# Landscape analysis & boundary detection of bog peatlands' transition to mineral land: The laggs of the eastern New Brunswick Lowlands, Canada

by

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# AUTHOR'S DECLARATION

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

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# Abstract

The wet zone – the lagg – that tends to form at the edge of ombrotrophic peatlands is believed to play an important role in promoting and maintaining the health of bog systems. The lagg is well-recognized by peatland scientists, yet empirical knowledge is surprisingly limited, and most of the characteristics associated with this ecotone come from qualitative observations. Understanding the role played by the lagg, and the potential impact its disturbance might have on the integrity of a raised bog system, is valuable for sustainable land management and peatland restoration science alike. This thesis explores and documents the basic ecohydrological characteristics of the lagg in the context of the neighbouring natural landscapes, and discusses the spatial properties of various types of laggs by exploring airborne LiDAR datasets to detect and position the ecotone. The specific objectives are 1) to describe the form and abiotic controls of the laggs and margins of bog peatlands, 2) to propose a conceptual model in cross-section of the "bog-lagg-mineral land" transition, 3) to explore the potential of data derived from aerial LiDAR (Light Detection And Ranging) to detect and locate laggs and lagg boundaries, and 4) to consider the spatial distribution of laggs around raised bog peatlands. Data were collected along 10 transects located within 6 relatively undisturbed bogs of the New Brunswick eastern lowlands, Canada. Each transect consisted of 4-6 wells, straddling the ombrotrophic bog and the adjacent mineral land, and of 3 nested piezometers in the center of each lagg. These instruments were used to monitor the position of the water table, to measure hydraulic gradient, hydraulic conductivity, and for water sampling. Dissimilarity analysis (edge-detection, split moving window) and similarity analysis (cluster, k-means) were used to test the delineation capacity of five variables derived from the LiDAR dataset; ground elevation (topography), vegetation height, topographic wetness index, and spatial frequency of both vegetation and ground LiDAR returns. The major abiotic control of the lagg appears to be topography. Two geomorphological categories were identified; confined and unconfined. The importance of topography is through the affect it has on water flow rates and direction, which in turn affect water chemistry, and most likely nutrient transport and availability, hence vegetation characteristics. Dissimilarity analysis of the five variables derived from LiDAR data revealed that some indicators were better at predicting the bog-lagg boundary (e.g. vegetation height), and others at finding the lagg-mineral land boundary (e.g. topography). In contrast, the similarity analysis gave more decisive influence to the topographic wetness index. When the lagg was confined between the bog and the adjacent

upland, it took a linear form, parallel to the peatland's edge. However, when the adjacent mineral land was flat or even sloping away, the lagg spatial distribution was discontinuous and intermittent around the bog. Our results confirms that laggs can take many forms, while suggesting two broad geomorphological categories from which they can more easily be studied and understood and highlight the potential offered by LiDAR technology in predicting their likely location around a raised bog. The results and conclusion from this research further our understanding of the goals to be achieved for ecological restoration, and favor sustainable management inclusive of the margins or bog peatlands.

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# Chapter 1

## Introduction

## 1.1 Context

### 1.1.1 The evolution of the lagg in the scientific literature

The lagg has taken various names and definitions in the peatland scientific literature. Among the first North American scientists to recognise this zone is George B. Rigg (1925) who, between 1908 and 1923, visited 78 bogs along the Pacific coast of North America (from Oregon to Alaska), and reported that for most of these sites, a "marginal ditch" characterized by swamp-like vegetation could be observed. A few years later, Rigg et al. (1927), described a bog near Seattle (Washington) as being completely encircled by a "natural marginal ditch", over 150 feet wide in some places, and very wet, even in mid-summer. In 1938, Rigg & Richardson remarked for bogs in Oregon, Washington, and British Columbia, that it is difficult to clearly define the extent of these zones, that they are very variable, and although usually very wet, they can sometimes be observed in drier conditions. If Rigg (1925), and Rigg et al. (1927; 1938) did not use the word "lagg", it is because its introduction to the English scientific literature came after their earlier work; the term was introduced by Hugo Osvald in 1933. Describing the vegetation of 5 bogs in the Vancouver (B.C.) region, Osvald – based in Uppsala (Sweden) – compared and translated terms used by Swedish peatland scientists to their English equivalence, suggesting that the expression "lagg" corresponding to the "natural marginal ditch" described by Rigg (1925), and Rigg et al. (1927), should not be translated as it had no English counterpart, and was already accepted in Northern Europe. During that same period, in Wales (U.K.), Godwin & Conway (1939) used the word "lagg" as it was suggested by Osvald, describing it as the zone where the bog meets the "hard ground" and accumulates waters from both the bog and the "upland". Ten years later, Conway (1949) further described the lagg as a "narrow zone" separating the mineral and bog plant communities, and recognized that it is not always present around bogs. This latter work being in central Minnesota (U.S.A.), Conway used the term "marginal fen" in place of "lagg", as it had not yet been accepted by the North American scientific community (Conway, 1949). In Australia, Millington (1954) used the term lagg with various adjectives (i.e. marginal lagg, lagg stream), while in England Hobbs (1986) preferred using variations of the word "margin" (i.e. wet margin or marginal fen). In the Atlantic provinces of Canada, Damman used the term "moat" to refer to the lagg in his work prior to the 1980s, but as the expression gained in popularity, he later used the word "lagg" on its own (Damman, 1986). At the beginning of the 21st century, the expression "lagg fen" seemed to be favoured in Europe, and was used by Bragg (2002) in Scotland, and in a book by Rydin and Jeglum (2006) describing the biology of peatlands. In the French Canadian literature, however, the term "lagg" is usually used alone, and was accepted by influential work such as Couillard & Grondin (1986) and Payette & Rochefort (2001).

The definition of the lagg is also inconsistent. In general, it includes at least one of three aspects: hydrology, topography, and/or vegetation. The authors mentioning vegetation describe the lagg as hosting swamp-like (Rigg, 1925), fen-like (Conway, 1949; Milington, 1954: Hobbs, 1986), or both swamp and fen-like vegetation (Rydin & Jeglum, 2006). In the French Canadian literature, the vegetation is simply described as minerotrophic (Couillard & Grondin, 1986; Payette & Rochefort, 2001). The topographic and morphologic aspects of the lagg are more or less clear. Some authors – including Osvald (1933) – refer to the lagg as being specific to raised bogs (Godwin & Conway, 1939; Couillard & Grondin, 1986; Hobbs, 1986; Bragg, 2002), while others make no specification about the morphology of the bog. Similarly, the terrain on the mineral side of the lagg has been referred to as upland (Godwin & Conway, 1939; Payette & Rochefort), as mineral terrain (Couillard & Grondin, 1986) or as mineral soils (Conway, 1949; Rydin & Jeglum). A few authors mentions that it is long (Couillard & Grondin, 1986), or narrow (Rydin & Jeglum, 2006), and all agree that it is found at the margin of bogs, but otherwise, there is no description of the spatial properties of the zone. A particularity of the French Canadian literature is the use of the word "depression" to describe the lagg, suggesting that it is found – or potentially found – at lower elevation than both its neighbours. The basic hydrological characteristics of the lagg are less controversial; most authors describe it as a wet zone receiving water from both the bog and the surrounding mineral soils.

There is obvious confusion about what constitutes a lagg, and a lack of knowledge concerning its ecohydrological functions, spatial properties, and the role it plays in a bog ecosystem. Does the bog have to be raised to support a lagg? Does the surrounding ground have to be elevated or otherwise sloping towards the lagg (i.e. upland)? Can the lagg be considered as part of the peatland complex, or is it merely adjacent to it? And perhaps more importantly, what does the lagg do? Answering some of these questions can be attempted from the existing literature. Rigg (1925) and Rigg & Richardson (1938) mention that laggs are most easy to identify when the bog occupies a depression, where it is very wet even in mid-summer, but recognize their presence in more subtle landscape, where it is difficult to define their extent. Damman (1977) reports that the laggs of plateau bogs with sharp slopes are in general wetter and better developed than for raised bogs with a gentle slope. In the original translation by Osvald (1933), the lagg is defined as the "wet margin of a raised bog". This suggests that the lagg is a feature of a raised bog, or at least has been more frequently observed in mature raised bogs, but does not necessarily have to be confined by an adjacent upland. From the existing literature, a basic definition – valid regardless of geographical region – can therefore be attempted; the lagg is the transitional zone between a raised bog and the surrounding mineral soils that is influenced by both, nutrient depleted bog water and enriched water from adjacent mineral environment.

### 1.1.2 Recent advances in lagg studies – Burns Bog and the Canadian context

Given its general recognition, it is surprising how little attention has been given to the lagg. Consequently, most of the characteristics and ecological functions associated with this ecotone are the results of qualitative observations. However, interest in quantifying and understanding the lagg in a holistic manner (i.e. as a function of both the bog and the surrounding mineral environments) is increasing in Canadian peatland studies. Driven by ecological conservation and restoration interests, a joint effort between the provincial government of British Columbia and the Delta Fraser Properties Partnership carried out an ecosystem review of Burns bog near Vancouver (B.C.); Delta Fraser Properties Partnership owns 2,200/3,000 ha of the bog. The objective of this report (Hebda, 2000) was to assess the ecological state of the urban bog, and suggests actions for maintaining and/or regaining ecological integrity. One of the conclusions of this report is that the lagg zone is necessary for the long-term ecological integrity of the ecosystem. A few years later, Whitfield et al. (2006) proposed a conceptual model (in cross-section) of what the laggs of Burns Bog might have looked like prior to anthropogenic disturbance. They identified four different types of transitions between bog and mineral terrain, ranging from wet and well defined to dry and diffused The authors also point out that laggs are complex structures acting as a peripheral drainage system, and raise the question of the possibility for laggs to be re-created or otherwise engineered, especially when it is impossible to favor a natural gradual transition to the neighbouring environment, as it is the case when human development encroaches on an ecosystem's boundary. Whitfield et al. (2006) highlight the complexity and variety of lagg systems, and the need for more studies to understand their hydrology, hydrochemistry, and their general relation to ecosystem composition and structure. In a follow up study, Howie et al. (2009) used historical aerial photography and stereography to locate where these laggs might have occurred around Burns Bog. They theorized that vegetation can be used as an indicator of water table levels and soils chemical properties, and that vegetation height increases from bog to lagg, to then level off in the surrounding forests. The authors point out that data limitations (low resolution from historical photos and the absence of a Digital Elevation Model (DEM)), keeps some of their conclusion as speculations, but that technology such as LiDAR (Light Detection and Ranging) might help in finding subtle topographic variation that might be key to the formation and maintenance of lagg zones. In subsequent work (Howie et al., 2011) proposed a new definition for the lagg that would include the possibility for laggs to be "sharp" or "diffused", and based on scientific literature (as it was not measured), the presence of a thin peat layer of relatively low hydraulic conductivity.

In eastern North America, Richardson et al. (2009) addresses some of the spatial and general geomorphic properties of the lagg, by developing a lagg width index (LWI) based on the characteristic morphology of a peatland derived from a LiDAR DEM. They found a correlation between the lagg identified by the LWI, and spatial variations of methylmercury (MeHg) concentration as measured in near surface pore water. The authors highlight the unprecedented opportunity that airborne LiDAR data gives to characterize the geomorphic properties of subtle landscapes such as the northern peatlands. In New Brunswick, a yet to be published manuscript by Paradis et al. (2014) reveals that the vegetation structure of the lagg might differ from both its neighbours (the bog and the mineral forest); it exhibits a more complex structure where *Sphagnum*, tall shrubs, herbaceous plants and trees are present.

### 1.1.3 Relevancy

Understanding the lagg zone is of interest to both ecological restoration and ecosystem conservation and management. In restoration, recreating hydrological and biogeochemical conditions favorable to the re-establishment of *Sphagnum* species is essential for the return to a peat-accumulating ecosystem (Gorham & Rochefort, 2003). Blocking the ditches used for draining the peatland for harvesting is vital and normally the first attempt at regaining favorable hydrological condition, but is often not sufficient for successful restoration (Price et al., 2003). Other techniques such as the creation of bunds and terraces are used to retain water within the remaining peatland, but the balance between deficit and excess of water is delicate (Price et al., 2003). The establishment of a buffer zone beyond the peat body has also been recommended to protect the bog from external hydrological regime (Eggelsmann, 1980; Gorham & Rochefort, 2003). Among the suspected functions of the lagg is its capacity to help retain water within the peat body (by lowering the hydraulic gradient of the water exiting the raised bog) during drier periods, or removing excess water in time of excessive moisture. A better understanding of the hydrological functioning of the lagg, and a quantification of its morphology could help comprehend this delicate balance and set goals for restoration.

The detection and delineation of peatlands is essential for their responsible management. Whatever the technique used (e.g. visual interpretation from stereography, or automated image classification from satellite imagery), the gradual changes observed in lagg ecotones are challenging to delimit. If they are detected – as it is often the case when a field characterization is carried out – they are misclassified, usually as fen, which can subsequently affect decisions made concerning their conservation and management. Documenting and quantifying the role and impact of the lagg on the peatland complex will shed valuable information for land managers to understand and better judge the consequences of alteration made within, or complete disruption of bogs marginal areas. When anthropogenic disturbances are planned around a raised bog, early remote detection of potential lagg area – even informal – and the connectivity that might exist between a bog and its neighbouring environment could help direct policy for responsible management of the bog's margins.

## 1.2 Objectives

The general objectives of the work presented here is to add to the scarce body of scientific knowledge about the lagg zone. The specific interests lie in the geomorphology, general hydrology and hydrochemistry, vegetation patterns and spatial properties of the ecotone. Based on the conceptual models of Whitfield et al. (2006) and Howie et al. (2009), the goals are 1) to describe the form and abiotic controls of the transition from *Sphagnum* dominated bog ecosystem to the surrounding mineral forest, and 2) to suggest a conceptual model of the "bog-lagg-mineral land" transition for the Canadian Atlantic provinces. Following its ecohydrological characterization, subsequent objectives pertain to the remote detection and analysis of the ecotone. The specific aims are to 3) to explore, through techniques of landscape ecology and remote sensing, the potential of information derived from aerial LiDAR datasets to detect and locate laggs and lagg boundaries, and 4) to consider the spatial distribution of laggs around raised bog peatlands.

## 1.3. General Methods & Organisation

This thesis is composed of two standalone manuscripts that explore and document 1) the basic ecohydrological characteristics of the lagg in the context of the neighbouring natural landscapes (i.e. mineral forest and bog ecosystems), and 2) discuss the spatial properties of various types of laggs by exploring the possibility offered by the increasing accessibility of rich remotely sensed information; in this case LiDAR datasets. The first manuscript entitled "Landscape analysis of nutrient-enriched margins (lagg) in ombrotrophic peatlands, New Brunswick" is the study of 10 transects situated in 6 bogs of the New Brunswick eastern lowlands. These transects were composed of wells and piezometers spanning from the bog dome to the surrounding mineral forests, and were monitored for variations in 4 gradients; hydrology and hydrochemistry (field monitoring), and vegetation patterns, and topography (from LiDAR). The second manuscript "Exploring LiDAR data for the detection of lagg boundary" make use of the knowledge acquired in the first manuscript to explore the possibility for laggs and lagg boundaries to be detected and positioned from airborne LiDAR, with the help of available tools and algorithms.

The study's initial concept, planning and implementation was effectuated under the guidance of Dr. Jonathan Price. My involvement in this project was to plan and perform the field data acquisition as well as the analysis, and in regards to the LiDAR data, plan and carry all analysis from classified point cloud format to final results. I was also responsible for writing the first edition of both manuscripts, on which Dr. Price provided valuable feedback. This study was funded by the Industrial Research Chair in Peatland Management held by Dr. Line Rochefort (Université Laval, Québec). Dr. Rochefort gave valuable feedback on the second chapter of this thesis.

# Chapter 2

## Landscape analysis of nutrient-enriched margins (lagg) in ombrotrophic peatlands, New Brunswick

### 2.1 Summary

Scientific knowledge and understanding of the transition between ombrotrophic bog and mineral land is surprisingly limited. The wet zone – the lagg -- that tends to form at the edge of ombrotrophic peatlands is nevertheless believed to play a role in promoting and maintaining the health of the bog system. This study aims to improve the understanding of the ecological functions of this transition by describing the form and abiotic controls of the laggs and margins of bog peatlands. Data were collected along 10 transects located within 6 relatively undisturbed bogs, between the town of Bertrand (47°45'N, 65°03'W), and the eastern limit of Miscou Island (47°59'N, 64°31'W) in north-eastern New Brunswick. Each transect consisted of 4-6 wells, straddling the ombrotrophic bog and the adjacent mineral land, and of 3 nested piezometers in the center of each lagg. These instruments were used to monitor the position of the water table, to measure hydraulic gradient, hydraulic conductivity and for water sampling. Water levels remaining near or above the surface (5 ± 8 cm) confirm the lagg as part of the wetland complex. Hydraulic conductivity (K) of the upper peat layer resembles that of bog environments, but quickly reduces with depth impeding downward water flow. Analysis of Variance ($p < 0.00$), and of Least Significant Difference ($n=90$, $p<0.05$) suggests that while having characteristics similar to the mineral land in terms of electrical conductivity (95±11 µS/cm-1), the lagg is different from both adjacent systems when looking at pH (4.8±0.4) and water levels.

### 2.2 Introduction

"Lagg" refers to the transitional zone that forms at the margin of natural ombrotrophic peatlands; some are distinct and others are not. In its hydrology and hydrochemistry, it takes on qualities of both the bog and the adjacent mineral terrain (Whitfield et al., 2006). As acidic water from the bog meets mineral-enriched waters from surrounding environments, rapid ecohydrological changes occur over short distances (Howie et al., 2009; Paradis et al., 2014). This can easily be observed in the vegetation (Damman, 1986; Paradis et al., 2014), which transition from dominantly *Sphagnum* mosses in the bog center, to shrubs, then trees in the neighbouring mineral forest. The lagg plays three key functions in a raised bog ecosystem: 1) high water levels in this zone reduces the hydraulic gradient in the margin of the adjacent bog, which helps it retain water (Schouwenaars, 1995); 2) during wet periods the lagg can efficiently move excess water away from the system (Godwin & Conway, 1939); and 3) it plays a critical role in the bog growth and expansion by impeding lateral expansion thus promoting vertical growth of the peatland (Godwin & Conway, 1939; Hobbs, 1986; Damman, 1986). Laggs are not commonly recognized as an integral part of the peatland complex. Due to this lack of recognition, adjacent land-uses often encroach on laggs (Howie, 2013), or they are drained or otherwise damaged in peat harvesting, resource extraction operations or urban development. Little attention has been paid to their restoration and management, in part because their hydrological and ecological functions have not been well described, and remain poorly understood (Whitfield, 2006, Howie et al. 2009; 2011; 2013). This lack of knowledge and understanding compromises the ability of land managers, who must make decisions without a clear understanding of the impact of developing within the margin, or in peripheral areas of bog peatlands (Murphy et al., 2007).

In Canada, most of the research on lagg function comes from the study of a large urban peatland: Burns Bog (Vancouver, British Columbia) – which has lost much of its natural lagg to anthropogenic disturbances and land use changes – and other costal bogs through the work of Hebda et al. (2000), Whitfield et al. (2006), and Howie et al (2009;2013). After many decades of restoration efforts, researchers are recognising that for a raised bog to be viable and maintain its integrity, lagg zones must be present and functioning (Hebda et al., 2000). Whitfield et al. (2006) conceptualized the lagg structures that might have existed prior to the disturbance of Burns Bog. They identified four forms of transition from peatland to mineral terrain likely to have occurred at different locations around the peatland: 1) between the bog and a relatively steep mineral slope, 2) confined between a natural river levee and the bog, and subject to occasional flooding from the nearby river, 3) spreading across an ancient beach formation, and 4) in an area assumed to have been dominated by natural discharge from the bog across a flat deltaic terrain (Whitfield et al., 2006; Howie et al., 2009). Whitfield's model was later refined by Howie et al. (2009), using historical aerial photography and stereography to hindcast the historical location of the lagg, based on vegetation height. This latter model includes predictions of the expected presence of four ecological gradients for the bog-lagg-mineral terrain transition where 1) the height of the vegetation is expected to increase from bog to lagg and mineral forest, 2) the hydrological gradient is presumed to be steeper on the upland side (relatively steep mineral slope) compared to the bog side, 3) the chemical gradient is suspected to have higher concentration in the mineral soil and gradually decreasing towards the bog,  and 4) the soil permeability is expected to be lower in the catotelmic bog peat than in the mineral land.

