Bogs and their laggs in coastal British Columbia, Canada: Characteristics of topography, depth to water table, hydrochemistry, peat properties, and vegetation at the bog margin

by

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Dissertation Submitted In Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

in the
Department of Geography
Faculty of Environment

SIMON FRASER UNIVERSITY

Spring 2013

Approval

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Degree: **Doctor of Philosophy (Geography)**

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Abstract

The transition zone at the margin of raised bogs (the lagg) is rarely studied, yet it can be important for maintaining a high water table in the peat mound. Drainage of the lagg may result in a lower water table in the bog, resulting in increased peat oxidation, peat compression, loss of *Sphagnum* moss cover, and establishment of trees in the bog. Therefore, hydrological protection zones that include the historic lagg area have been recommended as part of bog conservation. Where the lagg has been damaged or lost to agriculture, industry, or residential development, it may be necessary to restore a functional lagg inside the historic bog boundary to maintain the ecological health of the bog.

Seventeen laggs from raised bogs in coastal British Columbia (BC) were studied to determine the natural range of lagg characteristics in this region. The laggs could be separated into two hydrotopographic forms: Marginal Depression (with mean early summer depth to water table of 12 cm and mean tree basal area of 2.8 m^2/ha) and Flat Transition to forest (with mean early summer depth to water table of 34 cm and mean tree basal area of 26.3 m^2/ha). These hydrotopographic forms were further classified into four vegetative lagg types: 1) Spiraea Thicket, 2) Carex Fen, 3) Peaty Forest, and 4) Direct Transition to forest (no lagg ecotone). The Carex Fen and Direct Transition lagg types were generally found in the Pacific Oceanic wetland region (cool, wet climate), while the Spiraea Thicket and Peaty Forest lagg types were more common in the Pacific Temperate wetland region (relatively warmer and drier climate).

Regional differences in bog and lagg characteristics appear to be related to mean annual precipitation and mean annual temperature. The timing of seasonal fluctuations in depth to water table were similar for bogs and laggs, but the amplitude was generally greater in the lagg. Near-surface pore-water chemistry varied across the bog expanse – bog margin transition: pH, Ca^{2+} concentrations, and pH-corrected electrical conductivity generally increased from bog to lagg, although not consistently for individual study transects. Mg^{2+} and Na^{+} concentrations increased from bog to lagg for less than half of the studied transects. The most consistent indicators of the lagg, which may be of greatest use for delineation of lagg conservation zones include: topography, depth to water table, tree basal area, ash content of the peat, and dominant species.

Keywords: bog; lagg; ecotone; depth to water table; hydrochemistry; vegetation

Acknowledgements

I wish to thank my supervisor, Dr. Ilja van Meerveld, for this project would not have been possible without her academic guidance, and in particular for all her hard work with me in the field, her dedication to spending many hours and days editing this thesis, and her support and understanding. I would also like to thank the members of my committee, Dr. Richard Hebda and Paul Whitfield, who have provided a great deal of important insight and guidance over the past four years. I very much appreciate the wisdom shared by Dr. John Jeglum, whose passion for peatland ecology research and international perspective inspired me to take this journey.

Thanks to Metro Vancouver Regional Parks for providing financial support for travel and field materials. Thanks to Les Lavkulich and Martin Hilmer at the University of British Columbia for making their soil lab available for analysis of the peat samples, to Environment Canada for analyzing the water samples, and to Karen Golinski for kindly volunteering to identify over 100 *Sphagnum* samples. I would also like to thank The Corporation of Delta for providing staff resources and field equipment to assist with this research, and especially for supporting me as an employee in this endeavour.

I am extremely grateful to everyone who generously volunteered their time to trudge through the peat with me: Will Howie, Seb Howie, Kate Howie, Gordon Howie, Jonathan Hughes, Thiago Andrade, Adam Snow, Andrew Robinson, Elizabeth Baird, Christina Baird, Nicholas Baird, Angela Danyluk, Erin Riddell, Kim Houghton, Ashley Graham, Candice Vecmanis, Jing Niu, Natasha Murphy, Brad Jones, Stephan Zimmerman, Tanner Aldridge, Devon Franklin, Delta co-op students, and Metro Vancouver park operators. Words cannot express my gratitude to Will Howie for his incredible dedication and ability to find humour in difficult situations, and to Angela Danyluk for always listening to me and reminding me that there is life after work.

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List of Acronyms

BC	British Columbia
OP	Pacific Oceanic wetland region
TP	Pacific Temperate wetland region
BG	Study site on transect in open bog
R1	Study site on transect between bog and lagg (=rand), closer to bog
R2	Study site on transect between bog and lagg (=rand), closer to lagg
LG	Study site on transect in lagg
MN	Study site on transect in forest or minerotrophic soil outside the bog margin
FT	Flat Transition hydrotopographic lagg form
MD	Marginal Depression hydrotopographic lagg form

1. Introduction

1.1. Purpose of the Research

Peatlands cover three percent of the land area worldwide (Rydin and Jeglum, 2006), but are more common in Canada where they cover 13% of the land surface (Tarnocai et al., 2005). Peatlands are widespread in the cool-moist climate of coastal British Columbia (BC), covering up to 75% of the land in some areas (National Wetlands Working Group (NWWG), 1988). Natural peatlands (bogs, fens, and some swamps) store approximately one-third of the world's total soil carbon and are generally a net sink of atmospheric carbon dioxide (Waddington et al., 2009). Many raised bogs have been damaged or lost to peat extraction, drainage, agriculture, and industrial/residential development. Due to the shallow depth of peat at the bog margin, the lagg of a raised bog (i.e. the transition zone between an ombrotrophic ("rain-fed") bog and the mineral soils of the surrounding landscape) is often disturbed, even for bogs that are otherwise relatively undisturbed. The lagg is, however, a rarely studied part of the bog ecosystem. Whitfield et al. (2009) recommend further research in the form of hydrological and hydrochemical transects across the transition zones between minerotrophic and ombrotrophic sites, and note that the "role of the lagg as a transition and as a boundary needs to be better understood and modeled". It is therefore important to study raised bogs and their laggs to improve our understanding of these systems in order to assist with conservation or restoration of raised bogs for maintenance of carbon stores and protection of these habitats for rare and endangered species and for regional biodiversity.

The primary goal of this study was to increase the existing knowledge of laggs in low elevation coastal British Columbia. The lagg is often referred to as minerotrophic and is generally described as containing fen plant communities (Rydin et al., 1999; Damman and French, 1987), although Rydin and Jeglum (2006) expand the definition to include fen or swamp plant communities. The lagg may be sharp or gradual, depending on topographic constraints (Hebda et al., 2000; Svensson, 1988; Howie et al., 2009a), or may not be present as a distinct feature if the transition from bog to mineral soil is very gradual (Damman, 1977). The variation in nutrient and base cation concentrations across the lagg often correlates with the vegetative boundary between eutrophic and oligotrophic (bog) plant communities (Ivanov, 1981). Where lagg transitions are not obvious in terms of vegetation patterns, one can delineate the border between bog water and minerotrophic water by observing changes in the hydrology and pore-water chemistry (Svensson, 1988). Hughes and Barber (2003) note that the “fen-bog transition” has received little research emphasis, and suggest that it is necessary to understand the processes in this transition zone with respect to raised bog management and restoration.

1.2. Research Questions

One could assume, on the basis of mean annual precipitation, mean annual temperature, and proximity to the Pacific Ocean, that in the coastal BC geographic region, bogs are more similar to each other in terms of hydrology, hydrochemistry, and vegetation than they are to bogs in other (e.g. continental) regions. However, there are observable differences amongst the bogs of coastal BC. Bogs of the Fraser Lowland tend to have a more developed lagg, evidenced by a clear ecotone at the bog margin, compared to bogs further north that tend to shift rather abruptly from bog to forest. This disparity was noted by Allen Banner (BC Forest Service), Will MacKenzie (BC Forest Service), Dr. Adolf Ceska (retired BC vegetation specialist), and Dr. Karen Golinski (BC *Sphagnum* and peatland expert) (personal communication), and also by my own observations in the field prior to this study. One important aspect of this research therefore was to characterize this variability along the coast.

The specific research questions that were explored in this broad regional study were:

1. What are the different physical lagg forms in the coastal BC region?
2. What are the different vegetative lagg types in coastal BC, and how are they related to the physical lagg forms?

3. How do bogs and laggs vary along the coast of BC and what are the principal gradients (e.g. from south to north, distance from the ocean)?
4. What are the hydrological and hydrochemical gradients across the bog margin? Do these gradients differ regionally?
5. How do plant communities change across the bog margin of raised bogs in coastal BC?
6. Can vegetation along a lagg transition be used as an indicator of the hydrological and hydrochemical gradients?
7. What lagg restoration strategies can be developed based on these gradients?

For a more detailed temporal study that took place in two Fraser Lowland bogs, the following additional questions were explored:

8. How do depth to water table and near-surface pore-water chemistry change seasonally?
9. For which parameters is a one-time survey sufficient to characterize the gradients across the bog margin (i.e. relatively temporally stable), and which require more frequent measurements (i.e. change over time)?

It was expected that answering these research questions would significantly increase knowledge of laggs in coastal BC through identification of the various physical lagg forms and vegetative types, and by gaining a better understanding of the gradients in hydrochemistry, depth to water table, peat properties, and vegetation across the bog margin, as well as how these gradients are correlated and change over time. This new information could assist bog management agencies in developing lagg restoration plans, consistent with the ecological integrity of the raised bog ecosystem, both in the study area and outside this region.

1.3. Approach and Expected Results

1.3.1. Selection of the Study Sites

The bogs for the temporal study (Burns Bog, Blaney Bog, and Campbell River Bog) were chosen because they exhibit particularly well-developed laggs, and were accessible for repeat observations. These bogs are located in the Fraser Lowland (southwest BC) and on the east coast of Vancouver Island. The other 10 bogs that were included in the study represent different geographic regions of coastal BC, including the north and west coasts of Vancouver Island, the Prince Rupert area, and Haida Gwaii. The aim was to study a representative sample of the most common types of bogs in coastal BC. Accordingly, the bogs were selected by examining aerial photographs of the study region, helicopter and ground reconnaissance, reviewing student theses about bogs in this area, as well as communicating with people who had formerly conducted research on bogs in coastal BC (e.g. Dr. Richard Hebda (Royal BC Museum, University of Victoria), Dr. Karen Golinski (Gallatin, Tennessee), Dr. Adolf Ceska (Victoria, BC), Will MacKenzie (Smithers, BC), and Allan Banner (Smithers, BC)).

