Analyzing the impacts of road construction on the development of a poor fen in Northeastern Alberta, Canada

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Linear disturbances such as powerline rights of way, seismic lines and roads are common in areas of intensive resource development. Roads that bisect wetlands can alter their hydrologic connectivity on a local or landscape scale. These impacts were studied in a poor fen located 45 km south of Fort McMurray, Alberta, where a raised road was built across the northern fringe of the fen in 1977. Examination of the fen's response to this impoundment provided insight into post-disturbance vegetation succession patterns and peatland development. The objectives of this study were to map the spatial and temporal extent of hydrological disturbance from road construction, to quantify the response of peatland vegetation to this disturbance and to determine the successional pathway of the system.

The study site is an 8 ha poor fen situated on Stoney Mountain (~740 masl), about 45 km south of Fort McMurray in the Athabasca oil sands region of northeastern Alberta. The dominant groundcover of the fen is *Sphagnum* moss, with Ericaceae shrubs and *Picea mariana* (black spruce) also abundant. Construction of the raised road began in 1977, and the fen now drains through a culvert built under the road in the northwest corner. Complete tree dieback occurred within 220 m up-gradient of the road.

Tree rings were used as a proxy for hydrological change, because depth to water table is the main limiting factor for growth in peatland trees. Forty-two living and dead black spruce trees in the peatland were sampled and used for analysis, and 18 in the surrounding upland hillslopes. Dead trees were cross-dated using a combination of the list method and skeleton plots, and verified with COFECHA. Tree ring chronologies were built in R, and correlation coefficients between climate and ring width index (RWI) values for each chronology were calculated in Dendroclim2002. Water table was measured weekly at three groundwater wells and bulk density of the peat was calculated at several locations across the fen. In sixteen 50 m^2 (25x2 m) transects, recent moss growth was calculated by measuring the depth to the root crown of black spruce trees. Tree density and the age of saplings were also measured in these transects. Vegetation cover, along with several abiotic variables was measured in 279 1 m^2 plots. Vegetation was analyzed in the statistics program R using Non-metric Multidimensional Scaling and Ward's Minimum Variance cluster analysis.

The upland tree chronology had less ring width variability than the peatland tree chronologies, and the peatland RWI had a stronger relationship with climate than the upland

RWI. After road construction, there is a positive relationship with temperature in the year of growth for living and dead trees, and a mixed response to precipitation especially in June and July. Most of the trees within 220 m up-gradient of the road died in 1989, and these are all located within an elevation of 83.5 cm relative to the culvert top. Temporal uniformity of dieback suggests a single flooding event in 1988 or 1989 that drowned these trees, and the relationship with elevation above the culvert suggests that its blockage caused the flooding. The impact of flooding from culvert blockage on fen tree cover underlines the importance of natural drainage patterns in controlling vegetation composition and peatland type.

High bulk density values below the surface and loose *Sphagnum* moss carpets contribute to low storativity close to the culvert in the most disturbed area of the fen, as evidenced by rapid flooding and drying. The abundance of saplings decreases towards the culvert. The average depth of recent moss growth was greater immediately up-gradient of the road (37.6 cm) compared with undisturbed areas (15.5 cm). Analysis of vegetation using non-metric multidimensional scaling reveals dominance of non-hummock forming species closest to the culvert. These data suggests that periodic blockage of the culvert leads to flooding in the immediate area that encourages non-hummock forming species of sedge and moss, making an unfavourable environment for black spruce germination. This cycle of hydrologic disturbance may be preventing some areas of the fen from regaining the original vegetation structure, with implications for the system's development.

Both tree growth and vegetation structure continue to be impacted by past flooding events caused indirectly by road construction, and directly by inadequate drainage through the culvert. Maintaining a natural hydrologic regime is integral to maintaining the function of a peatland. This research has implications for peatland construction projects in the Athabasca oil sands, and the design and maintenance of linear features in this region and nationally.

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1.0 Introduction

Canada is crossed by networks of linear disturbances, especially in areas of intensive resource extraction. These features, which include roads, seismic lines, pipelines and powerline rights-of-way, fragment the boreal landscape and disrupt natural biological and hydrological processes (Lee & Boutin, 2006; Turetsky & St. Louis, 2006; Dubé et al., 2011; Williams et al., 2013). Linear features create edges that deplete interior habitat, and open the remaining land to greater light infiltration, changes in temperature, predation of sensitive interior species by edge-tolerant species, increased exposure to wind, dust and debris, and invasion of exotic species (Findlay & Bourdages, 2000; James & Stuart-Smith, 2000; Laurance, 2000; Laurance et al., 2007; Dubé et al., 2011). Roads are common vectors of invasive plants especially in nutrient poor environments, because they are often constructed from materials that are more alkaline than the local soil (Jodoin et al., 2008). Road run-off increases pH and available nutrients, and benefits invasive over endemic species that are adapted to more nutrient poor conditions (Johnston & Johnston, 2004; Müllerová et al., 2011).

Some roads bisect wetlands, and alter the hydrologic regime on a local or landscape scale, in addition to the introduction of invasive species (Dubé et al., 2011; Nielsen et al., 2012). Road construction across a wetland requires a mineral soil roadbed to be built and raised above the ground surface. One or more culverts are typically placed on the former ground surface to allow water to flow beneath the road (Graf, 2009). If placed at an elevation that is too high, water pools above the road, raising water levels for some distance up-gradient and the channelized water may lower the water table below the road. Culverts are easily blocked with sediment, whether from the natural flow of matter through the system or from beavers. If the culvert is the only drainage output of the system, flooding occurs if it is blocked.

In the western boreal plains (WBP) of Alberta, peat-accumulating wetlands cover 30% of the land area (Vitt & Chee, 1990; Vitt et al., 1996). In Canada, a peatland is classified as a wetland with at least 40 cm of organic soil (National Wetlands Working Group, 1997). Peatlands are divided by vegetation type and hydrology into ombrotrophic bogs and minerotrophic fens. Bogs receive all of their water input from precipitation, and fens receive at least part of their water input from groundwater (National Wetlands Working Group, 1997). Groundwater has a higher pH and nutrient content than precipitation because of its exposure to minerals in the soil, so fens are less acidic and often have greater species diversity (Rydin & Jeglum, 2006). As peat accumulates in fens and the depth of the unsaturated zone increases, the surface is cut off from groundwater inputs and the system can transition into an ombrotrophic bog (Belyea & Baird, 2006). Peatlands typically follow a successional pathway from rich fen, to poor fen, to bog, as the surface becomes more removed from the groundwater (c.f. Zobel, 1988). This process is controlled by both autogenic (internal) and allogenic (external) factors. An example of an allogenic factor is the growth of *Sphagnum* moss; it acidifies its environment and contributes to a thicker peat layer through slow decomposition rates (Granath et al., 2010). Examples of allogenic, or external factors include climate change, drainage for forestry or agriculture and flooding from impoundment. These events can increase, or even reverse peatland succession, because they cause a rapid change in the hydrologic regime.

Hydrologic regime determines vegetation composition, peatland type and its development (Zoltai & Vitt, 1995; Asada et al., 2005; Rydin & Jeglum, 2006; Granath et al., 2010). Natural poor fens are characterized by shallow water tables that are highest during spring melt, with little seasonal variation (Rydin & Jeglum, 2006). Water table depth and variance (Asada, 2002; Rochefort et al., 2002; Kowalski & Wilcox, 2003; Pellerin et al., 2009; Talbot et al., 2010), water chemistry (Andersen et al., 2011), hummock/hollow microtopography (Peach & Zedler, 2006; Økland et al., 2008) and light availability (Pouliot et al., 2011) are important indicators of vegetation diversity and composition. Vegetation is simultaneously influenced by all of these variables to some degree (Eppinga et al., 2009; Kapfer et al., 2011). An allogenic impact such as flooding changes the water chemistry and encourages non-hummock forming species of *Sphagnum* and sedge. These vegetation changes push the system onto a new successional trajectory.

Hydrological change, such as flooding, can be reconstructed in treed peatlands using tree rings as a proxy for annual differences in water table. Tree rings are useful proxies for environmental change when one variable is limiting to growth. In peatlands, where trees are generally stunted and slow-growing due to oxygen deficient root zones, depth to water table is the biggest limiting factor for growth (Lieffers & Rothwell, 1987; Linderholm et al., 2002; Moir et al., 2011). During a year of low water tables, tree growth in peatlands may increase, as tree roots have access to a larger unsaturated zone (Dang & Lieffers, 1989). Flooded conditions reduce soil aeration, substrate temperature and nutrient availability (MacDonald & Yin, 1999).

Peatland trees including black spruce (*Picea mariana*) and tamarack (*Larix laricina*) can develop shallow or adventitious roots that access the aerobic zone, but if this layer is inundated at a rate that exceeds root growth, tree death can occur (Schwintzer, 1978; Reddoch & Reddoch, 2005; Rydin & Jeglum, 2006; Calvo-Polanco et al., 2012). Therefore, it can be assumed that a wide growth ring indicates low water tables in the peatland, a thin ring indicates high water tables, and tree death indicates prolonged flooded conditions (Gunnarson, 1999). Peatland trees are not sensitive to short term climate fluctuations (Webb et al., 1993), but will react quickly to water table changes (Linderholm, 1999). This makes them a useful proxy in reconstructing hydrological change in impacted peatlands (Wilmking & Myers-Smith, 2008; Cedro & Lamentowicz, 2011).

1.1 Objectives

A byproduct of the intensive resource extraction industry in the oilsands region of northeastern Alberta is a dense network of pipelines, seismic lines and roads, connecting features such as steam-assisted gravity drainage oil recovery systems. Some research has been done in peatlands in this region on the impact of linear disturbances on vegetation (Lee & Boutin, 2006; Wood, 2007; Miller, 2011) and large fauna (James & Stuart-Smith, 2000; Dunne & Quinn, 2009), but little is known about how the hydrological changes from these disturbances impact peatland development. In addition, peatland trees are rarely used to reconstruct hydrological change, and have never been used in dendrohydrological analyses in northern Albertan peatlands.

The impacts of a raised road on the hydrology and development of a fen peatland were studied at a site in northeastern Alberta. The objectives of this study are as follows:

1. Use tree ring analysis to reconstruct the spatial and temporal patterns of hydrological change in the peatland;
2. Compare upland versus peatland growth patterns and determine the impact of topography on the limits to tree growth;
3. Evaluate how the relationship between climate and peatland tree growth changed after road construction, and how this illustrates changes in the peatland environment;
4. Compare how changes in hydrology from road construction have impacted tree growth, microtopography and vegetation;

5. Characterize vegetation changes along the existing hydrologic gradient and the role of the road in creating these gradients;
6. Determine the role of disturbance in influencing peatland development.

1.2 General Approach

This thesis consists of two separate but related manuscripts on the impacts of road construction on the hydrology and vegetation of a poor fen in northeastern Alberta. I was primarily responsible for the design, implementation and execution of field and laboratory work, and the writing of both manuscripts. The first manuscript (*Using tree ring analysis to reconstruct water table change in a disturbed peatland*) uses dendrochronological methods to determine the temporal and spatial patterns of black spruce dieback in the peatland, and the relationship between dieback and road construction. A single interval correlation analysis was used to compare the relationships between climate variables and ring width indices of the peatland trees before and after road construction. The objective of this manuscript is to reconstruct the hydrological changes that occurred after road construction.

The second manuscript is entitled: *How hydrological changes from road construction impact the vegetation succession and development of a poor fen*. The objective of this manuscript is to determine the impact of the hydrological changes, as outlined in manuscript one, on the vegetation composition and successional trajectory of the peatland. Vegetation percent cover and several abiotic variables were collected throughout the study site, and analyzed using multivariate and cluster analyses to determine how communities are ordered along hydrologic gradients in relation to the road. These data, along with sapling regeneration rates, depths of recent moss growth and hummock measurements, were used to determine the successional trajectory of the system. Together, these manuscripts present a multi-proxy approach to analyze how linear disturbances impact the hydrology of fen peatlands, and how these hydrologic changes affect vegetation and peatland development. As roads and other linear disturbances are common features in the oil sands region of northeastern Alberta, the results of this research will help the industry quantify, and perhaps mitigate, the impacts of this support infrastructure on the surrounding boreal landscape. This study presents data from one road-impacted site, but there are several studies that have produced similar results in regards to vegetative and hydrologic changes in fens after road construction (e.g. Jeglum, 1975; Schwintzer, 1978; Umeda et al., 1985; Wood, 2007; Miller, 2011)

2.0 Manuscript 1: Using tree ring analysis to reconstruct water table change in a disturbed peatland

2.1 Abstract

Linear disturbances such as powerline rights of way, seismic lines and roads are common in areas of intensive resource development. When they cross peatlands, they can interrupt natural hydrologic regimes and often cause flooding on the up-gradient side and water table drawdown on the down-gradient side. Tree rings can be used as a proxy for hydrological change, because depth to water table is the main limiting factor for growth in peatland trees. Tree rings were used to reconstruct hydrological change after a road was built in 1977 across a poor fen in northeastern Alberta. The study fen is 8 ha and is located approximately 45 km south of Fort McMurray. Complete tree dieback occurred within 220 m up-gradient of the road. Forty-two living and dead black spruce trees in the peatland were sampled and used for analysis, and 18 in the surrounding upland hillslopes. Dead trees were cross-dated using a combination of the list method and skeleton plots, and verified with COFECHA. Tree ring chronologies were built in R, and correlation coefficients between climate and ring width index (RWI) values for each chronology were calculated in Dendroclim2002. The upland tree chronology had less ring width variability than the peatland tree chronologies, and the peatland RWI had a stronger relationship with climate than the upland RWI. Before road construction, both living and dead peatland RWI were consistently negatively correlated with temperature and precipitation. After road construction, there is a positive relationship with temperature in the year of growth for living and dead trees, and a mixed response to precipitation especially in June and July. Most of the trees within 220 m up-gradient of the road died in 1989, and these are all located within an elevation of 83.5 cm relative to the culvert top. Temporal uniformity of dieback suggests a single flooding event in 1988 or 1989 that drowned these trees, and the relationship with elevation above the culvert suggests that its blockage caused the flooding. The impact of flooding from culvert blockage on fen tree cover underlines the importance of natural drainage patterns in controlling vegetation composition and peatland type.

2.2 Introduction

Linear disturbances such as seismic lines, roads, pipelines and powerline rights-of-way are common features in regions where there is intensive resource extraction (Lee & Boutin, 2006). These linear features fragment the landscape and alter local vegetation and hydrologic regimes, especially in wetland environments (Williams et al., 2013). Alteration of the hydrologic regime may change site water table depth and dynamics, which may be reflected in tree growth evident in their annual ring width patterns (Dang & Lieffers, 1989; Freléchoux et al., 2000; Linderholm, 2002; Cedro & Lamentowicz, 2011). Examining the response of a wetland's biota to hydrologic alterations caused by roads can provide insight into the processes of vegetation change and peatland development.

Roads, ranging from highways to small tracks, create edges that deplete interior habitat, and open the remaining land to greater light infiltration, changes in temperature, predation of sensitive interior species by edge-tolerant species, increased exposure to wind, dust and debris from roadsides, and invasion of exotic species (Findlay & Bourdages, 2000; James & Stuart-Smith, 2000; Laurance, 2000; Laurance et al., 2007; Dubé et al., 2011). Some roads bisect wetlands and alter the water source and hydrologic connectivity to downstream areas on a local or landscape scale (Nielsen et al., 2012). There is a dense network of unpaved roads in northeastern Alberta; Turetsky and St. Louis (2006) found over 230 gravel roads in their 6000 km^2 study area. Road-building techniques have improved in the last several decades, and more permeable road base materials are used, or multiple culverts are built to help maintain a more natural hydrologic regime (Graf, 2009).

In the western boreal plains of Alberta, peat-accumulating wetlands cover 30% of the land area (Vitt & Chee, 1990; Vitt et al., 1996). Road construction across a peatland requires a mineral soil roadbed to be built and raised above the peat surface. One or more culverts are typically placed on the former ground surface to allow water to flow beneath the road. If placed at an elevation that is too high, water pools above the road, raising water levels for some distance up-gradient and the channelized water may lower the water table below the road. Depth to the water table is a critical environmental variable influencing plant species composition (Andersen et al., 2011; Kapfer et al., 2011), peatland type (Asada, 2002; Pellerin et al., 2009) and tree growth (Lieffers & Rothwell, 1986; Cedro & Lamentowicz, 2011). In addition, mineral rich run-off from the road surface into a peatland can alter local ion concentrations and change vegetation composition, especially in acidic peatlands such as poor fens (Wood, 2007). A water level increase up-gradient of roads can cause tree death in forested peatlands. Increased water levels create poor growing conditions by reducing soil aeration, substrate temperature and nutrient availability (MacDonald & Yin, 1999). Peatland trees including black spruce (*Picea mariana*) and tamarack (*Larix laricina*) can develop shallow or adventitious roots that access the aerobic zone, but if this layer is inundated at a rate that exceeds root growth, tree death can occur (Schwintzer, 1978; Reddoch & Reddoch, 2005; Rydin & Jeglum, 2006; Calvo-Polanco et al., 2012).

Dendrochronology uses tree rings as a proxy for changes in environmental variables through time (Fritts, 1976). Tree rings are useful indicators of change when one variable is limiting tree growth. For example, in arid regions, precipitation may limit tree growth, whereas in cold regions, temperature during the growing season is critical (e.g. Stokes & Smiley, 1968). Several studies have used tree rings as proxies for hydrological variables such as groundwater levels (Ferguson & St. George, 2003; Perez-Valdivia & Sauchyn, 2011), lake levels (Bégin, 1999; Meko, 2006) or streamflow (Case & MacDonald, 2003). In peatlands, where trees are generally stunted and slow-growing due to oxygen deficient root zones, depth to water table is the biggest limiting factor for growth (Lieffers & Rothwell, 1987; Linderholm et al., 2002; Moir et al., 2011). In impacted peatlands the water table may be artificially altered, and tree ring analysis can be used to identify the year when changes occurred, and the effects of these changes on tree growth (Cedro & Lamentowicz, 2011).

Previous research has shown that peatland trees are not ideal for dendroclimatic analysis, but could be well suited for dendrohydrology that uses tree rings to reconstruct changes in hydrologic regimes (Fritts, 1976; Watson & Luckman, 2006; Cedro & Lamentowicz, 2008). Undisturbed bogs have been used to reconstruct historical precipitation patterns, because they are ombrotrophic, and changes in water levels, and tree growth are determined primarily by precipitation (Linderholm, 1999). However, this relationship becomes less important if the bog is disturbed, or in minerotrophic peatlands (fens) (Cedro & Lamentowicz, 2011). This is because tree growth is correlated more strongly with water levels than with climate variables. If water levels change due to a disturbance, such as drainage, a beaver dam or flooding, then tree growth will change regardless of the climate (Wilmking & Myers-Smith, 2008). Climate conditions that typically limit growth, such as drought, will not impact peatland trees as strongly, where water availability remains high in the root zone (Pepin et al., 2002). During droughts, tree growth in peatlands may increase, as tree roots have access to a larger unsaturated zone (Dang & Lieffers, 1989). Peatland trees are not sensitive to short term climate fluctuations (Webb et al., 1993), making it difficult to cross-date using nearby upland chronologies that are more climate-limited. However, peatland trees will react quickly to water table changes (Linderholm, 1999). High water table limits tree growth in peatlands (Lieffers & Rothwell, 1986), and wide growth rings should represent years with low water tables, narrow growth rings years with high water tables, and tree death long-duration flooded conditions. Using these assumptions, the changes in water table after road construction can be analyzed.