The presence and the character of the lagg varies within and between peatlands, and its lateral and longitudinal extents remain a challenge to define (Paradis et al., 2014). This is true within a single geographical region and it becomes more problematic to generalize for different climatic, hydrogeomorphic and ecological regions. Consequently, this has resulted in inconsistent terminology and/or definitions for this zone, which has variously been referred to as marginal ditch (Rigg, 1925; Rigg et al., 1927; Rigg & Richardson, 1938), marginal fen (Conway, 1949), wet margin (Hobbs, 1986), lagg fen (Bragg, 2002; Rydin & Jeglum, 2006), lagg stream (Millington, 1954) and lagg  (Whitfield et al., 2006; Howie et al., 2009,2011,2013; Richardson et al., 2010). Among the few studies specifically focussed on laggs (Blackwell, 1992; Smith et al., 1999; Howie et al., 2009), few (e.g. Mieczan et al., 2012) have studied truly undisturbed ecosystems.

The impact of the landscape on the formation and functioning of the lagg have been mentioned by many authors (Godwin & Conway, 1939; Damman, 1986; Hebda et al., 2000; Whitfield et al., 2006; Howie et al., 2009;2013), but few (Richardson et al., 2010) have quantified its geomorphology. The lagg is hydrologic in nature, and influenced by both the bog and the adjacent mineral land. To understand the landscape processes that control the form and functions of the lagg, its neighbouring ecosystems also need to be examined (Howie et al., 2009; 2013; Paradis et al, 2014). Based on the conceptual models of Whitfield et al. (2006) and Howie et al. (2009), our goals are 1) to describe the form and abiotic controls of the transition from *Sphagnum* dominated bog ecosystem to the surrounding mineral forest and, 2), to suggest a conceptual model of the “bog-lagg-mineral land” transition for the Canadian Atlantic provinces.

## 2.3 Study Area

All study sites were part of the New Brunswick Eastern Lowlands, located between the town of Bertrand (47°45'N, 65°03'W), and the eastern limit of Miscou Island (47°59'N, 64°31'W) (Figure 2-1). The region is characterised by a cool, moist climate, with 4 months below freezing (Canadian Climate Normals 1971-2000, Bathurst, NB).  Mean annual temperature in the region is 4±1 °C, and mean annual precipitation is 1059 mm (30% as snowfall) (Canadian Climate

Normals 1971-2000, Bathurst, NB). The growing season of 2011 – the study period – was particularly wet with an average May-September precipitation of 617±10 mm compared to the 435 mm average for normal years (Canadian Climate Normals 1971-2000, Bathurst NB). The peninsula is underlain by red and grey sandstone, interbeded with mudstone and conglomerate, which combined with the flat topography (ranging from 0 m to ~ 45 m above sea level (MASL)), often results in poor drainage (Colpitts et al. 1995). Consequently, organic soils have developed in many of the regional glacial depressions, and nearly half of New Brunswick wetlands are found in the eastern lowlands (Zelazny, 2007).

| Site (peatland) | Northing | Westing | ha | Elevation (MASL) | Peat Depth max (m) | Transect Names | Length (m) |
|---|---|---|---|---|---|---|---|
| A | 47° 59' 41" | 64° 31' 30" | 619 | 4 | 5 | A1 | 210 |
| B | 47° 56' 18" | 64° 32' 41" | 31 | 9.2 | 1.5 | B1 | 104 |
| C | 47° 56' 05" | 64° 31' 55" | 1,500 | 8.2 | 5.5 | C1 | 102 |
| | | | | | | C2 | 179 |
| | | | | | | C3 | 222 |
| D | 47° 44' 25" | 64° 45' 08" | 160 | 4 | 2.9 | D1 | 673 |
| | | | | | | D3 | 550 |
| E | 47° 45' 58" | 64° 57' 29" | 148 | 19.8 | 4 | E2 | 76 |
| | | | | | | E3 | 199 |
| F | 47° 44' 33" | 64° 03' 21" | 114 | 27.3 | 5.5 | F1 | 246 |

Table 2-1: *Study sites.* In 2011 6 peatlands (A to F) were instrumented with a total of 10 transects (A1 to F1). Peatland sizes varied between 31 and 1,500 ha, and transect length between 76 m and 673 m.

In June 2011, 6 relatively undisturbed ombrotrophic peatlands of various sizes (between 31 and 1,500 ha) were instrumented with a total of 10 transects comprising wells and piezometers, straddling the bog and the adjacent mineral land (Table 2-1). Each of these were selected to cover lagg transitions ranging from wet and well defined, to dryer and more diffuse. These ecotones were identified mainly based on the presence of transitional vegetation (e.g. *Alnus incana* ssp. *rugosa*, *Ilex (Nemopanthus) mucronatus, Rhododendron canadense, Viburnum nudum* ssp. *cassinoides*), near or above ground water table (late May), surface water chemistry (higher values in relation to adjacent peatland) and the presence of peat.

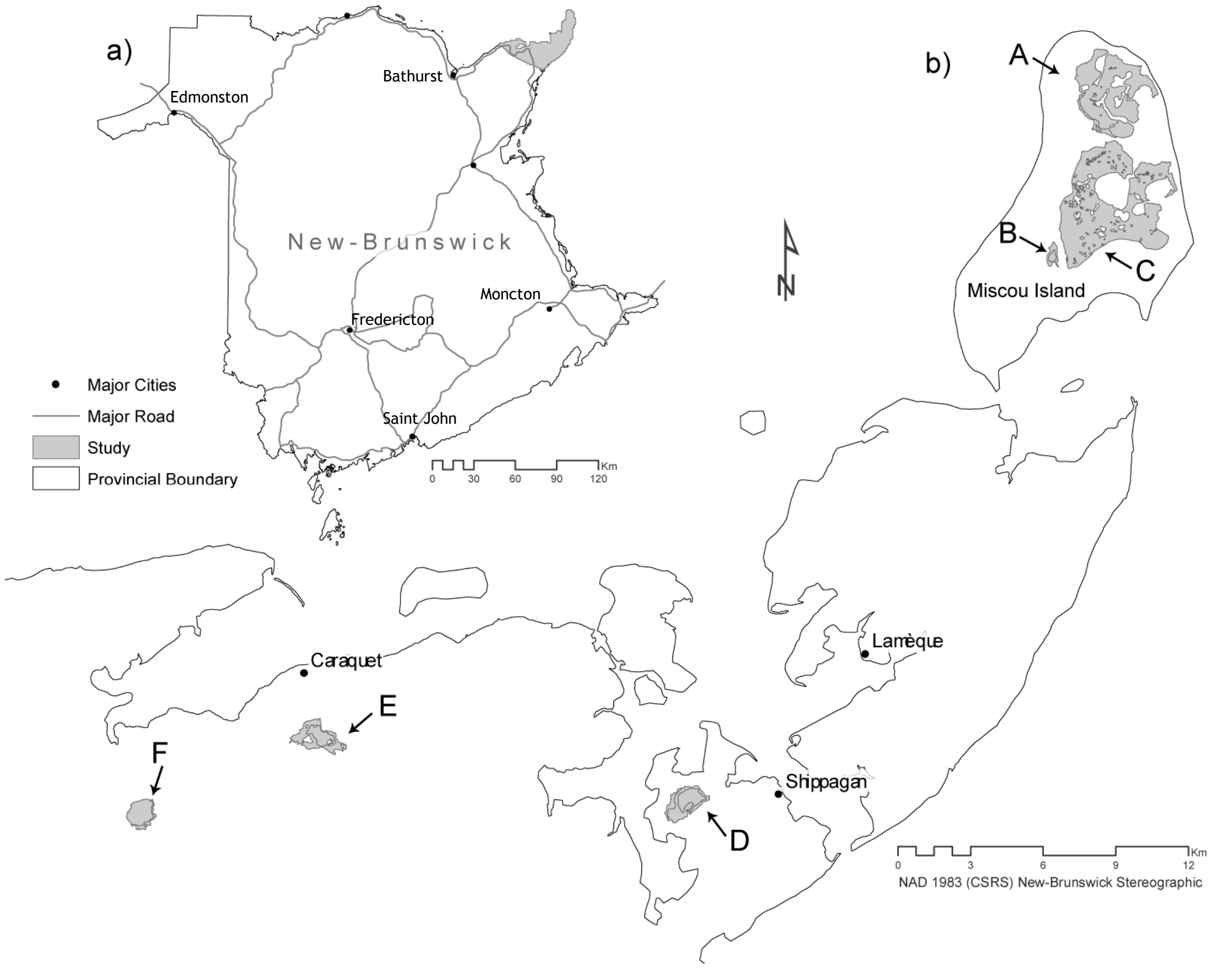



Figure 2-1: *Study sites.* a) All six study sites were located within the eastern lowlands of north eastern New Brunswick. b) The capital letters indicate each of the individual study sites, located between the town of Bertrand near Caraquet, and the eastern limit of Miscou Island.

The transects can be considered in 5 landscape units; 1) mineral land, 2) lagg (as described above), 3) lower rand, 4) upper rand, and 5) bog. The mineral land units were forested (mixed) with no peaty soil. The rand can be described as the sloping margin of a raised bog (Godwin & Conway, 1939; Damman, 1986; Hebda et al., 2000; Wheeler & Shaw, 1995; Howie et al., 2011), found between the dome and the lagg, towards the edge of the peatland. The rand occurs where the hydraulic gradient of the bog steepens at the edge of the dome, resulting in lower water tables that promote the growth of woody vegetation including shrubs and small trees. The terms "upper" and "lower" rand is also utilized to describe the section of the rand that is respectively, closer to the central bog dome, or the edge of the peatland (Godwin & Conway, 1939; Boatman et al. 1981; Howie et al., 2011). Finally, the bog unit can be described as *Sphagnum* dominated and above the sloping margin.

## 2.4 Methods

For each of the 10 transects, wells were installed across the transition zone in each of the 5 landscape units described above. For the majority of our sites, a thick band of trees dominated by black spruces (*Picea mariana*) grew within the rand, at times closer to the bog center (higher rand), and other closer to the lagg (lower rand). The wells of the lower and upper rand are therefore comparable (between sites) in terms of their relative geographical position, but not in terms of vegetation. Wells were generally ~120 cm in length, ~95 cm of which was slotted, and placed below the ground surface. In the lagg, however, shallow peat and high water levels (often above ground) necessitated both shallower wells (~65 cm of open pipe) and a longer stick-up. A nest of 3 piezometers (20 cm slotted intake) was also installed in the center of each lagg. Absolute piezometer depth differed for each site, but all had a shallow piezometer centered ~10 cm above the mineral layer, a second one centered ~10 cm below the mineral layer, and a deeper one at refusal, or as deep as the equipment allowed (between ~150-~190 cm below ground). Wells, shallow and mid-depth piezometers were 4.2 cm ABS plastic pipes (inner diameter 3.17 cm). However, because of the nature of the mineral soils and its suspected lower hydraulic conductivity ($K_{sat}$), smaller 2.5 cm PVC pipes, were used for the deepest piezometers. All wells and piezometers were covered with screens along the slotted section.

Each instrument was measured weekly between July 4th and August 23$^{rd}$, 2011 (some exceptions), and once at the end of October, 2011. After measuring hydraulic head, wells and piezometers were purged and allowed to recover (some only partially) then electrical conductivity (EC), pH and temperature were measured with a portable EC and pH meter (accuracy pH: 0.05, EC/temp.: 2%). In a costal bog environment, most of the EC is driven by H ions and therefore the field measurement for EC need to be corrected for $H^+$. Popular correction methods such as the one suggested by Sjörs (1950) rely on the concurrent measured pH values. For accurate measurement of pH in low EC waters, low ionic strengths buffers and high accuracy electrodes are preferred. To gain confidence in our field measurements, we performed an error analysis using the portable instrument and buffer solutions that were used in the field (measured), and instruments with higher precision (0.001/0.5%) and low ionic strengths buffer (standard). We tested 10 water samples composed of different ratios of bog/tap water (in 10% increments), and compared the measurements (average of 10 measurements at ~ 1 minute interval per samples). The resulting correction curves indicated that the EC field values were acceptable ($R^2_{linear}$ = 0.999), but that a correction was needed for the pH values ($R^2_{linear}$ = 0.966). The field instrument used with regular ionic strength buffers had a tendency to overestimate pH values for solution ≤ 5.5, and to underestimate for solution > 6.0. After calculating the correction factors (CF = standard/measured) values were forecast between each of the 10 individual calibration points (linear regression). This allowed for the pH values to be corrected, and for the $H^+$ correction to be applied. The formula developed by Sjörs (1950), as presented in Rydin & Jeglum (2006), was utilised for this correction.

Hydraulic conductivity ($K_{sat}$) was measured in wells and piezometers 4 times over the summer in both wet and dry conditions, using bail tests (Hvorslev, 1951). For transect E3 however, slug tests (Hvorslev, 1951) were necessary in some occasions for the bog and for the lagg shallow piezometer. The $K_{sat}$ used for analysis is the geometric mean result of these 4 tests for each instrument.

Three horizontal gradients were evaluated at each site; water table, pH and EC were monitored from the wells placed in each landscape unit. In the lagg, wells were placed below the peat surface. However, in laggs where water levels were high (> ~25 cm above the peat surface) at the time of installation (early June), the peat was often "swollen" making the boundary between the standing water and the peat surface difficult to determine. We later realized that with dropping water levels following the spring peak, the peat in very wet laggs subsided, leaving part of the slotted section of pipe in the standing water, and in one instance, above it (open air). Consequently, the hydrochemical data (pH and EC) analysed for the lagg horizontal gradient is a mixture of surface, organic and mineral water, which we deemed representative of the water available in the lagg. For this same reason however, we could not use the $K_{sat}$ values recorded in the lagg wells, and used the shallow piezometer values (centered ~10 cm above the mineral interface), which are representative of the organic soil only.

Between August 23 - 25, 2011, 5 (C1, D1, D3, E2, F1, see table 2-1) of the 10 laggs' surface water, well, and piezometers (3) were sampled (25 samples total). Pipes- were purged before the collection of the samples and the tube used to pump the water was rinsed twice with distilled water before use. The samples were filtered within 24h (0.45 μm), and acidified with a

1% $HNO_3$ solution (1ml of diluted solution in a 45 ml sample) for transportation and preservation. Samples were analysed within 4 months of collection with a Dionex chromatography system (ICS-3000) for their ionic composition (Ca, Na, K, Cl, Mg).

To evaluate the topographic gradients and vegetation height of the bog-lagg-mineral terrain transition, the Department of Natural Resources of New Brunswick (NBDNR) provided airborne LiDAR (Light Detection And Ranging) data. This was acquired by Leading Edge Geomatic Ltd. on November 4$^{th}$ 2009, at an altitude of 1,600 m (system: Optech 3100 ALTM), with an accuracy of ±0.15 m vertically, and ±0.8 m horizontally (95% confidence). A Differential Global Positioning System (DGPS) survey of the pipe top elevation was completed during the fall visit, when deciduous trees in the lagg and mineral forest had shed their leaves, for better satellite signal strength. A Leica Viva GNSS (Global Navigation Satellite System) with a sub-centimetre vertical accuracy was used in conjunction with Real Time Kinematic (RTK), placed over monuments tied to the Provincial High Precision Network (HPN). The survey was carried in a known coordinate system (NAD83 CSRS New Brunswick Stereographic) to be used with the LiDAR data.

### 2.4.1 Data analysis

The LiDAR data were classified by the provider into ground, low vegetation, mid-vegetation and high vegetation. These classes were manually verified for each site and points were reclassified or removed if necessary. Point density across the sites (from 0.6 to 1.2 points / $m^2$) allowed for the creation of high resolution (1x1 m) Digital Elevation Models (DEMs) and Digital Surface Models (DSMs) using an inverse distance weighted method with a low power (optimized for lower Root Mean Square Error (RMSE) by the geostatistical analyst in ArcGIS 10.1), with a minimum of 4 and a maximum of 6 neighbours (to avoid for excessive spatial aggregation). These surfaces were used to derive a third surface of the vegetation's residual elevations (DSM-DEM).

For each of the 10 transects, spatial patterns for vegetation heights (residuals) in cross-section (10 m buffer strips) were analysed with a running average moving window (Fortin & Dale, 2005). The window size was kept small (4 m) with a 2 m increment (n = 40/windows), with the intention to characterize the changes in vegetation heights approaching the lagg, which are themselves relatively narrow (from ~10 m to ~70 m for our study sites). To analyse the general topography and derived attributes, 10 m buffer strips of LiDAR data in point cloud (as opposed to interpolated surface) were extracted, spanning beyond the length of individual transects to include the local maximum elevation on each side of the lagg (transect length: 120 m to ~700 m). A quadratic polynomial regression was fitted to the ground returns to yield information about the slope and concavity of the terrain between the lagg and the local maxima on either side of it (bog and mineral land). To make it easier to compare results between the transects, the LiDAR ground elevation value at the location of the lagg wells were considered as base elevation and given a value of zero. The original lagg elevation was then subtracted from all data points, residuals were kept for analysis. The DEMs and DSMs models were created using ESRI ArcGIS 10.1 geostatistical analyst, the running average and morphometric analysis were carried with the open source R statistical software (http://cran.r-project.org).

One way analysis of variance (ANOVA) was used on the data collected in the wells and piezometers to determine whether or not the landscape units could be considered as separate entities, or if it would be beneficial to group similar units (e.g. should the rand be divided into two units or analysed as one?). Subsequently, the analysis was repeated for data recorded at different depths in the lagg (peat, interface and mineral), to explore similarities and differences in the water chemistry of the different soils. Data were log-transformed to comply with the normality assumption of the parametric test, but did not consistently respect assumptions concerning the equality of variance. Therefore, when the null hypothesis was rejected, Fisher's Least Significant Difference test (LSD) was performed to compare the group treatment means and assess significance of differences between those groups. All analyses were completed with R statistical software, using the Basic and Agricolae packages.

The hydraulic gradient and specific discharge (q) were calculated using Darcy's Law (Freeze & Cherry, 1979) to assess the gradient and fluxes of water between adjacent landscape units (horizontal), and between the different depths within the lagg (vertical). Estimates for the lagg lateral fluxes were calculated from lower rand to lagg, and from mineral terrain to lagg, using the $K_{sat}$ of, respectively, the lower rand and mineral land. A negative specific discharge (q) should be interpreted as lateral water influx to the lagg. The vertical hydraulic gradient was calculated from higher to lower screens, starting with the wells (from well to shallow piezometer, shallow to mid-depth, and mid-depth to deep): a negative gradient indicates upward flux.

## 2.5 Results

### 2.5.1 Topographic gradient – Two types of transitions

The slope of the mineral land ranged from -1.5% to 6.7%, with 6 out of 10 transects above average (1.8%±2.2%; Figure 2-2. a,b,c,d,g,h). The remaining 4 transects had a mineral slope below average, 3 of them sloping away from the lagg (negative slope: -0.2 to -1.5%, Figure 2-2. f,i,j). On the bog side, relief was more subtle with a range of ~0 to 0.8%. With the exception of one (D1; Figure 2-2. j), the transects with a lower mineral slope also presented a lower bog slope. Bogs with a higher slope also had a lower concavity index (higher convexity) as determined by fitting a second order polynomial to LiDAR ground returns (note that negative values should be interpreted as higher convexity, and positive as concave). Average concavity of the bog for the 6 sites with a higher mineral slope was $-6.1\text{x}10^{-05}\pm7.0\text{x}10^{-05}$, and $-2.0\text{x}10^{-06} \pm 7.0\text{x}10^{-05}$ for the remaining 4. The laggs bordered by an above average mineral slope (6/10) were found at the mesotopographic (local) minimum elevation. In contrast, for the 4 transects with a mineral slope below average, the lagg was not at the transect's minimum elevation. Based on the lateral slopes leading to the lagg, the 10 transects were placed into two geomorphic categories; 6/10 as "confined" transition, and 4/10 as "unconfined" ; respecting terminology previously used by Hulmes, (1980) and Morgan-Jones et al. (2005). Confined transitions had a topographic gradient sloping towards the lagg on both sides; a mineral slope ≥ 1.8 %, and a bog slope ≥ 0.5 %, and the elevation of the lagg center was at the local minimum elevation. Bogs of confined transition tended to have higher convexity. Unconfined transitions had a lower, even negative mineral slope, and often a small vertical drop between the peatland's dome and the lagg. In unconfined transitions the lagg was not in a topographic depression, and usually not at the lowest point of the transition.

### 2.5.2 Vegetation height – The margin

Generally, vegetation height was lowest in the bog, to highest in the mineral terrain, but not always with a gradual, monotonic increase. Frequently, a ~10 m to ~100 m wide band of ~ 6 m high black spruce trees (*Picea mariana*) occur within the rand; in some instances adjacent to the lagg, at the bottom of the sloping margin (Figure 2-3.a), and others at the edge of the bog plateau, where the bog starts sloping (Figure 2-3.b). We refer to this band of black spruce as the rand-forest, and the outward sloping part of the bog as the rand-slope.

