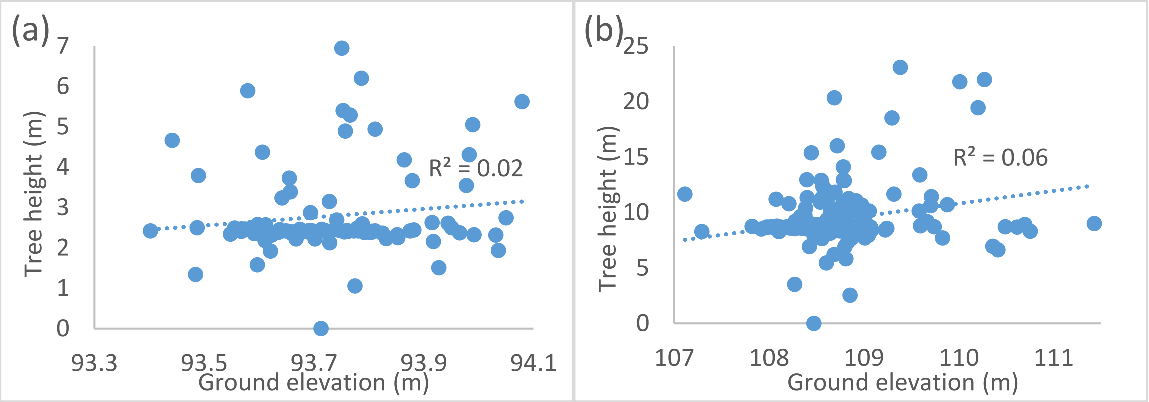

Figure 2-14. Linear correlations between DEMs and CHMs from randomly sampled values, in Mud Lake bog (a) and North Cranberry Lake bog (b).

Table 2-3. Canopy height statistics (m) in Mud Lake bog and North Cranberry Lake bog, by three elevation classes.

Mud Lake bog	**DEM class 1**	**DEM class 2**	**DEM class 3**
Mean	0.69	0.73	0.76
Max	8.06	10.91	3.31
Median	0.26	0.31	0.50
Standard deviation	1.08	1.06	0.74

North Cranberry Lake bog	**DEM class 1**	**DEM class 2**	**DEM class 3**
Mean	0.88	2.77	7.08
Max	34.11	32.06	20.16
Median	0.25	1.15	7.28
Standard deviation	1.74	3.65	5.18

2.4 Discussion

Spatiotemporal vegetation dynamics in bogs

Land cover changes over 72 years in the Mud Lake bog showed a clear decline of bog and a corresponding increase in tree cover, especially in the eastern and southern portions. The North Cranberry bog seemed more complicated: the northern part also experienced tree invasion during the 89 years but the southern part had a sharp reduction in trees in the bog, especially by 1976. Despite differences between the two studied sites and fluctuations over time, a general trend of bog tree dynamics can be generated: it seems that in the future there will be an almost complete absence of some open peat bog ecosystems. Similar situations were observed or inferred in other areas even though they were interpreted by various methods and time scales. Scherer & Lorscheitter (2014) confirmed that Araucaria forests in the southern Brazilian highlands originated from bogs. Ongoing tree spread in Lithuanian peat bogs has been documented through multiple approaches (Edvardsson et al et al., 2015). Open peat bogs in the Netherlands are likely to be less resilient and shift to a tree-dominated state under the scenario of constant warming and drying (Heijmans et al., 2013). Similarly, accelerating rates of converting non-forested area to forested area were documented for 1968-1996 and 1951-1968 in south-central Alaska (Berg et al.,2009). Tree encroachment rates in this study tended to slow down over time in both examined bogs while remaining positive, as more trees became established.

In the earlier recorded years, trees started to settle near the peat bog border; in the following years, tree stands developed towards the middle part of the peat bog, though still leaving some sparse open areas. This type of tree encroachment pattern coincides with the study of woody species invasion on a drained transitional peat bog in western Poland, where stands of *Betula pubescens* trees dominated the edge of the bog with decreased density and basal area towards the center of the bog (Dyderski, Gdula, & Jagodziński, 2015). This pattern of tree encroachment pattern may also explain the decreasing rates of tree establishment in the two studied bogs: trees have been filling into an enclosed space instead of open area, plus some pioneers already established, leaving limited resources and a competitive environment.

I also found some differences between the two studied bogs. In this study, the vegetation dynamics of North Cranberry Lake bog could be tracked as far back as 1928, at which time the proportion of tree crown was already > 25%, while the earliest recorded year for Mud Lake bog was 1945, with only 10% tree cover. This suggests that the history of tree encroachment in North Cranberry Lake bog is at least twenty years longer than that in Mud Lake bog. It is also reasonable to expect various vegetation dynamics in North Cranberry Lake bog throughout the ninety years since it is three times larger than the Mud Lake bog: northern and southern parts of the bog had exactly opposite land cover change trends. Therefore, the proportion of tree cover remained stable for the entire bog, at around 40%-50%, except in the year of 1928 and 1986. In contrast, Mud Lake bog's tree cover substantially expanded through the 72 years, though it still took up a relatively smaller proportion. The stable tree cover dynamics might also be a result of limited resources and space for seedling germination (Edvardsson et al., 2015), which could also be inferred by comparing the timing and spatial pattern of established trees: tree encroachment started relatively earlier and more trees were developed thus open area is sparse and fragmented in the North Cranberry Lake bog.

Factors contributing to tree encroachment

The essence of preserving bogs is to maintain hydrological activities (Holden, 2006). Ideally, bog hydrology is mainly affected by the climate and the relief of the terrain including precipitation, temperature and topography. Thus, it is sensible to ascribe vegetation changes in bogs to climate fluctuations: warmer summer and drier topographical microsites. For instance, hummocks could favor tree recruitment in peatbogs through facilitative interactions between trees and shrubs (Holmgren et al., 2015). Drying peatlands has promoted black spruce and shrub succession (Berg et al., 2009) and some palaeoenvironmental studies in Sweden used bog-tree growth as a climate proxy to reconstruct local humidity and temperature dynamics (Edvardsson, 2013). On a regional scale of the Kejimkuji National Park, the variability of annual average temperature and precipitation (Fig. 2-15) measured near the study area was too great to be described as a single clear pattern (Environment and Climate Change Canada, 2007). However, on a larger scale, many studies have shown that temperature in North America did rise and led to the recent thirty years to become the warmest period in the last 250 years; precipitation exhibited the opposite trend as it increased since the mid-1970s (Mann, 2001; Environment and Climate Change Canada, 2016, 2018). Future climate scenarios (Canadian Global Climate Model) also confirm the above trends: Nova Scotia is projected to be continuously warmer and wetter in the 2020s, 2050s and 2080s (Province of Nova Scotia, 2014).

Therefore, warming temperature likely accelerated persistent vegetation shifts in the two studied bogs, but tree encroachment detected in my study did not seem to be related to decreasing precipitation, which conflicted with the proposed expectation that wetter climate facilitates tree expansion (Province of Nova Scotia, 2014). This is probably because of moisture, the key factor in in bog hydrology and vegetation dynamics, is a balance between precipitation and evaporation, as well as catchment in- and outflows in peatlands (Edvardsson et al., 2015). Even though historical records and future projections show increasing precipitation, it is still hard to estimate changes in moisture since local evaporation dynamics are still unknown.

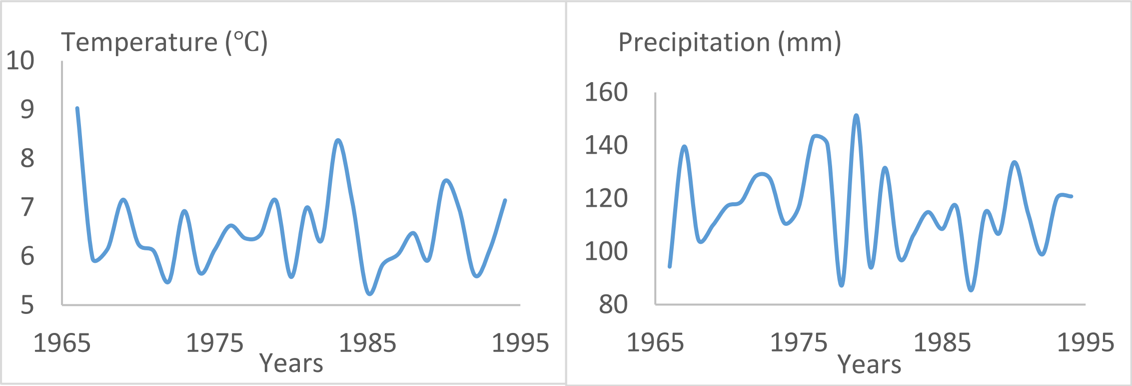

Figure 2-15. Average climatic variations in Nova Scotia from 1966 to 1994. Credit to Environment and Climate Change Canada, 2007

The role of topography has been commonly recognized for hydrological process (Graniero & Price, 1999), species diversity (Collins & Foster, 2008), and vegetation community properties (Florinsky & Kuryakova, 1996; B. Wang et al., 2015; J. Wang et al., 2016). The relationship between tree growth and topographical characteristics, which was evaluated in my study by relating tree height to elevation, had no linear correlation but in general taller trees did develop on higher elevation. This result indicated that hummocks might be more favorable for seedling survival or tree growth, due to less chance of being saturated. Thus, trees could establish earlier or grow faster on hummocks. This is also consistent with a study that tested the influence of artificially-created microtopography on a wetland tree species (Kangas et al., 2016).

Besides climatic conditions and topography, other factors also play an indispensable role in the process of tree encroachment in bogs. Whether in dry or wet locations, tree survival in bogs is still highly dependent on stand features, for example, the ability to grow roots fast and high seed mass (Limpens et al,, 2014). Tree colonization in peatlands has also been attributed to interactions between individual trees since understory vegetation and upper layers tend to affect seedlings by different degrees (Jagodziński et al., 2017); positive tree-shrub interactions were observed as well in a vegetation shift from moss to tree-dominated systems (Holmgren et al., 2015). Meanwhile, some neutral opinions demonstrated that bogs in northeastern Europe still maintained their resilience under the influence of climate change over the last 150 years (Stivrins & Stivrins, 2017); moreover, due to the intensive human modification, some vacuum-mined bogs in southern Quebec might not always have similar vegetation assemblages or changing patterns compared to those in undisturbed peatlands (Lavoie et al., 2005).

Disturbance has also been identified as an important driver of tree community dynamics in wetlands (Machado & Oliveira-Filho, 2010). In the present study, North Cranberry Lake bog seemed to have two different tree cover change processes during the past ninety years: the northern part of the bog experienced tree encroachment in general while the southern part underwent significant tree degeneration. The park and historical photos recorded that a man-made berm (probably built between 1945 and 1965) along the North Cranberry lake (Fig. 2-16). It seems that this berm has blocked the natural flow from wetland to the North Cranberry lake since 1960s, causing raised water level in the bog. Since water level limits vegetation growth in peatland environments, it is highly possible that the man-made berm changed the local drainage so the flow of water was stuck in the southern part and the saturated conditions caused tree death. The berm was visible in 1965 and 1976 aerial images and became unclear in 1992 imagery. However, it was completely invisible in the 2010 air photo since it was eventually abandoned (Fig. 2-17). This is also consistent with the results that higher tree mortality was found in North Cranberry Lake bog (Chapter 3). Not surprisingly, there have been few studies clarifying the cycle of hydrologic disturbance in peatland vegetation because significant vegetation changes always lag behind hydrological activities (Bellamy et al., 2012; Miller, 2011). But some results could still be found in some studies regarding the effects of road construction and blocked drains on peatland succession and development. For example, there was a lot of black spruce dieback after a flooding event in a fen in northeastern Alberta (Bocking, 2015); tree productivity increased and moss productivity decreased where drainage was impacted by roads or ditches in Alberta boreal peatlands (Miller, 2011). In the UK, vegetation biomass was found to be lower under some peatland restoration or management practices, compared to intact systems (Ramchunder, Brown, & Holden, 2009).

Figure 2-16. A man- made berm near North Cranberry Lake bog, photos taken in 2017

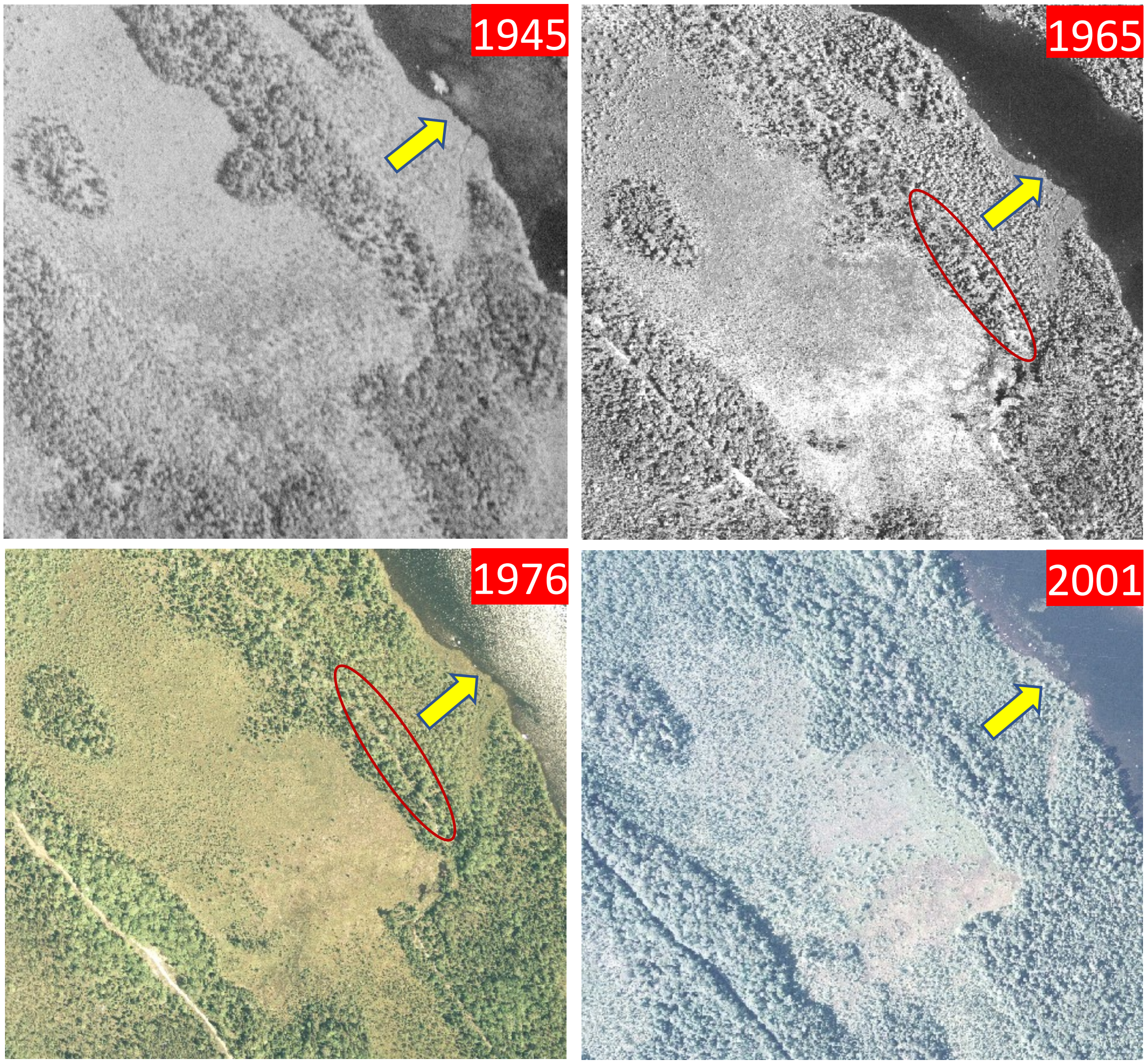

Figure 2-17. Aerial photos of North Cranberry Lake bog in 1945, 1965, 1976 and 2001. The red circle shows the location of this trail. Yellow arrow points out the direction of natural drainage.

