Changes in peatland plant community composition and stand structure due to road induced flooding and desiccation

by

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Abstract:

Roads built through peatlands with horizontal water flow can to act as dams that affect local hydrology and thus vegetation composition and structure. On the 'upstream' side of roads, soils can become waterlogged causing either increased tree mortality, or stunted tree growth; conversely, the 'downstream' side may experience drying resulting in deeper root growth and increased canopy cover. Interestingly, this phenomenon is not consistent between classes of peatlands (i.e. bogs, fens, and swamps) and comparable roads may disrupt tree growth patterns in one peatland, while another may be unaffected. This study examines the conditions that maintain or alter stand structure and vegetation composition in different types of road-bisected peatlands, namely that of landscape position and mineral soil substrate composition (clay, sand, silt). I assessed tree stand structure for 96 peatlands in northeast Alberta using airborne LiDAR-derived canopy cover. Vegetation data were collected for 25 peatland sites in northeastern Alberta. These sites were subsampled with 4 plots per peatland, one pair adjacent to the road, reflecting the dry versus wet conditions, and a second pair 100 meters from the road. Generalized Linear Mixed Models (GLMMs) and distance-based redundancy analyses were used to evaluate relationships between LiDAR-derived canopy cover, vascular plant species richness, vegetation cover among different groups of species or species indicators, and overall species composition among different peatland types, environmental factors, landscape postion, and road characteristics. Canopy cover and tree species composition increased on the downstream side of roads and decreased on the upstream side of roads. Species richness increased in bogs on the upstream side of roads, while being comparably lower on the upstream side than on the downstream side of roads in fens. *Carex limosa, Carex canescens*, and *Andromeda polifolia* were identified as indicators of the upstream side of roads in fens, swamps, and bogs respectively, with significant differences confirmed in GLMMs. Substrate conditions below the peat further affected responses of plants, with ericaceous shrubs positively related to amount of clay, while some forbs and sedges were positively related to amount of sand. Substrate underlying the peat also influenced the effect that roads had on species composition. Bogs developed over substrates with high sand content had floristic shifts on the upstream side of the road whereas vegetation communities were similar on both sides of the road in bogs with very little sand. This study demonstrates the value of LiDAR-derived vegetation structure metrics in evaluating changes in woody vegetation structure for road-fragmented peatlands and that wetland classifications stratified with surficial geology can be a useful indicator of responses of vegetation to roads. However, responses were variable among sites due to interactions between road orientation, substrate texture, landscape position, and peatland type.

Preface:

Chapter 2 and 3 of this thesis will be submitted for publication by C.N. Willier, K.J. Devito, and S.E. Nielsen. I was responsible for concept formation, data collection, analysis and the manuscript composition. S. E. Nielsen assisted with concept formation, analysis and edits of manuscript, while K.J. Devito assisted with concept formation and edits of manuscript.

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Chapter 1: General Introduction

1.1 Background

Peatlands are wetlands that have rates of peat accumulation which greatly exceed their rates of peat decomposition. For this reason, peatlands are capable of influencing their own growing conditions through a number of positive feedbacks (Vitt, 1994; Waddington et al., 2015). Peatlands maintain a high water table for the majority of the growing season with excess water being a limiting factor for tree and shrub growth (Funk et al., 1994). Depending on the depth to water table and how long these levels are sustained, trees and most woody vegetation in peatlands may not survive or dominate the site. Aquatic sedges and sphagnum mosses are often better adapted to consistent high water tables. Peatlands also vary in their water chemistry from mildly basic to highly acidic in pH influencing the nutrients available to plants. Ultimately, water pH and the position of the water table, which are the products of hydrologic inputs, affect peatland community assemblage (Chee and Vitt, 1989).

The water balance influences the spatial and temporal fluctuations in the water table, while the origins of these inputs influence their water chemistry. When a road is constructed through a wetland it can disrupt hydrologic linkages, acting as a dam by increasing the water table on one side and lowering the water table on the other, resulting in changes in vegetation composition (Gillies, 2011; Siegel and Glaser, 1987). An increased water table can result in a shallower rooting zone with a high rate of mortality for trees established prior to road construction (Asada et al., 2005). This flooding can be compared to the disturbances caused by beavers, where an area previously forested becomes waterlogged and the trees die.

A drop in the water table can also result in a much deeper rooting zone with existing trees growing larger and establishment of new species, such as aspen and poplar, that could not survive before construction (Miller et al., 2015; Minkkinen et al., 1999). Figure 1-1 shows an example of a peatland with flooding on one side and drying on the other.

However, the effects of roads on peatland hydrology is highly variable. Not every road through a peatland causes these contrasting patterns of flooding and drying (Gillies, 2011). Likewise, the degree and extent of this effect is highly variable (Miller et al., 2015).

This thesis focuses on the changes in vegetation composition and structure associated with road impacts to hydrologic linkages in peatlands (including swamps). The overall goal of this thesis is to identify the environmental and landscape conditions under which road fragmentation of peatlands causes structural and compositional changes in vegetation.

1.2 Conceptual model

My conceptual model of road impacts is comprised of four environmental and road features. The first is accumulation, which is how much water is in the peatland. The second is connectivity which is the ability for water to move through the peatland. I also considered the road orientation to longest axis of the wetland, in other words the main flow direction, and the type of vegetation growing in the wetland which we will referred to as peatland type. (Figure 1-2) (Table A2-1).

1.3 Hierarchy of controls

To understand the changes in peatland vegetation associated with the presence of roads, one must consider the conditions that form and maintain a peatland. By identifying the environmental and landscape conditions that maintain and influence both vegetation and its structure, we are also identifying the factors that determine changes to peatland vegetation.

To define each wetland, I consider a hierarchy of controls in which subsequent variables affect changes in the system's vegetation composition and structure. Specifically, I hypothesize that the presence of one type of variable will influence the magnitude of responses caused by another. I predict that these interactions will result in the creation of distinct differences in vegetation composition and structure.

1.4 Peatland Classification

Peatland communities are strongly affected by hydrology and water chemistry with peatland classification based on plant community assemblage (i.e. the Alberta Wetland Classification System or the Ducks Unlimited Enhanced Wetland Classification). In fact, Vitt (1989) suggests that peatland hydrology can be inferred from vegetation and attributes specific hydrologic characteristics to four different classes of peatlands outlined below.

1.4.1 Bogs

Nutrient poor bogs, which are characterized by having low plant diversity, are dominated primarily by sphagnum mosses, black spruce trees, and ground lichen. They receive water primarily through precipitation and thus have isolated and stagnant water. because rainwater is has little to no dissolved solids, these bogs have few nutrients giving sphagnum mosses a competitive edge (Waddington et al., 2015). An abundance of sphagnum will further acidify the environment and the bog's undecomposed accumulated organic matter (peat), resulting in the formation of humic acid. The resulting nutrient-poor and highly acidic environment is suitable for a narrow range of plant species (e.g. sphagnum mosses, ericaceous shrubs, Black spruce trees, and cotton grasses) (Vitt, 1994). Another unique characteristic of bogs is that they build up over time as they accumulate peat, even rising above the water table. In fact, in some cases these bogs can form overtop of fens (Siegel and Glaser, 1987).

1.4.2 Fens (rich, moderate and poor)

Vitt (1994) describes three types of fens based on nutrient content: poor fens, moderate fens and rich fens. Fens are distinguished from bogs based on water pH and species composition. Fens have a complex combination of surface, subsurface, and groundwater interactions that connect them to other wetland systems over large distances (Ducks Unlimited, 2015; Vitt, 1994). Rich fens have a neutral to basic pH and are high in total dissolved solids (primarily calcium and magnesium). Rich fen vegetation is generally associated with brown mosses and sedges. Poor fens have an acidic pH and are low in total dissolved solids with fewer species of sedges sharing a similar species assemblage to bogs (Ducks Unlimited, 2015; Vitt, 1994). Moderate fens have a pH between rich and poor fens and a mixture of the two plant assemblages.

Based on these hydrological classifications (which are, in turn, based on vegetation), predictions can be made about the impact of roads on wetland vegetation. Specifically, we expect a stagnant, rainwater fed system with local recharge and limited lateral flow such as a bog to be largely unaffected by the construction of an intersecting road, as it would not be interrupting water flow. In contrast, a fen that is characterized by flowing water would be significantly affected by road development due to the blockage of water flow.

Although vegetation-based classifications are widely used, and for many intents and purposes they are accurate and easy ways to group peatlands, there is speculation that plant-based classifications systems may not be accurate enough to group wetlands by hydrologic function. Klijn and Witte (1999) suggested that vegetation assemblages are the product of complex interactions and cannot accurately indicate hydrology, because vegetation only indicates site-specific factors, such as soil moisture, available light and depth to water table which they refer to as operative factors with operative factors being the product of complex interactions between landscape attributes (e.g., climate, geology, soil texture, and solar radiation) that are referred to as conditioning factors. For example, soil texture is a conditioning factor which influences the operative factor of soil moisture. Plants utilize soil moisture, which is a product of both soil texture and the water that enters the system. Consequently, changes to conditioning factors, such as constructing a road through a peatland, will alter the site topography and substrate permeability. This would ultimately change the water table influencing the type of plants that grow in the area and the size and abundance of those plants. The relationship between conditioning factors and operative factors is complex and influenced by their interactions across different scales, making it difficult to relate plants to conditioning factors (Klijn and Witte 1999). Thus, wetlands with similar vegetation assemblages, and therefore classifications, may have a different water balance (Devito and Mendoza, 2006).

Additionally, the water balance and its inputs can have an influence on peatland vegetation. Peatland vegetation is strongly associated with nutrient availability, water levels, and acidity. As discussed earlier, the classification of peatlands into bogs and fens does not indicate where the water is coming from, or the movement and transit times of water. Therefore, vegetation classifications alone cannot predict the effects that anthropogenic features will have on hydrology, vegetation composition, and vegetation structure.

To accurately define peatlands or hydrologic function, where, hydrologic function includes the ability for wetlands to store surface water, recharge ground water and provide aquatic environments for organisms, I will consider in this thesis the effects of substrate texture/geology and landscape position on vegetation structure and composition. Substrate conditions are likely to influence both water chemistry, water flow, and thus water table depth and fluctuation and are widely mapped across northeast Alberta.

1.5 Road orientation

The most successful way to impede water flow in a wetland is to build the dam perpendicular to the water flow. A road built perpendicular to a wetland’s water flow should therefore have its greatest effect, while minimal effects when built parallel to a wetland's water flow. (Figure 1-4)

Although this appears to be a relatively simple concept, peatlands are complex, as is their hydrology. Water movement within peatlands has been shown to fluctuate both spatially and temporally. For example, Siegel 1988 showed that water recharges at one peat mound and discharges at another and that these topographic oscillations in the landscape influence flow reversals. Because of the complex nature of peatlands, numerical models are needed to determine the interrelationships between different factors (Wieder et al., 2006).

Due to the scope of this thesis and the broad scale (extent) at which wetlands were sampled (sites were sampled from an area of 63687 km^2), hydrology was inferred using a number of different sources of information. This thesis therefore investigates how the presence and orientation of roads affects landscape-scale changes in vegetation composition and stand structure. This thesis does not, therefore, describe local-scale measures of water movement. Regardless, road orientation in relation to the general direction of water flow should have major effects on vegetation composition and structure. Specifically, I predict large differences in vegetation composition and structure on opposing sides of roads perpendicular to water flow in fens and little to no difference in community composition and stand structure of fens when the road is parallel to the general flow of water. Assuming that bogs have little flowing water, there should be no effect of road orientation on vegetation composition and structure. Finally, vegetation in swamps is already adapted to fluctuating water tables and thus I hypothesize little to no effect of road presence and orientation on vegetation composition and structure.

1.6 Permeability and texture of surficial geology/ soil substrate below the peat

Interactions among vegetation, nutrient dynamics, and carbon are regulated by hydrology (Waddington and Roulet, 1997). Hydrology also controls wetland function and development (Mitsch and Gosselink, 1993). Reeve et al., (2000) study showed that vertical ground water flow is primarily controlled by mineral soil permeability.

When the permeability of the substrate below the peatland is low lateral flow of water in the upper position of the peat is dominant. Therefore, bogs on impermeable soils are isolated and only receive atmospheric inputs, while fens can receive inputs from upland runoff. Fine-textured surficial geology, mineral soil consisting primarily of silt and clay, has low infiltration rates and lower rates of lateral subsurface water transmission (Devito et al. 2012). Slow water movement through the fine-textured surficial geology limits conductivity between uplands and peatlands (confined to local gradients). Peatlands on fine-textured surficial geology are typically isolated or perched with water table gradients that often slope from peatland to adjacent forests and recharge from adjacent forests that often occur on hill slopes (Devito et al., 2012). We expect that peatlands on fine – textured surficial geology, with low hydraulic conductivity, will restrict the amount of surface water flow and result in dominance of near surface horizontal water movement thought the landscape (Devito et al. 2012)

We expect that peatlands on fine-textured surficial geology to have more horizontal water movement, and lack the substrate permeability that facilitates hydraulic conductivity, restricting the amount of surface water flowing through the landscape.

When the permeability is high, bogs may function as areas of recharge. Precipitation water flows vertically down through bogs and flushes solutes from the peat (Siegel and Glaser, 1987). Fens are areas of discharge and are fed by the flushed waters from the bogs and ground water discharge (Siegel et al. 1995). Consequently, we expect that bogs in coarse textured- surficial geology will have similar canopy because the hydraulic conductivity is high and most of the water movement is vertical. In these conditions, we expect large effects due to high conductivity and the large amounts of discharge in these peatlands. The is also a possibility that high conductivity and high substrate permeability could allow for water to flow under the road.

1.7 Landscape position

This thesis defines landscape position within a peatland complex as it relates to the amount of water accumulation. If the system is at the top of a peatland complex, it has less accumulated water flow than if it had several wetlands draining into it. Landscape position relates to the type of surficial geology or mineral soil type below the peat, because substrates influence the hydraulic conductivity. Thus, a more hydraulically-connected landscape will have more water flowing through to the low (downstream) portion of the peatland.

The fundamental controls of water flow may change when compared at different scales or under different surficial geology. To understand the dynamics of peatlands and the effects of scale, it is important to understand the interactions between topography and the movement of water with coarse- or fine-textured surficial geology. Soil and surficial geology texture/ permeability can indicate the potential for water movement, but the amount and duration is dependent on many other factors, such as precipitation, snowmelt, and regional connectivity (Glaser et al., 1981). The impacts to roads and wetlands will be a product of the type of hydrology and the duration and volume of water that flows through the wetland. Examining the different wetland classes in association with their substrate texture will indicate the connectivity of hydrology and the proportional inputs of surface and subsurface flow, as well as the vertical and horizontal flows, although landscape position must also be taken into account.

The amount of water in the system also needs consideration. If fine-textured surficial geology is considered isolated, the volume of water flowing through these systems would be low, particularly in headwater systems. Given these relationships, I predict that when the road is perpendicular and the wetland is located in a fine-textured surficial geology that is in the headwaters of a peatland complex, there will be minor differences in stand structure and composition between the two sides of the road. However, when the road is perpendicular to water flow, and the wetland is located in fine-textured surficial geology that is below the headwaters (low in the peatland complex), there will be significant differences in stand structure and vegetation composition. Fine textured peatlands are expected to have greater accumulation in below head water, whereas coarse textured peatlands have high hydrologic conductivity between the upland and therefor have less accumulation. (Figure 1-4 & 1-5)

Likewise, roads on coarse-textured surficial geology that are in headwaters are not predicted to disrupt the water flow because water can flow beneath the road. Additionally, peatland below the headwaters in coarse-textured surficial geology are expected to have large amounts of water moving horizontally through the landscape so we expect that water will still damn along roads and thus cause differences in stand structure and vegetation composition.

1.8 Study Area

The study was conducted in Boreal Plains of northeast Alberta spanning 350-km east-west from highway 88 near Lesser Slave Lake to the Saskatchewan border and 450-km north-south from Boyle to Fort Chipewyan (Figure 1-6). The Boreal Plain is characterized by glacial outwash and low topographic relief (Fenton et al., 1994) with a sub-humid climate of 382 to 623 mm of annual precipitation (Environment Canada, 2010).

1.9 Research questions

My study examined the physical properties of roads and wetlands to identify which properties caused differences in spatial patterns of vegetation communities and canopy cover. I addressed the following questions:

a. Do roads cause differences in canopy height and cover in forested wetlands?
b. What factors contribute to variation in canopy height and cover in road-dissected peatlands?
c. Do roads cause differences in vegetation community composition in forested wetlands?
d. Are there types of wetlands or environmental characteristic that exaggerate these differences caused by roads?

Dendrochronology sample sand bryophyte samples were taken at each field site but were not analyzed for this thesis.

1.10 Figures

Figure 1-1: Photograph depicting a road-fragmented peatland with flooding on the left side of the road (water source; up flow-side) and increased tree growth and recruitment on the right side (down flow-side). This location is near Conklin, Alberta on Hwy 881 (55°15'01.6"N 111°19'17.4"W, facing south, May 2016, photo by Caitlin Willier).

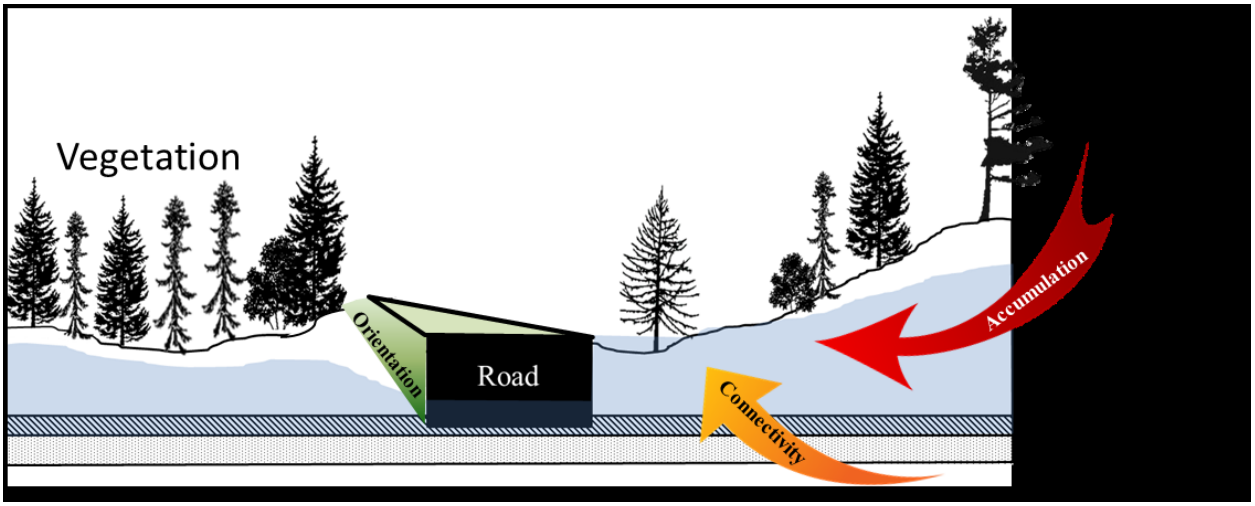

Figure 1-2: Conceptual model depicting how roads can intercept water flow in peatlands. The hydrology of a peatland is a product of conductivity and total amount of water. Road orientation influences the effectiveness of reducing flow (damming). Canopy cover is reduced on the up-flow side (right) due to tree mortality from flooding, while increased on the down-flow side due to tree and shrub encroachment and growth.

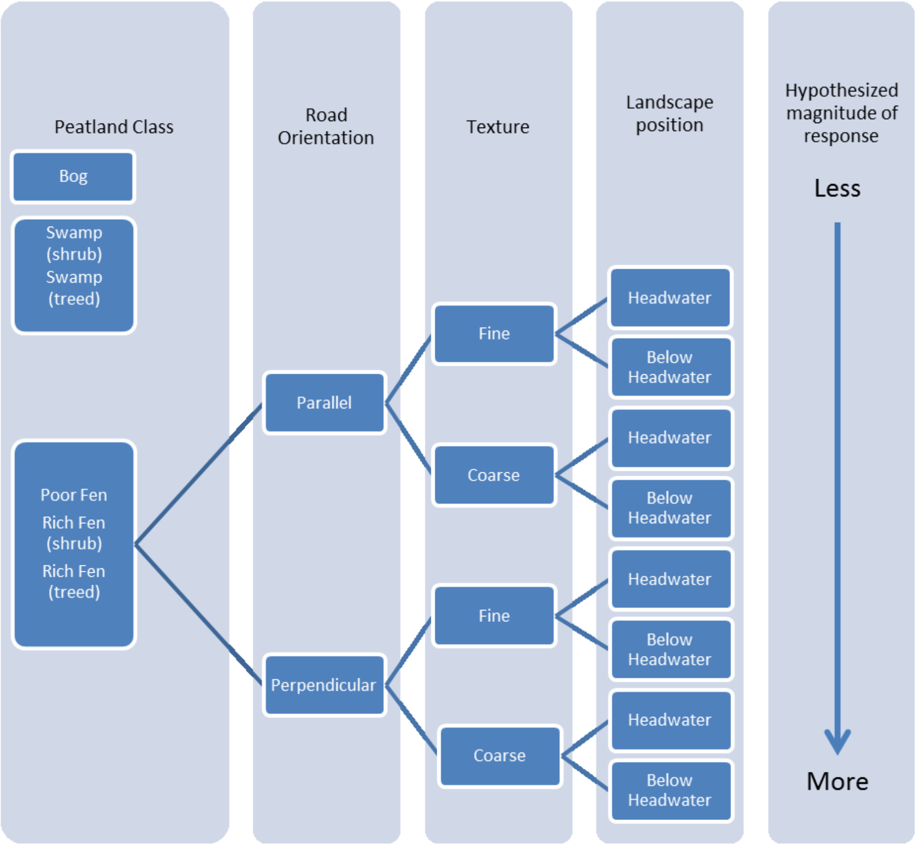

Figure 1-3: Hypothesized hierarchy of environmental variables where peatland class influences the effects of roads on vegetation. Here I predict bogs and swamps to have little difference in vegetation between the up-flow and down-flow side of the road. Fens will be the most impacted and influenced by road orientation, peatland substrate texture, and landscape position. The last column depicts the hypothesized magnitude of response in vegetation.

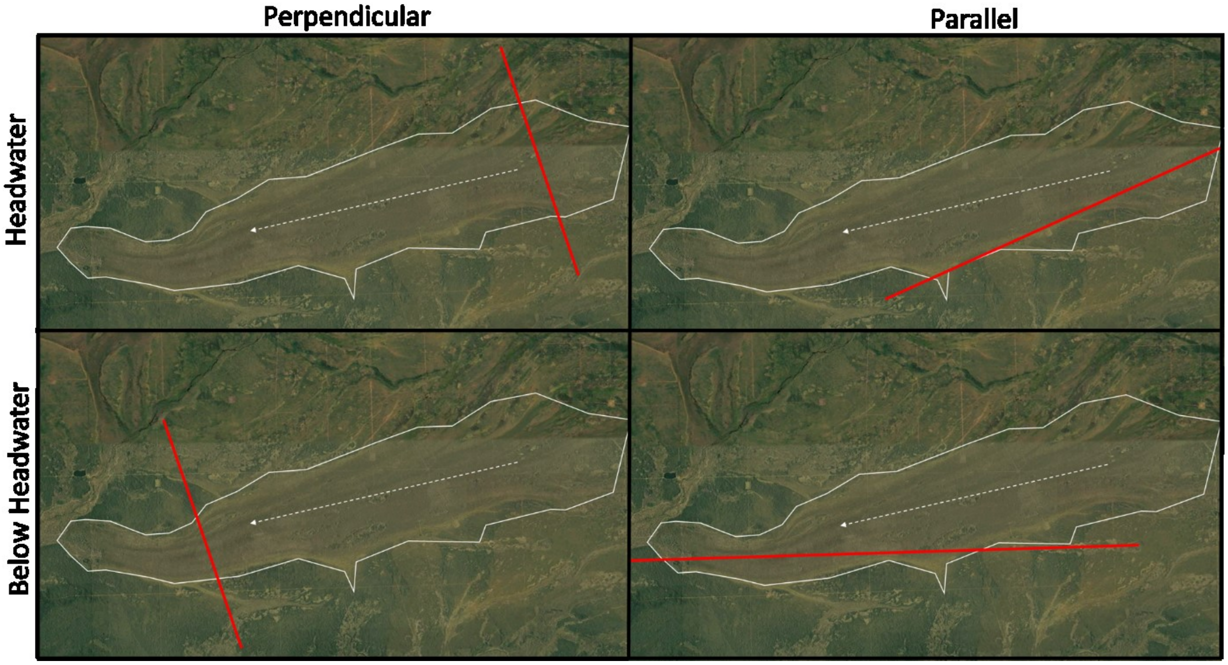

Figure 1-4: Showing the delineation of road orientation and headwater in a fen. The red line represents a hypothetical road, while the white soil line delineates the boundary of the fen. The dotted arrow depicts the main direction of flow in the fen.

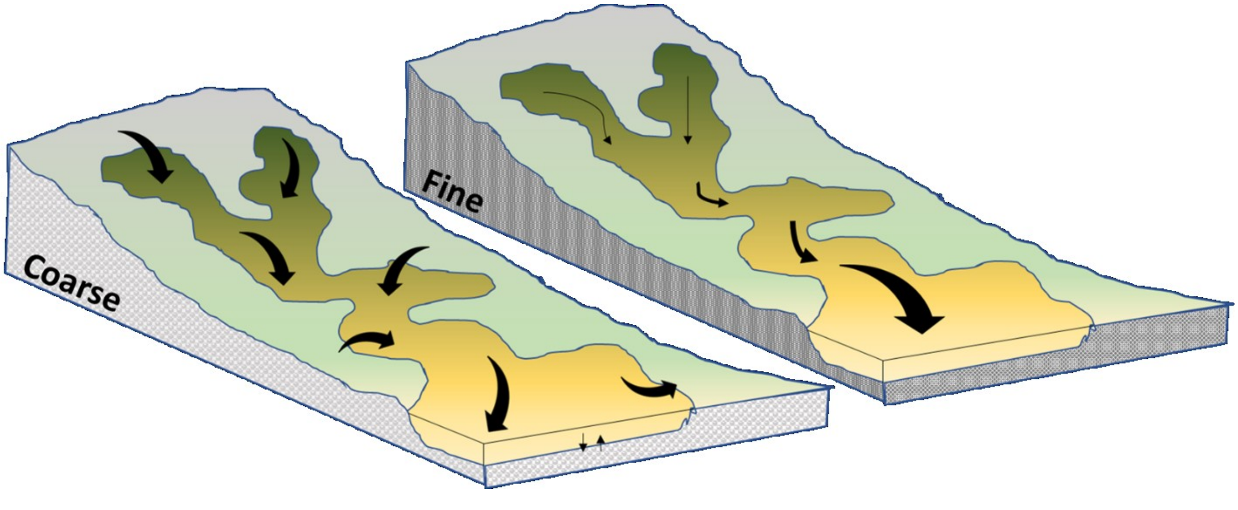

Figure 1-5: Conceptual model depicting landscape position and how soil/surficial geology influences flow accumulation. The size of the arrow represents predicted flow rates. The dark green coloured part of the polygon is the head water portion and the yellow part of the polygon is

below the head water.