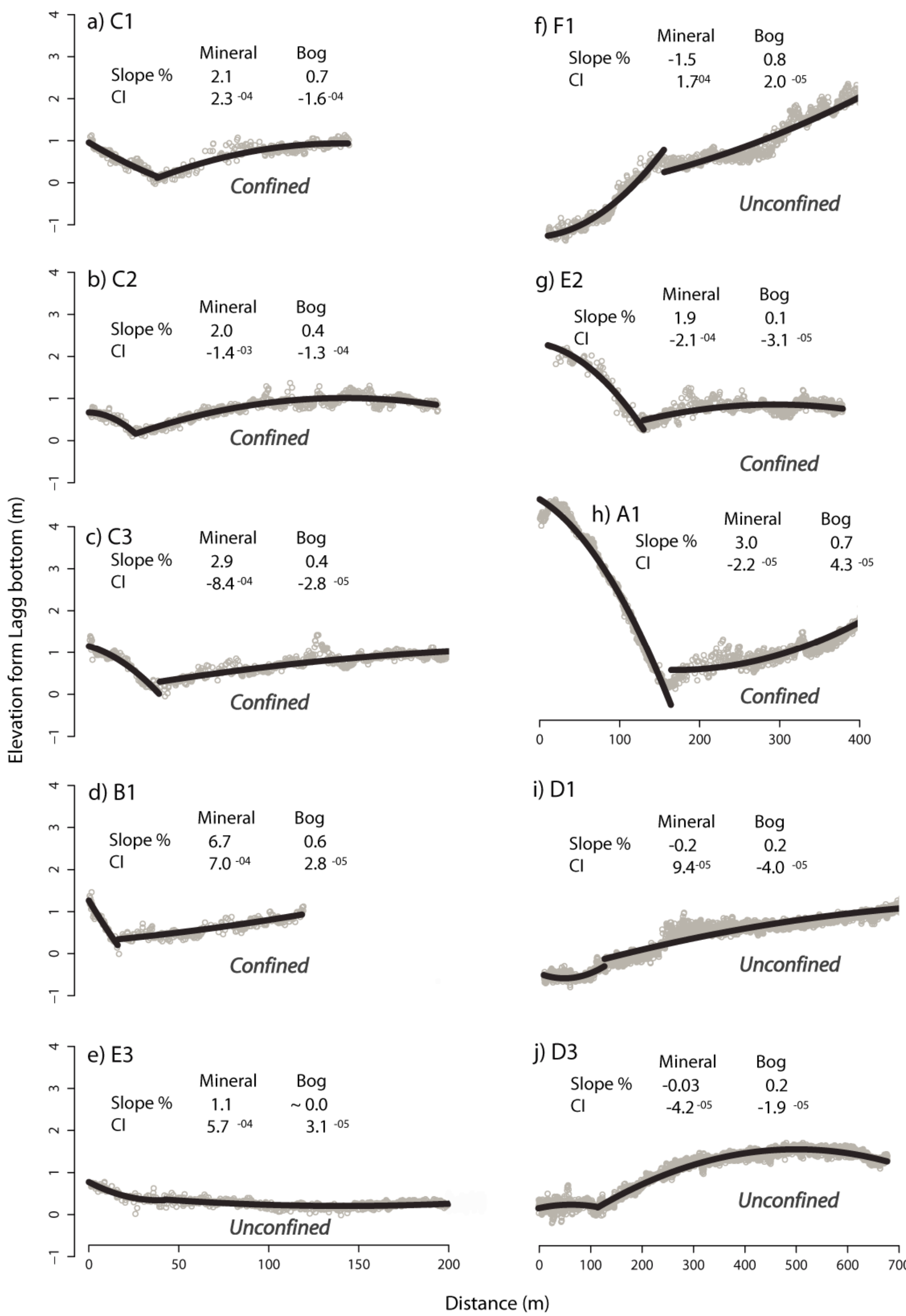



Figure 2-2: *Concavity index (CI) and lateral slope*. The dark line is a quadratic fit of a 10 m buffer LiDAR ground returns extraction (grey shadow) for each transect. The model was fitted between the local maximum elevations on each side of the lagg, with the exception of transect F1, D1, and D3 which had negative mineral slope. Based on slope, the transects were placed in two topographical categories: confined and unconfined. Transect locations are given in Table 1.

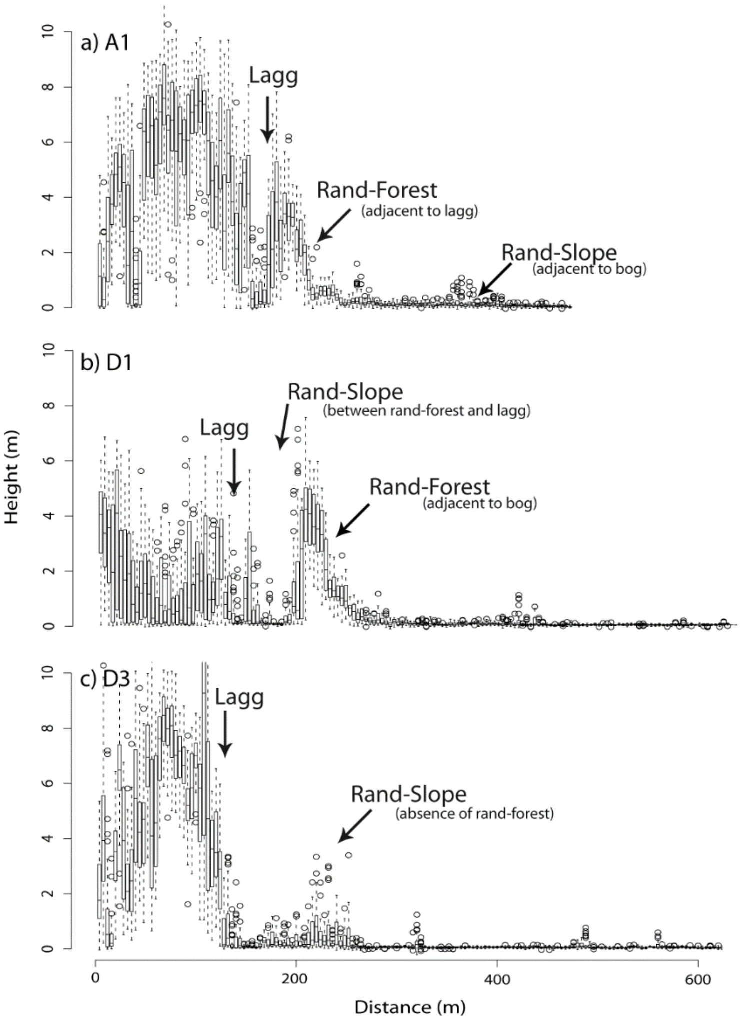
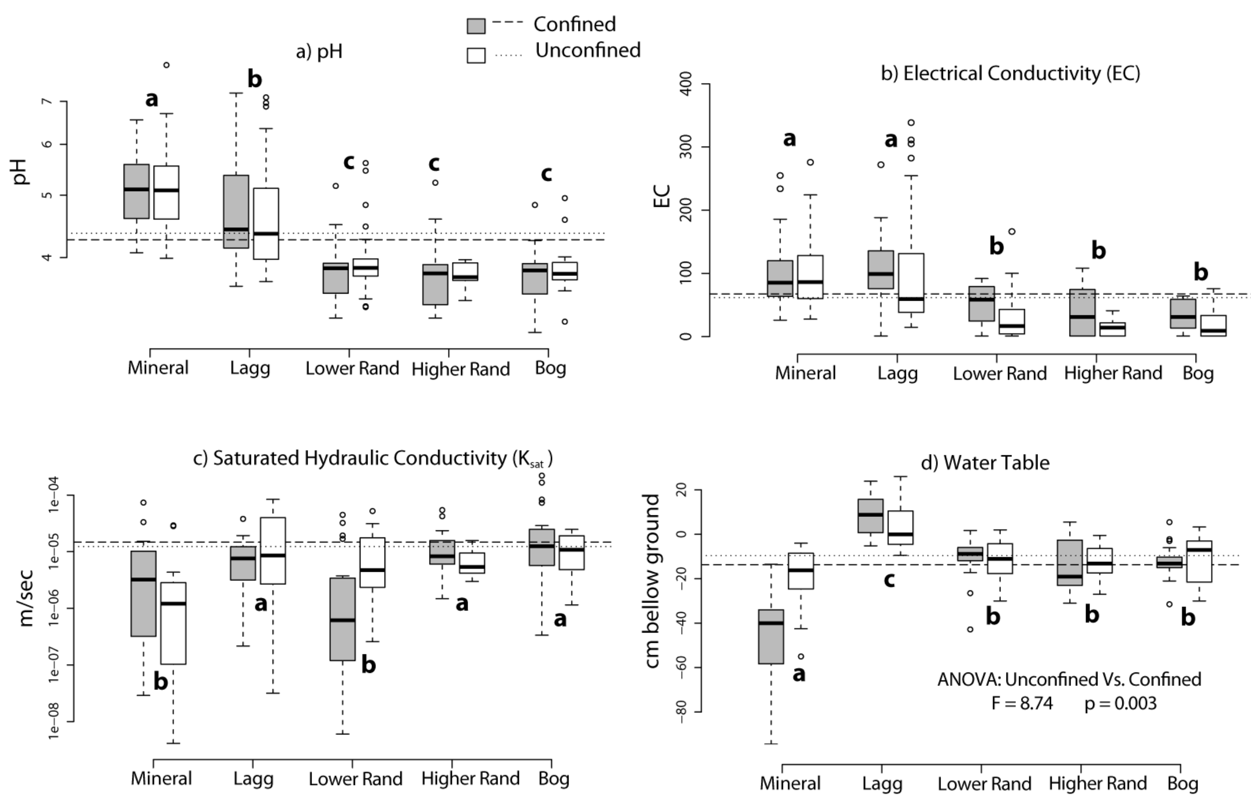



**Figure 2-3** (Left): *Vegetation patterns from running mean (boxplot)*. Examples of moving average of the residual vegetation elevation (vegetation height) (DSM-DEM) where a) a rand-forest developed adjacent to the lagg. b) a rand-forest is found at the edge of the bog dome, and c) vegetation in the rand-slope increases towards the mineral land. Windows size are 4 m, with a 2 m increment (n=40/window).

**Figure 2-4** (Bottom): *Lateral hydro-chemical gradients*. Box and whisker plots of the lateral hydro-chemical gradients. The horizontal line within the box indicates the median, boundaries of the box indicate the 1st and 3rd quartiles, the whiskers indicates maximum and minimum values within 1.5 interquartile range (IQR), and the individual points are values outside 1.5 IQR. ANOVA shows significant differences between at least one of the landscape units for all variables ($p<0.00$). Fisher Least Significant Difference test (LSD), shows that with the exception of saturated hydraulic conductivity ($K_{sat}$), the bog units are not significantly different, but the lagg, bog and mineral land are. For the two transition types, ANOVA shows significant difference only for water table levels ($p=0.003$), which differs (unconfined vs. confined) in both the mineral land and lagg. Dotted lines represent the mean per transition type. Groups with similar letters on the graphs are not significantly different as defined by the LSD test, for variables pooled by landscape units regardless of their geomorphological category.



Seven of the 10 transects developed a rand-forest: 3/7 at the edge of the bog plateau (e.g. Figure 2-3.b), where the hydraulic and topographic gradients are steepening, and 4/7 grew at the lower edge of the rand-slope, adjacent to the lagg (e.g. Figure 2-3.a). In the rand-forest, *Sphagnum* mosses were absent or occurred only where the tree canopy was thinner. For the 3 transects without a rand-forest, the vegetation height gradually increased from the rand-slope towards the mineral forest (Figure 2-3.c). For 5/10 of the transects, the vegetation in the lagg was significantly lower ($p < 0.00$), compared to adjacent landscape units (fall scan). The analysis of the upper 25% of the LiDAR's vegetation returns revealed that the average height changes from 8.8±1.8 m in the mineral forest closest to the lagg, and 6.0±2.1 m on the bog side (often rand-forests) to 2.3±1.6 m in the lagg.

### 2.5.3 Spatial variation in hydrochemical gradients

2.5.3.1 Lateral gradient (from bog to mineral land)

To assess the similarities and differences between the geomorphological categories and landscape units, 4 variables were statistically tested, pH, $EC_{corr}$, water levels (n=90), and hydraulic conductivity ($K_{sat}$) (n=40). ANOVA showed no significant difference between the means of the 2 types of transitions (confined/unconfined, within similar landscape units) for $EC_{corr}$, pH and $K_{sat}$, but did for water table ($p=0.003$), where water levels in the mineral land as well as in the lagg differs between the two transitions types (Figure 2-4. a,d). Topography aside (i.e. when the data were pooled by landscape units regardless of their geomorphological characteristics) there was a significant difference between at least one of the means of the 5 landscape units ($p < 0.00$). LSD (Fisher) tests were therefore performed to investigate the nature of this dissimilarity.

Looking at the lateral gradient (as opposed to vertical; depth within the lagg), values for pH and EC typically decrease from mineral land to lower rand (the first of the 3 ombrotrophic landscape units). Water extracted from mineral soils on average recorded pH of 5.2±0.8; these values were lower in the lagg wells (4.8 ±1.0), and then lower again, but changed little through the rand and bog sections (3.8±0.4) (Figure 2-4.a). Electrical conductivity ($EC_{corr}$) in the mineral terrain (100±56 µS $cm^{-1}$) and lagg wells (108±83 µS $cm^{-1}$) were not statistically different; however they were significantly higher than both the rands (lower: 44±35 µS $cm^{-1}$, higher: 30±32 $cm^{-1}$µS) and bog units (27±24 µS $cm^{-1}$) (Figure 2-4.b).

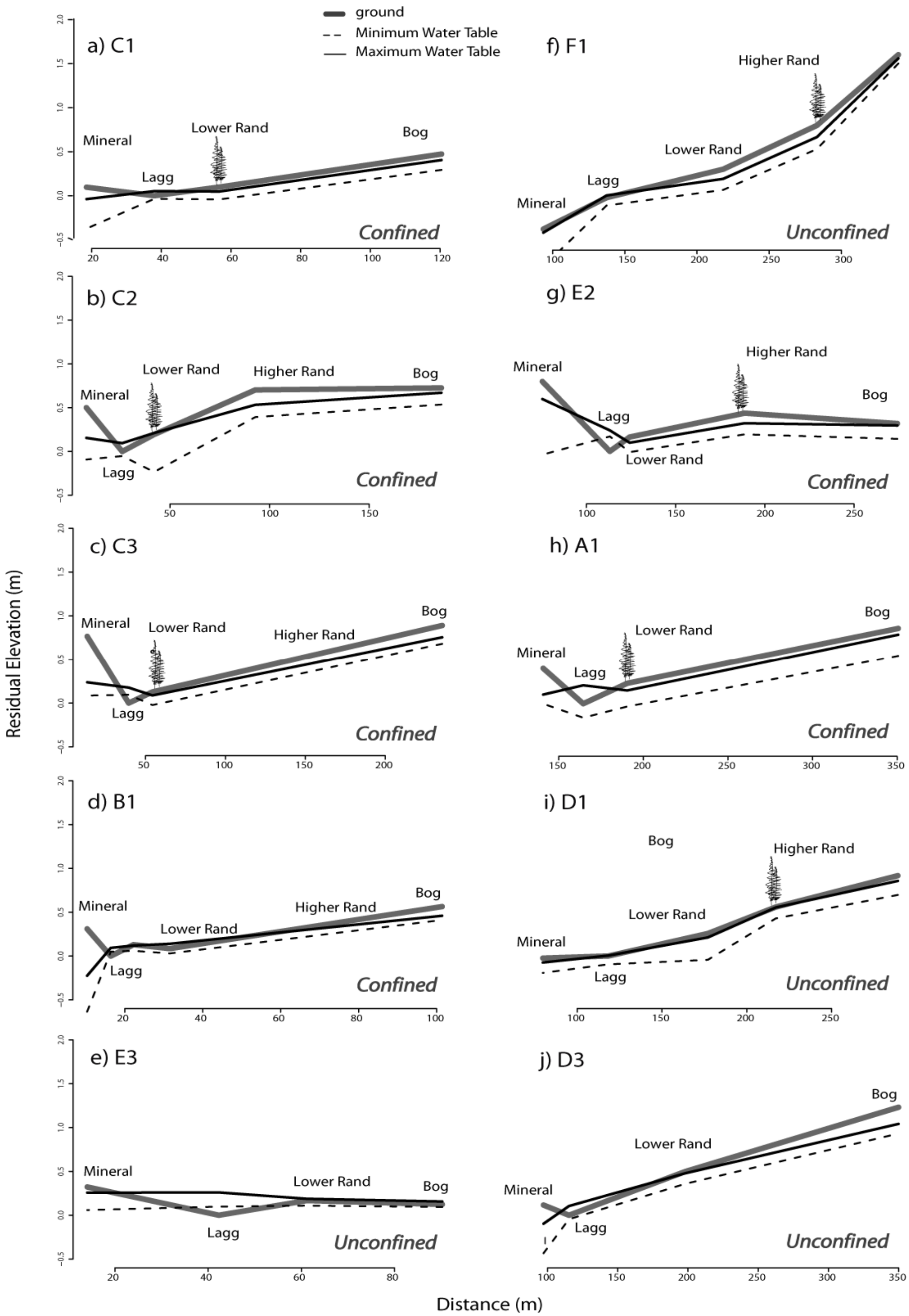



Figure 2-5: *Lateral hydrological gradient*. Ground surface (from DGPS survey), minimum and maximum Water table for each transect. The hydraulic gradient of confined transition generally slopes towards the lagg. At minimum water table, however, it has the tendency to slope away from it. Thus, mean hydraulic gradient does not always follow topography. Sketched trees indicate the location of a rand-forest.

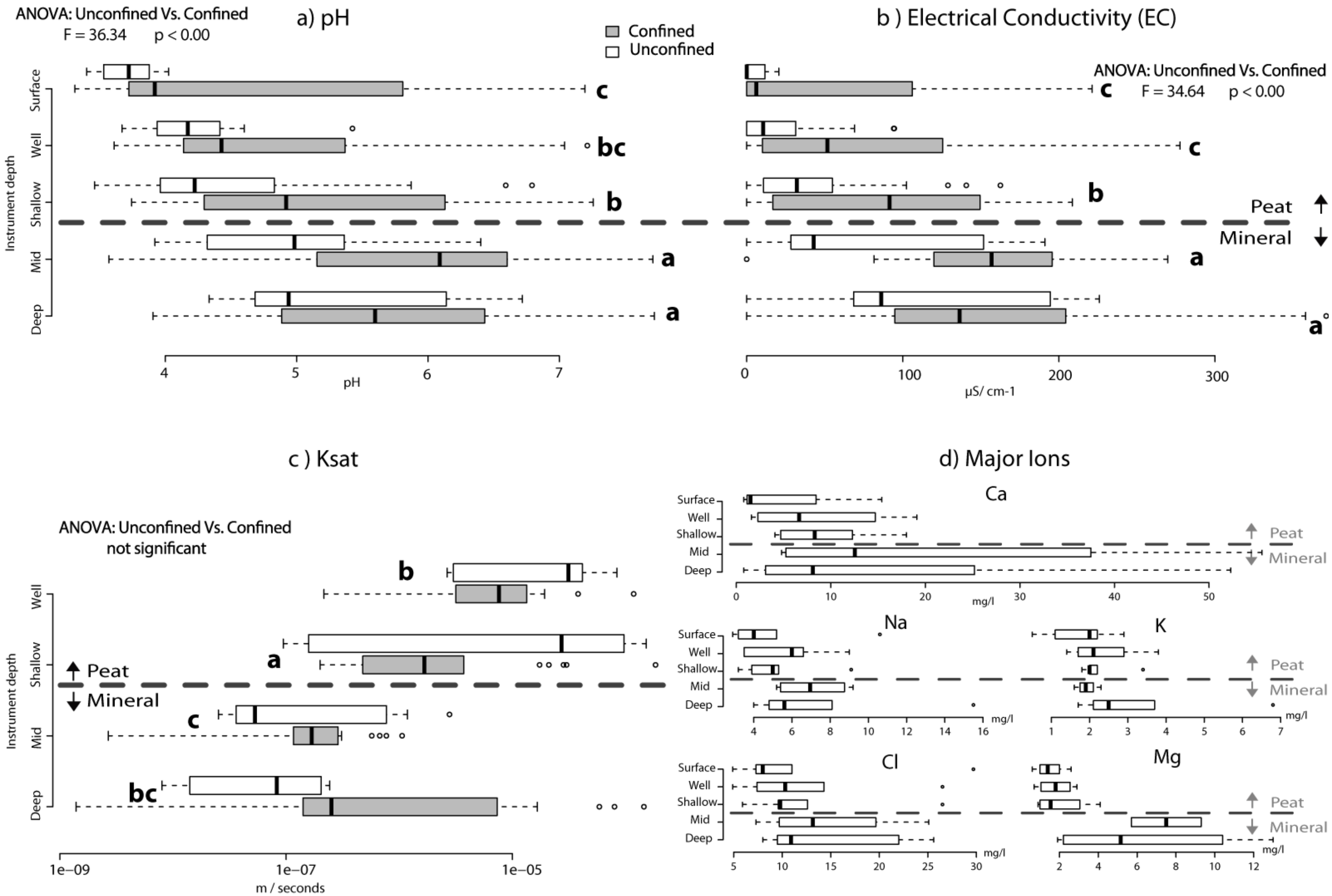



Figure 2-6: *Vertical Hydro-chemical gradients.* Box and whisker plots of the lateral hydro-chemical gradients. The vertical line within the box indicates the median, boundaries of the box indicate the 1st and 3rd quartiles, the whiskers indicates maximum and minimum values within 1.5 interquartile range (IQR), and the individual points are values outside 1.5 IQR. For pH, EC, and $K_{sat}$, ANOVA shows significant differences between at least one of the measurement depth ($p<0.00$). Fisher Least Significant Difference test (LSD), shows that for pH, EC, and $K_{sat}$, there is a significant difference between the surface, organic, and mineral waters. For the two transition types, ANOVA shows significant difference for both pH and EC ($p<0.00$), confined transition having higher values. Lower pH and EC values for the surface waters of the unconfined transitions suggest a stronger influence of the bog water inputs. Groups with similar letters on the graphs are not significantly different. Dotted line indicates the interface between organic (above) and mineral (below) soils. Values in this figure exclude transect D3.