This research analyzes the spatial and temporal patterns of water level change in a road-impacted peatland in northeastern Alberta. This is regionally important because of the dense network of roads through peatlands accessing steam-assisted gravity drainage oil recovery systems in the oil sands region (Dunne & Quinn, 2009). Using the principles and techniques of dendrohydrology tree rings were used as a proxy for water table changes in the study fen. This study has three primary objectives: (i) Use tree ring analysis to reconstruct the spatial and temporal patterns of hydrological change in the peatland; (ii) Compare upland versus peatland growth patterns and determine the impact of topography on the limits to tree growth; iii) Evaluate how the relationship between climate and peatland tree growth changed after road construction, and how this illustrates changes in the peatland environment.

2.3 Site Description

The study site is an 8 ha poor fen located on a local topographic high (Stony Mountain, ~740 masl), 45 km south of Fort McMurray, Alberta (56°22'30''N, 111°14'05''W) (Fig. 2-1). The region has an average annual temperature of 1°C, and receives on average 437 mm of precipitation annually (Environment Canada, 2014; www.climate.weather.gc.ca). During the period of data collection at the fen (2011-2014), precipitation was higher, and temperatures cooler than the averages for data collected by Environment Canada at the Fort McMurray airport (Table 1). The fen is located in a basin, has a maximum peat depth of 11 m, a median peat depth of 160 cm, and the groundwater has an average pH of ~4.5. The dominant ground cover is *Sphagnum* moss, primarily *S. angustifolium, S. capillifolium* and *S. magellanicum*. The ericaceae shrubs *Chamaedaphne calyculata, Rhododendron groenlandicum, Vaccinium vitis-idaea* and

Andromeda polifolia, as well as *Carex aquatilis* and *Eriophorum spp., Smilacina trifolia* and *Equisetum spp.* are abundant. Tree cover is discontinuous and dominated by stunted *Picea mariana* and some *Larix laricina*, with densities in the treed areas ranging from 0.16 to 2.3 trees/m^2. More than 80% of trees within 220 m up-gradient of the road are standing dead. The hill slopes are underlain by glacial till. The understory vegetation in the uplands is dominated by feather moss, the shrubs *R. groenlandicum* and *V. myrtilloides*, as well as *Cornus canadensis* and *Lycopodium spp*. There is a dense tree cover composed primarily of *Populus tremuloides*, *Picea mariana* and *Pinus banksiana*.

Construction of Range Road 90A began in 1977 to access a communications tower built at the end of the road. A single culvert 92 cm in diameter was installed under the road on the west side of the fen. A year-round pool of standing water occurs up-gradient of the culvert in a depression likely excavated during construction. The vegetation down-gradient of the road follows a hydrological and topographic gradient from dry in the east, with a dense cover of *R. groenlandicum*, *Chamaedaphne calyculata* and *Rubus chamaemorus* on the shrub level, with *S. angustifolium* the dominant ground cover, and some dense stands of *P.mariana* in the margin, to low and wet near the culvert in the west with increasing cover of *Carex aquatilis, C. canescens* and *B. pumila*. A small area immediately down-stream of the culvert opening is flooded during the spring melt, and colonized by *Typha latifolia*. The fen drains through the culvert and towards the northwest. During wet periods, the outflow is visible as a stream that continues out of the fen and down Stony Mountain.

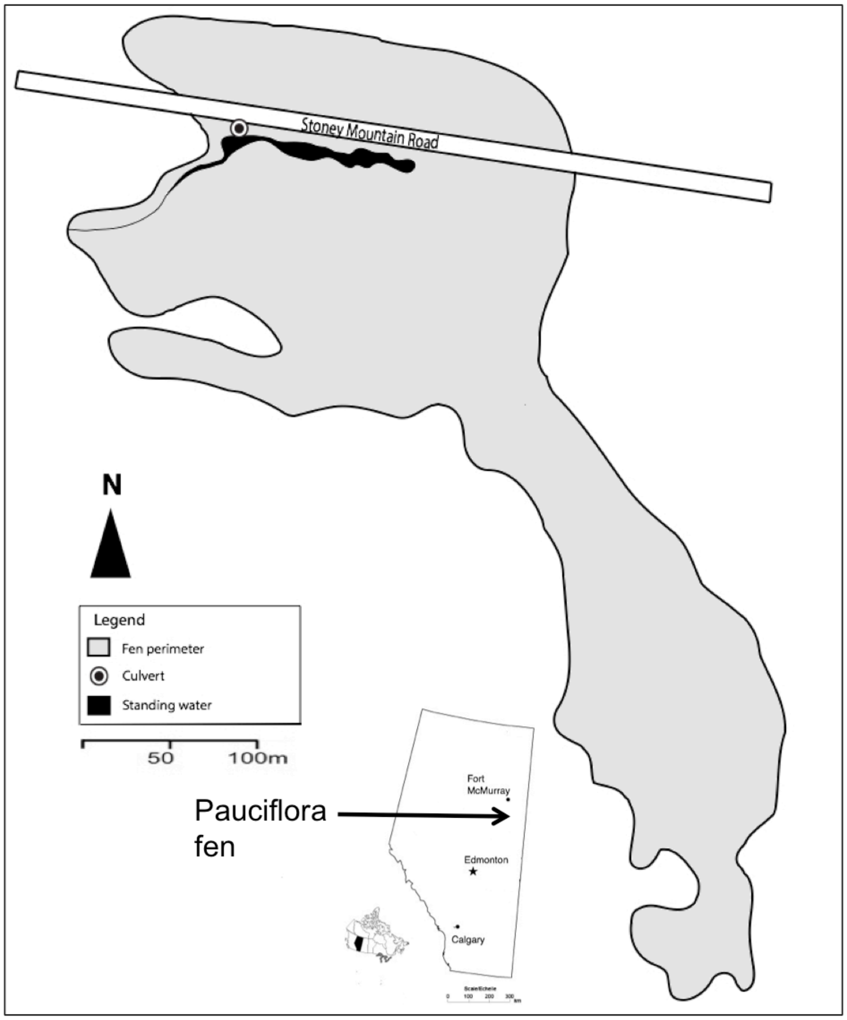

Figure 2-1: Map of the study site, with surface water as of Summer 2013, and Stony Mountain Road.

2.4 Methods

Field and Lab Methods

Living and dead black spruce trees were sampled in the peatland and upland, both up- and down-gradient of the road. In both areas, trees growing on flat ground were selected to minimize compression wood caused by slope. When a conifer tilts, usually from sloping ground, compression wood is formed from thick walled tracheid cells on the down-slope side, to 'push' the tree upright. Where possible, isolated trees were chosen to avoid growth impacts from surrounding trees, and taller trees, thought to be older, were targeted to get longer growth increment records and increase the length of the chronology. In the upland, trees were sampled using a 4.3 mm diameter increment borer. Two radii were taken from each tree from opposite sides, perpendicular to the hillslope, approximately 1.3 m above the ground (Stokes & Smiley, 1968). At each tree, the sample number, species, GPS coordinates, height (measured using a clinometer), diameter at base and breast height, and understory vegetation were recorded (Speer, 2010).

Trees in the peatland were cut down with a chainsaw to collect a full cross section for analysis, and because tree diameter was too small for the increment borer. At each tree, the sample number, species, GPS coordinates, height, diameter at base, mortality, general physical characteristics, depth to water table at the nearest groundwater well, substrate type and understory vegetation were noted (Speer, 2010). Forty-three trees were sampled in the upland from the surrounding east, west and north slopes, and 52 trees in the peatland, including 32 dead and 20 living trees. During sample analysis, several samples were discarded due to rot. Eighteen upland trees and 42 peatland trees, 23 of which were dead and 19 living, were used in the analysis.

After a period of air-drying, the discs were dried in an oven at 105°C for 24 hours. The cores were glued onto wooden mounts. The discs were sanded on a belt sander and finished with progressively finer-grade sand paper, up to 600-grit. The polished samples were digitally scanned at 1200-4800 dpi.

Chronology Development

The samples were cross-dated visually using a combination of skeleton plots and the list method (Stokes & Smiley, 1968; Yamaguchi, 1991). Skeleton plots were made on 5:1 cm graphing paper, where each square represented a single annual growth ring. Annual rings are marked by the difference in colour and cell density between latewood, which is made of thick-walled tracheid cells produced toward the end of a growing season, and the following year's earlywood, which is made of thin-walled cells that are lighter in colour (Stokes & Smiley, 1968). Vertical lines on the skeleton plot mark thinner than average rings, with the longest lines representing the thinnest rings. After a skeleton plot was made for each sample, a single master plot was created for the site, by averaging the lines across all samples for each year. Once a master was built from the living trees, the dead trees were cross-dated by matching patterns of marker years (long lines) against the master plot. The list method was also used, as it is faster and more efficient when fewer marker years are present. This involves listing the years that appear to be marker years, either because of particularly thin latewood or thin ring width. After a list of marker years is made for each sample, a master list was made of the most common marker years. The dead trees' growth increments were then lined up against this list to determine their year of death. During cross dating, it was established that there were no missing or double rings in the series, which are uncommon in black spruce compared with other species (Wilmking & Myers-Smith, 2008).

All ring widths were measured on a computer using the program CooRecorder. This program creates a ring width file for the program CDendro (Cybis Elektronic, 2013). From these ring width files, CDendro creates chronologies with built-in options for standardization and normalization. Cross dating was checked using COFECHA, a DOS program that provides statistical quality control for an initial cross dating effort by correlating each core against the master chronology (Holmes, 1983; Grissino-Mayers, 2001). COFECHA was also used to calculate mean sensitivity and series intercorrelation values of the chronologies. Mean sensitivity is a unitless measure of the complacency or sensitivity of a series, ranging from 0 (every ring is the same width) to 1 (every ring is different). A value of 0.2 is ideal for dendroclimatology analysis (Speer, 2010). Series intercorrelation (r) is the average correlation of every tree series against the master chronology.

Two master chronologies were built based on topography: "Peatland living" and "upland". Once cross-dated, a third chronology was created for the dead trees entitled "Peatland dead". These chronologies were created using the Dendrochronology Program Library in R (dplR) (Bunn, 2008; R Core Team, 2013), which detrends ring widths using a modified negative exponential curve to remove some of the confounding effects of tree age from the growth curve. The dplR calculates both the standardized and the residual ring width indices when creating chronologies. The latter removes autocorrelation, so the former was chosen for this analysis so that potentially important climate data relating to previous years' growth would not be removed (Wettstein et al., 2011). The Expressed Population Signal (EPS), which measures the common variability in a chronology, was calculated in R for each year of the chronologies. It is calculated as follows: $EPS_t = \frac{t*r_{bt}}{t*r_{bt}+(1-r_{bt})}$, where t is the number of tree series and r_{bt} is the mean between-tree correlation (Speer, 2010). Generally an EPS >0.85 is acceptable; below that, the chronology is more likely to be dominated by individual tree patterns, rather than a stand signal (Wigley et al., 1984; Cook & Kairiukstis, 1990).

To examine the individual tree-level response to hydrologic change, the raw ring widths of the dead trees were plotted individually, and grouped based on location in the fen. These groups were determined based on differences in current hydrology, vegetation and percentage of dead trees.

Statistical Analysis

The precipitation and temperature data for the period 1944-2007 for Fort McMurray airport, 60 km from the study site, were accessed from Environment Canada (www.climate.weather.gc.ca). Meteorological data were collected at Pauciflora fen from Summer 2011-14 with a HOBO data logging rain gauge and temperature probes. The available data were regressed against the airport data, to compare the two data sets and test that the latter presents an accurate picture of the study site climate.

Correlation coefficients between climate variables and tree growth were computed using the program DENDROCLIM2002 (Biondi & Waikul, 2004). This program, which was designed for dendroclimatology analyses, calculates either single or moving interval correlation and response function coefficients, and improves upon the accuracy of previously used programs by using bootstrapping to estimate the standard error of the coefficients. Single interval correlation functions were used to determine the seasonality of the relationship between climate and tree growth. The single interval refers to the entire period of the instrumental climate data set (1944-2007). The program calculates correlation coefficients between annual RWI values and monthly climate variables, and averages them together for one value per month for the entire interval. Since climate conditions in the year prior to growth can impact tree productivity the following year, climate data from January of the previous year through to October of the current year were used. This analysis was repeated for the upland, Peatland living and Peatland dead tree chronologies. To isolate the impact of the road on the peatland trees, the data were split into two periods (1946-1977 and 1974-2006) and a single interval analysis was performed on each.

2.5 Results

Climate data

The relationships between average daily temperatures recorded at the study site and the airport are strong (2012: r^2 = 0.96; 2013: r^2 = 0.98), with average temperatures at Pauciflora being lower by 0.47 °C (Table 1). Pauciflora received a total of 348 mm more precipitation than the airport in the summer months of 2012 - 2014, and the relationship between the two data sets of daily values is moderate (2012: r^2=0.68; 2014: r^2=0.69) (Table 1). Unfortunately, the airport data set is the nearest long-term meteorological data set, and it is likely that extremes in temperature or precipitation were regional rather than site specific. The average annual regional precipitation from 1945-2007 was 437 mm. The driest year was 1998, with 242 mm, and the wettest 1973 with 675 mm. The average annual temperature was 0.3°C, the warmest year was 1987 at 3.2°C, and the coldest was 1951 at -2.7°C.

Table 2-1: Comparison of climate data between the Fort McMurray airport (collected by Environment Canada) and the meteorological station at the study site during periods of data collection.

Climate variable	Year	Period	Airport	Pauciflora
Total Precipitation (mm)	2012	Apr 3 – Sep 18	342.2	533
	2013	Apr 15 – May 18	14.2	31.2
	2014	Mar 31 – Oct 6	325	459.5
Average Temperature (°C)	2011	May 30 – Dec 31	7.1	6.38
	2012	Jan 1 – May 5	-5.53	-5.55
	2012	Jul 2 – Dec 31	3.72	2.22
	2013	Jan 1 – Aug 22	3.17	1.86
	2013	Oct 16 – Dec 31	-13.02	-12.46

Analysis of tree measurements

Peatland black spruce trees were older than the upland trees, averaging 93 vs. 75 years. The oldest sampled tree had at least 216 rings, and germinated around 1779, but the innermost rings were lost to rot. Peatland trees average 6.6 m tall with an average basal diameter of 11 cm while upland trees average 14.4 m tall and 23 cm in basal diameter. The percent dead trees was highest near the culvert with 100% mortality within 220 m, and > 50% mortality within 260 m up-gradient of the culvert. At distances exceeding 290 m, tree mortality was reduced to nearly 0% (see Chapter 3). Down-gradient of the road, tree mortality rates decreased eastward, away from the culvert.

Marker years

Trees were cross-dated visually using marker years that were more apparent in peatland than upland trees, suggesting that peatland trees were more sensitive to variations in climate and local environmental conditions. The most common marker year was a thin ring at 1949 that appeared after a year of low precipitation (262 mm). Another marker year was 1982 that was narrow and also had very thin latewood, likely because it was a colder year than average, with an average temperature of -1.6°C (Fig. 2-2).

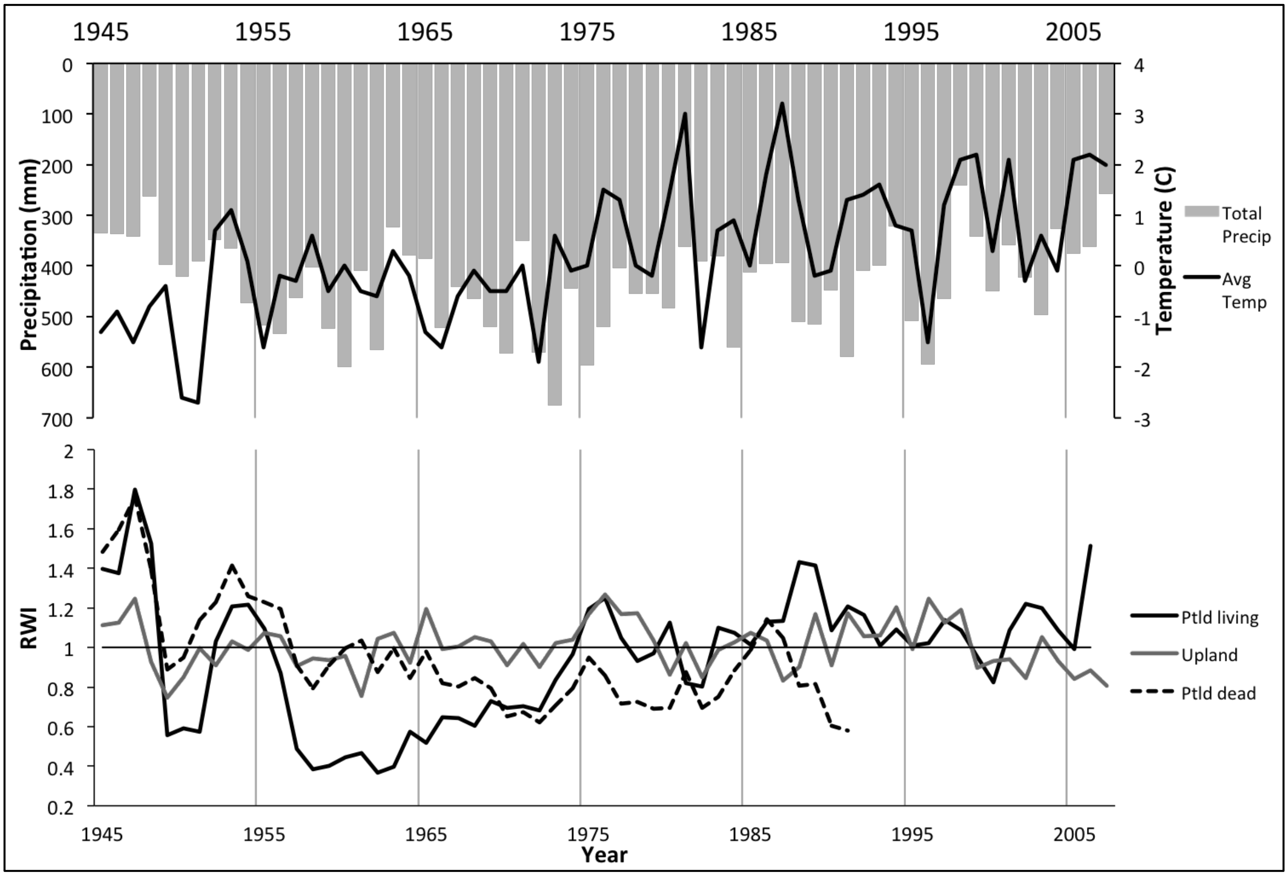

Figure 2-2: Climate data from Fort McMurray airport (A); Standardized ring width indices from the study site (B); Peatland living represents the trees sampled in the peatland that were alive; Upland represents the trees sampled in the surrounding upland hillslopes; Peatland dead represents the trees sampled in the peatland that were dead.

Tree ring chronologies

Both the Peatland living and dead chronologies include trees from up- and down-gradient of the road. Each chronology was truncated to accommodate the available climate data from 1945-2007, and maintain acceptable EPS scores (>0.85) (Table 2).

The upland chronology is complacent and has little ring width variability compared with the peatland chronologies, and does not deviate far from a RWI value of 1.0 despite changes in climate (Fig. 2-2). The peatland chronologies are more sensitive, with lengthy departures from the mean. The flat peaks in both peatland chronologies suggest a strong autocorrelation between years, where climate conditions impact growth for multiple consecutive years. The Peatland dead tree chronology mirrored the Peatland living tree chronology at first, although only the living chronology exhibits a pronounced drop in growth rates during the late 1950s to early 1960s. After 1975, growth rates in the Peatland dead chronology are the lowest of the three, which corresponds with road construction and presumably the beginning of tree stress in the peatland (Fig. 2-2).

Table 2-1: Chronology statistics. EPS values calculated in R, mean ring width, mean sensitivity (unit-less value) and inter-series correlation are outputs of COFECHA.