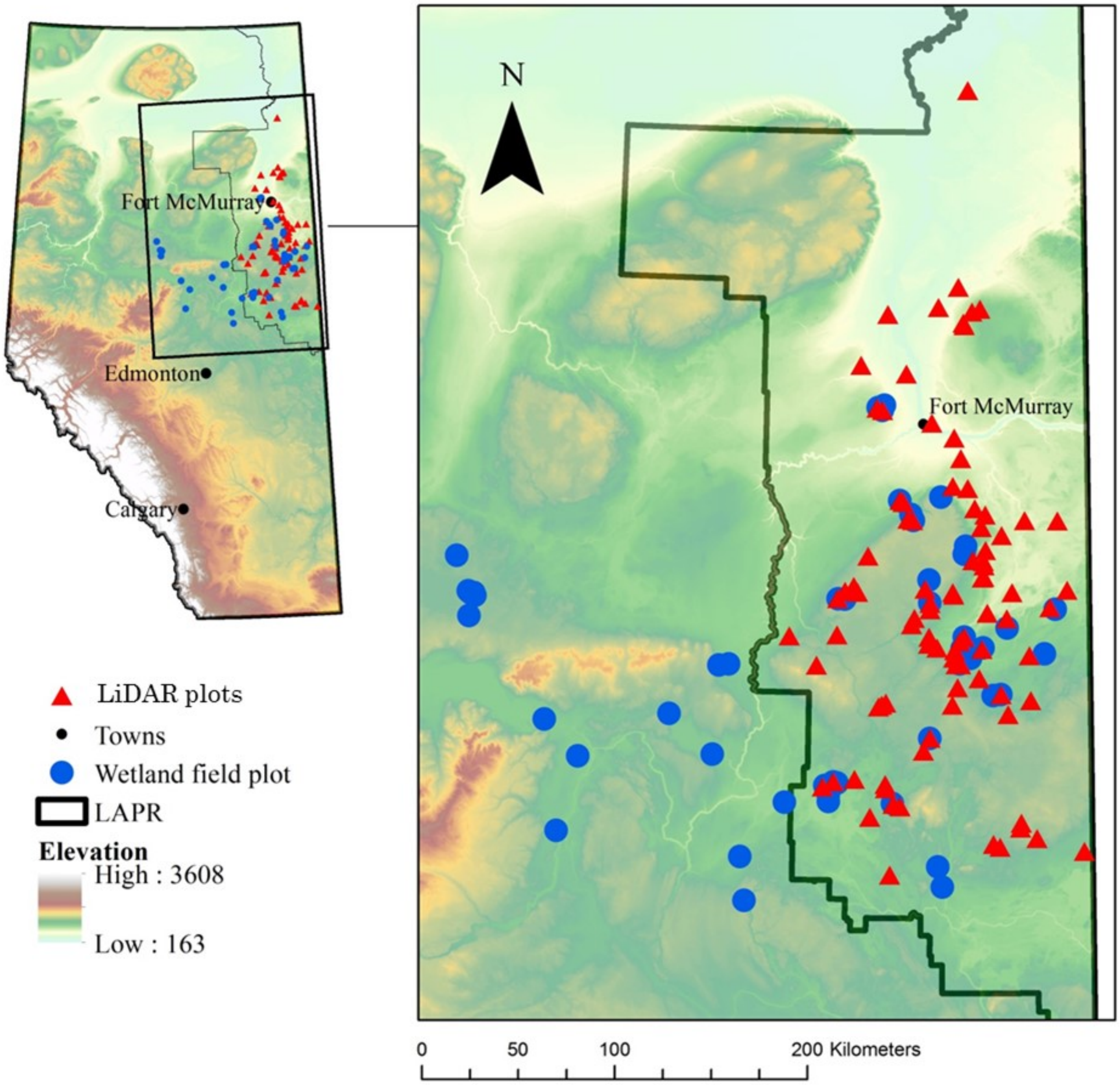

Figure 1-6: Map of study sites in northeast Alberta, Canada. The Lower Athabasca Planning Region (LAPR) is outline in black on the map and inset. The yellow triangles are the remotely sensed airborne LiDAR sample locations, while the blue circles represent field plots.

Chapter 2: Using airborne LiDAR to evaluate changes in woody vegetation structure in road-fragmented peatlands

Abstract

When a road is built through a peatland, with horizontal water flow, the road can act as a dam. As a result, trees on the ’upstream’ side of a road can become waterlogged and either die or become stunted; whereas, on the ’downstream’ side of a road, a prolonged drop in the water table can cause the trees to root deeper and grow taller than normal. Interestingly, this phenomenon does not occur consistently. In fact, the same road constructed through two different wetlands may disrupt tree growth patterns in one peatland while the other may appear unaffected. This study examines the conditions that maintain peatland tree cover by peatland type based on landscape position, surficial geology and road conditions. To do this, we examined with Generalized Linear Mixed Models variation in airborne LiDAR-derived tree cover with site variables across 81 road-fragmented peatlands in northeast Alberta, Canada. My results support the general observation that drying of peatlands increases wood canopy cover, but found that variations in responses among sites was due to interactions between road orientation, substrate texture, landscape position, and peatland type. This study demonstrates the value of LiDAR-derived vegetation structure metrics in evaluating changes in woody vegetation structure for road-fragmented peatlands.

1. Introduction

The province of Alberta has a landscape that is intersected by a wide array of man-made linear features (Lee and Boutin, 2006; Pattison et al., 2016). These features include extensive networks of roads, pipelines, and seismic lines. This man-made infrastructure fragments ecosystems by creating corridors that influence the movement patterns of humans (Revel et al., 1984) and wildlife, such as wolves (Dickie et al., 2017), and caribou (Dyer et al., 2002) which are a conservation priority in Alberta. These features also disrupt the movement of water and nutrients, particularly in peatlands (Turetsky and St. Louis, 2006).

Approximately 20-80 % of the boreal is covered by wetlands (Vitt et al., 1996) that serve essential ecosystem functions. This includes habitat for plants and wildlife, recharge and discharge of groundwater, flood storage and desynchronization, and dissipation of erosive forces through shoreline anchoring (Adamus, 1983; Dahl and Zoltai, 1997; Winter and Woo, 1990). Some Alberta wetlands support especially rare flora and fauna. For example, rich graminoid fens are the primary habitat for yellow rails, a species of special concern in Canada (Leston & Bookhout 2015).

Peatlands are wetland ecosystems with more than 40 cm of accumulated partially decomposed organic matter known as peat (Alberta Environment and Sustainable Development, 2014). Peatlands are an integral part of boreal forest (Turetsky and St. Louis, 2006; Wieder et al., 2006) with peatlands holding approximately 85% of North America's soil carbon and the destruction of which has led to large fluxes in available carbon (Bridgham et al., 2006). Approximately 50% of the land base in northeast Alberta is covered by wetlands and of those 90% are peatlands (Vitt et al., 1996). Avoiding peatlands when constructing roads in Alberta's boreal forest is therefore not always an option. Indeed, in 2014, *in situ* oil sands extraction became the largest form of oil sands production and is projected to double by 2040 (National Energy Board 2016). These developments rely on subsurface oil wells and associated infrastructure, including roads, to access and manage the oil resources. With expected future increases in resource development, demands on current road infrastructure will increase, as well as the need for future road develop. A greater understanding of where sites are more or less sensitive to road development is therefore important for planning and mitigating their impacts.

Changes in hydrological regime can have significant effects on vegetation communities (Groot, 1998; Miller et al., 2015; Minkkinen et al., 1999). This is particularly true of wetlands, as wetland plant species are adapted to hydrophytic conditions for most, if not all, of the growing season. A lower water table across multiple growing seasons shifts species composition from wetter graminoid/sedge-dominated communities to drier shrub-dominated communities (Weltzin et al., 2003).

Roads have been known to influence the subsurface flow systems that maintains forested wetlands and cause significant changes in tree and woody vegetation on opposing sides of roads. There are often obvious visual signs that indicate that roads disrupt the hydrology of wetlands with roads acting as dams and blocking subsurface water flow. As a result, trees on the 'upstream' side of a road can become waterlogged resulting in increased mortality or stunted growth of wood vegetation, including trees. In contrast, the ’downstream’ side of a road can have a prolonged drop in the water table causing trees to root deeper with greater growth rates than normal. Interestingly, this phenomenon does not appear to be consistent in all road-dissected wetlands. Although studies have examined the effects of roads on forested wetlands, most have focused on the effects of drying and ditching associated with roads (Glaser et al., 1981; Miller et al., 2015). No studies have investigated the forest structural changes associated with both the adjacent upstream flooded side of the road and the adjacent downstream desiccated side of the road.

Given the volume and extent of the Light Detection and Ranging (hereafter LiDAR)-derived vegetation stand structure data in Alberta’s boreal forest (Coops et al., 2016; Guo et al., 2017), data from LiDAR vegetation metrics could represent a valuable source of information for evaluating patterns and relationships between roads and changes in peatland woody plant (tree/shrub) cover. The objective of this study is to investigate the effects of flooding and drying patterns observed in roads built through peatlands on vegetation structure and cover. Specifically, the objectives of this paper are to: (1) use LiDAR-derived data (vegetation stand structure metrics) to measure tree and shrub cover on opposing sides of road features in peatlands in northeast Alberta; and (2) determine which factors most affect vegetation stand structure to better understand the factors affecting patterns in vegetation resulting from road-induced water impoundment. This research will provide information that can be used to inform mitigation strategies based on knowledge of environmental variables that influence canopy cover in forested peatlands with roads.

2. Methods

2.1 Study Location and Site Selection

The study area consists of 63,687 km^2 of boreal forest with in the Lower Athabasca Planning Region of northeast Alberta (Figure 2-1). Available LiDAR-derived vegetation structure data extends from Lake Athabasca south to Wolf Lake in the Cold Lake region (Coops et al., 2016; Guo et al., 2017). Much of the study area is in the Central Mixedwood Natural Subregion with some study locations within the Lower Boreal Highlands in the west-central parts of the study area and the Athabasca Plain in the far north. This study focuses on peatlands (organic wetlands) and in particular fen and bog ecotypes, which need saturated soils for a large portion of the year (Vitt, 1994). Common species of trees and shrubs associated with fens and bogs are listed in Table 2-1 along with their associated ranges in height.

Northeast Alberta is associated with the Cold Lake and Athabasca oil sands that represent the third largest petroleum reserve in the world (National Energy Board 2016). The major drivers of road construction in the region are historically forestry and more recently oil sands extraction projects and their associated infrastructure have drastically increased road disturbances. Total length of road disturbance in the study region is 30,338 km covering an area of 330 km^2 (ABMI Human Footprint Inventory for 2012 conditions, Version 3) which is ~50% of the area cleared and mined in the region for oil sand extraction.

2.2 Sampling protocols for predictor variables

Sample locations were identified using the Ducks Unlimited Enhanced Wetland Classification (DU-EWC; Ducks Unlimited Canada 2015) where fen, bog, and swamp wetland types were used to stratify land cover types. Swamps are treed and/or shrubby with little to no peat accumulation and a water table at or above the soil surface for part of the year with seasonal water fluctuations (Stewart and Kantrud, 1971). Both fens and bogs accumulate peat, however, fens are dominated by brown mosses and contain sedges and forbs with flowing water (Vitt 1994). Fens can be further divided into nutrient poor and nutrient rich. In contrast, bogs are primarily rain fed, with little water flow and dominated mainly by sphagnum and ericaceous shrubs (Vitt 1994). In many areas of Alberta boreal plain, bogs are dominated by feather mosses and lichen due to the dry climate. Poor fens and bogs can have similar low nutrient levels, however poor fens have flowing water and generally wetter.

A total of 100 fens or bogs with roads were randomly selected in a GIS (ArcGIS v10.3.1). Some sites were later omitted for either having no airborne LiDAR data or too small to sample resulting in a total of 81 sites. Each peatland was delineated (digitized) with Google Earth imagery (Google Earth v7.1.8.3036) to encompass the entire wetland on both sides of the road. The ‘upstream’ and ’downstream’ sides were identified for each peatland based on the direction of water flow, elevation, and topographic patterning.

I defined the landscape positon of a peatland as the location of a peatland within a peatland complex (a series of hydrologically connected peatlands). Landscape position was estimated using visual delineation. Peatlands with less than 1 km of peatland flowing into the road were considered at the top of the peatland complex and categorized as a 'headwater' peatland, while those with more than 1 km of peatland feeding into them were considered 'below headwater'.

Random systematic locations were selected within each peatland with an equal area-based sampling intensity of 1 location for every 30 m X 30 m pixel matching the resolution of the summarized LiDAR canopy data (raster) up to a maximum distance of 250 meters from the road. Human-modified sites of roads, ditches, and seismic lines were excluded. Environmental factors were extracted for each location, including LiDAR-derived stand height/structure and anthropogenic disturbances (Figure 2-2). Distance to road was calculated for each sample location using the ABMI human footprint classification (ABMI Human Footprint Inventory for 2012 conditions, Version 3), while distance to upland (edge of peatland) was based on upland classes from the Ducks Unlimited enhanced wetland classification.

Substrate texture of the surficial geology was delineated for each site using Surficial Geology of Alberta polygon features (DIG 2013-0002; 1:1,000,000) and converted to binary classes either fine or coarse textued (Devito et al., 2017). All these factors were used to evaluate responses in canopy cover from LiDAR to the presence or interaction with roads (Table 2-2).

2.3 Defining forest canopy cover

Existing airborne LiDAR-derived vegetation structure data for the region (Coops et al., 2016; Guo et al., 2017) was used to represent canopy cover variation at a 30-m raster cell size. Specifically, canopy cover was estimated as the proportion of first returns above 1.37 m height representing the height used in forestry to measure trees.

LiDAR-derived vegetation metrics are unable to differentiate between tree types, there for changes in composition due to road impacts are not captured in this study. LiDAR data was captured in 2008 during "leaf-on" conditions to reduce inconsistencies in canopy cover due to season.

A logit transformation was applied to canopy cover measured as proportions to bound predictions between 0 and 1 (Newcombe, 2001), and then back-transformed to percent in predictions.

2.4 Statistical analysis

Generalized linear mixed models (GLMMs) were used to compare how canopy cover changes as a function of anthropogenic and environmental predictor variables (e.g., distance to road, road orientation). Locations within each peatland system were identified in the model as a random effect. I used the lme4 package (Bates et al., 2015) in R (R development Core team 2012) to fit a series of candidate models to assess the importance of factors influencing changes in vegetation structure.

2.5 Explanatory variables used to explain canopy cover

2.5.1 Side of road

An important variable for our hypothesis was side of road. If the road is acting as a dam, the upstream side of the road is expected to experience prolonged inundation and high water tables for most of the growing season. Increases in the water table for long periods of time will result in tree mortality and stunted woody vegetation due to anoxic rooting conditions (Asada et al. 2005) and thus we predicted lower canopy cover. See Table 2-2.

2.5.2 Land cover types

Three peatland land cover types were examined based on the classifications from the DU EWC, bogs, rich fens, and poor fens. Bogs are nutrient poor and characterized as having low species diversity, dominated by sphagnum mosses, black spruce (*Picea mariana*), and ground lichen (Wieder et al., 2006). They can be isolated and stagnant, receiving water primarily through precipitation resulting in low nutrient levels (Vitt, 1994). Bogs continually accumulate peat potentially rising above the water table and thus in some cases forming overtop of fens (Siegel and Glaser, 1987). We predicted that the water movement in bogs would not be great enough to cause flooding on the upstream side of the road and drying on the downstream side of the road, thus canopy cover should be similar on both sides of the road.

Fens are distinguished from bogs based on water pH and species composition. Fens have a complex combination of surface, subsurface, and groundwater interactions that connect them to other peatland systems over large distances (Vitt 1994, Ducks Unlimited 2015). Rich fens have a neutral to basic pH and are high in total dissolved solids (primarily calcium and magnesium). Rich fen vegetation is generally associated with brown mosses, tamarack (*Larix laricina*), and sedges. Poor fens have an acidic pH and are low in total dissolved solids with fewer species of sedges and thus sharing a similar species assemblage to bogs (Vitt 1994, Ducks Unlimited 2015). We hypothesized canopy cover in both poor and rich fens would be different between sides of road, where the upstream side of the road would have reduced canopy due to flooding and the downstream side of the road would have increased canopy from drying.

Peatland structure was also determined using the DU-EWC (Ducks Unlimited Canada 2011). Each peatland was determined to be either shrub-dominated (canopy consisting of more than 25% shrub cover and less than 25% tree cover) or tree-dominated cover (canopy consisting of more than 25% tree cover). Peatlands dominated by shrubs generally have water tables within 10 cm of the peat surface (Alberta Environment and Sustainable Development, 2014). I predict that peatlands dominated by shrubs will have higher water tables thus overall lower canopy cover, but also greater flooding and drying impacts as a result of roads.

2.5.3 Surficial Geology

Interactions among vegetation, nutrient dynamics, and carbon are regulated by hydrology (Waddington and Roulet, 1997). Hydrology also controls wetland function and development (Mitsch and Gosselink, 1993). Reeve et al., (2000) study showed that vertical ground water flow is primarily controlled by mineral soil permeability. The surficial geology of peatland sites was used to capture the variability in mineral soil permeability by delineating peatlands into two texture classes: coarse-textured (sand and gravel); or fine-textured (silt and clay) substrates.

When the permeability of the peatland substrate is low (fine-textured surficial geology), later flow of water in the upper position of the peat is dominant. Therefore, bogs on impermeable soils are isolated and only receive atmospheric inputs, while fens receive inputs from upland runoff. Fine-textured surficial geology has low infiltration rates and lower rates of lateral subsurface water transmission (Devito et al. 2012). Slow water movement through the fine-textured surficial geology limits conductivity between uplands and peatlands (confined to local gradients). Peatlands on fine-textured surficial geology are typically isolated or perched and recharge from adjacent forests that often occur on hill slopes (Devito et al. 2012). I predict that peatlands on fine-textured surficial geology to have more horizontal water movement, however lack the substrate permeability that facilitates hydraulic conductivity, restricting the amount of water flowing through the landscape. Road-induced water impoundment in peatlands is these conditions are therefore expected to be minimal in bogs which are characteristic of little flowing water, and high in fens with large areas of peatlands connected upstream.

When the permeability is high (coarse-textured surficial geology), bogs are areas of recharge. Precipitation water flows vertically down through bogs and flushes solutes from the peat (Siegel and Glaser, 1987). Fens are areas of discharge and are fed by the flushed waters from the bogs and ground water discharge (Siegel et al. 1995). Consequently, we expect that bogs in fine textured-surficial geology will have similar canopy because the hydraulic conductivity is high and most of the water movement is vertical. In fens we expect road effects in these conditions due to high conductivity and the large amounts of discharge in these peatlands.

2.5.4 Landscape position

Within a peatland complex, there are often interconnected fens and bogs. Bogs are areas of recharge and fens are often areas of discharge. Flow within the peatland complex is both a product of the connectivity within the peatlands and between the uplands and the peatlands, as well as the amount of water within and entering the system (Devito et al., 1997; Reeve et al., 2000; Siegel and Glaser, 1987). I speculated that road location within the peatland (landscape position) would influence canopy cover and the responses in canopy on either side of the road. We hypothesized headwater systems would have less water and overall lower water tables and thus have more canopy cover. Because of this, we also hypothesized peatlands in the headwaters would have less road effects when comparing differences between sides of road.

2.5.5 Distance to road

Distance from the road is expected to influence canopy cover because the road will cause water impoundment close to the road and dissipate with distance from the road. When the road is perpendicular to the direction of water flow, I expected a positive relationship between canopy and the distance to road since perpendicular roads will more effectively damn flowing water.

For the ’downstream’ side of roads, we hypothesize that the canopy will increase because roads will block water flow causing a drop in the water table and thus allowing deeper rooting zone with better conditions for tree and shrub growth (Laiho and Laine, 1997; Miller et al., 2015; Minkkinen et al., 1999). As the distance from roads increase, surface and groundwater inputs will normalize and the effects of roads will attenuate.

2.5.6 Distance to water bodies

Distance ($\log_{10}$) to open water (nearest hydropolygon) was estimated in ArcGIS (DU-EWC; Ducks

Unlimited Canada, 2011). I hypothesized canopy would decrease in cover near water bodies due to high water tables that would limit trees. Vegetation on the shore of an open body of water may tend toward graminoid- and shrub-dominated conditions because of the high water table (Vitt et al., 2001).

2.5.7 Distance to peatland edge

The distance to the upland-peatland interface (peatland margin) was characterized in our model as distance to edge. Distance ($\log_{10}$) to edge was also estimated in ArcGIS using polygons encompassing each peatland. Polygons of peatlands were digitized along the upland-wetland interface using the DU-EWC and satellite imagery (Google Earth v7.1.8.3036 & DU-EWC; Ducks Unlimited Canada 2011). I hypothesized that canopy cover would decrease with distances to the wetland edge (Table 2-2).

2.5.8 Road orientation

The most successful way to impede water flow in a wetland is to build the dam perpendicular to the water flow. A road built perpendicular to a wetland's water flow should therefore have its greatest effect, while minimal effects when built parallel to a wetland's water flow.

It is likely that no one single variable would be suitable to predict the effects of roads on canopy cover, but rather the interactions between variables, including type of peatland.

2.6 Model Selection and analysis

A priori candidate models were developed based on our hypothesized responses to explanatory variables (Table 2-3) by peatland type (bog, rich fen, and poor fen). I first compared models with all hypothesized fixed effects with a random effect for peatland sample. Variables were then sequentially removed for those with the lowest significance until parsimony was achieved based on Akaike's Information Criteria (AIC; Pan, 2001). Interaction terms were then fit and compared with initial additive models again using AIC. Models with the fewest variables were selected when models had equal support within 2 AIC units (Anderson and Burnham, 2002).

3. Results

3.1 Peatlands class and road variables

Total number of peatlands in this study was 81. Surficial geology within bogs was dominated by sites on fine-textured substrates (surficial geology). Rich fens had the highest marginal-R^2 for fixed effects on canopy cover at 0.34, while poor fens were lower with a marginal-R^2 of 0.22. In contrast, the bog model explained less variation in canopy cover with marginal-R^2 of 0.16. (Table 2-4).

As hypothesized, interactions between side of road and distance to road were supported in poor and rich fens. However, contrary to my predictions an effect of roads was also observed in bogs on fine textured surficial geology. Upstream sides of roads were negatively related to canopy cover in all peatland types (Table 2-6). Although I hypothesized that road orientation would have a major effect on canopy cover, only a weak negative relationship with perpendicular orientation were observed in bogs and poor fens. In contrast, perpendicular roads in rich fens increased canopy cover on the downstream side of the road.

Maximum canopy cover was predicted for bogs and fens in headwater systems on coarse-textured substrates and on the down flow side of a parallel-orientated road. Interestingly, I observed that road orientation with the highest canopy cover for rich fens was with parallel roads. Maximum canopy cover in poor fens was in fine-textured headwater systems on the down flow side of parallel orientated roads, but at the furthest distances from roads (Figure 2-3).

Bogs had the most variation in canopy cover ranging from 0 to 100 % cover and the largest disparity in canopy cover between opposing roadsides. The maximum disparity in canopy among roadsides of bogs was observed in roads that were perpendicular to water flow on a fine-textured substrate with a headwater landscape position.

Rich fen sites also had large disparity in canopy cover between opposing roadsides, particularly on coarse-textured sites with parallel road orientation to water flow (Figure 2-3). A similar, but weaker trend was apparent with perpendicular roads with secondary effects of substrate texture.

Although a significant factor for rich fens, I found that shrub and treed fens had similar responses in canopy, but with treed fens having as expected greater canopy cover. Finally, poor fen had less difference in canopy cover among roadsides with differences mainly due to landscape position.

4. Discussion

I found that both side of the road and distance to the road were significant factors in explaining LiDAR-measured canopy cover in forested boreal peatlands of northeast Alberta, Canada. In general, the downstream (dry) side of roads had greater canopy cover than their adjacent upstream counterparts, demonstrating the effect that roads have on the structure of peatlands. These results support other studies, which demonstrate that the drying of wetlands leads to increased and woody vegetation and canopy cover (Miller et al., 2015). However, I found that these effects were site dependent and related to a series of complex interactions between road orientation, substrate texture, landscape position, and peatland type.

I hypothesized that fens would have the largest differences in canopy height on opposing sides of the road; instead we saw that bogs had the largest differences in canopy cover when located on fine-textured surficial geology. Interestingly, bogs with coarse texture surficial geology had little to no road impacts. I can therefore conclude that road impacts to stand structure in bogs appears to be highly dependent on the texture of the surficial geology. As suggested by the Reeve et al., (2000) study, peatland substrate with low permeability (fine-textured surficial geology) favors lateral water flow, which is blocked by the presence of roads. Tracer tests conducted in peat from a blanket bog demonstrated that most water flows in the upper layers of peat (Hoag and Price, 1997), which is the flow path expected to be most affected by roads. Coarse textured surficial geology has less lateral flow and higher conductivity, which may allow water to flow under the road. A general increase in canopy cover with distance to road was also observed in bogs. This may be a result of ditching and culverts.

Fens, both rich and poor peatland classes exhibited canopy cover differences between the upstream and downstream side of the road. Rich fens had noticeable differences in canopy cover on opposing sides of roads. This partially supports our hypothesis that because rich fens are supported by flowing, nutrient-rich water, roads would have greater impacts on trees in these systems than in poor fens. However, bogs on fine-textured surficial geology had greater differences. We speculate that this could be due to the types of trees found in rich fens, poor fens, and bogs; also the types of tree and shrub species that colonize once changes in the water table have occurred. Fens are commonly dominated by tamarack (*Larix laricina*) and bogs by black spruce (*Picea mariana*). Tamaracks are a more water tolerant species than black spruce (Montague and Givnish, 1995).

Additionally, rich fens may have more nutrients to support species such as paper birch (Betula paperifera or Betula neoalaskana) and aspen (*Populus tremulodies*) once the road has caused the water table to drop. This may explain why the canopy cover on the downstream (drier) sides of roads in rich fens experience greater canopy cover while the upstream side remains relatively constant. More research is needed to investigate the changes in species composition associated with road construction through peatlands.

In rich fens, our results showed that both coarse and fine-textured surficial geology is affected by the presence of roads. The differences in canopy on either side of the road are the result of interactions between road orientation and substrate texture. When a road is parallel to water flow and substrates are coarse textured, canopy differences are greatest and when the road is perpendicular, landscape position has a strong effect on the canopy differences between upstream and downstream roadsides. Likewise, in poor fens, landscape position, not substrate texture, has the strongest effect on canopy cover.

Poor fens had smaller differences between canopy cover on opposing sides of the road than rich fens. We also found that poor fen canopies had a negative response in the below headwater landscape positions. Poor fens on fine textured surficial geologies and located in below headwater had greater differences between sides of the road than any other poor fen scenarios. This supports our hypothesis that lateral flow would be greater in fens with fine-textured substrates, but also a function of where in the peatland complex the road is located.