The growing season of 2011 received 42% more precipitation than the 30-year normal (Canadian Climate Normals 1971-2000, Bathurst NB). Precipitation was rather well distributed throughout the season with May being the wettest month (157 mm or 25%) and August being the driest (91 mm or 15%). For each month, a rain event over 40 mm was recorded (Environment Canada meteorological tower at Bas-Caraquet, N.-B. (47°48'08N, 64°50'00W)). Figure 2-5 illustrates the minimum and maximum water table position for each site with respect to the ground surface as measured by the DGPS survey. Water levels were lowest in the mineral sites (-33.6±20.1) and highest in the lagg, with an overall (above ground) average (6.9 ±9.6 cm; Figure 2-4.d). Water table depth for the rands (LR:-10.2±7.5, HR:-13.4±9.9) and bog (-12.0±7.5) were not significantly different from one another (Figure 2-4.d). Hydraulic gradients were usually highest in the rand leading to the lagg. For half of the transects (B1, C1, D1, D3, F1: Figure 2-5), the mean hydraulic gradient was sloping towards the mineral land and away from the lagg. Specific discharge (q), calculated from lower rand to lagg and from mineral land to lagg suggests that on average, water tends to move away from the lagg and towards the mineral land at a highly variable rate (from 10 mm $d^{-1}$(F1) to 0.005 mm $d^{-1}$ (E3)). For 3 out of the 10 transects, however (all confined), the mean mineral hydraulic gradient sloped towards the lagg, resulting in specific discharge (q) for these locations between 2 mm $d^{-1}$ (C2) to 0.16 mm $d^{-1}$ (C3, E2).

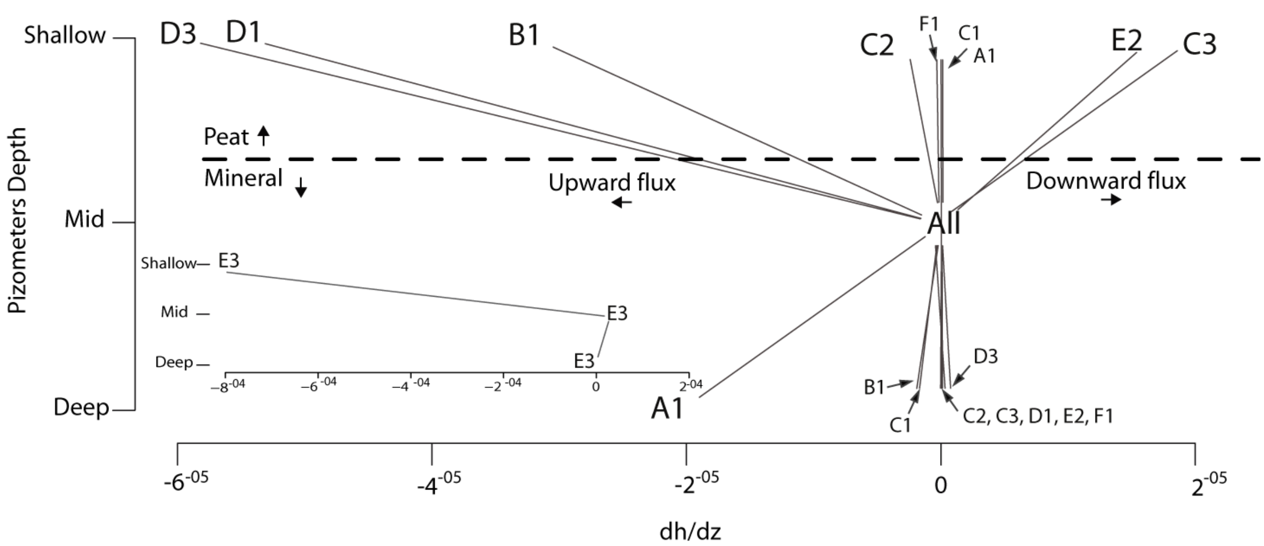



Figure 2-7: *Vertical fluxes within the lagg (n=10).* Values were calculated from higher to lower screen (suspected origin of flow-destination), starting with the wells. Unconfined transitions (D1, D3, E3, and F1) show a tendency towards upward fluxes from the organic peat layer, especially for E3 which is one order of magnitude faster (inset graph). Some confined transitions, however, tend to downward fluxes in the top peat layer, and upward fluxes from the deepest mineral instrument. In all cases, the piezometer at mid-depth (~10 cm below the peat mineral interface), recorded no or very little fluxes. A negative gradient indicates upward flux.

2.5.3.2 Vertical gradient in the lagg (from surface water to mineral soils)

For the lagg vertical gradients, pH and $EC_{corr}$ increased with depth for both confined and unconfined transitions, from 42±67 µS $cm^{-1}$, and 4.5±1.3 pH at the surface to 210±247 µS $cm^{-1}$, and 5.9±1.2 pH for the deeper piezometer (Figure 2-6). One transect (D3) consistently recorded higher than average values, up to 885±397 µS $cm^{-1}$, and 8.0±0.5 pH for the deeper piezometer. Saturated hydraulic conductivity ($K_{sat}$) was typically at its highest in the peat layer (~10 cm above the mineral interface) (Figure 2-6.c) – comparable to that of the bog (Figure 2-4.c), and at its lowest ~10 cm below the mineral interface (mid-depth piezometers). For pH, EC and $K_{sat}$, there was a significant difference between values from the mineral soil (Figure 2-6), and those from the organic soil. Furthermore, ionic composition also increased with depth (Figure 2-6.d). Average concentrations of Ca ranged from from 4.4±4.8 mg/l in the surface waters to 14.7±15.6 mg/l found in the deepest piezometers. Average concentrations of Mg were 1.1±0.7 at the surface to 4.7±3.7 in the deeper instruments (Figure 2-6.d). The respective values for K, Na and Cl were 1.9±1.0 mg/l and 2.5±0.9 mg/l, 5.5±3.6 mg/l and 5.6±1.8 mg/l , and 13.22±11.2 mg/l and 13.5.±8.1 mg/l. The small number of samples collected (n=5/depth) do not allow for a statistical comparison between transition types.

Seven out of 10 of the shallow instruments recorded upward flux (Figure 2-7). For the deeper piezometers, the gradients are much smaller, yet 6/10 showed upwards movements confirming the lagg as a discharge zone, at least periodically. As for the piezometers placed just below the interface (mid), gradients were even smaller, and half the instruments recorded negligible flow. Nevertheless, 3 of the mid-depth piezometers showed a small upward movement. The 2 strongest upward fluxes for the shallow instruments were observed in unconfined transitions (D3 & E3, Figure 2-7). In contrast, downward flux were observed in the shallow piezometers of the two transects with strong mineral slopes (1.9% (C3) - 2.9% (E2) - confined transitions), and a relatively small lateral slope (0.1% (E2)-0.4% (C3)) on the peatland side (Figures 2 & 6).

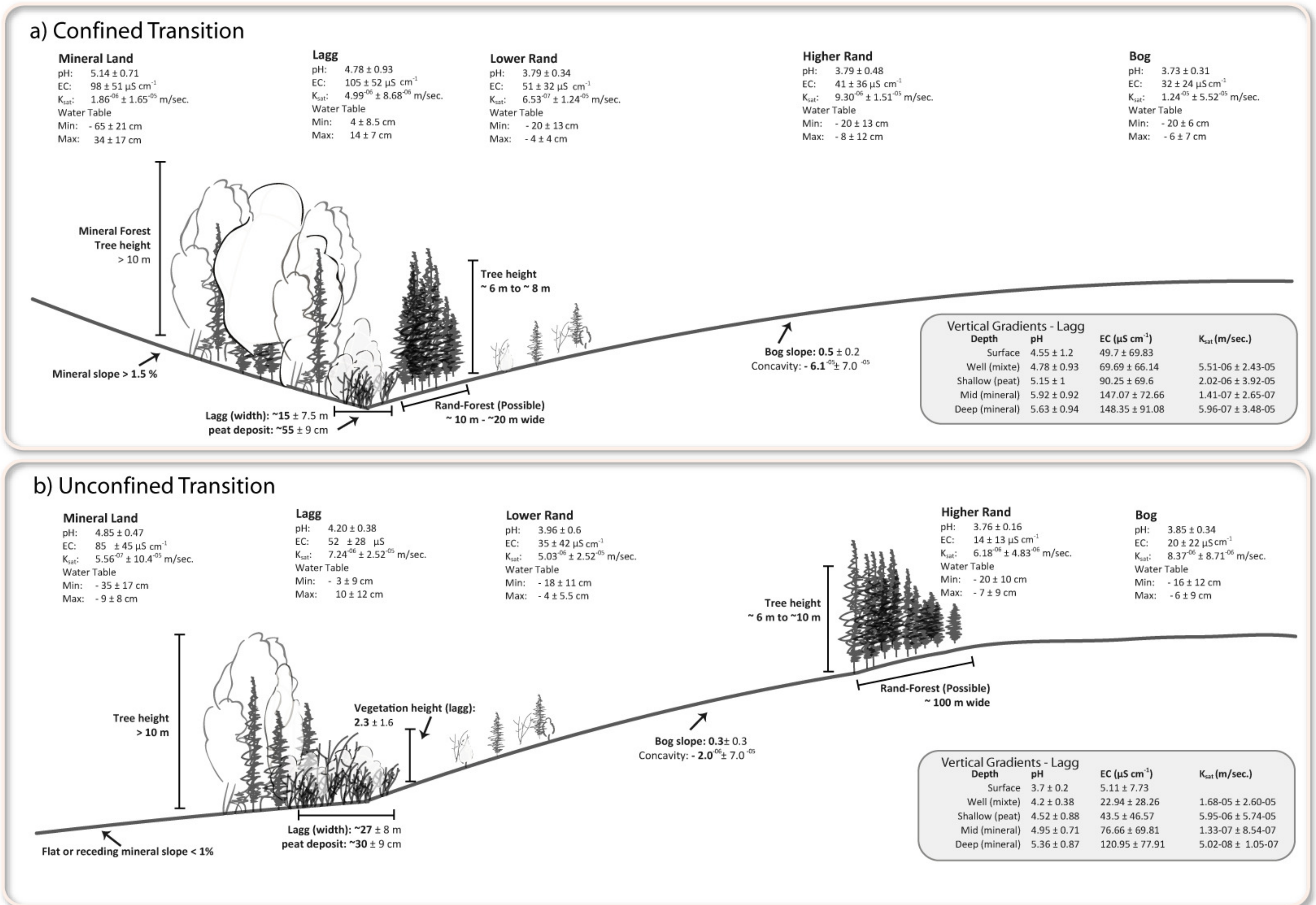



Figure 2-8: *Conceptual Model – Atlantic Provinces.* Landscape units (lateral) and lagg depth with associated hydro-chemical and morphological characteristics for confined (n=6) and unconfined (n=4). Chemical values reported for the unconfined transition exclude transect D3 which recorded unusually high values, unfit for generalisation.

## 2.6 Discussion

### 2.6.1 Major controls: Topography and Hydrology

We identified two main topographic settings (confined and unconfined; Figure 2-8) and three vegetation patterns (rand-forest adjacent to the lagg, rand-forest at the edge of the bog dome, absence of rand-forest; Figure 2-3) for the transition between bog and mineral forest for the Atlantic provinces of Canada. Such morphological differences have been previously mentioned by Whitfield et al. (2006), Howie et al. (2009; 2013) and Morgan-Jones et al. (2005), but without distinguishing their respective hydrochemical and hydrological properties. Although the confined vs. unconfined morphology had little influence over the general chemistry of the transition, it did impact the amount, fluctuation, and ratio of bog/mineral water input to the lagg zone. In confined transition (Figure 2-8.a) the bog met a relatively sharp mineral slope (the upland) and the lagg was found at the local minimum elevation of the transition. Because it was spatially confined between the bog and the mineral terrain, this type of lagg tended to be narrow (~15±8 m), with a substantial peat layer (~55±9 cm), and consistently high water levels (9.0 ± 8.3 cm). This type of lagg was easier to identify as both its vegetation and water levels changed distinctly on each side. In times of high precipitation or at snow melt, water levels in the lagg rose above the local micro-topography, which normally locally traps the water in stagnant puddles, and flowed laterally (parallel to the peatland), creating a lagg stream that removed excess water from the system (cf. Godwin & Conway, 1939). For unconfined transitions (Figure 2-8.b), the bog met a flat or receding slope (sloping away from the lagg), and was not at the local minimum elevation. Because it was not spatially limited in the way confined transitions were, these laggs tended to spread more widely across the landscape (~27 ± 8m), and were difficult to clearly identify on the basis of vegetation patterns. Water levels were lower (3.7 ± 10.7 cm), falling at or below ground level in late summer, and the peat layer was thinner (~30 ± 9 cm). Recognising the lateral extent was most challenging for this type of lagg.

Chemically, we found no significant differences between the 3 landscape units of the bog (bog, higher rand, and lower rand), or between the two types of transition (confined and unconfined, when all landscape units were pooled together). Chemical differences occurred between the mineral land, the lagg, and the bog units, regardless of their geomorphic shape. However, when the remarkably high pH and EC values in the lagg of transect D3 were removed from the analysis, the laggs from confined transitions became significantly ($p < 0.00$) richer in both pH (4.8±0.9 vs. 4.2±0.4) and EC (105±52 $\mu S\ cm^{-1}$, vs. 52±28 $\mu S\ cm^{-1}$) (well instruments; Figure 2-6 & Figure 2-8). Surface water values in the lagg, especially for unconfined transition, were however observed to be comparable to concentration found in the bog units (Figure 2-6), suggesting a stronger influence/proportion of bog water (runoff) than for confined transition. Paradis et al. (2014), measured pH values in the peat of laggs for the same region in New Brunswick to be 4.4, and found no significant differences between the lagg and the bog in terms of EC, and cation concentrations. These low values compares to the ones we have recorded in the pore water of the peat found in unconfined laggs (4.5±0.8), and in the standing water of the confined lagg (4.6±1.2). However, as mentioned above, pore water chemistry rapidly changes with depth in the lagg, and is influenced by nearby topography. In addition to different water chemistry in the lagg, hydrology and vegetation patterns also distinguish the two geomorphological categories, with the confined transition having the tendency to grow a rand-forest adjacent to the lagg while the vegetation heights increased more gradually towards the lagg when the rand-forests were observed closer to the dome (unconfined transitions), or when no rand-forests were observed.

In a raised bog, water moves mostly through the acrotelm from the dome towards the edge of the peatland (Clymo, 1984). Based on two-dimensional groundwater flow and flow sensitivity models, Lapen et al. (2005) suggested that saturated hydraulic conductivity ($K_{sat}$) must be higher at the center of the peatland, but significantly reduced at the margins. This was later confirmed by Baird et al. (2008), and more recently by Lewis et al. (2011). Our results are in accordance with these studies, as $K_{sat}$ recorded at the lower rand location was significantly lower than at the bog and higher rand (Figure 2-4.c). Although we did not measure bulk density, Lewis et al. (2011) reported similar results to correspond with sections of the margin where shallower peat of higher bulk density and shear strength was found. This might be especially pertinent for confined transition, where the lower rand was vegetated by a thick band of black spruce with little to no *Sphagnum*. This shift in vegetation affects the composition of the top layer of peat, which presented hemic properties (moderately to well decomposed), and lower $K_{sat}$ (Figure 2-4.c). When the water draining from the bog and higher rand reaches the lower rand , the reduced $K_{sat}$ at this location helps retain water within the peat resulting in a higher water table (although not significant), slowing the outward movement of bog water to the lagg. As suggested by Price (2003), this could be an important self-preservation mechanism for bogs. However, we observed lower water levels in the rand-slope when a rand-forest grew in the higher rand rather than adjacent to the lagg. Rand-forests occurring at the higher rand, which reduces $K_{sat}$, could favour the retention of water in the more central part of the bog (dome). Baird (2008) suggests this low peripheral $K_{sat}$ to be important to bog development.

In the lagg, we consistently observed a layer of densely compacted soil directly below the peat layer, which had $K_{sat}$ (mid-depth piezometer) significantly lower than that of the overlying peat layer (Figure 2-6.c). Consequently, water moving down the bog through the acrotelm and down the mineral land slope becomes trapped laterally between two landscape units of lower $K_{sat}$, and vertically constrained by a low permeability layer below the peat. We often observed upward water movement from the shallow piezometers, more noticeably for the unconfined transitions (Figure 2-7), which could explain some of those laggs being consistently wet despite the low topography. Without signs of anthropogenic influence, transect D3 (unconfined) showed, in addition to high pH and EC values, the highest values for calcium and magnesium. This specific location also had the most variable water levels of all laggs (33 cm range), and the second most important upward water fluxes from the shallow piezometers. Further investigation of broader regional scale processes is needed to explain the atypical character of this location.

In some cases, the hydraulic gradient on the mineral side of the lagg did not always follow the topography, resulting in some of the confined transitions (B1 and C1) to have a flat or even negative water table gradient (away from the lagg), especially at minimum water table (Figure 2-5). In general, most of the groundwater inflow to the lagg came from the bog. Only 3/10 transects were on average receiving water from both the bog and the mineral land (E2, C2, C3; Figure 2-5). For two of these transects (E2 and C3) the lateral contribution of mineral water input was small (specific discharge: 0.18 mm $d^{-1}$ and 0.16 mm $d^{-1}$, respectively); specific discharge from mineral slopes was about 1% of that measure from bogs. However, at transect C2 (located only 150 m from transect C3) the situation is reversed; the specific discharge from the bog (0.18mm $d^{-1}$) was only 1% of that from the mineral side (2 mm $d^{-1}$). Comparing the 2 locations, transect C2's mineral soils were composed of coarse sand to a depth of ~55cm, and $k_{sat}$ was high ($8.9\text{x}10^{-06}\pm5.2\text{x}10^{-06}$ m $s^{-1}$) whereas C3 was lower ($1.5\text{x}10^{-06} \pm 3.3\text{x}10^{-07}$ m $s^{-1}$). Furthermore, at C2 the low $k_{sat}$ of the peat below the lower rand-forest ($6.3\text{x}10^{-08} \pm 2.6\text{x}10^{-07}$ m $s^{-}$

[1]) reduced the flow of bog water to the lagg. The close proximity of these two transects (C2 and C3) and their contrasting flow dynamics illustrates the potential variability of lagg function within a given peatland. Overall, however, groundwater flows during the measurement period were all relatively low and probably make only a small contribution to the lagg water budget (which we did not measure), albeit a larger contribution to the water chemistry. Flows during the snowmelt period are likely much more important, and strongly influence water levels over the ensuing summer period.

Water levels in the lagg were consistently high. This was especially true for confined transitions, where minimum water table (n=6) was 3.7±8.4 cm generally reached in October, and maximum water table was 13.3±6.0 cm (Figure 2-4). For unconfined transitions (n=4), minimum water table was -3.3±9.0 cm and maximum was 9.9±11.6 cm. Unconfined laggs, where water was "lost" to the mineral side, had a somewhat more variable water table, and were more diverse in their character; some dryer and others wetter and richer despite the low mineral topography. Given the prevalence of ponded water in the laggs, the water table variability was not as great as for an equivalent water storage change in a soil matrix (i.e. where the specific yield is $<< 1$); this increased the overall variability in water table in unconfined laggs (since they were less likely to have ponded water).

### 2.6.2 Landscape units and vegetation height

The motivation behind the documentation of the changes and variation in vegetation height throughout the transition comes from the difficulty to identify and map the location of the lagg around a bog. Howie et al. (2009) theorised that lagg location (prior to disturbance) for Burns Bog could be, based on vegetation height, extracted from historical stereographic photos, but suggested that LiDAR technology might be best for this purpose. If there is indeed a pattern for the recognition of lagg location, it could be extracted and mapped from both traditional and computerized stereography, as well as LiDAR data.