Site	Mean length of series	Total Period	Length (years)	# Trees	EPS Cutoff year (EPS>0.85)	Mean ring width (mm)	Mean Sensitivity	Interseries Correlation (*r*)
Upland	77	1912-2013	102	18	1924	1.07	0.188	0.519
Peatland Living	86	1890-2013	124	19	1909	0.66	0.244	0.4
Peatland Dead	99	1779-2008	230	23	1911	0.51	0.224	0.323

Relationship between climate and RWI of Peatland and Upland trees: 1945-2006

Correlation coefficients were calculated between a given years' ring-width and the monthly value of the climate variable from January of the year preceding growth to October of the year of growth. Peatland living and upland tree growth were compared to understand the effect of topography and soil type on the relationship between RWI and climate. The longest possible time span (1945-2006) was used to increase the accuracy of the analysis.

Temperature

The Peatland living trees have a stronger relationship with temperature than the upland trees, and their growth is significantly positively correlated (previous December: r=0.26; current January: r=0.37) with early winter temperatures of the current year, and current mid-summer temperatures (July: r=0.24) (Fig. 2-3). This means peatland trees had greater radial growth when winters were mild, and mid-summer temperatures were high. Upland growth is less temperature-limited, but there is a significant negative relationship with November temperatures from the previous year (r=-0.20). This suggests that the upland trees had greater radial growth when temperatures were lower in the late fall.

Precipitation

As with temperature, the correlation between peatland living tree growth and total annual precipitation is stronger than between upland tree growth and precipitation, and the two chronologies display different responses. In the peatland population, a significant negative relationship exists between ring width and precipitation from the previous fall, particularly September (r=-0.26) and December (r=-0.32), and precipitation of the current August (r=-0.25). This suggests that these trees benefited from less precipitation in the fall and late summer. In the upland population, there is a significant positive relationship with precipitation from the previous summer, particularly June (r=0.33) and August (r=0.30), suggesting that tree growth rates increased when precipitation was high, or decreased when precipitation was low during these months (Fig. 2-3).

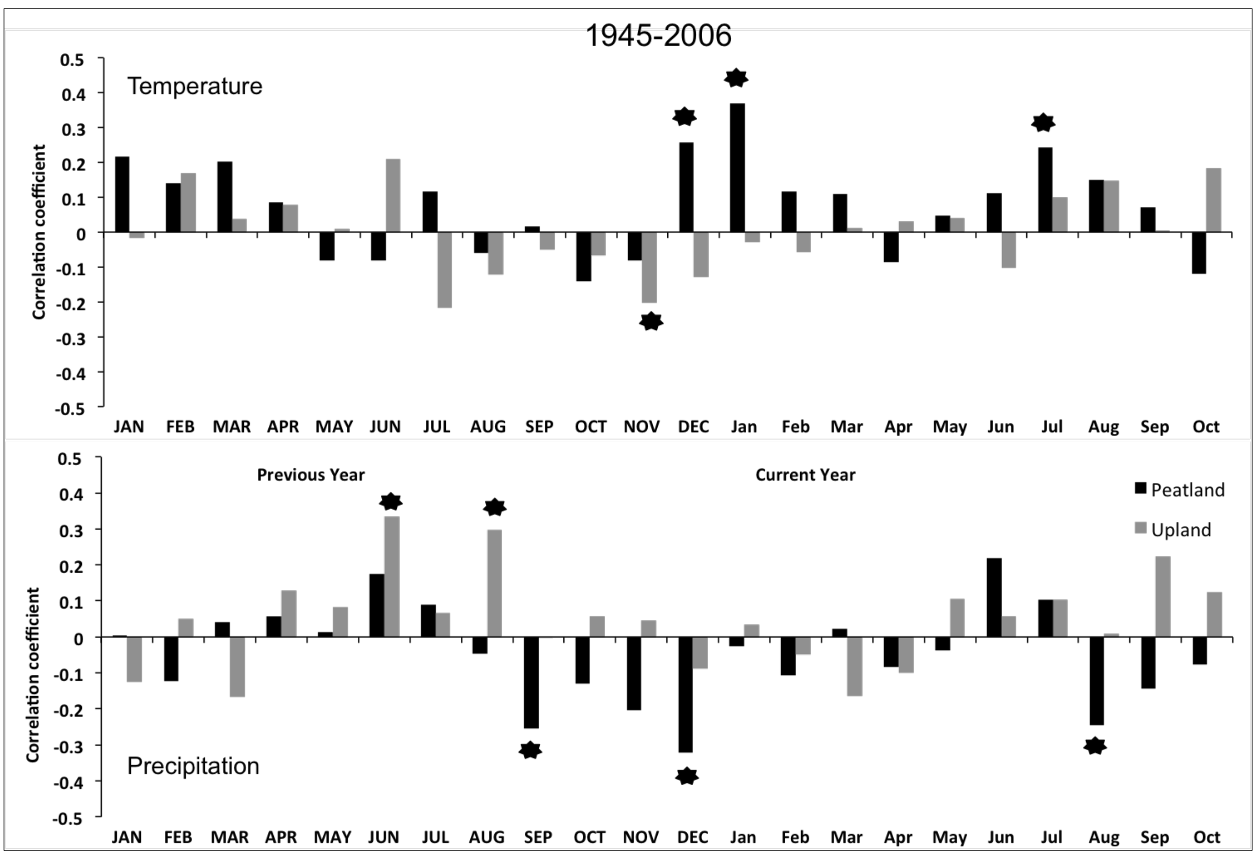

Figure 2-3: Single interval correlation values between temperature (top), precipitation (bottom) and standardized ring width indices for upland and Peatland living trees, for the period 1945-2006. Black stars indicate significant values (p<0.05).

Relationship between climate variables and RWI of Peatland dead and Peatland living trees: Pre-Road (1945-1977)

The relationships between temperature and precipitation were compared between living and dead peatland tree RWI before and after road construction began in 1977.

Temperature

Before road construction (Fig. 2-4), both chronologies had similar relationships with climate variables. A strong negative correlation exists between late spring and summer temperatures indicating that during this time, the peatland population experienced greater ring growth associated with cool temperatures, and vice-versa. This is contrary to the relationship found during a longer time slice (1945-2006, Fig. 2-3), where the sampled peatland trees are positively correlated with late summer temperatures.

Precipitation

There is a negative correlation between precipitation and peatland tree growth during most of the previous and current year. This relationship is significant in the fall months of the previous year (September: r=-0.35; October: r=-0.39; November: r=-0.35) and October (r=-0.36) of the current year. These relationships indicate that peatland tree growth increased in years with lower precipitation.

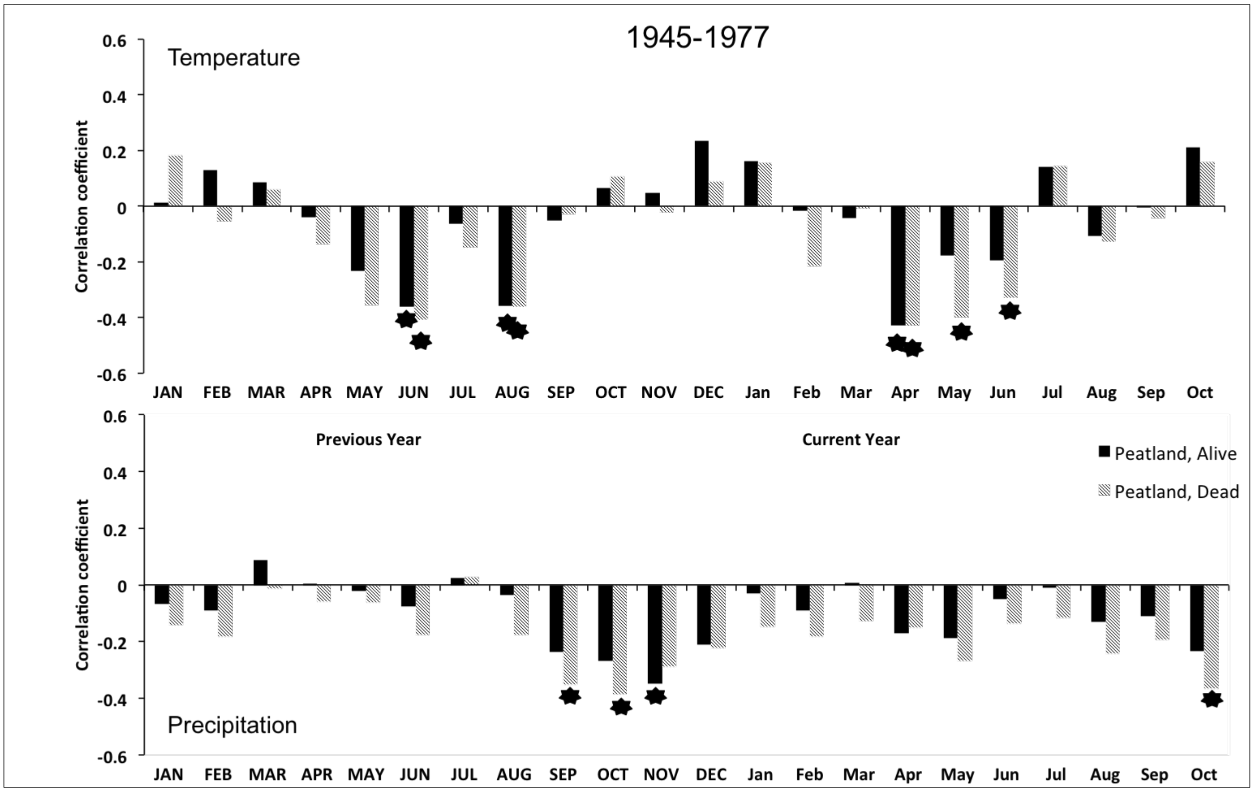

Figure 2-4: Single interval correlation values between temperature (top), precipitation (bottom) and standardized RWI for Peatland living and dead trees, for the period 1945-1977. Black stars indicate significant values (p<0.05).

Relationship between climate variables and RWI of Peatland dead and Peatland living trees: Post-Road (1974-2006)

Temperature

The relationship between temperature and peatland tree growth changed after road construction (Fig. 2-5). Both chronologies are positively correlated with temperature during this period, except for the previous August (Peatland dead, r = -0.25) and October (Peatland living, r = -0.35). Both chronologies are significantly positively correlated with current January values (Peatland living: r = 0.43; Peatland dead: r = 0.36). The Peatland living chronology is correlated with the current June (r = 0.30) and August (r = 0.46) temperatures, and the Peatland dead chronology with the current April (r = 0.32) and May (r = 0.25) temperatures. Mild conditions in the early winter contributed positively to radial growth in all peatland trees. The Peatland dead chronology was more limited by warm conditions in April and May, while the unaffected peatland population benefited from high temperatures in June and August of the current growth year.

Precipitation

After road construction, there was also a shift in the relationship between tree growth and precipitation in both peatland chronologies from consistently negative to a mixed response. Living peatland trees were positively correlated with previous (r = 0.39) and current (r = 0.48) June precipitation, and negatively with previous December (r = -0.31) and current August (r = -0.35) precipitation. The Peatland dead chronology was negatively correlated with previous June (r = -0.27), and positively with previous July (r = 0.38) and current May (r = 0.25) precipitation rates. Precipitation in June elicits a contrasting response in the two chronologies. Evidently, during this period the Peatland dead (dying) trees benefitted from dry conditions in the early summer. The living peatland trees, in the undisturbed areas of the fen, benefitted from high precipitation values.

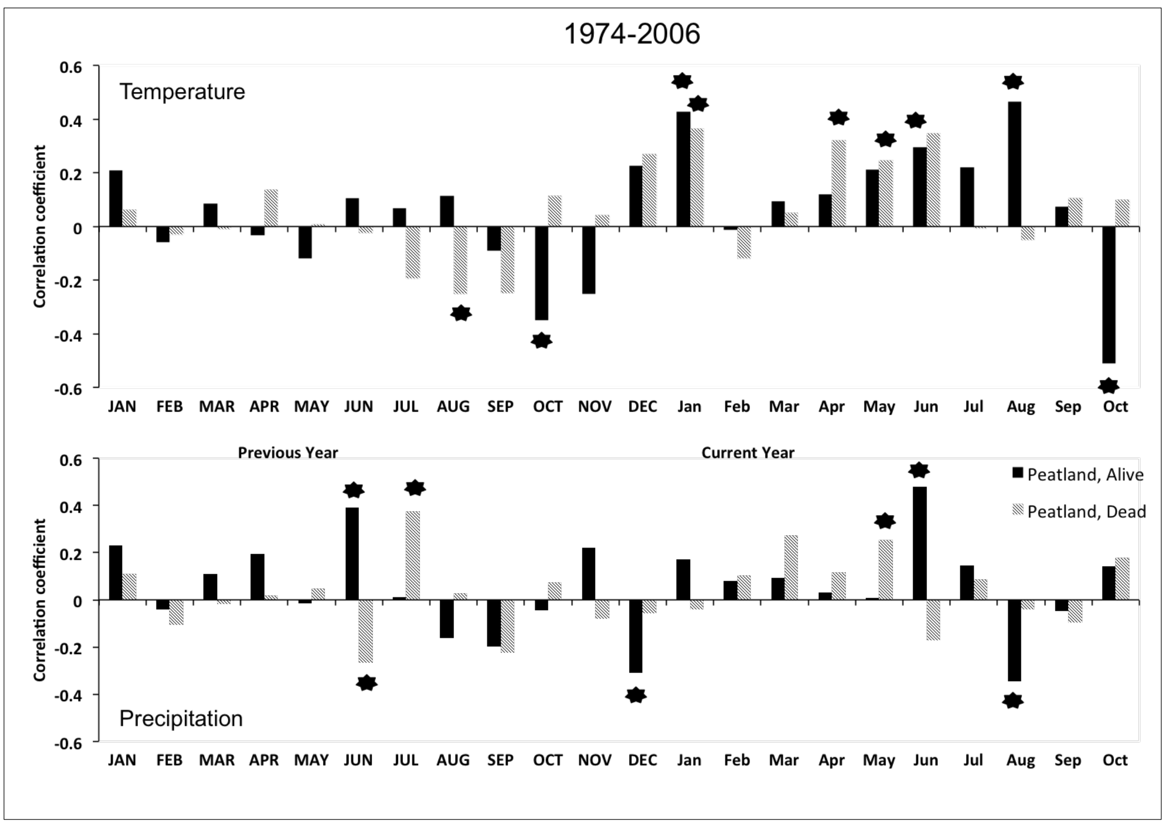

Figure 2-5: Single interval correlation values between temperature (top), precipitation (bottom) and standardized RWI for Peatland living and dead trees, for the period 1974-2006. Black stars indicate significant values (p<0.05).

Spatial and temporal patterns of dieback

Most sample trees died in 1989, approximately a decade after road construction (Fig. 2-6). Dead trees occur within 260 m up-gradient of the road (Fig. 2-7). Greater temporal variability in tree mortality was found further from the road in a transition area where a mix of living and dead trees occurs, and down-gradient of the road. Down-gradient, trees died earlier in locations closer to the culvert outlet and in more recent years farther from the culvert. Two trees located behind a mound immediately up-gradient of the road (likely made from spoil materials from the ditch excavated adjacent to the road) have more recent dieback dates. All measured trees below a threshold elevation relative to the culvert top of 83.5 cm died in 1989, and one in 1990 (Fig. 2-8). Above this threshold, the measured trees died in increasingly later years at elevations higher than the culvert (Fig. 2-8).

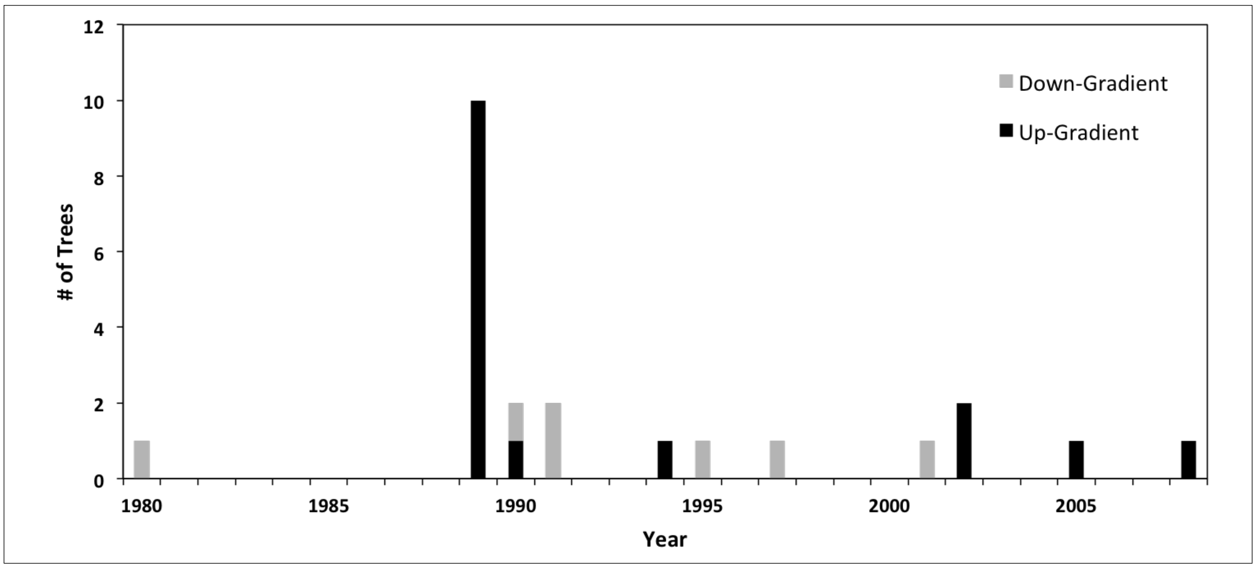

Figure 2-6: Histogram representing number of sampled peatland trees, up- and down-gradient of the road, that died each year since 1980; 23 trees sampled, 7 down-gradient and 16 up-gradient.

Tree response to the road

Approximately 2 trees were impacted immediately and decline in growth from 1977-78. Three decrease in growth in 1977, and then increase in growth before dying in 1989, and 9 had no change in growth until they died in 1989 (for individual growth curves see Appendix 1 and 2). Fig. 2-9 shows the average ring width curves for trees from four areas in the fen (circled in Fig. 2-7) from 1970 to 1989, the year when most of the trees died. The trees responded in several ways to the road. Of the four growth curves (Fig. 2-9), the trees in the transition area had the widest growth rings at the end of this time period, because 3 of the 4 trees sampled in this area survived past 1989. Trees in the East experienced an increase in growth after road construction in 1977, before gradually decreasing until all of the sampled trees died in 1989. The trees in the West displayed a similar trend, but there was no growth recovery after road construction. Trees down-gradient of the road showed increased radial growth in the early 1980s, but a rapid decline in growth beginning in 1986.

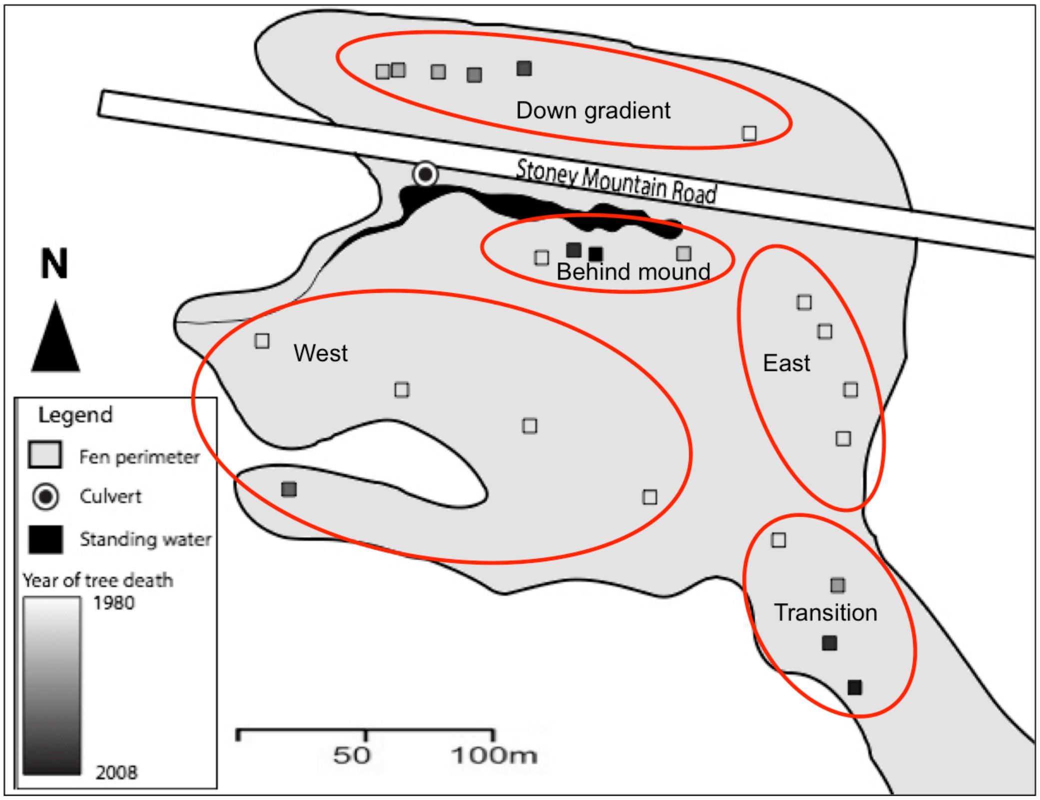

Figure 2-7: Map of the impacted zone of the study site, showing rates of tree dieback. Each square represents one sampled tree. The lighter the square, the earlier the year of death. Most of the trees died in 1989.