In all models, results for landscape position did not support our hypothesis. I found that canopy cover was higher further from roads in the headwater system than below headwaters. This partially supports our hypothesis in that the headwaters have less water flow and therefore should have higher cover. However, wetlands classified as being in the headwater showed the greatest differences in canopy cover between the upstream side and the downstream side of roads. This is contrary to our hypothesis that headwaters would have less water accumulation and thus smaller effects of roads on canopy. One explanation for this is that the vegetation in the headwater systems is less adapted to hydrophytic conditions and we see higher tree mortality in these systems. This justification is further supported by the slope of canopy cover in fine-textured substrates on either side of the road. In fine-textured headwater systems, we expect species adapted to low hydraulic conductivity and less stable water tables. Model predictions demonstrate that the greatest changes in canopy cover among adjacent roadsides would be on the upstream side of headwater roads (where we have water impoundment) with canopy cover greatest at further road distances. More gradual changes in canopy were predicted on the downstream side of roads.

In many of our predictive models canopy cover on the upstream and downstream sides of the road did not converge at the same value before or at the maximum distance (250 m) from roads. We assumed that cover would at some distance converge. This suggests that in some peatlands the effects of roads maybe further than 250 m or the presence of a natural gradient in tree cover with distance along the flow direction of peatlands. In some models, canopy cover was lower at the furthest distances from roads than on both roads edges (as in the coarse textured bog scenario) or increased at the furthest predicted values (like in some of the fen scenarios). This may be a result of ditching and/or culverts which were not directly evaluated in this study. Other studies have demonstrated the distance of drainage effects on the upper portion of the peat to range from 10 m to 200 m (Van der Schaaf 1999; Trettin et al. 1991).

5. Conclusions

This study demonstrates that roads built through large hydrologically-connected boreal peatland ecosystems influence forest stand structure canopy closure. Among peatland classes, we observed overlap in the degree of road-caused changes in canopy. This suggests that mitigation strategies based on wetland classification alone may not be effective in preventing disruptions to hydrologic linkages that result in altered forest stand structure. This study found that road impacts were also due to the interplay with surficial geology, landscape position, and road orientation.

This study highlights the usefulness of LiDAR-derived vegetation structure to evaluate that structure's change in road-fragmented wetlands. Further research is needed to explore the effectiveness of culverts in reducing the flooding and drying effects of roads and to explore the relationship between the permeability of the surficial geology and canopy height by road distance. Research into the responses of peatland vegetation to changes in hydrology is important and is needed for further understanding human disturbance.

6. Tables

Table 2-1: Common woody species that contribute to canopy cover in fens, bogs, and swamps within northeast Alberta, Canada. Heights are estimates from Moss 1983 & Huang et al. 1992.

Type	Tree/ Shrub	Latin name(s)	Heights (m)
Bog, fen, swamp	Black Spruce	*Picea mariana*	7-10
Bog, fen, swamp	Dwarf Birch	*Betula pumila*	2
Fen, swamp	Tamarack	*Larix laricina*	6-15
Fen, swamp	Willow	*Salix planifolia*	0.5-4
		Salix pyrifolia	1-3
		Salix bebianna	0.5-5
Swamp	Birch	*Betula neoalaskana/* *Betula paperifera*	3-15
Swamp	Alder	*Alnus incana* ssp. *Tenuifolia*	2-8

Table 2-2: Variables used to explain canopy cover in the generalized linear mixed model. For categorical variables, the level withheld and used as a reference is italicized in the column for type.

Variable	Abbreviation	Type	Prediction	Source
Upstream/Downstream				
1. Side of the road with water impoundment	side	Categorical upstream, *downstream*	Canopy cover will be lower on the "upstream" side of road.	Google earth visual delineation
Land cover type				
2. Peatland land cover types	type	Categorical Bog, rich fen, poor fen	Bogs will be less effected than rich and poor fens because they are rainwater fed, more dry and stagnant	Ducks Unlimited Enhanced Wetland Classification
3. Dominant vegetation growth form of canopy species	structure	Categorical treed /*shrubby*	Shrubs dominated peatlands will have lower canopies and are expected to have higher water tables which will cause greater road impacts	Ducks Unlimited Enhanced Wetland Classification
Landscape characteristics				
4. Surficial Geology	texture	Categorical coarse/ *fine*	Coarse-textured substrate facilitates water flow. Dramatic differences in cover with distance from roads	Alberta Geological Survey 2012 and HRA conversion chart (Devito & Merten unpublished)
5. Landscape position	headwater	Categorical below headwater / *headwater*	Headwater has the least about of flow accumulation. No effect on canopy.	Google earth and Satellite imagery
Distance				
6. Distance to road	$\log_{10}$(dist_road)	Continuous	The effect of road will decrease with distance	Arc Map generation
7. Distance to open water	$\log_{10}$(dist_opw)	Continuous	(negative linear) Closer to wetland edge (smaller distance) will have less canopy cover.	Arc Map generation

			(positive linear).	
8. Distance to peatland edge	$\log_{10}$(dist_edge+1)	Continuous	Canopy cover with decrease with distance from wetland edge (smaller distance).	Arc Map generation
Road Characteristics				
9. Water flow and road orientation	perpendicular	Categorical perpendicular, *parallel*	Perpendicular is when the wetlands' longest axis and the road intersect within 45° to 90°. Perpendicular orientation is predicted to block more water than parallel roads.	Google earth visual delineation and flow accumulation (WAM)

Table 2-3: Summary of hypothesis and predictions for interactions in candidate models for generalized linear mixed models (GLMMs) with logit transformation and Gaussian distribution. (see Table A2-1 for summary of hypotheses and predictions)

Candidate Models (predictor variables)	**Hypothesis rationale**	**Prediction**
setting + Texture + Landscape position (H4)	Additive: landscape position influences the amount of water and texture influences whether that water is transported through the system	Tree cover decrease in coarse-textured soils. Tree cover will be lower in wetlands that have one or more peatlands feeding into them
setting + Texture X side (*H5*)	Interactive: The effect of side of road is dependent on texture.	Coarse-textured substrate facilitates water flow and causes decreased cover on the upstream side of road.
setting + Landscape position X side (*H6*)	Interactive: The effect of side of road is dependent on landscape position.	There will be greater flow below the headwater causing decreased tree cover on the upstream side.
setting + Perpendicular X side (H7)	Interactive: The effect of side of road is dependent on road orientation	Perpendicular roads more effectively block water flow causing decreased tree cover on the upstream side
setting + texture X Landscape position (H8)	interactive: landscape position influences the amount of water, while texture influences whether that water is transported through the system. When combined the effect on tree cover is greater.	When wetland substrate texture is coarse and in a low order wetland, there will be more of a decrease in tree cover.

setting + texture X distance to road (H9)	Interactive: Texture of the substrate will influence the amount of water that flows under the road and how fast water will move back into or out of the road for the impacted part of the wetland.	Road effects will be exaggerated on coarse-textured substrates.
setting + Landscape position X perpendicular (H10)	Interactive: Landscape position will influence the amount of water in the wetland system. Road orientation will affect the amount of water blocked. When the two are combined, there will be a more pronounced effect.	Below head water will have lower canopy cover when the road is perpendicular.
setting + Texture X perpendicular (H11)	Interactive: Texture influences conductivity. High conductivity results in more flowing water that can be dammed by roads. Road orientation will characterize the effectiveness of damming.	When the road is perpendicular and within a coarse-texture substrate the flooding and drying effect will increase resulting in lower canopy heights.
distance to road X perpendicular (H12)	Interactive: Road orientation will characterize the effectiveness of damming. Canopy cover will change with distance to road based on how effective the road is at damming water flow.	Locations closer to perpendicular roads will have greater flooding (lower canopy cover) and drying (increased canopy cover).
distance to road X Landscape position (H13)	Interactive: The Landscape position will characterize the potential water in the wetland. Canopy cover will change with distance to road based on how much water is in the wetland	Locations closer to roads built below headwaters will have greater flooding (lower canopy cover) and drying (increased canopy cover).

Table 2-4: Ranking of candidate models and the null model for canopy cover for each wetland type. The heading the “X” means the linear terms and their interaction. Degrees of freedom (*df*), log likelihood (logLIK), Akaike’s information criterion (AIC_c), delta Akaike (delta), Akaike weights (weight) for the most supported GLMMs. Pseudo-R^2 for each model as Marginal R^2 and Conditional R^2. Marginal R^2 is the proportion of variance explained by fixed effects (road and environmental variables) and the Conditional R^2 is the proportion explained by both the fixed effects and the random effects (peatland unit).

Rich Fen		***df***	**logLik**	**AIC_c**	**delta**	**weight**	**Marginal R^2**	**Conditional R^2**
F(H17)	Side & Texture interactions	17	-4593.5	9221.16	0	1	0.34	0.86
F(H18)	Side & Road distance interactions	18	-4650.55	9337.29	116.12	0	0.27	0.70
F(H15)	All side interactions	15	-4667.79	9365.71	144.55	0	0.26	0.70
F(H14)	Hydrology & Side interactions	14	-4670.09	9368.3	147.13	0	0.26	0.70
Null-F	Null	3	-5023.35	10052.7	831.53	0	0.00	0.49

Poor Fen		***df***	**logLik**	**AIC_c**	**delta**	**weight**	**Marginal R^2**	**Conditional R^2**
P(H16)	side & order interactions	17	-12273.2	24580.49	0	1	0.22	0.50
P(H18)	Side & Distance to road interactions	17	-12287.8	24609.73	29.24	0	0.23	0.49
P(H14)	Hydrology & side interactions	13	-12300.4	24626.88	46.39	0	0.23	0.49
P(H15)	all side interactions	14	-12301.7	24631.53	51.04	0	0.23	0.49
Null-P	Null	3	-12725.4	25456.81	876.32	0	0.00	0.40

Bog		***df***	**logLik**	**AIC_c**	**delta**	**weight**	**Marginal R^2**	**Conditional R^2**
B(H18)	Side & Distance to road interactions	17	-2170.57	4375.57	0	1	0.16	0.69
B(H9)	Texture X distance to road	10	-2186.88	4393.91	18.34	0	0.17	0.62
B(H15)	all side interactions	14	-2184.17	4396.63	21.05	0	0.15	0.67
B(H4)	Texture and Landscape position	10	-2188.68	4397.52	21.95	0	0.17	0.62
Null B	Null	3	-2263.01	4532.03	156.46	0	0.00	0.37

Table 2-5: Summary of beta (β) values, standard error (SE), and Standardized beta values (St. β) for the most supported models for each wetland type. The contrast variable is in parenthesis for categorical variables. The heading the "X" means the linear terms and their interaction.

	Bog			**Poor Fen**			**Rich Fen**		
Variable	**β**	**SE**	**St.β**	**β**	**SE**	**St.β**	**β**	**SE**	**St.β**
Intercept	-10.68	2.46	-2.22	-2.35	0.66	0.6	3.95	1.59	-0.14
side (upstream)	-3.26	0.49	-0.74	-1.66	0.2	-0.89	-1.18	0.19	-0.23
log10(distance to road)	-1.36	0.48	-0.36	0.4	0.07	0.12	0.11	0.06	0.03
road orientation (perpendicular)	1.6	1.28	-0.17	-0.45	0.7	-0.45	0.46	0.63	0.46
Texture (coarse)	7.66	2.9	0.79	0.08	0.26	-1.18	1.52	0.3	-0.13
Landscape position (below headwater)	-2.22	1.98	1.34	-1.44	0.7	-1.44	-1.1	1.18	-1.1
Structure type (treed)	----	----	----	----	----	----	0.27	1.11	0.27
distance to open water	3.65	0.52	0.71	0.79	0.05	0.36	-1.2	0.12	-0.42
distance to wetland edge	-0.16	0.08	-0.07	-0.23	0.03	-0.15	-0.28	0.04	-0.14
distance to road X side (upstream)	1.23	0.21	0.33	0.38	0.09	0.11	0.46	0.09	0.13
side (upstream) X texture (coarse)	-0.2	1.27	-0.2	0.42	0.08	0.42	-0.85	0.08	-0.85
road orientation (perpendicular) X side (upstream)	-0.29	0.12	-0.29	0.07	0.06	0.07	-0.28	0.06	-0.28
log10(distance to road) X texture(coarse)	-3.34	1.42	-0.89	-0.62	0.12	-0.18	-0.8	0.13	-0.23
log10(distance to road) X perpendicular	-0.86	0.22	-0.23	----	----	----	----	----	----
log10(distance to road) X order (below headwater)	1.73	0.5	0.46	----	----	----	----	----	----
Order (below headwater) X side (upstream)	0.56	0.26	0.56	0.35	0.06	0.35	-0.12	0.07	-0.12
Order (below headwater) X Road orientation (perpendicular)	----	----	----	0.16	0.81	0.16	----	----	----
Road orientation (perpendicular) X Texture (coarse)	----	----	----	----	----	----	-2.69	0.24	-2.69
Order (below headwater) X texture (coarse)	----	----	----	0.64	0.11	0.64	----	----	----

7. Figures

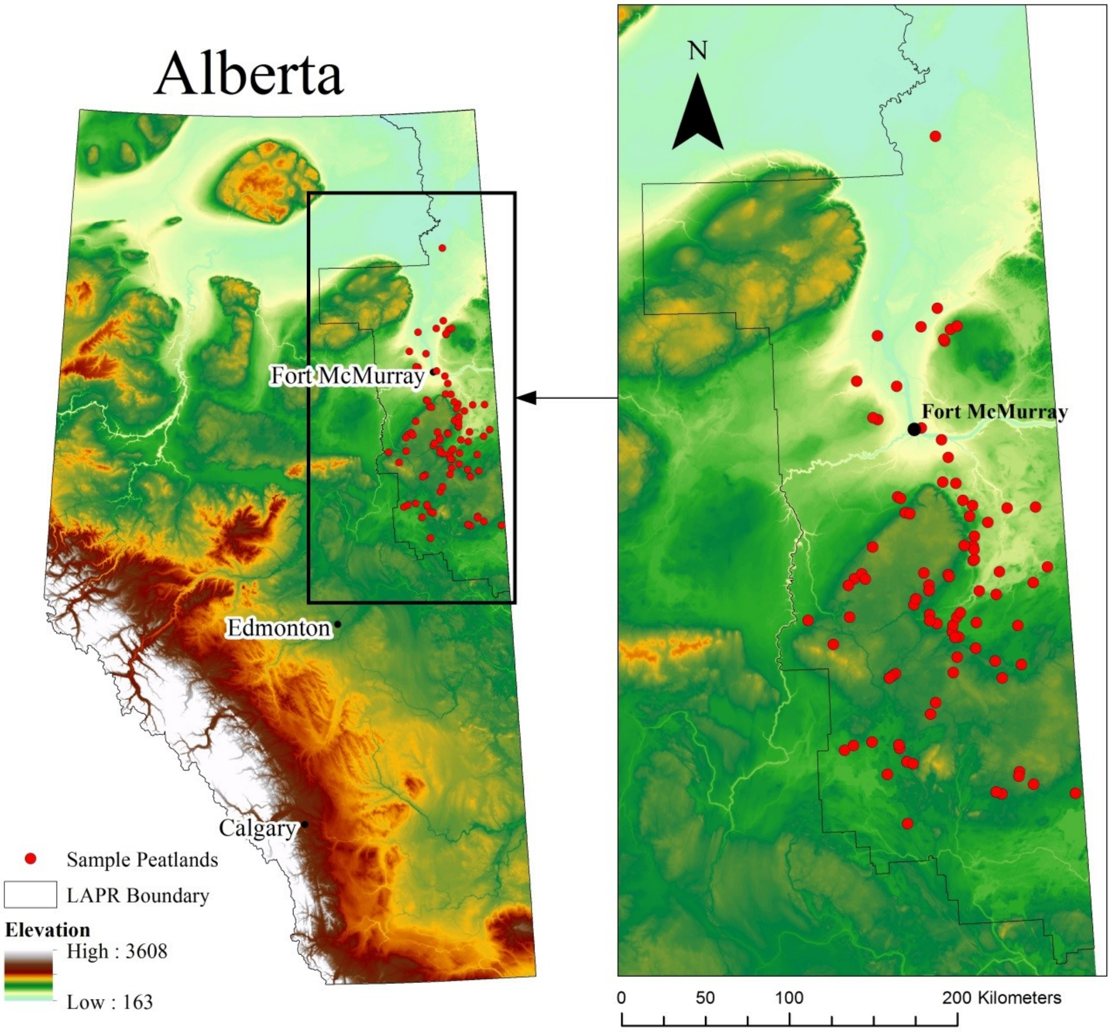

Figure 2-1: Map of study sites in northeast Alberta, Canada. The Lower Athabasca Planning Region (LAPR) is outline in black on the map and inset. The red circles are the remotely sensed airborne LiDAR sample locations.

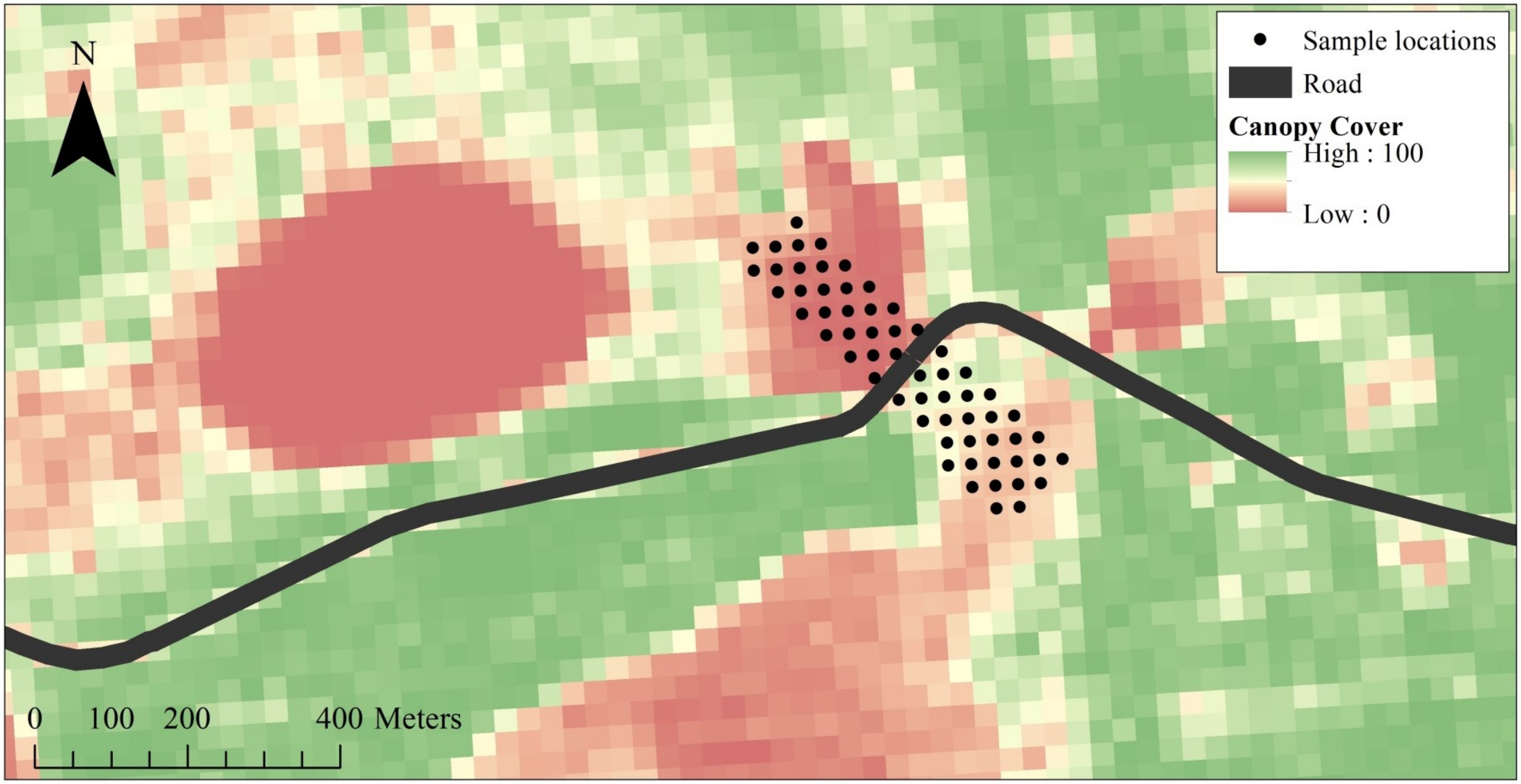

Figure 2-2: Example sample locations for a road-dissected wetland west of Fort McMurray, Alberta along Tower road (56°47'32.86" N, 111°46'19.35" W). Patterns in LiDAR canopy cover defined as percent returns over 1.3 m. Image is illustrating raster data and sample points in Arc GIS.

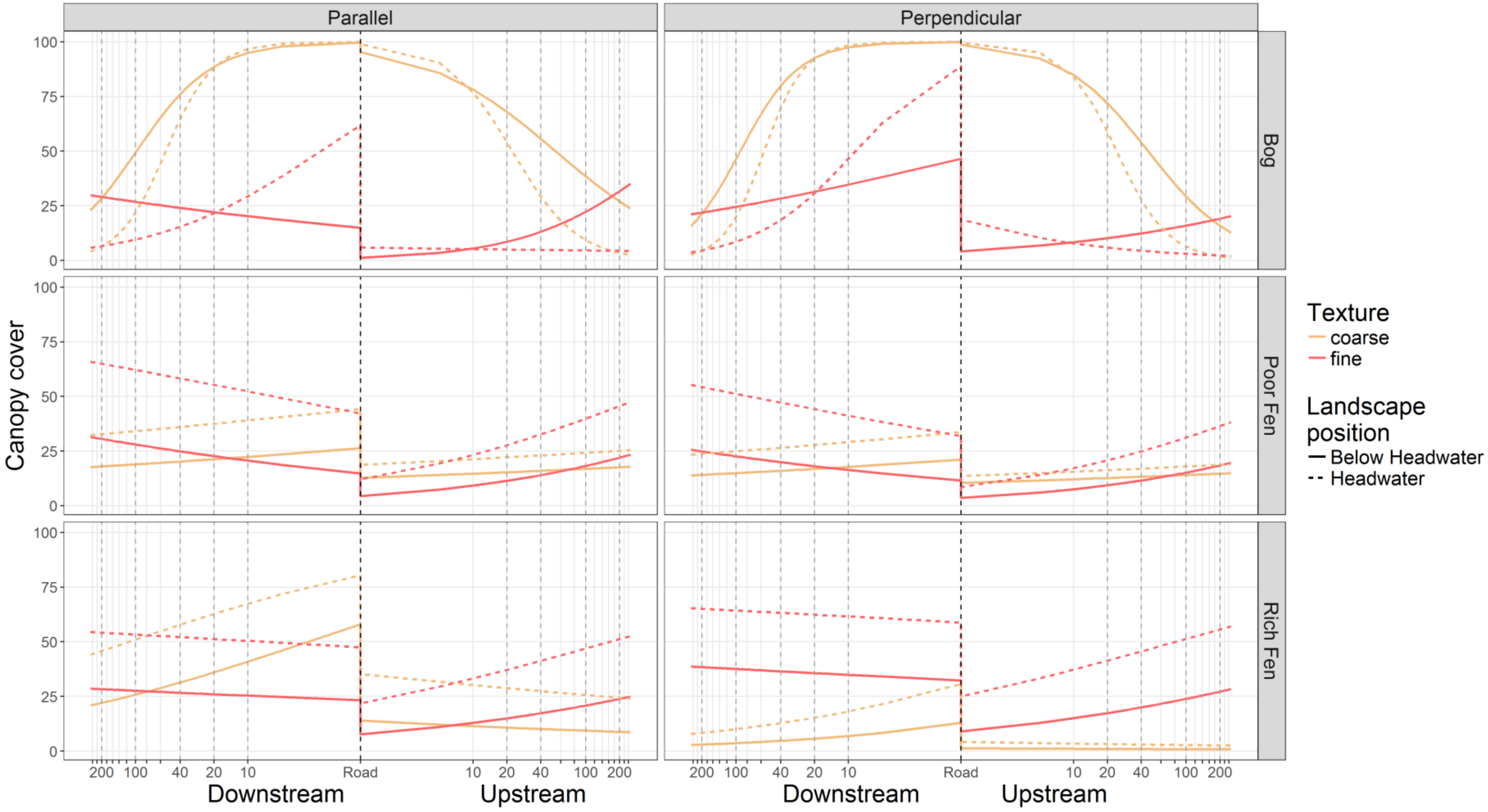

Figure 2-3: Canopy cover (y-axis) by wetland type (labeled on the right in grey frame), landscape position (headwater or not), and road orientation (left vs. right columns) by distance from road (x-axis) and substrate texture (coarse- and fine-textured).

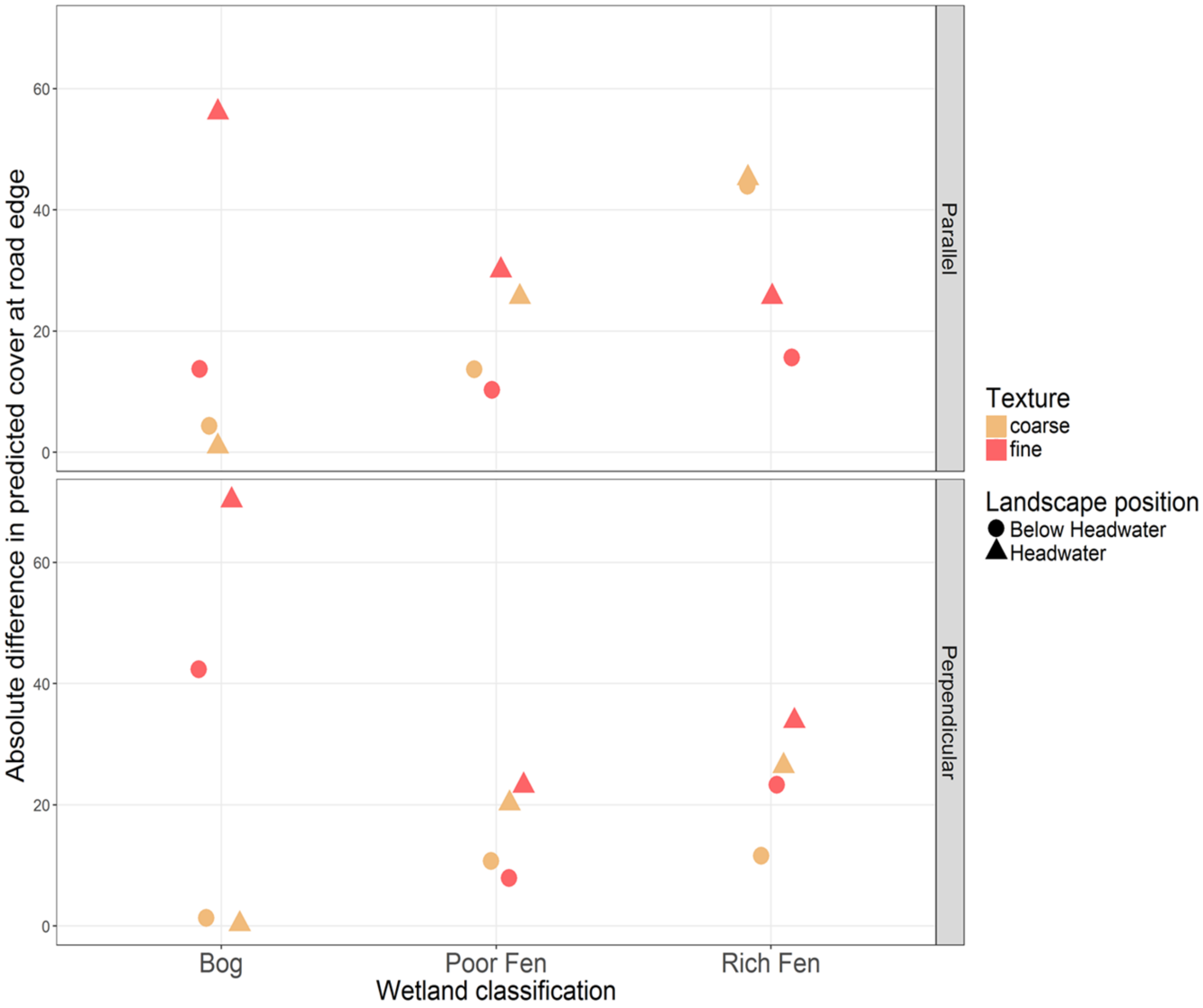

Figure 2-4: Absolute difference in predicted canopy cover at road edges by wetland type, landscape position, and substrate. Parallel road orientation is in the top frame and perpendicular road orientation in the bottom frame.