1.3.2. Lagg Transects

To characterize laggs of raised bogs in coastal BC, information was collected along transects oriented at right angles to the lagg. The depth to water table and water chemistry are known to change from ombrotrophic to minerotrophic moving from bog to lagg (Wheeler and Shaw, 1995). Vegetation is also known to change across this transition zone (Wassen and Joosten, 1996; Vitt and Chee, 1990); plant species composition is most strongly influenced by hydrology and water chemistry (Rydin and Jeglum, 2006). This approach has previously been used to characterize vegetation across the bog margin (e.g. Rigg and Richardson, 1938; Asada et al., 2003).

There were generally five sampling locations across each of the studied lagg transects: 1) inside the bog ("BG"), 2) between the bog and lagg (closer to bog; "R1"), 3) between the bog and lagg (closer to lagg; "R2"), 4) approximate centre of the lagg ("LG"), and 5) outside the bog in mineral soil ("MN"). These five locations were determined in the field based on plant communities that indicated the position along the transect. BG sites were defined as *Sphagnum*-dominated heath or open woodland heath, LG sites were defined as a thicket of *Spiraea douglasii* Hook. or sites containing larger shrubs and trees than the bog, and MN sites were defined as the mineral-soil forest surrounding the bog. Measurements were not taken at a fixed distance between the bog expanse and the bog margin because of large differences in the size of the studied bogs.

1.3.3. Field Methods

Peat Characteristics

Peat cores were collected at 10, 50, and 100 cm below the surface to analyze how the character of the peat changes across the bog margin. The following peat/soil properties were determined for each location on the study transects:

- Von Post level of humification**:** At depths of 10, 50, and 100 cm, the von Post scale of humification (Rydin and Jeglum, 2006) was used to assess the degree of humification of peat. Although this method is subjective, it has proved adequately reproducible in the field and is the most widely used method for determining the degree of peat decomposition in central and northern Europe (Egglesmann et al., 1993). Two bog experts, Dr. John Jeglum (Emeritus Professor in Forest Peatland Science, Swedish University of Agricultural Sciences, Umeå) and Dr. Håkan Rydin (Professor in Plant Ecology, Uppsala University, Sweden), suggest that this field technique is accurate to ± one point on the scale (personal communication).
- Ash content: Ash content is the amount of mineral (non-combustible) material (as % of dry weight of the sample) remaining after burning the peat samples at 550^0C for 24 hours. Ash content was expected to increase with depth, and to increase from the bog outward.
- Peat Depth: Depth of peat was measured at each location on the transects and was expected to decrease across the transect from bog to lagg.

Depth to water table and hydraulic gradient

The lagg of a raised bog is the outer discharge area that collects runoff from the bog and, in many cases, from the surrounding minerotrophic upland. Knowledge of the hydraulic gradient across the bog margin is critical for understanding the importance of the lagg for maintaining the water mound in the bog. Depth to water table is closely related to plant form, distribution, and growth (Rydin and Jeglum, 2006). Piezometers and an electronic water level meter were used to determine depth to water table. This is the most common form of hydrological monitoring in bogs because depth to water table reflects the entire surface water balance, the individual components of which are much more difficult to measure (Bragg, 2002). Shallow piezometers were used instead of wells in this study to avoid “short-circuiting” of water during rainfall events or flooding. Due to the relatively shallow depths at which the piezometers were installed (mean depth: 0.53 m), it was assumed that the water level measured in the piezometer represented the location of the water table, and that the uncertainty in the location of the water table due to the use of shallow piezometers instead of wells was similar to the measurement accuracy and the uncertainty in determining the bog surface. Previous studies in Burns Bog have shown that the difference in the water level measured in a well and in a shallow piezometer is generally <1-2 cm (mean: 0.8 cm) (unpublished data from The Corporation of Delta).

Water Chemistry

Water chemistry is expected to vary across the lagg transition, as nutrient-poor water from the bog mixes with minerotrophic water from the surrounding mineral soils. By characterizing pore-water chemistry across the bog margin, a more detailed understanding can be derived of the dependence of vegetation on the underlying chemical conditions. Both pore-water chemistry and peat chemistry have been used in research relating to chemical gradients in bogs; there is generally a close relationship between the chemical composition of the peat and the pore-water (Rydin and Jeglum, 2006). Water chemistry is more influenced by the variations in precipitation and evapotranspiration than peat chemistry. On the other hand, there are differences between hummock, lawn, and carpet peat, and thus the chemical composition of peat will vary both vertically and laterally. Groundwater is a good indicator to characterize the site as a whole, and is much easier to sample in the field and to characterize using readily available and inexpensive probes (Rydin and Jeglum, 2006). Therefore, pore-water chemistry was used to characterize the chemical changes across the bog margin. One out of nine water samples was replicated (seven replicates in total) to assess sampling and analytical error (see Appendix A).

The following hydrochemical parameters were determined at each piezometer:

- pH: This parameter is frequently recognized as the single most important chemical factor in peatlands (Tahvanainen and Tuomaala, 2003), and generally increases from the bog expanse to the bog margin (e.g. Bubier, 1991; Bragazza et al., 2005). pH was measured in the top 10-15 cm of the water column in the piezometers because pH in bog peat can increase with depth below the surface (e.g. Baird, 2011).
- Electrical conductivity: Similar to pH, electrical conductivity (EC) tends to increase from the bog expanse to the bog margin due to the increasing influence of minerotrophic water at the bog margin. EC was also measured in the top 10-15 cm of the water column in the piezometers to ensure that measurements were not affected by stratification in the peat (see above).

- calcium: The Ca^{2+} concentration is often used to distinguish the mineral soil water limit (Bourbonniere, 2009), which was expected to be located along each lagg transect. Ca^{2+} concentrations were expected to increase approaching the lagg, in part because Ca^{2+} concentrations are higher in minerotrophic soils than in bogs (Bourbonniere, 2009) and also because Ca^{2+} is positively correlated with pH in pore-water due to cation exchange in the peat (Rydin and Jeglum, 2006). The Ca:Mg ratio has been suggested as one indicator of the mineral soil water limit; a ratio of 1:1 may point to the location of the ombrotrophic-minerotrophic divide in some bogs (Nauke et al., 1993).
- magnesium: Tahvanainen et al. (2002) observed that Mg^{2+} concentrations were correlated with pH across a poor-rich gradient. Mg^{2+} was therefore expected to increase approaching the lagg, and also with proximity to the ocean.
- sodium: Na^{+} concentrations were expected to increase with proximity to the ocean.
- potassium: K^{+} enters an ombrotrophic bog by dustfall, and the lagg by runoff from minerotrophic uplands. K^{+} concentrations are generally not strongly correlated with the bog-lagg transition (Bourbonniere, 2009), although the concentration was expected to increase approaching the lagg as the influence of mineral water becomes greater.
- chloride: Moderately-rich fens have the highest Cl^{-} concentrations of bog and fen water types (Bourbonniere, 2009), so it was expected that Cl^{-} concentrations might increase slightly in the lagg. Cl^{-} concentrations were also expected to increase with proximity to the ocean.
- sulphate: Only rich fen pore-water is high in SO_4^{2-} concentrations (Bourbonniere, 2009). We measured SO_4^{2-} concentrations to see whether there was an increase in SO_4^{2-} concentrations approaching the lagg.
- acidity: Acidity, or “base neutralizing capacity”, is the “equivalent sum of the acids that are titratable with a strong base” (Shotyk, 1988). Although pH is more commonly used in bog research, acidity is also relevant, so both parameters were analysed in this study.
- dissolved organic carbon: Dissolved organic carbon (DOC) is the carbon component of dissolved organic matter. Average DOC for bogs and fens is 20-40 mg/l (Rydin and Jeglum, 2006). DOC was expected to decrease approaching the lagg, as the amount of organic matter in the soil decreases. However, Kolka et al. (2001) found that DOC in the lagg was almost double that in the bog; the DOC in the bog was similar to the surrounding upland. This indicates that DOC may accumulate in the lagg from bog runoff, where bog water is the dominant source of water to the lagg.

Vegetation Methods

Rigg and Richardson (1938) conducted a study of BC, Washington, and Oregon bogs, noting that many of the bogs were “bordered in part by swamps characterized by sedges, *Carex* spp., or hardhack, *Spiraea douglasii*”. In preliminary field investigations, it was observed that the Fraser Lowland bogs tend to be surrounded by hardhack and other species that are tolerant of a high and fluctuating water table (e.g. *Picea sitchensis* (Bong.) Carr., *Rhamnus purshiana* DC., *Malus fusca* Raf., *Rosa* spp., *Myrica gale* L., and *Lysichiton americanum* Hultén & St. John, whereas the northern bogs tend to blend into wet forest with only a subtle band of *Carex* spp. in the transition zone. A key research objective therefore was to determine the cause of this regional variation in bog and lagg plant communities.

Vegetation sampling followed Brett et al. (2001), using standard phytosociological methods for vegetation data collection (Mueller-Dombois and Ellenberg, 1974) and standardized taxonomic nomenclature for species identification (vascular plants: Hitchcock and Cronquist, 1973; bryophytes: Klinkenberg, 2012). Square vegetation plots were located in a portion of a plant community that was relatively uniform and representative in floristic composition, structure, and site attributes (e.g. slope position, aspect, gradient, and ground cover); the piezometers at each study site were always used as one corner of the vegetation plots. Species presence and cover were measured in 5 x 5 m vegetation plots. Species, height, and diameter of trees were measured in 10 x 10 m tree plots, from which basal area was calculated. Bog vegetation can be heterogeneous (patchy), thus the relatively large vegetation and tree plots were used in order to obtain a representative sample of the vegetation at each measurement site.