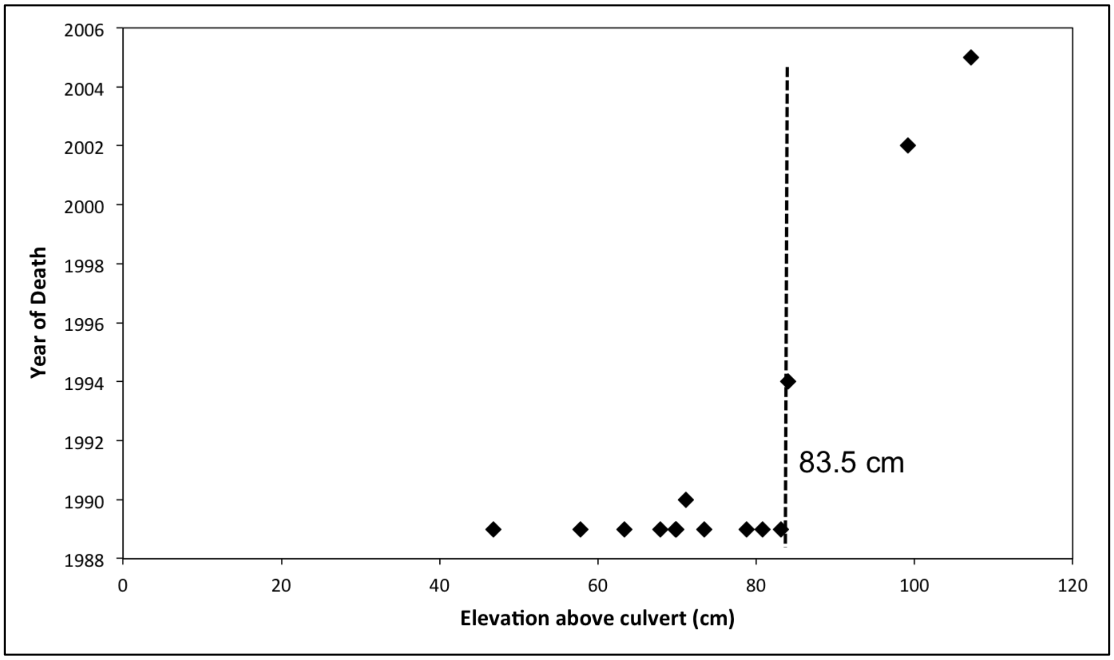

Figure 2-8: Distance above culvert top vs. year of death. Each point represents one tree sample. Vertical dashed line represents the threshold elevation of 83.5 cm, below which most of the trees died in 1989.

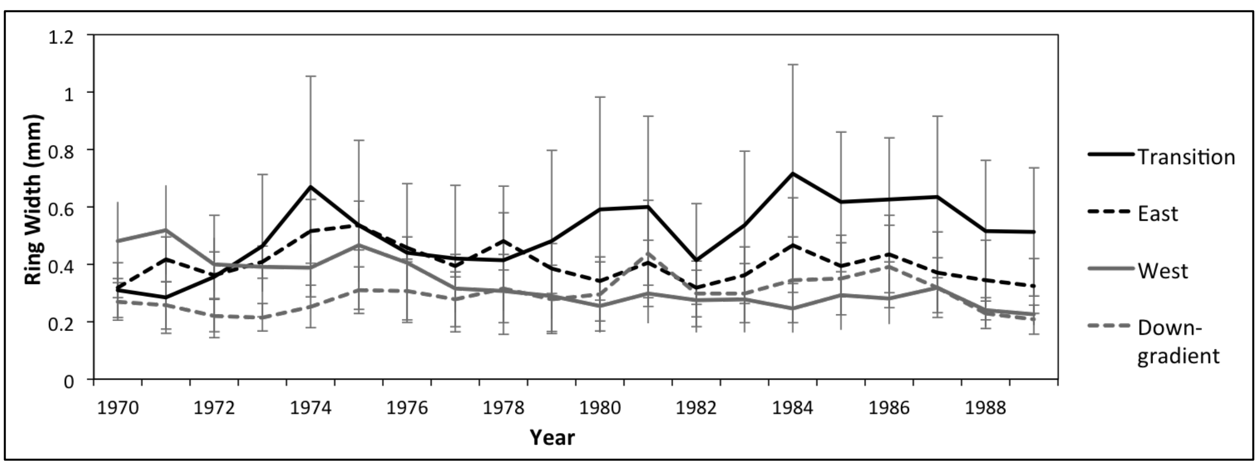

Figure 2-9: Average raw ring widths for four areas in the disturbed zone of the fen. Transition (n=4) refers to the 'saddle' of the fen, where there is mixed tree mortality. East (n=4) and west (n=4) both refer to the treed areas immediately up-gradient of the road where tree mortality is high. Down-gradient (n=6) is the area north of the road. Each line represents the average raw ring widths of all cross-dated trees in each area. Error bars represent the standard error. See Appendix 2 for growth curves of each individual cross-dated tree for this period, and a table of raw ring width values.

2.6 Discussion

The role of moisture gradients and disturbance in regulating climate-growth responses in peatland black spruce

Based on the correlation analysis, upland and peatland trees at this site were limited by different processes. The optimal weather conditions for peatland tree radial growth included dry fall months followed by mild winters (Fig. 2-3). Optimal upland tree growth occurred during wet summers followed by a cool fall. Climate in the fall and winter, when the trees are in senescence, is particularly significant to peatland trees because the winter snowpack is an important indicator of peatland water tables the following year - melting snow is the first major moisture input of the growing season (Juday & Alix, 2012). Winters with low temperatures delay ground ice thaw and the start of the growing season in the peatland. These sampled peatland trees are more sensitive to changes in the environment and climate than the upland trees, and therefore they have higher correlation coefficients than the upland chronology (Fig. 2-2b and Fig. 2-3). The upland chronology displays more complacent ring width patterns and is less variable because this area is the middle of the ecological range for upland black spruce, and they experience less stress than the peatland trees (NRCAN, 2011). It is environmental stress that causes ring width variability (Briffa et al., 1998).

The pre-construction period (1945-1977) represents the undisturbed peatland and two trends are documented: (1) tree ring widths are negatively correlated with spring and summer temperature, and (2) with precipitation throughout the year, but particularly in the fall (Fig. 2-4). Negative relationships between temperature and black spruce growth is widely reported in boreal Canada (Brooks et al., 1998; Juday & Alix, 2012; Drobyshev et al., 2013; Walker & Johnstone, 2014). Black spruce typically grows more slowly when temperatures are warmer and conditions are dry, because they are sensitive to moisture stress (Walker & Johnstone, 2014). The relationship between precipitation and RWI is dependent on local conditions (Brooks et al., 1998; Vitas & Erlickyte, 2007 [scots pine]; Ohse et al., 2012; Drobyshev et al., 2013). When RWI is negatively correlated with temperature and positively with precipitation, it may be a sign that the trees are drought sensitive. Warm temperatures and low precipitation leads to increased evapotranspiration and decreased soil moisture, which decreases radial growth in boreal spruce (Wilmking & Juday, 2005; Subedi & Sharma, 2013). While it may seem counterintuitive, drought can negatively impact peatland trees because their roots are very shallow and even a small water table decline will reduce water availability to the tree (Fritts, 1976). The pre-road fen was not moisture limited, as evidenced by the consistently negative relationship with precipitation. In the period from 2011-2014, depth to the water table in undisturbed areas of the fen did not drop below 20 cm (see Chapter 3). In these conditions, abundant precipitation raises the water table to the soil surface (Fig. 2-2a,b) reducing soil oxygen and limiting root growth (Conlin & Lieffers, 1993; Walker & Johnstone, 2014).

In the post-road period (1974-2006) trees benefited from warm temperatures in January, spring and summer, and the RWI was positively correlated with spring and summer precipitation (Fig. 2-5). Although trees were not growing in January, warmer winter temperatures can lead to earlier growth initiation in the spring and increased radial growth (Fritts, 1976; Vitas & Erlickyte, 2007). Tree growth was positively correlated with spring temperatures during the year of growth for the same reason - earlier growth initiation allowed more time for radial growth (Vaganov et al., 2006; Subedi & Sharma, 2013). Growth slowed in August, which explains the positive relationship with temperature, and a warmer late summer could elongate the growing season (Fritts, 1976). Positive relationships with temperature usually occur when conditions are cooler (Juday & Alix, 2012); however, average regional temperatures have increased since 1946, making the second period warmer, especially in the winter months (Fig. 2-10).

Monthly precipitation patterns were compared between the two periods, and there was a shift over time to increased precipitation earlier in the growing season, rather than later in the summer (Fig. 2-10). This could account for some of the variance in the undisturbed peatland trees after road construction. In studying the response of Alaskan trees to rising temperatures, Wilmking and Juday (2005) found that local moisture conditions influenced whether trees were drought sensitive. On such a short time scale, however, a change in the relationship between climate and RWI is more likely related to a change in local environmental conditions, rather than climatic change (Trindade et al., 2011). Trees in wet areas tend to have a negative response to precipitation (Ohse et al., 2012), as in the pre-road period. Positive correlations with precipitation, especially in the warmer seasons, suggest that water levels dropped in the peatland post-road construction. This corresponds with the idea that the culvert initially drained the fen, before becoming blocked. The culvert was likely blocked by beaver activity, which can be mitigated by installing multiple culverts or regular culvert maintenance.

The impacts of the road on the peatland can be isolated by comparing the relationship between climate and RWI for the living and dead trees after road construction (Fig. 2-5). Both chronologies are positively correlated with temperature in January and early summer, suggesting that trees benefited from warmer temperatures, which allow earlier growth initiation in the spring and a longer growing season. Only living peatland tree growth was negatively correlated with October temperatures. This could be an artifact of the living trees down-gradient of the road, which experienced a few years of release growth after road construction because of drier conditions. This could produce climate relationships similar to the upland tree response, which had a negative relationship with fall temperature.

The chronologies diverged more in their relationship with precipitation. The living trees are significantly positively correlated with June values of both the current and previous year relative to growth, while the dead trees are negatively correlated with June precipitation of the previous year. This would seem to contradict the theory that the culvert initially drained the impacted area, because a negative relationship implies that this area remained wet, and tree growth was negatively impacted by increased precipitation. However, the dead trees are positively correlated with July precipitation. A positive relationship with precipitation during the warmest month suggests that trees in this area were moisture stressed, as radial growth increased with precipitation. Overall, more divergence occurs between the living and dead trees in relation to precipitation. This suggests that precipitation was more important than temperature in reinforcing environmental conditions that were unfavourable for tree survival.

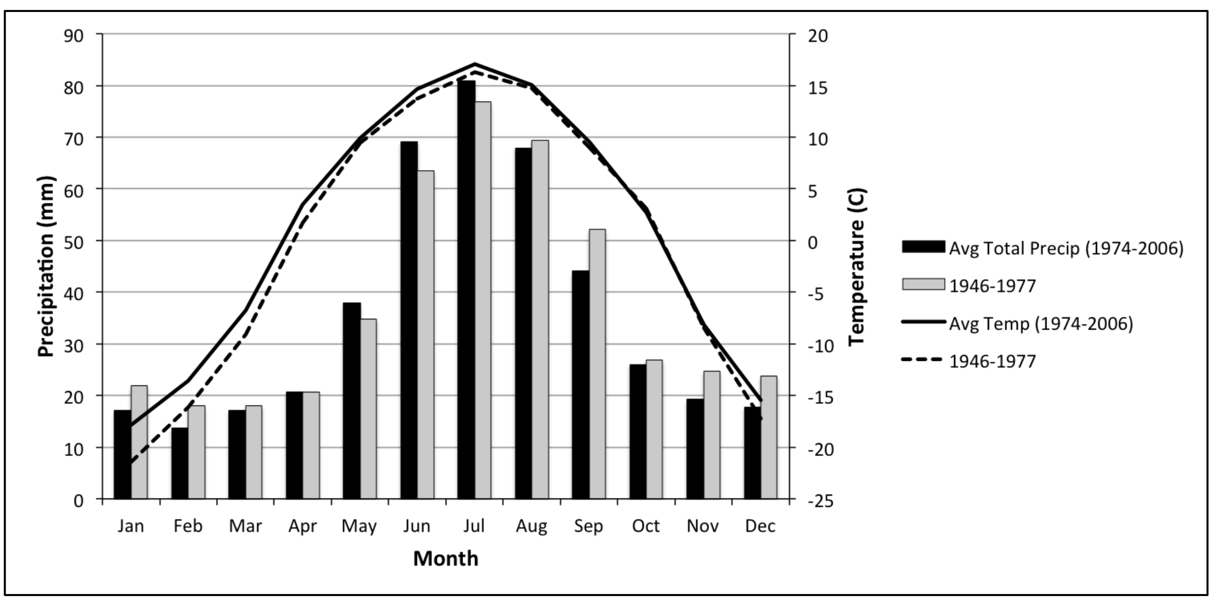

Figure 2-10: Average temperatures and average total precipitation per month before and after road construction.

Reconstructing recent hydrological change in a peatland using tree rings

Most of the trees up-gradient of the road died in 1989, twelve years after road construction began (Fig. 2-6). The current ground surface of these trees are within 83.5 cm above the culvert top, and more gradual dieback occurred in trees up to 107 cm above the culvert (Fig. 2-8). Relative elevation above the culvert is critical because the culvert is the only surface water drainage for the fen. When the culvert is blocked and water levels reach the culvert top, the system continues to flood until the blockage is cleared. Tree death likely occurred when surface water levels rose above tree root crowns and remained at this elevation for a sustained time. Minor rises in water levels that did not inundate the soil may allow trees to develop adventitious roots in unsaturated soils (Calvo-Polanco et al., 2012). The dieback elevation of 83.5 cm above the culvert top indicates that water levels were sustained at this elevation for a long duration in 1989. Elevation above the culvert is a more important predictor of tree dieback than distance to the road.

Growth curves for dead trees (Fig. 2-9) indicate that few trees were immediately impacted by road construction, likely due to the topology of the fen. The culvert is the fen's lowest point, where all water flows towards the northwest. When the road was first constructed, the new culvert probably drained the fen in the immediate area, and nearby trees experienced a growth increase (Fig. 2-9) following construction. Over the following ten years, ring-widths, especially in the East and West (Fig. 2-9) sectors, decreased, suggesting that water levels in the fen rose, likely because the culvert was blocked by sediment or beaver activity. Beaver-induced flooding is well known to cause tree mortality in wetlands (Reddoch & Reddoch, 2005). During the summer of 2013, beavers blocked the culvert with branches and sediment. This led to a 34 cm water level rise within days of the blockage (Bocking, unpublished data (Chapter 3)).

Measured water levels relative to the ground surface near the culvert were similar to those throughout the fen. However, the vegetation in this area is more characteristic of a rich fen or marsh, indicating that the area is frequently, but not permanently, flooded. Many of the trees that died in later years experienced a dramatic decrease in growth in 1989 (Fig. 2-9). It is possible that a beaver blocked the culvert in 1989, causing widespread and sustained flooding in the fen.

Implications for peatland succession and constructed fen systems

Tree dieback occurred because road construction impeded natural drainage patterns in the fen. The culvert is easily blocked with sediment whether through natural processes or beaver activity, which either gradually reduces discharge over time or impedes flow completely, causing flooding. Flooding of the system, whether gradually or rapidly, impacts succession because it favors vegetation that can survive in intermittently flooded conditions, rather than trees such as black spruce (Laine et al., 1995). A constructed fen peatland system should be designed to allow water to flow freely out of the system without relying on a single drainage outflow point. Occasional or sustained flooding of peatlands has implications for vegetation cover type, which in turn is an important control on the amount and rate of carbon sequestration (Laiho, 2006).

2.7 Conclusions

Tree ring analysis used to reconstruct recent hydrological changes in a poor fen in northeastern Alberta indicated that most peatland trees died a decade after road construction began in 1977. The road was constructed with one culvert that allowed surface water to flow from the peatland. However, the narrow culvert made it vulnerable to blockage from sediment or beaver dam building activity, and the eventual blocking of the culvert apparently led to widespread and sustained flooding that drowned hundreds of trees. Relative elevation above the culvert top was the most important predictor of temporal and spatial patterns of tree dieback. The uniformity of dieback below the elevation threshold of 83.5 cm is an indicator of water level height when the fen was flooded. That most of the trees in a large area died in one year suggests a single widespread flooding event rather than a gradual rise in water table after road construction.

The impacted peatland became more sensitive to precipitation during the warmest months of the year, suggesting an environment that became saturated even with little precipitation, and dried out quickly when precipitation decreased. This increased hydrological flashiness has important implications for vegetation composition and peatland development in general. In the years since the road was constructed, road-building techniques have improved, and more permeable road base materials are used, or multiple culverts to reduce chances of blockage and subsequent flooding. This research demonstrates the importance of meso-environmental conditions in determining individual tree response to hydrological change, and is one of the few studies to use dendrochronology to analyze these changes in peatlands.

Acknowledgements

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3.0 Manuscript 2: How hydrological changes from road construction impact the vegetation succession and development of a poor fen

3.1 Abstract

Roads that bisect wetlands can alter their hydrologic connectivity on a local or landscape scale. These impacts were studied in a poor fen located 45 km south of Fort McMurray, Alberta, where a raised road was built across the northern fringe of the fen in 1977. Examination of the fen's response to this impoundment provided insight into post-disturbance vegetation succession patterns and peatland development. The objectives of this study are to quantify the impacts of the road on peatland tree growth, vegetation and microtopography, characterize vegetation changes along the existing hydrologic gradient and the role of the road in creating these gradients, and to predict its successional trajectory based on current vegetation and hydrology. Water table was measured weekly at three groundwater wells and bulk density of the peat was calculated at several locations across the fen. In sixteen 50 m^2 transects, recent moss growth was calculated by measuring the depth to the root crown of black spruce trees. Tree density and the age of saplings were also measured in these transects. Vegetation cover, along with several abiotic variables was measured in 279 1 m^2 plots. High bulk density values and loose *Sphagnum* moss carpets contribute to low storativity close to the culvert in the most disturbed area of the fen, as evidenced by rapid flooding and drying. There were no saplings near the culvert, very few within 220 m up-gradient of the road (12% of total trees), and many saplings in the transects furthest from the road (57%). The average depth of recent moss growth was greater immediately up-gradient of the road (37.6 cm) compared with undisturbed areas (15.5 cm). Analysis of vegetation using non-metric multidimensional scaling reveals dominance of non-hummock forming species closest to the culvert (located in the NW corner). These data suggests that periodic blockage of the culvert leads to flooding in the immediate area that encourages non-hummock forming species of sedge and moss, making an unfavourable environment for black spruce germination. This cycle of hydrologic disturbance may be preventing some areas of the fen from regaining the original vegetation structure, with implications for the system's development.