Vegetation height generally increases from the bog plateau through the transition zone to the mineral terrain; we documented three distinct patterns (Figure 2-3). At 4/10 locations, we observed a band of black spruce 10-25 m wide, along the edge of the peatland, adjacent to the lagg (e.g. Figure 2-3.a). These were at the very foot of the rand-slope, and associated with confined transitions and wetter laggs. We observed more prevalent and deeper ponding of water in these lagg (6.6±7.5 cm; e.g. Figure 2-5.a, b, c, and h) than for sites with a rand-forest closer to the bog plateau (-3.0±3.2 cm; e.g. Figure 2-5.f, g, and i). Downslope of these lower rand-forests, the lagg typically supported more minerotrophic vegetation better adapted to regular flooding (e.g. *Alnus incana ssp. rugosa, Ilex mucronata, Viburnum nudum ssp.cassinoides*), or constantly wet conditions (e.g. *Myrica gale, Calamagrostis canadense, Carex aquatilis*). In these cases, there was a clear drop in the vegetation height in the lagg, which makes the boundary between peatland and lagg more distinct and easier to extricate (A1, C1, C2, C3, and D1). The rand-forest that were adjacent to the plateau grew on the steeper part of the rand (slope > 0. 6%), between ~150-200 m from the lagg; trees were generally ~6 m but up to ~10 m high, and occupied a band > 100m wide (e.g. Figure 2-3.b) We associate the rand-forest found in the higher rand with unconfined transition and poorer/dryer lagg. As previously suggested, the lower $K_{sat}$ associated with the peat of this rand-forest retains more water in the dome. Water levels for rand-slope following an upper rand-forest were generally lower than for rand-slopes lacking a rand-forest, or where it was located adjacent to the lagg (Figure 2-5). Damman & Dowhan (1981) also documented a slope forest found in the steepest and best drained part of Western Head bog slope (Nova Scotia). They described this as a shrubby forest, less than 6 m high, found locally in slopes generally over 6%. The data suggest that the low $K_{sat}$ associated with rand-forests is important in retaining water in the domed bog.

## 2.7 Conclusion

There appears to be no one typical lagg. Depending on multiple factors, some of which were studied here, the lagg (and its transition) can take place in one of (at least) two geomorphological categories and three different vegetation patterns, which do not always have clear boundaries. Nevertheless, most laggs studied here shared a few key characteristics; high water levels, water chemistry influenced by both the bog and mineral terrain, and a low-permeability mineral soil layer below a shallow peat deposit. The most important distinction between the laggs related to whether or not they were “confined” by a mineral slope directing flow toward the lagg, or away from it (unconfined). These two geomorphological models are shown in Figure 2-8. The topographic factor was a major control for the formation and function of the lagg, dictating water flow rates and direction, which in turn affects water chemistry and most likely nutrient transport and availability, hence vegetation characteristics. Confined laggs were generally wetter and supported higher pH and EC values than unconfined. Outside of the laggs themselves however, there were no significant differences between the chemistry (pH and EC) of the two geomorphological categories. If water table position for unconfined transition was higher in the mineral terrain and lower in the lagg than for similar landscape units of the confined transitions, it was however comparable for all bog units (lower rand, higher rand, and bog), and all transects studied. Our data suggests that spatial variation within a single peatland may be more significant than between them. Moreover, it must be noted that although some of our sites were not as obviously hosting a lagg (F1) as others (A1), we selected each one based on known lagg characteristics (relatively high water level, transitional vegetation and chemistry), but that laggs were not present (or recognized) at all location along the margin of any given bog. Systematic instrumentation of a single peatland to document the range of margin conditions and functions would shed a clearer picture of the connectivity between bog and mineral land, and the role of laggs as a water conveyance feature.

We agree with Howie et al. (2009) that the changing height of the vegetation approaching the edge of a peatland could be used to predict the presence and perhaps some key characteristics of a lagg. In mineral terrain noticeably sloping towards the peatland, laggs of confined transitions were often (4/6) bordered by a lower rand-forest on the bog side (e.g. A1, C1, C1, C3), which we associate with deeper and more consistent ponding of water. Thus, following the rand-forest (located in the lower-rand), vegetation height is lowered in the lagg, to then rise again in the mineral terrain in a way that could be depicted from LiDAR's vegetation residual elevation returns. In some cases, however (e.g. D3, Figure 2-3c), this shift in vegetation is much more subtle. It is therefore unclear if the vegetation gradient (height) alone is sufficient for the delineation of lagg boundaries. We are currently working on identifying the necessary information and exploring techniques that could detect the edge of the lagg from LiDAR data.

Up to now, the margins of bog peatlands have not been recognized as an integral and essential part of a peatland ecosystem. This research has demonstrated that the features of the transition zone that include the lagg, influence the quantity and variability of water within the peatland, and should be considered as integral part of the peatland complex. The rand-forest was associated with a lower hydraulic conductivity in the peat that plays a role in regulating water outflow from the bog. Until now, the poor understanding of lagg function (actually, of the entire transition zone), has made it difficult for resource managers to defend these relatively small, inconsistent, and often difficult to identify systems, and thus protect them from development. Furthermore, the role of the bog margin, including the lagg, should not be overlooked in peatland restoration projects. Where the lagg of a disturbed peatland has been drained or otherwise compromised, restoration measures should recognize the functions the lagg may have originally performed in sustaining high water tables in the bog, and as a conduit for flow during wet periods. Establishing the hydrological role of this ecotone on the integrity of the peatland as whole is therefore essential not only for the improvement/development of restoration techniques inclusive of bog's margins, but also for resource managers to be able to make informed decision about the impact of projects located within the margin, or in the peripheral areas of bog peatlands.

# Chapter 3

# Exploring LiDAR data for the detection of lagg boundary

## 3.1 Summary

Peatland boundaries are at the base of the decision making process when it comes to their conservation and management. Typically, they are mapped as crisp, absolute feature and the transitional lagg zone – the ecotone found between a raised bog and the surrounding mineral land – is usually overlooked. In this study, we aim 1) to explore the potential of data derived from aerial LiDAR datasets to detect and locate laggs and lagg boundaries, and 2) to consider the spatial distribution of laggs around raised bog peatlands. The delineation capacity of 5 variables was evaluated; topography, vegetation height, topographic wetness index, and spatial frequency of both vegetation and ground LiDAR returns. Looking for dissimilarity (edge-detection, split moving window analysis), we found no one variable to accurately depict both edges of the lagg. Some indicators however, were better at predicting the bog-lagg boundary (i.e. vegetation height), and others at finding the lagg-mineral land boundary (i.e. topography). In contrast, the similarity analysis (cluster, k-means) gave more decisive influence to the topographic wetness index. When the lagg was confined between the bog and the adjacent upland, it took a linear form, parallel to the peatland's edge. However, when the adjacent mineral land was flat or even sloping away, the lagg spatial distribution was discontinuous and intermittent around the bog. Our results suggest that it is possible, at least for confined transition, to predict the lagg's likely location around a raised bog.

## 3.2 Introduction

The location, size, classification and landscape connectivity of a wetland affects its ecological value, and subsequently the decisions made regarding its management (Murphy et al., 2007). In Canada, such spatial information is commonly acquired through the interpretation of remotely sensed data, at a scale allowing for the depiction of wetlands as small as 0.5 ha to 1 ha. In the natural environment, however, boundaries are often indistinct, forming an ecotone where properties of both neighbouring systems can be observed. These zones influence the fluxes and exchanges of material between adjacent ecological systems, promoting diversity and stability (Delcourt & Delcourt, 1992; Fortin et al., 2000). Identifying the location, width and length of transitional zones has been an issue in ecology and cartography (Fortin et al., 2000; Murphy et al., 2007). Traditionally, ecologists have focussed on the characterization of homogenous portions of ecosystems to understand the processes that govern them (Fortin, et al., 2000). In concept, ecotones are scale-independent and can be observed at very coarse (continental/biome), or very fine (ecosystem/population) spatial scales (Fortin, et al., 2000). In remote sensing approaches, problems of scale and data resolution, and the difficulty in representing fuzzy boundaries have often prohibited the identification of these transitional zones, at least at finer spatial scales. Furthermore, gradual changes – as is typically observed in ecotones – are challenging to delimit using either human interpretation (e.g. visual interpretation from stereography), or automated algorithms (e.g. image classification (spectral pattern recognition) from satellite imagery). Consequently, ecotones are often reduced to a one dimensional, crisp boundary between adjacent ecosystems (Fortin, et al., 2000). Assuming that these boundaries are absolute suggests that there are no exchanges, no movement or flow of nutrients and organisms across neighbouring systems; an assumption that is unlikely to hold true in nature (Hansen & Castri, 1992; Buechner, 1987; Stamps et al., 1987; Wiens, 1985).

In the case of raised bog peatlands, this transitional zone is known as the lagg. It can be described as the marginal area that is influenced by both acidic/nutrient depleted waters draining from the bog, and mineral enriched waters from adjacent mineral land. It is characterised by a water table near or above the surface, a shallow peat layer and transitional vegetation and chemistry (Chapter 2; Paradis et al., 2014; Howie et al., 2013). Laggs are highly dependent on local environmental conditions, namely topography and hydrology (see Chapter 2). As a result, they are spatially intermittent, and can take different forms, even around a single peatland. Increasingly, work is being done in trying to identify the best indicators for the delineation of lagg ecotone. Richardson et al. (2010), compared concentrations of methylmercury ($CH_3Hg^+$) with topographic indices derived from airborne LiDAR (Light Detection And Ranging) data to create a lagg width index for sites in southern Ontario and the northern United-States. Paradis et al. (2014) examined the relationship between plant communities and peat depth, using a split-moving window technique to identify lagg boundaries based on the presence/absence of plant species for 20 transects in various regions of New Brunswick. In British Columbia, Howie et al. (2009) hypothesized that vegetation's height increases from bog to lagg and mineral forest, and used historical aerial photography and stereography to hindcast the location of the lagg, and more recently suggested ash content in organic soil as a possible indicator for lagg delineation

(Howie et al., 2013). As for most ecotones, confident delineation of the lagg is a difficult and perhaps subjective task. This is true from a field perspective, making remote detection even more uncertain.

Typically, wetlands are mapped as crisp features (binary membership functions) through the interpretation of remotely sensed data (Murphy et al., 2007). The transitional lagg zone is therefore unaccounted for in current wetland mapping techniques. This is not unexpected as wetland inventories are usually carried out at spatial scales that do not allow for the depiction of smaller features (<0.5 ha) such as the lagg (often from 10-20 m up to 100-150 m wide; see Chapter 2). While the representation of a peatland boundary as a crisp, absolute feature is sufficient at the regional scale, it can become problematic at the local scale, particularly when a system is pressured by encroaching anthropogenic activities, and decisions are made based on boundaries. In Canada, there is no legislation specific to the protection of wetlands. In most provinces, however, a permit is required for any alteration within (i.e. Québec) or in the near vicinity (i.e. New Brunswick; 30 m buffer) of a wetland. Wetland maps, and the boundaries associated with them, are therefore at the base of the decision making process when it comes to their conservation and management. In these cases, a more accurate location of the true peatland complex boundary, including its ecotone, is needed and a field characterization is commonly required. Newer technology, such as airborne LiDAR survey could allow for a more holistic understanding of a site's connectivity to its surrounding, thus helps in the decision-making process.

Previously (Chapter 2), we identified 2 main topographic settings in which laggs of north-eastern New Brunswick can be observed; confined and unconfined. Laggs of confined transitions were easier to identify as both vegetation and water levels changed rapidly on either side. These transitions often had a lower rand-forest – a thick band of black spruce ~ 6 m in height growing within the peatland, parallel to its edge (see Chapter 2) – and the vegetation in the lagg was observed to be lower than both the mineral forest and the adjacent bog (i.e. rand-forest). Laggs of unconfined transition were harder to identify; water levels had a tendency to fall below the ground surface, and gradients in both vegetation height and topography were weak. Nevertheless, Paradis et al. (2014), found the lagg to have a vegetation structure higher in complexity than both its neighbours. Using airborne LiDAR data, it could theoretically be possible to identify potential lagg locations from 1) the residual height of vegetation (above ground) to evaluate the vegetation gradient, 2) the elevation data to evaluate the topographic gradient, 3) the use of wetness indices to identify potential flow accumulation zones, and 4) the spatial frequencies of LiDAR vegetation and ground returns, used as a proxy for the complexity of the vegetation's structure. Our aims are 1) to explore, through techniques of landscape ecology and remote sensing, the potential of information derived from aerial LiDAR datasets to detect and locate laggs and lagg boundaries, and 2) to consider the spatial distribution of laggs around raised bog peatlands.

## 3.3 Study Sites

The ten field transects used for parametrization were located in six different relatively pristine peatlands (sites A to F, see Table 3-1) within the New Brunswick Eastern Lowlands, between the town of Bertrand (47°45'N, 65°03'W), and the eastern limit of Miscou Island (47°59'N, 64°31'W) (Figure 3-1). The eastern lowlands are host to a cool and moist climate, with 4 months below freezing (Canadian Climate Normals 1971-2000, Bathurst N.-B). Mean annual temperature in the region is 4.2±1.2 °C, and mean annual precipitation is 1059 mm (30% as snowfall) (Canadian Climate Normals 1971-2000, Bathurst N.-B). The field transects were divided into 5 landscape units; 1) mineral land, 2) lagg, 3) lower rand (sloping part of the bog closer to the lagg), 4) upper rand (sloping part of the bog closer to the dome), and 5) bog, as described in Chapter 2.

| Site | Northing | Westing | ha | Elevation (MASL) | Peat Depth max (m) | Transect Names | Length (m) | Lagg App. Width (m) | Category |
|---|---|---|---|---|---|---|---|---|---|
| A | 47° 59' 41" | 64° 31' 30" | 619 | 4 | 5 | A1 | 210 | 20 | Confined |
| B | 47° 56' 18" | 64° 32' 41" | 31 | 9.2 | 1.5 | B1 | 104 | 4 | Confined |
| C | 47° 56' 05" | 64° 31' 55" | 1,500 | 8.2 | 5.5 | C1 | 102 | 22 | Confined |
| | | | | | | C2 | 179 | 13 | Confined |
| | | | | | | C3 | 222 | 22 | Confined |
| D | 47° 44' 25" | 64° 45' 08" | 160 | 4 | 2.9 | D1 | 673 | 13 | Unconfined |
| | | | | | | D3 | 550 | 31 | Unconfined |
| E | 47° 45' 58" | 64° 57' 29" | 148 | 19.8 | 4 | E2 | 76 | 9 | Confined |
| | | | | | | E3 | 199 | 29 | Unconfined |
| F | 47° 44' 33" | 64° 03' 21" | 114 | 27.3 | 5.5 | F1 | 246 | 32 | Unconfined |

Table 3-1: *Study sites and transects*. In 2011 6 peatlands (A to F) were instrumented with a total of 10 transects (A1 to F1). Peatland sizes varied between 31 and 1,500 ha, and transect length between 76 to 673 m. The width of each lagg location was measured in the field based on vegetation, peat depth and soil water chemistry. The transitions were placed in two geomorphological categories: Confined (confined between positive slopes on each side) and unconfined (mineral slope is flat, or sloping away from the lagg).

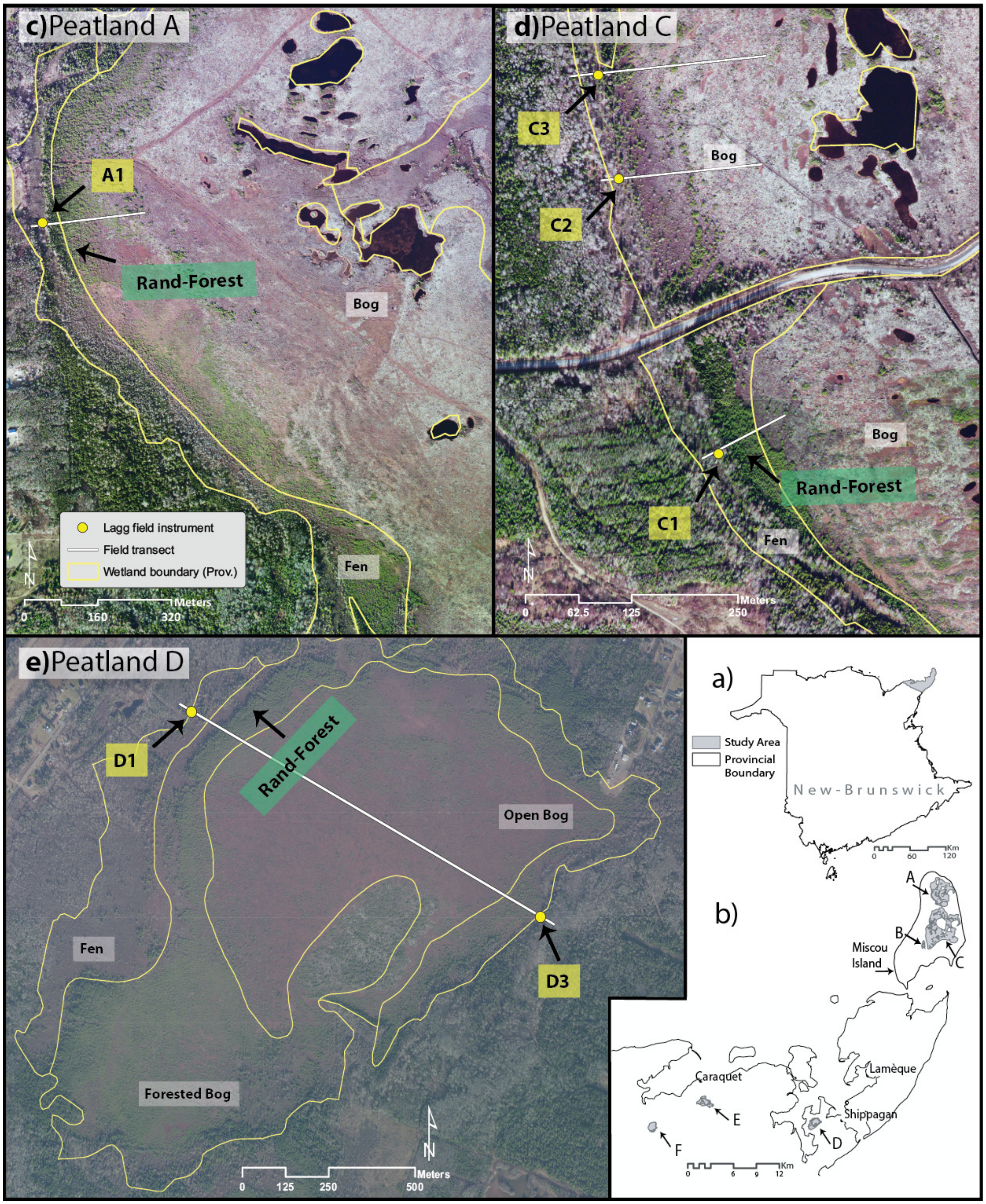



Figure 2-1: *Study sites*. a) All six study sites were situated within the eastern lowlands of north eastern New Brunswick. b) The capital letters indicate each of the individual study sites, located between the town of Bertrand near Caraquet, and eastern limit of Miscou Island. c to e) Aerial photography of respectively, peatland A,C and D. The location of each known lagg location (field) is identified (yellow boxes). The boundaries and classification of each sites as defined by the New Brunswick Department of Natural Resources (NBDNR) is visible (yellow lines). Lagg A1, C1, ad D1 are within the boundaries of the areas classified as fen peatlands.

Sites A, C, and D (see Table 3-1) were used to further evaluate the possibility of identifying potential lagg locations and their spatial distribution through clustering techniques. These three sites were chosen as they hold 6 of the 10 study transects (1 in peatland A, 3 in peatland C, and 2 in peatland D), and are representative of both types of geomorphologic settings (confined and unconfined) as well as the 3 vegetation patterns identified in Chapter 2 (rand-forest located at the higher-rand, lower rand, or the absence of rand-forest).

Peatland A (47° 59' 41"N, 64° 31' 30"W; Figure 3-1.c) is a 619 ha peatland complex, 29 ha of which is classified as fen (in its periphery) by the New Brunswick Department of Natural Resources (NBDNR), in the 2003-2012 photo-cycle wetland classification (data accessed online from http://geonb.snb.ca/geonb/ on 2014-03-05). According to a geological survey carried out on the Eastern lowlands peatlands by the Department of Natural Resources in 1976, maximum peat depth reaches 5 m, and most underlying material is sand, although silt and till is sometimes present. This coastal raised bog is bordered by a relatively sharp mineral slope (~3 %) on the western side and a beach formation to the east. The western lagg of peatland A is confined, with a lower rand-forest separating it from the open part of the bog (Figure 3-1.c)

Peatland C (47° 56' 05"N, 64° 31' 55"W; Figure 3-1.d) is a 1,500 ha coastal raised bog that, similarly to peatland A, is bordered by a relatively sharp mineral slope (from ~2% to ~3 %) to the west and beaches to the east. It is crossed in its center by a local road (15 m wide). The road is parallel to the gradient of interest and it had little apparent effect beyond a few meters (10 -15 m) on each side; the transects (three of them) were located a minimum of 130 m from the road. Maximum peat depth for peatland C is 5.5 m, and the underlying material is mostly sand. This site hosts confined laggs, though the vegetation pattern differs from one transect to the other. The population of Miscou Island – on which Peatland A and C are situated – is rather low, and anthropogenic disturbance are limited to local recreational activities; occasional ATV and snowmobile or cloudberry gathering.