Limitations and concerns

The intent of the research addressed in this paper was to evaluate temporal changes of treed bogs through historical image interpretation. However, like most optical remote sensing applications, the work was limited by the availability, quality and processing of the image and modeling data.

Not all years of aerial photos are of sufficiently high quality to be interpreted, digitized and classified into different land covers. For example, the imagery time line for both bogs began in 1928, but the aerial imagery for the Mud Lake bog in 1928 was too coarse to identify trees or bog area, so the earliest available aerial photo for the Mud Lake bog was from 1945. There was also a lack of continuous years of aerial photos for each study section. Gaps within an image time series were as large as 20 years (North Cranberry Lake bog 1945-1965), which could have obscured short term canopy changes. LiDAR-derived DEMs and UAV data-based CHMs were used in this study to examine the influence of microtopography on tree encroachment. Although whether high-resolution LiDAR could actually improve topographic characterization is debatable (Kraus & Pfeifer, 1998), there is still a concern that the resolution of DEMs (1 m) might not be fine enough to model and capture microtopography features, especially as coarse DEMs tended to reduce depression, smoothing surface (Habtezion et al., 2016).

The purpose of generating orthomosaics from UAV images in this study was to delineate land cover and make measurements of areas within the maps, regardless of the exact locations of features. This meant that relative accuracy rather than absolute accuracy would be sufficient for this study and that ground control points (GCPs) were not required for drone mapping. Processing quality reports showed that both study sites had a high degree of relative accuracy of more than 96% of images with geolocation errors falling in the -1 to 1 times ground sampling distance (GSD) error range (Pix4D, 2018; Pix4D, 2017). However, absolute geolocation accuracy, which considers the study region as a whole and compares geographic information of individual features between maps and the real world, did not achieve the precision as expected, since more than 20% of images with geolocation errors had larger deviations of more than -3 to 3 times GSD error intervals (Pix4D, 2018; Pix4D, 2017). This suggests that if time and resources were available, GCPs are still necessary and recommended in future drone mapping projects, especially for elevation land monitoring and vegetation index data surveys (PrecisionHawk, 2018).

The land cover classification based on aerial photos in this study proved to be effective, which could support statements mentioned above. The object-based imagery analysis (OBIA) of treed bogs seemed to have lower accuracy in older images, though the classification of the latest drone images did not perform as well as expected despite their high spatial resolution. Another concern about the OBIA classes is that land cover in both studied treed bogs was only divided into three categories and they tended to be misclassified. According to confusion matrix tables, it was also difficult to determine which pair of classes was more likely to be confused during the process of OBIA. Thus, refining the classes among bog land, tree crown and shadow could reduce errors and enhance accuracy assessment. Shadow, an inevitable factor influencing the interpretation of remote sensing images (Ye et al., 2012), caused difficulty in land cover classification and changes in detection. Shadow had different spectral information than the remaining classes, but observed shadows were supposed to be either bog land or tree crown. Therefore, shadow brought errors into the classification because of unfavorable filming conditions or image analysis. Results for Mud Lake bog were less affected by shadow, which increased over time and affected up to 25% of the area. This is in line with the convention that trees grow up as time goes on and taller trees would cause more shadow. However, shadow affected the classification of the North Cranberry Lake bog in various ways, covering up to more than 30% of the image. Hence, the attempt at shadow removal has become a very important step in aerial remote sensing image processing (George, 2011; Mishra et al., 2017; Ye et al., 2012). Unfortunately, due to time and technical limitations, I did not include shadow removal in my study and this is expected to be improved in subsequent research. Additionally, effective rule set settings and workflow of OBIA are still being explored by later researches to develop a better land cover classification.

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Chapter 3 Understanding Tree Encroachment Processes from Treed Bog Community Structure and Spatial Pattern

3.1 Introduction

In the Canadian Wetland Classification system, bogs are classified as peat-covered wetlands with raised surface relative to the surrounding landscape (National Wetlands Working Group 1997). The surface water of bogs is strongly acidic and the upper peat layers are generally nutrient poor. The plant community is dominated by Sphagnum moss, pitcher plants and shrubs, etc. or may also be treed with black spruce or larch. The formation and characteristics of bogs determine that bogs are sensitive to local climate change: any change in the hydrology is mainly related to precipitation as well as to temperature, because that affects how much water evaporates. Although bogs can alleviate the greenhouse effect by serving as huge storage depots for carbon, it is predicted that a moss dominated open peat bog could develop into a tree-dominated bog with continued temperature rise and drought events (Heijmans et al., 2013). On the other hand, results from a bog ecosystem model suggested vegetation changes should also been taken into account when predicting the effects of global warming on peatlands, indicating the interacting effects of components of global change. (Heijmans et al., 2008).

In 1988, an assessment of peatlands identified bogs as a main resource of Nova Scotia peat deposits, but also mentioned that inland and lowland Nova Scotia peat bogs tended to be heavily treed, especially in Hants and Cumberland counties (Anderson & Broughm, 1988). People have acknowledged the contributions of peat bogs to carbon storage, fresh water supply and biodiversity maintenance (Nova Scotia Department of Natural Resources, 2009). However, there is still a lack of comprehensive understanding of past and ongoing tree community dynamics locally, which could provide insights into the formation of forested bogs and local climate change.

Elsewhere, relationships have been found between climate and tree growth in bogs. In China and Sweden, progressive tree establishment 4000 yr BP or even during the early Holocene (12000 cal. yr BP) may suggest periods of increasing temperature and decreasing water-level or moderate precipitation in response to local climate fluctuations (Edvardsson, 2013; Ma, 2012). Similarly, forest shifts in southwestern Lithuanian bogs have been identified from aerial photos, indicating that the spread of trees in peat bogs could be ascribed to climate variations and environmental features, especially warmer and drier climatic conditions (Edvardsson et al., 2015).

The studies of bog vegetation dynamics described above often benefited from a multiproxy approach and dendrochronology, which always have some difficulties to implement since they require long-term records of climate change or a large sample of trees measurements. Therefore, other predictors or indicators may be useful for understanding tree encroachment in bogs. With a unique ecosystem, bog habitat changes can be determined directly from the structure of overstory or understory vegetation and tree growth traits (Czerepko, 2010; Jagodziński et al., 2017). Structural attributes include species composition, stand density, basal area, age-height categories, functional diversity, and mortality (Czerepko, 2010; Dyderski et al., 2016; Jagodziński et al., 2017; Rodríguez-González et al., 2010). Moreover, people recently studied bog dynamics and tree encroachment by taking advantage of remote sensing technology, like multispectral or multi-temporal images (Conner et al., 2002; Czerepko, 2010; Edvardsson et al., 2015), giving more intuitive results from multiple perspectives.

Understanding the spatial structure among individual trees is one of the important ways to reveal underlying ecological processes. The appearance and interpretation of patterns and associations can change with the spatial scale of study (Wiegand, 2014). At a plant-to-plant level, neighbor proximity and the pattern of arrangement rather than stand density are highly related to the variation in plant biomass (Mack & Harper, 1977). Based on this, Kenkel (1988) used nearest neighbor statistics and second-order spatial statistics to test density-dependent intraspecific competition of Jack Pine. A combination of field data and simulation modeling also showed how self-thinning and mutual inhibition affected mangrove stands interactions during two decades (Khan et al., 2013).

Given the importance of altered structure and functions of peat bogs, the aim of the present study was to determine whether and how trees encroached into peat bogs in Kejimkujik National Park, Nova Scotia, Canada. To achieve this, I had the following objectives:

1. To identify the tree density and composition in open and treed bogs;
2. To analyze spatial patterns of trees in open and treed bogs;
3. To compare differences in community structure, tree mortality and spatial interactions between open and treed bogs;
4. To understand structural development, tree succession and the underlying tree establishment process in bogs.

Compared to open bogs, more dispersed tree distribution patterns in tree-dominated bogs may indicate greater competition for resources such as light, whereas more clustered patterns may suggest more heterogeneity in topography since trees are expected to be clumped on hummocks, where water levels may be shallower. Moreover, intra- and interspecific competition can play a critical role in the development of stand structure throughout succession of a forest wetland (Gray, 2009a). During forest wetland structural development, different stages of the community have different habitat requirements and can have different spatial patterns. Tree mortality analysis also contributes to a further understanding of community dynamics and population mechanisms (Larson et al., 2015).

Specifically, I tested (1) the spatial patterns of all trees or a particular tree species; (2) the spatial associations between tree individuals based on different species or height; (3) the spatial aspects of tree mortality. For the interpretation of these spatial analyses, I used the following common hypotheses (Table 3-1):

Table 3-1 Potential ecological process behind different spatial patterns of trees

Categories	**Within a population**	**Between populations**	**Spatial context of mortality**	**Spatial outcome of mortality**
Spatial aggregation	Habitat-limited establishment; low dispersal distance	Facilitation	Density-dependent mortality due to competition	Spatial contagious mortality like diseases
Spatial dispersion	Competition (self-thing)	Interspecific competition	Agent-based mortality, i.e. biological and physical processes	Density-dependent mortality due to competition

3.2 Methodology

Study Area

The study was conducted in Kejimkujik National Park, Nova Scotia. Two bogs were selected near Mud Lake (44°20'54.18"N, 65°11'16.82"W) and North Cranberry Lake

(44°20'6.98"N, 65°14'31.15"W) (Fig. 3-1). Mud Lake bog covers an area of approx. 6.3 ha, whereas North Cranberry Lake (NCL) bog covers an area about 30 ha.

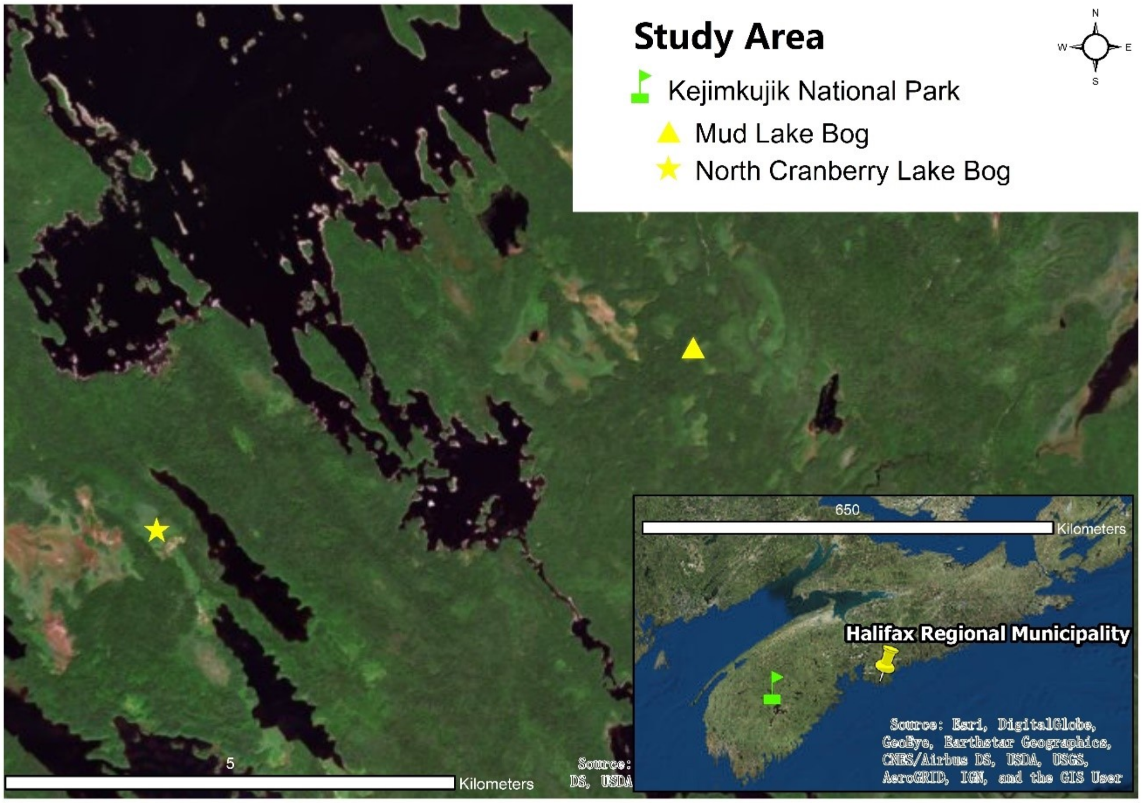

Figure 3-1. Location of two study sites: Mud Lake bog and North Cranberry Lake bog. (M. Smith, personal communication, March 14, 2017)

The area has a humid continental climate with warmer temperatures and higher precipitation than eastern Nova Scotia (Environment Canada, 2017). The park is dominated by mixed Acadian forest, a transition between typical southern deciduous and northern evergreen forests (Parks Canada, 2017). With an coverage of 40,400 ha in the southern upland region of Nova Scotia, the park has been well preserved and was not widely impacted by local industrial development or other point sources of pollutants, except for commercial cutting (Canada's Historic Places, 2017). With abundant *Sphagnum* moss, stands of black spruce and open water, bogs are the most common type of wetland in Nova Scotia, and are also a significant habitat in the park. Due to poor drainage and water saturation, only moisture-tolerant trees or shrubs can survive on raised hummocks or around bog edges (Parks Canada, 2017).