3.2 Introduction

Northern Canada is crossed by networks of linear disturbances, especially in areas of intensive resource extraction. These features, which include seismic lines, roads, pipelines and powerline rights-of-way, fragment the boreal landscape and disrupt natural biological and hydrological processes (Lee & Boutin, 2006; Martell et al., 2006; Turetsky & St. Louis, 2006; Dubé et al., 2011; Williams et al., 2013). When built over wetlands, raised infrastructure such as roads alter natural drainage patterns, often simultaneously causing flooding and desiccation up- and down-gradient of the impoundment, respectively (Jeglum, 1975; Umeda et al., 1985; Miller, 2011). As depth to the water table is a key indicator of the hydrologic regime that influences wetland plant species composition and type, by examining vegetation patterns in a post-road impacted wetland, we can gain insight into wetland development.

In the western boreal plains of Alberta, peat-accumulating wetlands cover 30% of the land area (Vitt & Chee, 1990; Vitt et al., 1996). When built over wetlands, infrastructure projects, such as roads, are raised above the ground surface on a bed of mineral fill to deter flooding and subsidence (Graf, 2009). At least one culvert is typically built beneath the road to mitigate water impoundment and a restricted drainage regime, but they are easily blocked by sediment, whether through natural flow of material through the system, or dammed by beavers (*Castor canadensis*) (Graf, 2009; Vitt et al., 2011). To further avoid impoundment, roads can be built of semi-porous material, or with multiple evenly spaced culverts (Graf, 2009). Beaver may have high local populations throughout northern Canada and are prodigious builders. For example, Woo & Waddington (1990) reported a density of 14.3 dams/km of stream in the James Bay lowlands. Beavers commonly plug road culverts to create ponded habitats (Brown et al., 2001).

The effects of a road on peatland succession and development were studied at a poor fen located 45 km south of Fort McMurray, in northeastern Alberta. One of the most visible indicators of vegetative change at this site is the large number of dead black spruce trees (>80%) located within 220 m up-gradient of the road. A dendrochronological analysis of several of these trees revealed that most of the dieback occurred from 1989-1990, more than a decade after the road was built in 1977 (Bocking, Chapter 2). Growth curves of the dead trees from 1970-1990 show a diverse response over this decade due to the importance of micro-environmental controls in regulating growth, but the uniformity of dieback suggests a significant event that affected a large area. Since water table limits tree growth in peatland environments (Lieffers & Rothwell, 1987; Linderholm et al., 2002; Moir et al., 2011), this event was likely a flood that occurred in 1988-89, 10 years after road construction, when water levels rose high enough for a sustained period to kill all of the trees within 220 m up-gradient of the road. Flooding reduces oxygen levels in the root zone and lowers soil temperatures. Wetland trees can adapt to high water tables by producing adventitious roots in the aerobic zone (Calvo-Polanco et al., 2012), but dieback occurs when the rate and duration of flooding is faster than root growth (Reddoch & Reddoch, 2005; Rydin & Jeglum, 2006). Likely caused by a blocked culvert, raised water levels drowned the trees. The presence of old chewed stumps and a lodge suggest that beavers have at least intermittently occupied this site and could have triggered flooding.

Hydrologic regime determines vegetation composition, peatland type and its development (Zoltai & Vitt, 1995; Asada et al., 2005; Rydin & Jeglum, 2006; Granath et al., 2010). Natural poor fens are ecologically similar to bogs, but receive mineral-rich groundwater inflow (Zoltai & Vitt, 1995). They are characterized by shallow water tables that are highest during spring melt, with little seasonal variation (Rydin & Jeglum, 2006). Water table depth and variance (Asada, 2002; Rochefort et al., 2002; Kowalski & Wilcox, 2003; Pellerin et al., 2009; Talbot et al., 2010), water chemistry (Andersen et al., 2011), microtopography (Peach & Zedler, 2006; Økland et al., 2008) and light availability (Pouliot et al., 2011) are important indicators of vegetation diversity and composition. Vegetation is simultaneously influenced by all of these variables to some degree (Eppinga et al., 2009; Kapfer et al., 2011). Allogenic impacts on these environmental gradients influence peatland development, and can impact the successional trajectory (Hughes & Dumayne-Peaty, 2002; Tuittila et al., 2007; Eppinga et al., 2009; Hájkova et al., 2012). Flooding in bogs or poor fens, for example, is often associated with an increase in sedge species richness and the reversal of a typical fen-bog successional gradient (Gunnarsson et al., 2002; Bauer et al., 2003; Barthelmes et al., 2010; Granath et al., 2010).

I hypothesized that continual disturbance is impacting the successional trajectory of the peatland. This study has three main objectives: (i) Analyze how changes in hydrology from road construction have impacted tree growth, microtopography and vegetation; (ii) Characterize vegetation changes along the existing hydrologic gradient and the role of the road in creating these gradients; (iii) Determine the role of disturbance in influencing peatland development. This study adds to our understanding of how hydrological disturbance impacts vegetation composition, and how these vegetation changes can shift peatland development onto a new successional pathway.

3.3 Site Description

The study site is an 8 ha poor fen located on a local topographic high (Stony Mountain, ~740 masl), 45 km south of Fort McMurray, Alberta (56°22'30''N, 111°14'05''W) (Fig. 3-1). The region has an average annual temperature of 1°C, and receives on average 437 mm of precipitation annually (Environment Canada, 2014; www.climate.weather.gc.ca). During the period of meteorological data collection at the fen (2011-2014), precipitation was higher, and temperatures cooler than recorded at the Fort McMurray airport (Environment Canada) (Table 1). The fen is located in a basin with a maximum peat depth of 11 m, a median peat depth of 160 cm, and an average pH of ~4.5. The dominant ground cover is *Sphagnum angustifolium*, with *S. capillifolium* and *S. magellanicum* also present. The ericaceae shrubs *Chamaedaphne calyculata, Oxycoccus microcarpus, Rhododendron groenlandicum* and *Andromeda polifolia*, the sedges *Carex aquatilis, C. canescens, C. pauciflora* and *Eriophorum* spp. and other vascular plants such as *Smilacina trifolia* and *Equisetum* spp. are also abundant. Tree cover is discontinuous and dominated by stunted *Picea mariana* and some *Larix laricina*, with tree densities ranging from 0.16 to 2.3 trees/m^2. Within 220 m up-gradient of the road, more than 80% of the trees in the fen are dead.

The hillslopes are underlain by glacial till but with a duff layer typical of the Western Boreal Forest (cf. Miyanishi & Johnson, 2002). The understory vegetation in the uplands is dominated by feather moss, the shrubs *R. groenlandicum* and *V. myrtilloides*, and also *Cornus canadensis* and *Lycopodium* spp. There is a dense tree cover composed primarily of *Populus tremuloides*, *Picea mariana* and *Pinus banksiana*.

Construction of the road, which is an extension of Range Road 90A, began in 1977 to allow construction of a communications tower located at the end of the road. A culvert of 92 cm diameter was built through the peatland road crossing on the west side. A year-round pool of standing water collects up-gradient of the culvert in a depression likely excavated during construction, and is fed by an ephemeral stream draining the west hillslope, as well as water seeping from the poor fen up-gradient of the road. The vegetation down-gradient of the road follows a hydrological and topographic gradient from dry in the east to low and wet near the culvert in the west. The vegetation transitions accordingly from a dense cover of *R. groenlandicum*, *C. calyculata* and *Rubus chamaemorus* on the shrub level with *S. angustifolium* the dominant ground cover and dense stands of *P.mariana* in the margin, to *C. aquatilis, Calamagrostis canadensis* and *B. pumila* near the culvert. A small area immediately down-stream of the culvert opening is flooded during the spring melt, and dominated by *Typha latifolia*. The fen drains through the culvert and towards the northwest. During wet periods, the outflow is visible as a stream that continues out of the fen and down Stony Mountain.

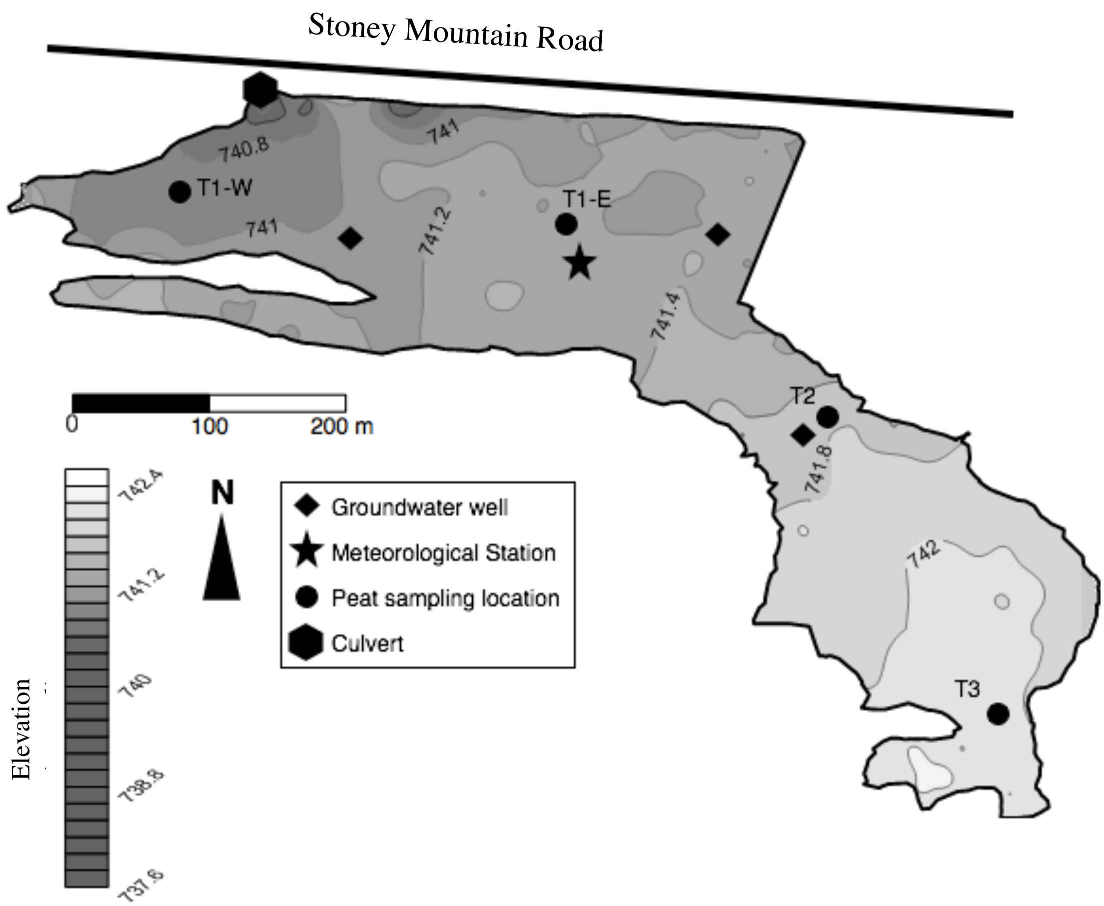

Figure 3-1: Topographic map of the study site, with peat sampling locations (labeled), groundwater wells and Stony Mountain Road.

Table 3-1: Comparison of climate data between the Fort McMurray airport (collected by Environment Canada) and the meteorological station at the study site during periods of data collection.

Climate variable	Year	Period	Airport	Pauciflora
Total Precipitation (mm)	2012	Apr 3 – Sep 18	342.2	533
	2013	Apr 15 – May 18	14.2	31.2
	2014	Mar 31 – Oct 6	325	459.5
Average Temperature (°C)	2011	May 30 – Dec 31	7.1	6.38
	2012	Jan 1 – May 5	-5.53	-5.55
	2012	Jul 2 – Dec 31	3.72	2.22
	2013	Jan 1 – Aug 22	3.17	1.86
	2013	Oct 16 – Dec 31	-13.02	-12.46

3.4 Methods

Peat physical properties

Six peat cores were collected, four using a Wardenaar corer, and two using 10 cm diameter PVC pipe, where the peat was too wet for the Wardenaar. The cores varied in length from 23.5 – 69.0 cm, depending on field conditions. The cores were frozen until used for lab analysis. The peat cores were sub-sampled using 4 cm diameter PVC pipe rings at 10 cm intervals. After the samples were drained, they were dried in an oven at 80°C for 6 days, until they were completely dried. Bulk density was calculated as follows:

$$(1) \qquad BD = \frac{Oven\ Dried\ Weight}{Volume}$$

Oven dried peat samples were sub-sampled and placed in ceramic crucibles that had previously been dried in a muffle furnace at 550°C for ten minutes. The peat was heated in a muffle furnace at 550°C for 3 hours. Percent organic matter was calculated as follows:

$$(2) \qquad LOI = \left(\frac{Pre\ Ignition\ Weight - Post\ Ignition\ Weight}{Pre\ Ignition\ Weight}\right) * 100$$

Water table measurements

Depth to the water table was measured weekly between May and August in 2012 and 2013 from four east to west transects of 2.5 cm diameter wells situated up- and down gradient of the road. The wells were constructed with 1 m sections of polyvinyl chloride (PVC) pipe, perforated along their length and lined with a geotextile screen.

Tree density transects

Nineteen 50 m^2 (25 x 2 m) transects were established parallel to the road. The height of every hummock above the water table was measured along the transects. Depth to the root crown (DTR) from the current moss surface was measured (Walter & Breckle, 1994) for every tree greater than 1 m tall. The position of the root crown, which is the germination point, relative to the current ground surface, provides insight into historical water levels and ground surfaces, as *P.mariana* sends out thick lateral roots close to the ground surface, and above the water table, at time of germination (Lieffers & Rothwell, 1987; Cooper et al., 2003). Thus, the root crown indicates the ground surface prior to the road construction that triggered flooding and rapid moss growth that buried the root crown. Baseline or 'natural' DTR values were calculated by averaging the DTR values from the Undisturbed transects.

Every tree and sapling along each transect was measured to calculate tree density as well as its height, basal diameter, species and mortality. Heights were directly measured with a tape measure where possible, and a clinometer when taller than 4 m. Basal diameter was measured with calipers or a diameter tape. Mortality was determined by the presence or absence of needles. GPS coordinates were taken with a handheld Garmin GPS for trees >1 m tall.

Twenty-seven living saplings (<1 meter tall) were collected from across the peatland and aged to determine rates of moss accumulation. The entire sapling was collected and current live moss ground level marked with a zip tie. Hummock height, nearby species composition and GPS coordinates were noted for each sample. In the lab, the sapling stem was cut into 10 cm lengths. Each face was sanded, and the rings counted. The lengths were cut into increasingly smaller sections until the point with the largest number of growth rings was found identifying the germination point. The distance between the germination point and the current ground surface is the thickness of moss accumulation since sapling establishment (Berglund & Ralska-Jasiewiczowa, 1986). Moss accumulation rates were calculated by dividing the moss thickness by sapling age.

Vegetation cover

Percent canopy cover for each plant species present was visually estimated across the study site in 279 1 m^2 quadrats. Vegetation was analyzed between July 19th and August 12th 2013. Plot location was chosen first by ensuring that every community was represented and replicated and second by ensuring an even coverage across the fen. Each plot was horizontally and vertically homogenous, representing one community type and elevation or microtopographic form. Precise estimates of cover were taken in the field, and later converted to Braun-Blanquet (1932) cover classes: <1% (trace) = 1; 1-5% = 2; 5.1-25% = 3; 25.1-50% = 4; 50.1-75% = 5; 75.1-100% = 6.

Several additional variables were collected while measuring vegetation cover. Depth to water table, hummock height, capitula density in four 36 cm^2 squares when *Sphagnum* was present, percent cover of litter, bare ground and open water were estimated. If present in the plot, the height and basal diameter of all trees were measured.

In mid August 2013 water temperature, pH, salinity and EC were measured in each plot by submersing an YSI probe in the groundwater. A DGPS was used to identify the location and elevation (masl) of each plot. Elevations above sea level and positions of the plots are accurate to 1 cm.

Statistical analysis

Linear regressions were used to test the strength of the relationships between distance to the culvert and sapling density, and depth to root and percent tree death. A Shapiro-Wilks test was used to determine that the moss growth rate data are not normal. A Kruskal-Wallis one way ANOVA by ranks was used to test whether rates of moss growth in the Undisturbed and Disturbed areas are significantly different.

Ecological analysis of the vegetation was done in R using the package “Vegan” (Oksanen et al., 2013; R Core Team, 2013). An unconstrained ordination was conducted on the vegetation data to plot the relationships between species and to illustrate any important environmental gradients that influence their distribution. Nonmetric multidimensional scaling (NMDS) was chosen because it avoids assumptions of normalcy, that is often unattainable in ecological data sets but that are essential for other ordination methods (Peck, 2010). Rather than order the samples based on distance (i.e. Euclidean), NMDS maximizes the rank order correlation between samples (Digby & Kenton, 1987; Borcard et al., 2011). Environmental variables were plotted on the NMDS plot as vectors and surface contours after the species were plotted to explain variation in species distribution. The length of the vectors indicates the strength and direction of correlation between species on the biplot. The angle of the vector relative to other vectors and species points represents the sign of the relationship, where less than 90° is positive and greater than 90° is negative.

Ward's minimum variance clustering was used to group the sampled vegetation plots into communities. This method defines groups by minimizing the within-group sum of squares (Borcard et al., 2011). A dendrogram was created from the analysis, and four communities were identified subjectively based on the four largest clusters that also made ecological sense. The vegetation plots were colour-coded by community type and plotted on a NMDS biplot.

3.5 Results

Characterizing Disturbed vs. Undisturbed areas

The percent dead trees was highest near the culvert (Fig. 2) with 100% mortality within 220 m, and > 50% mortality within 260 m up-gradient of the culvert. At distances exceeding 290 m, tree mortality was reduced to nearly 0%. Thus at distances greater than 260 m up-gradient from the culvert, the fen was considered 'undisturbed', and within 260 m of the culvert, the fen was considered 'disturbed'. Down-gradient of the road, tree mortality was 11%, even within 40 m of the culvert, and decreased from west to east.

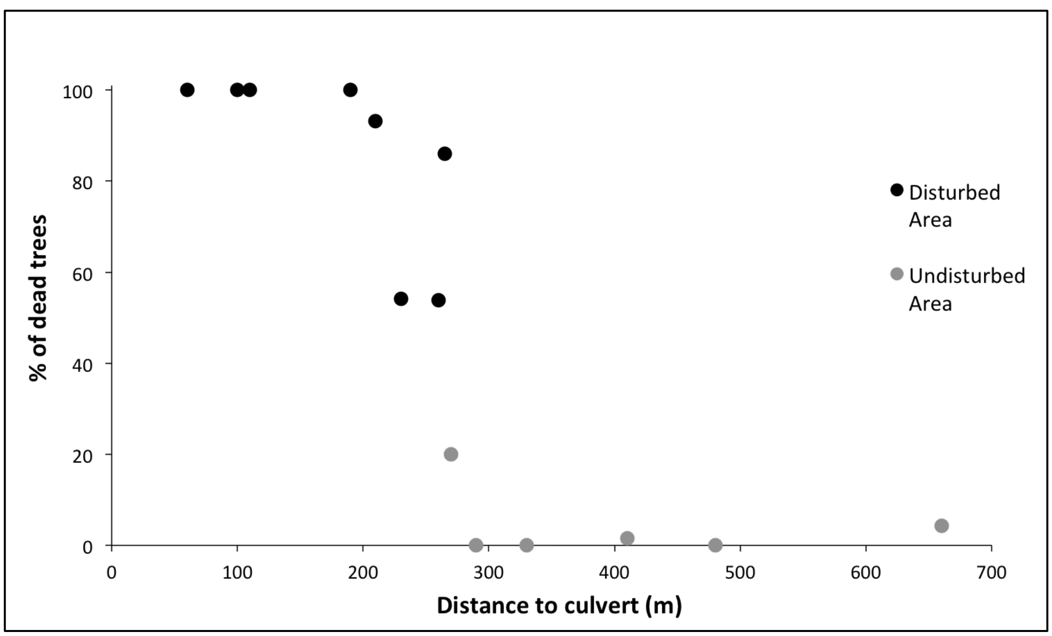

Figure 3-2: Scatterplot of % of dead trees vs. distance from the culvert in meters. Each point represents data from one 50 m² tree density transect.