1.4. Structure of this Thesis

This thesis is “paper-based”. Seven papers are presented separately as chapters, which collectively advance the understanding of laggs of raised bogs in coastal BC. The final chapter summarizes the key findings of this study.

Chapter 2: The essential role of the lagg in raised bog function and restoration: a review

> This paper presents a literature review of lagg research to date, and builds a case for the importance of lagg research and including the lagg in raised bog conservation sites. This paper has been published as: Howie, S.A. and I. Tromp-van Meerveld. 2011. The essential role of the lagg in raised bog function and restoration: a review. Wetlands 31: 613-622.

doi: 10.1007/s13157-011-0168-5. Chapter 2 presents this paper as published, with the exception of minor editorial changes. The references are presented at the end of this thesis and the acknowledgements are given at the beginning of this thesis.

Chapter 3: Temporal variation in depth to water table and hydrochemistry in three raised bogs and their laggs in coastal British Columbia, Canada

This paper describes the results of the 1.5-year temporal study on depth to water table and hydrochemistry in three bogs (Burns Bog, Blaney Bog, and Campbell River bog), as well as the effects of clear-cutting at one lagg site on the depth to water table. This paper also includes a description of how depth to water table and hydrochemistry change across the bog expanse - bog margin transition and determined whether a one-time survey as used in the regional study of this thesis (Ch. 5-7) is representative (i.e. whether the spatial variation in depth to water table and hydrochemistry is greater than the temporal variation). This chapter addresses research questions 4 and 8. Appendix B shows the results of ANOVA tests to determine significant differences in hydrochemical characteristics across the study transects and over the 1.5-year sampling period. Appendix C provides additional information with respect to the most appropriate time of year for hydrochemical sampling.

This paper has been published as: Howie S.A., van Meerveld H.J. (2012) Temporal variation in depth to water table and hydrochemistry in three raised bogs and their laggs in coastal British Columbia, Canada, Hydrol. Earth Syst. Sci. Discuss., 9, 14065-14107, doi:10.5194/hessd-9-14065-2012. Chapter 3 presents the revised version of the manuscript that was submitted on March 9, 2013. The references are presented at the end of this thesis, and the acknowledgements are given at the beginning of this thesis.

Chapter 4: Small scale spatial variability in depth to water table, hydrochemistry, and peat properties in Burns Bog, Delta, BC

This paper describes a detailed investigation of small-scale spatial variability of some of the key study parameters. The purpose of this study was to determine whether a measurement (such as those used in this research) can be considered representative of the surrounding area. This chapter addresses research question 9. This paper has not been published at the time of preparation of this thesis, but is intended for submission to an academic journal, co-authored by H.J. van Meerveld. The references are presented at the end of this thesis, and the acknowledgements are given at the beginning of this thesis.

Chapter 5: Regional and local patterns in depth to water table, hydrochemistry, and peat properties of bogs and their laggs in coastal British Columbia

> This paper presents the local and regional gradients in depth to water table, pore-water chemistry, peat depth, and ash content for the 13 studied bogs. This paper addresses research questions 3 and 4. Appendix D shows the correlation between pH and calcium concentrations in pore-water samples. This paper, co-authored by H.J. van Meerveld, was submitted to Hydrol. Earth Syst. Sci. Discuss. on March 12, 2013.

Chapter 6: Regional vegetation patterns in bogs and their laggs in coastal British Columbia

> This paper describes the data from the 168 vegetation plots and 84 tree plots in the studied bogs, and answers research questions 3, 5, and 6. This paper describes the regional differences in plant community composition and species diversity in both bogs and laggs, and how these differences are related to gradients in climate and site-scale conditions (early summer depth to water table, pore-water chemistry, and peat properties). Appendix E provides a list of all plant species observed in this study. This paper has not been published at the time of preparation of this thesis, but is intended for submission to an academic journal, co-authored by H.J. van Meerveld.

Chapter 7: Hydrotopographic lagg forms and vegetative lagg types in coastal British Columbia bogs: vegetation response to environmental gradients

> This paper describes the lagg classification that was developed based on the results of chapters 5 and 6, and answers research questions 1, 2 and 6. A dichotomous key and graphic depiction of the lagg classification is presented in Appendix F. This paper includes a discussion about the relation between lagg plant community composition and environmental gradients. This paper has not been published at the time of preparation of this thesis, but is intended for submission to an academic journal, co-authored by H.J. van Meerveld.

Chapter 8: Characteristics of depth to water table, hydrochemistry, and vegetation of the lagg remnants of Burns Bog in British Columbia, Canada, and options for lagg restoration

This paper uses the information obtained in this study and an assessment of the existing lagg of Burns Bog to provide recommendations for conservation and restoration of the lagg of Burns Bog. Recommendations for conservation of additional lagg areas of Burns Bog are given in Appendix G. This chapter addresses research question 7. This paper has not been published at the time of preparation of this thesis, but is intended for submission to an academic journal, co-authored by H.J. van Meerveld.

1.5. Summary

The lagg is an integral element of the raised bog landscape unit. Most raised bog research to date has focussed on the bog itself, with little emphasis on the rand slope or lagg. Generally, these studies mention the lagg in passing, either briefly describing its character or commenting on the loss of the lagg to agriculture or development. The primary goal of this research was to substantially increase the knowledge of laggs of raised bogs of coastal British Columbia, specifically focusing on their hydrological, hydrochemical, vegetation, and peat characteristics. Aside from providing information to the scientific community about the gradients across the bog expanse – bog margin transition, this research may assist bog management agencies in managing and restoring raised bog ecosystems.

2. The essential role of the lagg in raised bog function and restoration: a review

Published as:

Howie, S.A. and Tromp-van Meerveld, I. (2011). The essential role of the lagg in raised bog function and restoration: a review. *Wetlands*, 31, 613-622. doi: 10.1007/s13157-011-0168-5.

2.1. Abstract

The lagg of a raised bog is a transition zone where runoff collects from the ombrotrophic (rain-fed) bog and adjacent mineral soils. Distinct hydrological and hydrochemical gradients exist across the lagg, resulting in specific plant communities. Little research emphasis has been placed on the lagg in the past, with studies tending to focus on the more easily-defined bog instead. Recently, peatland researchers have begun to discuss the importance of the lagg to raised bog restoration. This paper reviews current knowledge on laggs, the function of this transition zone, useful indicators to determine its location in the field, and argues that restoration of the lagg should be a key element in raised bog restoration.

2.2. Introduction

Lagg is a term in peatland ecology that refers to the transition zone between an ombrotrophic bog and the mineral soils of the surrounding landscape. Osvald (1933) was one of the first authors to recommend the use of the Swedish term "lagg" in the English literature, and defined lagg as the wet margin around a raised bog. Rigg (1925) and Rigg and Richardson (1938) used the term "marginal ditch", when referring to swamps and thickets found at the borders of the North American bogs they studied. Millington (1954) makes reference to a "lagg stream" drainage feature in Australian bogs, noting that the vegetation changes sharply on either side of the lagg. Damman and French (1987) define lagg as “the nutrient-enriched zone at the margin of a raised bog, receiving water from the surrounding mineral ground and from the bog itself”. The lagg is often referred to as minerotrophic and is generally described as containing fen plant communities (Rydin et al., 1999; Damman and French, 1987), although Rydin and Jeglum (2006) expand the definition to include swamp plant communities.

The lagg and rand are both elements of the raised bog margin. The rand is defined as the outward-sloping margin of a raised bog (Wheeler and Shaw, 1995) situated between the bog and the lagg. The lagg is most strongly developed in bogs with steep rand slopes and abundant runoff. Bogs with a low summer moisture surplus and flatter rand have a less clearly-defined lagg (Damman, 1979). Wheeler et al. (1995) note that smaller bogs generally lack the characteristic elements of a raised bog, such as hummock-hollow or pool-string systems, lagg, rand, and central plateau, suggesting that only large bogs produce the complete raised bog complex. Raised bogs that are physically constrained by basins often develop a “moat-like” lagg, where waters from the bog and surrounding upland converge and cannot easily escape from the topographic depression. A more diffuse lagg may form if the bog grows beyond the confines of the basin or if the surrounding landscape is relatively flat. Where rivers or streams converge with a raised bog, an entirely different form of “riparian” lagg develops in which the transition zone can be relatively abrupt and may be influenced by occasional flooding. Many of these different lagg forms have been described in reference to Burns Bog, a raised bog in western Canada, by Howie et al. (2009a).

The lagg may be lacking from some areas of the bog margin, be barely discernible, or not present as a distinct feature at all. This may occur in cases where the transition from bog to mineral soil is very gradual (Damman, 1977) or where the raised bog merges with a blanket bog or bog forest (Banner et al., 1986). Gorham (1950) conducted a detailed study of a “fen lagg” of a Swedish raised bog and found that the lagg was “clearly developed” in one quadrant of the mire whereas lagg development was “negligible” at other locations around the margin. Eurola (1962) and Aartolahti (1965) (as cited in Lindholm and Heikkilä (2006) and Laitenen et al. (2007)) both observed that a significant number of Finnish raised bogs do not contain laggs.

In order to describe this landscape feature in terms of the latest understanding of its form and function, we propose the following expanded definition for lagg based on the above definitions and the additional details presented in this paper:

> Lagg: a transition zone at the margin of a (usually raised) bog receiving water from both the bog and surrounding mineral ground, characterized by fen or swamp plant communities, transitional water chemistry, and shallow peat of relatively low hydraulic conductivity; the lagg transition may be sharp or diffuse (depending on the topography), or may not be present as a distinct feature.