Chapter 3: Effects of road-induced flooding and drying on vegetation in peatlands

Abstract:

Roads built through peatlands with horizontal water flow have the potential to act as dams that affect local hydrology and thus vegetation. On the “upstream” side of the road, trees may become waterlogged and either die or grow stunted, whereas those on the “downstream” side may demonstrate drying with deeper root growth and increased tree height than is typical for peatlands. Interestingly, this phenomenon is not consistent. Comparable roads constructed through different peatlands may disrupt tree growth patterns in some locations, while others appear unaffected. This study examines the conditions that maintain or alter stand structure and vegetation composition in different types of road-bisected peatlands, namely that of landscape position and mineral soil substrate composition (clay, sand, silt). Vegetation data were collected for 25 peatland sites in northeastern Alberta with 4 plots per peatland that represented each side of the road (dry vs. wet) and more distant controls. Generalized Linear Mixed Models (GLMMs) and distance-based redundancy analysis were used to evaluate relationships between vegetation cover and species composition among peatland type, environmental factors, and road characteristics. Canopy cover and tree species composition increased on the downstream side of roads. Species richness of vascular plants increased in bogs on the upstream side of roads, while being lower on the upstream side of roads in fens. An indicator species analysis identified *Carex limosa, Carex canescens*, and *Andromeda polifolia* as indicators of the upstream side of roads in fens, swamps, and bogs respectively with significant differences confirmed in GLMMs. Substrate conditions below the peat further affected responses of plants with ericaceous shrubs positively related to amount of clay, while some forbs and sedges were positively related to amount of sand. Peatland substrate also influenced the effect roads had on species composition. Bogs with substrates high in sand content had floristic shifts on the upstream side of the road whereas vegetation communities were similar on both sides of the road in bogs with very little sand.

1. Introduction

Approximately 50% of northeastern Alberta is covered by wetlands with 90% being peatland (Vitt et al. 1996). Peatlands make up an integral part of the landscape and serve important ecological functions, including habitat for plants and wildlife, recharging and discharging of groundwater that facilitates flood storage and desynchronization, and dissipating erosive forces and shoreline anchoring (Adamus, 1983). Some Alberta wetlands support rare flora and fauna; for example, rich graminoid fens are primary habitat for the yellow rail, which is a species of concern in Alberta (Bookhout, 1995).

A variety of man-made linear features are present within Alberta's peatlands, including railways, roads, pipelines and seismic lines. These linear features effectively fragment ecosystems disrupting the movement of water and nutrients (Turetsky and St. Louis, 2006) and creating corridors which influence the movement patterns of both humans and wildlife, including the federally threatened woodland caribou (*Rangifer tarandus*) which are priority for conservation (Dyer et al., 2002; Revel et al., 1984; Semeniuk et al., 2014). This has led to an emphasis of linear feature restoration in peatlands (van Rensen et al., 2015).

Given the considerable extent of peatlands in northern Alberta's boreal forest and the increasing need for roads to support natural resource extraction, a better understanding of how roads affect peatlands is important for identifying where impacts are most likely and which mitigation actions may be effective. Impacts of roads on peatlands have been previously observed in peatland ecosystems (Gillies, 2011; Siegel and Glaser, 1987). Roads built through peatlands with horizontal water flow have the potential to act as dams and disrupt local hydrology. Trees on the "upstream" side of a road can become waterlogged and either die or grow stunted, as the higher water table limits the rooting zone causing anoxic conditions that lead to mortality of previously established trees (Asada et al., 2005).

In contrast, on the "downstream" side of a road there can be prolonged decreases in the water table with increased above- and belowground (root) trees growth more than expected in peatlands. Indeed, many peatland plant species are hydrophytic and adapted to tolerate anaerobic rooting conditions during the growing season. A lower water table maintained across multiple growing seasons can therefore produce shifts in species composition from wetter graminoid- or sedge-dominated communities to drier shrub-dominated communities (Weltzin et al. 2003). Miller et al.

(2015) demonstrated that fens desiccated by drainage had vegetation community assemblages with more dry-adapted species (trees and shrubs) than those of undisturbed fens, including aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) (Miller et al., 2015; Minkkinen et al., 1999). However, patterns of flooding and desiccation are not consistent among peatland sites. Comparable roads constructed through different sites may disrupt tree growth in some locations, but others may appear unaffected.

The goals of this study were to better understand changes in vegetation patterns following road-induced water impoundment and desiccation, and to examine differences in plant community composition in peatlands bisected by roads. We surveyed a variety of peatland types intersected by roads and examined their plant communities. Because responses are dependent on road and site characteristics, we examined the interaction between substrate type from surficial geology (fine vs. coarse-textured), landscape positions in the peatland complex (headwater peatland vs. not), road orientation (parallel vs. perpendicular to flow), side of road (dry vs. wet), and presences or absence of culverts.

2. Methods

2.1 Study area and site selection

The study occurred in Boreal Plains of northeast Alberta spanning 200-km east-west from highway 88 near Lesser Slave Lake to the Conklin and 250-km north-south from Boyle to Fort McMurray (Figure 2-1). The Boreal Plain is typified by glacial outwash and low topographic relief (Fenton et al., 1994) with a sub-humid climate of 382 to 623 mm of annual precipitation (Environment Canada 2010).

Satellite imagery was used to identify road-fragmented peatlands in northeast Alberta, Canada. Sites were then stratified into different peatland types using the Ducks Unlimited Enhanced Wetland Classification (DU-EWC), a 30-m land cover classification for the region. Landscape position was estimated for each site using satellite delineation of the landscape peatland complex. Peatlands with less than 1 km of upslope peatlands were considered at the top of the peatland complex and categorized as headwater. In contrast, peatlands with more than 1 km of upslope peatland were considered to be below the headwater.

Peatlands fulfilling the following criteria were then selected for field sampling: (1) peatlands had to be categorized as a bog, fen, or swamp; (2) peatlands had to have a road dissecting at least a third of the peatland; and (3) the road must be an all-weather gravel road. Based on this selection criteria, 25 peatlands were selected for field surveys (six bog sites, 13 fen sites (five poor fens, eight rich/moderate fens), and five swamp sites).

2.2 Vegetation sampling

Four vegetation plots were surveyed in each peatland. Two plots were placed on the water impounded side of the road (upside of the road) with one plot adjacent to the cleared edge of the road and one plot 100 m from the cleared edge (Figure B3-1). The same was done on the opposite, downstream side of the road. Each plot consisted of a 50 m transect run parallel to the road with five 1 m^2 quadrates every 10 m. Vascular plant species cover was measured in each quadrate and the entire plot was surveyed for presence of species. Canopy cover was measured over the center of each quadrat using 4 spherical densitometer readings each from a cardinal direction and averaged. Vegetation community composition associated with distance to road and side of road, individual quadrats within the same plot were consolidated by using the mean percent cover for each species per plot (Plot layout is shown in Figure B3-1 in the supplemental appendix).

2.3 Peat substrate sampling

Substrate conditions below each site were quantified at the center of each plot by collecting a sample using an extendable soil auger. Soil samples we analyzed by hydrometer to determine physical proportions of three particle sizes (sand 2000-50um, silt 50-2.0um, and clay <2.0um) (American Society for Testing & Materials International, 2007; Bouyoucos, 1962; Carter and Gregorich, 2008). Samples were analyzed at the University of Alberta Natural Resources Analytical Laboratory.

2.4 Statistical analysis

2.4.1 Species richness analysis

Data were separated by peatland type and analyzed individually to avoid complex third-order interactions between type of peatland, road characteristics, and landscape/substrate. Richness was determined by the total number of species found in the 1000 m^2 plot. Generalized linear mixed models (GLMMs) with a Gaussian family (R development Core team 2012) was used to compare species richness among sites and conditions with a nested random effect for peatland site and plot, where the intercept vary among peatland sites and among plots within peatlands sites. To examine differences in vegetation structure, we used the lme4 package (Bates et al., 2015) in R (R development Core team 2012) and evaluated differences in a series of candidate models with different factors.

2.4.2 Species community analysis

A dissimilarity matrix was calculated using a Bray-Curtis coefficient and the abundance data was transformed by adding a constant of 0.001 to eliminate the large number of zeros in the matrix. We created models of the multivariate analysis of variance using a distance based redundancy analysis (db-RDA) again using a Bray-Curtis distance with the capscale function of vegan. The db-RDA models of each variable were used to calculate the proportion of variance in the dissimilarity matrix explained by environmental measures. A db-RDA model was created for each hypothesis for the environmental variables to assess the most influential variables on community composition. Significant variables ($p = 0.01$) were combined to create models for each peatland type (fen and bog). The model fit was examined by testing the global db-RDA with an analysis of variance (ANOVA) and the R squared adjusted. The statistical analysis was performed using the "vegan" package in R (R development Core team 2012).

2.4.3 Indicator species analysis

Indicator species values were calculated using the *indicspecies* package (De Caceres and Legendre, 2009) in R (R development Core team 2012) to identify indicator species that are responding most to road-impacted peatlands. This was done for each type of peatland where comparisons of species and treatments were made to identify species associated with each type of peatland. We used the multi-level pattern analysis to assess the relationship between cover of vascular plant species and the side of the road (upstream or downstream).

2.4.4 Species analysis

Zero-inflated generalized linear mixed models (ZIGLMM) were then used to examine species responses to environmental predictor variables for each of the indicator species. Specifically, truncated Gaussian distributions were used to account for the large number of zeros in the data. In addition to individual indicator species, ZIGLMMs were fit using the glmmadmb package (Skaug et. al. 2006) in R (R development Core team 2012) and evaluated differences in a series of candidate models with different factors.

We also created ZIGLMMs for two dominant plant families common to peatlands: sedges and ericaceous (dwarf) shrubs (see supplemental Table B3-1 for species). Ericaceous shrubs are typically more dominant in bogs, while sedges are more strongly associated with fens.

2.5 Variables and hypothesized responses

2.5.1 Wetland type

Wetland vegetation community assemblages have strong associations with site factors, primarily water chemistry and hydrology. At present, wetlands are grouped based on plant community assemblages (i.e. the Alberta Wetland Classification System and the Ducks Unlimited Enhanced Wetland Classification). In addition, Vitt (1994) suggests that peatland hydrology can be inferred based on vegetation with specific hydrologic characteristics identified for four classes of peatlands outlined further below.

Nutrient poor bogs that are characterized as having low species diversity are dominated by sphagnum mosses, black spruce, and tree and ground lichen (Wieder et al., 2006). They are isolated and stagnant, receiving water primarily through precipitation resulting in low nutrient levels (Vitt, 1994). Sphagnum mosses have the competitive edge in these environments and are thus able to dominate the forest floor (Swanson and Flanagan, 2001). The presence and dominance of sphagnum further acidifies the environment due to increased H+ ions (Aerts et al., 1999). It also acidifies undecomposed organic matter accumulation (peat), resulting in the formation of humic acid (Waddington et al., 2015). The resulting nutrient-poor and highly acidic environment is suitable for only a few species (e.g. sphagnum mosses, ericaceous shrubs, black spruce and cotton grasses) (Vitt, 1994). Bogs continually accumulate peat potentially rising above the water table and thus in some cases forming overtop of fens (Siegel and Glaser, 1987). Groundwater having a long transit time through an anoxic, nutrient poor, acidic environment may limit the amounts of total dissolved solids in the bog and acidify the water that reaches the bog vegetation (Siegel, 1988).

Vitt (1994) describes three types of fens based on nutrient content: poor fens, moderate fens, and rich fens. Fens are distinguished from bogs based on differences in pH and species composition. Fens have a complex combination of surface, subsurface, and groundwater interactions that connect them to wetland systems over vast distances (Vitt 1994, Ducks Unlimited 2015). Rich fens have a neutral to basic pH and are high in total dissolved solids (primarily calcium and magnesium) with its vegetation generally composed of brown mosses and sedges. In contrast, poor fens have an acidic pH and are low in total dissolved solids with fewer species of sedges and some species associated with bogs (Ducks Unlimited, 2015; Vitt, 1994). Moderate fens have a pH between rich and poor fens with a mixture of the two species assemblages and have flowing water.

Finally, swamps are not typically classified as peatlands being characterized as having less than 40 cm of peat accumulation and greater temporal fluctuations in water (Alberta Wetland Classification System 2015; Stewart and Kantrud 1971).

Based on these hydrological classifications (which are themselves based on vegetation), we would expect a stagnant, rainwater-fed system, such as a bog to be largely unaffected by the construction of an intersecting road, since the road would not interrupt any significant water flow. In contrast, a fen system (characterized by flowing water) would be significantly affected by the construction of a road due to the blockage of regular water flow. Finally, swamps would have the potential to block water flow, but since water flow is typically highly variable it is not expected to alter vegetation composition that already is adapted to strong variations in the water table.

2.5.2 Peatland substrate

Interactions among vegetation, nutrient dynamics, and carbon are regulated by hydrology (Waddington and Roulet, 1997). Hydrology also controls wetland function and development (Mitsch and Gosselink, 1993). Reeve et al. (2000) study showed that vertical ground water flow is primarily controlled by mineral soil permeability.

When the permeability of the peatland substrate is low (mineral soil consist largely of silt and/or clay), later flow of water in the upper position of the peat is dominant (Reeve et al., 2000). Therefore, bogs on impermeable soils are isolated and only receive atmospheric inputs, while fens receive inputs from upland runoff. Silt and clay has low infiltration rates and lower rates of lateral subsurface water transmission, therefor bogs are largely isolated (Devito et al. 2012). Slow water movement through the fine-textured mineral soils limits conductivity between uplands and peatlands (confined to local gradients). I expect peatlands on fine-textured surficial geology to have more horizontal water movement, however lack the substrate permeability that facilitates hydraulic conductivity, restricting the amount of water flowing through the peatland landscape. Road-induced water impoundment in peatlands is these conditions are therefore expected to be minimal in bogs which are characteristic of little flowing water, and high in fens in fine-textured landscapes.

When the permeability is high (mineral soil consists largely of sand), bogs can be areas of recharge. Precipitation water flows vertically down through bogs and flushes solutes from the peat (Siegel and Glaser, 1987). Fens are areas of discharge and are fed by the flushed waters from the bogs and ground water discharge (Siegel et al. 1995). Consequently, we expect that bogs in fine textured-soil will have similar canopy because the hydraulic conductivity is high and most of the water movement is vertical. In fens, we expect road effects in these conditions due to high conductivity and the large amounts of discharge in these peatlands.

2.5.3 Landscape position

Within a peatland complex, there are often interconnected fens and bogs. Bogs are areas of recharge and fens are often areas of discharge. Flow within the peatland complex is both a product of the connectivity within the peatlands and between the uplands and the peatlands, as well as the amount of water within and entering the system (Devito et al., 1997; Reeve et al., 2000; Siegel and Glaser, 1987). I speculated that road location within the peatland (landscape position) would influence canopy cover and the responses in canopy on either side of the road. We hypothesized headwater systems would have less water and overall lower water tables and thus have more canopy cover. Because of this, we also hypothesized peatlands in the headwaters would have less road effects when comparing differences between sides of road.

2.5.4 Water chemistry

In addition to changes in hydrology, roads may also cause changes in water chemistry. Plant communities can be altered as a result of hydrological disturbances blocking nutrient flows. For example, a reduction in nutrient flow can shift a rich fen – one with more species and nutrients and a more neutral pH – to a poor fen, which is less species diverse, nutrient poor and more acidic pH (e.g. Podniesinski & Leopold 1998). Chee & Vitt (1989) found that pH, conductivity, calcium, and magnesium distinguish fen types. Conductivity and pH were lowest in poor fens and increased with richness. I predict that nutrient flow dammed by roads will shift species communities on the upstream side to more neutral fen communities and the downstream side to poorer more acidic plant communities.

Minerals associated with the roadbed may also influence roadside community types. For example, salts used to limit freezing may cause water stress in plants (Goodrich et al. 2009). Calcium used for hardening the road can also enrich what would have been a nutrient deficient bog.

2.5.5 Hypothesized response to road orientation

I expect road orientation in relation to the general direction of flow in peatlands to affect vegetation. In fens with flowing water, roads that are perpendicular to water flow should have large differences in vegetation composition and stand structure on opposing sides of the road, while little to no difference when the road is parallel to water flow. Since bogs have little flowing water, road orientation should have little effect. Lastly, vegetation in swamps is adapted to fluctuating water levels and road orientation is expected to have little impact on vegetation communities.

3. Results

A total of 257 plant species were identified across all peatland types with 112 species occurring in more than 5% of sample plots and species richness ranging from 1 to 25 per m^2 (per quadrat).

3.1 Species richness

Species richness varied among peatland types being lowest in bogs and higher and similar among fens and swamps, although richness was significantly higher in plots 100 m from roads on the upstream side of swamps than in fens (Figure 3-2).

The most supported model for species richness in bogs contained side of road, plot location (distance to road), landscape position, and the interaction between the side and location to road (Table in the supplemental appendix Table B3-2). In bogs, a headwater position was negatively related to species richness (Table 3-1; Figure 3-3 & 3-4). Species richness in bogs was highest adjacent to roads on the upstream sides and decreasing by distance from roads. On the downstream side of roads, species richness in bogs was lowest adjacent to the road, while increasing with distance from roads (Figure 3-3 & 3-4).

The most supported model of species richness in fens contained side of road, location to road, road orientation, landscape position, and the interaction between road orientation and side of road. Perpendicular roads had a strong negative effect on species richness on the upstream side of the road, while species richness was higher on the downstream side of roads than the upstream side of roads when the road was perpendicular. Location to road had a positive effect on species richness in plots adjacent to the road. Similar to bogs, headwater landscape positions were negatively related to species richness (Figure 3-3 & 3-4).

The most supported model of species richness in swamps contained the side of road, road orientation, landscape position, percent clay substrate, and the interaction between road orientation and side of road. Higher species richness was observed in swamps with parallel roads with a weak negative effect on species richness for roads on the upstream side that are parallel to water flow. Perpendicular roads had a strong positive effect on species richness on the upstream side of the road (Figure 3-3 & 3-4).

3.2 Species composition: Distance based redundancy analysis

The most important factors affecting vegetation composition in fens were canopy cover, conductivity, landscape position, interactions between side of road and landscape position, interactions between side of road and amount of clay substrate, interactions between side of road and culvert presence, and water chemistry (calcium, potassium, and magnesium). Water chemistry of potassium and magnesium were the most significant variables. Overall, these variables explained 55% of the variation in species composition ($R_{adj}^2 = 0.36$, $F = 2.6$ $p < 0.001$). We also saw a weak effect of plot location for single term db-RDA models (*R-squared* = 0.10, $R_{adj}^2 = 0.02$, $p = 0.020$). In the ordination plot of the fen db-RDA illustrated greater tree species composition and canopy cover on the downstream side of roads than the upstream side (Figure 3-5). This supports our hypothesis that drying would increase woody composition, although some woody shrubs such as dwarf birch (*Betula pumila*), bog rosemary (*Andromeda polifolia*) and bog willow (*Salix pedicellaris*) were more strongly associated with the upstream side of the road than downstream. These shrubs are, however, peatland specialists and not associated with drier upland forests. Amount of clay in the substrate and water conductivity were inversely related to each other and not correlated with road effects.

The interaction between headwater and the upstream side of roads demonstrated a shift in community composition to more tree-dominated communities. Although not significant and therefore not included in the fen db-RDA biplot, the interaction between culverts and side explained 14% of the floristic variation on the upstream side of the road (*R-squared* = 0.14, R_{adj}^2

= 0.07, p = 0.011).

The only significant variables from the single term db-RDA models for bogs were the interaction terms for amount of sand in the substrate and side of road. The model containing the interaction between side of road and amount of sand explained 24% of the variation in species composition (R_{adj}^2 = 0.13, F = 2.2, p = 0.010). Ordination plots demonstrate that species such as leatherleaf, water sedge (*Carex aquatilis*), and three-leaved Solomon's seal (*Maianthemum trifolium*) were associated with increased amount of sand in the substrate and the wet-side of roads (Figure 3-5). Interestingly, canopy cover did not influence the tree species on side of road in bogs, but was influential in fens. There was also more overlap in community composition between the upstream and downstream side of the roads in bogs where the wet side in sandy sites had greater differences in species composition.

The most important factors affecting species composition in swamps include canopy and water chemistry of salt, conductivity, calcium, and magnesium. Overall, 50% of the variation in species composition in the swamps were explained by these variables (R_{adj}^2 = 0.34, F = 2.9, p < 0.001), although side of road did not significantly affect species composition (see biplot in supplemental Appendix B3-2).

3.3 Indicator species and their responses

Several species indicators were found for the upstream side of roads for each peatland type (Figure 3-7), while none were found on the downstream side of roads. Bog rosemary (*Andromeda polifolia*) was an indicator of the wet-side of roads in bogs (p = 0.045), while *Carex limosa* was an indicator of the upstream side of roads in fens (p = 0.010) and *Carex canescens* of the upstream side of roads in swamps (p = 0.020).

3.3.1 Responses of bog rosemary along roads in bogs

Bog rosemary cover differed by side of road, location (distance) to road, amount of silt substrate, and the interaction between location to road and side of road (Table 3-2 & Figure 3-8). Bog rosemary cover increased on the upstream side of the road with the interaction of location adjacent to the road increasing bog rosemary cover. Bog rosemary cover was inversely related to amount of silt in the substrate.

3.3.2 Responses of *Carex limosa* along roads in fens

Carex limosa cover differed by side of road, location (distance) to road, amount of silt in substrate, and the interaction between silt and location to road. *Carex limosa* cover was positively related to the upstream side of roads when in the adjacent plot (Table 3-2 & Figure 3-7). An interaction between plot location and side of road was tested but not supported. *Carex limosa* cover increased in peatlands having higher silt substrate content. When silt content was low, plots adjacent to roads had higher cover of *Carex limosa* than plots 100 m from roads. The opposite was true for peatlands with high silt content where we observed higher *Carex limosa* cover in the plots 100 m from the road than in plots adjacent to roads.

3.3.3 Responses of *Carex canescens* along roads in swamps

Carex canescens cover differed by side of road, but not other factors. Specifically, *Carex canescens* cover increased on the upstream side of roads (Table 3-2 & Figure 3-8).

3.4 Responses in sedges and ericaceous shrubs

3.4.1 Responses of sedges and ericaceous shrubs in bogs

Sedge cover in bogs differed by side of road, location (distance) to road, road orientation, and the interaction between road orientation and side of road. Sedge cover increased on the upstream side of roads that were parallel in orientation to water flow, whereas sedge cover decreased marginally on the upstream side of roads that were perpendicular to water flow (Table 3-3 & Figure 3-8). Ericaceous shrub cover in bogs differed by side of road, amount of silt in the substrate, and the interaction between road and amount of silt. Ericaceous cover was negatively related to amount of silt content on the upstream side of the road, while ericaceous cover increased on the downstream side of roads having higher amounts of silt. At low silt levels, ericaceous shrub cover was higher on the upstream side of roads than the downstream side of roads. When silt levels were high, the downstream side of roads had higher ericaceous shrub cover than the upstream side of roads.

3.4.2 Responses of sedges and ericaceous shrubs in fens

Sedge cover in fens differed by side of road, location (distance) to road, landscape position, amount of sand, and the interaction between side of road and amount of sand. Sedge cover was negatively related to percent sand on the upstream side of roads and a strong positive effect with increasing sand content on the downstream side of the road. Headwater landscape position and distance to road were negatively related to sedge cover (Table 3-2 & Figure 3-8).

Ericaceous shrub cover differed by side of road, road orientation, landscape position, amount of clay, and the interaction between side of road and road orientation. Landscape opposition in the headwaters had a negative effect on ericaceous shrub cover, while clay content had a positive effect on ericaceous shrub cover (Table 3-3 & Figure 3-8). Ericaceous cover was positively related to upstream side of roads that were perpendicular to water flow and a negatively related to down streams side of roads. Ericaceous shrub cover was highest on the upstream side of roads when the road was perpendicular to water flow and nearly as high on the downstream side of the road when the road was parallel to water flow.

3.4.3 Responses of sedges and ericaceous shrubs in swamps

Sedge cover in swamps differed by side of road, amount of sand, and the interaction between side of road and sand. Sedge cover increased with sand content on the upstream side of roads, while being weakly negative to sand content on the downstream side of roads (Table 3-3 & Figure 3-8). Ericaceous shrub cover in swamps differed by side of road, landscape position, amount of sand, and the interaction between sand and side of road. Ericaceous shrub cover was positively related to landscape position in headwaters and sand content on the upstream side of roads. In contrast, ericaceous cover was negatively related to sand content on the downstream side of roads.

4. Discussion

Roads had an impact on species composition. Differences associated with the upstream and downstream side of the road were observed in our analysis, of community composition species richness of vascular plants and individual species cover.

Among all types of peatlands vascular plant species richness was highest in swamps. In swamps species richness on either side of the road was a product of road orientation. Perpendicular roads had a strong negative effect on species richness on the upstream side of the road, while parallel roads had a weak positive effect on species richness on the upstream side of roads. A potential explanation for this is that seasonal water fluctuations in swamps create a higher number of available niches relative to water availability (Callaway, 1995). Roads in swamps may be acting like a dam stabilizing the water table and attenuating the effect of flooding that helps to maintain high species richness in swamps. This is supported by road orientation where parallel roads would have less effect on blocking water movement and water fluctuations and thus maintain higher species richness.

Compared to swamps, fens had lower species richness and less variation among sites in species composition, while bogs had the lowest species richness and the least variation in species composition. The lower richness in bogs was especially evident on the downstream side of roads. Side of road in fens had the opposite effects. Species richness decreased on the upstream side of roads in fens. This is possibly due to the formation of new niches created by increases in water table, including standing water in bogs. In fens however, species richness is already higher than in bogs and the water table is also generally higher (Vitt, 1994). Bogs flooded by beaver dams have been shown to experience changes in vegetation from forested communities to minerotrophic fen communities, however many of the typical bog species persisted among the fen species (Mitchell and Niering, 1993). Fens experiencing flooding due to roads become too wet to maintain the typical bog species such as black spruce (*Picea mariana),* and Labrador tea (*Rhododendron groenlandicum*).