Evidence of hydrologic change is evident in that most live saplings germinated between 1978-1990. Saplings were found in most transects, except within 110 m up-gradient of the culvert (Table 2). The highest sapling density was found in the transect furthest from the culvert, where 184 saplings/ha were counted. There is a strong positive relationship ($R^2 = 0.74$) between distance to the culvert and density of saplings.

Recent moss growth

Average depth to root (DTR) was highest in transects that had the highest proportion of dead trees (Fig. 3). There is a positive relationship between DTR and tree death ($R^2 = 0.63$). The 'natural' amount of moss accumulation is 15 cm. Baseline or 'natural' DTR values were calculated by averaging the DTR values from the Undisturbed transects. In the Disturbed transects, moss growth was 19.8-34.7 cm higher than this natural level. Rates of annual moss accumulation range from 0.13 – 2.28 cm/year, and average 0.84 cm/year. Moss accumulation rates are not significantly different between the Undisturbed and Disturbed areas of the fen (p=0.404) (Fig. 4). However, these annual growth rates could not be calculated in the most Disturbed areas with the highest DTR measurements, because there were no saplings.

Table 3-2: Statistics of tree density transects. Each transect was 50 m² and orientated parallel to the road. Percent dead trees and percent saplings out of all trees counted in each transect.

Transect #	Distance to culvert (m)	Tree density (trees/m^2)	% Dead trees	% Saplings	Average tree height (cm)	Notes
1	660	2.3	4.3	80.0	62	
2	480	0.44	0.0	68.2	105	
3	410	1.32	1.5	59.1	113	
4	330	0.48	0.0	37.5	212	
5	290	0.78	0.0	46.2	182	
6	270	0.4	20.0	70.0	96	
7	260	0.78	53.8	38.5	134	
8	230	0.48	54.2	41.7	76	
9	210	0.58	93.1	3.4	174	
10	190	0.72	100.0	0.0	199	
11	187	0.62	80.6	19.4	120	
12	105	0.62	38.7	29.0	157	
13	265	1	86.0	12.0	234	
14	110	0.16	100.0	0.0	666	
15	100	0.32	100.0	0.0	313	
16	60	0.3	100.0	0.0	417	
17	170	2.48	4.0	52.4	172	Down-gradient
18	150	1.38	1.4	31.9	266	Down-gradient
19	40	0.18	11.1	11.1	328	Down-gradient

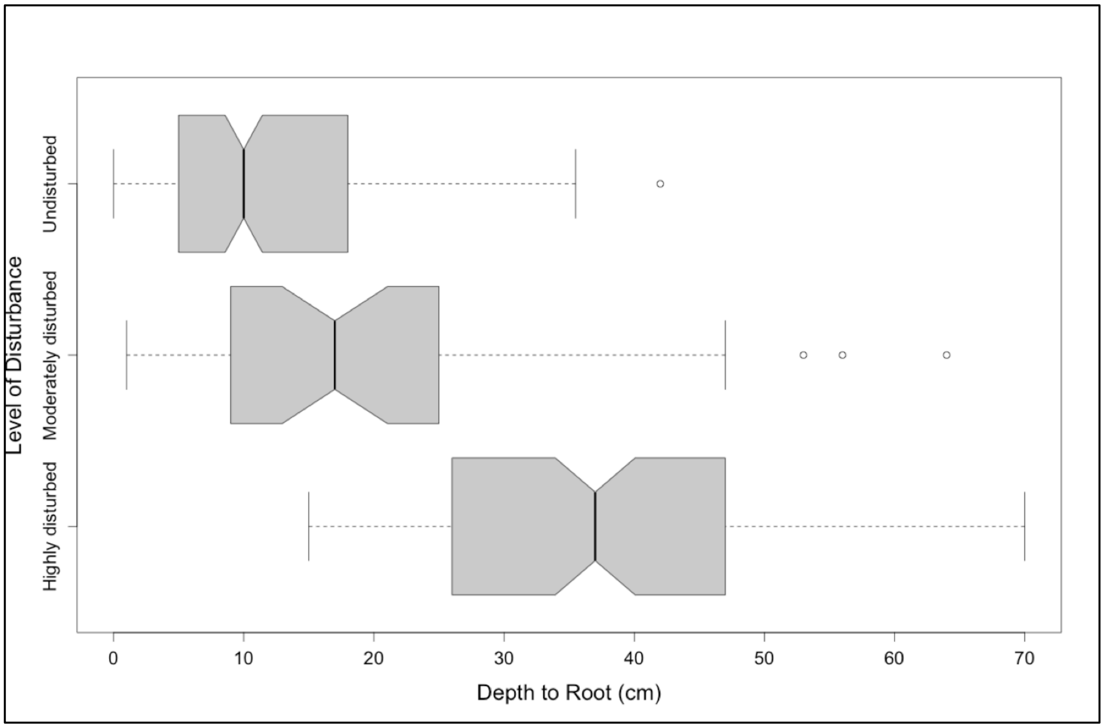

Figure 3-3: Average depth to root, classified by proportion of dead trees per transect, from undisturbed (0 -25% tree death), to moderately (25.1% - 75%) and highly (75.1% - 100%) disturbed. Horizontal bars indicate minimum and maximum values, the box defines the lower and upper quartiles, and the thick horizontal line is the median. Circles are outliers in the data.

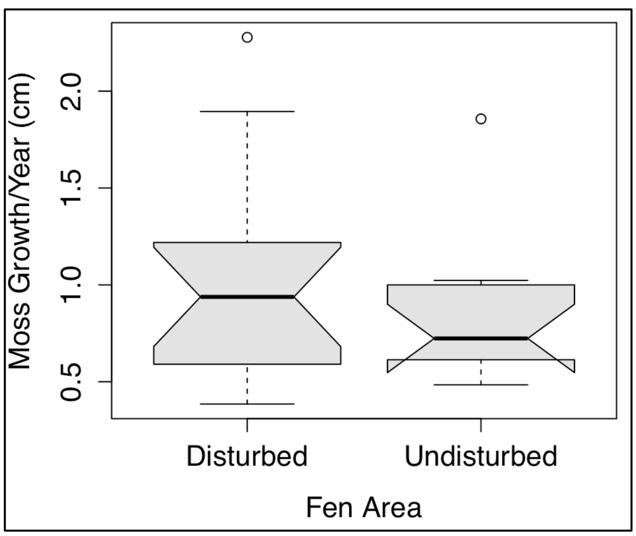

Figure 3-4: Notched boxplots representing the rates of annual moss growth in the Disturbed (<260 m up-gradient of the road) and Undisturbed (> 260 m) areas. Each measurement based off 1 sapling. Disturbed: n=15; Undisturbed: n=12. The boxplots are not significantly different according to a Kruskal-Wallis rank sum test, chi-squared=0.239, degrees of freedom = 1, p=0.625). Horizontal bars indicate minimum and maximum values, the box defines the lower and upper quartiles, and the thick horizontal line is the median. Circles are outliers in the data.

Characterization of site bulk density and hydrology

Undisturbed areas (T2 and T3) and the east side of the lower lobe (T1-E) had low soil bulk density that increased from about 0.04 g/cm^3 at the surface to 0.10 g/cm^3 at 50 cm depth. Higher bulk densities were observed down-gradient of the road (T-N), ranging from 0.06 to 0.15 g/cm^3. The most dense peat was located in the top 20 cm of the highly disturbed lower lobe west side (T1-W), where the bulk density was 0.16 g/cm^3 (Fig. 3-5). The core in T1-W was taken in an area of exposed peat, which accounts for the high bulk density values at the surface. Loose *Sphagnum* moss carpets cover the ground in other parts of the disturbed lower lobe west side.

In 2012, the water table was below the surface at all locations, except after heavy precipitation in early July caused flooding in the west of the Disturbed area (Fig. 3-6). Abundant precipitation in early June in 2013 contributed to flooding in all three locations (Fig. 3-6). From June 10th – July 4th, the culvert was blocked by beavers, which prevented the lower lobe (east and especially west) from draining. After several attempts of cleaning debris a "beaver deceiver" was installed in early July, which is a L-shaped perforated 10 cm diameter PVC tube with upright section upstream of the culvert, and horizontal section extending into the culvert. It was effective and water levels dropped especially in the west of the Disturbed area. Water levels in the western lower lobe changed by 48 cm between June 10th and July 4th. After this period, the water table in all locations was at or just above the surface. Precipitation values for 2013 as reported in Fig. 3-6 are from the Fort McMurray airport, and underrepresent precipitation values at the study fen (Table 3-1).

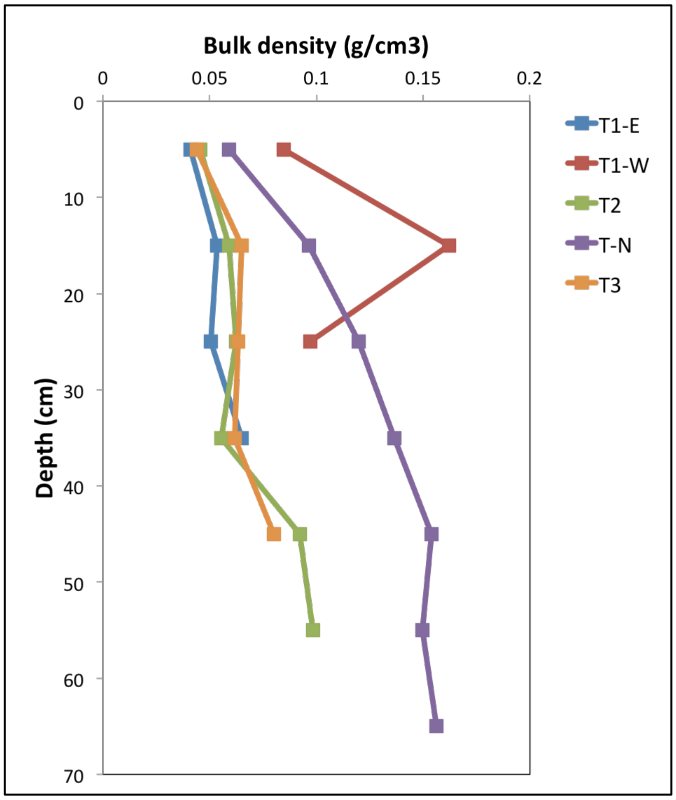

Figure 3-5: Bulk density across the fen. T1-E = lower lobe, east side; T1-W = lower lobe, west side; T2 = Undisturbed area, ~350 m from culvert; T3 = Undisturbed area, ~ 550 m from culvert; T-N = down-gradient (north) from the road. Locations of peat cores marked and labeled on site map (Fig. 3-1).

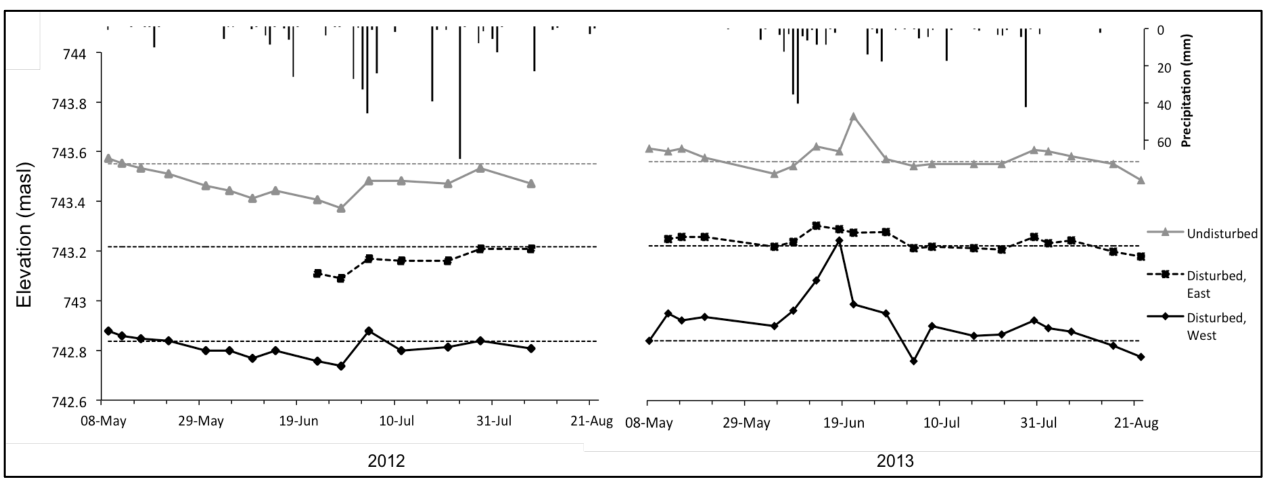

Figure 3-6: Depth to the water table in 3 groundwater wells located in the Undisturbed area (grey), the east side of the Disturbed area (dashed), and the west side of the Disturbed area (black), from 2012 and 2013. Horizontal dashed lines represent the ground surface level at each well. Precipitation values are from a tipping bucket located on site (2012) and Fort McMurray airport (all of 2013) when local data were unavailable.

Vegetation composition analysis

In the 279 vegetation plots analyzed, 73 species were identified including 3 trees, 11 shrubs, 21 grasses and sedges, 19 other vascular species and 19 bryophytes (Table 3). Every entry was identified to species except for individuals in the genera *Salix*, *Festuca*, *Juncus* and *Cladonia* (Table 3). 'Brown moss' was used to refer to rich fen species that were occasionally (12 plots) found in small patches.

The most abundant species was *Sphagnum angustifolium* found in 88.5% of the plots, and often covering 100% of the ground surface. *S. magellanicum* was the second most common moss species occurring in 44.8% of plots. *Carex aquatilis* (68.5%), *C. canescens* (21.9%) and *C. pauciflora* (14.7%) were the most common sedges. C*hamaedaphne calyculata* (63.1%), *Oxycoccus microcarpus* (59.9 %) and *Rhododendron groenlandicum* (43%) were the most common shrubs; *Picea mariana* was the most common tree species (10.8%) and *Smilacina trifolia* (53%) and *Equisetum fluviatile* (11.1%) were also common (Table 3).

The most statistically and ecologically useful variables were capitula density, hummock height, pH, temperature and distance to culvert. Of the measured environmental variables, some were eliminated because they were redundant (water table and hummock height, as well as distance to culvert and elevation are pairs that are closely related), statistically less significant such as EC ($p = 0.03$) and salt content ($p = 0.04$), or measured in few enough plots that occasional high values might overstate their importance, such as % surface water, % bare ground and % litter.

Table 3-3: Species inventory at the study site, and frequencies. Bolded entries are in the NMDS biplot (Fig. 3-7). Communities refer to the results of the cluster analysis (Figs. 8 and 9), and the representation (# of plots) of each species in each community is listed. Community 1 = Poor fen lawn; Community 2 = Poor fen hummock; Community 3 = Margin; Community 4 = Road impacted.

Species/Genus	**Community 1**	**Community 2**	**Community 3**	**Community 4**	**Total # Plots**	**% Plots**
TREE						
Picea mariana	10	4	11	5	30	10.8
Larix laricina	-	1	-	1	2	0.7
Betula papyrifera	7	1	-	4	12	4.3
SHRUB						
Andromeda polifolia	38	21	24	23	109	39.1
Betula pumila	10	8	4	12	34	12.2
Chamaedaphne calyculata	47	33	51	42	176	63.1
Kalmia polifolia	10	6	6	8	31	11.1
Oxycoccus microcarpus	52	30	51	30	167	59.9
Rhododendron groenlandicum	26	29	35	30	120	43.0

Rubus chamaemorus	12	14	30	24	80	28.7
Salix spp.	10	5	6	3	24	8.6
Vaccinium myrtilloides	3	1	1	3	8	2.9
Gaultheria hispidula	-	-	-	2	2	0.7
Vaccinium vitis-idaea	11	9	25	21	66	23.7
GRASSES and SEDGES						
Agrostis scabra	4	1	-	9	14	5.0
Beckmannia syzigachne	2	-	-	-	2	0.7
Calamagrostis canadensis	9	-	2	17	28	10.0
Carex aquatilis	70	29	53	39	191	68.5
Carex canescens	30	3	8	20	61	21.9
Carex limosa	11	5	2	6	28	10.0
Carex pauciflora	8	10	12	11	41	14.7
Carex paupercula	9	1	5	-	15	5.4
Carex rostrata	2	-	-	-	2	0.7
Carex trisperma	4	14	11	9	38	13.6
Carex utriculata	2	-	-	-	2	0.7
Eleocharis palustris	6	-	-	2	8	2.9
Eriophorum angustifolium	-	-	-	1	1	0.4
Eriophorum scheuchzeri	18	-	1	9	32	11.5
Eriophorum vaginatum	10	9	11	6	36	12.9
Festuca spp.	-	-	-	1	1	0.4
Juncus spp.	6	-	-	-	6	2.2
Poa palustris	1	-	-	-	1	0.4
Scheuchzeria palustris	16	-	-	1	17	6.1
Typha latifolia	2	-	-	3	5	1.8
Scirpus microcarpus	11	-	-	1	12	4.3
OTHER VASCULARS						
Bidens cernua	-	-	-	2	2	0.7
Callitriche verna	3	-	-	2	5	1.8
Cicuta spp.	-	-	-	1	1	0.4
Cornus canadensis	-	1	-	-	1	0.4
Drosera rotundifolia	1	1	-	-	2	0.7
Epilobium palustre	3	-	2	1	6	2.2
Equisetum fluviatile	21	2	-	8	31	11.1
Equisetum palustre	6	-	-	-	6	2.2
Equisetum pratense	6	1	0	2	9	3.2
Equisetum sylvaticum	1	4	9	6	20	7.2
Galium boreale	-	-	-	2	2	0.7
Hippuris vulgaris	6	-	-	2	8	2.9
Menyanthes trifoliata	3	3	-	-	6	2.2
Potamogeton perfoliatus	1	-	-	-	1	0.4
Potentilla palustre	-	-	2	-	2	0.7
Ranunculus aquatilis	1	-	-	1	2	0.7
Sarracenia purpurea	3	-	-	1	4	1.4
Smilacina trifolia	51	30	49	16	148	53.0
Sparganium spp.	4	-	-	1	5	1.8
MOSS						
Aulacomnium palustre	12	3	9	13	37	13.3
Cladonia spp.	-	-	-	1	1	0.4
Dicranum undulatum	-	-	-	2	2	0.7
Pleurozium schreberi	-	4	7	10	21	7.5
Polytrichum commune	0	3	6	4	13	4.7
Polytrichum strictum	18	1	2	5	26	9.3

Pohlia nutans	2	3	4	1	10	3.6
Ptilium crista-castrensis	-	-	-	1	1	0.4
Sanionia uncinata	10	-	-	5	15	5.4
Sphagnum angustifolium	81	46	62	54	247	88.5
Sphagnum capillifolium	3	-	-	2	5	1.8
Sphagnum fallax	2	-	-	-	2	0.7
Sphagnum fuscum	16	5	13	10	44	15.8
Sphagnum magellanicum	31	28	39	24	125	44.8
Sphagnum riparium	12	-	1	-	13	4.7
Sphagnum russowii	13	13	21	7	54	19.4
Sphagnum squarrosum	4	-	-	1	5	1.8
Sphagnum wulfianum	-	-	-	1	1	0.4

The species are organized along a gradient approximated by distance to the culvert on the NMDS biplot (Fig. 3-7). Furthest from the culvert are three clusters of poor fen species. At the top, negatively correlated with pH, are *Menyanthes trifoliata*, *Sarracenia purpurea*, *Eriophorum scheuchzeri* and *Scheuchzeria palustris*. These were all found in areas of low pH in lawns or hollows. The second cluster, more closely related to higher moss capitulum densities, is *Betula pumila, C. pauciflora, S. angustifolium, Larix laricina* and *Smilacina trifolia*. This was a common community in moderately hummocky areas. The last poor fen cluster, which is most correlated with hummock height, contains *Vaccinium myrtilloides, Sphagnum capillifolium, Pleurozium schreberi, Rubus chamaemorus, Rhododendron groenlandicum*, *V. vitis-idaea*, *Picea mariana* and *S. fuscum* (not shown). These species are characteristic of the driest plots in the fen.

pH is another significant gradient. *Calamagrostis canadensis*, *Equisetum pratense*, *Salix* spp. and *B. papyrifera* are positively related to higher pH values, and there is a negative relationship between pH and the previously mentioned poor fen clusters, which exist in more acidic conditions. On the far left of the plot are the species that are only found closest to the culvert, such as *Potamogeton perfoliatus*, *Callitriche verna*, *Cicuta* spp., *Bidens cernua* and *Typha latifolia*. These species are only found within 50 m of the culvert, according to the contour lines on the biplot that represent distance to the culvert. On the opposite end of the gradient, the poor fen species are not often found closer to the culvert than 250 m (Fig. 3-7). In the middle of the biplot are several *Carex* species that are negatively correlated with hummock height such as *C. rostrata*, *C. canescens* and *C. paupercula*. These sedge species were common on tussocks or lawns, but rarely on hummocks. *S. fallax* is most strongly correlated with temperature, because it was usually found in plots with open water. *S. wulfianum* is negatively correlated with temperature because it was found in large hummocks in margin communities with a dense tree canopy, where it was cooler.