We recommend using the general term “margin” to encompass both the rand and lagg transitional elements, or to refer simply to the bog border where these elements are not distinguishable, and using “lagg” specifically for the transition zone that develops where ombrotrophic bog waters mix with minerotrophic runoff. Fig. 1 summarizes the role of the lagg in graphical form. The dotted line represents the boundary between the acrotelm and catotelm, or the average low point of the water table. The water table drops in the rand, allowing increased tree growth at the margin of the bog. Water collects between the bog and upland, promoting the growth of sedges and other fen species. In contrast, the runoff in the gradual lagg transition diffuses over the surface, allowing larger shrubs and trees to establish. Bog water also spreads further in the flat lagg transition, particularly in winter, which strongly influences species composition at the bog margin. Calcium concentration and pH increase from bog to mineral soil. Hydraulic conductivity (*K*) is highly variable in the bog and often lower in the denser peat of the lagg. Each of these aspects is described in detail in this paper.

A lagg is an ecotone: a transition or tension zone between two adjacent plant communities evidenced by a relatively sharp change in plant species composition in space (Gosz and Sharpe, 1989; Groenveld and Or, 1994; Kent et al., 1997). An ecotone is dynamic, responding to fluctuations in environmental constraints, and can be a sensitive indicator of changes in influencing abiotic factors (Gosz and Sharpe, 1989) and the interactions with adjacent plant communities (Groenveld and Or, 1994). Since sharp changes in hydrology, chemistry, and species composition may occur across an ecotone (Gosz, 1992), these landscape forms are often high in biological diversity and productivity (Risser, 1995). The diverse species composition of laggs may thus be an important element in regional biodiversity.

Much research has focused on the abiotic/biotic characteristics and processes, history, development, and restoration of bogs. The majority of these studies have focused on the central bog expanse, with little discussion about the lagg. The exception is the literature related to the development and structure of raised bogs (e.g., Ivanov, 1981; Ingram, 1982, 1983; Hobbs, 1986; Damman and French, 1987). The classic model of raised bog formation often describes a wetland system passing through lacustrine and fen stages before peat accumulates to the point that part of the surface becomes ombrotrophic and drains towards a remnant marginal lagg fen (Ivanov, 1981; Svensson, 1988). McNamara et al. (1992) further expand upon the concepts of Ivanov (1981) and Ingram (1982) to suggest that differential accumulation of peat in some fens results in the formation of ombrotrophic conditions, whereby peat accumulation is supported both by impeded drainage and the presence of springs at the bog margins. Thus, where a lagg fen is present at the margin of a newly forming bog, the lagg may enhance peat accumulation and water mound formation due to low hydraulic conductivity of lagg peat and a water table supported by minerotrophic streams or springs in the lagg (McNamara et al., 1992).

Several studies have investigated the poor-rich gradient in peatlands, whether between separate fen and bog sites (Glaser, 1992; de Mars and Wassen, 1999; Tahvanainen et al., 2002; Hájková and Hájek, 2004) or along the "mire margin – mire expanse" gradient within a particular bog landscape unit (e.g., Sjörs, 1950; Malmer, 1986; Bragazza et al., 2005; Sottocornola et al., 2009). Most commonly, these studies attempt to isolate the key influences on plant species composition, such as depth to water table, acidity-alkalinity, and fertility (Bragazza et al., 2005). Field researchers examining the transition from bog center to margin rarely extend their study beyond the mire margin into the surrounding minerotrophic ecosystem (e.g., forest), and therefore tend to ignore the variable chemical composition of runoff from the adjacent landscape.

Only a few studies specifically looked at laggs. Blackwell (1992) explored the sources of water to the lagg of an Irish bog and developed a two-dimensional model of flow into the lagg. Similarly, Smit et al. (1999) focused on the hydrological conditions of a lagg in Scotland. Peregon et al. (2009) looked at the historic rate of lateral expansion of two Siberian raised bogs, which included characterizing the vegetation and geomorphology of the lagg. As illustrated in these examples, where research has been conducted in laggs, the goal is rarely to develop a holistic understanding of the lagg itself or its relation to the adjacent areas; rather, the lagg tends to be a venue for research on specific elements of this transitional zone, such as hydrology, hydrochemistry, or vegetation.

Marginal zones, such as the lagg, tend to be disturbed first due to agriculture or other development, and are frequently disturbed even for bogs that are in a (near) natural condition in their central parts. In studies related to restoration of raised bogs, there has been surprisingly little emphasis on restoration of the lagg system in conjunction with restoration of the associated raised bog. Hughes and Barber (2003) note that the “fen-bog transition” has received little research emphasis, and suggest that it is necessary to understand the mechanisms involved in this transition zone with respect to raised bog management and restoration. Holden (2005) similarly comments that researchers have only begun to think about integrating the area outside the bog in terms of hydrological management, while most restoration efforts continue to focus on the bog itself or just the area within the bog that has been set aside for conservation. Whitfield et al. (2009) recommend further research in the form of hydrological and hydrochemical transects across the transition zones between minerotrophic and ombrotrophic sites, and note that the “role of the lagg as a transition and as a boundary needs to be better understood and modeled”. In this paper, we review the form and function of the lagg transition zone, some useful lagg indicators, and argue that restoration of the lagg is a critical element in raised bog restoration.

2.3. Lagg Formation and Hydrology

As an ombrotrophic peatland develops, rising above the surrounding water table and spreading outwards, the minerotrophic (lagg) plant community usually becomes marginal and a small stream develops at the bog border (Godwin and Conway, 1939). The lagg stream shifts outward to accommodate the outward spread of the bog, but as a lagg stream deepens and the flow rate increases, the lagg may eventually become so deep and mineral-rich that *Sphagnum* growth will be inhibited and the lateral spread of the bog cannot continue (Godwin and Conway, 1939; Ingram, 1983). The water table of a raised bog can become elevated several meters above the water table in the lagg. Depth to water table is typically smallest in the bog center and increases towards the lagg, at which point the water table may reach the surface again as flow is impeded by topography or other physical barriers (Damman, 1986).

Ombrotrophic bogs are often described as being separate from the regional groundwater system; ombrotrophic literally means “rain-fed”. However, Glaser et al. (1997) presented evidence that raised bogs in northwestern Minnesota are buffered from changes in climatic conditions by groundwater recharge, suggesting that these bogs are not maintained by precipitation alone. Groundwater was found to move upwards into the water mounds of these raised bogs during drought conditions, whereas during wet periods the infiltrating water pushed the upwelling groundwater down and away from the bogs (Glaser et al., 1997). Since groundwater upwelling only occurred periodically and on a short-term basis, the pore-water chemistry and plant communities did not appear to be affected by this upwelling. McNamara et al. (1992) found similar evidence of upwelling, and suggested that the bog surface was not affected due to very slow movement of solutes through the peat. This groundwater influence could be an important element of raised bog formation in drier regions (Glaser et al., 1997).

The hydraulic conductivity of catotelmic peat is generally very low, and flow through the catotelm only represents about 1% of discharge from the bog; most excess water flows laterally through the acrotelm (Damman, 1986). The low permeability of the catotelmic peat results in rapid runoff during heavy rain events; runoff increases as the acrotelm becomes saturated (Bragg, 2002; Holden, 2005). The domed form of a raised bog causes all of this surplus water to pass through the rand and lagg, so that the bog margin receives the largest amounts of water (Damman and Dowhan, 1981). Because of the continuous saturation of the catotelmic portion of the peat mass, it is often assumed that there is water seeping out of the bog year-round to maintain baseflow in watercourses downstream (Bragg, 2002). However, there are instances during dry weather when water is retained within the lagg, or indeed when water is retained within the peat mass and does not reach the lagg at all (Bragg, 2002). Minor drainage features on the bog surface can dry up quickly in the absence of precipitation (Holden, 2005), and the lagg stream may become stagnant or even dry out (Hebda et al., 2000). The annual water table fluctuations are usually larger at the bog margin, and consequently the peat in the lagg is more aerated (both spatially and temporally) compared to that in the bog center (Økland et al., 2001). Low summer flows and high winter runoff create growing conditions that restrict the vegetation in the lagg to species that are adapted to a fluctuating water table and a range of nutrient conditions (e.g., *Spiraea*, *Malus*, *Betula*).

Baird et al. (2008) observed that the peat at the margins of a raised bog had a significantly lower hydraulic conductivity than peat in the bog center, suggesting that the marginal peat may assist in retaining water in central bog areas, and that this low hydraulic conductivity at the margin might allow the bog to grow higher than if the marginal peat was more permeable. A lower hydraulic conductivity in the lagg could indicate that the lagg peat is more similar to catotelmic peat than the more porous acrotelmic peat. However, Levrel et al. (2009) presented soil and peat profiles from eastern Canada showing that acrotelm and catotelm layers are present in the lagg, but that each layer is thinner than its counterpart in the adjacent bog. In addition, the von Post values (von Post 1924) in the peat profiles transitioned relatively sharply with depth in the lagg, changing from H1–H2 (slightly decomposed) to H5–H6 (moderately well decomposed) over a 15 cm depth, whereas they varied more gradually with depth from H1 to H7 in the bog proper (Levrel et al., 2009).

2.3.1. Influence of Adjacent Land Use

While raised bogs are fed only by rainwater (and in some cases periodically supported by groundwater upwelling in drier regions), the lagg is dependent on water from both the raised bog and the surrounding lands. Thus, if land use changes occur in the surrounding catchment, the lagg may be more sensitive to subsequent hydrological changes than the bog itself, which may partially account for the loss of most laggs in developed areas (Schouten, 2002). The relative independence of a bog from regional groundwater is only in the short to medium term. If regional groundwater levels become low enough, the water mound in the bog will drop, followed by compaction and shrinkage of the peat (Schouten, 2002).

The lagg plays a role in buffering the bog from the influence of mineral-rich water (Hebda et al., 2000). Once a bog develops an ombrotrophic center, the influence of mineral soil water is restricted to the lagg (Damman, 1986). However, it may not be possible for the lagg to adequately respond to anthropogenic changes in land use in the upland areas surrounding the bog, and the buffering capacity may be diminished or lost due to increased runoff entering the lagg from the surrounding areas. Once mineral-rich water enters a peatland, the water chemistry changes rapidly and impacts vegetation, peat chemistry, and rate of decomposition (Damman and French, 1987). These changes have been observed in Burns Bog, where mineral-rich runoff from surrounding industrial lands altered the plant community in a perimeter bog ditch from historic lagg species (e.g., *Spiraea douglasii* Hook*., Sphagnum* spp.) to a near monoculture of invasive reed canarygrass (*Phalaris arundinacea* L.) (Dr. Richard Hebda, personal communication).