Data Collection

Tree community surveys were carried out from May to July 2017. Based on Google Earth imagery and aerial photos, I established two types of plots (30 ×30 m) in each bog (Fig. 3-2): an open plot, which stayed relatively open since 1928 with some sparse trees but still with an open expansive view, and a tree-dominated plot, with no detectable trees during early last century but became closed canopy recently.

In each studied plot, I identified all standing trees to species, measured their diameter at breast height (dbh ≥ 5 cm) (Appendix C) and height (Canada's National Forest Inventory, 2016; Mcgarrigle et al., 2011). Fallen trees and stumps were excluded in this research. All tree locations were mapped manually in the field with x, y coordinates in each plot. Also, I evaluated the health condition of all standing trees as living or dead. Generally, the two bogs were dominated by eastern larch (*Larix laricina*), red maple (*Acer rubrum*), black spruce (*Picea mariana*) and white pine (*Pinus strobus*), but tree density and age distribution varied between bogs.

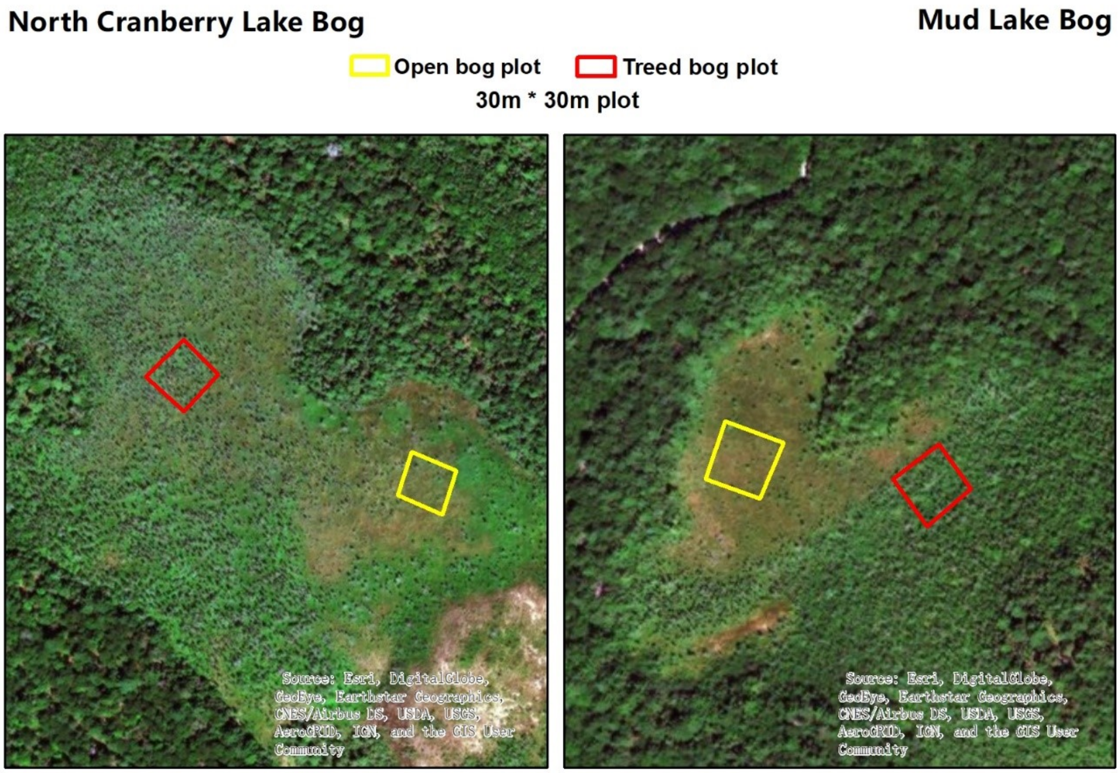

Figure 3-2. Location of the two sampling plots in each bog. Imagery source from Google Earth; Imagery date: 08/02/2016

Spatial Pattern Analysis

Spatial point pattern analysis has been extensively applied in plant ecology (Kenkel, 1988; Dale, 1999) by conducting statistical tests of point locations and point attributes. A commonly used statistic is the Ripley's K(r) function, which estimates the average number of neighboring objects found within a given distance, *r,* of each individual (Ripley, 1976). However, due to its cumulative characteristics, the interpretation of K(r) function might be spurious with the confounding effects of patterns at shorter distances obscuring patterns at longer distances (Illian, 2008). In this study, I implemented the pair correlation function, g(*r*), a derivative of Ripley's K function, also called the radial distribution function, to describe how tree density varies within a circular ring of radius *r* and width *dr* from a typical point (Stoyan & Stoyan, 1994), in which d must equal a proportion or number between 0 and 1:

$$g(r) = \frac{dK(r)}{2\pi r \cdot dr}, \qquad r \geq 0$$

Thus, g(r) will be able to give a non-cumulative result: the neighborhood of points near the specified radius is given a greater weight whereas points lying outside the bandwidth are not considered in the calculation at that radius (The Landscape Toolbox, 2012), allowing for a more accurate and informative estimation of the spatial pattern of point aggregation or dispersion (Illian, 2008; Velázquez et al., 2016a; Velázquez et al., 2016b). The radius r parameter sets the scale of analysis; in this case the limit is 15 m (half the length of a side of the plot) and the precision is 0.5 m. I applied three types of point pattern analyses to each plot: univariate point pattern analyses, bivariate point pattern analysis and qualitatively marked point pattern analyses.

Data Processing

In this study, only dominant species, with more than 5% of the overall composition of at least two stands, were included in further analysis because infrequent events may lead to a statistically unreliable result. Positive tree height-age relationships have been found in western white pine, western hemlock and Engelmann spruce in Northern Rocky Mountains, USA, though this is also a complicated correlation regarding overstory density, elevation, site preparation and habitat types (Ferguson et al., 2010). So in this study, tree height classes were used as a proxy for tree ages, due to the lack of dendrochronological records. Measured tree heights were then classified into three classes as short trees (≤ 0.50

m), medium tall trees (0.50 m < 2.00 m) and tall trees (≥ 2.00 m) for further spatial point pattern analysis. Similarly, only tree mortality greater than 5% was analyzed. For all analyses, confidence envelopes for null models were estimated by extracting the 5th and 95th quantiles from 199 Monte Carlo simulations, corresponding to a significance level of 95% for a two-tailed test.

Univariate pattern analyses quantified spatial aspects of a particular attribute of tree, such as species, height classes and all trees combined. Pair correlation functions for each plot were then compared to expected values under a null model of complete spatial randomness, which assumed no interaction among points and constant plot intensity. If $g(r)$ is greater than that for a random distribution, the distribution is clustered; if the number is smaller, the distribution is dispersed (Wiegand, 2014).

Bivariate pattern analyses used the bivariate pair-correlation function $g_{12}(r)$, which counts the number of individuals of category 2 around an individual of category 1, describing the spatial relationships between different species or height classes. The null model used was the toroidal shift (Lotwick and Lotwick, 1982), which randomly moved one of the patterns in its entirety, while holding the other pattern fixed. Results under toroidal shift indicated independence between two patterns; more points of category 2 found in the neighborhood of category 1 than the expectation indicates a pattern of aggregation; conversely, fewer points of category 2 found in the neighborhood of category 1 refers to segregation (Wiegand, 2014).

Qualitatively marked pattern analyses of tree mortality used a null model of random labeling, allocating the attribute or mark randomly over the points of an univariate pattern (Wiegand, 2014). To test for departures from random labeling, I used $g_{d, d}(r)$ to detect the spatial pattern of dead trees (*d*); density-dependent mortality $g_{d, a}(r) - g_{h, a}(r)$ to detect the spatial context of mortality, comparing patterns of initial (total or all trees = *a*) neighborhoods around dead and living or healthy (*h*) trees; and $g_{h,h}(r) - g_{a,a}(r)$ to compare patterns of trees with and without dead trees, identifying the spatial influence of mortality (Larson et al., 2015).

3.3 Results

Community Structure and Composition

At each site, open plots had larger tree populations compared to the treed plots; I also found many more standing dead trees in the treed plots (Fig. 3-3). Tree stands in open plots appeared to have much higher proportions of short trees (i.e. shorter than 0.50 m) as shown with the left-skewed tree height peak distribution (Fig. 3-4a, c); whereas those in treed plots had comparatively evenly distributed heights though there were a lot of trees taller than 5 m (Fig. 3-4b, d).

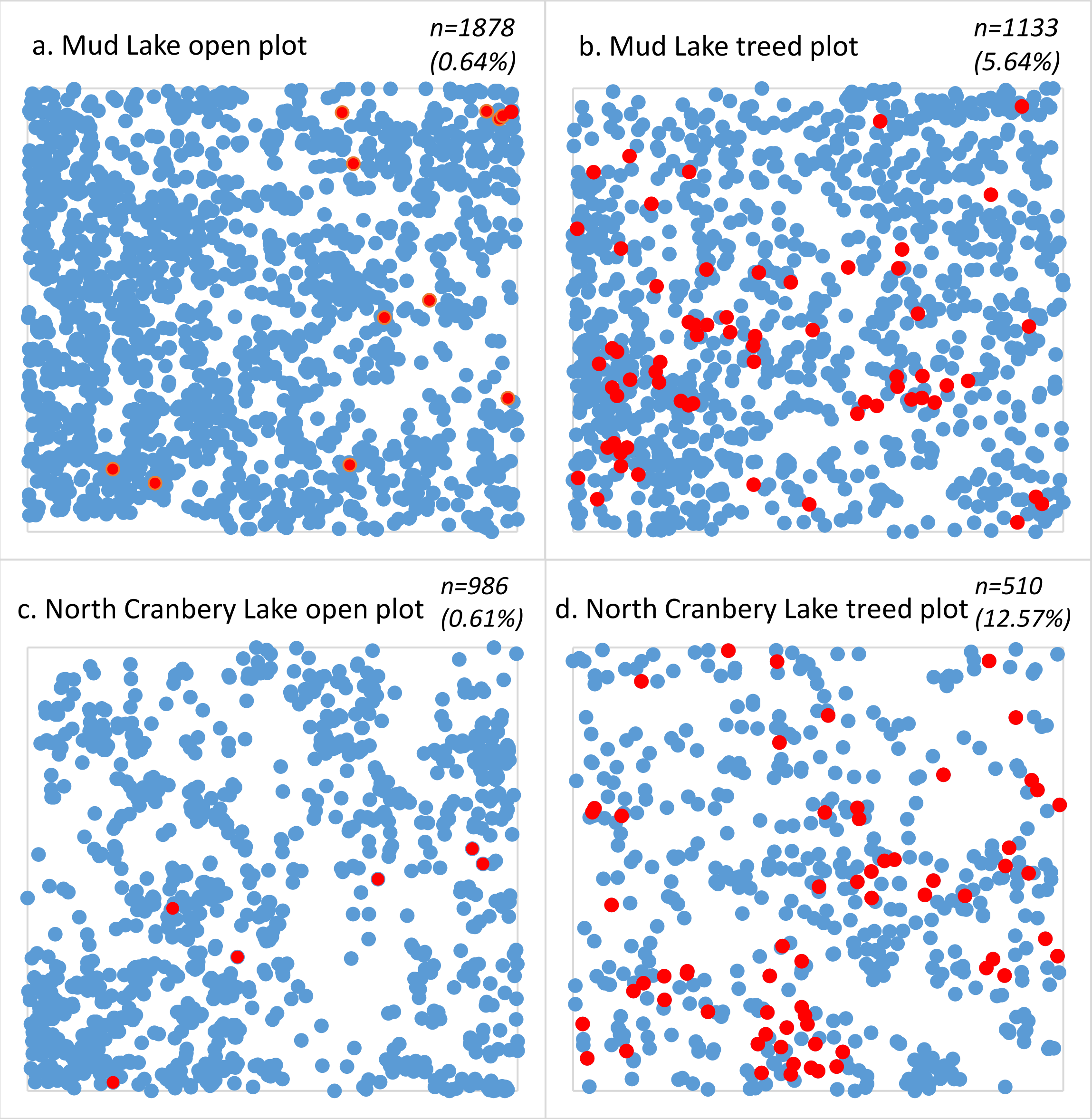

Figure 3-3. Spatial distribution of trees in the four plots. Blue and red dots indicate the locations of living and dead trees, respectively. n = number of trees. The proportion of trees that are dead is indicated in brackets.