Indeed, the community analysis (db-RDA biplot) also shows a florist shift in bogs on the upstream side of the road, however floristic shifts were also influenced mineral soil texture. Bogs with substrates high in sand content had floristic shifts on the upstream side of the road whereas vegetation communities were similar on both sides of the road in bogs with very little sand. An increase in some low heather shrub species such as *Chamaedaphne calyculata, Vaccinium oxycoccos,* and *Andromeda polifolia* was observed*. Chamaedaphne calyculata* was also identified as one of the dominant species increasing with beaver flooding (Mitchell and Niering, 1993). Similarly, more variation in species composition on the upstream side of roads in bogs. and even greater divergence in composition on the upstream side of the road when sand composition mineral soil substrate was high was observed.

The fen community analysis demonstrated that species such as *Carex prairea, Carex limosa,* and *Carex diandra* were associated with the upstream side of roads in fens having low levels of clay in its substrate, while *Carex chordorrhiza*, *Carex aquatalis*, leatherleaf (*Chamaedaphne calyculata*) and bog willow (*Salix pedicellaris*) were associated with the upstream side of roads in sites with high clay composition. Species that were strongly associated with the downstream side of roads in fens were tamarack *(Larix laricina),* black spruce *(Picea mariana),* and Labrador tea

(*Rhododendron groenlandicum)*.

Canopy cover and distance from road (plot location) did not affect species composition in bogs. However, in the fen community analysis canopy cover and tree species composition increased on the downstream side of the road, and although not significant ($p = 0.165$) plot location explained 10% of the vegetation community variation in our db-DRA. Peatland substrate also influenced the effect roads had on species composition. This finding also supports previous studies that found that lower water tables caused an increase in woody plant species cover (Miller et al., 2015). Minkkinen et al. (1999) found that plant community composition remained relatively constant in bogs, but changed significantly in fens after drainage.

Variation in water nutrient availability, water table, and water acidity (hydrochemistry), has been shown to influence floristic composition in wetlands (Malmer et al., 2017). Our results suggest road may be altering the hydrochemistry of peatlands, particularly on the upstream side of roads. Periodic flooding with neutral water removes acid fractions and nutrients in peatlands, as seen in peatlands influenced by monsoons (Hotes et al., 2001). The strong negative correlation of nutrient content on the upstream side of roads could be due to flooding from snow melt or rainwater. Drying may also alter nutrients on the downstream side of roads because of drying can cause aerobic conditions that result in the mobilization of nutrients (Laiho et al., 2003, 1999). Water chemistry did not significantly affect community composition in bogs. Bog vegetation community composition is known to be associated with ombrotrophic hydrology, in which the peatland's primary source of water is rainwater and thus has very few available cations such as calcium or sodium (Chee and Vitt, 1989).

Communities on the upstream side of roads with culverts had a floristic shift to wetter communities. Rothwell et al. (1996) found that the water content of the peat was highest at ditch edges. Although useful for examining general changes in plant species composition among types of peatlands, the paired plot design may not be the most effective way to study the influence of culverts on plant communities. It is difficult to determine whether the culvert it was influencing the vegetation community or if it was flooding issues of the road prior to culvert installation however we assume most culverts were installed prior to road construction.

As we had hypothesized, landscape position was an important factor in vegetation composition. In fens, more tree cover, lower richness, and sedge cover in fens in headwater systems was observed. Community composition in headwater fens was similar on both sides of roads, but more tree-dominated regardless of road impacts.

Similar to what we found with the community analysis peatland substrate appears to play an important role in the response of some species groups to road induced flooding and drying. In fens with high sand content (~80%) there was no effect of side of road on sedge cover, however at low substrate sand content the downstream side of the road had a strong negative effect on sedge cover and the upstream side of the road had high sedge cover. This contradicts our hypothesis that sandy substrates would have higher hydraulic conductivity and therefore more water to be impacted by roads. It could be that the road has less effect on sedges when the substrate has a high sand content. I speculate that high sand content in fens may facilitate water movement and allow water to move under the road. Substrate below the peat had significant effects on species composition. Ericaceous shrubs were positively related to amount of clay, while some forbs and sedges were positively related to amount of sand.

An indicator species analysis identified *Carex limosa, Carex canescens*, and *Andromeda polifolia* as indicators of the upstream side of roads in fens, swamps, and bogs respectively with significant differences confirmed in GLMMs. Substrate conditions below the peat further affected responses of plants with ericaceous shrubs positively related to amount of clay, while some forbs and sedges were positively related to amount of sand.

Roads significantly affected vegetation composition in bogs and fens, but not swamps, with side of road explaining 5% of the floristic variation in fens and 4% in bogs. This supports our prediction that swamps would not be less affected by roads due to their naturally high seasonal variability in hydrologic conditions. Swamps also lack deep peat accumulation (Stewart and Kantrud, 1971), which may influence the effect roads have on this community. However, side of road and road orientation did have an effect on species richness in swamps with higher richness in sites where roads were parallel to water flow regardless of side of road and weak negative effects on richness for the upstream sides of perpendicular roads.

5. Conclusion

Determining which peatlands have higher risk for road failure and those that are more susceptible to environmental degradation is needed for maintaining the health of road-bisected peatlands. This study demonstrated that wetland classifications can be a useful indicator of responses in vegetation to roads. However, other environmental factors interact with wetland type, such as soil mineral substrate, road orientation, and landscape positon. Avoiding road construction in peatlands may not be an option where peatlands dominate areas of resource development, such as in northeast Alberta. With expected increases in resource development, particularly those associated with oil sands (National Energy Board 2016), demands for more roads will increase, as will information to guide placement of roads that minimize their impacts. A greater understanding of the effects of roads on hydrology is needed to more fully understand the drivers affecting vegetation communities and the habitat they provide.

6. Tables

Table 3-1: Summary of beta (β) values and standard errors (SE) describing responses in species richness by each wetland type (most supported AIC-model). Dashed lines are for variables not included (supported). Values of variables in parentheses represent the variable estimated for binary variables.

	Species richness					
	Bog		Fen		Swamp	
Variable	**β**	**SE**	**β**	**SE**	**β**	**SE**
Intercept	15.83	3.71	14.72	3.14	27.25	4.82
side of road (upstream)	-5.17	2.98	1.25	3.23	-1.75	3.28
location (distance) to road (adjacent)	-5.00	2.90	4.06	1.52	---	---
road orientation (perpendicular)	---	---	6.48	3.50	-12.46	6.75
Landscape position (headwater)	-1.33	4.57	-3.63	3.95	12.13	7.85
location to road (adjacent) X side (upstream)	11.67	4.22	---	---	---	---
road orientation (perpendicular) X side (upstream)	---	---	-4.96	3.66	5.92	4.24

Table 3-2: Summary of beta (β) values and standard error (SE) describing responses of indicator species by peatland type to site factors. Dashed lines are for variables not included (supported). Variables are shown on the left the contrast is in parenthesis where applicable.

	Bog wet		**Fen wet**		**Swamp wet**	
	Andromeda polifolia		*Carex limosa*		*Carex canescens*	
	β	**SE**	**β**	**SE**	**β**	**SE**
Intercept	2.41	1.32	-6.50	3.89	0.02	0.07
side of road (upstream)	0.71	1.45	6.55	2.05	0.19	0.08
location (distance) to road (adjacent)	0.12	1.84	3.00	3.79	---	---
road orientation (perpendicular)	---	---	---	---	---	---
% silt	-0.07	0.03	0.30	0.10	---	---
%silt X location to road (adjacent)	---	---	-0.27	0.11	---	---
location to road (adjacent) X side (upstream)	4.10	2.19	---	---	---	---

Table 3-3: Summary of beta (β) values and standard error (SE) for most supported models for each species group for each peatland type. Species groups are sedges and ericaceous. Dashed lines are for variables not included in the most supported model. Variables are shown on the left the contrast is in parenthesis where applicable.

	Bog				**Fen**				**Swamp**			
	Sedges		Ericaceous shrubs		Sedges		Ericaceous shrubs		Sedges		Ericaceous shrubs	
	β	**SE**	**β**	**SE**	**β**	**SE**	**β**	**SE**	**β**	**SE**	**β**	**SE**
Intercept	4.99	5.66	23.84	8.41	3.06	5.95	14.01	6.83	11.84	5.90	8.36	3.17
side of road (upstream)	32.41	7.28	28.78	9.13	29.74	8.04	-11.48	8.49	-9.46	8.20	-8.69	3.37
location to road (adjacent)	-6.72	3.29	---	---	-0.55	3.13	---	---	---	---	---	---
road orientation (perpendicular)	8.83	6.01	---	---	---	---	-11.71	7.63	---	---	---	---
Landscape position (headwater)	---	---	---	---	-12.43	4.86	-10.96	5.82	---	---	10.80	2.10
% sand	---	---	---	---	0.15	0.09	---	---	-0.02	0.11	-0.07	0.06
% silt	---	---	0.41	0.25	---	---	---	---	---	---	---	---
% clay	---	---	---	---	---	---	0.51	0.15	---	---	---	---
% sand X side (upstream)	---	---	---	---	-0.35	0.12	---	---	0.30	0.15	0.16	0.07
%silt X side (upstream)	---	---	-0.82	0.28	---	---	---	---	---	---	---	---
road orientation (perpendicular) X side (upstream)	-35.20	8.11	---	---	---	---	25.00	9.44	---	---	---	---

7. Figures

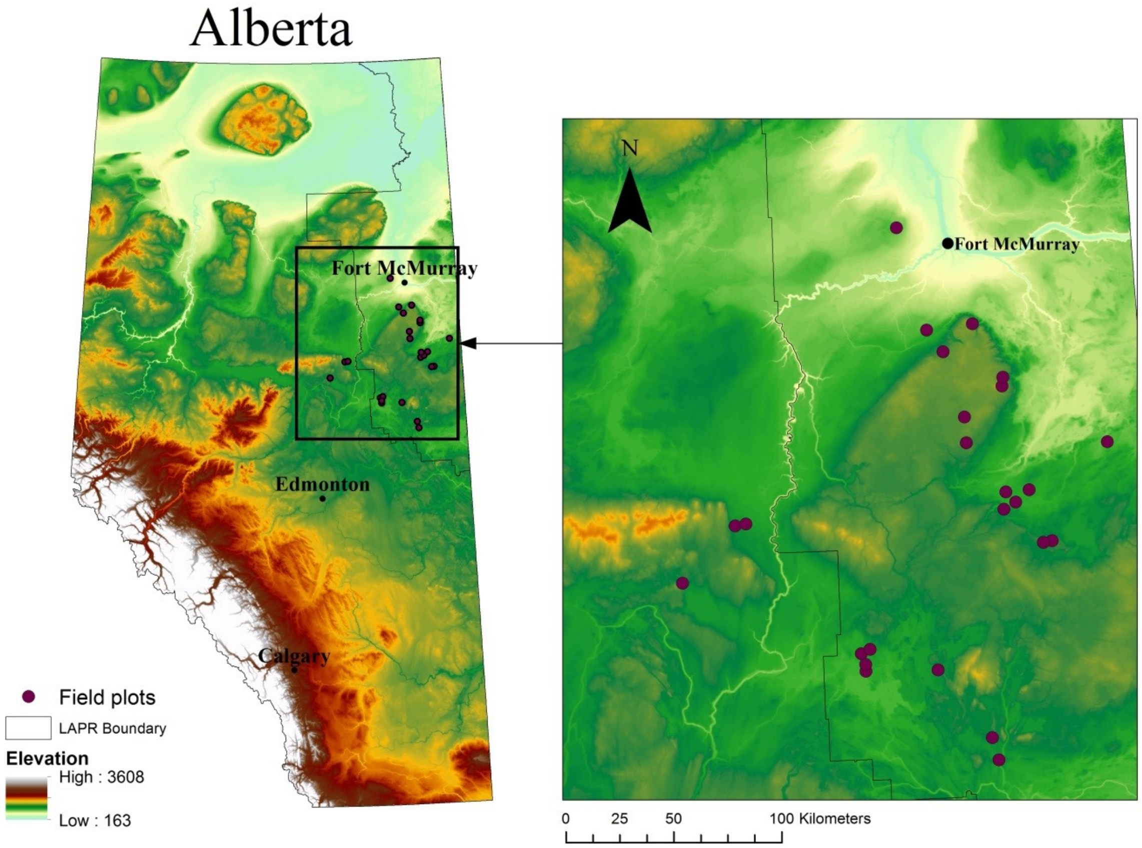

Figure 3-1: Map of study sites in northeast Alberta, Canada. The Lower Athabasca Planning Region (LAPR) is outline in black on the map and inset.

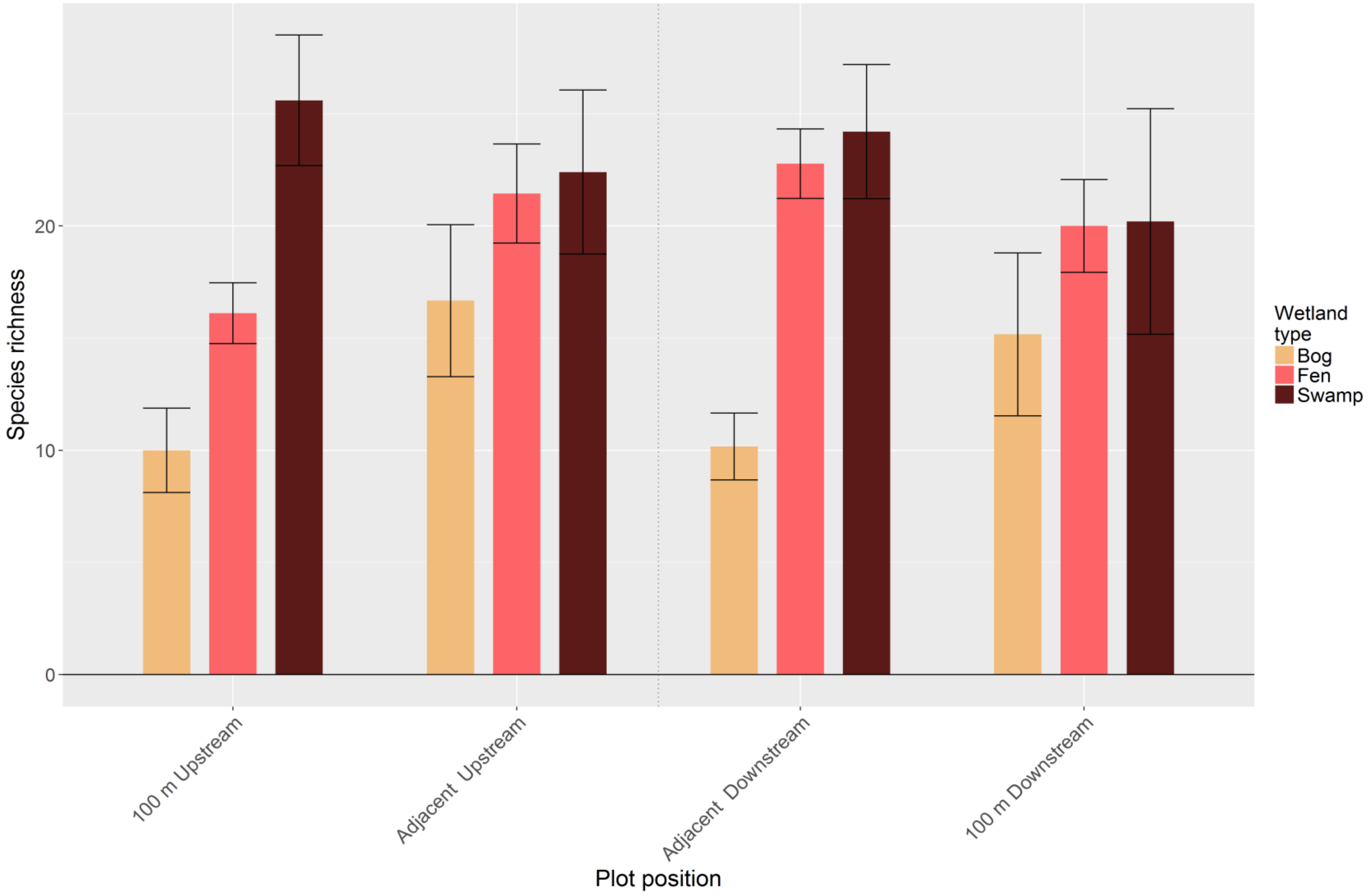

Figure 3-2: Average species richness by wetland type and plot position relative to road location. Dotted line in the centre of the x-axis represents the road location with sites to the left being upstream and sites to the right being downstream of roads. Standard errors presented for each response.

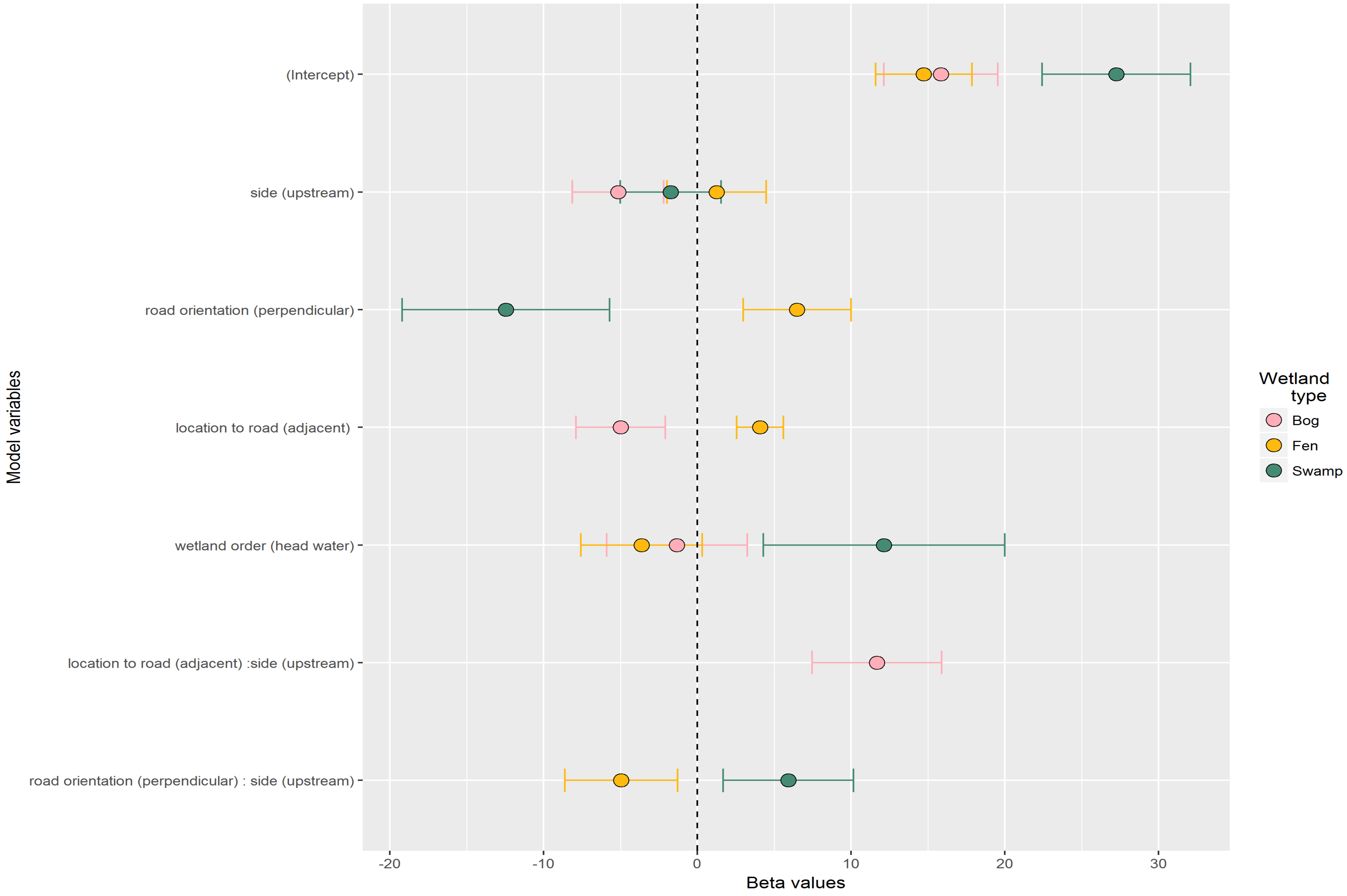

Figure 3-3: Plots of beta values and standard errors for factors affecting species richness by peatland type. Variables are shown on the left the contrast is in parenthesis where applicable. Beta value is on the x-axis with 0 denoted by a black dotted line. Peatland type is distinguished by the colour of the points.

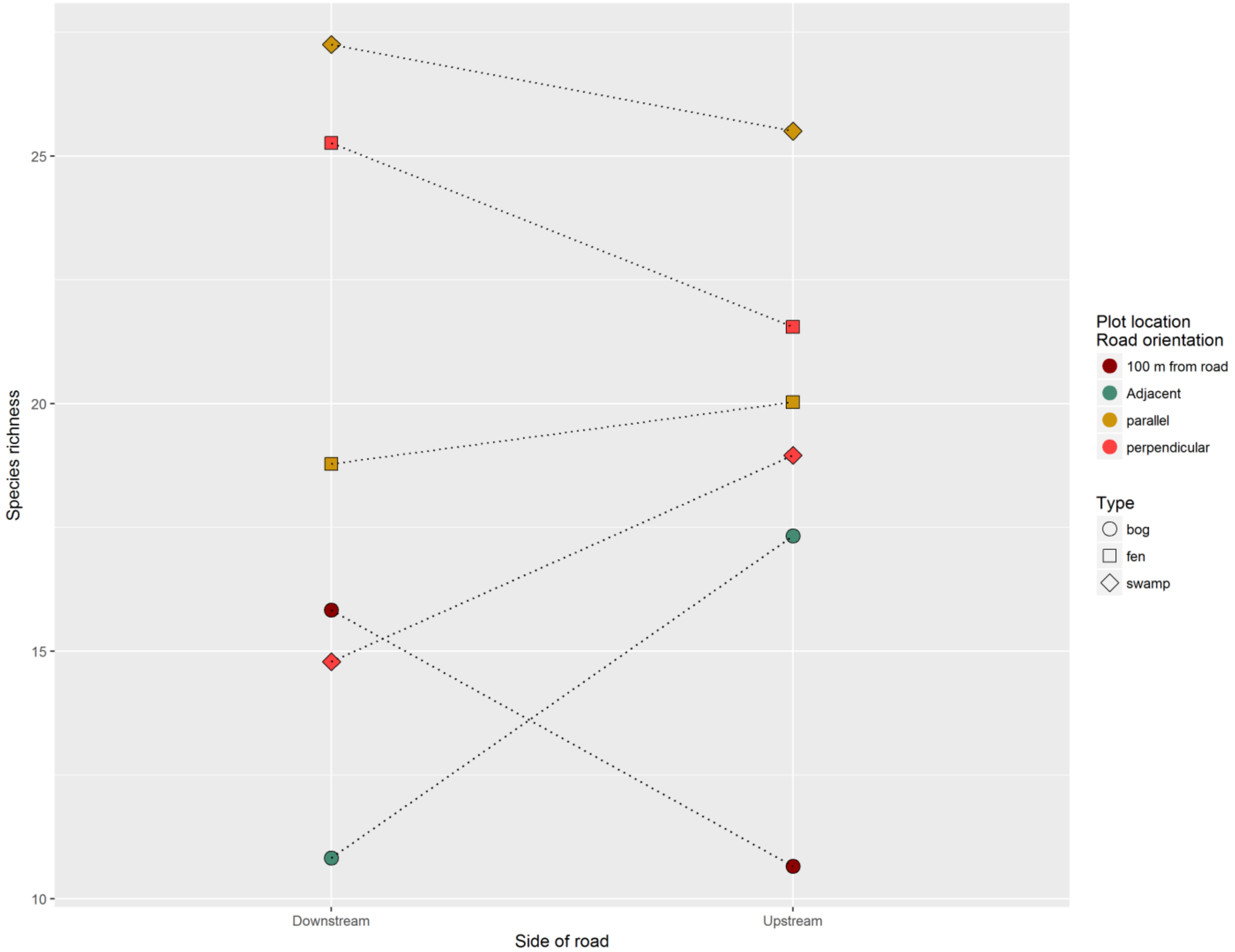

Figure 3-4: Predicted species richness as a function of interactions among site variables. Peatland type have different shapes, while colour depicts different site conditions interacting with side of road (plot location or road orientation).

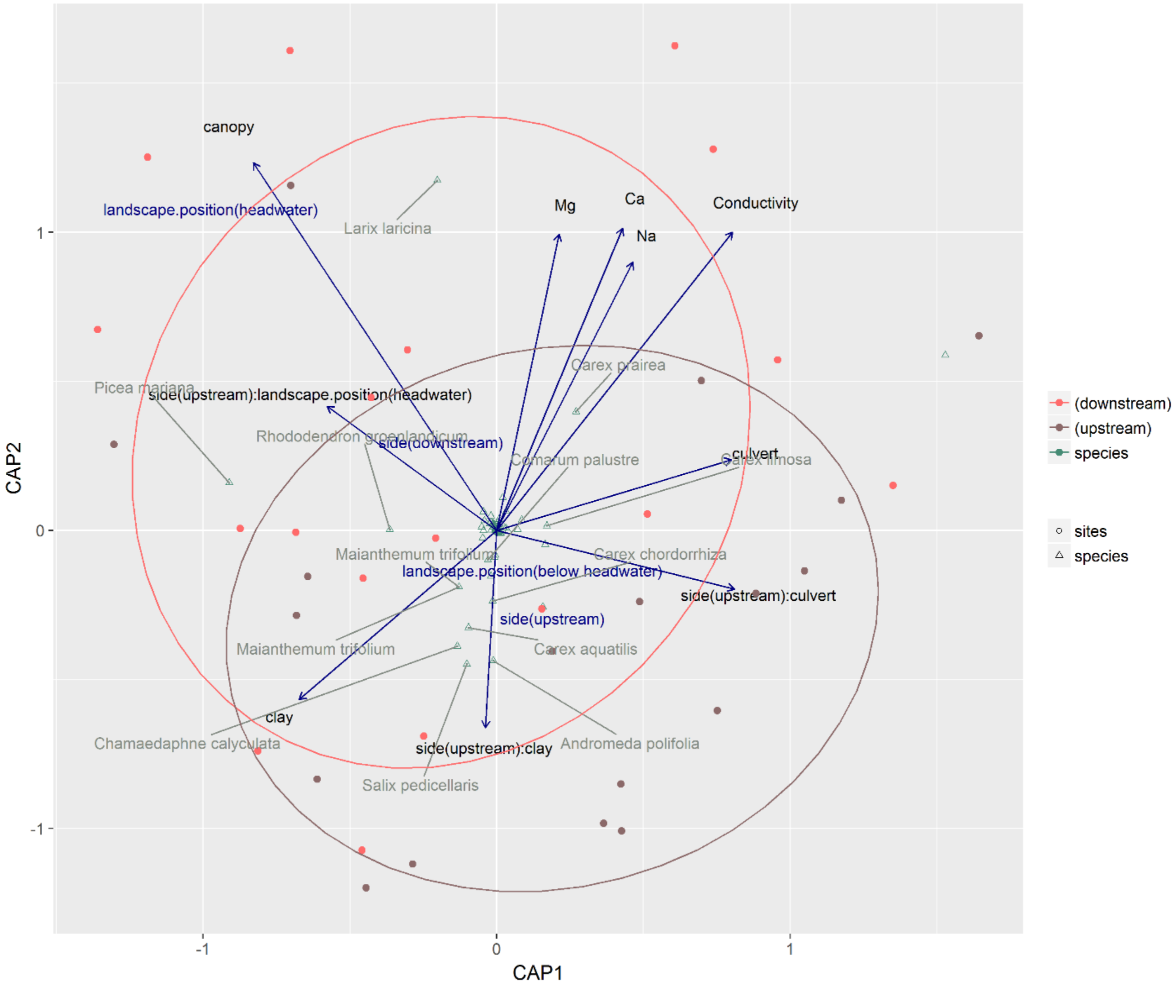

Figure 3-5: Biplot of the distance-based redundancy for fen species communities based on nine variables, an interaction between landscape position and side of road, and an interaction between side of road and culvert ($R_{adj}^2 = 0.36$, $F = 2.6$, $p < 0.001$). Both species and plot sites are shown with vectors are showing continuous variables and categorical variables are labeled in blue. Ellipses are 60% confidence intervals for side where brown is the upstream stream side of the road and pink is downstream side of the road.