2.4. Lagg Indicators

The lack of lagg-specific research may be due in part to the difficulty of determining the actual location of the lagg of a raised bog. While there may be a clearly defined band of vegetation indicating the transition zone at the bog margin, there are many instances where the lagg is not obvious to the observer in the field. Being a transition between two different ecosystems and receiving runoff from both areas, the characteristics of a lagg are influenced by both the bog and the surrounding landscape. The mineral and nutrient quality of the minerotrophic sites surrounding bogs can vary widely, and thus the characteristics (e.g., chemistry, vegetation) of laggs can be equally variable. This variation creates challenges for defining specific hydrochemical or vegetation characteristics for laggs, even within a particular geographic region. Although the topographic depression of the lagg can be precisely located with high-resolution survey techniques (e.g., LiDAR, total station), these methods are not often available in the field. In the absence of such data, there are a number of indicators that may assist in locating the lagg of a raised bog, benefitting not only field researchers but also those who may wish to define lagg boundaries for mapping or conservation purposes. In the following sections on chemistry and vegetation, we review the available literature on lagg-related research and discuss the utility of this information for lagg designation.

2.4.1. Chemistry

Ombrotrophic bogs are almost entirely fed by precipitation, resulting in relatively uniform hydrochemistry within a particular region. In contrast, the hydrochemistry of laggs is influenced by water from surrounding mineral soils and may vary widely within a region or even around a specific bog. Many researchers have proposed the use of chemical indicators to define the limit of influence of mineral soil water in ombrotrophic peatlands. Some of the most common measurements of the level of inflow of mineral soil water include pH, alkalinity, electrical conductivity, and calcium and bicarbonate concentrations in water (Bragazza and Gerdol, 2002; Bourbonniere, 2009). For example, calcium content can be ten times greater in mineral-influenced water than in bog water (Naucke et al., 1993; Hebda et al., 2000), where it is typically less than 2 mg/l (Tahvanainen, 2004). A pore-water calcium concentration of 1 mg/l may be the lower limit for fen species (Waughman, 1980). Calcium is thus a useful indicator of the lagg transition. Other ions that have been found in higher concentrations in the lagg than in the bog, and which may be useful indicators of the mineral soil water limit, include sodium, magnesium, aluminum, manganese, and silicon dioxide (Bragazza and Gerdol, 1999; Tahvanainen et al., 2002; Bragazza et al., 2005).

The Ca:Mg ratio has been suggested as another indicator of the mineral soil water limit. A ratio of less than 1 has often been used to indicate ombrotrophic conditions (Waughman, 1980). The Ca:Mg ratio in the upper peat layers of an ombrotrophic bog is typically less than that of rain water, indicating that the major source of calcium to the site is precipitation (Shotyk, 1996). If the measured ratio is higher than local rainwater, it is probable that the additional calcium is of minerotrophic origin (Weiss et al., 1997; Muller et al., 2006). Bragazza et al. (2005) found that the Ca:Mg ratio dropped sharply within a few meters of the minerotrophic margin, particularly where the slope of the rand was steepest.

A Ca:Mg ratio of 1 may point to the location of the ombrotrophic-minerotrophic divide in some bogs (Naucke et al., 1993). However, as mentioned earlier, the chemical composition of the lagg is influenced by runoff from the surrounding mineral uplands, which may result in a wide range of calcium and magnesium concentrations even at different locations around a single bog. The ratio is also influenced by the distance from the ocean and annual precipitation (Waughman, 1980). Glaser et al. (1990) and Proctor (2003) found a Ca:Mg ratio of less than 1 in some of the bogs they studied, whereas Vitt et al. (1995) observed a Ca:Mg ratio of 2.5 in a bog, compared to 1.2–1.8 in fen sites. Wells (1996) suggested a Ca:Mg ratio of 2.5 as the mineral soil water limit, while Bragazza and Gerdol (1999) recommended a limit of greater than 2. Clearly, these values are specific to the geographic regions of study, highlighting the importance of site specific research into laggs instead of assuming universal ion concentrations. A general Ca:Mg ratio cannot be used to identify the mineral soil water limit unless a broad assemblage of these ratios has been measured for a representative number of bogs in the region of interest, and the average chemical composition of rainwater is known (Shotyk, 1996).

pH is another well-established measure used to differentiate between bogs and fens (Tahvanainen, 2004; Sjörs and Gunnarsson, 2002; Vitt et al., 1995). Calcium may be correlated with pH across the lagg transition, and it is common for both indicators to be used when surveying the poor-rich gradient (Tahvanainen, 2004). For example, Balfour and Banack (2000) used these two key indicators to define three broad water types for Burns Bog. Type I (pH: 3.5–5.5; Ca^{2+}: 0–3 mg/l) was defined as “bog water”, correlating closely with typical bog plant communities and the extent of the water mound. Type II (pH: 4.5–6.0; Ca^{2+} 3–10 mg/l) was “transitional water” surrounding the bog water but remaining within the peat mass. The presence of this transitional water type, and vegetative indicators, were used to delineate the locations of remnant lagg areas (Hebda et al., 2000). Type III water (pH: 5.0–8.0; Ca^{2+}: >10mg/l) was found outside the peat deposit and thus defined “non-bog water”. This minerotrophic water type was rich in dissolved anions and cations, contained high concentrations of ammonia, iron, and manganese, and had a high electrical conductivity (Hebda et al., 2000). Glaser (1992) reported similar values for the bog – rich fen gradient in Minnesota peatlands: bog / poor fen, pH 3.7–4.6 and Ca^{2+} 0.6–5.5 mg/l; weakly minerotrophic fen, pH 4.1–5.9 and Ca^{2+} 0.9–13 mg/l; transitional rich fen, pH 5.9–6.8 and Ca^{2+} 10–32 mg/l. A number of researchers have reported a bimodal distribution in the pH of peatlands, with bog pH below 4.5–5.0 and fen pH above 5.5–6.0 (Wheeler and Proctor, 2000; Bourbonniere 2009), although a bimodal distribution is not found in all cases (e.g., Økland et al., 2000).

Blackwell (1992) used electrical conductivity (EC) as an indicator of the origin of water in the lagg of an Irish bog. Bog water is low in solutes, and thus has a very low EC. As ion concentrations increase toward the margin of the bog, so does the EC (Rydin and Jeglum, 2006). EC measurements across the lagg therefore may indicate where the low conductivity water from the bog meets the water from the surrounding minerotrophic lands. Blackwell (1992) found that EC increased with depth and with proximity to a ditch at the bog border. Bubier (1991) similarly found that electrical conductivity increased significantly in the transition from open bog to rand forest and lagg.

Mitchell et al. (2008) found "hotspots" of methylmercury (MeHg) in the upland/peatland interface of bogs in Ontario and Minnesota, particularly within 5 m of the upland interface. MeHg was higher in the lagg than in either the upland or bog, suggesting that these hotspots are a result of net MeHg production within the lagg itself, rather than transport into the lagg from either the upland or the bog, although they do allow for the possibility of accumulation of MeHg-rich runoff in the lagg in addition to *in situ* production. In a related study, Richardson et al. (2010) observed elevated concentrations of sulfate, pH, total mercury, and MeHg in lagg areas (determined using LiDAR data) of forested wetlands.

Despite the value of the above chemical parameters for assisting field researchers in determining the location of the lagg and the mineral soil water limit, it should be noted that the bog-lagg transition is a continuous gradient with considerable overlap between fen and bog water types that does not display discrete boundaries (Sjörs and Gunnarsson, 2002; Bourbonniere, 2009). Wheeler and Proctor (2000) have even suggested abandoning the mineral soil water limit as a useful boundary between ombrotrophic and minerotrophic sites, due to inconsistencies in the correlation of vegetation and water chemistry. On the other hand, Økland et al. (2001) argue that the mineral soil water limit is hydrologically distinct and "characterized by at least a local set of indicator species" and suggest that it remains a useful concept. We concur with Økland et al. (2001) that the mineral soil water limit is useful and may be a key element in locating the lagg within the bog margin – bog expanse gradient. However, it should be stressed that the hydrochemical gradients causing vegetation changes across this transition zone are site specific, only locally valid (Wheeler and Proctor, 2000; Bragazza et al., 2005), and change seasonally (Fig. 1).

2.4.2. Vegetation

Dense tree and shrub layers tend to be associated with the lagg (Rydin et al., 1999), with sedges and herbaceous species making up the understory (Hebda et al., 2000). Peat is relatively shallow in the lagg (e.g., <0.5 m), allowing deeply rooted vascular plants to make contact with the underlying mineral soil (Gorham, 1950; Rydin et al., 1999). Surface water in the lagg generally flows faster than in the bog, and therefore is more aerated than the often stagnant bog water, enabling growth of plant species that are not tolerant of bog conditions, e.g., those that lack aerenchyma or depend on mycorrhiza (Rydin et al., 1999). Since trees and larger shrubs are able to colonize the lagg, productivity is much higher in the lagg than the center of a raised bog. Damman (1979) reports that nutrient-poor fen vegetation in a lagg is 10–20 times more productive than vegetation in the bog center. Despite a higher productivity in the lagg, the lack of aeration and lower pH in the bog center results in a much-reduced rate of decomposition and faster peat accumulation in the bog center than in the lagg.

The plant species composition of the lagg is strongly influenced by the amount, level, fluctuation, and chemical quality of the water from the bog and surrounding lands (Ivanov, 1981), in other words, the depth to water table and the pore-water/peat chemistry (Hájková and Hájek, 2004; Bragazza et al., 2005). The variation of these environmental gradients across the “bog margin - bog expanse” transition will affect not only species composition, but also the distribution and vegetational patterns (Jeglum, 1971). Hydrochemical changes are associated with both plant species composition and physiognomic variations within species (Damman, 1986). When it is not possible to conduct detailed field observations on the hydrological and hydrochemical properties of the lagg transition, it may be possible to use vegetational changes as an indicator of these lagg characteristics (Howie et al., 2009a).