There is overlap between the four communities identified by the cluster analysis (Fig. 3-8a). Community 1 is negatively correlated with pH, and to a lesser degree with hummock height and water table. Community 3 is positively correlated with hummock height and water table. On the NMDS biplot, Community 2 is between, and overlaps with, communities 1 and 3, suggesting that these groups coexist spatially. Community 2 is most highly correlated with capitula density. Community 4 is the most distinct of the four groups and is positively correlated with pH, surface water and temperature.

When the spatial distributions of the four communities are mapped it is clear that Community 3 is a margin community (Fig. 3-8b). The fourth community is clustered close to the road, and in other areas where there is a high percentage of standing water. The first two groups are poor fen communities divided by microtopography (1=lawn, 2=hummock). Boxplots representing the range of plot microtopography show that hummock height is a key factor in determining community type (Fig. 3-9).

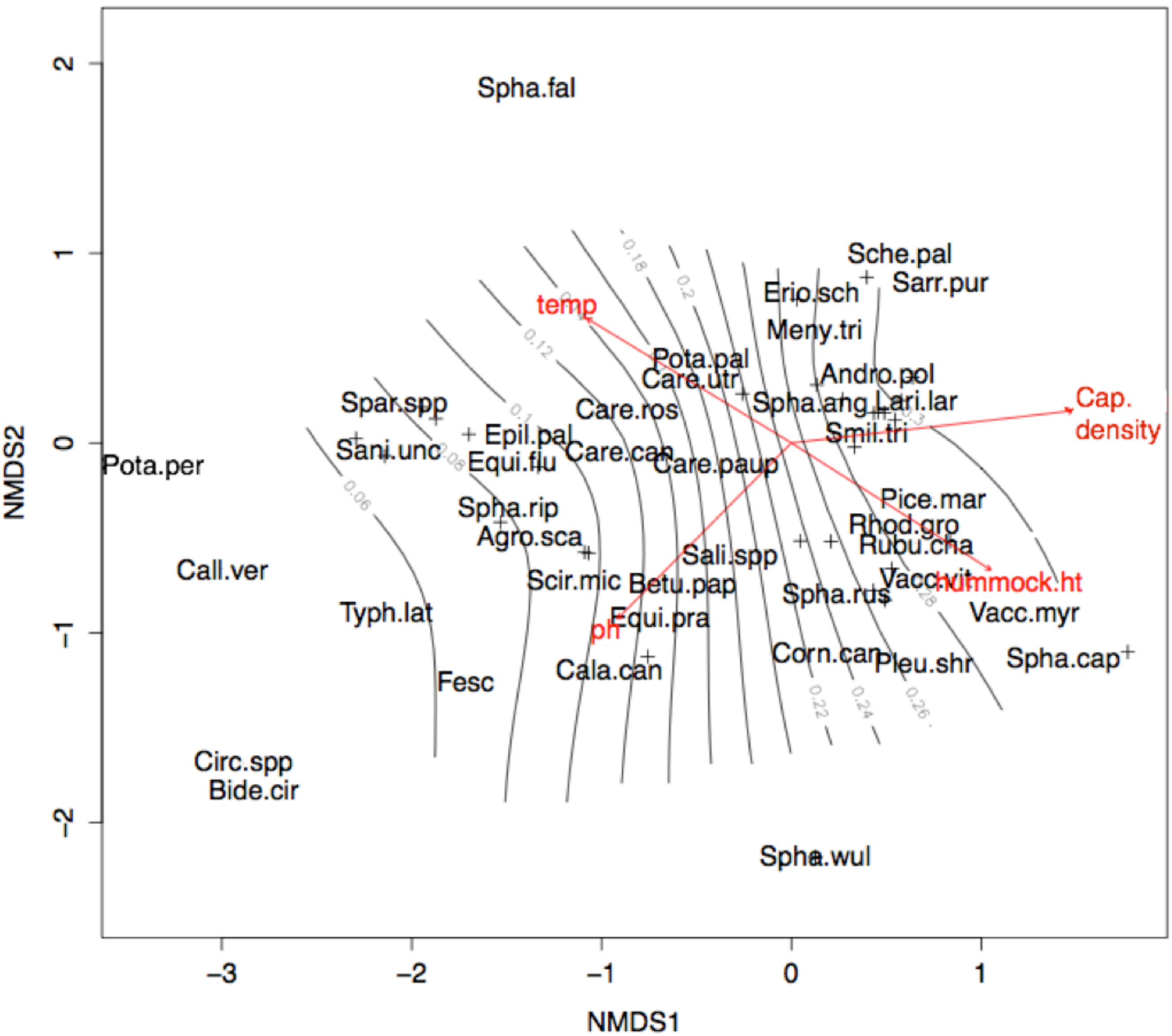

Figure 3-7: NMDS plot of 73 species from 279 vegetation plots, selected abiotic variables (red vectors) and distance to the culvert in km (contour lines). For clarity, only the most abundant species are displayed. Temp = temperature, hummock.ht = hummock height (cm), cap. density = Sphagnum capitula/cm², ph = pH. Vectors are significant (p<0.01). Stress = 0.12. Distances are calculated with Bray-Curtis dissimilarity. Refer to Table 3 for full species name (bolded in table).

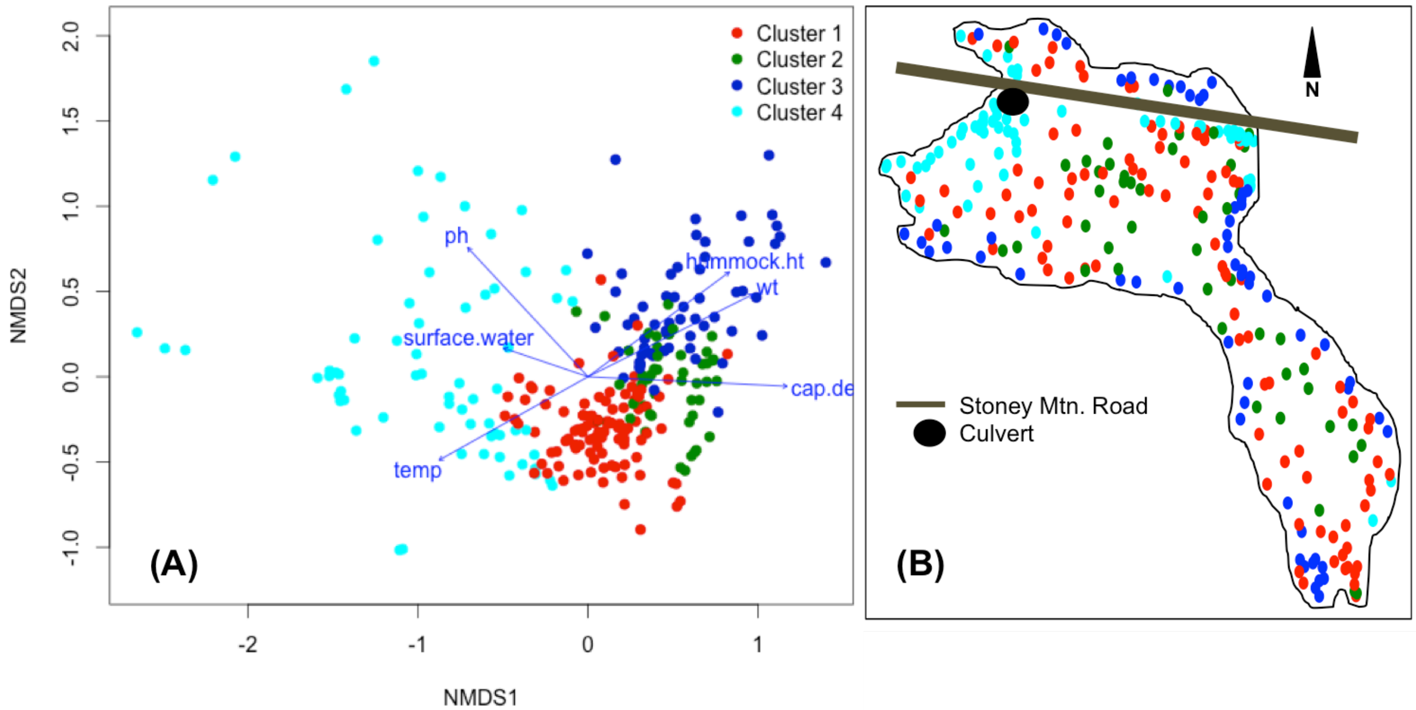

Figure 3-8: Results of Ward's Minimum Variance cluster analysis. Distances are calculated with Bray-Curtis dissimilarity. Points are coloured according to results of cluster analysis. (A): NMDS biplot of 279 vegetation plots and selected abiotic variables (blue vectors). Temp = temperature, hummock.ht = hummock height (cm), cap.de = Sphagnum capitula/cm², ph = pH, wt = depth to water table (cm), surface.water = % standing water in plot at time of measurement. Vectors are significant (p<0.01). Stress = 0.12. (B): Spatial distribution of vegetation plots divided into first 4 clusters, overlain on map of the study site.

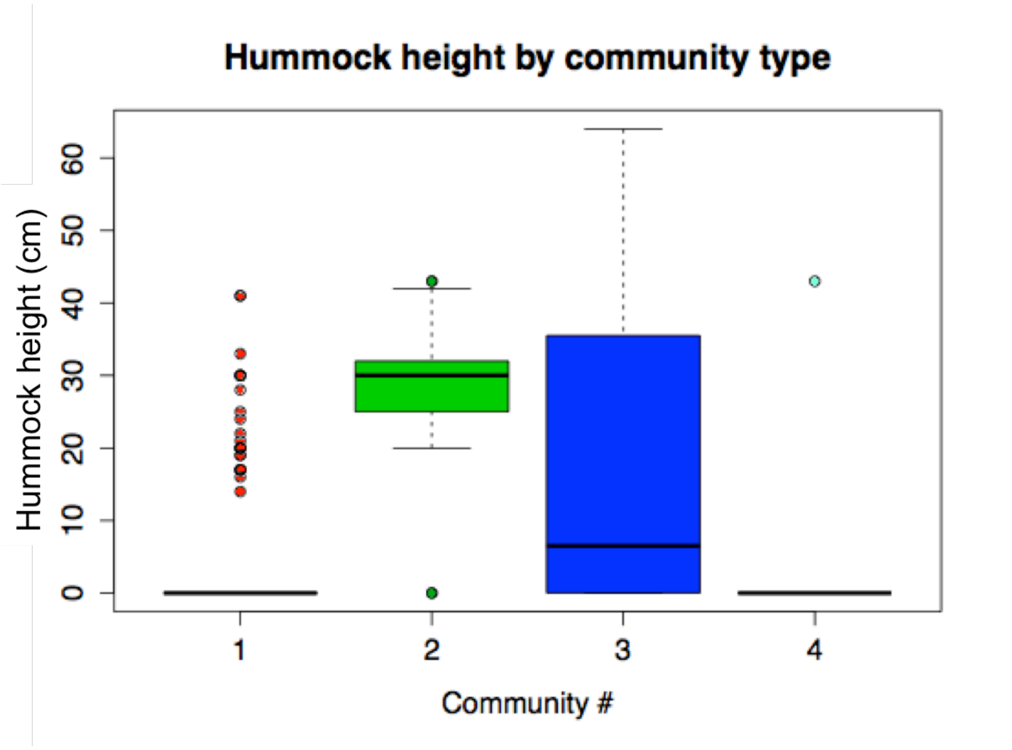

Figure 3-9: Boxplots of the distribution of hummock heights in the first 4 vegetation communities identified in the dendrogram (Appendix 3). 1 = poor fen lawn, 2 = poor fen hummock, 3= fen margin, 4 = road impacted. Horizontal bars indicate minimum and maximum values, the box defines the lower and upper quartiles, and the thick horizontal line is the median. Circles are outliers in the data.

3.6 Discussion

The role of hydrology in regulating peat structure and vegetation

In peatlands, hydrology, vegetation and microtopographic structure influence each other, and ultimately determine the system's development. The contrast in vegetation composition in the fen is in part due to differences in peat physical properties, which can influence local hydrology during and after flooding events. While most of the fen, including the eastern lower lobe, is characterized by thick deposits of moderately decomposed peat, the peat near the culvert is dense (Fig. 3-5). When drainage through the culvert is impeded, water levels rise quickly after high precipitation events, because the dense peat has lower storativity (Waddington et al., 2010). Flooding at this location is exacerbated by hillslope runoff from an ephemeral stream that itself is likely an artifact of the road. When the culvert is not blocked, water levels decrease rapidly, because the specific yield in the dense peat is low. The vegetation also plays an important role. Large lawns of loose *Sphagnum* grow rapidly under wet conditions, but hold little water during dry conditions (Rochefort et al., 2002), further decreasing the area's water retention capabilities. The rapid rise and fall of water levels was visible over a two-week period in June-July 2013, when the water table changed by 48 cm after the culvert was blocked and subsequently cleared (Fig. 3-6). This area is also the lowest elevation. It is the most vulnerable to flooding from culvert blockage, since water levels must rise substantially higher to impact other areas. Theoretically, this occurred at least once in the 1980s to cause substantial tree dieback (Chapter 2). However, local disturbances near the culvert likely occur more frequently. These repeated disturbances and fluctuating water levels have impacted the vegetation in a way that may be impacting ecological succession.

Defining and characterizing disturbed versus undisturbed areas

The fen was partitioned on the basis of the proportion of dead trees, in which areas with over 50% mortality were defined as being Disturbed. Accordingly, the line between Undisturbed and Disturbed was placed 260 m up-gradient of the road at the mouth of a narrow saddle in the fen (Fig. 3-1 and Fig. 3-2). South of this line and up-gradient from the road the fen is undisturbed.

Vegetation in the Undisturbed area is typical of other poor fens in the region (i.e. Nicholson & Vitt, 1990 [Mariana Lakes]; Nicholson & Vitt, 1994 [Elk Island National Park]), and there is a mixture of lawn and hummock communities (Table 3; Fig. 3-8). The average hummock height is 16 cm. Water levels are highest during snowmelt, and generally decrease towards the end of summer, increasing again in the fall (Fig. 3-6; Wells, unpublished data). Tree cover is discontinuous and stunted, but the proportion of saplings is high at 57% (Table 2).

While tree mortality is uniformly high in the Disturbed zone, it is heterogeneous in other respects. This lobe can be split into two halves: west (closer to the culvert) and east. On the east side, the vegetation more closely resembles that found in the Undisturbed area, with the addition of some lawn species such as *Carex limosa* and *C. paupercula*. An entirely open and mostly flat expanse in the center has a dense cover of *Eriophorum* spp., fringed by a unique and locally rare (Alberta rank S1S2) community of *Andromeda polifolia*, *S. angustifolium* and *Sarracenia purpurea* (pitcher plants) (Allen, 2012). The average hummock is 15 cm tall, and the large hummocks support some black spruce sapling regeneration (Table 2). Water levels are on average shallower than in the Undisturbed area, but consistent, with little seasonal fluctuation (Fig. 3-6). All of the mature trees were dead, but tree mortality is only 78% because of some sapling regeneration.

The vegetation in the more highly disturbed western half of the lower lobe is distinct, not only from the east of the lobe but also from the rest of the fen. It has the largest representation of the fourth community identified by the cluster analysis (Fig. 3-8), which is characterized by lawn or tussock microtopography but not *Sphagnum* hummocks, and species not usually found in poor fens, such as *Calamagrostis canadensis*, *S. squarrosum, Carex rostrata* and several aquatic species found only near the culvert such as *Potamogeton perfoliatus* (pondweed). There are no saplings, and 100% tree mortality (Table 2). During most years, water levels are comparable in variability to those measured in the Undisturbed area further south in the fen (Fig. 3-6).

The role of the road in determining vegetation distribution

Distance to the culvert is an important variable that determines species distribution in the fen, with most poor fen indicator species appearing 220 m away from the culvert (Fig. 7). However, this is an artificial gradient. Vegetation is ordered along a hydrological gradient, which in this study is most reliably approximated by hummock height, because it is highly correlated with depth to the water table (Fig. 8a). Hummock height is positively correlated with distance from the culvert, because microtopographic variation increased away from the culvert. Community 4, the group of vegetation plots closest to the road, is characterized by lawns and sedge tussocks with one recorded *Sphagnum* hummock (Fig. 9). Microtopographic variability is an important driver in peatland development because the combination of hummocks and hollows provide multiple habitats along a hydrologic gradient that encourages species diversity (Økland et al., 2008; Little et al., 2010; Campbell & Bergeron, 2012). The vegetation found closest to the culvert are not poor fen indicator species, and they are not hummock forming, e.g. *Carex rostrata* or *S. riparium*. Hydrological variability and high water tables favoured rapid moss growth of lawn species such as *S. riparium* and *S. squarrosum* that have in-filled and smothered the pre-existing hummocks in this highly disturbed area. Recent moss growth in the most disturbed areas is up to 34.7 cm higher than the site average, which has completely impeded the growth of new *P. mariana* trees close to the culvert (Table 2; Fig. 2). Saplings require dry hummock tops for germination, and their root structure supports further hummock growth (Pouliot et al., 2011). Their absence is evidence that microtopographic variability has decreased, and is also an indicator that succession has taken place. Not only are there no hummocks, but also the necessary biotic and abiotic conditions for hummock formation are not available.

Flooding creates species diversity by creating new, often more nutrient-rich and less acidic environments that are favourable to a higher diversity of species than is usually found in acidic peatlands (Asada et al., 2005). Road construction and the resulting ponding at this study site led to the creation of niches that are filled with species that otherwise would not exist at this site, such as *Scirpus* spp. and *Hippuris vulgaris*.

Determining the fen's successional pathway

Road construction and subsequent flooding has caused a shift in the vegetation communities that has altered the development of the system. The culvert design makes it vulnerable to repeated blockages that have introduced an artificial cycle of flooding and drainage. On a short timescale, continual disturbance near the culvert will likely continue as long as the culvert is repeatedly blocked, and continual flooding will slow, or even reverse, succession (Eppinga et al., 2009; Granath et al., 2010). One of the key indicators that succession has occurred is the lack of spruce regeneration, compared with other areas in the fen that experienced similar rates of tree dieback, such as in the east of the Disturbed lower lobe (Table 2).