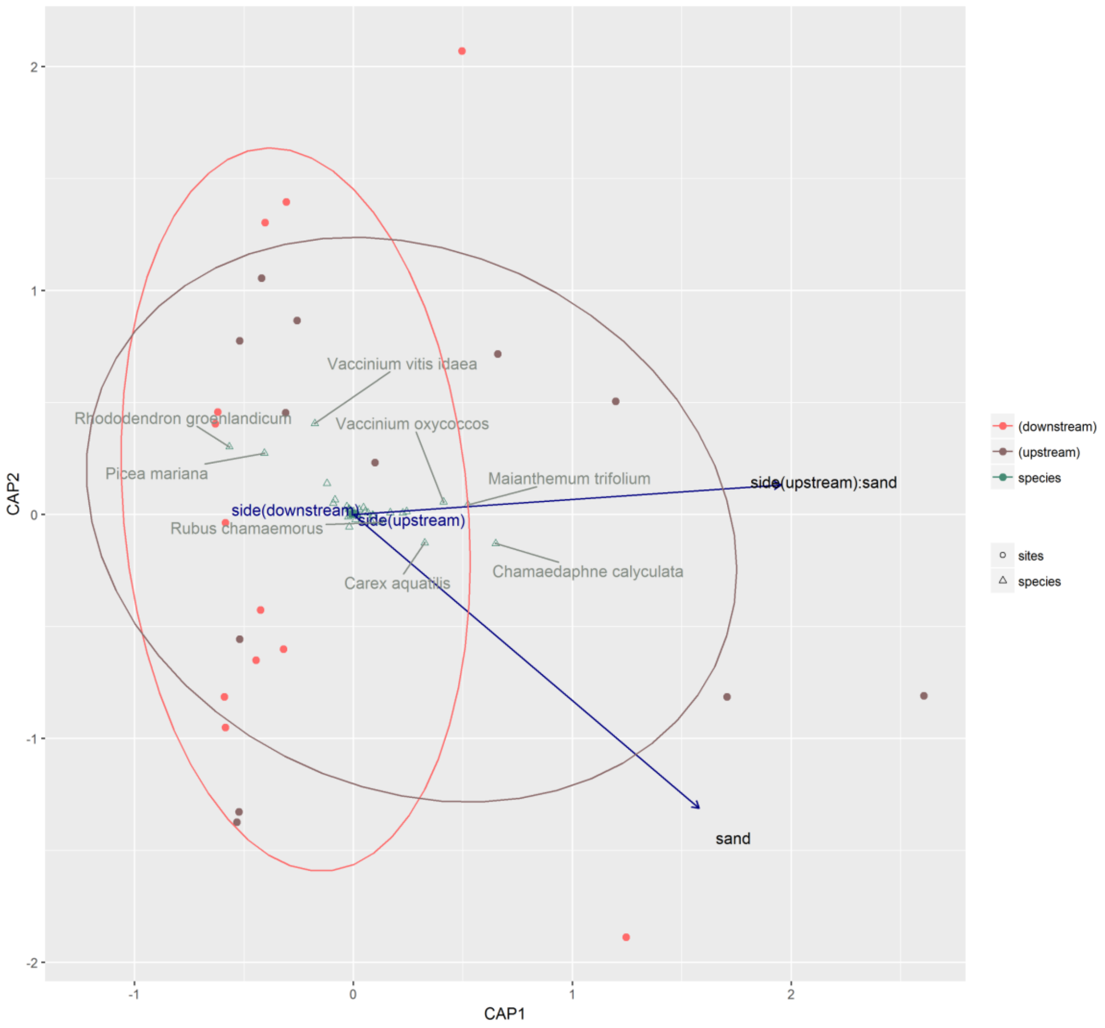

Figure 3-6: Biplot resulting from the distance-based redundancy for bog species communities with two variables and an interaction between side of road and substrate sand content ($R_{adj}^2 = 0.13$, $F = 2.2$, $p < 0.01$). Both species and plot sites are shown with vectors are showing continuous variables and categorical variables are labeled in blue. Ellipses are 60% confidence intervals for side where brown is the upstream stream side of the road and pink is downstream side of the road.

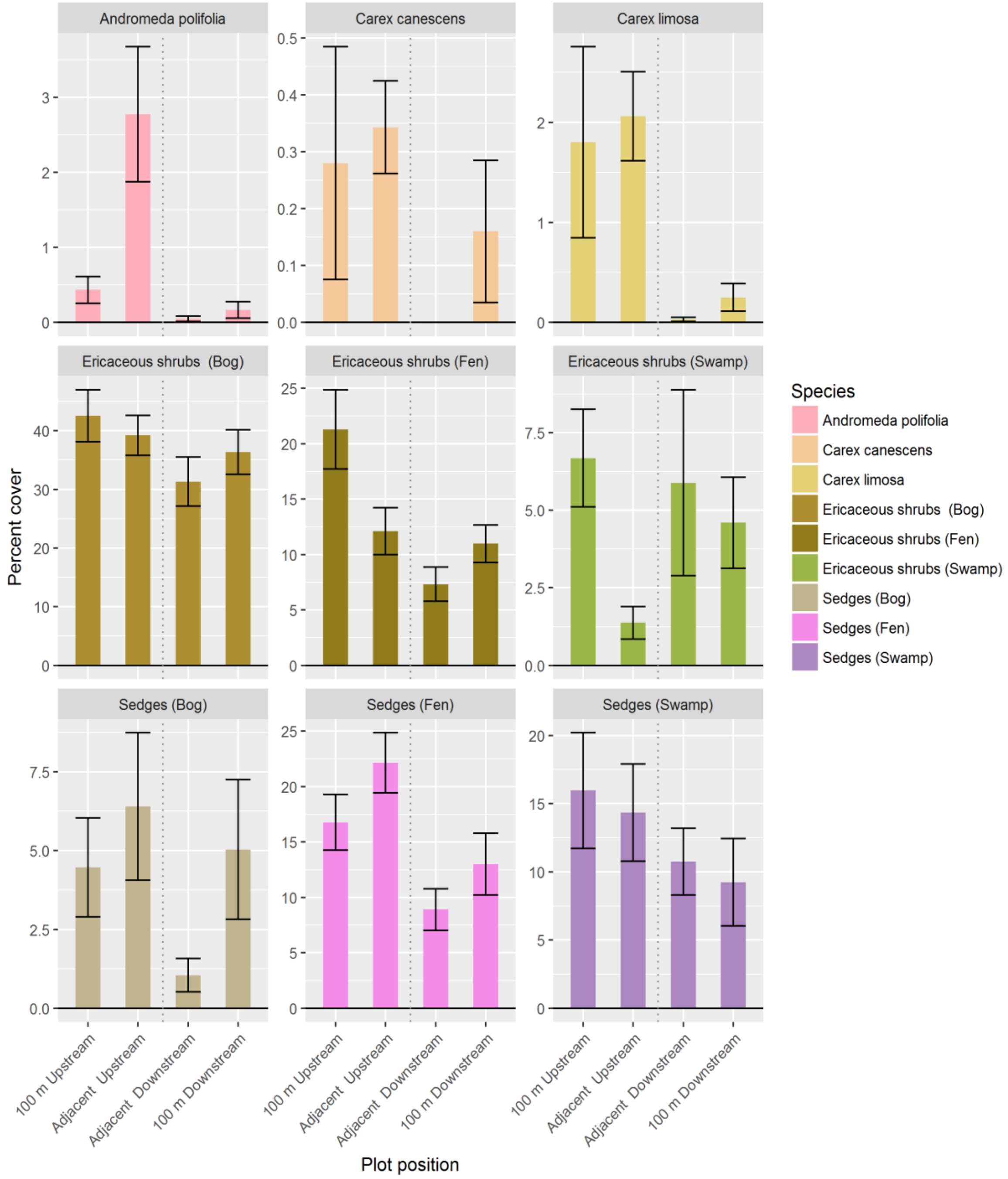

Figure 3-7: Responses in cover of species and species family groups to plot location and peatland type. In the center is a dotted line representing the road and the right are averages for wetland types in plots next to the road on the downside of the road. On the far right are averages for plots 100 m from the road on the downstream side of the road. All bars have standard error bars.

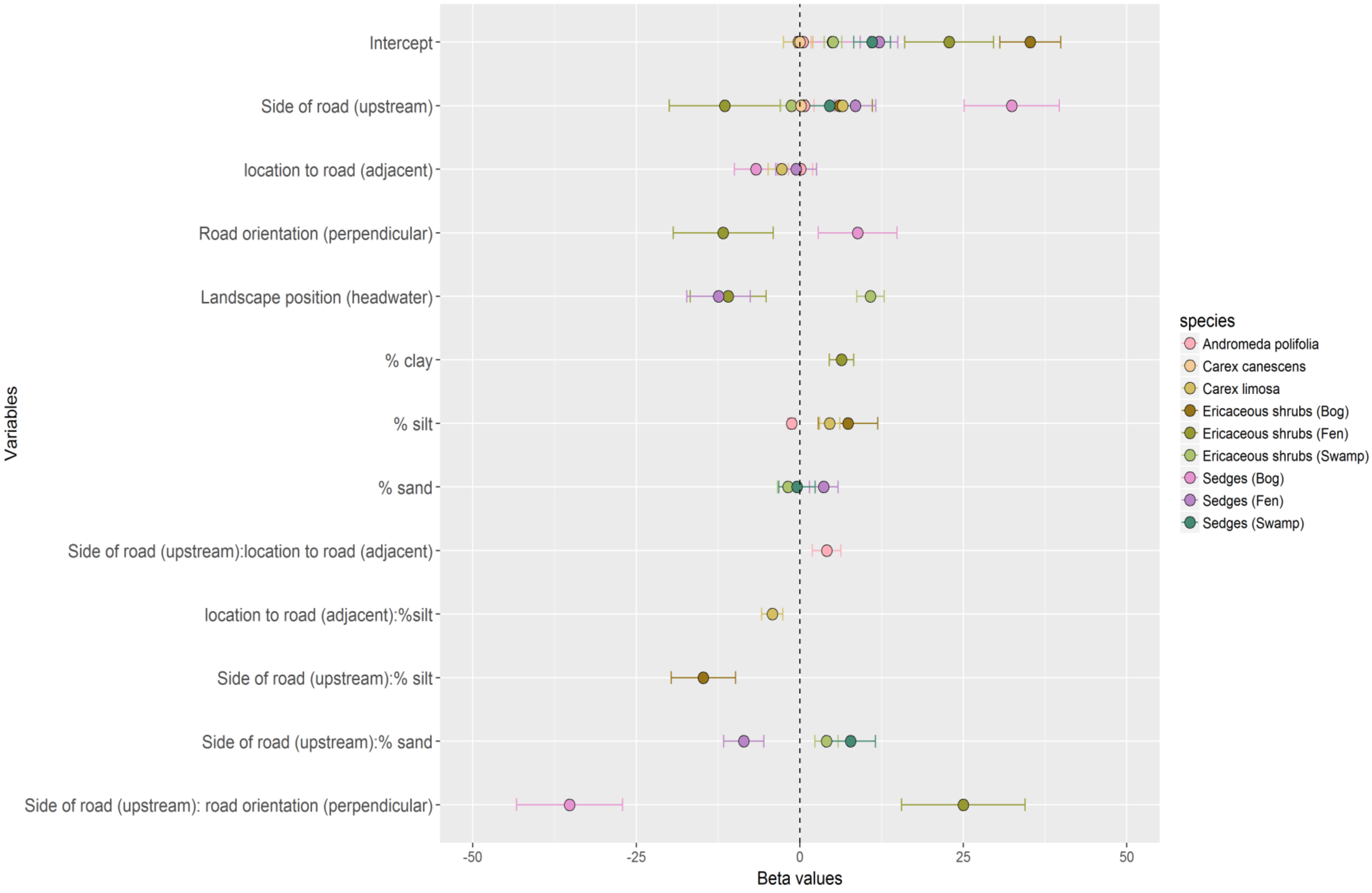

Figure 3-8: Plot of standardized beta values and standard errors for species and species group models. Variables are shown on the left the contrast is in parenthesis where applicable. Beta value is on the x-axis with 0 denoted by a black dotted line. Wetland type is distinguished by colour.

Chapter 4: General Conclusion

4.1 Summary and implications of our findings

The sight of dead trees on one side of a road and living trees on the opposite side of the same road is neither an inconspicuous, nor uncommon phenomenon in Northeastern Alberta. However, few scientific studies have examined the community responses to disturbances caused by the presence of roads. To do this, I examined 121 forested wetlands in Northeastern Alberta to find trends and patterns in vegetation and forest canopy cover associated with road fragmentation. Of those sites, twenty-five were surveyed for: vegetation composition, substrate below the peatland for soil texture, water chemistry and shrub and tree density. Ninety-six were surveyed using LiDAR to quantify canopy cover. I structured our research to examine bogs, fens and swamps as separate categories in order to account for their obvious differences in hydrology, chemistry, and maintenance / formation.

I hypothesized that the different types of wetlands would have different community response patterns associated with the presence of roads. In particular, I hypothesized that bogs would have minimal variation in both vegetation composition and canopy cover on either side of an intersecting road due to their stagnant hydrology. Conversely, we assumed that fens would exhibit noticeable disparity on opposite sides of an intersecting road due to a road's ability to impede the actively flowing groundwater that maintains a fen's nutrient and water levels. Unlike bogs and fens, little is known about swamps in northeastern Alberta. I therefore based our hypothesis on the assumption that swamps have temporal water fluctuations; this allowed us to predict that if swamps have species that are adapted to fluctuating water levels, road-induced water table fluctuations should be comparable to the disturbance already experienced in these systems (i.e. road fragmentation should cause little change to the plant communities in swamps, as they are already so adaptable to changes in hydrology).

The LiDAR biological models and our vegetation community analysis quantified the disturbance to wetlands caused by road fragmentation by producing numerical evidence of this process. The generalized linear mixed models GLMMs of forested wetlands predicted higher canopy cover on the downstream side of the road and lower canopy cover on the upstream side. I found the magnitude of impact to the wetland is- in part- a result of the interplay between peatland substrate (clay(fine), silt, sand(coarse)), road orientation (perpendicular or parallel), landscape position (headwater or below headwater) and wetland type (bog, fen, swamp). The interrelationships between these variables are complex and at times idiosyncratic, but I did succeed in identifying common trends.

First, I discovered that the texture of the substrate below the wetland's peat influences the disparity in canopy height on either side of the intersecting road. Vegetation communities on either side of the road were characterized by different species in bogs on sandy soils (whereas bogs with low sand composition had little differences in species composition on either side of the road.

In the canopy height study, I noted that wetlands at the top of a peatland complex had more disperse canopies on the upstream side of the intersecting road (likely from tree mortality) than at the bottom of a peatland complex on the upstream side of the road. The vegetation data showed that wetlands at the top of the peatland complex are characterized by the presence of dry adapted species such as Black spruce and Labrador tea. Dry adapted species may be more susceptible to anoxic conditions- resulting in higher mortality- than systems with tree species such as tamarack which may be stunted by the influx of water but not die there by still contributing to canopy cover.

As I had hypothesized, our study confirmed that road orientation affects canopy cover in forested wetlands transected by roads, but the intensity and nature of this variable's effect is dependent on both the geologic setting of the wetland (parallel, perpendicular, etc.) and the wetland type (bog, fen, swamp). Results suggest, fens with roads that run parallel to groundwater flow in coarse textured HRUs have the largest differences between the down flow and up flow sides of the road. This could be a result of the connectivity between the upland and the peatland. Regional water flow may be moving directly from uplands through the sides of the peatland and channeling in the center of the peatland.

I also found that in the majority of our LiDAR model predictions, perpendicular road orientation resulted in more closed canopies on both sides of the road in comparison to predictions in the same scenarios (i.e. headwater, fine texture surficial geology) considering other geologic settings.

Additionally, road orientation was only a significant variable for explaining swamp vegetation community variation. I observed higher canopy cover and communities containing more *Betula* *neoalaskana* and *Larix laricina* in swamps with parallel roads. I speculate that is due to construction bias. Likely, the only time a road would be built perpendicular to a flow line would be in forested wetland that did not appear to be wet. This could be wetlands characterized by large trees and little standing water. This issue highlights a limitation we faced in undertaking a study that examined the effects of roads; in all of our scenarios, the roads were already built during our data gathering. I was therefore unable to analyze certain scenarios as not all combinations of variables have been enacted in road construction, and some are much less likely to be enacted than others.

Another challenge we faced during my study was gathering a large enough sample size for our community analysis. I surveyed ten control wetlands without any road disturbances, but have not yet used them in our analysis. I also choose to omit five wetlands that had paved roads as opposed gravel roads, which were used in the analysis. Additionally, three wetlands were damaged in the 2016 Fort McMurray fire before we could finish collecting site data. To solve the problem of sample size, I relied on LiDAR. I had many wetlands to choose from but without the field plots it would be difficult to understand the changes in canopy cover. Together the vegetation work in combination with the LiDAR canopy study we have a better idea about vegetation communities and canopy cover associated with road fragmentation.

4.2 road planning and best management practices

In 2014*, in situ* extraction became the largest form of oil sands production and is projected to double by 2040 (National Energy Board 2016). Roads are a necessary component of infrastructure required for resource extraction in the Canadian boreal forest. With expected increases in resource development, demands on current road infrastructure will increase and the need for more roads will increase. Approximately 50% of the land base in Northeastern Alberta was covered by wetlands and of those 90% were peatlands (Vitt et al. 1996). Therefore, avoiding peatlands is often not an option when constructing roads in Northeastern Alberta.

Little is known about the effects of roads on wetlands and how to mitigate those effects. Our study examined the physical properties of roads and wetlands to identify which properties caused differences in spatial patterns of vegetation communities and canopy cover.

With the exception of bogs on coarse (sandy) substrate we predicted canopy covers on the upstream side of the road to be less than 25% in most scenarios. The downstream side of the road had high fluctuations in canopy cover predictions. Bogs had some of the largest canopy cover differences in our LiDAR study. However, in the field plots the vegetation communities showed little change on clay soils and some changes in species composition on sandy substrates. It is likely that true bogs which are isolated from regional groundwater systems are less vulnerable to road impacts, however it is difficult to distinguish between a bog and a poor fen. I speculate that most of our bogs that demonstrated road impacts were likely poor fens with elevated moss domes. Siegel (1988) described multiple scenarios where bogs with low horizontal and vertical hydrologic gradients are still connected to the regional groundwater systems.

Fens have vertical hydrologic gradients and we saw this with the road impacts. All the fen models showed vegetation patterns with drying on the downstream side and flooding on the upstream side. It is our recommendation that fens be avoided when planning for road construction.

Overall, wetlands with parallel roads had higher predicted canopy cover. Fens, however, also had the greatest difference in canopy cover in sandy fens with parallel roads. I speculate that this could be due to upland wetland conductivity. Sand would facilitate water flow from the sides and funnel into the center of the peatland. The only potential reason to not build perpendicular roads is that the center of the peatland may have too much water to build though it. There is a need to investigate road orientation further.

I suspect that road impacts extend further than we measured. In the LiDAR study I surveyed 250 m from the road edge and in our field plots we surveyed 100 m from the road. In many of our predictive models the up flow and down flow sides of the road do not converge at the same cover value before or at a distance of 250 m. I predicted that the cover would, at some distance, converge at a common cover height on both sides of the road. In several of our predicted canopy cover models we had few covers reach a leveling out point. However, most of our opposing side predictions at 250 m were similar.

All wetlands appear to have some patterns associated with roads, but there are still more unanswered questions, in particular for swamp wetlands. I found weak patterns with road fragmentation and vegetation communities in swamps.

4.3 Future research

This thesis focused on the response of vegetation to roads. Wetland type, surficial geology and position within the peatland complex were used to get an impression of hydrology. This research is limited to describing vegetation responses, but the addition groundwater flow information can provide insight into the impacts roads have on hydrology and as a result vascular plants. Using a combination of ground water data and vegetation metrics could aid in the development of best management guidelines.

Future research should investigate the conductivity between uplands and peatlands as we believe that effects of road orientation may be linked to the amount of water flowing from the upland into the wetland. Further investigation into the effects on isolated bogs is needed to definitively conclude that bogs are unaffected by roads.

I had some interesting observations unrelated road fragmentation is the relationship between substrate texture below the peat and vegetation community composition on the surface. The average peat depth was an estimated 3 m with some of the wetlands having 6 m of peat, a shocking depth to still influence plant communities. I found that clay content was associated with bog community types such as ericaceous shrubs, Labrador tea and Black spruce. Future studies should examine this pattern.

My study demonstrates that road compaction and fragmentation of fens which are large hydrologically connected wetland ecosystems influences the forest vegetation composition. Given the growing influence of climate change on our planet, it is expected that warmer, drier conditions will become more prevalent in the coming years. A lower water table is expected to reduce carbon stores in rich minerotrophic peatlands (Laiho and Laine 1997; Minkkinen et al. 1999; Laiho et al. 2003). This issue is compounded by increases in woody plant composition, drying and proximity to roads which can increase peatland forest fires (Arienti et al. 2009) exacerbating climate change (Oris et al. 2014). As a management prescription, the results of this study indicate that fen peatlands should be avoided during road construction.

Future studies should investigate road impacts to other biota such as bryophyte communities. Further investigation into the impacts roads have on trees could be measured using dendrochronology. Additionally, air photos could be used to determine time since road construction and potentially to compare before and after canopy cover.

4.4 Final conclusion

Wetlands are complex ecosystems and finding trends and special patterns both difficult and all too easy. This thesis has aims to identify drivers in peatlands with hydrology disrupted by roads. A better understanding of vegetation patterns associated with road impacts can help mitigate destruction to wetlands and valuable wildlife habitat. With the Alberta resource industry still developing there is an opportunity plan for wetland conservation and there will be no better time than right now!

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Supplemental Appendix:

Supplemental Appendix B: Tables for Chapter 2

Table A2-1: Summary of hypothesis and predictions for single variable candidate models for generalized linear mixed models (GLMMs) with logit transformation and Gaussian distribution.

Candidate Models (predictor variables)	Hypothesis rationale	Prediction
setting + Landscape position (*H1*)	Landscape position influences the amount of water in the system and therefore a higher water table will result in less tree cover	Tree cover is lower in wetlands that have one or more peatlands feeding into them
setting + Texture **(H2)**	Texture influences the conductivity within the wetland and the wetland to the upland. Higher conductivity means more water and therefore a higher water table resulting in less tree cover	Tree cover decreases in coarse-textured substrates
setting + Perpendicular **(H3)**	Road orientation will influence the amount of water that is blocked in the wetland by the road	Road orientation will be significant in interactions with other variables
setting + Texture + Landscape position (H4)	Additive: landscape position influences the amount of water and texture influences whether that water is transported through the system	Tree cover decrease in coarse-textured soils. Tree cover will be lower in wetlands that have one or more peatlands feeding into them

Table A2-2: Summary of hypothesis and predictions for multiple interactions in candidate models for generalized linear mixed models (GLMMs) with logit transformation and Gaussian distribution.

Candidate Models (multiple interactions)	**Hypothesis rationale**	**Prediction**
setting + H5 + H6 (H14)	**Hydrology and side** Hydrology as a function of landscape position and texture interact with side to determine canopy cover	Coarse-textured substrate facilitates water flow and causes decreased cover on the upstream side of road. Below headwater has greater flow in the system causes decreased tree height on upstream side
setting + H5 + H6 + H7 (H15)	**all side interactions** whether you are on the upstream or downstream side of the road will influence the effect of all the variables which include: Texture which is flow, Landscape position which is amount of water and road orientation which is the effectiveness of the dam	Coarse substrate type facilitates water flow and causes decrease trees on upstream Below headwater has greater flow in the system causes decreased tree height on upstream side perpendicular to the road blocks water flow more and causes decreased tree height on upstream side
H5 +H6+H7+ H8 + H9+ H10 (H16)	**side and order interactions** Landscape position influences the amount of water available texture will influence the conductivity and road orientation will influence how much water is dammed by the road. Texture of the substrate will influence the amount of water that flows under the road and how fast water will move back into or out of the road impacted part of the wetland.	Side interaction predictions + Below headwater systems will have more water when combined with coarse textured substrates (high hydraulic conductivity) resulting in lower canopy cover. low landscape position (more water) will result in even lower canopy cover if the road orientation is perpendicular. Coarse

		texture will have higher impacts with closer distances to road but will level out quickly.
H5 +H6+H7+ H11 +H9 (H17)	**Side and texture interactions** Texture of the substrate will influence the amount of water that flows under the road and how fast water will move back into or out of the road impacted part of the wetland.	Side interaction predictions + Coarse textured substrate (more flow) will result in even lower canopy cover if the road orientation is perpendicular. Coarse texture will have higher impacts with closer distances to road but will level out quickly.
H5 +H6+H7+ H9+ H12 + H13 (H18)	**Side and Distance to road interactions** Texture of the substrate will influence the amount of water that flows under the road and how fast water will move back into or out of the road impacted part of the wetland Landscape position which is amount of water will influence the canopy height adjacent to the road. Road orientation which is the effectiveness of the dam will influence the effect of the road	Coarse texture will have higher impacts with closer distances to road but will level out quickly. Perpendicular road orientation will also increase road effects. Locations closer to the road when the wetland has one or more peatlands feeding into it will have greater flooding (lower canopy cover) and drying (increased canopy cover)

Supplemental Appendix B Chapter 2: Swamp analysis

Table B2-1: Summary of beta (β) values, standard error (SE), and Standardized beta values (St. β) for the most supported models for each wetland type. The contrast variable is in parenthesis for categorical variables.