Since runoff from bogs will tend to be similar to rainwater, it is the mineralogy of the parent materials surrounding the bog that will, in part, determine the variability of lagg species around the bog perimeter (Damman and French, 1987). The origin and thus hydrochemistry of this water is dependent on the types of mineral deposits it has passed through and the time spent in each soil type (Schouten, 2002). The soil and vegetation of the surrounding landscape are usually not uniform around a raised bog, resulting in variable species composition at different locations within the lagg. For example, Damman and Dowhan (1981) observed that most of the lagg surrounding a bog in Nova Scotia consisted of an extremely nutrient-poor fen, but one section of the lagg was characterized by a richer fen as a result of a stronger influence by minerotrophic waters.

Some researchers have suggested that one can use fen species as an indicator of the mineral soil water limit (e.g., Rydin et al., 1999). This idea is based on the premise that most species are not tolerant of ombrotrophic conditions, and thus would only be present if the mineral/nutrient conditions support species not typical for a bog environment. However, there are a number of reasons, other than the presence of the lagg, that fen or swamp species may be present in a bog. For example, some bogs may be young or very slow in developing, such that the depth of peat is less than the rooting zone of some species, allowing non-bog species to survive in what is technically an ombrotrophic environment (Glaser et al., 1990). In other instances, mineral soaks or flushes may appear in the center of a bog (Schouten, 2002) and not be related to the lagg at the bog margin. One must also keep in mind the geographic variation in species distribution; a genus that is only found in fens in one part of the world may be tolerant of bog conditions in another region. In order to identify fen indicator species for a particular site, one must be aware of the response of plant species to the abiotic conditions specific to that site (Bragazza et al., 2005). If the distribution of particular species can be correlated to other parameters across the lagg transition, such as pH or calcium concentrations, it may be acceptable to consider these as indicators of the mineral soil water limit or lagg transition.

2.4.3. Tree Height and Density

A raised bog is often open in the center with scattered, dwarfed coniferous trees, while the lower rand may support a marginal forest (Rydin et al., 1999). Tree growth in peatland margins is related to increased nutrient availability, a lower water table resulting in peat aeration, and peat decomposition (Bubier, 1991; Bragazza et al., 2005). The high water table limits tree development in the bog center (Freléchoux et al., 2004). The greater slope, more rapid drainage, and steeper hydraulic gradient result in a lower water table below the rand of a raised bog (Ingram, 1983). As the water table drops through the rand and nutrient concentrations increase in the bog margin, the typical vegetation response is an increase in tree height and density (Malmer, 1986). Howie et al. (2009a) studied historic air photos of Burns Bog and determined that tree height increased through the rand. Freléchoux et al. (2004) found similar results in Switzerland, where pine trees at the margin of a bog grew on average three times faster than those in the wettest study plots (where there were also numerous dead pines). Bubier (1991) similarly found a significant increase (approximately double) in tree height in the rand adjacent to a lagg stream. Drainage of a peat bog can exacerbate this effect, improve growth and allow trees to invade and establish further toward the center of a bog (Brooks and Stoneman, 1997).

In terms of tree density, Freléchoux et al. (2000) observed a low density of small pine trees in the central, wetter parts of bogs, compared to a higher density of taller pines in the drier rand of the bog. Bubier (1991) found similar results for *Picea mariana* (black spruce) for a raised bog in Vermont. However, the trend in tree density across the bog margin can be less clear in the presence of other tree species; Freléchoux et al. (2004) looked at the pine-spruce interface and found that pine density decreased as spruce density increased towards the bog margin. Once trees have become established in the rand, they further enhance conditions for their own growth through increased evapotranspiration and nutrient additions via leaf litter (Damman and Dowhan, 1981), leading to higher rates of seedling establishment and subsequently greater stand density.

Tree growth increases in the rand (Damman and French, 1987), and can be used to indicate the general region of transition from bog to lagg. The presence of tall and dense trees may indicate the lower rand or the zone immediately adjacent to the lagg rather than the lagg. The lagg itself tends to be an area where water collects as it leaves the bog. For example, Keogh and Pippen (1984) observed a high water table in laggs following rain, and Malmer (1986) showed that water level fluctuations are more extreme at the bog margin where the water table rises quickly after rain and drops quickly during drought. Due to the relatively high and fluctuating water table, this zone is often associated with floating *Sphagnum* species (e.g., *S. cuspidatum* Ehrh. ex Hoffm.) (Keough and Pippen, 1984), sedges, and shrubs (Hebda et al., 2000). However, there are also cases where water does not collect in a topographic depression between bog and upland, but rather diffuses gradually across relatively flat land (Fig. 1; Howie et al. 2009a). In these situations, the water table may be lower and larger trees (e.g., swamp forest) may dominate the lagg vegetation (Hebda and Biggs, 1981; Hebda et al., 2000).

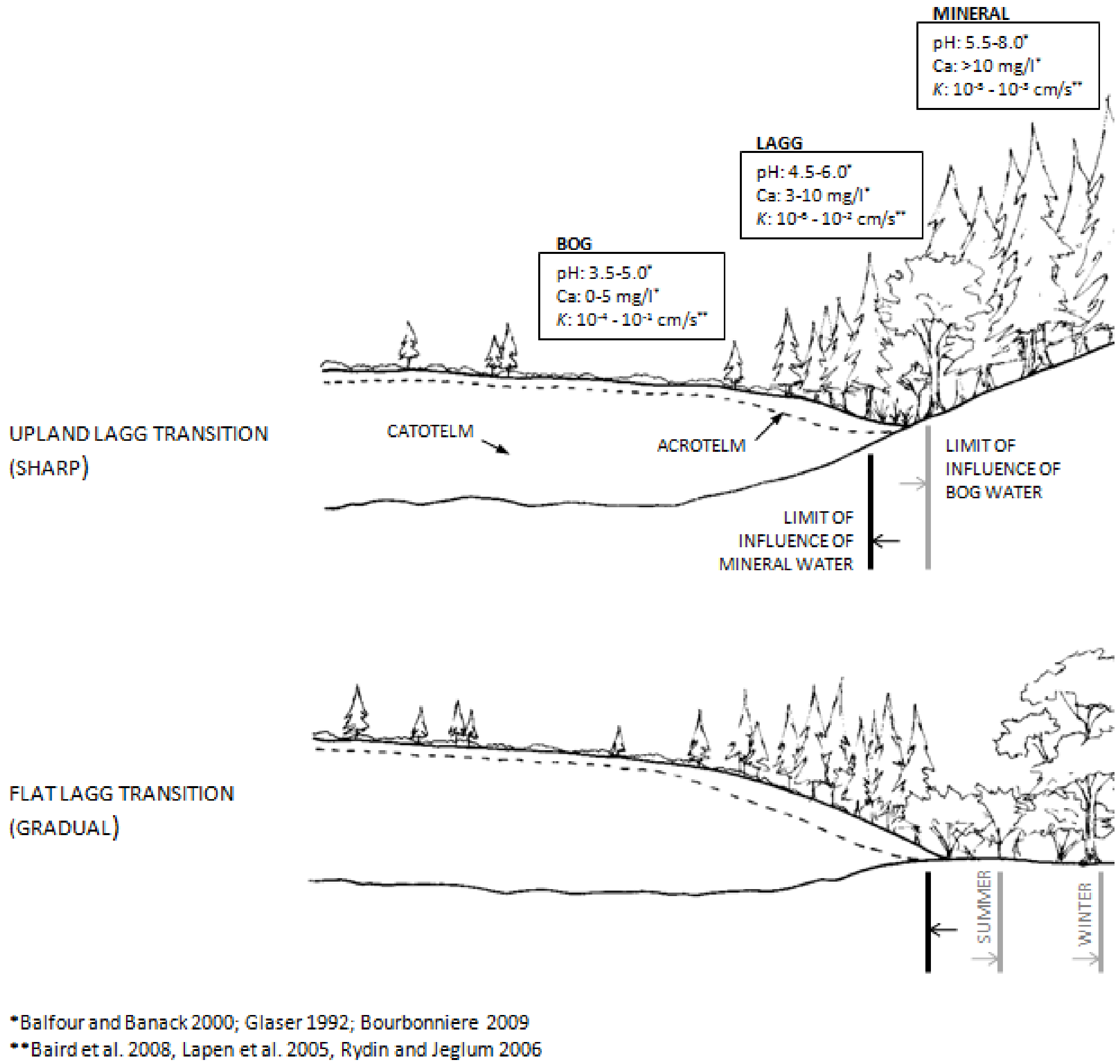

Figure 1. ***Cross section of two lagg forms (upland and flat), with associated hydrological, hydrochemical, and vegetative characteristics of each. Calcium, pH, and hydraulic conductivity values are compiled from numerous studies for illustrative purposes; actual values will vary by region.***

2.5. The Role of the Lagg in Raised Bog Restoration

Raised bogs have been heavily impacted by peat mining, agriculture, and drainage worldwide. Bogs that have been mined and/or drained do not usually regenerate to a proper functioning condition without intervention (Price et al., 2003) due to increased evapotranspiration, dry surface conditions, crust formation, peat compression, and forest encroachment. The two main bog restoration techniques currently used are rewetting and revegetation (Price et al., 2003). Rewetting can be achieved by ditch blocking, construction of “bunds” or dykes around the peat mass, or digging lagoons to raise the water table locally (Wheeler and Shaw, 1995). Rewetting is generally a pre-requisite for revegetation. Natural recolonization may be supplemented by transplanting from suitable donor sites, seeding with local stock, or broadcasting diaspores of *Sphagnum* and other bog species. Tree removal may assist in the establishment of desired plant species (e.g., *Sphagnum*) by removing a significant source of evapotranspiration, leaf litter, and shade. Two examples of current restoration projects include Burns Bog in western Canada (Howie et al., 2009b), and the Bois-des-Bel peatland in eastern Canada (Andersen et al., 2010).