Given enough time and if there are no further significant disturbances, it is likely the entire system would regain the vegetative structure of a poor fen. The widely accepted successional trajectory of peatlands is a transition along a minerotrophic to ombrotrophic gradient, and many systems have evidence of a sedge-dominated, wet stage at the beginning of their development (Nicholson & Vitt, 1994; Glaser et al., 2004). High water tables and low microtopographic relief facilitates extensive *Carex* coverage over hummock-forming species, but over time, there will be a thick enough layer of sedge peat to raise the surface above the water level and encourage hummock-forming species (Caners & Lieffers, 2014). The same theory was applied to the active restoration of well pads in northern Alberta, by planting *C. aquatilis* on a mineral layer close to the water level, to mimic early successional stages of peatland development (Vitt et al., 2011).

Implications for constructed peatland systems

An increased understanding of peatland succession after disturbance can improve designs for constructed fen peatland systems. Frequent flooding events and high water tables favor the growth of non-hummock forming species. If hummock communities are desired in a constructed system, the abiotic conditions must favor the growth of hummock-forming species, including trees and shrubs whose roots provide structure (Pouliot et al., 2011). As seen in this study, occasional flooding events are enough to impact vegetation structure, even if the system dries out the following year. One year of sustained flooding can cause tree dieback, and regular flooding events discourages the regeneration of saplings. In recently constructed systems with undeveloped vegetation, exposed, wet peat or ponded areas are easily colonized with fast-growing species like *Typha latifolia* that have a high tolerance to a range of abiotic conditions (Bourgeois et al., 2012). To encourage the establishment of fen species, it is advised to regulate water tables to avoid hydrological flashiness that ultimately favor non hummock-forming vegetation communities. Active restoration of microtopographic relief and lowering water tables have been shown to speed the succession of reclaimed well-pads by providing habitat for hummock-forming species (Caners & Lieffers, 2014).

3.7 Conclusions

Road construction at the study site created impounded conditions that led to large-scale dieback of black spruce, and a change in vegetation community structure. The culvert design is vulnerable to repeated blockages because it is too small to adequately drain sediment from the fen and surrounding hillslopes. Dense peat combined with loose *Sphagnum* moss carpets close to the culvert contribute to low storativity that facilitates rapid flooding and also rapid drainage. This increased hydrological flashiness favors non-hummock forming species of *Sphagnum* and *Carex* that have in-filled and replaced the pre-existing hummock communities. Rapid moss growth, occasional flooding and the infilling of hummocks discourage regeneration of black spruce saplings. Currently, the abiotic conditions are not conducive to hummock-forming species, and the lack of microtopographic variation is a sign that succession has occurred.

Contemporary road building techniques take into account the importance of maintaining hydrologic flow regimes in wetland systems. To avoid impoundment, they can be built of semi-porous material, or with multiple evenly spaced culverts. Ideally, the culvert would be dredged frequently to avoid blockage by sediment or beaver dams.

Over time, the build up of sedge peat above the water table could create conditions that favour the growth of hummock-forming species.

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4.0 Conclusions & Implications

This study used a multidisciplinary approach to analyze the impacts of road construction on the development of a poor fen. Growth rings from several peatland trees were used as a proxy for recent recent hydrological change, and dead trees were cross-dated to determine the timing of large flooding events that caused the dieback. After establishing the rate and spatial extent of hydrological disturbance from road construction, the vegetation and several abiotic variables including seasonal water table fluctuation, peat bulk density and water chemistry were measured to analyze the impact of this hydrological change on the successional pathway of the fen.

Most of the peatland trees died in 1989, a decade after road construction began at the study site in 1977. The road was constructed with one culvert that allowed surface water to flow from the peatland. However, the narrow culvert made it vulnerable to blockage from sediment or beaver dam building activity, and the eventual blocking of the culvert apparently led to widespread and sustained flooding that drowned hundreds of trees. Relative elevation above the culvert top was the most important predictor of temporal and spatial patterns of tree dieback. The uniformity of dieback below the elevation threshold of 83.5 cm is an indicator of water level height when the fen was flooded. Trees with root crowns above this elevation survived because their roots were not in the saturated zone for a prolonged period of time. That most of the trees in a large area died in one year suggests a single widespread flooding event rather than a gradual rise in water table after road construction. A single flooding event is supported by the average ring widths from the dead trees, which show a rapid, rather than gradual decline in growth in the late 1980s.

Single interval correlation analysis between tree rings and climate variables suggest an environment that became saturated even with little precipitation, and dried out quickly when precipitation decreased. Dense peat combined with loose *Sphagnum* moss carpets close to the culvert contribute to low storativity that facilitates rapid flooding and also rapid drainage. This was seen in early July 2013, when water levels in the most disturbed area fluctuated by 48 cm in a two-week period, when the culvert was blocked and subsequently unblocked. This increased hydrological flashiness favors non-hummock forming species of *Sphagnum* and *Carex* that have in-filled and replaced the pre-existing hummock communities. Rapid moss growth, occasional flooding and the in-filling of hummocks discourage regeneration of black spruce saplings.

Currently, the abiotic conditions are not conducive to hummock-forming species, and the lack of microtopographic variation is a sign that succession has occurred.

Within 250 m up-gradient of the road, there was both widespread tree dieback and a shift in vegetation communities. The NMDS analysis revealed that poor fen communities characteristic of hummocks and hollows are most prominent 250 m from the road, with lawn and tussock species more common within the disturbed area. The flooding event that caused tree dieback continues to have an influence on vegetation composition. Occasional flooding events can impact the development of a system, even if the system is not permanently flooded.

Road construction at the study site created impounded conditions that led to large-scale dieback of black spruce, and a change in vegetation community structure. The culvert design is vulnerable to repeated blockages because it is too small to adequately drain sediment from the fen and surrounding hillslopes. Contemporary road building techniques take into account the importance of maintaining hydrologic flow regimes in wetland systems. To avoid impoundment, they can be built of semi-porous material, or with multiple evenly spaced culverts. Ideally, the culvert would be dredged frequently to avoid blockage by sediment or beaver dams.

An increased understanding of peatland succession after disturbance can improve designs for constructed fen peatland systems. Frequent flooding events and shallow water tables favor the growth of non-hummock forming species. If hummock communities are desired in a constructed system, the abiotic conditions must favor the growth of hummock-forming species, including trees and shrubs whose roots provide structure. Flooding of the system, whether gradually or rapidly, impacts succession because it favors vegetation that can survive in intermittently flooded conditions, rather than trees such as black spruce. To encourage the establishment of fen species, it is advised to regulate water tables to avoid hydrological flashiness that ultimately favor non hummock-forming vegetation communities. A constructed fen peatland system should be designed to allow water to flow freely out of the system without relying on a single drainage outflow point. Much of the support infrastructure associated with oil sands development is composed of linear features, many of which are constructed on peatlands. Maintaining the integrity of natural hydrologic regimes is a key component in reducing the ecological impact of these disturbances.

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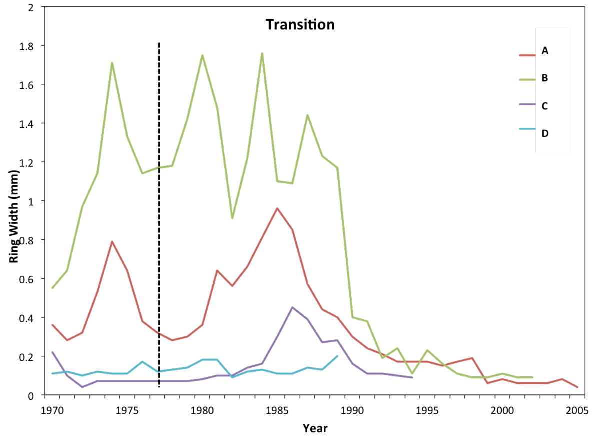
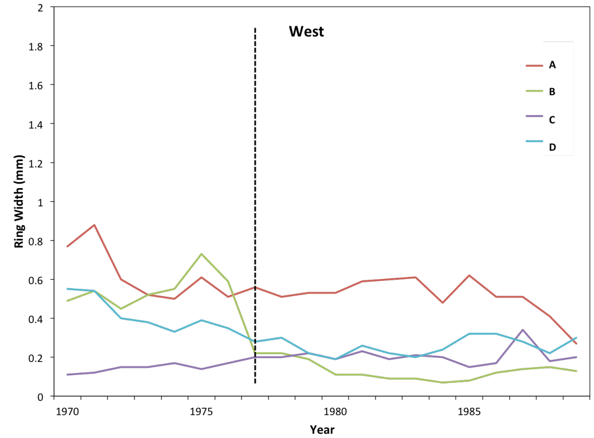
Appendix 1

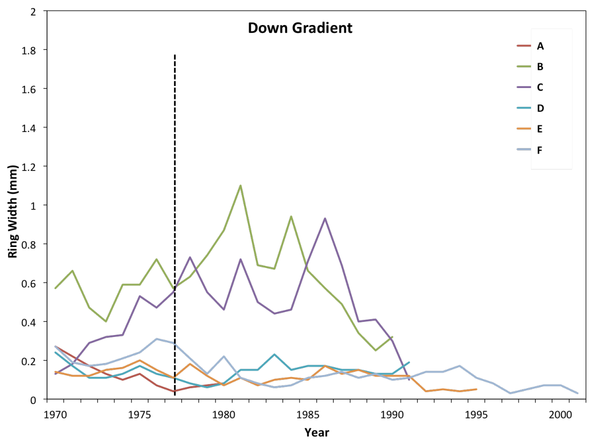
	Transition				East				Middle				West					Down-gradient				
Year	**D1**	**D2**	**D3**	**D4**	**D7**	**D8**	**D9**	**D10**	**D13**	**D14**	**D15**	**D16**	**D18**	**D20**	**D22**	**D23**	**D25**	**D26**	**D27**	**D28**	**D29**	**D30**
1970	0.36	0.55	0.22	0.11	0.28	0.25	0.34	0.4	0.37	0.11	0.26	0.21	0.77	0.49	0.11	0.55	0.27	0.57	0.13	0.24	0.14	0.27
1971	0.28	0.64	0.1	0.12	0.32	0.33	0.37	0.65	0.46	0.17	0.28	0.36	0.88	0.54	0.12	0.54	0.22	0.66	0.18	0.17	0.12	0.19
1972	0.32	0.97	0.04	0.1	0.21	0.3	0.35	0.59	0.48	0.19	0.3	0.24	0.6	0.45	0.15	0.4	0.17	0.47	0.29	0.11	0.12	0.17
1973	0.53	1.14	0.07	0.12	0.25	0.45	0.42	0.51	0.45	0.22	0.35	0.25	0.52	0.52	0.15	0.38	0.13	0.4	0.32	0.11	0.15	0.18
1974	0.79	1.71	0.07	0.11	0.32	0.77	0.34	0.63	0.38	0.28	0.53	0.24	0.5	0.55	0.17	0.33	0.1	0.59	0.33	0.13	0.16	0.21
1975	0.64	1.33	0.07	0.11	0.42	0.62	0.37	0.73	0.27	0.54	0.87	0.2	0.61	0.73	0.14	0.39	0.13	0.59	0.53	0.17	0.2	0.24
1976	0.38	1.14	0.07	0.17	0.38	0.52	0.4	0.53	0.2	0.36	1.03	0.24	0.51	0.59	0.17	0.35	0.07	0.72	0.47	0.13	0.15	0.31
1977	0.32	1.17	0.07	0.12	0.36	0.42	0.31	0.49	0.22	0.29	1.27	0.17	0.56	0.22	0.2	0.28	0.04	0.57	0.55	0.11	0.11	0.29
1978	0.28	1.18	0.07	0.13	0.34	0.58	0.29	0.71	0.18	0.2	1.63	0.2	0.51	0.22	0.2	0.3	0.06	0.63	0.73	0.08	0.18	0.21
1979	0.3	1.42	0.07	0.14	0.28	0.5	0.2	0.56	0.12	0.17	1.14	0.22	0.53	0.19	0.22	0.22	0.07	0.74	0.55	0.06	0.12	0.13
1980	0.36	1.75	0.08	0.18	0.27	0.5	0.2	0.4	0.17	0.28	1.05	0.22	0.53	0.11	0.19	0.19	0.08	0.87	0.46	0.08	0.07	0.22
1981	0.64	1.48	0.1	0.18	0.47	0.54	0.18	0.43	0.25	0.31	0.68	0.22	0.59	0.11	0.23	0.26		1.1	0.72	0.15	0.11	0.11
1982	0.56	0.91	0.1	0.09	0.3	0.43	0.16	0.39	0.26	0.28	0.23	0.17	0.6	0.09	0.19	0.22		0.69	0.5	0.15	0.07	0.08
1983	0.66	1.22	0.14	0.12	0.23	0.56	0.16	0.5	0.34	0.27	0.16	0.18	0.61	0.09	0.21	0.2		0.67	0.44	0.23	0.1	0.06
1984	0.81	1.76	0.16	0.13	0.32	0.96	0.26	0.33	0.45	0.35	0.5	0.13	0.48	0.07	0.2	0.24		0.94	0.46	0.15	0.11	0.07
1985	0.96	1.1	0.3	0.11	0.36	0.71	0.25	0.26	0.53	0.36	0.84	0.18	0.62	0.08	0.15	0.32		0.66	0.71	0.17	0.1	0.11
1986	0.85	1.09	0.45	0.11	0.36	0.81	0.4	0.17	0.63	0.36	1.29	0.21	0.51	0.12	0.17	0.32		0.57	0.93	0.17	0.17	0.12
1987	0.57	1.44	0.39	0.14	0.42	0.75	0.19	0.13	0.33	0.39	1.14	0.22	0.51	0.14	0.34	0.28		0.49	0.69	0.15	0.13	0.14
1988	0.44	1.23	0.27	0.13	0.28	0.75	0.21	0.14	0.19	0.39	1.9	0.2	0.41	0.15	0.18	0.22		0.34	0.4	0.15	0.15	0.11
1989	0.4	1.17	0.28	0.2	0.34	0.59	0.19	0.18	0.09	0.35	1.91	0.23	0.27	0.13	0.2	0.3		0.25	0.41	0.13	0.12	0.13
1990	0.3	0.4	0.16						0.07	0.3	0.35							0.32	0.3	0.13	0.12	0.1
1991	0.24	0.38	0.11							0.22	0.63								0.1	0.19	0.12	0.11
1992	0.21	0.19	0.11							0.21	0.42										0.04	0.14
1993	0.17	0.24	0.1							0.16	0.48										0.05	0.14
1994	0.17	0.11	0.09							0.22	0.24										0.04	0.17
1995	0.17	0.23								0.56	0.19										0.05	0.11
1996	0.15	0.16								0.81	0.14											0.08
1997	0.17	0.11								0.84	0.09											0.03
1998	0.19	0.09								0.49	0.09											0.05
1999	0.06	0.09								0.25	0.08											0.07
2000	0.08	0.11								0.69	0.09											0.07
2001	0.06	0.09								1.58	0.09											0.03
2002	0.06	0.09								1.29	0.17											
2003	0.06									0.74												
2004	0.08									0.27												
2005	0.04									0.45												
2006										1.02												
2007										0.82												
2008										0.9												

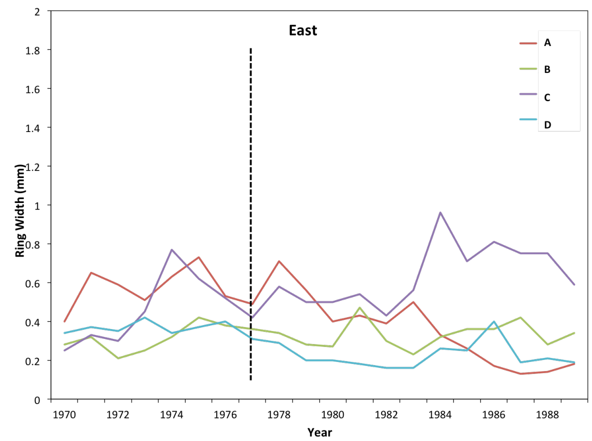
Appendix 1: Raw ring width values between 1970-2008 for all of the dead cross-dated trees.

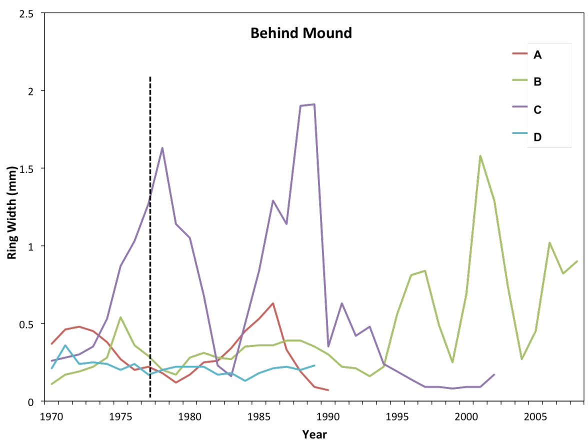
Appendix 2





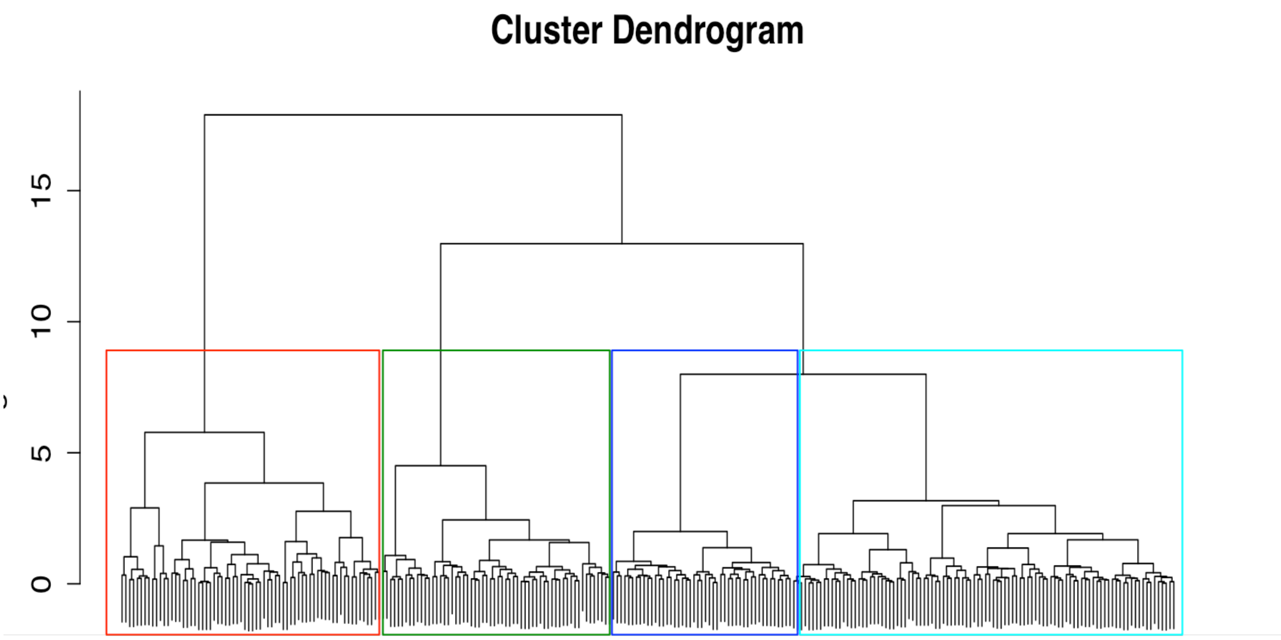






Appendix 2: Raw ring widths of dead trees, grouped by location in the fen. Locations marked in Fig. 7. Dotted line marks 1977, the year when road construction began. Each line represents one tree.

Appendix 3



Appendix 3: Cluster dendrogram of vegetation composition, using Bray-Curtis dissimilarity, and Ward's Minimum Variance clustering. Coloured boxes mark the four communities subjectively identified by cluster size.