Peatland D (47° 44' 20"N, 64° 45' 17"W; Figure 3-1.e) is a 160 ha open bog hosting two transects; it has ~18 ha at its periphery classified as fen. Peat depth at this site varies between 3 m at its center to 0.3 m near its edge. The underlying material is mostly sand, although clay is more prevalent in some locations. There is ~2.5 m of vertical drop between the highest point and the surrounding mineral terrain, which is generally flat or slopping away from the bog. It is an asymmetrical convex domed bog for which the higher elevation (the dome) is located nearest its south-east boundary. Consequently, the slope on the north-western side of the dome is much more gradual than on the south-east side. This gives rise to different vegetation patterns, where tree heights increases steadily from the dome to the lagg on the eastern side, whereas a rand-forest grows at the higher-rand of the western side (Figure 3-1.e). Peatland D is located near the town of Shippagan, but apart from one non-commercial terrain (tool shed), development has been kept at a minimum of 260 m from its edge. As it was the case for peatland A and C, the anthropogenic influence in peatland D is limited to recreational activities.

## 3.4 Methods

In Chapter 2, we characterized 10 transects (within 6 peatlands; A to F) from bog to mineral land in terms of their general hydrology, hydro-chemistry, topography and vegetation patterns. During the growing season of 2011, peatlands A to F were visited weekly to collect data on water table, saturated hydraulic conductivity ($K_{sat}$), pH, electrical conductivity (EC), and water samples for determination of major ions (Chapter 2). These field surveys familiarized us with the ground setting, the spatial distribution of vegetation and the changing characteristics of each site throughout the growing season. The 10 transects cover lagg transitions ranging from wet and well defined, to drier and more diffuse, and were identified based on peat depth, transitional vegetation, ponding or near-surface water table, and surface water chemistry (see Chapter 2). During the fall visit (late October), we took advantage of the thinner canopy to perform a DGPS (Differential Digital Positioning System) survey of the landscape units. The system used was a Leica Viva GNSS (Global Navigation Satellite System) with a sub-centimeter vertical accuracy in conjunction with Real Time Kinematic (RTK) satellite navigation, placed over a datum tied to the Provincial High Precision Network (HPN).

We used data derived from the LiDAR survey for the above-mentioned transects to evaluate the most suitable information for the detection and localisation of the lagg. First, we analysed, in cross section, the 10 transects characterized in the field for dissimilarity with a split-moving window edge detection technique (Cornelius & Reynolds 1991). Second, we looked for similarity in the gridded data (a 2 dimensional study zone was considered, as opposed to a 1 dimensional cross-section) for site A, C, and D using a k-means clustering techniques (Rubin, 1967).

### 3.4.1 LiDAR derived raster grid

The LiDAR dataset was made available by the New Brunswick's Department of Natural Resources (NBDNR). The survey was conducted by Leading Edge Geomatic Ltd., and carried out in the fall of 2009 (November 4th) at an altitude of 1,600 m, with an Optech 3100 ALTM laser sensor. Following the American Society for Photogrammetry and Remote Sensing (ASPRS) guidelines (Maune, 2007), the provider calculated the vertical accuracy to be ±0.15 m, and the horizontal ±0.8 m (95% confidence). Prior to delivery, the data were classified into ground, low-vegetation, mid-vegetation, and high-vegetation (4 returns). After delivery, the data were manually verified for miss-classification; points were reclassified or removed when required. The point density across all sites varied between 0.6 to 1.2 points per $m^2$, allowing for the creation of 1x1 m Digital Elevation Models (DEM's; ground elevation) and Digital Surface Models (DSM's; vegetation height). Considering the high density of the data, a simple Inverse Distance Weighted (IDW) method was preferred for the interpolation of the gridded surfaces from the LiDAR data points. The Geostatistical Analyst in ArcGIS 10.1 was used to optimize the choice of neighbours, aiming for a low Root-Mean-Square-Error (RMSE); a minimum of 4 and a maximum of 6 neighbours were used.

The average RMSE for all sites is 0.14±0.07 m for the DEMs and 0.19±0.24 m for the DSMs. These surfaces were used to derive a third raster grid of the vegetation's residual elevations (VRH = DSM - DEM). The open source GIS software SAGA was used to derive a fourth surface of a topographic wetness index (TWI), which is a representation of the tendency of a cell to produce runoff, or to become saturated, based on catchment area (contributing upslope area for each cell) (Cimmery, 2010). In low relief environments such as the lowland raised bogs, catchment algorithms have the tendency to create random-like flow patterns, which then diminishes the predictive ability of secondary indices such as the TWI (Böhner & Selige, 2006). The SAGA TWI, however, is based on a modified calculation of the catchment area, which assumes rather homogenous hydrological conditions in these flatter areas (Böhner & Selige, 2006). The fifth surface was a simple count per $m^2$ of the frequencies of the vegetation returns, and similarly the sixth surface was a count of the frequencies of the ground returns. The last 2 surfaces were created with the intention to evaluate the possibility of identifying potential lagg location based on the complexity of the vegetation's structure often found in the lagg (Paradis et al., 2014); areas with a more complex vegetation structure would equate to higher vegetation return frequency.

### 3.4.2 Data Analysis

For each transect, data were extracted from the above mentioned grids in 20 m buffer strips and a Split Moving Window Dissimilarity Analysis (Cornelius & Reynolds 1991) was used to examine the different gradients between bog and mineral land. We evaluated the delineation capacity of 5 variables derived from airborne LiDAR; 1) the digital elevation model (DEM) (topography), 2) vegetation residual height (VRH), 3) topographic wetness Index (TWI), 4) spatial frequency of vegetation returns (VSF), and 5) spatial frequency of ground returns (GSF). Based on the lagg location identified in the field, each indicator was evaluated in its capacity to find 1) the mineral land – lagg boundary, 2) the lagg-bog boundary, or 3) to accurately position the lagg's center location. During field reconnaissance, we measured some laggs to be no wider than ~15 m (Table 3-1); we thus chose the window size (length along the transect) for the analysis to be 10 m, 20 m, and 30 m. Window lengths smaller than 10 m were too sensitive (false edges), and the edges revealed by windows larger than 30 m, were not accurate in positioning the lagg based on its field identification. The squared differences between the mean of each adjacent window (Squared-Euclidean Distance; SED) was graphed for all variables and scales (n = 400 for 10 m windows, n = 800 for 20 m, n = 1,200 for 30 m) (Figure 3-2). With the Cornelius & Reynolds (1991) method, peaks with maximum values indicate locations of maximum dissimilarity within the data, and should be interpreted as edges, or boundaries. Values lying 3 standard deviations above the mean were considered as significant. Considering the 3 possible boundaries (bog-lagg, mineral-lagg, and center location), the 3 scales of analysis (10 m, 20 m, and 30 m), and the 5 variables studied (as mentioned above), the total potential number of edges is 45 for each transect, and 450 for all 10 of them. R statistical software was used for the split moving window analysis (http://cran.r-project.org).

Five clustering exercises were performed for peatland A, C, and D; 1) using the vegetation's residual elevation grid (VRH), 2) the Digital Elevation Model (DEM), 3) the SAGA topographic wetness index (TWI), 4) a combination of the VRH+TWI, and lastly 5) a combination of the VRH+TWI+DEM. In contrast to edge detection (dissimilarity), cluster analysis seeks clusters of data points (or raster grid cells in this case) with similar characteristics, based on either one (i.e. VRH, DEM, or TWI) or multiple variables (i.e. VRH+TWI and VRH+TWI+DEM). This "step-by-step" approach had 2 major advantages, 1) it allows for the visualisation of the influence of each variable on the overall results, and 2) clusters that remain unchanged throughout several analyses (e.g. DEM,VRH,and TWI) could be viewed as robust, less sensitive to small change in the input data. The k-means hill-climbing algorithm (Rubin, 1967) available in SAGA GIS was chosen for its accessibility (open source, ready to be used), its stronger sensitivity to local structure (to minimize spatial aggregation of the lagg itself), and for its computational efficiency. The k-means algorithm aims to find a user-defined number of non-overlapping (strict partitioning) k clusters (Wu, 2012). The initial centroids (the mean of each k cluster) are arbitrary, and each point in the dataset is assigned to the nearest centroid. When all data points are given a centroid, each collection of points belonging to a same centroid becomes a cluster. At each pass (iteration), the means of the centroids are updated to reflect the new composition of the clusters. This process is repeated until the clusters are stable, and the data points no longer switch between them (Wu, 2012). Choosing the number of k clusters for this type of analysis is somewhat subjective, and a good understanding of the data to be analysed is recommended (Wu, 2012). Nevertheless, techniques have been developed to remedy this issue. In this paper, the number of clusters was optimized with the Caliński-Harabasz (1974) index. This partitioning technique is analogous to the F-statistics, and aims to minimize the within group variance (Caliński & Harabasz, 1974). The optimization tests were run for clusters composed of VRH+TWI+DEM. R statistical software was used for the cluster optimisations using the *cascadeKM* function in the *cclust* package. The clustering was carried out in SAGA GIS 2.1.0 (Imagery – Classification / Cluster Analysis for Grid).

The vegetation and ground returns spatial frequencies surfaces (VSF & GSF) were excluded from the cluster analysis. This data is only useful when considered at very large cartographic scale (small area) as was the case for the moving window analysis. To be compared, the spatial frequency data must be from non-overlapping flight paths (no duplication), and scanned at relatively similar angle (scanning angles affects beam penetration). This condition is reachable for transect analysis (scanning angle ranged ±1°), but not for larger areas (±20°), and was therefore removed from the clustering exercise.

# 3.5 Results & Discussion

### 3.5.1 Edge detection – Dissimilarity Analysis

The edges (peaks) were classified as "primary" and "secondary". Primary indicators were those that appeared to be most reliable; more stable (found at more than 1 scale, i.e. 10 m, 20 m or 30 m) and/or had strong peak(s) (sharp and rising far above 3 standard deviations (*SD*), or softer but with a lengthier portion above the 3 *SD* mark; see Figure 3.2). As for secondary edge indicators, they were either 1) observed at only one scale (unstable) or only slightly above the 3 *SD* mark, or 2) were not as clearly depicting the edges as another indicator (identified as primary) for the same boundary, and rather acted as supporting/secondary indicator. It was not our intention to quantify the success of the variables at finding other landscape units' boundaries (i.e. rand-forest), therefore only the peaks roughly matching the field identified lagg boundaries were quantified. The edge detection exercise was carried out for all 10 transects; an example of the output is shown for peatland A (Figure 3-2).

Peatland A's lagg was measured (in the field) to be ~20 m wide, which corresponds to the approximate length of the dip in the vegetation at the location of the actual lagg (Figure 3-2.a). The results from the dissimilarity analysis show a strong response for the VRH (10 m window) on both sides of the lagg zone, and the absence of dissimilarity (no peak) signify a rather homogenous vegetation height between them, in the most central part of the lagg (Figure 3-2.b). The steeper part of the mineral slope results in a long edge (DEM), and although its position is slightly offset compared to the actual lagg, the fact that it is consistent at all scales makes it a primary edge for the mineral boundary (Figure 3-2.c). The TWI is analogous to the DEM for the mineral boundary (Figure 3-2), yet was considered as secondary (not as consistent as the DEM). In this study, when two closely related variables (i.e. TWI is derived from DEM; or VSF & GSF – which nearly mirror one another) found and positioned a

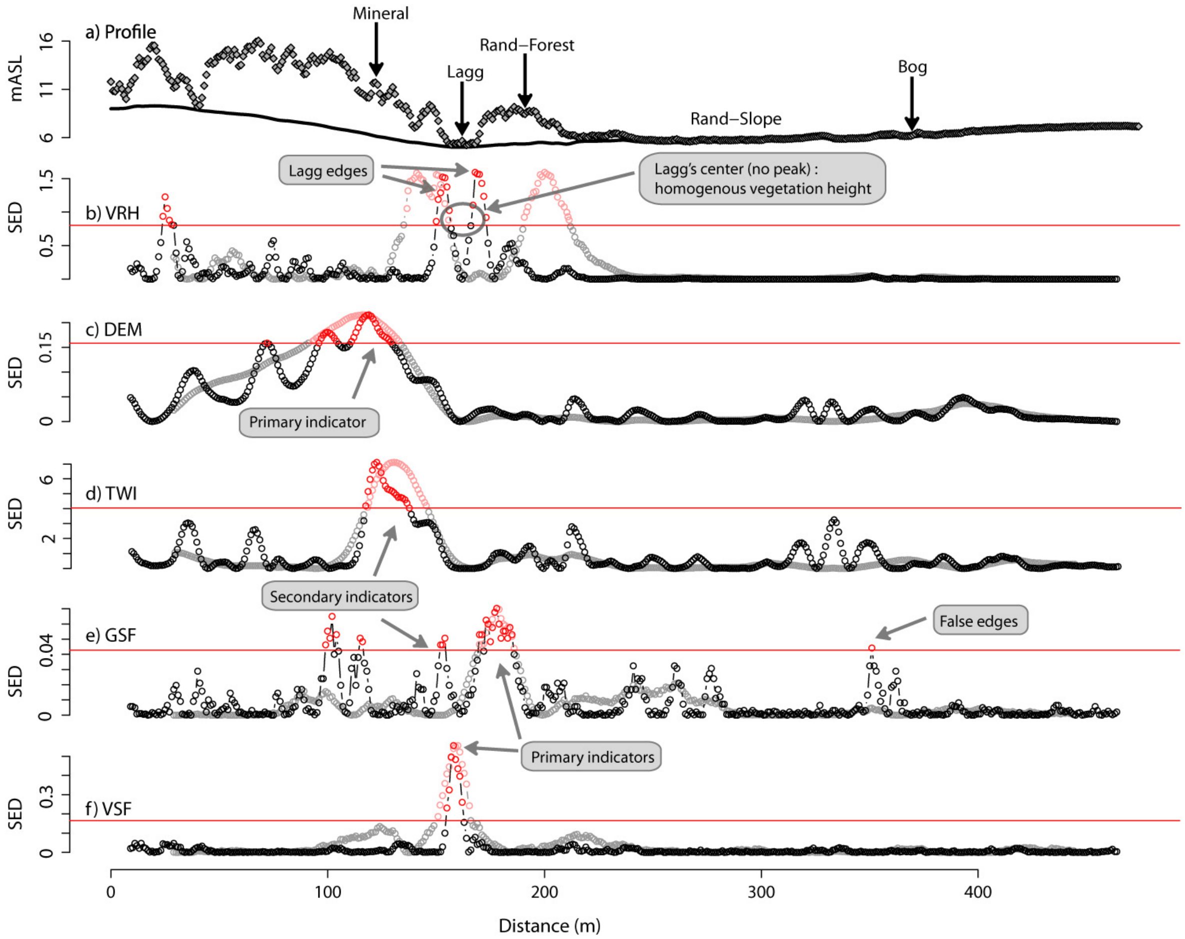



Figure 3-2: *Example results from peatland's A dissimilarity analysis.* The profile graph (a) is a cross-section representing, for peatland A, the LiDAR returns classified as vegetation and ground in meters above sea level (MASL). Graphs b to f are examples of dissimilarity (edge-detection) analysis. Sharp peaks indicate points of high dissimilarity, while results closest to zero shows zones of homogeneity. The x-axis represent the distance along the transect in meters, and the y-axis is the Square-Euclidean Distance (SED) between the means of adjacent windows. Two scales of analysis are visible, 10 m window (opaque), and 30 m window (faded).

boundary in a similar manner (analogous peaks as it is the case for DEM & TWI for the transect of lagg A1, Figure 3-2), only the most effective edge was considered as primary. The intention was to not overestimate the importance of secondary (derived) indices such as the TWI; if a secondary index adds no new information to the edge detection exercise, the creation (and analysis) of this index could become redundant. Although not quantified, the rand-forest is evident in the GSF response (Figure 3-2.e); the laser beam being intercepted by the thick vegetation does not reach the ground as frequently as it does in both its neighbours (the bog and the lagg). Finally, the VSF indicator found a strong edge (rising high and constant at all scale) in the center of the actual lagg (Figure 3-2.f). The effect that window size can have on the depiction and positioning of an edge is most visible in Figure 3-2.b (VRH); being larger than the lagg itself, the 30 m window fails to notice the clear shift in vegetation height approaching the lagg, while the 10 m window successfully position the boundaries on either side.  The interpretation for this and the other sites is summarized in Figure 3-3.

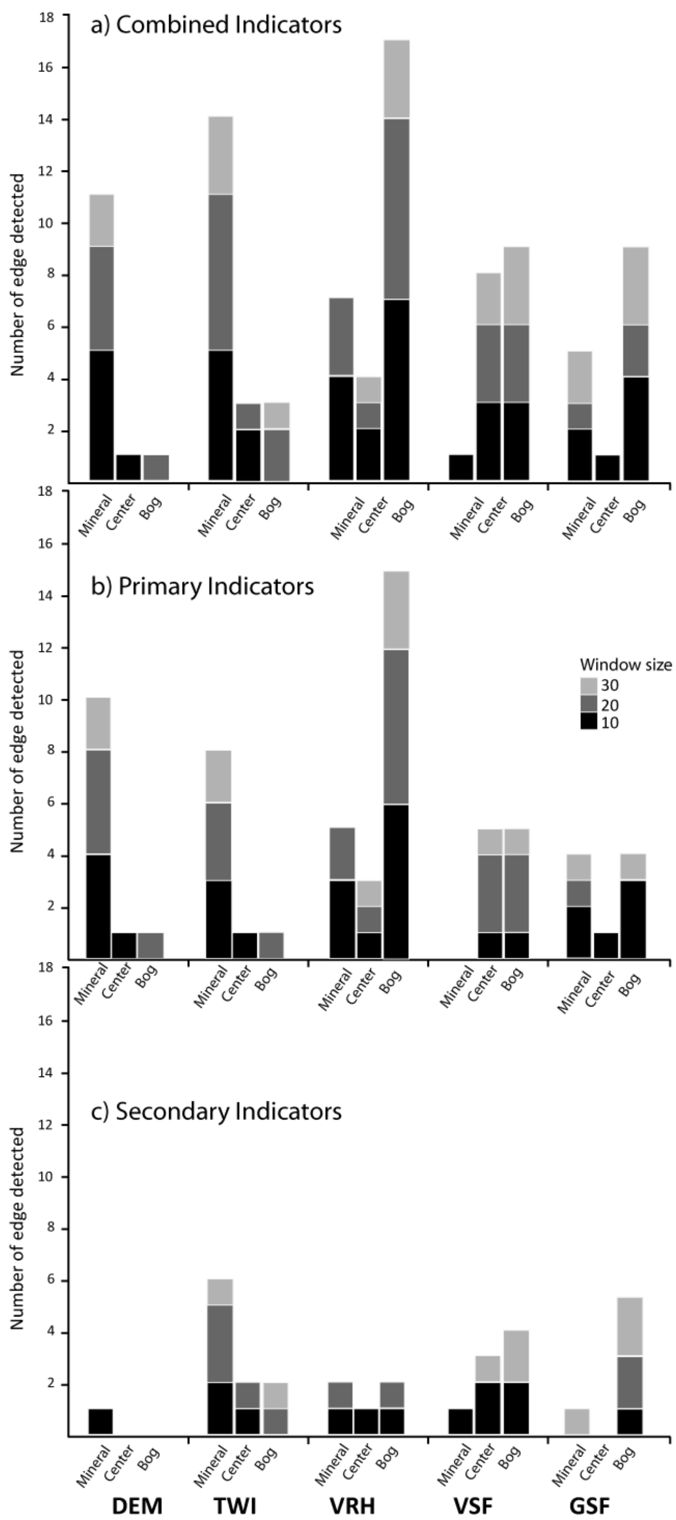



Figure 3-3: *Summary of the dissimilarity analysis*.  From left to right: Digital Elevation Model (DEM), Topographic Wetness Index (TWI), Vegetation Residual Height (VRH), spatial frequency of vegetation (VSF) and ground returns (GSF). Topographic indices (DEM &TWI) are effective at finding the mineral – lagg boundary while vegetation indicators (VRH & VSF) give best results for the bog-lagg boundary.