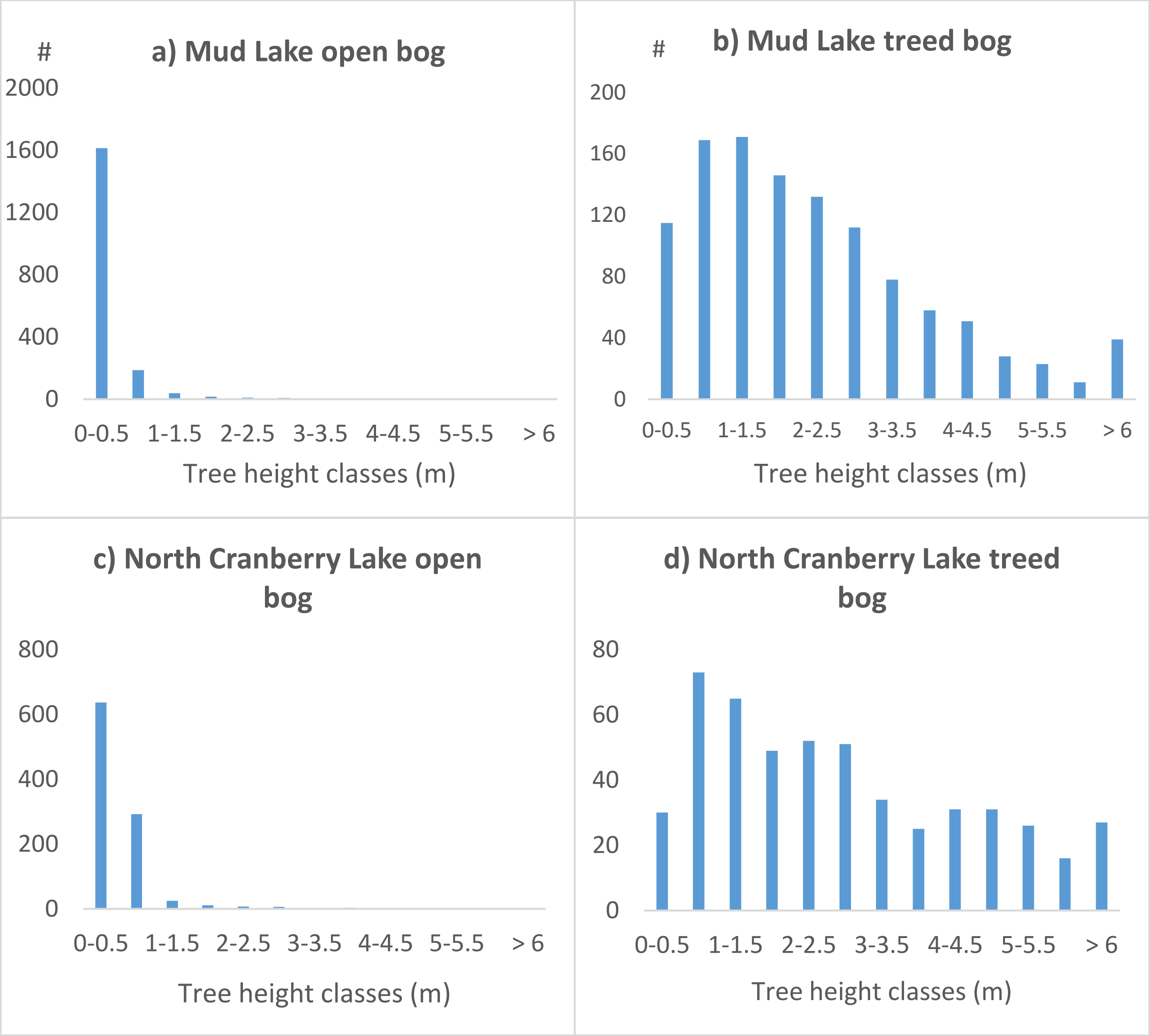

Figure 3-4. Histogram of tree heights in each studied plot, with 0.50 m class width. The last class is tree heights taller than 6.00 m.

White pine, black spruce and larch were the three dominant species in the Mud Lake open plot (Fig. 3-5a). The Mud Lake treed plot consisted of 28.7% red maple *(Acer rubrum)* and 42.6% larch, remaining trees were black spruce and white pine (Fig. 3-4b). The North Cranberry Lake open plot was mostly occupied by larch, with black spruce as the sub-dominant species (Fig. 3-5c). Black spruce occupied more than 90% of the North Cranberry Lake treed plot (Fig. 3-5d). Pine dominated in the Mud Lake open plot but only 12.4% of trees were pine in the Mud Lake treed plot; larch had the reverse pattern with less than 10% in the open bog to being the dominant species in the treed bog. In the North Cranberry Lake bog, less larch was found in treed plot, compared to the open one; however, spruce became the dominated one in treed plot with a considerable amount (Fig. 3-5).

For later analyses, tree heights were classified into different categories: short trees (tree height ≤ 50 cm), medium sized trees (50 cm < 200 cm) and tall trees (≥ 200 cm). Based on this tree height classification, open plots showed the typical inversed "J"-shape tree height distributions for all species (Fig. 3-5a, 5c), compared to the "J"-shaped tree height distribution found in both treed plots (Fig. 3-5b, 5d). Specifically, more than 97% of white pine were considered as short trees in the Mud Lake open bog, suggesting their recent recruitment (Fig. 3-5a). The majority in the North Cranberry Lake open bog was short larch, whereas that in the North Cranberry Lake treed bog was tall spruce.

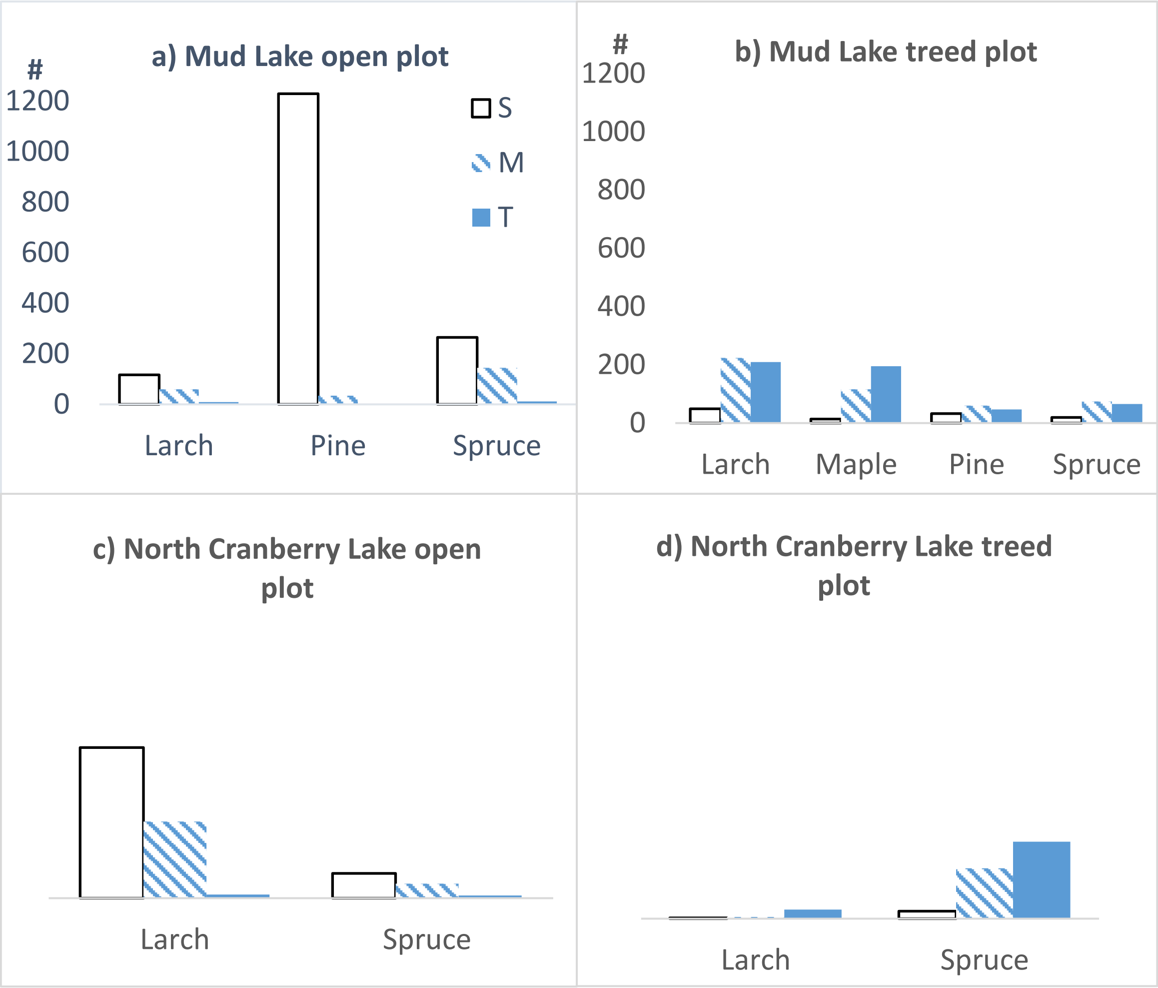

Figure 3-5. Number of trees of dominant species in three height classes (short (S), medium (M), tall (T)).

Spatial Patterns of Trees

Below is an example of univariate spatial point pattern analysis results in the Mud Lake open bog (Fig. 3-6). Values of g(r) within the simulation envelopes indicate that trees are distributed randomly for the corresponding scales, whereas values above the simulation envelopes means more short trees were found 0-4.5 m apart than expected, which indicates an aggregated distribution pattern. Alternatively, values below the simulations envelope (green area) indicates a scattered distribution pattern of evenly spaced trees 12.5-15.0 m apart.

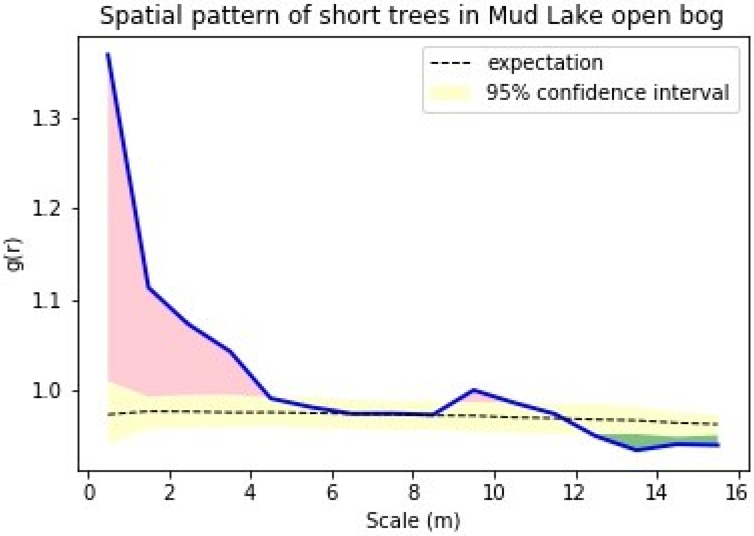

Figure 3-6. Example of univariate spatial point pattern analysis for short trees in the Mud Lake open plot. The observed values (solid line) that fall above, below and within 95% Monte Carlo Simulations indicate an aggregated (pink shading), regular (green shading) or random distributed pattern (yellow shading) at that scale, respectively. Results came from Programita (Wiegand, 2017).

The spatial distribution of all trees in the Mud Lake open plot tended to be dispersed but with trees aggregated at fine scales up to 4.2 m (Table 3-2). Similarly, a clumped pattern was detected in the Mud Lake treed plot up to 6.5 m, whereas a dispersed pattern was found at distances greater than 9.5 m. The distribution of all trees in the North Cranberry Lake open plot also exhibited aggregation at fine and medium scales (6 m) then changed to a more even distribution (7.5 m). Conversely, the spatial pattern of trees in the North Cranberry Lake treed plot was strongly aggregated at distances less than 2.5 m, then started fluctuating between randomness and aggregation at the remaining scales, suggesting a distinct pattern of being clumped.

hort trees in both open plots had approximately the same distribution pattern as for all trees (Table 3-2). In the Mud Lake treed plot, short trees were clustered at scales up to 10.4 m then dispersed at distances larger than 11 m; in the North Cranberry Lake treed plot, the spatial pattern of short trees was aggregated at fine and medium scales but dispersed at 11.0-12.0 m. Medium sized trees had similar distribution patterns as for all individuals in the four plots, although there was more evenness in the Mud Lake open plot and the North Cranberry Lake treed plot. By contrast, tall trees showed different patterns compared to the entire tree community: they were distributed randomly in both open plots but showed more significant clumps in the two treed plots, especially in the North Cranberry Lake treed plot (Table 3-2).

As for dominant species, the distribution of larch had the same pattern as that of all trees in the North Cranberry Lake open plot and it followed a random distribution except for a few aggregations in the Mud Lake open plot and the North Cranberry Lake treed plot (Table 3-2). Spruce in the North Cranberry Lake treed bog had the same distribution pattern as for all individuals. In both open plots, spruce also showed similar distribution patterns of clustering at scales up to 4.3 m (and larger scales for the Mud Lake bog) then even between 5 m to 8.5 m. In the North Cranberry Lake treed plot, spruce trees were mostly aggregated at multiple scales. Pine was only dominant in the Mud Lake bog and was highly aggregated at most distances, in both treed and open plots. Maple in the Mud Lake treed bog followed a random distribution at most scales except for dispersed at some middle and large scales.

Table 3-2. Spatial pattern of all trees, trees classified by height and the dominant tree species within each plot. Distances (m) indicate scales at which trees were significantly aggregated (top lines), or over-dispersed (bottom lines in italics) based on the 95% confidence envelope calculated for the g(r) function. Complete spatial randomness is indicated as ns (not significant). N/A means there were not enough trees (n < 2…) in this category. "+" refers to scales up to the maximum in the analysis (15 m).

Categories	**Mud Lake open plot**	**Mud Lake treed plot**	**North Cranberry Lake open plot**	**North Cranberry Lake treed plot**
All trees	0.0-4.2 *7.5-8.5, 12.5+*	0.0-6.5 *9.6+*	0.0-5.9 *7.5+*	0.0-2.4, 8.5-11.0, 13.4+ *ns*
Short trees	0.0-4.2, 9.4 *12.5+*	0.0-10.4 *11.1+*	0.0-5.5 *6.5+*	0.0-2.4, 6.9-8.6 *11.2-11.8*
Medium trees	0.0-4.8 *5.3-6.0, 7.3-9.5*	0.0-8.5 *10.0+*	0.0-6.0 *10.0+*	0.0-1.5, 7.0-9.5 *3.2-3.8, 5.5-6.5*
Tall trees	ns	0-1.3, 9.0-10.0 *ns*	14.2-14.8 *ns*	0.0-5.9, 12.2-14.5 *ns*
Larch	0.0-2.0 *ns*	0.0-8.4 *9.8+*	0.0-6.5 *8.0+*	6.2-6.8, 11.4-11.9 *ns*
Spruce	0.0-4.3, 11.5-12.9 *5.2-8.5*	0.0-1.8 *7.2-7.7, 13.6+*	0.0-4,3 *5.5-8.0*	0.0-2.5, 8.2-11.1, 13.3+ *ns*
Maple	N/A	0.0-1.5 *5.2-5.8, 7.3-7.7, 12.1-13.0*	N/A	N/A
Pine	0.0-11.4 *13.4+*	0.0-2.5, 4.4-6.2, 7.5, 12.4-13.0 *ns*		

Spatial Interactions Among Trees

Instead of comparing points within one type, two different types of points are considered in bivariate analysis. Here I also provide an example of bivariate analysis results in the Mud Lake treed plot (Fig. 3-7). Values of g(r) within simulation envelopes indicate that maple and black spruce were generally distributed independently in the Mud Lake treed plot; however, maple and black spruce were negatively correlated between 12.0-13.0 m. No significant aggregation of maple and black spruce was found.