	Swamp		
Variable	**β**	**SE**	**St.β**
(Intercept	-5.77	1.70	-0.86
side (upstream)	-1.23	0.35	-0.86
$\log_{10}$(distance to road)	2.13	0.25	0.69
road orientation (perpendicular)	3.27	0.83	-0.45
Texture (coarse)	-17.74	17.46	-1.82
Landscape position (below headwater)	-0.09	0.76	-1.26
Structure type (treed)	1.46	1.14	1.46
distance to open water	0.40	0.20	0.15
distance to wetland edge	-0.30	0.06	-0.15
distance to road X side (upstream)	0.18	0.16	0.06
side (upstream) X texture (coarse)	-0.74	1.35	-0.74
road orientation (perpendicular) X side (upstream)	0.42	0.14	0.42
$\log_{10}$(distance to road) X texture(coarse)	7.83	7.57	2.53
$\log_{10}$(distance to road) X perpendicular	-1.83	0.21	-0.59
$\log_{10}$(distance to road) X order (below headwater)	-0.57	0.21	-0.19
Order (below headwater) X side (upstream)	0.03	0.13	0.03
Order (below headwater) X Road orientation (perpendicular)	----	----	----
Road orientation (perpendicular) X Texture (coarse)	----	----	----
Order (below headwater) X texture (coarse)	----	----	----

Table B2-2: Ranking of candidate models and the null model for canopy cover for swamp. The heading the “X” means the linear terms and their interaction. Degrees of freedom (*df*), log likelihood (logLIK), Akaike’s information criterion (AIC_c), delta Akaike (delta), Akaike weights (weight) for the most supported GLMMs. Pseudo-R^2 for each model as Marginal R^2 and Conditional R^2. Marginal R^2 is the proportion of variance explained by fixed effects (road and environmental variables) and the Conditional R^2 is the proportion explained by both the fixed effects and the random effects (wetland unit).

Swamp		***df***	**logLik**	**AIC_c**	**delta**	**weight**	**Marginal R^2**	**Conditional R^2**
S(H18)	Side and Distance to road interactions	18	-4140.08	8316.42	0	0.99	0.12	0.62
S(H12)	Rd orientation X distance to road	11	-4152.41	8326.92	10.5	0.01	0.08	0.59
S(H7)	Road Orientation X side	11	-4184.53	8391.17	74.75	0	0.08	0.58
S(H16)	side and order interactions	18	-4177.6	8391.46	75.04	0	0.21	0.58
nullS	Null	3	-4316.9	8639.8	323.38	0	0.00	0.51

Differences in canopy between sides of the road in swamps were marginal. Our hypothesis was supported for swamps where canopy cover did not vary among roadsides, although canopy cover did decrease when near roads, likely due to the temporal water fluctuations associated with swamps. Swamps lack the stabilizing feedback that peatlands have and likely respond differently to roads. We suspect that the results we observed may be influenced by ditching and clearing. During wetland delineation, we avoided cleared edges of ditches, but it is possible that trees could have been removed from the areas next to the roads, there by influencing the amount of canopy cover estimated in our models. In swamps, perpendicular road orientation was the strongest driving factor of canopy differences, although differences overall were quite minor.

Appendix B of Tables

Table B3-1: Explanatory variables used in the generalized linear mixed model.

Variable	Abbreviation	Type	Source
Upstream/Downstream			
1. Side of the road with water impoundment	sidew	Categorical (upstream (sidew), downstream(contrast)	Google earth visual delineation and site assessment using culvert flow and water table
Distance			
2. Distance to road	road	Categorical (upstream 100 m, upstream adjacent, downstream adjacent, downstream 100 m)	Plot location of field measure
Road Characteristics			
3. Water flow and road orientation	perpendicular	Categorical (perpendicular, parallel (contrast))	Google earth visual delineation and flow accumulation (WAM)
Landscape			
4. Landscape position	headw	Categorical Headwater (headw)\ below headwater (contrast)	Google earth and Satellite imagery
5. Percent **silt** composition of soil below the peat	silt	Continuous	field measure (particle size analysis)
5. Percent **clay** composition of soil below the peat	clay	Continuous	field measure (particle size analysis)
5. Percent **sand** composition of soil below the peat	sand	Continuous	field measure (particle size analysis)

Table B3-2: species used in sedge and ericaceous models.

Sedge species		Ericaceous species	
Latin name	Common name	Latin name	Common name
Carex aquatilis	Water Sedge	*Andromeda polifolia*	Bog Rosemary
Carex atherodes	Awned Sedge	*Chamaedaphne calyculata*	Leatherleaf
Carex aurea	Golden Sedge	*Empetrum nigrum*	Crowberry
Carex brunnescens	Brownish Sedge	*Kalmia polifolia*	Northern Laurel
Carex canescens	Short Sedge	*Rhododendron groenlandicum*	Common Labrador Tea
Carex capillaris	Hair-like Sedge	*Vaccinium myrtilloides*	Common Blueberry
Carex chordorrhiza	Prostrate Sedge	*Vaccinium oxycoccos*	Small Cranberry
Carex deweyana	Dewey's Sedge	*Vaccinium uliginosum*	Bog Bilberry
Carex diandra	Two-stamened Sedge	*Vaccinium vitis-idaea*	Bog Cranberry
Carex disperma	Two-seeded Sedge	Latin name	Common name
Carex gynocrates	Northern Bog Sedge	*Andromeda polifolia*	Bog Rosemary
Carex interior	Inland Sedge	*Chamaedaphne calyculata*	Leatherleaf
Carex lasiocarpa	Hairy-fruited Sedge	*Empetrum nigrum*	Crowberry
Carex leptalea	Bristle-stalked Sedge	*Kalmia polifolia*	Northern Laurel
Carex limosa	Mud Sedge	*Rhododendron groenlandicum*	Common Labrador Tea
Carex magellanica	Boreal Bog Sedge	*Vaccinium myrtilloides*	Common Blueberry
Carex pauciflora	Few-flowered Sedge	*Vaccinium oxycoccos*	Small Cranberry
Carex prairea	Prairie Sedge	*Vaccinium uliginosum*	Bog Bilberry
Carex rostrata	beaked sedge	*Vaccinium vitis-idaea*	Bog Cranberry
Carex sartwellii	Sartwell's sedge		
Carex tenuiflora	Thin-flowered Sedge		
Carex trisperma	Three-seeded Sedge		
Carex utriculata	Small Bottle Sedge		
Carex vaginata	Sheathed Sedge		

Table B3-3: Ranking of candidate models and the null model for species richness for each wetland type. Degrees of freedom (df), log likelihood (logLIK), Akaike's information criterion (AICc), delta Akaike (Delta AICc), Akaike weights (weight) for the most supported GLMMs.

Fen					
	df	logLik	AICc	Delta AICc	weight
headw	4	-506.76	1021.71	0.00	0.17
headw+road+silt	6	-504.69	1021.80	0.09	0.16
headw+road+silt+road*silt	7	-503.73	1022.01	0.30	0.14
headw+perpendicular+road	6	-505.01	1022.44	0.73	0.11
headw+road+sand+road*sand	7	-504.01	1022.58	0.87	0.11
headw+road+clay+clay*road	7	-504.38	1023.31	1.60	0.07
headw+road+clay	6	-505.56	1023.52	1.81	0.07
headw+perpendicular+road+silt+road*silt	8	-503.44	1023.59	1.88	0.06
headw+perpendicular+road+sand+road*sand	8	-503.47	1023.65	1.94	0.06
headw+perpendicular+road+clay+clay*road	8	-503.84	1024.39	2.68	0.04
Null	1	-539.95	1081.91	60.20	0.00

Bog					
	df	logLik	AICc	Delta AICc	weight
road+side+road*side	6	-314.01	640.64	0.00	0.22
perpendicular+road+side+road*side	7	-313.29	641.42	0.78	0.15
perpendicular	4	-316.66	641.62	0.98	0.14
headw+perpendicular+road+side+road*side	8	-312.44	641.98	1.33	0.11
road+side+road*side+silt	7	-313.73	642.30	1.66	0.10
road+side+road*side+sand	7	-313.80	642.44	1.79	0.09

road+side+road*side+clay	7	-313.93	642.71	2.06	0.08
headw+perpendicular+road+side+road*side+clay	9	-312.06	643.50	2.86	0.05
perpendicular+road+side+road*side+clay	8	-313.21	643.52	2.87	0.05
Null	1	-342.80	687.63	46.99	0.00

Swamp

	df	logLik	AICc	Delta AICc	weight
clay+headw+perpendicular+side+perpendicular*side	8	-298.90	615.10	0.00	0.24
clay+headw+perpendicular+side	7	-300.55	616.09	0.99	0.15
clay+headw+perpendicular+side+perpendicular*side+road	9	-298.32	616.28	1.18	0.13
headw+perpendicular+side+perpendicular*side+sand	8	-299.67	616.63	1.53	0.11
headw+perpendicular+side+sand	7	-301.17	617.34	2.24	0.08
headw+perpendicular+side+perpendicular*side+silt	8	-300.04	617.38	2.27	0.08
perpendicular+side+perpendicular*side+silt	7	-301.28	617.55	2.45	0.07
clay+headw+side	6	-302.52	617.78	2.67	0.06
perpendicular+side+silt	6	-302.67	618.09	2.98	0.05
clay+headw+perpendicular+side+road+perpendicular*road	9	-299.67	618.97	3.87	0.03
Null	1	-338.53	679.09	63.99	0.00

Table B3-4: Single term db-RDA results for each wetland type.

	fen			**bog**			**swamp**		
variance explained	**constrained**	**Pr(>F)**	**R_{adj}^2**	**constrained**	**Pr(>F)**	**R_{adj}^2**	**constrained**	**Pr(>F)**	**R_{adj}^2**
side	0.05	0.030	0.03	0.04	0.37	0.00	0.04	0.636	-0.01
road	0.02	0.757	-0.01	0.03	0.582	-0.01	0.04	0.749	-0.01
side*road	0.10	0.181	0.02	0.11	0.64	-0.02	0.13	0.8	-0.03
side*perpendicular	0.11	0.079	0.04	0.12	0.483	-0.01	0.22	0.035	0.07
side*wetland order	0.18	0.001	0.12	0.15	0.247	0.03	0.17	0.348	0.01
side*clay	0.15	0.002	0.08	0.23	0.009	0.13	0.17	0.263	0.02
side*silt	0.09	0.318	0.01	0.22	0.025	0.11	0.20	0.08	0.06
side*sand	0.11	0.09	0.03	0.24	0.009	0.13	0.21	0.058	0.06
side*culverts	0.14	0.011	0.07	0.13	0.39	0.00	0.15	0.556	-0.01
perpendicular	0.04	0.206	0.01	0.02	0.816	-0.02	0.13	0.003	0.08
culverts	0.06	0.013	0.04	0.03	0.46	-0.01	0.06	0.336	0.01
Canopy cover	0.13	0.001	0.11	0.11	0.02	0.07	0.18	0.001	0.14
distance to upland	0.06	0.03	0.03	0.10	0.043	0.06	0.04	0.703	-0.01
distance to water	0.05	0.058	0.02	0.03	0.725	-0.02	0.09	0.03	0.04

pH	0.04	0.196	0.01	0.03	0.599	-0.01	0.04	0.769	-0.01
conductivity	0.11	0.001	0.09	0.06	0.183	0.02	0.12	0.002	0.07
clay	0.07	0.005	0.05	0.14	0.006	0.10	0.09	0.053	0.04
silt	0.01	0.941	-0.02	0.08	0.10	0.04	0.09	0.035	0.05
sand	0.03	0.303	0.00	0.11	0.017	0.07	0.10	0.031	0.05
ca	0.08	0.007	0.06	0.03	0.685	-0.02	0.11	0.004	0.06
fe	0.04	0.078	0.02	0.02	0.627	-0.02	0.05	0.577	0.00
k	0.07	0.016	0.04	0.04	0.37	0.00	0.07	0.116	0.02
mg	0.08	0.003	0.06	0.03	0.586	-0.01	0.12	0.001	0.07
na	0.07	0.01	0.04	0.06	0.185	0.02	0.12	0.002	0.07
wetland order	0.10	0.002	0.08	0.07	0.146	0.03	0.08	0.065	0.03
plot location	0.10	0.165	0.02	0.03	0.571	-0.01	0.04	0.767	-0.02

Table B3-5: Ranking of candidate models and the null model for indicator species cover and combined cover for species groups for each wetland type. Degrees of freedom (*df*), log likelihood (logLIK), Akaike's information criterion (AICc), delta Akaike (Delta AICc), Akaike weights (weight) for the most supported GLMMs.

Andromeda polifolia (bog upstream indicator)	*df*	logLik	AICc	Delta AICc	weight
road+side+road*side+silt	9	-145.58	310.54	0.00	0.34
road+side+road*side+sand	9	-145.72	310.81	0.27	0.30
road+side+road*side+clay	9	-146.40	312.18	1.63	0.15
perpendicular+road+side+road*side+silt	10	-145.54	312.78	2.24	0.11
perpendicular+road+side+sand+road*sand	10	-146.00	313.71	3.17	0.07
headw+perpendicular+road+side+road*side	10	-147.29	316.29	5.74	0.02
headw+perpendicular+road+sand+road*sand	10	-147.41	316.52	5.98	0.02
Null	5	-157.83	326.11	15.57	0.00
perpendicular+road+side+clay+perpendicular*road	10	-152.25	326.21	15.66	0.00

Carex limosa (fen upstream indicator)	*df*	logLik	AICc	Delta AICc	weight
road+side+silt+road*silt	9	-277.52	573.94	0.00	0.23
perpendicular+road+side+perpendicular*road	9	-277.82	574.55	0.61	0.17
perpendicular+road+side+perpendicular*road+silt	10	-277.22	575.54	1.60	0.10
road+side+sand+road*sand	9	-278.39	575.68	1.74	0.10
perpendicular+road+side+perpendicular*road+sand	10	-277.37	575.84	1.89	0.09
perpendicular+road+side+silt+road*silt	10	-277.43	575.96	2.01	0.08
headw+road+side+silt+road*silt	10	-277.51	576.12	2.18	0.08
headw+perpendicular+road+side+perpendicular*road	10	-277.81	576.73	2.79	0.06

headw+perpendicular+road+side+perpendicular*road+silt	11	-277.20	577.73	3.79	0.03
headw+road+side+sand+road*sand	10	-278.37	577.84	3.90	0.03
Null	5	-284.07	578.44	4.50	0.02

Carex canescens (swamp upstream indicator)

	df	logLik	AICc	Delta AICc	weight
side	6	-61.60	135.94	0.00	0.18
perpendicular+side+silt	8	-59.34	135.97	0.03	0.17
perpendicular+side+silt	9	-58.81	137.25	1.31	0.09
perpendicular+side+silt	9	-58.81	137.25	1.31	0.09
headw+perpendicular+side	8	-60.19	137.67	1.73	0.07
clay+headw+perpendicular+road+sand+side+clay*side	12	-55.45	137.81	1.87	0.07
road+side+silt	9	-59.22	138.08	2.14	0.06
headw+perpendicular+road+side	9	-59.34	138.31	2.37	0.05
perpendicular+road+side+silt+perpendicular*road	10	-58.23	138.48	2.54	0.05
perpendicular+road+side+silt+perpendicular*side	10	-58.27	138.56	2.62	0.05
Null	5	-64.03	138.59	2.65	0.05
Clay+headw+perpendicular+side	9	-59.72	139.08	3.14	0.04
headw+perpendicular+sand+side+sand*side	10	-58.89	139.79	3.85	0.03

Ericaceous bog

	df	logLik	AICc	Delta AICc	weight
side+silt+side*silt	8	-621.76	1260.61	0.00	0.35
perpendicular+side+silt+side*silt	9	-621.32	1262.03	1.42	0.17
Null	5	-625.89	1262.22	1.61	0.16
road+side+silt+side*silt	9	-621.65	1262.68	2.07	0.12

perpendicular+road+side+silt+side*silt	10	-621.21	1264.13	3.52	0.06
headw+perpendicular+side+silt+side*silt	10	-621.22	1264.15	3.54	0.06
perpendicular+side+clay+perpendicular*side	9	-622.64	1264.66	4.05	0.05
headw+perpendicular+road+side+silt+side*silt	11	-621.11	1266.28	5.67	0.02
headw+perpendicular+side+clay+perpendicular*side	10	-622.63	1266.96	6.35	0.01
headw+road+side+sand+road*side	10	-625.30	1272.30	11.68	0.00

Carex bog

	df	logLik	AICc	Delta AICc	weight
perpendicular+road+side+perpendicular*side	9	-316.07	651.53	0.00	0.50
headw+perpendicular+road+side+perpendicular*side	10	-315.96	653.62	2.09	0.18
perpendicular+road+side+perpendicular*side+clay	10	-316.05	653.80	2.27	0.16
perpendicula+road+side+perpendicular*side+sand	10	-316.05	653.81	2.27	0.16
Null	5	-326.93	664.31	12.78	0.00

Carex fen

	df	logLik	AICc	Delta AICc	weight
headw+perpendicular+sand+side+sand*side	10	-881.00	1783.10	0.00	0.20
headw+sand+side+sand*side+road	10	-881.01	1783.13	0.03	0.20
headw+side+silt+side*silt	9	-882.24	1783.37	0.27	0.17
headw+perpendicular+sand+side+sand*side+road	11	-880.98	1785.30	2.20	0.07
headw+sand+side	8	-884.37	1785.45	2.35	0.06
headw+perpendicular+side+silt+side*silt	10	-882.22	1785.55	2.46	0.06
headw+side+silt	8	-884.56	1785.83	2.73	0.05
headw+side+clay	8	-884.67	1786.06	2.96	0.05
headw+side+road	8	-884.78	1786.27	3.17	0.04

perpendicular+sand+side+sand*side	9	-883.78	1786.46	3.36	0.04
sand+side+sand*side+road	9	-884.04	1786.98	3.88	0.03
side+road+clay+clay*side	9	-884.33	1787.56	4.46	0.02
headw+perpendicular+side+road+silt+side*silt	11	-882.21	1787.75	4.66	0.02
Null	5	-889.78	1789.85	6.75	0.01

Ericaceous fen

	df	logLik	AICc	Delta AICc	weight
clay+headw+perpendicular+road+side+perpendicular*side	11	-702.31	1427.94	0.00	0.20
clay+headw+perpendicular+side+perpendicular*side	10	-703.48	1428.06	0.11	0.19
clay+perpendicular+side+perpendicular*side	9	-704.88	1428.67	0.72	0.14
clay+perpendicular+road+side+perpendicular*side	10	-703.81	1428.72	0.78	0.14
clay+headw+side	8	-706.55	1429.81	1.87	0.08
clay+side	7	-707.79	1430.12	2.18	0.07
clay+headw+side+clay*side	9	-705.97	1430.84	2.90	0.05
clay	6	-709.73	1431.88	3.93	0.03
perpendicular+side+perpendicular*side+sand	9	-706.54	1431.98	4.03	0.03
headw+perpendicular+road+side+perpendicular*side+sand	11	-704.34	1432.00	4.06	0.03
perpendicular+road+side+perpendicular*side+sand	10	-705.48	1432.07	4.13	0.03
clay+headw+perpendicular+road+side+perpendicular*road	11	-705.10	1433.53	5.59	0.01
Null	5	-713.20	1436.70	8.75	0.00

Ericacious Swamp

	df	logLik	AICc	Delta AICc	weight
headw+side+sand+sand*side	9	-292.43	604.50	0.00	0.27
headw+side+silt+side*silt	9	-292.75	605.14	0.64	0.20

headw+side+road+road*side	9	-292.76	605.15	0.65	0.20
headw+side+sand+sand*side+road	10	-292.07	606.17	1.66	0.12
headw+side+silt	8	-294.74	606.77	2.27	0.09
headw+side+silt+side*silt+road	10	-292.47	606.95	2.45	0.08
Null	5	-298.57	607.67	3.16	0.06

Carex Swamp

	df	logLik	AICc	Delta AICc	weight
sand+side+sand*side	8	-504.36	1026.01	0.00	0.29
side+clay+clay*side	8	-504.71	1026.72	0.71	0.20
Null	5	-508.35	1027.22	1.21	0.16
perpendicular+sand+side+sand*side	9	-503.89	1027.41	1.40	0.14
headw+side+clay+clay*side	9	-504.32	1028.27	2.26	0.09
side+clay+road+clay*side	9	-504.65	1028.94	2.93	0.07
headw+perpendicular+sand+side+sand*side	10	-503.88	1029.79	3.78	0.04

Appendix B of figures

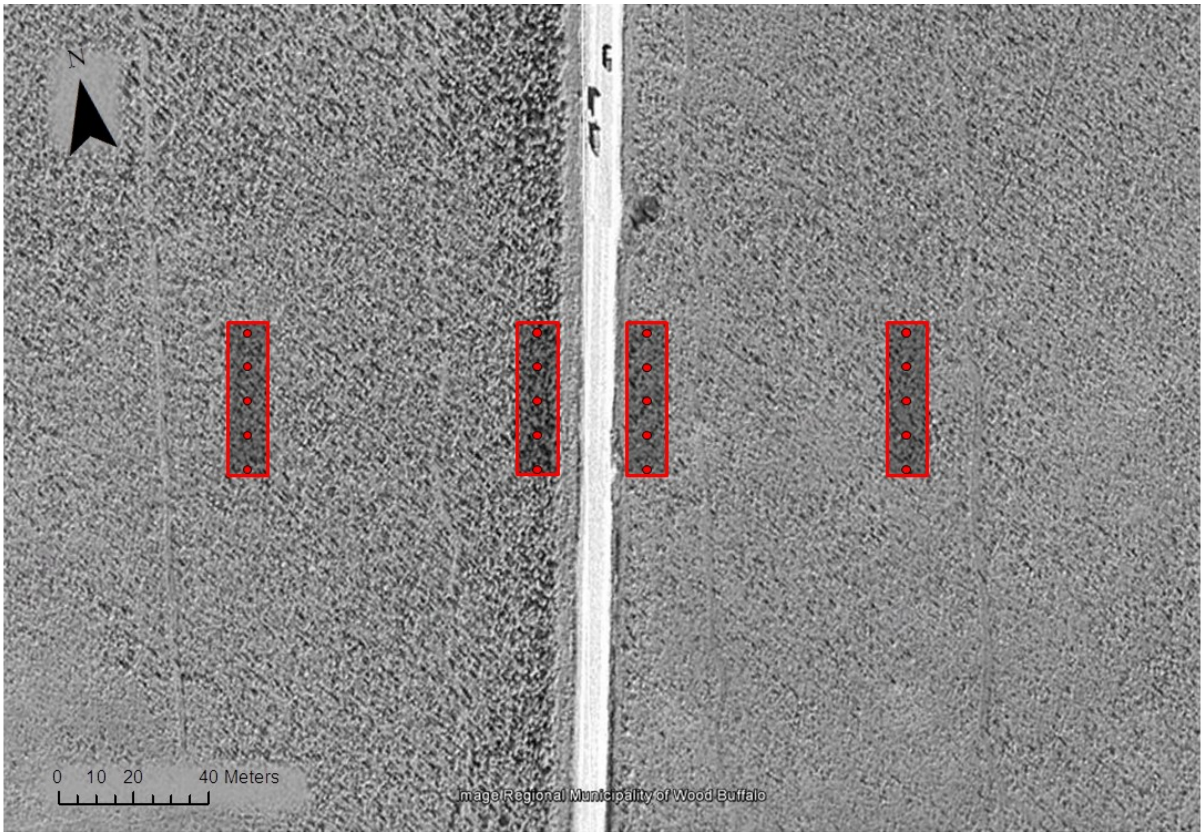

Figure B3-1: Example of plot layout. Two plots were placed on the water impounded side of the road (upside of the road); on adjacent to the cleared edge of the road and one 100 m from the cleared edge. The same was done on the opposite side of the road (downstream side). The red dots are the 1 meter quadrates. This is an actual site we surveyed in Conklin, Alberta (55°15'01.6" N 111°19'17.4" W), Google earth image 2008.

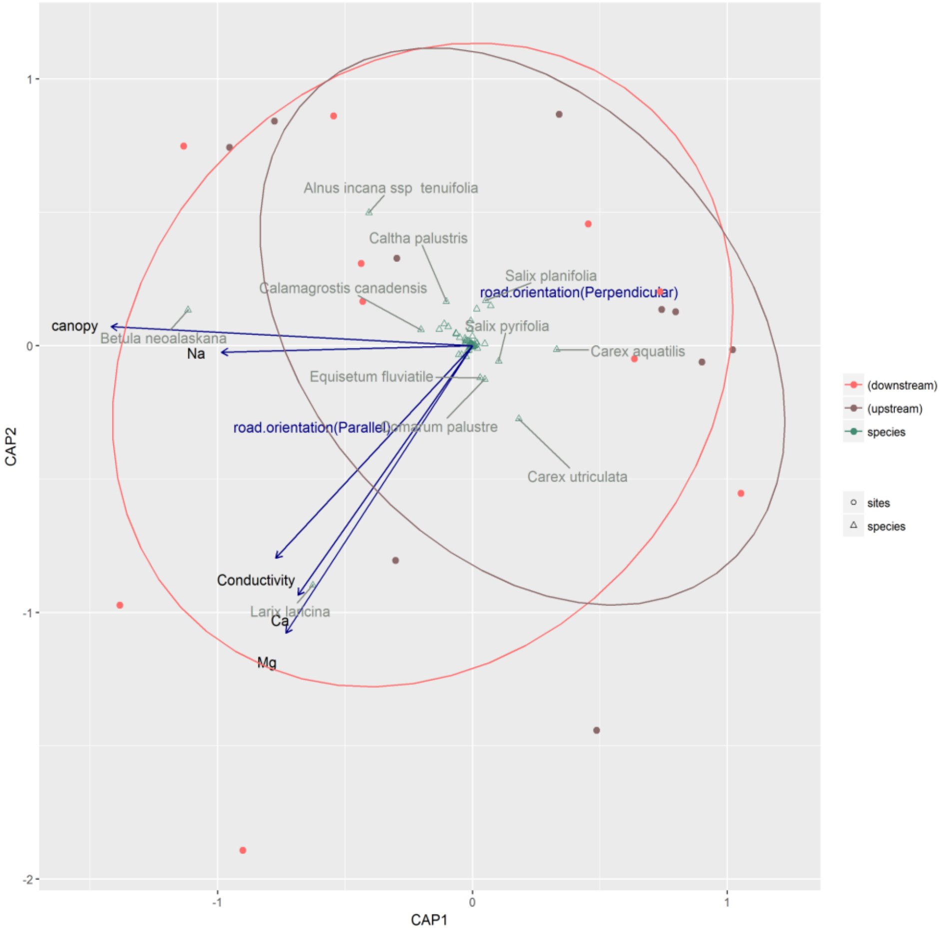

Figure B3-2: Biplot resulting from the distance-based redundancy for swamp species communities with six variables ($R_{adj}^2 = 0.34$, $F = 2.9$, $p < 0.001$). Both species and plot sites are shown with vectors are showing continuous variables and categorical variables are labeled in blue. Ellipses are 60% confidence intervals for side where brown is the upstream stream side of the road and pink is downstream side of the road.