Out of the 450 potential edges (all indicators and scales combined), 94 edges (peaks) were identified for the 10 transects: 64 as primary and 30 as secondary (Figure 3-3). The most effective combined (primary + secondary) indicator was VRH, which found 28 of all 94 identified edges, closely followed by TWI with 20/94 (Figure 3-3.a). Looking at the 64 primary edge indicators, VRH was again the most successful (23/64) while DEM came second (12/64) (Figure 3-3.b). For the 30 secondary edge indicators, TWI was most effective finding 10/30 (Figure 3-3.c). The 10 m window found 40/94 edges, and was the preferred window size of analysis for both primary and secondary indicators. The 30 m window analysis, however, had slightly better results than smaller windows for the depiction of secondary edges (see Figure 3-3). The variables were not equally effective at depicting the three different boundaries (on the bog or mineral side, or the central location of the lagg). Although we found no one variable (or ensemble of variables) to accurately and consistently depict either edges of the lagg (or its center location), some appeared to be better predictors.

VRH is a good indicator of the bog-lagg boundary. When the lagg is found adjacent to a lower rand-forest - a thick band of black spruces ~ 6 m in height (see Chapter 2) – as it is most common for confined transitions , the vegetation is significantly lower in the lagg in comparison to its surrounding (Chapter 2), making the graphed edges clear and distinctive (Figure 3-2.b). In contrast, the vegetation found in unconfined transitions has a tendency to rise more gradually from bog to mineral land, often leaving the interpretation of the boundary more subjective. In these later cases, other variables such as the vegetation returns spatial frequency (VSF) - a proxy for the vegetation structure complexity - can be inspected. In this study, the VSF was more responsive for unconfined transition than it was for confined transition. All scales combined, VSF was successful at finding 4/4 bog-lagg boundaries, and 3/4 center locations for the unconfined transitions, but only 1/6 bog-lagg and 1/6 center lagg locations for the confined transitions. Perhaps this is a reflection of the more complex vegetation structure found in unconfined laggs, where less frequent flooding and shallower peat (Chapter 2) promotes the growth of both a prominent shrubby strata and taller vegetation (Paradis et al., 2014) compared to wetter confined transitions. The topographic indicators (DEM & TWI) had little success for this boundary. Issues of scale might explain this surprisingly poor success. The laggs of confined transition – where the topographic indices could be expected to be most defining - are usually narrow (15±7.5 m, see Chapter 2), thus better depicted by small windows. Conversely, the topographic indices are rather subtle on the bog side, thus often visible through larger windows. Yet larger window sizes (as large as, or larger than the feature of interest: the lagg) will misposition the lagg boundary (if depicted at all) resulting in edges many meters away from the actual lagg boundary, and therefore were not quantified in the present study. In addition, the statistical significance of the peaks (edges) is relative to the entire transect data for that variable, meaning that large variation at one end of a transect might overpower smaller variation elsewhere (peaks below the 3 *SD* mark). Considering that we measured the average bog slope to be 0.4±0.3% compared to 1.8±2.2% on the mineral side (see Chapter 2), the greater mineral slope generally overpowers the smaller gradient on the bog side. This translates in a greater success of the topographic indices at finding the mineral – lagg boundary, especially for laggs of confined transition where the steeper part of the mineral slope results in a long – and strong – edge (DEM) (e.g. Figure 3-2.c). The dissimilarity analysis had very poor success in positioning the central location of the lagg; only the VSF indicator had moderate success (Figure 3-3).

Simply put, the dissimilarity analysis shows varied potential not only for the 5 variables studied, but also for the 3 scales of analysis; the different window sizes influence the type of edges found. The 10 m window tended to give sharper edges that were usually more accurate in terms of positioning the lagg in comparison to its field identification. These were most appropriate when the gradients were steep, as it is the case for confined transitions. For very gradual transitions however, larger windows were more successful at predicting changes that were spread out over larger distances, and reflecting smaller gradients such as the one observed in unconfined transitions. With this edge detection technique, small windows are more successful at finding abrupt changes, and larger windows at gradual changes.

### 3.5.2 Spatial distribution of the lagg – Similarity (Cluster) analysis

The 5 similarity (cluster) analyses carried out for peatland A, C, & D (VRH, DEM, TWI, VRH+TWI, and VRH+TWI+DEM) allowed for the gradual exploration of the influence of each variable on the final cluster analysis (VRH+DEM+TWI).

We found the lagg of peatland A to be the easiest to delineate (Figure 3-4.a). Near the field instrument location, this lagg is enclosed between two zones of higher vegetation; from 0.11±0.17 in the lagg (Figure 3-4.b, cluster 1) to 4.3±0.69 in the adjacent zones (Figure 3-4.b, cluster 3). As mentioned previously, the width of this lagg was measured in the field to be ~20 m (at the field instrument location; Table 3-1), corresponding to a dip in the vegetation (Figure 3-2.a). At that same location, the DEM analysis places the lagg in a ~35 m wide zone of lower elevation (Figure 3-4.c, cluster 2), with a mean elevation 1.1 m lower than that of the surrounding cluster. As for the TWI analysis, it positions the lagg in a ~30 m wide zone of higher wetness (Figure 3-4.d). South of the field transect, however, there is no zone of taller vegetation (rand-forest) between the lagg and the bog and the topographic indices (DEM and TWI) indicate a widening of the zone of low elevation (Figure 3-4.c; cluster 2), and high wetness (Figure 3-4.d; cluster 1). This same pattern is observable in the final analysis where the cluster associated with the lagg follows topography on the bog side, and a mixture of vegetation height and wetness on the mineral land side, forming a clear and continuous potential lagg zone (Figure 3-4.a; cluster 1). In the final analysis, the limits of the lagg cluster around the field instrument are ~ 20 m apart, which matches very closely the field identified lagg boundary.

Similar observations were made for peatland C (Figure 3-5). In the VRH analysis, the 3 lagg locations average low vegetation height, from 0±0.18 m to 0.9±0.3 m (Figure 3-5.b). In terms of elevation, in all 3 cases the lagg is located at lower elevation than its surrounding, although lagg C2 is found in a cluster averaging higher elevation (cluster 5; 8.4±0.1 MASL) than lagg C1 and C3 (cluster 4; 7.9±0.2 MASL). The wetness index is the most spatially defining variable; it is the only indicator that defines one single, continuous cluster that is common to all 3 field identified lagg locations (Figure 3-5.d; cluster 2). In fact, the main difference between peatland A and C's final results lies in the spatial continuity of the identified lagg cluster; thick and well define for peatland A (Figure 3-4.a; cluster 1), and although clearly following a similar linear trend parallel to the peatland border's, thinner and somewhat irregular for site C. Nevertheless, when compared to the lagg width measured in the field, the cluster's estimated width is ±3 m.

For these two confined sites (A & C), the lagg locations identified in the field clearly match clusters of higher wetness and lower elevation, and form a linear band running parallel to the edge of the peatland (Figure 3-4 & 3-5). In the periphery of the identified lagg clusters, a combination of decreasing wetness values and rising ground elevation and vegetation height seems to indicate the boundaries of the laggs, where the lowered water level allows for the growth of trees (i.e. rand-forest). These sites most resembled the “moat-like” lagg described by Damman &Dowhan (1981), and in other literature (Vitt and Slack, 1975; Rebertus 1986; Gignac et Vitt, 1990), as they are found at the lowest (in elevation) part of the transition, and are characterized by above ground water levels (see Chapter 2).

There were very little differences between the results of the VRH+TWI (data not shown) and the VRH+DEM+TWI analyses for peatland A. This is a reflection of the stronger topographic gradient at this site (3% mineral slope & 0.7% bog slope, see Chapter 2) which prevails over smaller landscape variations (i.e. microtopography), greatly reducing their impact on the TWI’s results. The VRH+DEM+TWI analysis comprises 3 gridded surfaces of equal importance (weight). In the case of peatland A, the TWI and DEM show a very similar spatial distribution of the lagg clusters (Figure 3-4.c & 3-4.d), and reinforce each other (as opposed to being discriminant), thus giving more weight (in the final analysis) to the similar lagg pattern they exhibit. At peatland C however, the gradients are slightly weaker (2% mineral slope & 0.4% bog slope; see Chapter 2), and the DEM and TWI surfaces provide complementary yet different information to the final clustering exercise (Figure 3-5.c & 3-5.d). In this case, adding the DEM surface to the final analysis becomes helpful (more so than for peatland A) in defining a more spatially continuous lagg cluster.

For peatland D the spatial distribution of the unconfined lagg is less instinctive, and resembles more a patchwork of discontinuous potential zones (Figure 3-6.a). As mentioned previously, the mineral terrain bordering this site is generally flat, or slopping away from the lagg. This is observable in the DEM analysis, which places one single cluster of highest elevation in the center of the peatland (as opposed to two separate clusters of highest elevation in the peatland’s center and the surrounding mineral land, as it is the case for peatland A & C), with clusters of decreasing elevation towards the edges of the study area (Figure 3-6.c). Highly impacted by smaller topographic features, the TWI clustering results are less intuitive than the ones from peatland A and C. Considering that the zones of lower elevations are found all around the peatland, it is not unexpected to find the results of the TWI analysis outlining zones of higher soil moistures beyond the periphery of peatland D (Figure 3-6.d). However, since the wetness index is calculated based on upslope contributing area, slight variation in topography present in the original digital elevation model (data not shown) affects the soil moisture distribution of the TWI, where zones of higher moisture are not equally distributed along the edge of the peatland. The distribution of the VRH is also spatially irregular, particularly on the western side of the bog. Combined together, the DEM+TWI+VRH analysis generally results in discontinuous lagg clusters (Figure 3-6.a) representing the areas of higher wetness and lower elevation among the study zone. Although the two field-identified laggs for peatland D possess slightly different physical characteristics (the eastern lagg (D3) is richer and wetter than the western one (D1), see Chapter 2) they both fall into the same combination of clusters (Figure 3-6.a; clusters 1&2). The major difference between the two locations lies in the actual spatial distribution of their respective cluster. The eastern lagg resembles the laggs observed in peatland A and C, running linearly, parallel to the north eastern side of the peatland, possibly acting as a water conveying feature (water was observed to flow north in times of heavy rain), removing excess water from the system. In fact, the final analysis places lagg D3 in a well-defined ~38 m wide cluster (at the field instrument location), which was measured in the field to be ~31 m wide. Conversely, the dryer western lagg (D1) lies in a disconnected cluster. Even if development has been kept a minimum of 260 m away, peatland D's periphery is the one (among the study sites) that has been the most impacted by human activity (mostly to the west), and the outcomes of the clustering analysis should be interpreted with this in mind. Nevertheless, our results suggest that the western lagg could easily extend to the road (~150 m to ~300 m away), and maybe have existed beyond this prior to its construction. This supports the important distinction between the two types of laggs, especially when it comes to peatland management where the 30 m protection zone is more likely to fall short for unconfined than for confined peatlands.

In summary, the k-means partitioning (Caliński-Harabasz) results for the VRH+DEM+TWI identified the optimal number of clusters for each peatland; 5 for peatland A, 11 for peatland C, and 7 for peatland D. The incidence and location of the confined laggs (see Chapter 2) found in the periphery of peatland A and C were easier to identify than for the unconfined laggs (peatland D). The spatial distribution of the confined laggs was intuitive; continuous and following obvious topographic elements (i.e. positive slopes on either side of the lagg). Conversely, the unconfined laggs of peatland D were spatially discontinuous and inconsistent, reacting to more subtle landscape features. With the similarity analysis, the wetness index becomes a much better predictor of the potential location of the lagg, especially for confined transition. As for the VRH, it has not proven itself a sufficient indicator, at least on its own. Yet, when used in combination with the wetness index and topographic data, it allows for a more accurate depiction of the lagg's potential location. In fact, for all but the western lagg of peatland D (D1), the width of the lagg measured from the results of the final analysis were within 2.6±3.3 m of the one measured in the field.

### 3.5.3 Provincial wetland map – classification/misclassification of the lagg

Half of the 6 known lagg locations (A1, C1 and D1) included in the similarity analysis were located in the peripheral portions of each peatland classified as fen by the NBDNR (2006). The other half was either 20-40 m within (C2 & C3), or outside (D3) the bogs' mapped borders (Figure 3-1). This inconsistency in mapping the lagg area can be attributed to a variety of factors. First, the focus and the intent of the map; a wetlands map executed as part of a natural resources inventory (e.g. for peat harvesting) might be more likely to overlook smaller area of lesser interest as one produced for conservation purposes. Second, the technical limitations; the resolution of the data used might prevent the clear differentiation of ecotones. Since these classifications are made based on vegetation (usually using stereography), a fall vs. summer survey might also give different results. Third, the possibility of human error; the training and experience of the analyst has an impact. And lastly, the nature of the lagg itself; as previously stated, the lagg is difficult to identify from a field perspective, making remote detection challenging.

Although mispositioned and misclassified, the fact that zones of changing characteristics – corresponding to known lagg area – have been recognized and mapped by the NBDNR is encouraging, confirming that lagg areas (at least some) can be visualized from conventional mapping techniques. It also suggests that, when a somewhat linear zone in the periphery of a raised bog is classified as a minerotrophic wetland (in this case fen), it is likely that this zone corresponds to a lagg. With new advances in technology, and with the use of, or a combination of analysis such as the one presented in this study and conventional mapping techniques, laggs could be mapped with more confidence.

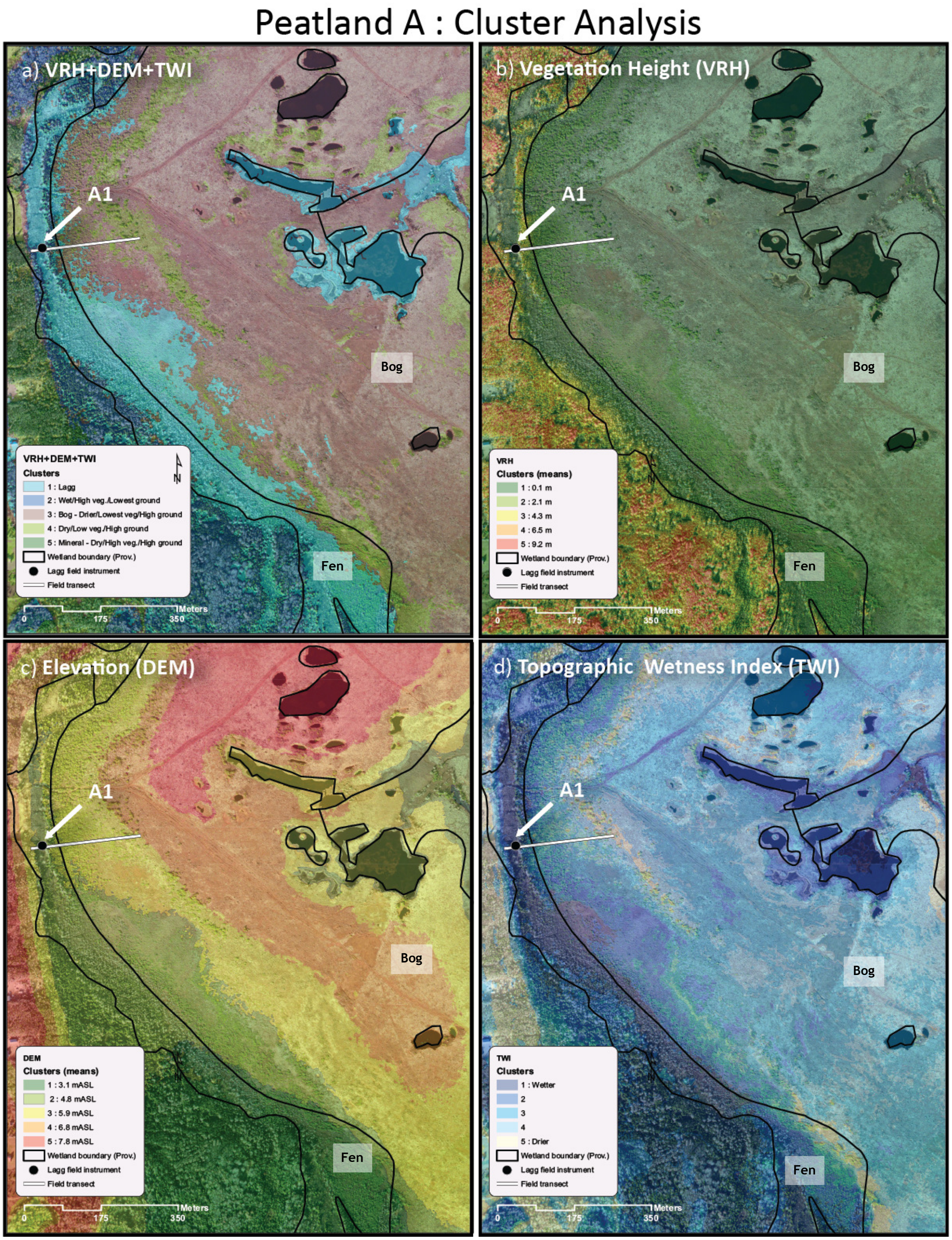



**Figure 3-4**: *Similarity analysis for peatland A (confined);* a) Is the result from the final analysis including the VRH, DEM, and TWI grids as input data, and b),c) and d) are the results from the individual components, respectively. In a) the legend summarizes the relative value of the components and the cluster to which they belong. In b) and c), the legend indicates the mean value (centroid) of each cluster. In c) clusters are ranked by degrees of wetness. For all, the black lines mark the location of the peatland's boundary as identified by the NBDNR; the different classification (e.g. Fen/Bog) is indicated within their respective limits. In a) the final analysis, the lagg cluster (in blue) clearly follows the edge of the peatland, playing a role in regulating water levels within the peat body. The high water level in this zone reduces the hydraulic gradient in the margin of the adjacent bog, which helps it retain water. During wet periods, the lagg of peatland A flows south, removing excess water from the system.

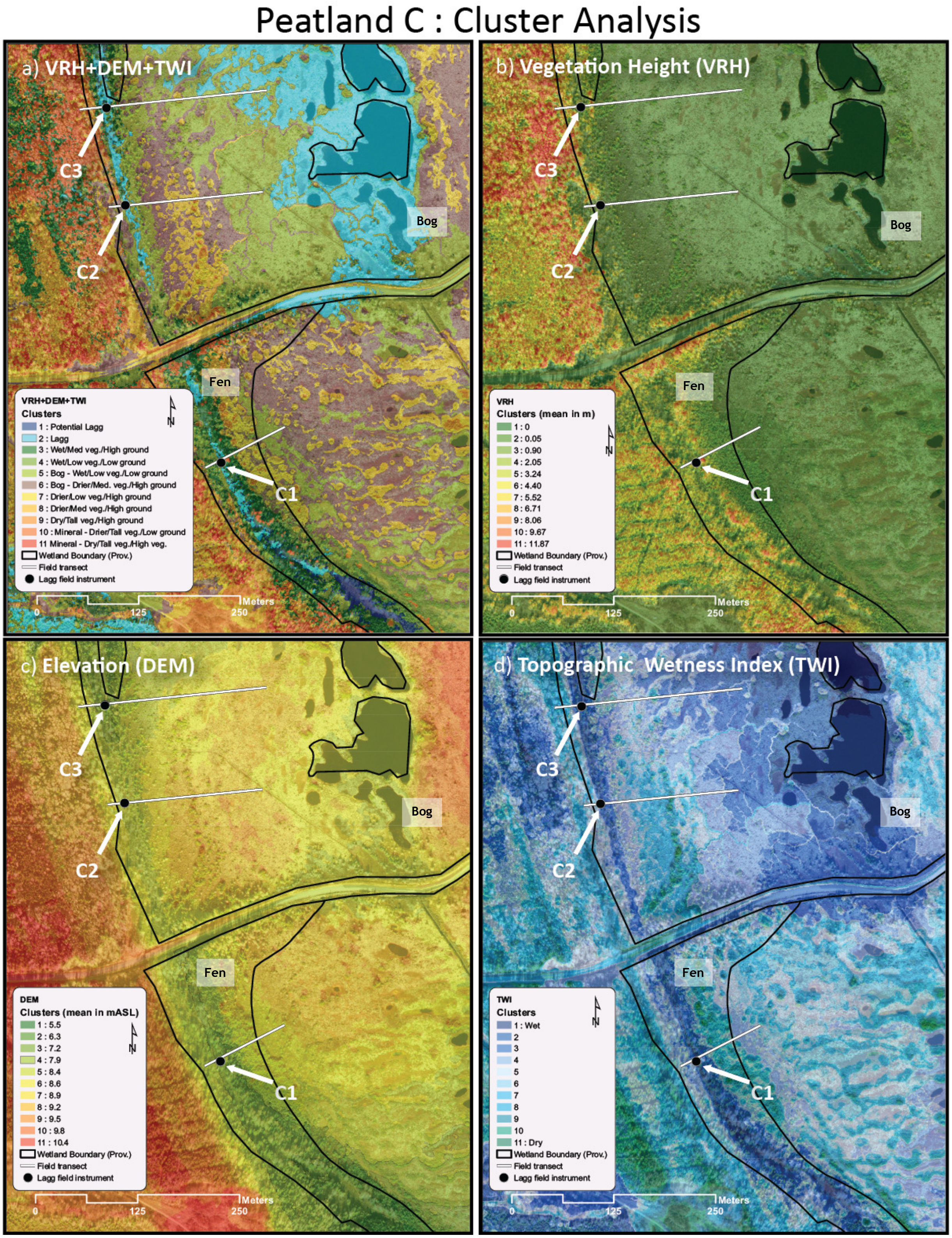



Figure 3-5: Similarity analysis results for peatland C (confined). The TWI index is the most spatially defining variable for peatland C; providing a distinct unique cluster common to all known lagg location. A more detail description of each map is available in the caption of Figure 3-4