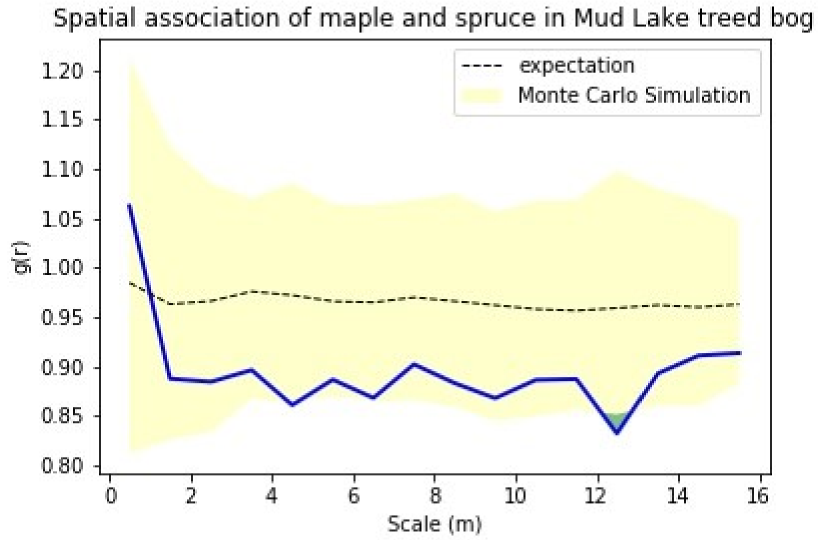

Figure 3-7. Example of bivariate spatial point pattern analysis for the association between maple and spruce in the Mud Lake treed plot. Observed values that fall above, below and within 95% Monte Carlo Simulations indicate an aggregated (pink shading), regular (green shading) or random distributed pattern (yellow shading) at that scale, respectively. Results came from Programita (Wiegand, 2017).

Medium sized and short trees (Table 3-3) were distributed independently in all plots, although there was a positive association at very fine scales in the North Cranberry Lake bog. Tall and medium sized trees were also distributed independently at most scales in all four plots though they were aggregated together at 1.5 m in the Mud Lake open plot and tended to be segregated (significantly before 2.5 m) in the Mud Lake treed plot. The spatial associations between tall and short trees exhibited spatial independence in the Mud Lake open and North Cranberry Lake treed plots; but strong negative correlations were found in the Mud Lake treed and North Cranberry Lake open plots.

The interspecific interaction (Table 3-3) between larch and spruce in all four plots tended to be uniform at greater scales, though it demonstrated strong attraction at distances smaller than 3.5 m in the North Cranberry Lake open bog. There was no significant interspecific interaction found between pine and spruce nor pine and larch, except pine were segregated from spruce (0-2.7 m) in the Mud Lake open plot. The interspecific interactions between maple and other species were mostly independent in the Mud Lake treed bog, except for a few segregations for spruce and larch.

Intraspecific spatial relationships generally exhibited independence between tall and short trees, in all sampled plots, though in the North Cranberry Lake open plot small larches tended to be apart from taller ones at a few scales (Table 3-4). Interspecific associations between tall and short trees also showed a spatial independence, except for the Mud Lake treed plot, which had distinct segregations between tall and short trees of all the interspecific pairs (Table 3-4).

Table 3-3. Spatial interactions between dominant species and between trees of different heights within each plot. Distances (m) indicate scales at which trees in different categories are positively (top figures), or negatively correlated (bottom figures in italics) based on the 95% confidence envelope calculated for the g(r) function. The lack of significant correlation at all scales is indicated as ns (not significant). N/A means there were not enough trees (n < 2…) in this category. "+" refers to scales up to the maximum in the analysis (15m).

Categories	**Mud Lake Open bog**	**Mud Lake Treed bog**	**North Cranberry Lake open bog**	**North Cranberry Lake treed bog**
Medium-Short	ns	ns	0.0-2.5 *ns*	0.0-1.5 *ns*
Tall-Medium	0.0-1.0 *ns*	0.0-2.5 *ns*	ns *3.2-3.7, 9.4*	ns
Tall-Short	ns	ns *0.0-1.5, 4.5-7.0, 9.5-10.5*	ns *1.2-2.0, 14.5*	ns
Larch-Spruce	1.5-2.5 *ns*	ns	0.0-3.4 *ns*	ns
Spruce-Pine	ns *0.0-2.7*	ns		
Pine-Larch	ns	ns		
Maple-Larch		ns *7.2-7.8*	N/A	N/A
Maple-Pine	N/A	Ns		
Maple-Spruce		*ns* *4.2-4.7, 11.9-13.1*		

Table 3-4. Intra- and inter-specific spatial relationships between tall and short trees. Distances (m) indicate scales at which trees are positively (top figures), or negatively (bottom figures in italics) correlated based on the 95% confidence envelope calculated for the g(r) function. Complete spatial randomness is indicated as ns (not significant). N/A means there were not enough trees (n < 2…) in this category. "+" refers to scales up to the maximum in the analysis (15m).

Tall vs. Short	**Mud Lake Open bog**	**Mud Lake Treed bog**	**North Cranberry Lake Open bog**	**North Cranberry Lake Treed bog**
Larch	ns	ns	ns *0.8-2.0, 14.0+*	5.5-6.5 *ns*
Spruce	0.0-1.3, 14.5 *ns*	ns *2.5*	ns	ns
Maple	N/A	ns	N/A	N/A
Pine		ns		
Spruce - Larch	ns	ns *3.5-5.0*	ns	ns *0.5-2.0*
Larch - Spruce	ns	ns *10.9-12.2, 13.0-14.5*	ns	ns
Larch - Pine	ns	ns *13.2-14.5*	N/A	N/A
Pine - Larch	N/A	ns *0.0-1.0, 10.5*		
Spruce - Pine	ns *1.0-2.5*	ns *6.8*		
Pine - Spruce	N/A	ns *2.5-3.0*		
Pine - Maple	N/A	ns *2.5*		
Maple - Pine		ns *1.5-2.0, 5.0-6.5, 9.5*		

Tall vs. Short	**Mud Lake Open bog**	**Mud Lake Treed bog**	**North Cranberry Lake Open bog**	**North Cranberry Lake Treed bog**
Maple - Spruce		ns *2.3-3.0, 6.0-7.0, 9.0-10.0*		
Spruce - Maple		ns *3.5-5.0*		
Maple - Larch		ns *0.5-1.0, 6.5*		
Larch - Maple		ns *0.0-0.5, 8.0-9.0*		

Spatial Aspects of Tree Mortality

Tree mortality rates were low (< 5%) in the open plots. Thus, mortality hypothesis tests were only applied to two treed plots. Dead trees in both treed bogs were mostly clustered at smaller scales and some medium scales in Mud Lake treed plot (Fig. 3-8a, d). The density-dependent mortality hypothesis tested if trees tended to aggregate with dead trees rather than living trees: initial neighborhoods of dead and living trees in the Mud Lake treed plot did not differ except more crowded neighborhoods around dead trees were detected near 5.5 m (Fig. 3-8e); whereas in the North Cranberry Lake treed plot, initial neighborhoods of dead trees were more scattered than those of living trees at medium and larger scales (Fig. 3-8b). As for the difference between initial and final conditions, the Mud Lake treed plot had the same spatial pattern of living trees before and after mortality (Fig. 3-8f); in contrast, the mortality caused spatial pattern of living trees in the North Cranberry Lake treed plot only showed more aggregations at a very fine scale (1.5 m), but then became increasingly uniform (Fig. 3-8c).

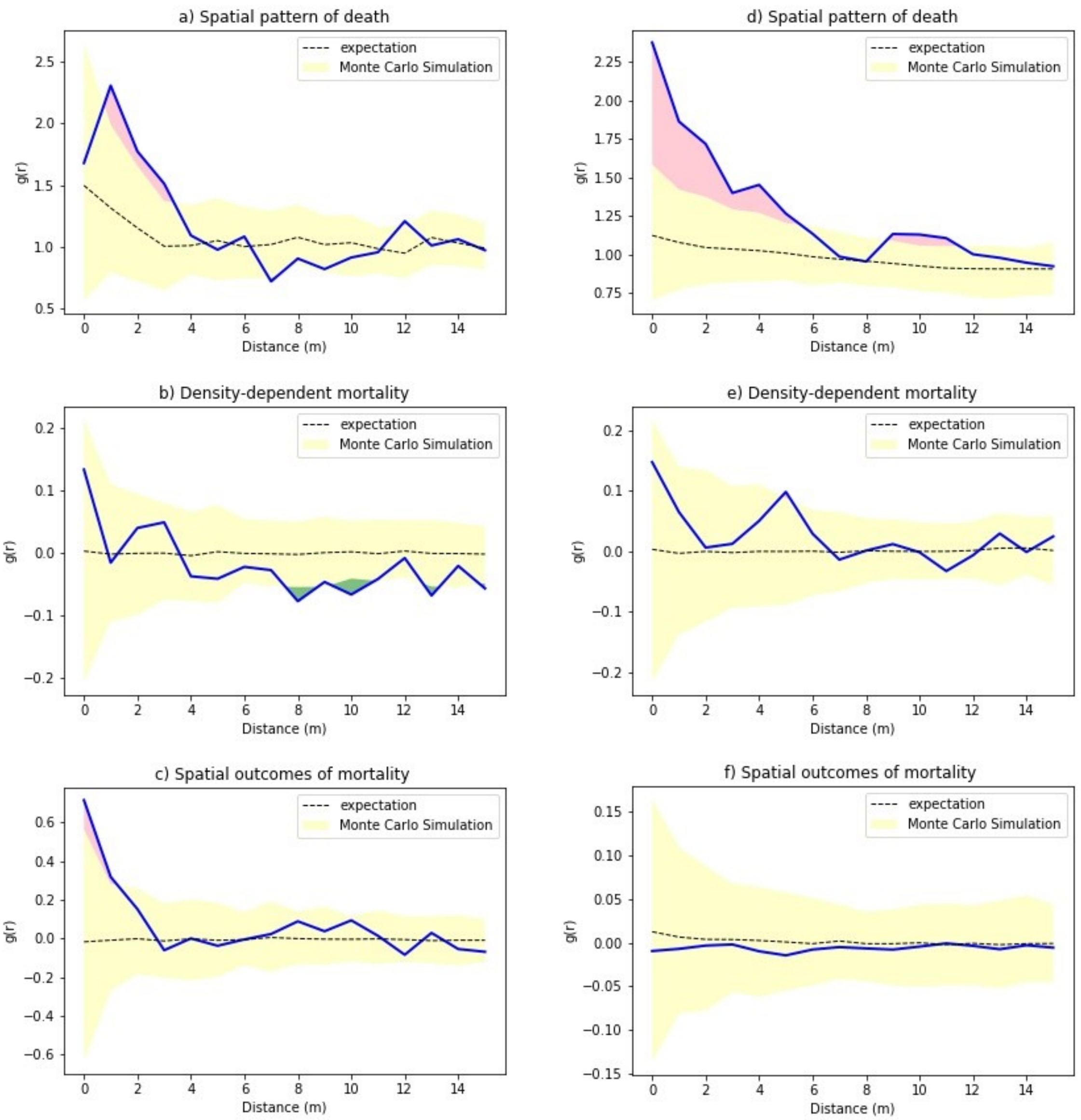

Figure 3-8. Spatial aspects of tree mortality in North Cranberry Lake treed bog (a-c) and Mud Lake treed bog (d-f): spatial pattern of dead trees (a, d); density-dependent mortality: positive (negative) values refer that trees tend to aggregate more with dead (living) individuals (b, e); spatial outcomes of mortality: positive (negative) values indicate that mortality has an aggregation (segregation) effect on all stands (c, f). Only plots with considerable mortality were tested. Values falling into the simulation envelop indicate an insignificant difference.

3.4 Discussion

Both Mud Lake and North Cranberry Lake open plots had relatively larger tree populations but most trees were very small and short. The prevalence of seedlings or saplings in open plots can be seen as a sign of new tree communities becoming established. Compared to the open plots, treed plots had fewer and larger individuals, which used to be early-established seedlings and presumably survived a self-thinning stage. Point pattern analysis results of each plot and different types of trees are summarized below for open and treed bogs (Table 3-5).

Table 3-5. Results summary table

	Open bog	Treed bog
Community structure development	Short trees dominated	Tall trees dominated
	Short trees: clustered at small scales; scattered at large scales	Short trees: same as open bog, but with larger clumps
	Tall trees: randomly distributed & scattered	Tall trees: randomly distributed & clustered
	Tall - short: independent and some dispersions at a few scales	Tall - short: independent
Successional changes	• Each species tended to be clustered at small scales, and random or evenly dispersed at larger scales. • No attractions detected between species. • Differences in patterns between open and treed bogs varied by species and study site.	
Mortality	• Negligible mortality	• Mortality in ML and NCL treed bogs was 5.64% and 12.57%, respectively. • Dead trees clustered at multiple scales but had no influence on tree spatial pattern.

Community structure development

Although trees have are different sensitivities (both in time and ontogenetically) to local biotic and abiotic factors that limit growth (De Fields, 2009), the study of spatial arrangement of trees from open to treed bogs can provide insights into the process of tree encroachment.