Increased drainage as a result of peat mining or agriculture may have long-term impacts on the water balance of a bog. Drainage of the lagg leads to increased runoff from the bog and less storage in the bog (Blackwell, 1992). Thus, drainage management at the border of the bog and beyond may be important to protect the hydrological function of the adjacent raised bog (Wheeler and Shaw, 1995; Ginzler, 1997). In terms of hydrological restoration of a raised bog, the lagg must perform two key functions: i) sustain the dome of water in the peat body by maintaining a high water level in the lagg and, ii) allow for excess water to leave the bog during times of high precipitation and runoff.

It has been recommended by a number of researchers that a buffer zone be included in any raised bog conservation area. Burlton (1997) includes the “catchment” that feeds the lagg system from outside the bog as an important element in conservation because the water level in surrounding lands impacts the water level in the lagg, which in turn influences the hydrology of the bog. Schouwenaars (1995) used the term “hydrological buffer zone” to recommend retaining a high water level in the lagg, thereby reducing the hydraulic gradient and promoting a higher water table in the bog itself.

Encouragingly, some discussion of lagg restoration has appeared in recent western European literature. In reporting on the Dutch-Irish bog restoration collaborative of the 1990s, Schouten (2002) emphasized the importance of restoring the hydrological conditions of laggs when attempting to restore Irish bogs. Brooks and Stoneman (1997) discuss the use of perimeter clay bunds around a raised bog in the re-creation of a lagg fen system, where mineral enrichment from the clay is acceptable at the bog border provided that the water table does not rise above the bog surface. Restoration of four lowland raised bogs in Cumbria, northwest England, included rewetting of the bog border and adjacent farmland to re-establish lagg conditions (Mawby and Brock, 2007). The UK Joint Nature Conservation Committee has introduced the concept of "hydrological protection zones" for the lagg areas around raised bogs; areas outside the peat body may be included in the conservation area such that the water table in these areas can be raised to support the water table in the bog (Morgan-Jones et al., 2005). The purpose of these hydrological protection zones is to maintain suitable hydrological conditions within the raised bog and to allow the occasional/seasonal flooding that naturally occurs in a lagg. Sottocornola et al. (2009) recommend the conservation of peatland borders and nearby areas of an Irish blanket bog to increase the plant biodiversity of the bog conservation area.

In North America, relatively little emphasis has been placed on lagg restoration to date. Most bog restoration research projects focus on restoring *Sphagnum* cover to remnant or cut-over sections of peatlands, rather than attempting to restore the function of the complete raised bog system. In 2006, an interdisciplinary technical workshop with invited government and academic experts was held in Vancouver, British Columbia to discuss lagg concepts in relation to the restoration of Burns Bog. The key message from the workshop was that it is important to restore the lagg at the same time as the bog is restored. It was noted that a high water table in the lagg will and must support the raising of the water table in the bog proper. The title of the document resulting from the workshop was "A Lagg is not a Ditch" (Peart, 2006). This referred to the perimeter ditches that surround Burns Bog (and other bogs) and inferred that they do not function like a natural lagg in terms of hydrology, hydrochemistry, and ecology. The central question, in this case, is whether a functional lagg can be artificially created for a degraded raised bog. Research focused on lagg characteristics and function (including hydrology, hydrochemistry, vegetation, and geomorphology) is necessary to answer these types of questions for restoration of damaged laggs, and correspondingly, for the restoration of the bog with which the lagg is associated.

3. Temporal variation in depth to water table and hydrochemistry in three raised bogs and their laggs in coastal British Columbia, Canada

An earlier version of this chapter was published as:

Howie, S. A. and van Meerveld, H. J. (2012). Temporal variation in depth to water table and hydrochemistry in three raised bogs and their laggs in coastal British Columbia, Canada, Hydrol. Earth Syst. Sci. Discuss., 9, 14065-14107, doi:10.5194/hessd-9-14065-2012.

3.1. Abstract

The laggs of three raised bogs in coastal British Columbia were studied in 2010 - 2011 to determine the temporal variation in depth to water table and hydrochemistry across the bog expanse – bog margin transition. The lagg is an integral, but rarely studied, part of a raised bog that may help to maintain the water mound in the bog and provides a buffer for runoff from adjacent mineral areas. Water level measurements in 25 piezometers displayed similar annual fluctuations, with the highest water level in winter and the lowest at the end of summer. The smallest fluctuations were recorded near the bog centre, and the largest fluctuations in the lagg and adjacent mineral soil sites. The hydroperiod of a bog or lagg in this region may be roughly approximated with a few measurements at key times of the year, such as winter, late spring, and at the end of the dry season in summer. Removal of a mature forest stand on one of the study transects resulted in a "watering-up" of the lagg site; the mean water level between August and November was 8 cm higher in 2011 than in 2010, while the mean water level between August and November was on average 13 cm lower in 2011 than in 2010 for the unlogged sites on the same transect. pH, pH-corrected electrical conductivity, and Na^+ and Mg^{2+} concentrations varied little during the study period, whereas Ca^{2+} and Cl^- concentrations and acidity were more variable. Mg^{2+} concentrations and pH increased most often from the bog to the lagg and mineral soil sites, but not for all study transects.

Despite this spatial trend, hydrochemical parameters were not consistently useful for determining the location of the lagg.

3.2. Introduction

The lagg is the transition zone at the margin of a raised bog, receiving water from both the bog and the surrounding mineral soil. Due to the lower peat depth in the lagg, and its location at the margin of the bog, the lagg is often the first area of the raised bog ecosystem to be damaged by drainage and conversion to other land uses (e.g. agriculture, industry). However, the lagg is an integral element of a raised bog because a high water table in the lagg helps to maintain the water mound in the bog by reducing the outward hydraulic gradient (Wheeler and Shaw, 1995; Lapen et al. 2005). The lagg is also a buffer zone that protects the bog from nutrient-rich upland runoff. Despite the importance of the lagg for a properly functioning raised bog ecosystem, little is known about the hydrological and hydrochemical conditions in the lagg, or even how many repeated measurements are needed to characterize the spatial gradients in depth to water table and hydrochemical characteristics across the bog expanse – bog margin transition. These spatial gradients in hydrology and hydrochemistry are correlated with plant species composition (Ivanov, 1981; Damman and French, 1987) and provide important information about the health of a bog (Price et al., 2003; Rydin and Jeglum, 2006).

The depth to water table and the seasonal water table fluctuation is generally smallest in the bog, greater in the outwardly-sloping rand forest at the bog margin, and greatest in the lagg (Schouten, 2002; Malmer, 1986; Damman, 1986). However, the fluctuation of the water table in undisturbed laggs may be less predictable than those in the bog due to the additional influence from upland runoff as water table fluctuations in the lagg are also determined by the topographic conditions around the margin of the bog. Freely-draining laggs, and areas that receive comparatively little discharge from the bog and surrounding upland areas, may be characterized by a smaller water table fluctuation than laggs that are topographically constrained and experience frequent flooding (Damman and Dowhan, 1981; Howie and Tromp-van Meerveld, 2011).

Depth to water table measurements are the most common form of hydrological monitoring in bogs because they reflect the entire water balance, the individual components of which are much more difficult to measure (Bragg, 2002). These measurements also provide important information on the health of a raised bog ecosystem. In places where bogs are at their climatic limit, or where bogs have been drained, mined, or afforested, the fluctuation of the water table can be an important indicator of the ecological health and future trajectory of the bog ecosystem. Depth to water table is closely related to plant form, distribution, and growth (Rydin and Jeglum, 2006). A high water table supports the soil moisture and soil-water pressure required for survival of *Sphagnum* colonies, the main peat-forming species in raised bogs. Most *Sphagnum* colonies grow in places where volumetric moisture content is above 50%, and where soil-water pressure is greater than -100 cm (Lavoie et al., 2003). Drier conditions prevent capillary movement of water to the bog surface, and since the non-vascular *Sphagnum* cannot survive long periods of drought and desiccation, this ultimately leads to the death of *Sphagnum* colonies (Lavoie et al., 2003; Price et al., 2003). If the summer water table frequently drops more than 40 cm below the surface, non-bog species such as *Betula* may outcompete *Sphagnum* due to their ability to tolerate a more widely fluctuating water table (Price et al., 2003). Drainage to facilitate peat mining, agriculture, or other activities lowers the water table, and can also result in irreversible changes to peat structure, including surface subsidence, compression, and oxidation, leading to changes in the hydraulic conductivity and a lower water retention capacity of the peat (Hobbs, 1986; Price et al., 2003; Holden et al., 2004). These conditions pose significant challenges for the regeneration of *Sphagnum*, and may lead to the establishment of alternate plant communities (e.g. forest).

Afforestation of a peatland may occur naturally in a drying climate, in response to disturbance (such as drainage or peat mining), or as an intended land use change. The result of afforestation is typically a lower water table, due to the increased interception and evapotranspiration losses (Fay and Lavoie, 2009). For example, Anderson et al. (2000) found a significant (mean: 7 cm) decline in water table compared to the control site two years after afforestation of a blanket bog. The opposite response occurs when trees are removed from peatlands; the rise in water table associated with decreased interception and evapotranspiration losses is commonly referred to as the “watering-up” effect (Jeglum et al., 2003; Päivänen and Hånell, 2012). The rise in water table following clearcutting is, on average, about 5 cm (Roy et al., 2000). Heikurainen and Päivänen (1970) found a water table rise of 5-14 cm following clearcutting of a forested peatland in Finland; the lower the pre-clearcut water table, the greater the water table rise following clearcutting. Roy et al. (1997) observed a mean water table rise of 4-6 cm after clearcutting an Ontario peatland.