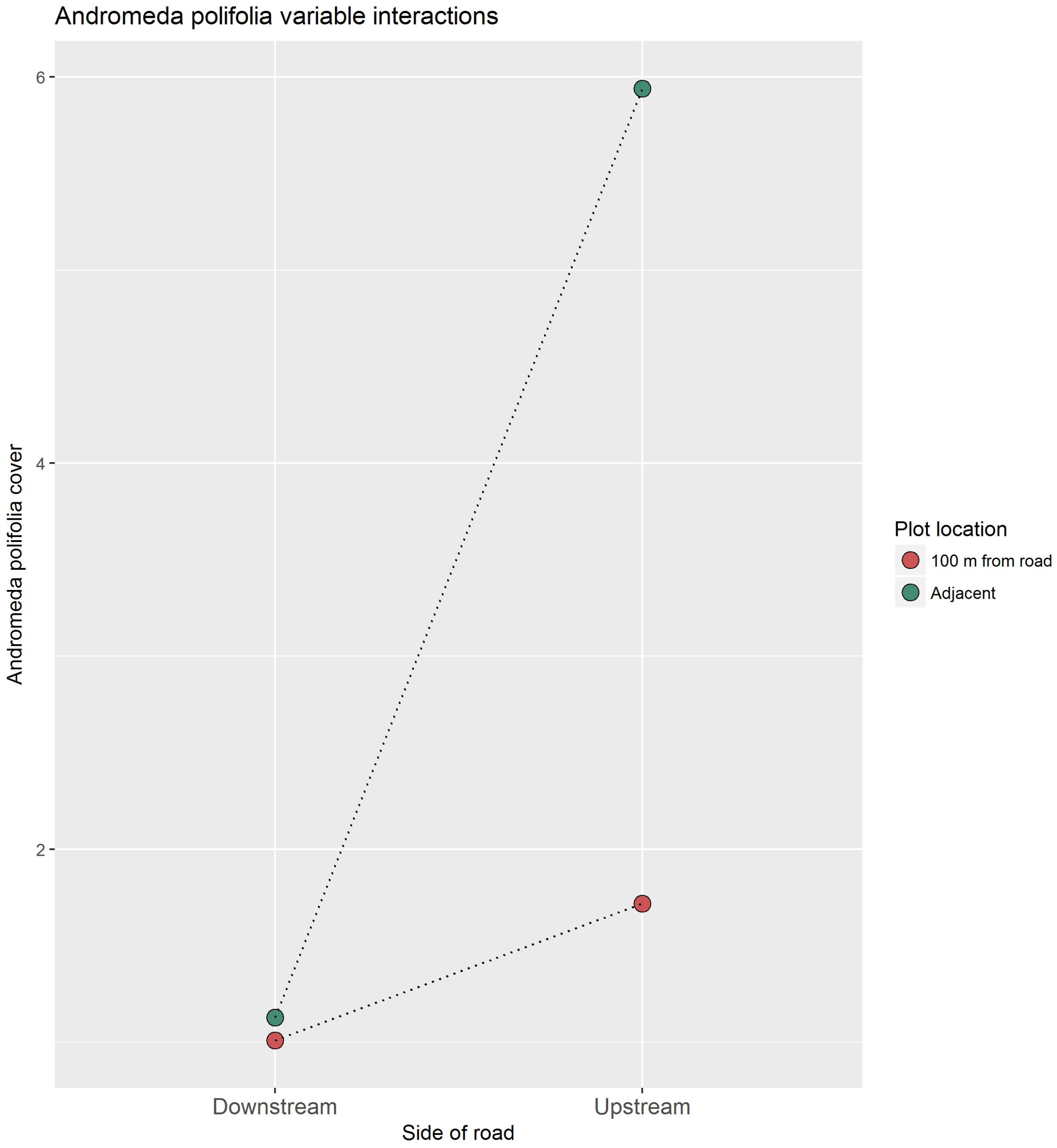

Figure B3-3: *Andromeda polifolia* cover model interaction plot. Colour is plot location and the x-axis is side of road. We see similar low estimates for plots next to the road and 100 m from the road on the downstream side of the road. On the upstream side of the road we see the highest predicted cover next to the road with a reduction in cover at a 100 m distance from the upstream side of road.

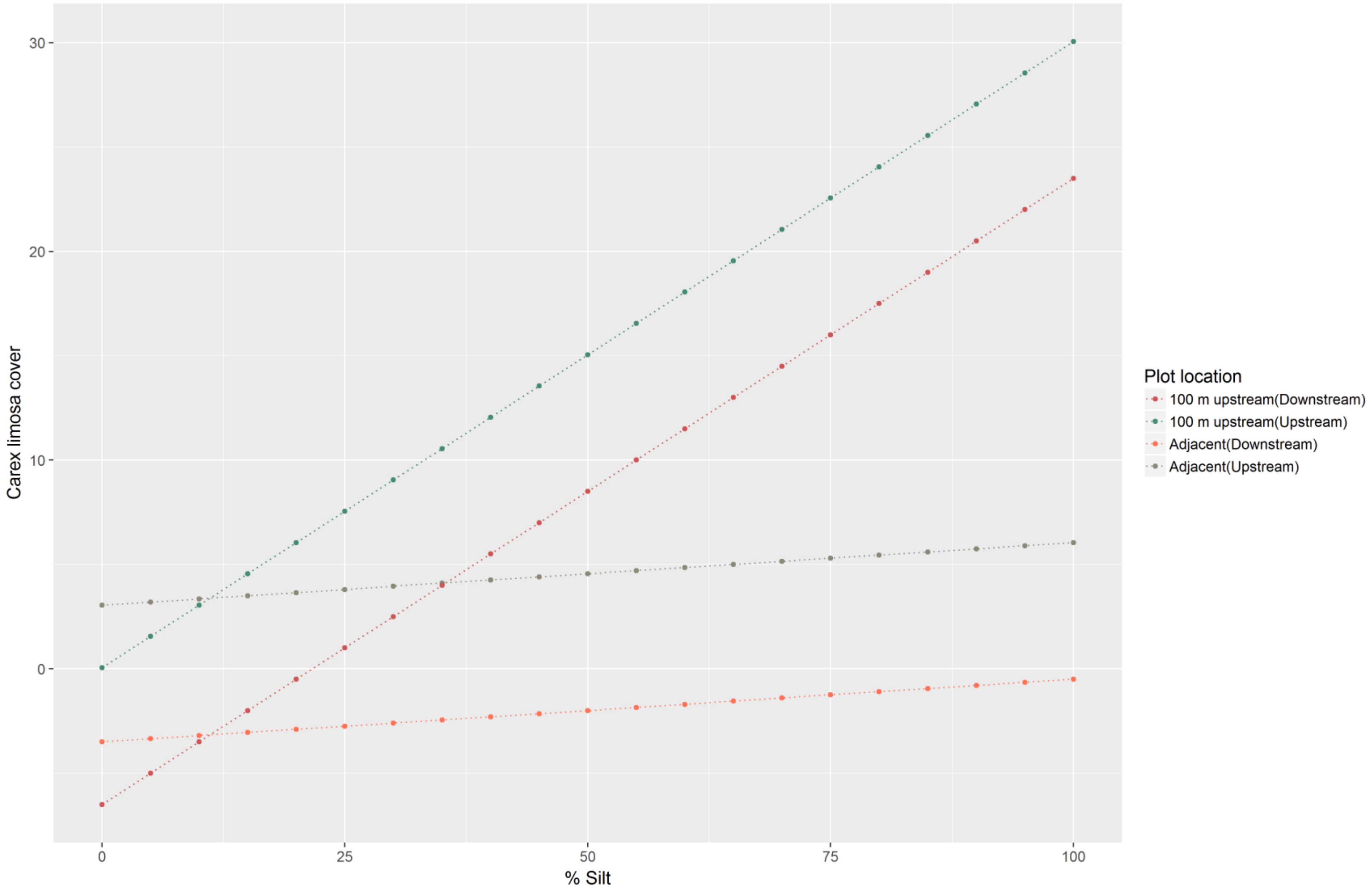

Figure B3-4: *Carex limosa* cover model interaction plot. When silt content was low there were similar estimates of cover (low values) for *Carex limosa*, while cover was higher on the upstream side of the road when silt content increased.

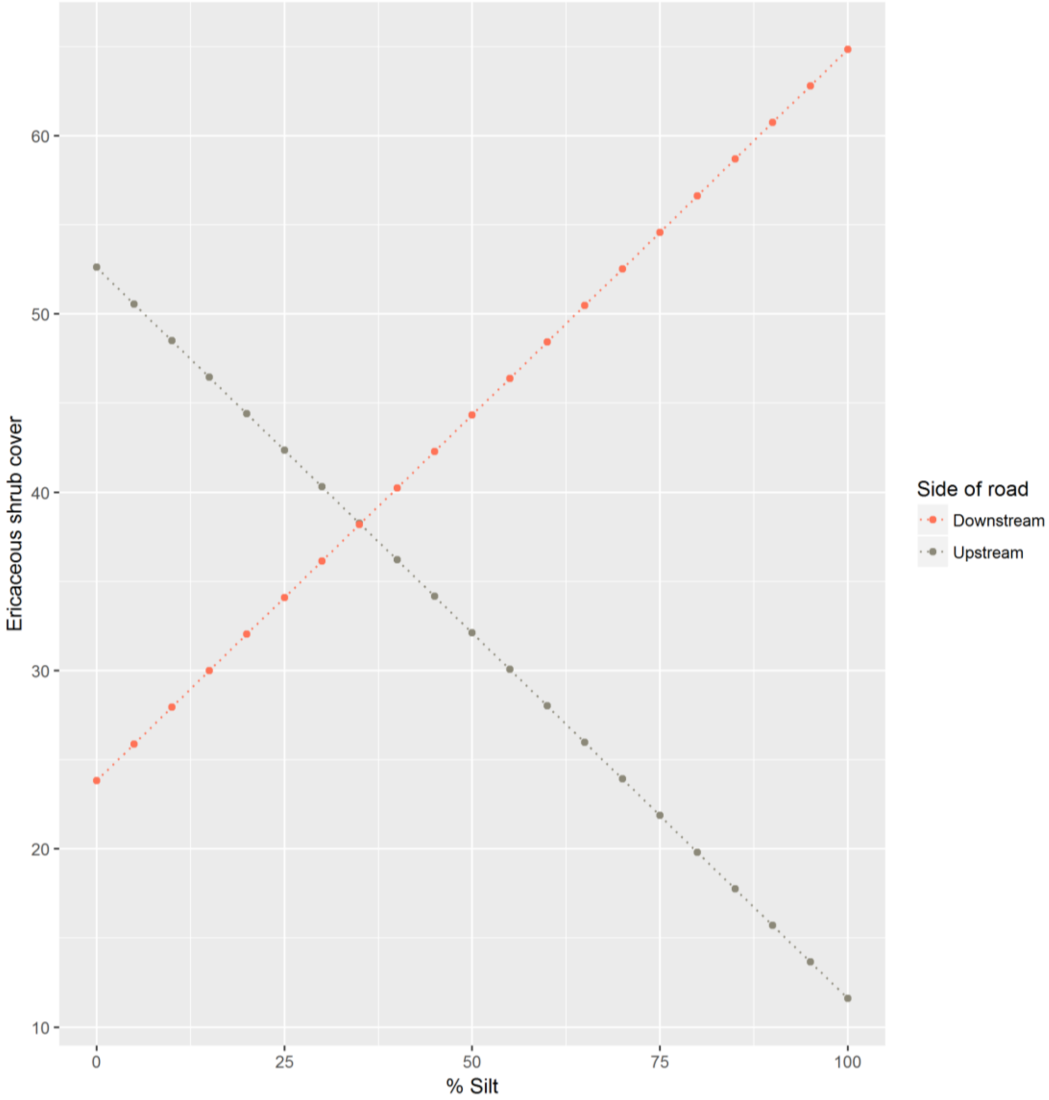

Figure B3-5: Interaction plots for ericaceous shrub cover in bogs. Predicted species cover is on the y-axis and percent silt is on the y-axis. Side of road is coloured. Pink is downstream and grey is upstream. When amount of silt was low there was more ericaceous shrub cover on the upstream side of road, while at high silt content there was more ericaceous cover on the downstream side of the road.

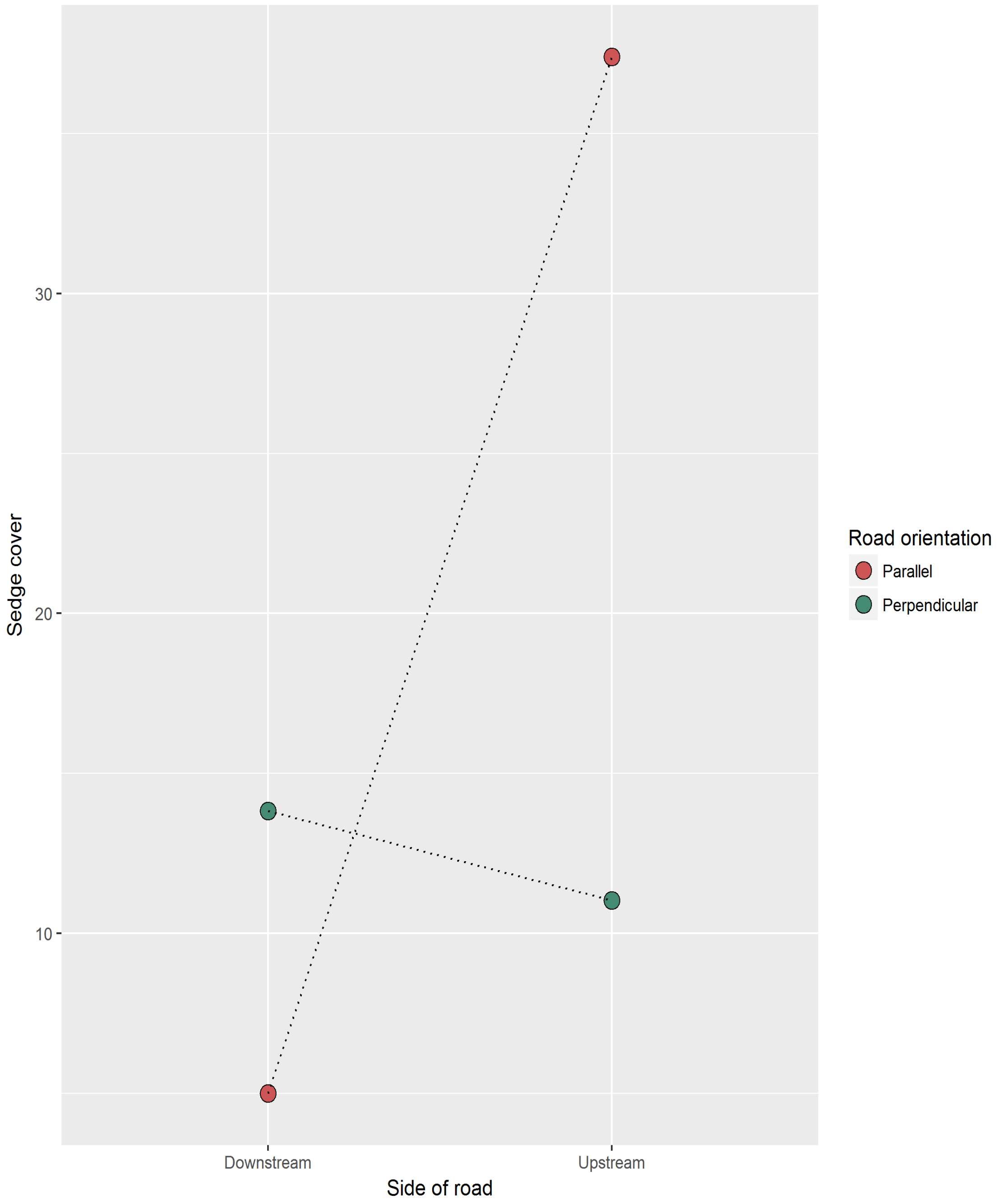

Figure B3-6: Interaction plots for sedges species groups in bogs. Cover is on the y-axis and side of road on the x-axis. When the road is parallel the downstream side of the road as low sedge cover and the upstream side of the road has high sedge cover. Perpendicular road orientation has a week negative effect on sedge cover.

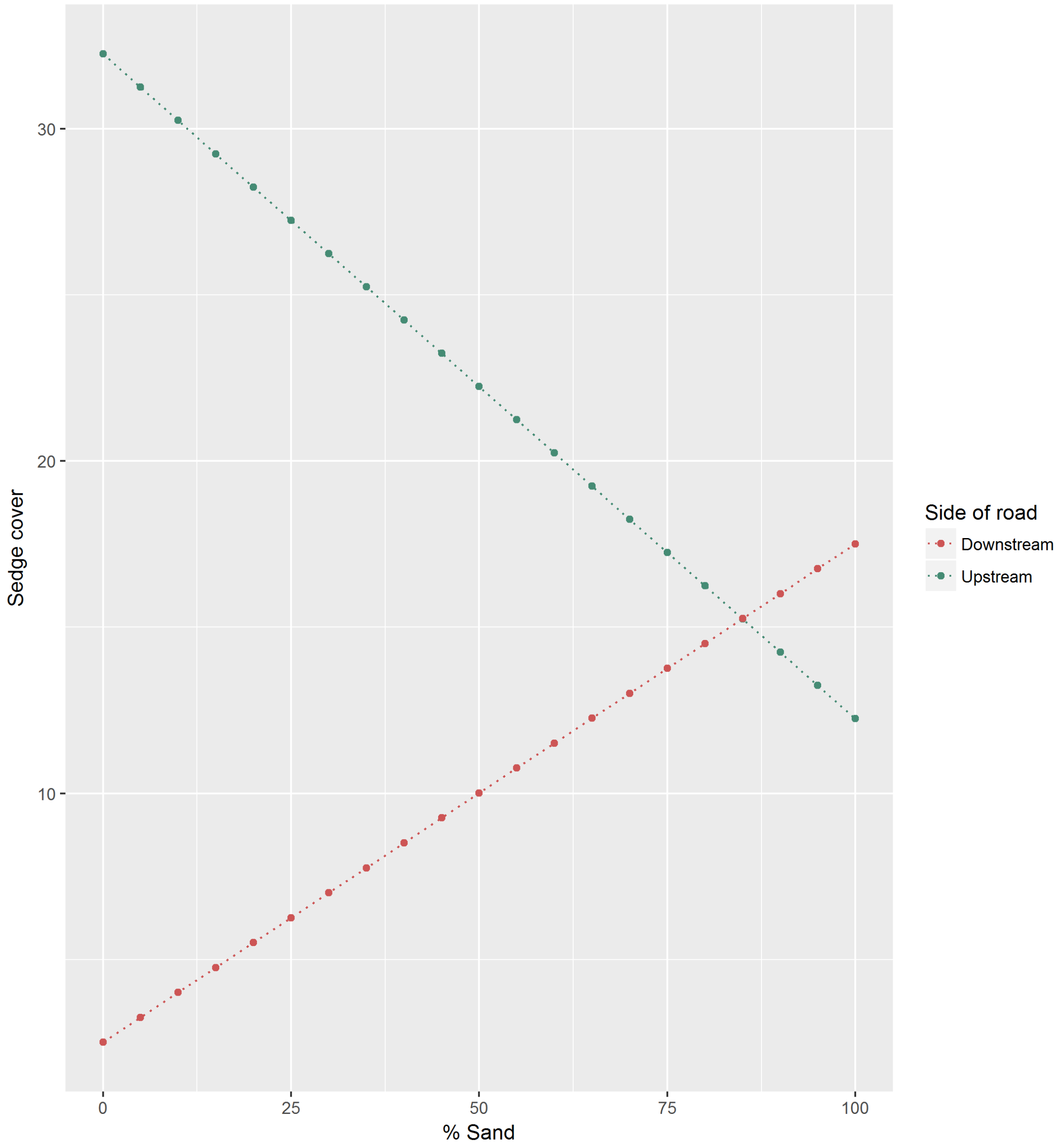

Figure B3-7: Interaction plots for sedge cover in the fen model. Cover on the y-axis and sand content on the x-axis. When the percent sand is low the sedge cover is high on the upstream side of the road and low on the downstream side of the road. At high percent sand the sedge cover is similar.

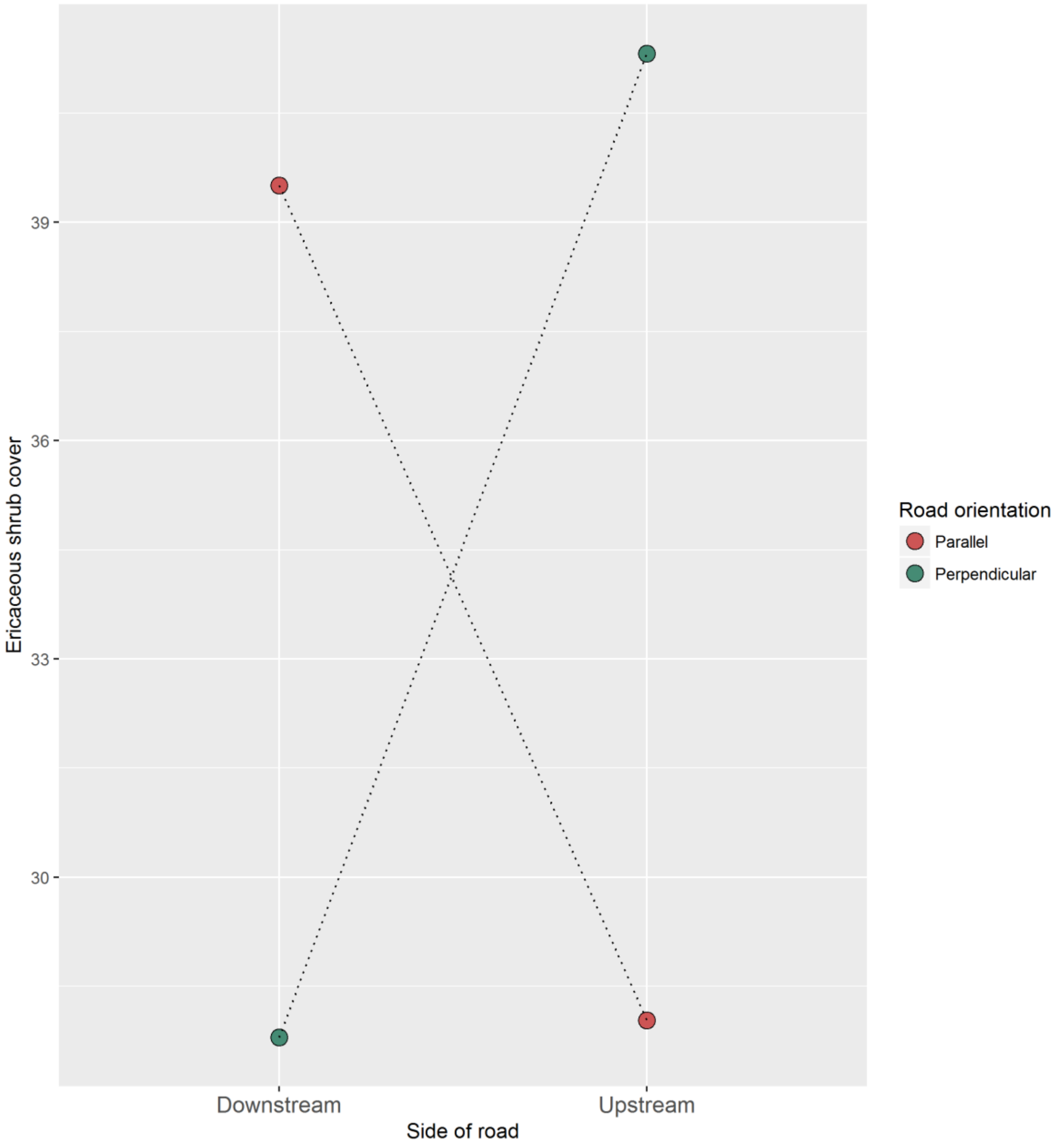

Figure B3-8: Interaction plot of ericaceous shrub cover in the fen model. Ericaceous shrub cover is high on the downstream side of the road when the road is parallel and low on the upstream side when the road is parallel. The opposite is true with perpendicular roads.

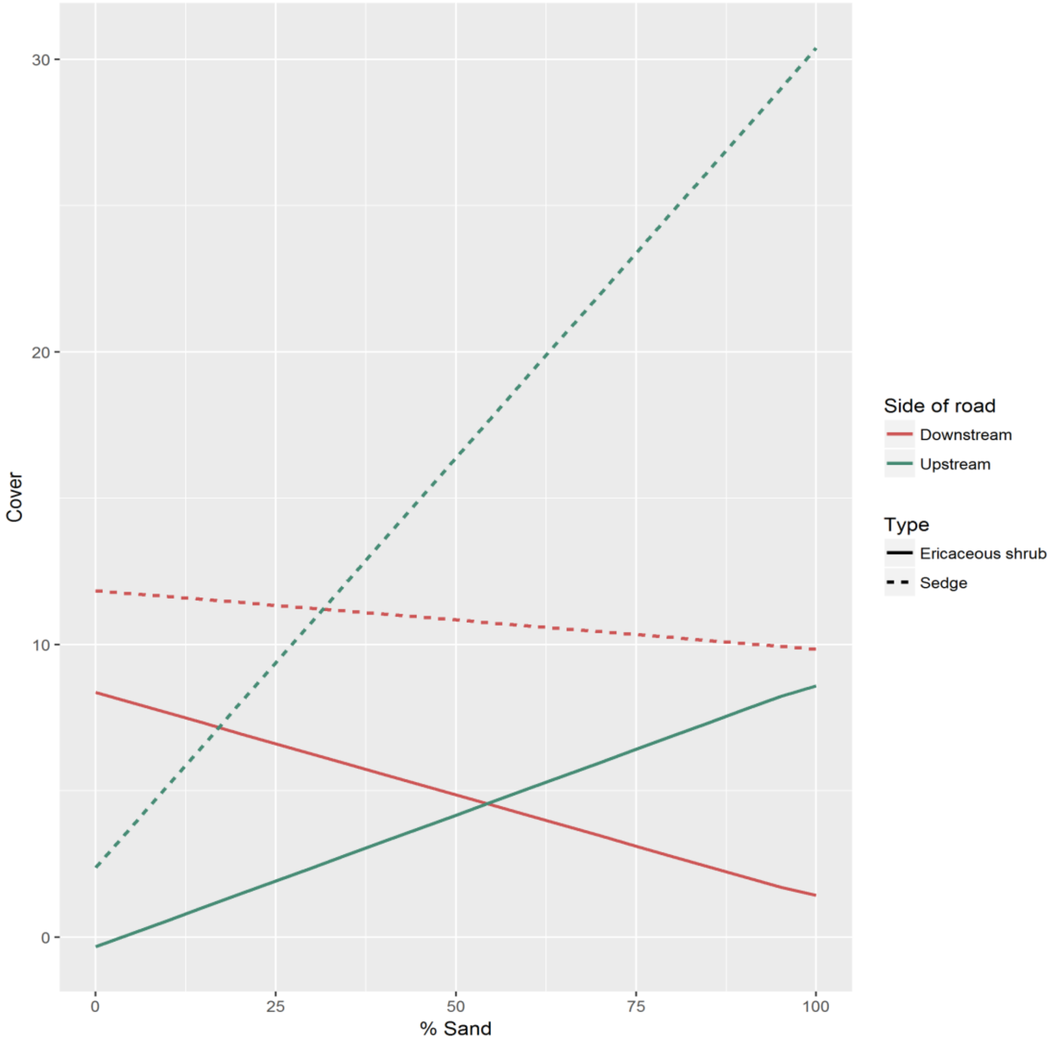

Figure B3-9: Interaction plots for ericaceous shrubs and sedges in swamp models. The y-axis is cover and the x-axis is percent sand. Dotted lines represent predicted cover for sedges and the sold are ericaceous shrubs. We see similar trend in both species however sedge cover is predicted to be much high.