Since open plots are still at the beginning stage of encroachment, the spatial pattern of trees in open bogs could help us understand the process of seedling establishment. In open bogs, younger trees were aggregated at small and medium distances but showed clear dispersions at large scales; by contrast, larger trees did not exhibit any significant interactions with each other. Thus, it could be inferred that seedlings tended to settle as clumps at some places but scatter over the rest of the area, but as they grew up, trees became more regularly spaced. The landforms on the bog surface may affect the growth and distribution of plants through hydrology, e.g., hummocks at higher elevation above the water table or puddles of saturated water (Collins & Foster, 2008; Wang, Zhang, & Duan, 2015). Therefore, the seedling settlement pattern might result from the spatial arrangement of favorable microsites (Strand et al., 2007). Hummocks provide a moderate moisture level and better soil conditions so that more seedlings could germinate, resulting in clustering at high clumps of moss; at a larger scale, clumps are scattered because of microtopographic heterogeneity (Weltzin et al., 2001; Kangas et al., 2016). Later, when trees became taller, it is likely that other effects among trees like competition would shape the spatial patterns of older trees over the early microtopography influence (De Fields, 2009). Results further showed that in open areas, there were no spatial associations between younger and older trees, suggesting that neither facilitation nor exclusion process can be found between trees of different ages. Analyses of tall versus short trees analyses between different species in open bogs also produced similar results, which might indicate again that the initial recruitment of trees in a bog is determined more by the availability of favorable establishment conditions, like microtopography, than by intra- or interspecific interactions or competition (Dohn, 2015). Further, comparisons of the scales of aggregation between open and treed bogs suggest that treed areas had more distinct and larger clumps of trees than open areas, implying that treed bogs might have larger or denser hummocks. This is due to the fact that tree-dominated areas have relatively longer history of tree establishment, so trees could interact with and shape the topography (Istanbulluoglu & Bras, 2005). During this process dead trees accumulate and gradually became layers of peat moss that form bigger hummocks, providing more area for establishment availability.

Successional changes

The difference in tree composition is clear between the two study sites: Mud Lake bog had a more diverse tree community compared to North Cranberry Lake bog. White pine and red maple were hardly detected in the two North Cranberry Lake plots, in accordance with the surrounding forest inventory: larch, spruce and other softwoods were the main species in the North Cranberry Lake bog area, whereas other hardwoods like white birch and red maple, oak and white pine also dominated the Mud Lake bog area (Nova Scotia Department of Natural Resources, 2016). Another critical factor that could affect community composition is the soil condition. The Canadian Soil Information Service provides very detailed soil descriptions for each bog (Agriculture and Agri-Food Canada, 2013a, 2013b): Mud Lake bog is imperfectly drained and always has water in the soil whereas North Cranberry Lake bog is well-drained and the water table is only present during the non-growing season. Root growth is more restricted in the soil of Mud Lake bog than North Cranberry Lake bog. These soil differences probably cannot explain the absence of some species in the North Cranberry Lake bog, since white pine and red maple usually grow and compete well on dry and well-drained soil (Nova Scotia Department of Natural Resources, 2018). This suggests that there might be some other reasons affecting tree composition rather than the soil or water table.

Open and treed bogs within each site had similar tree species. However, the relative proportions of the species differed between open and treed plots, for example, pine and larch in Mud Lake bog, and larch and spruce in North Cranberry Lake bog. In Eastern North America, black spruce is a shade tolerant species, whereas larch is very intolerant of shade, pine and red maple have intermediate tolerance to shade and become less tolerant with age (Montague & Givnish, 1996; Government of Ontario, Ministry of Agriculture, 2007; Lienard et al., 2015). Therefore, the decrease in larch and increase in spruce from open to treed area in North Cranberry Lake bog could be ascribed to their different shade tolerance, which has been recognized as an important factor affecting the regeneration mode of a species (Kobe et al., 1995; Muñiz-Castro et al., 2012; Torimaru et al., 2013). As neighboring trees grow taller, trees that are pervasive in the open area might be repressed in the treed area due to limited light; e.g., in Mud Lake bog white pine failed to gain a competitive place in the upper canopy though it grew in the open bog. The spatial pattern of black spruce in North Cranberry Lake bog showed more clusters and less segregation in the treed plot than in the open one, which also followed black spruce shade tolerance feature: as succession progressed in the treed bog, more spruce seemed to be able to establish and develop around older trees, which may be in favorable microsites, regardless of its own shade.

Competition and Mortality

Spatial point pattern analysis has proven useful in testing tree-to-tree competition that affects the development of stand structure, by comparing spatial relationships of individuals and assessing mortality patterns in a community (Getzin et al., 2006; Kenkel, 1988; Martens et al., 1997). In our study, spatial associations in treed bogs between the live and dead trees conveyed a clear pattern of regularity or even scattering, which resulted from intra- or inter-specific competition.

All trees in each plot were aggregated at small scales but over-dispersed on larger scales, except for the North Cranberry Lake treed plot, which showed aggregation at multiple scales. This pattern may be consistent with some previous studies, reporting that small-scale regularity was hard to detect in nature (Kenkel, 1988; He & He, 2000; Gray, 2009b). Competition can be inferred by comparing spatial patterns of short trees and large trees, especially when short trees showed aggregations while large trees tended to be spaced up to each other (Antonovics & Antonovics, 1980). Results in Mud Lake treed plot did suggest extensive competition among individuals: the spatial pattern of large trees was more regular than that of short trees or all trees together; significant segregations were also detected in large- short trees associations, even between different species (Table 3-3). By contrast, North Cranberry Lake treed plot showed different results regarding the influence of competition, exhibiting more aggregations in large trees than short trees and having random associations between large and short trees. However, the spatial pattern and population of larch in Mud Lake bog did not follow the expected pattern from light competition: as a shade-intolerant species, it had a larger population in the treed bog, which was filled by taller trees. Moreover, from open to treed area, more distinct clumps appeared in larch, indicating that they became established in proximity to other larches. This inconsistency suggests that light may not be the determinant factor of stand development in this study site, and some other processes are thus also involved.

Tree mortality was higher in the two treed plots, providing evidence of self-thinning. The North Cranberry Lake treed plot had much higher mortality than other plots and had a considerable number of unhealthy trees that will probably lead to increased mortality in the future. Results in the spatial context analysis of mortality showed that most mortality did not happen in the high population density situation, since initial neighborhoods in the North Cranberry Lake treed plot seemed to be closer to those of living trees instead of dead ones, which was opposite to the expected pattern for density-dependent mortality. It should be noted that in the Mud Lake treed plot, 87.5% of dead trees were larch, which accounted for 42.6% of total trees. Within those dead larch, over 60 % were shorter than 2 m; this non-random mortality in this area could also because of the competition for light.

Implications and future prospects

It was hard to find general trends between the open and treed area of bogs, which might be a matter of sample size, but more importantly, it also suggests that trends might be more site specific rather than specific to the type (open or treed) of bog. Tree populations and species composition differed strongly between Mud Lake and North Cranberry Lake bogs. Mud Lake bog had more trees and more species than North Cranberry Lake bog. Some variations and inconsistencies still appeared in the two study areas: with high mortality and many unhealthy trees, North Cranberry Lake treed bog did not exhibit strong evidence of competition; in Mud Lake treed bog, larch had an unexpected large population and more clumps than expected due to its shade intolerance. However, the two bogs were similar in general when it came to clues about tree establishment, with evidence of microtopography-dependent establishment in both open areas and intra- or inter-specific competition appeared to be the primary process in treed areas. But failing to detect a consistent result in all spatial pattern analyses may suggest that currently the community is experiencing a moderate reducing effect on population, instead of intensive competition (Getzin et al., 2006; Gray, 2009b), or it could also be explained as a short range positive feedback in the immediate vicinity of plants (Dunkerley, 2002; Tongway & Ludwig, 2001). Given the above differences between the two study areas, I would encourage more investigations on effects of soil, microtopography and hydrology, since some differences may be related to soil moisture conditions, which likely cause less/more favorable tree growth conditions.

The invasion of woody shrub species is prevalent in many ecosystems, and in most cases shrubs are considered to directly compete for resources with trees (Schwintzer & Williams, 1974; Van Auken, 2000). The C storage dynamics were also found to be affected by increased shrub cover in bog ecosystems (Chong, Humphreys, & Moore, 2012). I did not analyze the effect of shrubs on tree encroachment since I did not measure shrubs in the field. However, studies focusing on tree-shrub interactions more often demonstrated an independent or positive relationship rather than an antagonistic trend. Positive tree-shrub interactions in the bog seemed to be stronger under warmer and drier conditions. As a result, woody vegetation colonized in boreal bogs (Holmgren et al., 2015). In some other ecosystems like degraded tropical lands and forest-tundra ecotone, shrub density and height neither facilitated nor prevented tree establishment and growth, except for some species or at sapling stages (Duncan & Chapman, 2003; De Fields, 2009).

A lot of studies suggest that hydrological events can affect tree growth in peat bogs by changing water conditions (Talbot et al.,2010; Straková et al., 2012). To clarify interactions between vegetation dynamics and bog development, it will be necessary to look at local hydrology and drainage. In this study, North Cranberry Lake bog was adjacent to a man-made berm (400 m away from the treed plot and 200 m from the open plot), which blocked the natural outflow from the wetland. The park and historical photos recorded that this berm was probably built between 1945 and 1965. This might explain the high mortality of trees in the North Cranberry Lake bog; since water level limits vegetation growth in peatland environments, saturated conditions might cause tree death. The berm was still visible in 1965 and 1976 aerial images and became unclear in 1992 and 2001 images. However, it was completely invisible in the 2010 air photo since it was eventually abandoned (Fig. 3-9).

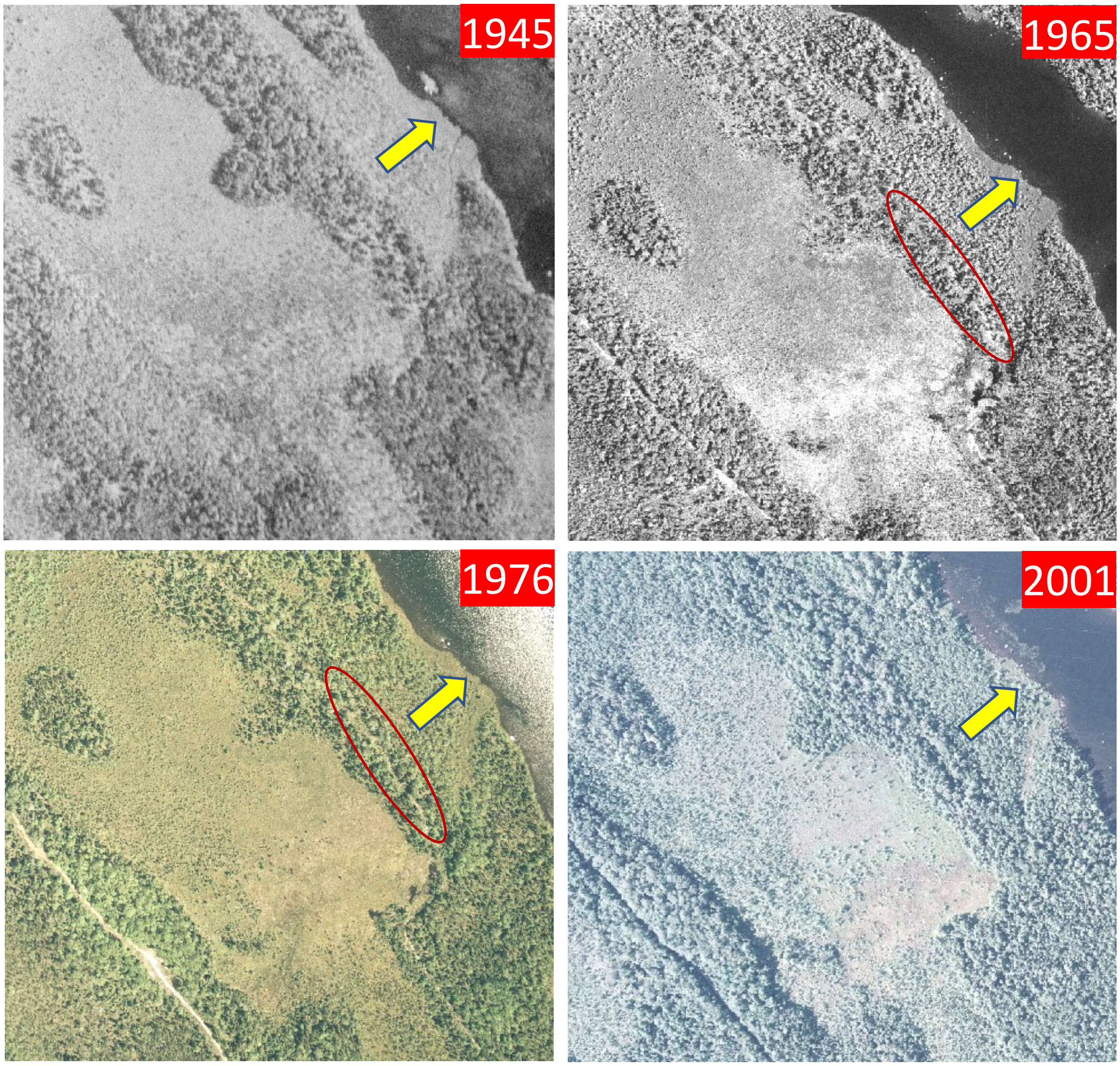

Figure 3-9. Aerial photos of North Cranberry Lake bog in 1945, 1965, 1976 and 2001. The red circle shows the location of this berm. Yellow arrow points out the direction of natural outflow.

Early seedling establishment has been recognized as the most severe bottleneck for tree recruitment in bogs because most germinated seedlings do not survive the seedling stage in bog ecosystems (Ohlson et al., 2001). Taking previous experiments and modeling into consideration, it is reasonable to believe that tree occurrence and dominance in bogs is highly related to local climate warming, like drought events and increased temperature, and depleted soil moisture through increased evapotranspiration rates (Edvardsson et al., 2015; Heijmans et al., 2013; Limpens et al., 2014). Moreover, later stand development would also gradually shape the environment and climate (Istanbulluoglu & Bras, 2005). In this study, the presence of hummocks may explain the presence of trees in the early succession stage because they provide greater support as *Sphagnum* moss accumulates and provide appropriate rooting wetness (Vallier, 2012). Thus, microtopographic variations are highly correlated with the spatial patterns of trees (Benscoter et al., 2018; Weltzin et al., 2001). Comparing spatial patterns of trees in open and treed bogs, treed bogs seem to have larger and denser hummocks that developed from the accumulation of partially decayed vegetation or organic matter (Table 3-2, 3-3 and 3-4). When more trees take over in a open bog, a moss-dominated peat bog may turn into a tree-dominated ecosystem. In this case, either increased evapotranspiration through more leaves or modified bog surface may further lower the water table, drying out the bog.