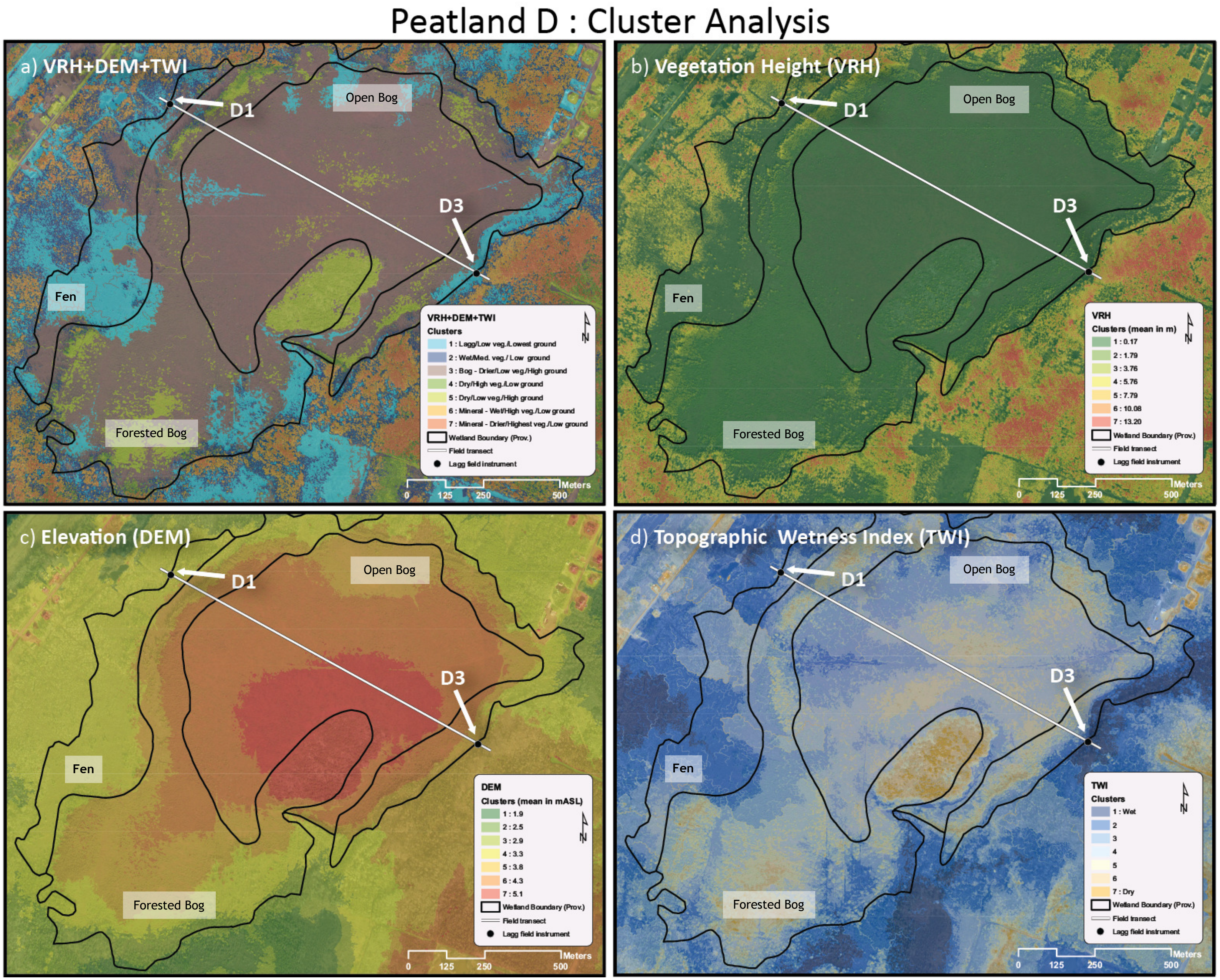



Figure 3-6: *Similarity analysis results for peatland D (unconfined).* Peatland D is unconfined, meaning that the adjacent mineral land is flat, or sloping away from it. The 2 clusters corresponding to peatland D's known lagg locations (figure 3-6.a, in blue) are spatially intermittent, reacting to the subtle topography of the site. A more detail description of each map is available in the caption of Figure 3-4.

## 3.6 Conclusion

As suggested by Howie et al. (2009), the vegetation indicators (VRH and VSF) were successful (dissimilarity analysis) in finding the bog-lagg boundary, yet were very poor indicators of the mineral land-lagg edge (Figure 3-4). For this latter case, the topographic variables were more effective (Figure 3-4). The practicality of edge-detection techniques (dissimilarity analysis) is that it can accurately indicate (position) places of maximum local variance – interpreted as boundaries – along a transect. In our case, a good understanding of the data (i.e. having walked the field transect many times) was necessary in order to 1) choose the appropriate window size for analysis and 2) to discriminate the resulting peak (edges) for significance (noisy results from massive LiDAR dataset). Consequently, interpreting the results from this analysis for unknown location was problematic. Nevertheless, this technique remains powerful as it allows us to investigate the cause/effect of small scale physical processes by relating coarser field (transect) data (i.e. vegetation composition, hydrology, chemistry, …) to rich landscape information (LiDAR), making it most useful for research purposes. The outcomes of this analysis are, however, of limited assistance in visualizing the potential spatial distribution of the lagg around a peatland. For this, the similarity (cluster) analysis was more effective.

The outcomes of the cluster analysis confirm that the spatial distribution – and the size – of the lagg are highly dependent on topography. According to our results, the laggs of confined transition have the tendency to exist as narrow linear features, parallel to the edge of the peatland, conveying excess water away from the system. Laggs of unconfined transition, however, are more difficult to interpret, and seem to be intermittent; in this study they appeared as discontinuous patches of various sizes, not always present around the peatland.

It was not our intention to produce a properly classified map of the lagg, but rather to explore the potential of a variety of information (beyond the frequently used DEM grid) solely derived from airborne LiDAR datasets to simply, yet efficiently, identify and locate potential lagg zones. For this purpose, the similarity analysis is useful in gaining a visual and holistic understanding of the landscape connectivity, of the possible governing processes, and of the potential impact of encroaching disturbances. Because of its ease of use and visual outcomes, this tool (or similar ones) can benefit both researcher and land manager alike.

More work needs to be done to truly understand the connectivity between bog ecosystems and their adjacent mineral lands. As we accumulate more knowledge about the lagg, its form, and its ecohydrological functions, accurate classification methods, including post analysis ground truthing and sensitivity/confusion analysis, will improve the remote detection potential of this ecotone. Nevertheless, with the similarity (cluster) analysis, we propose a first step in exploring non-conventional mapping techniques, allowing both scientist and land managers to visualise the potential distribution of lagg ecotone.

# Chapter 4

## Conclusion

This study set out to explore the form and abiotic controls of the laggs and margins of selected peatlands of the New Brunswick eastern lowlands, to suggest a conceptual model for the laggs of this region, to explore the potential of airborne LiDAR data in detecting and positioning this ecotone, and to consider its spatial distribution around raised bogs. The results and conclusions presented in this thesis add to a meager body of empirical research about laggs, and furthers our general understanding of the character of the lagg, and the role it plays in a raised bog complex, within the context of its natural landscape.

The greatest abiotic control of the lagg appears to be topography; affecting water flow rates and direction, which in turn affect water chemistry, and most likely nutrient transport and availability, hence vegetation characteristics. If the 2 geomorphological categories identified in chapter 2 (confined and unconfined laggs) have, in part, been recognized in previous studies (Morgan-Jones et al., 2005; Whitfield et al, 2006; Howie et al., 2009; 2013), the distinction made between them is usually minimal. A novelty of the work presented here is therefore the active distinction made between these two types of laggs, and of the quantification and analysis of some of their respective ecohydrological, and morphological character. Topography also greatly influences the size and spatial properties of the lagg, where confined laggs tend to follow a continuous and narrow linear pattern, while unconfined laggs appear to be less consistent, to spread wider, and to be spatially discontinuous.

There is no "typical" lagg; it can vary in size, character, and spatial properties even around a single peatland, if present (or observable) at all. Defining the lagg is therefore challenging, and in attempting to do so, we should strike for a balance between specific and general characteristics. Stripped to its most basic description, the lagg is the zone influenced by both ombrotrophic bog water and mineral enriched water from the surrounding environment. It is the core of the definition, and the one character of the lagg that is, as of today, agreed upon. As pointed out in the introduction, the original translation (Osvald, 1933), as well as many authors (e.g. Godwin & Conway, 1939; Couillard & Grondin, 1986; Hobbs, 1986; Bragg, 2002) associate laggs with raised bogs. This study, however, confirmed that not all lagg transitions are obvious, and even though some of them are wet and well define (i.e. confined), resembling the "moat" lagg described by Damman & Dowhan (1980), others are much less apparent (i.e. unconfined). In this sense, perhaps the definition should leave the possibility for all ombrotrophic-mineral transition to potentially classify as lagg, such as the transition between slope bogs and the surrounding mineral terrain, for example. More research is needed on this subject. The use of the word "upland" is also restrictive, as it would exclude laggs forming on a flat or receding mineral slope, as it is the case for unconfined transitions. Howie et al. (2011) proposed to include "peat of relative low hydraulic conductivity" in the definition of the lagg. In this research, however, we observed low $K_{sat}$ at the lower rand, but found the $K_{sat}$ of the lagg peat to be comparable to that of the bog. Although the lagg chosen for this study were randomly selected, a limitation of the conclusion made in this research certainly lies in the selective (and perhaps bias) criteria used for site selection (i.e. high water levels and transitional chemistry, presence of a shallow peat layer and transitional vegetation). As suggested in chapter 2, the systematic instrumentation of a single peatland could reveal new information about the lagg, its different form, its spatial distribution around a peatland, and its functions. Until more information is available to provide improved knowledge, over a number of different geographical regions, on the function of the lagg, perhaps its definition should remain unassuming, and reflective of the current level of scientific knowledge of this zone.

Setting goals for lagg restoration should account for the natural geomorphology of the site and of the adjacent landscape. Laggs that are spatially confined by uplands receive a larger mineral water input than the spatially unconfined laggs. In these conditions (confined), laggs should be expected to be richer in nutrients, have higher water levels, to be narrower, and eventually develop a deeper peat layer than their counterpart. Other elements of the transition seem to also play a role in regulating the outflow of water from the bog; the rand-forest for example, displays lower hydraulic conductivity, which might help retaining water within the peat body. This research has demonstrated that both the rand and the lagg are part of the transition zone, and influence the quantity and variability of water within the peatland, and should be considered as integral part of the peatland complex. Sustainable management should therefore be inclusive of the margins of raised bogs, including both the rand and the lagg.

Although peatland scientists acknowledge and recognize the existence and the potential ecohydrological functions of the lagg zone, there is still a dearth of empirical research specific to this ecotone. More studies are needed to characterize the connectivity between the bog and surrounding mineral land, through all types of transition, not limited to well-defined lagg zones, but also areas where laggs are not easily observable. The increasing availability of airborne LiDAR data offers unprecedented opportunities for mapping and remotely analysing the character of this zone, to relate it to field measurement, and holistically further our understanding of this complex ecotone.

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# Appendices

*Appendix A: Confined laggs - Pictures*

*Appendix B: Unconfined laggs - Pictures*

*Appendix C: Rand-forest - Pictures*

*Appendix D: Rand-slope - Pictures*

# Appendix A

## Confined laggs – Pictures

# *Examples of confined Laggs*


*Examples of confined laggs*. Pictures a & c are examples of lagg streams, picture b is a close-up of the near ground vegetation in the spring. Picture c is an example of lagg stream. Picture d was taken in late may, the drop in vegetation height observed in certain laggs is clearly visible.

# Appendix B

## Unconfined laggs – Pictures

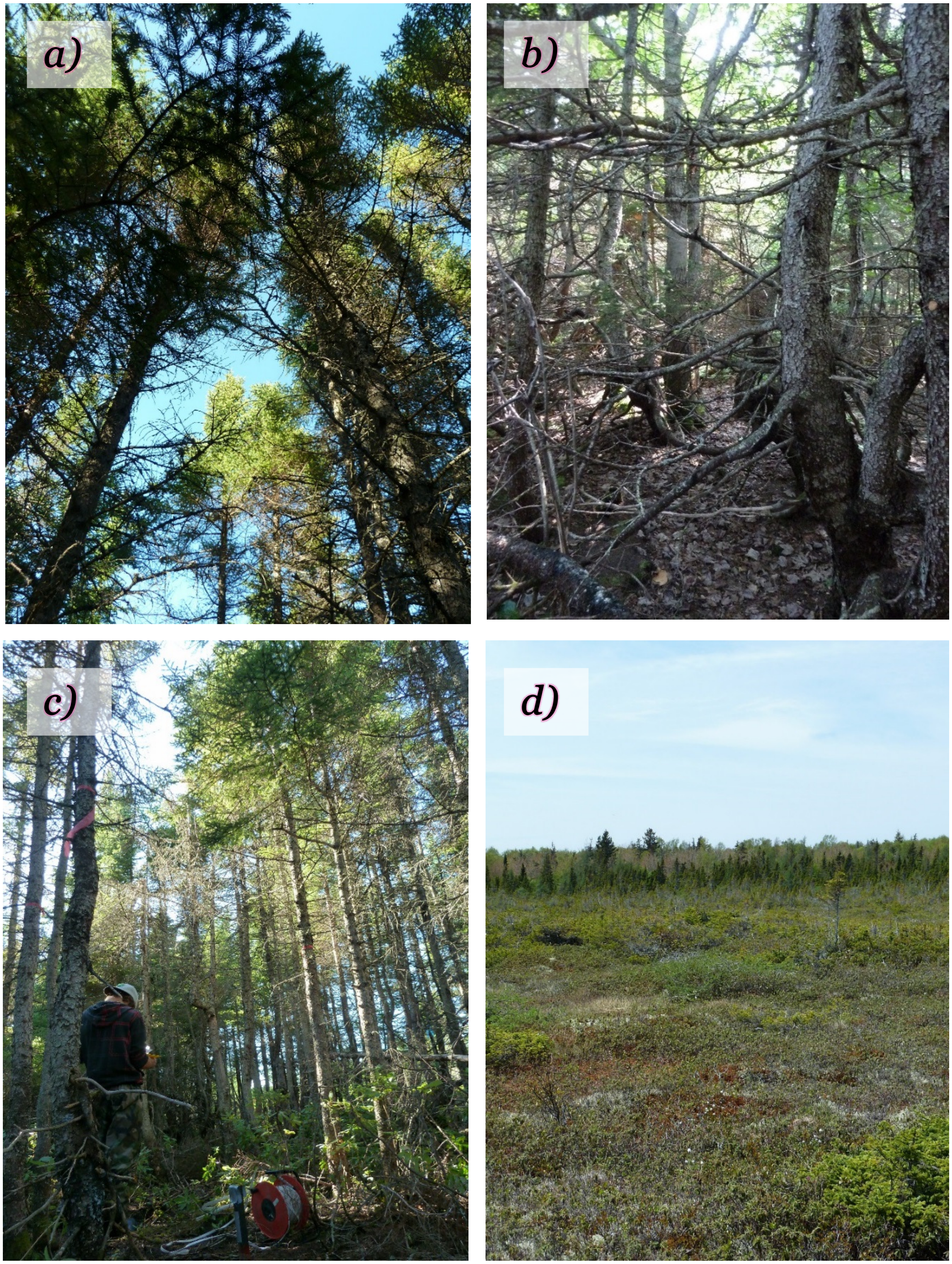
# *Examples of unconfined* Laggs


*Examples of unconfined laggs.* Pictures a & b are examples of locations where the lagg is least evident based on vegetation alone; to confirm the existance of a lagg, water levels, water chemistry, and soils had to be assessed. Picture c & d are from the same site (D3), where picture c was taken early June, and picture d in late October; water levels at this site dropped by close to 35 cm.

# Appendix C

## Rand-forest – Pictures

# *Examples of rand-forest*

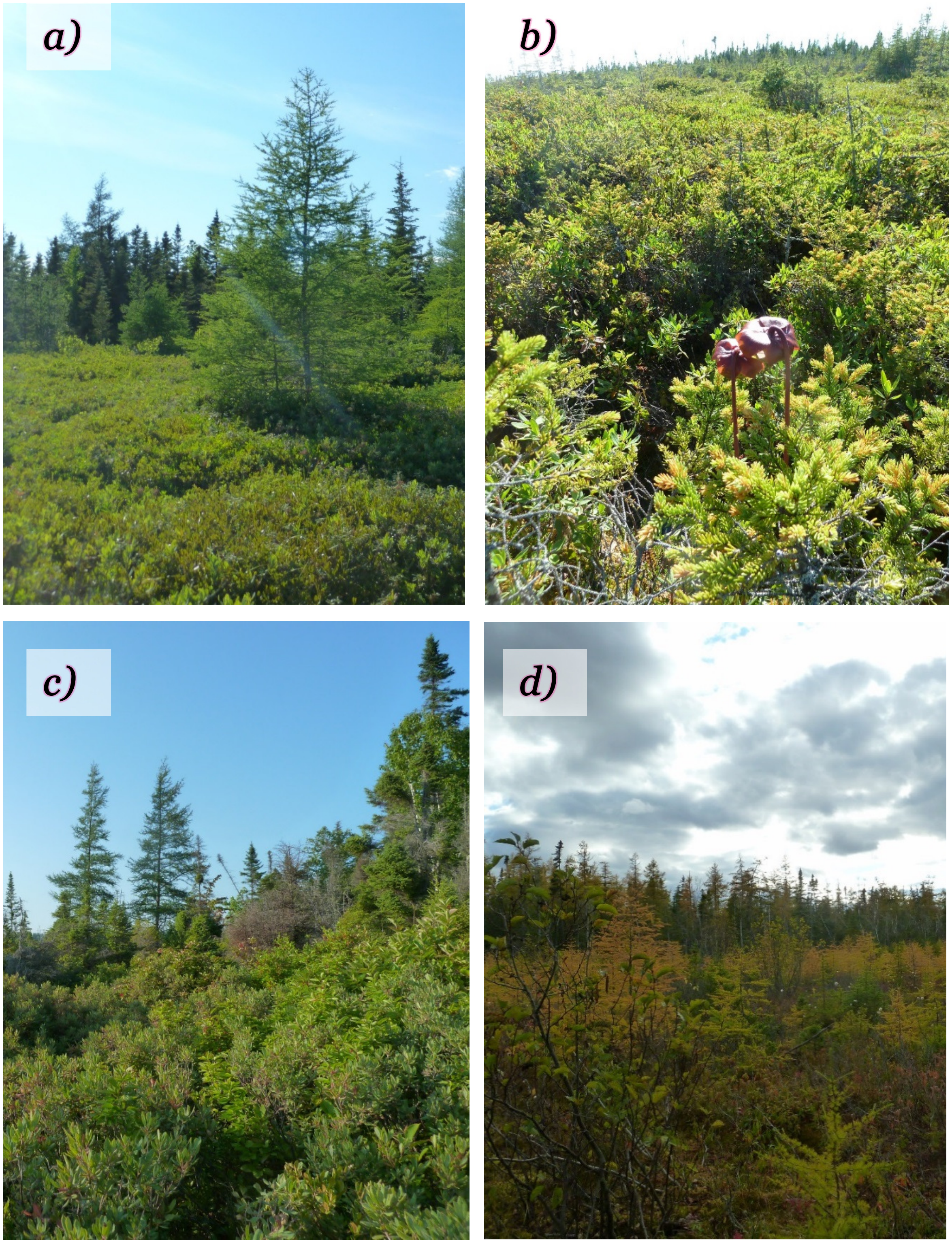



*Examples of rand-forest.* Picture a & c show tree heigh wich are on average 6 to 7 m. Picture b show the thikness of this band of trees and the lack of Sphagnum mosses on the ground; this perticular rand-forest was found at the edge of the dome. Picture d shows the rand-forest at the edge of the bog, and the mineral forest vegetation behind it.

# Appendix D

## Rand-slope – Pictures

# *Examples of rand-slope*




*Examples of rand-slope.* Picture a is an example of a rand-slope located between a rand-forest (situated at the dome) and the lagg. Picture b & c are examples of rand-slope where the vegetation increases more gradually towards the lagg. Picture d shows a location where the rand-slope is located between the bog and the rand-forest