However, it is also important to state that any interpretations from spatial point pattern analysis cannot be a single or impeccable argument to support conclusions. Bog and forest ecosystems are complex and numerous possible variables have effects on organisms' interactions, resulting in mixed and complicated observed patterns (McIntire & Fajardo, 2009). Therefore, simplifying and understanding individuals or groups by a two-dimensional point pattern might lead to biases and misconceptions. To avoid this problem, research related to seed dispersal is needed, which might be affected by forest edges and wind (Limpens et al., 2014; Vespa et al., 2014).

It is also important to know that there are mutual interactions between vegetation and topography (Boerner et al., 2014), so the modifications of vegetation on the bog physical setting should also be a significant consideration. Except for fundamental biases in analyses, sample size is probably another limitation in this study. These two study areas may not be representative enough to generate tree encroachment trends that are common for most bogs. Thus, a larger sample size or more careful study sites selection is required for future studies.

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Chapter 4 Conclusion

4.1 Key findings

In this thesis I mapped bogs from 1928 to 2017 based on historical aerial photos and current UAV imagery then measured the temporal-spatial changes of land cover over 90 years in two treed bogs in Nova Scotia. I also compared the spatial point patterns of trees in different tree encroachment stages and explored the process of tree encroachment into bogs. Combining two chapters together, this research presents overall tree dynamics in bogs and individual tree relationships. It is challenging to generalize the results in this study into a universal conclusion for all peat bog ecosystems. However, results from both the spatial point pattern analyses and the land cover mapping indicate ongoing encroachment of bogs by trees, but at decelerating rates recently, in two peat bogs in Nova Scotia. Trees first appeared in the outer area around the bog and gradually invaded into the center of bog. This establishment process is likely to be dependent on microtopography and shaped by inter- and intra- specific competition.

Finding 1: Trees have been encroaching in the two peat bogs but there is evidence that encroachment rates are decreasing. Land cover dynamics were evaluated from object-based mapping with historical images: for more than 72 years, there was a significant increase of tree crown area in both studied bogs. Moreover, tree height data revealed that open bogs are composed mainly of short trees (≤ 50 cm), which has been recognized as a feature of growing tree communities. Although there is still a possibility that trees in this area have been established for a very long time and just stopped growing because of nutrient-poor soils. I also calculated the average tree encroachment rates (m^2/year) for each time period. The long-term overall trend was that tree expansion has gradually slowed down over time. This conclusion could also be supported by the spatial point pattern analyses that detected few positive associations between and within species, which were considered as important facilitators in the process of tree colonization in other peat bogs (Holmgren et al., 2015).

Finding 2: During the process of tree encroachment in bogs, many factors could have contributed to successful seedling establishment and tree expansion. Although very little direct evidence was provided many clues in this paper and related literature suggest that topographic heterogeneity of the site could explain the complexity of tree spatial patterning and community structure in bogs. In Chapter 2, the relationship between Canopy Height Models and Digital Elevation Models showed how tree heights varied for different elevations: trees established earlier or grew faster on higher elevation positions. Chapter 3 indicated that well-established treed bogs tended to have larger tree clumps, compared to trees scattered at larger scales in newly-established tree communities. It is reasonable to assume that those tree clumps sit on higher elevation positions like hummocks, where woody plants are most commonly found (Collins, Perino, & Vankat, 1982; Lindsay, Birnie, & Cough, 2014). Since mature treed bogs have been shaped longer by organic debris like dead trees, they are expected to have deeper peat accumulation increasing elevation. However, it seemed that microtopography influenced tree encroachment mostly only at the seedling settlement stage, because I found that when trees grew up taller, small-scale tree clumps seemed to disappear. Meanwhile, higher mortality was observed in the two treed plots. These can be ascribed to intra- or inter-specific competition. To some degree, soil conditions and shade tolerance could also explain the differences in tree composition and tree growth.

Any type of natural or human disturbance would cause variations in the hydrological balance of the bog, like climate (temperature and precipitation) change, blocked drainage and road construction. It is worthy to mention that disturbance may have significant effects on tree community dynamics in peat bogs. This was also one of the reasons that results in this study sometimes varied between and within sites. In this study, North Cranberry Lake bog seemed to be affected by blocked drainage from a man-made berm, resulting in two opposite tree dynamic patterns in the same bog.

Finding 3: This study has also shown the potential of integrating spatial statistics and remote sensing technology in monitoring forested wetlands. The tree sampling data analyzed by spatial point pattern analyses helped me understand why trees were established and how they distributed in bogs. Univariate and bivariate individuals' associations arose in response to ecological processes, such as habitat heterogeneity and competition for nutrients and light. Additionally, this research also explored UAV implementation in land cover changes detection: it created true orthophotos of two bogs and built a tree height model from image derived point clouds. Object detection and wetland mapping provided a feasible and efficient way to present detailed bog land cover changes in a time series. Both accuracy of UAV imagery generation and aerial imagery processing were evaluated at a reasonable level, though ground truth control points could be added to improve the performance. Errors of digital imagery classification mainly came from the existence of shadow, implying that a considerate flight plan regarding shooting time, weather of day and shooting angle would be necessary to obtain flawless drone photos, as well as shadow removal techniques.

4.2 Implications

While this research has yielded clear and strong results, there are some issues and challenges, which should be addressed in future research. Temperature and moisture changes in bogs are thought to be the most important driver of increasing trees in bogs (Edvardsson et al., 2015; Hájková et al., 2011; Heijmans et al., 2008; Holmgren et al., 2015). But instead of relating tree dynamics and historical climatic conditions directly, I only compared their trends roughly and failed to find any significant results. Thus, future researchers should continue to look at their relationship in more details. Some results differed between the two studied bogs, suggesting that tree encroachment patterns depended on some site- or time-specific factors that influenced local sensitivity. For a more universal conclusion, future studies should determine what local factors make the difference and explore a better way to explore such differences between study sites. It would be interesting to see how ground control points could improve the UAV imagery generation and modeling, since they were not applied in this research.

Bog ecosystems provide valuable habitats for many organisms and significant ecosystem services to society, particularly the provision of drinking water purification and climate regulation. This study shows that increased tree encroachment has occurred in some bogs of Nova Scotia, so it is reasonable to be concerned about the consequences of tree encroachment in bogs, which has been shown to reduce the trophic level of some eukaryotic microbe communities lower in bog ecosystem primary production (Payne et al., 2016). Shifts from a moss-dominated bog ecosystem to one with a greater woody component can also alter the surface soil temperature, moisture, and light availability (Chong et al., 2012). Some empirical studies provided evidence that bog surface vegetation patterning dynamics might be highly linked with carbon sequestration in peat bogs: more dry-adapted plant communities might reduce carbon-sequestration rates (Loisel & Yu, 2013).

Unfortunately, neither the role of peat bogs in the supply of ecosystem services nor the influence of peat bogs shrinking has been widely appreciated. Widespread bog damage across the world may be caused by a number of factors including land use change, pollution, and increasingly, the adverse impacts of climate change (Gumbricht et al., 2017). The good news is that some regions have realized the priority of peat bogs for action, like some community projects promoting less carbon-intensive agriculture and planting native plants in degraded peatlands to retain water in Indonesia (PT Rimba Makmur Utama, 2018), as well as the famous peatland conservation and restoration project led by International Union for Conservation of Nature in the UK (International Union for Conservation of Nature, 2018). The main purpose of this study is to state the current status of some peat bogs in Nova Scotia, then appeal for public attention. Peat bogs are vulnerable and valuable ecosystems that deserve more concern and consideration from scientists, land use planners, miners and park managers, making significant contributions towards biodiversity, tackling climate change and other international obligations.

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Appendix A. Confusion matrix for the OBIA classification results (Mud Lake bog)

Prod.Acc (%) and User. Acc (%) represent producer's accuracy and user's producer, respectively; KIA is The Kappa index of agreement. (m^2)

Mud Lake 1945	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	377	29	0	406	92.86%
Shadow	18	141	94	253	55.73%
Tree crown	93	282	373	748	49.87%
Sum	488	452	467		
Prod. Acc (%)	77.25%	31.19%	79.87%	*Overall Accuracy*	*63.33%*
KIA Per Class	68.03%	16.11%	57.02%	*KIA*	*44.91%*

Mud Lake 1962	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1944	0	301	2245	86.59%
Shadow	0	793	0	793	100.00%
Tree crown	500	0	901	1401	64.31%
Sum	2444	793	1202		
Prod. Acc (%)	79.54%	100.00%	74.96%	*Overall Accuracy*	*81.96%*
KIA Per Class	58.61%	100.00%	63.41%	*KIA*	*70.13%*

Mud Lake 1971	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1742	0	0	1742	100.00%
Shadow	0	1281	25	1306	98.09%
Tree crown	194	199	1278	1671	76.48%
Sum	1936	1480	1303		
Prod. Acc (%)	89.98%	86.55%	98.08%	*Overall Accuracy*	91.14%
KIA Per Class	84.12%	81.41%	97.03%	*KIA*	86.66%

Mud Lake 1976	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1984	0	441	2425	81.81%
Shadow	0	1468	93	1561	94.04%
Tree crown	509	0	1071	1580	67.78%
Sum	2493	1468	1605		
Prod. Acc (%)	79.58%	100.00%	66.73%	*Overall Accuracy*	81.26%
KIA Per Class	63.82%	100.00%	53.54%	*KIA*	71.13%

Mud Lake 1986	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1141	472	139	1752	65.13%
Shadow	0	833	0	833	100.00%

Tree crown	64	104	851	1019	83.51%
Sum	1205	1409	990		
Prod. Acc (%)	94.69%	59.12%	85.96%	*Overall Accuracy*	78.39%
KIA Per Class	89.66%	46.83%	80.42%	*KIA*	67.71%

Mud Lake 1992	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1899	0	388	2287	83.03%
Shadow	0	1695	31	1726	98.20%
Tree crown	521	0	1593	2114	75.35%
Sum	2420	1707	2012		
Prod. Acc (%)	78.47%	99.30%	79.17%	*Overall Accuracy*	84.49%
KIA Per Class	65.69%	99.02%	68.24%	*KIA*	76.58%

Mud Lake 2001	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	608	0	24	632	96.20%
Shadow	0	506	21	527	96.02%
Tree crown	69	13	285	367	77.66%
Sum	677	519	330		
Prod. Acc (%)	89.81%	97.50%	86.36%	*Overall Accuracy*	91.68%
KIA Per Class	82.60%	96.17%	82.05%	*KIA*	87.13%

Mud Lake 2010	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	661	0	166	827	79.93%
Shadow	0	1142	0	1142	100.00%
Tree crown	124	0	752	876	85.84%
Sum	785	1142	918		
Prod. Acc (%)	84.20%	100.00%	81.92%	*Overall Accuracy*	89.81%
KIA Per Class	77.73%	100.00%	73.87%	*KIA*	84.54%

Mud Lake 2011	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1902	0	371	2273	83.68%
Shadow	0	1897	0	1897	100.00%
Tree crown	507	0	1388	1895	73.25%
Sum	2409	1897	1759		
Prod. Acc (%)	78.95%	100.00%	78.91%	*Overall Accuracy*	85.52%
KIA Per Class	66.34%	100.00%	69.32%	*KIA*	78.16%

Mud Lake 2017	Bog land	Shadow	Tree crown	Sum	User. Acc (%)
Bog land	1907	0	0	1907	100.00%

Shadow	580	1450	215	2245	64.59%
Tree crown	169	530	979	1678	58.34%
Sum	2656	1980	1194		
Prod. Acc (%)	71.80%	73.23%	81.99%	*Overall Accuracy*	74.37%
KIA Per Class	58.09%	56.47%	74.72%	*KIA*	61.25%

Appendix B. Confusion matrix for the OBIA classification results (North Cranberry Lake bog)

Prod.Acc (%) and User. Acc (%) represent producer's accuracy and user’s producer, respectively; KIA is The Kappa index of agreement. (m^2)

North Cranberry Lake 1928	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	394	177	0	571	69.00%
Tree crown	0	195	187	382	51.05%
Shadow	51	0	131	182	71.98%
Sum	445	372	318		
Prod. Acc (%)	88.54%	52.42%	41.19%	*Overall Accuracy*	63.44%
KIA Per Class	76.94%	28.28%	29.96%	*KIA*	43.53%

North Cranberry Lake 1945	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	2539	331	310	3180	79.84%
Tree crown	111	1179	143	1433	82.27%
Shadow	0	0	1127	1127	100.00%
Sum	2650	1510	1580		
Prod. Acc (%)	95.81%	78.08%	71.33%	*Overall Accuracy*	84.41%
KIA Per Class	90.61%	70.79%	64.32%	*KIA*	75.03%

North Cranberry Lake 1965	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	1492	73	131	1696	87.97%
Tree crown	199	966	0	1165	82.92%
Shadow	0	0	1230	1230	100.00%
Sum	1691	1039	1361		
Prod. Acc (%)	88.23%	92.97%	90.37%	*Overall Accuracy*	90.15%
KIA Per Class	79.90%	90.18%	86.24%	*KIA*	84.99%

North Cranberry Lake 1976	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	2300	204	0	2504	91.85%
Tree crown	201	1234	0	1435	85.99%
Shadow	0	0	1339	1339	100.00%
Sum	2501	1438	1339		
Prod. Acc (%)	91.96%	85.81%	100.00%	*Overall Accuracy*	92.33%
KIA Per Class	84.71%	80.52%	100.00%	*KIA*	87.95%

North Cranberry Lake 1986	Bog land	Tree crown	Shadow	Sum	User. Acc (%)

Bog land	1022	246	0	1268	80.60%
Tree crown	196	921	0	1117	82.45%
Shadow	0	0	1398	1398	100.00%
Sum	1218	1167	1398		
Prod. Acc (%)	83.91%	78.92%	100.00%	*Overall Accuracy*	88.32%
KIA Per Class	75.79%	70.09%	100.00%	*KIA*	82.42%

North Cranberry Lake 1992	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	3240	150	0	3390	95.58%
Tree crown	427	1851	817	3095	59.81%
Shadow	0	160	2238	2398	93.33%
Sum	3667	2161	3055		
Prod. Acc (%)	88.36%	85.65%	73.26%	*Overall Accuracy*	82.51%
KIA Per Class	81.17%	77.98%	63.37%	*KIA*	73.69%

North Cranberry Lake 2001	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	2936	0	185	3121	94.07%
Tree crown	93	1250	93	1436	87.05%
Shadow	0	123	1107	1230	90.00%
Sum	3029	1373	1385		
Prod. Acc (%)	96.93%	91.04%	79.93%	*Overall Accuracy*	91.46%
KIA Per Class	93.34%	88.08%	74.51%	*KIA*	85.96%

North Cranberry Lake 2010	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	1921	178	0	2099	91.52%
Tree crown	415	945	0	1360	69.49%
Shadow	0	54	2820	2874	98.12%
Sum	2336	1177	2820		
Prod. Acc (%)	82.23%	80.29%	100.00%	*Overall Accuracy*	89.78%
KIA Per Class	73.43%	74.90%	100.00%	*KIA*	83.93%

North Cranberry Lake 2011	Bog land	Tree crown	Shadow	Sum	User. Acc (%)
Bog land	1988	157	0	2145	92.68%
Tree crown	535	1538	254	2327	66.09%
Shadow	0	0	2179	2179	100.00%
Sum	2523	1695	2433		
Prod. Acc (%)	78.80%	90.74%	89.56%	*Overall Accuracy*	85.78%
KIA Per Class	68.70%	85.75%	84.47%	*KIA*	78.73%

North Cranberry Lake 2017	Bog land	Tree crown	Shadow	Sum	User. Acc (%)

Bog land	2292	98	0	2390	95.90%
Tree crown	1067	1887	9	2963	63.69%
Shadow	0	0	1427	1427	100.00%
Sum	3359	1985	1436		
Prod. Acc (%)	68.23%	95.06%	99.37%	*Overall Accuracy*	82.68%
KIA Per Class	50.94%	91.23%	99.21%	*KIA*	73.48%

Appendix C. Measurement of DBH (diameter at breast height) in the four plots.

DBH was defined as the tree diameter measured at 1.37 m (4.5 ft) above ground on the uphill side of the tree and was only measured for trees taller than 2.0 m. In this study, dbh records only served as supplementary information and were not used for data analysis. The number of trees larger than 5.0 cm and the total number of trees are given in the brackets.

Tree coordinates (x, y)/m		Height/m	dbh/cm	Species
		Mud Lake open bog (1/1878)		
0.91	28.41	3.50	5.2	larch
		Mud Lake treed bog (95/1133)		
1.68	1.46	4.80	10.5	larch
10.33	1.31	7.70	16.4	larch
12.94	0.60	5.20	8.1	spruce
15.40	0.43	5.30	6.8	maple
17.00	1.04	5.20	6.7	larch
17.27	1.65	4.90	6.0	larch
29.10	1.10	1.70	8.5	spruce
23.75	3.29	4.40	6.7	maple
12.89	4.34	4.20	7.2	spruce
18.31	4.06	5.00	5.3	larch
19.46	5.05	5.50	6.5	maple
19.55	4.82	3.10	8.3	maple
1.80	7.05	4.50	5.3	spruce
6.29	7.16	5.10	6.4	larch
6.99	7.72	4.00	5.5	larch
15.82	7.62	11.50	10.8	larch
26.18	7.73	7.60	5.0	larch
27.30	7.85	6.70	8.6	larch
29.89	7.00	7.00	11.2	larch
14.45	8.59	6.30	10.2	pine
20.90	9.28	5.30	7.9	spruce
22.00	8.20	5.80	8.5	spruce
9.73	10.22	6.50	7.5	larch
11.75	10.12	6.50	10.3	spruce
11.92	10.94	5.50	5.5	maple
13.40	10.48	4.80	5.0	birch
14.47	11.90	6.80	12.9	pine
16.52	10.88	5.80	6.3	larch
19.80	10.87	4.60	5.0	larch

21.39	10.54	4.30	6.8	spruce
23.20	11.05	6.80	8.6	spruce
25.70	11.38	6.80	8.8	spruce
29.51	10.16	4.70	5.8	spruce
4.00	14.00	6.30	7.5	larch
5.75	13.20	7.20	16.1	pine
8.20	14.00	5.10	7.3	spruce
10.49	13.36	3.40	5.3	pine
11.04	12.61	2.86	6.6	larch
13.72	12.49	5.40	6.2	larch
22.65	12.54	4.60	5.5	birch
23.47	12.12	5.20	5.8	maple
23.64	13.17	7.50	11.9	pine
4.92	15.89	4.70	7.6	spruce
9.02	14.50	6.80	7.7	larch
10.27	15.30	4.10	6.4	pine
10.40	14.15	5.20	7.0	spruce
12.98	15.46	7.50	8.5	larch
13.98	14.32	5.90	7.9	spruce
19.47	15.42	3.50	5.1	pine
20.97	15.09	6.00	7.6	larch
22.39	15.08	4.70	5.0	birch
27.14	15.43	3.70	5.0	larch
28.62	14.42	3.70	5.0	maple
29.43	15.03	7.50	11.8	larch
29.76	15.37	5.70	8.9	maple
6.30	16.60	6.70	7.3	larch
6.61	16.26	4.00	5.6	pine
15.63	17.10	6.20	9.1	larch
19.45	17.20	4.70	5.3	maple
2.66	18.59	4.40	7.9	spruce
4.59	19.52	3.80	5.0	larch
5.90	18.80	6.10	7.5	spruce
11.02	19.80	7.90	9.2	larch
15.27	18.65	5.30	6.6	larch
1.92	20.98	5.30	5.8	larch
3.60	22.00	4.80	5.4	spruce
4.77	21.39	5.00	7.6	pine
12.57	21.90	7.60	11.4	pine
12.60	20.79	7.50	7.3	maple
21.87	20.65	3.70	6.8	spruce
24.23	21.13	5.00	5.4	spruce
6.97	23.27	6.30	10.2	pine

9.05	22.13	7.10	6.8	larch
3.59	24.52	5.20	5.9	birch
5.66	24.51	4.30	5.0	pine
7.82	25.21	6.60	8.0	larch
10.00	25.82	3.70	5.4	spruce
11.21	24.00	6.60	9.1	larch
20.80	25.50	3.60	5.5	larch
23.82	24.46	4.30	6.2	pine
27.55	25.56	5.90	7.7	larch
28.37	24.14	7.80	9.7	spruce
0.04	26.10	3.30	5.9	pine
2.72	27.02	4.20	7.6	pine
7.38	26.11	4.50	7.3	larch
9.94	26.58	4.50	7.7	pine
13.70	27.93	5.50	5.0	maple
27.74	26.70	9.70	11.9	larch
4.00	29.07	7.50	9.0	larch
8.07	28.05	6.40	5.2	larch
8.75	29.59	5.70	6.8	maple
11.55	30.00	6.00	5.4	larch
14.22	28.31	12.00	13.4	larch
16.11	28.14	4.40	5.5	spruce
18.39	29.89	4.00	5.1	spruce

North Cranberry Lake open bog (3/986)

18.00	4.40	6.30	12.6	Larch
23.25	11.86	3.70	7.0	Larch
13.88	13.03	5.00	6.5	Spruce

North Cranberry Lake treed bog (141/510)

3.70	2.00	5.00	6.8	spruce
14.57	1.55	5.20	6.4	spruce
15.00	1.32	5.50	7.1	spruce
16.88	1.53	7.10	9.6	spruce
22.29	1.51	6.40	9.0	spruce
22.48	0.82	6.70	9.7	spruce
3.27	2.68	5.30	8.2	spruce
3.71	2.11	4.60	7.3	spruce
4.68	2.87	4.00	5.2	larch
6.02	3.78	4.10	5.5	spruce
8.61	2.80	7.20	9.8	spruce
11.32	3.17	5.30	7.8	larch
12.00	3.57	5.00	6.0	spruce
11.92	2.70	5.40	7.5	spruce
14.84	3.17	5.40	7.8	larch

15.97	3.62	5.50	7.8	spruce
18.23	3.92	3.10	6.5	larch
19.82	3.32	3.00	5.2	spruce
20.00	3.19	3.10	5.2	spruce
23.24	2.15	4.50	6.5	spruce
27.60	3.30	4.80	6.5	spruce
0.14	5.86	5.10	6.3	spruce
4.30	4.54	4.20	5.3	spruce
8.74	5.30	5.00	7.6	spruce
9.18	5.35	4.60	5.8	spruce
11.89	5.31	1.42	8.4	spruce
13.08	4.27	6.00	8.0	spruce
14.35	4.51	5.50	5.9	spruce
14.83	5.25	6.00	7.7	spruce
27.61	5.19	6.20	9.2	spruce
0.15	7.11	5.00	7.5	spruce
1.92	7.28	4.80	8.7	spruce
5.57	7.75	2.39	8.4	spruce
6.97	7.94	4.20	6.4	larch
7.36	7.15	5.80	7.8	spruce
12.03	7.77	7.80	9.3	spruce
22.30	7.40	5.50	7.3	spruce
24.65	6.97	8.00	9.2	spruce
26.42	7.79	5.40	6.9	spruce
27.50	7.46	5.80	8.4	spruce
4.20	8.06	4.20	6.2	spruce
4.64	8.77	5.00	6.9	spruce
4.73	10.00	6.40	8.8	spruce
6.99	8.09	4.40	5.9	larch
10.05	8.11	4.10	6.8	larch
11.42	9.10	3.90	5.9	spruce
14.00	8.77	4.30	5.8	spruce
15.96	9.28	4.20	5.3	spruce
15.90	9.23	5.50	6.3	spruce
18.00	9.56	5.50	6.8	spruce
18.50	9.50	7.80	9.6	spruce
22.26	9.11	4.60	5.9	larch
25.30	8.31	7.20	6.9	spruce
25.70	8.90	3.00	6.4	spruce
29.03	8.34	4.90	6.5	larch
29.66	9.11	6.50	10.0	spruce
10.36	12.00	5.40	6.5	spruce
16.98	11.55	5.90	7.5	spruce

20.97	11.38	5.10	6.8	spruce
27.07	10.50	5.50	7.6	spruce
28.90	10.28	6.00	10.5	spruce
2.36	12.57	4.10	6.8	larch
11.53	13.06	4.40	5.8	larch
13.36	12.83	4.60	5.8	spruce
15.52	12.17	6.20	7.5	spruce
16.61	13.67	5.00	6.0	spruce
17.07	13.73	5.80	6.9	spruce
19.45	12.29	4.60	7.7	spruce
18.87	14.00	5.90	9.0	spruce
20.00	12.25	4.60	7.2	spruce
22.29	12.78	6.30	8.7	spruce
23.84	13.50	4.20	5.8	spruce
24.00	13.18	4.40	5.1	spruce
24.93	12.72	5.60	8.1	spruce
2.73	14.42	1.82	5.8	snag
3.55	15.50	4.40	7.0	spruce
3.80	15.83	6.10	8.5	spruce
7.25	16.00	4.90	7.2	spruce
12.70	15.05	5.30	8.0	spruce
15.11	15.06	4.80	5.5	spruce
15.40	14.87	5.90	7.5	spruce
16.49	14.80	4.60	5.2	spruce
16.34	15.31	5.30	8.7	spruce
18.26	14.84	3.40	5.9	spruce
19.05	15.56	5.70	7.5	spruce
19.19	15.85	7.80	10.3	spruce
22.05	14.21	6.20	7.5	spruce
26.47	15.20	6.20	7.8	spruce
27.28	15.45	6.00	6.8	spruce
27.77	14.77	6.40	6.4	spruce
28.18	14.74	5.00	5.0	spruce
12.32	16.18	4.00	6.7	spruce
20.53	17.10	6.50	10.8	spruce
25.65	16.58	4.30	6.1	spruce
26.70	16.44	6.20	6.7	spruce
27.81	17.73	4.20	6.4	spruce
1.93	18.43	3.60	6.8	spruce
3.17	19.75	3.70	5.5	spruce
7.05	19.91	5.40	7.8	spruce
8.69	19.09	4.40	5.8	spruce
15.48	18.25	4.40	6.2	spruce

17.51	18.40	4.50	5.4	spruce
17.84	18.50	7.00	12.2	spruce
17.40	19.13	3.80	5.7	spruce
18.00	19.22	4.00	5.7	spruce
21.00	19.46	5.80	9.6	spruce
2.68	21.90	6.20	9.2	spruce
4.40	20.34	5.80	7.2	spruce
9.27	21.91	5.40	6.6	spruce
12.57	21.95	4.10	6.5	larch
16.05	21.51	3.00	6.0	larch
17.20	21.24	5.00	6.6	spruce
21.00	21.14	6.20	6.0	spruce
27.34	21.64	7.20	9.8	spruce
28.43	20.36	4.90	5.8	spruce
4.69	22.84	4.90	7.1	spruce
6.42	23.38	4.70	7.2	spruce
12.74	22.44	6.00	6.9	spruce
15.13	22.57	4.60	5.2	spruce
22.01	22.63	4.80	6.5	spruce
24.88	23.19	6.10	8.3	spruce
0.79	25.28	3.30	5.7	spruce
1.11	24.15	3.30	6.7	larch
10.33	24.62	5.00	6.9	spruce
11.30	24.52	4.80	8.0	spruce
12.43	24.58	6.20	8.9	spruce
14.97	25.70	5.20	8.5	spruce
15.53	25.73	5.40	7.8	spruce
19.45	24.15	5.30	8.4	spruce
28.99	24.71	5.40	6.8	spruce
2.10	28.00	5.00	7.7	spruce
14.95	27.57	5.20	7.5	larch
0.68	29.06	4.80	6.8	spruce
1.80	29.83	4.00	6.0	spruce
4.90	29.51	3.80	5.5	spruce
6.14	28.40	3.20	7.0	larch
9.51	29.78	5.70	8.2	spruce
12.43	29.80	4.20	6.0	spruce
23.01	28.07	5.00	5.9	spruce
27.10	29.86	5.40	8.4	spruce
29.65	29.53	5.00	6.4	spruce