Major cation and anion concentrations are typically higher at the bog margin than in the centre of the bog due to the influence of adjacent and underlying mineral soil (Naucke et al., 1993; Bragazza and Gerdol, 1999; Tahvanainen et al., 2002). For example, Bragazza et al. (2005) found for an Italian and Swedish raised bog that concentrations of Ca^{2+}, Mg^{2+}, Al^{3+}, Mn^{2+}, and SiO_2 in pore-water were higher in the lagg than the bog. The pH of pore-water is generally also lowest in the bog centre, and highest in the marginal lagg (Bubier, 1991; Bragazza et al., 2005). As concentrations of base cations and nutrients increase approaching the lagg, non-bog plant species such as sedges, deciduous shrubs, and trees are able to colonize and outcompete *Sphagnum*. Balfour and Banack (2000) used these chemical patterns to develop a classification of water types in Burns Bog, BC, Canada: Type I (bog/ombrotrophic water), pH 3.5 – 5.5, Ca^{2+} 0-3 mg/l; Type II (lagg/transitional water), pH 4.5-6.0, Ca^{2+} 3-10 mg/l; Type III (terrestrial/minerotrophic water), pH > 5.0-8.0, Ca^{2+} >10 mg/l. The lagg water type (Type II) was often found in areas characterized by a dense thicket of *Spiraea douglasii* Hook (Balfour and Banack, 2000; Hebda et al. 2000). It has also been suggested that the Ca:Mg ratio may indicate the location of the mineral soil water limit at the edge of a raised bog, whereby a ratio higher than 1-2 signifies a transition from ombrotrophic to minerotrophic conditions (Naucke et al., 1993, Glaser et al., 1990; Proctor, 2003; Lähteenoja et al., 2009), although the exact value varies depending on the chemical composition and amount of precipitation (Waughman, 1980; Shotyk 1996).

The chemistry of surface and near-surface pore-water in raised bogs is influenced by the chemical characteristics of precipitation, as well as evapotranspiration and biological activity (Naucke et al., 1993). Ombrotrophic bogs are nutrient deficient because atmospheric deposition, i.e. precipitation and dustfall, is usually the sole source of nutrients (Damman, 1986). Concentrations of nutrients in bog water are most similar to those in precipitation during times of high precipitation or snow melt (Damman and

French, 1987). As the water table declines during summer, evapotranspiration and subsequent concentration of major ions in the peat generally results in higher concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, and Cl^{-}, which causes the electrical conductivity to increase and pH to decrease (Proctor, 1995; Adamson et al., 2001). However, some studies have shown that undisturbed bogs are characterized by more stable concentrations of these elements than disturbed bogs, due to the ability of the *Sphagnum*-dominated surface of undisturbed bogs to buffer the chemical inputs (Andersen et al., 2010; Nelson et al., 2011) as a result of its high cation exchange capacity. For example, in a compilation of surface water data, Sjors and Gunnarsson (2002) noted that the effect of rainwater dilution in Swedish peatlands was temporary and that pH and cation concentrations in surface water were not highly variable, except for the strong dilution effect during snowmelt. Proctor (1994) observed that water chemistry was most stable for a blanket bog in a wet, oceanic climate and most variable in a raised bog in a drier climate.

The few studies on the temporal variability in water chemistry in bogs usually had a sampling frequency of 1-2 months (e.g. Wieder, 1985; Proctor, 1994; Andersen et al., 2010). Little is known about how water chemistry changes in bogs over shorter time periods (i.e. hours or days) in response to rainfall events. There is also little information about the sampling frequency that is necessary to determine the hydrochemical characteristics of bogs and their marginal zones. Management agencies generally do not have sufficient resources for frequent measurements, and thus it is important to determine how variable the hydrochemical gradients are in order to assess the value and representativeness of the measurements. If a one-time survey can reasonably characterize the hydrological and hydrochemical conditions in a bog and its lagg, this would lead to significant savings, and perhaps several bogs within an area can be studied or surveyed prior to developing regional bog management plans. If a one-time survey does not provide representative information on the hydrological and hydrochemical conditions in bogs and their laggs, repeated surveys are needed before management and protection plans are developed.

The objectives of this study were therefore: *i*) to improve the knowledge of the temporal variation in depth to water table and pore-water chemistry in coastal raised bogs in southwest BC, and in particular how these changes relate to the rarely-studied marginal lagg, *ii*) to determine whether a single sampling event is sufficient to characterize the hydrochemical gradients across the bog expanse – bog margin transition in coastal BC, and *iii*) to document the "watering-up" effect due to unexpected clearcut logging on one of the study transects. Our hypotheses were: *i*) that the water table in bogs follows a broadly similar pattern each year due to the close association between the depth to the water table and precipitation and evapotranspiration (Malmer, 1986) and that the lagg has a similar hydroperiod (i.e. the repeating and predictable cycle of water table fluctuations over time) as the open bog area, *ii*) that the hydrochemical gradients across the bog expanse – bog margin transition in early summer (June/July) are reasonably representative of the gradients throughout the entire year because this time of year has neither extended dry periods nor high rainfall, which can cause concentrations to increase or drop (Vitt et al., 1995), and *iii*) that the water table in the logged lagg site would be higher compared to the pre-logged condition and other lagg sites, due to the reduction in interception and evapotranspiration caused by the loss of the tree canopy.

3.3. Study Sites

Raised bogs are common in coastal British Columbia. Their distribution is determined primarily by climate (specifically the balance between precipitation and evapotranspiration) and the morphology of the land surface (National Wetlands Working Group, 1988). For example, in the Fraser River delta, 10-25% of the land area is covered by wetlands, while the surrounding Fraser River lowland contains 5-10% wetlands (National Wetlands Working Group, 1988). Apart from Golinski (2004) who developed a regional vegetative classification for Vancouver Island peatlands and compared the hydrology and chemistry of disturbed and undisturbed peatlands, a few local studies by university classes (e.g. Trinity Western University), and monitoring programs by wetland management agencies (e.g. for Burns Bog in Delta, BC), little is known about the seasonal and spatial variation in water level and hydrochemical characteristics of bogs in southwestern BC. We therefore studied six transects across the bog expanse-bog margin transition. Three transects located in Burns Bog (Delta, BC) were studied from June 2010 – December 2012, two transects in Blaney Bog (Maple Ridge, BC) were studied from June 2010 – December 2011, and one transect was studied in Campbell River Bog (Campbell River, BC) in May 2010 and May 2011 (Fig. 2, Table 1). Annual precipitation was lower in 2011 than in 2010, but precipitation in spring and summer was higher in 2011 than in 2010, except for Campbell River Bog (Table 2).

Burns Bog is a 3,000 ha raised bog situated on the Fraser River delta; it is bound to the north by the Fraser River and to the south by Boundary Bay. Peat extraction between the 1930s and the mid-1980s resulted in an extensive network of drainage ditches and a lowered peat surface in the central area of the bog. Despite this disturbance, 29% of Burns Bog remains relatively pristine. Much of the Burns Bog lagg has been lost to drainage, filling, and conversion to other land uses (i.e. agriculture, industry, and roads). However, some remnant lagg sites are relatively undisturbed. Three of these remnant lagg sites were studied from June 2010-December 2011: Sherwood Forest (swamp forest on peat adjacent to a slough), Cranwest (historically a relatively flat transition from the bog to a river delta), and the Delta Nature Reserve (DNR) (swamp forest adjacent to an upland) (Fig. 2, Table 1). A portion of the Sherwood lagg was unexpectedly logged halfway through the study period. The logged area was approximately 4.7 ha in size, and dominated by a second growth stand (~500 stems/ha) of western red-cedar (*Thuja plicata* Donn.) ranging from 10-40 m (median: 28 m) in height and 5-100 cm (median: 35 cm) in diameter. Measurements at this site were taken until December 2012.

To compare data from this study with longer time series, results from four other piezometers and one well in Burns Bog are reported here as well. For comparison of water level data, we include data from a piezometer that was installed in 2006 in an open bog site near the Sherwood transect (Fig. 2) and data from a piezometer and a well in the southeastern part of Burns Bog (Fig. 2). For pore-water chemistry, we present data from two piezometers (PF-100 and PF-200) installed in 2010 in a bog forest dominated by *Pinus contorta* var. *contorta* and *Gaultheria shallon* Pursh, 100 and 200 m from the bog margin, respectively, in the southeast corner of Burns Bog (Fig. 2). These hydrochemical data are not considered representative of the entire 3,000 ha bog area but are included to provide more information about the temporal variability of the hydrochemical conditions (i.e. cation and anion concentrations) for comparison with the transect data and the repeated measurements of electrical conductivity and pH of this study.

Blaney Bog is a 130 ha bog/fen complex in the Pitt River valley and a rare example of an undisturbed bog in the Greater Vancouver area. The wetland complex includes riparian, marsh, fen, and bog features (Gebauer, 2002). Approximately 10% of the wetland area consists of coalescing islands of raised bog that are developing over the fen surface (Gebauer, 2002). The entire lagg of the developing bog remains intact, providing a unique opportunity to study two undisturbed laggs that transition to an upland forest and a spring fen (Fig. 2).

The Campbell River site (~ 5 ha) contains a complex of open bog, bog forest, fen, and shrub thicket swamp. The bog has been partially impacted by roads to the east and north, and possibly by logging in the adjacent upland, but the studied lagg adjacent to a minerotrophic upland on the west side of the bog appears to be relatively undisturbed.

There were five sampling locations across each of the six studied lagg transects: *1*) inside the bog (“BG”), *2*) between the bog and lagg (closer to bog; “R1”), *3*) between the bog and lagg (closer to lagg; “R2”), *4*) approximate centre of the lagg (“LG”), and *5*) outside the bog (“MN”). These five locations were determined in the field based on vegetation characteristics. BG sites were defined as *Sphagnum*-dominated heath or open woodland heath, LG sites were defined either as *Spiraea*-dominated or containing larger shrubs and trees than the bog, and MN sites were defined as the forest surrounding the bog. The laggs on the Sherwood and DNR transects were large and spatially variable in terms of vegetation, which suggests a difference in depth to water table and hydrochemistry. Therefore, there were two exceptions to this transect configuration: the Sherwood Forest transect contained a second LG study site due to changes in plant species composition across the lagg. The Delta Nature Reserve transect also contained two LG sites (one in each of two different lagg plant communities) but no study location between the bog and lagg (due to the influence of a highway). The two LG study sites on each of these transects are named LG1 and LG2, with LG2 being located closer to the MN site.

All locations were recorded with an Oregon 300 handheld GPS unit, accurate to 5 m. The Blaney Bog and Campbell River transects were surveyed with a rod and level in March 2011 and May 2011, respectively. The Burns Bog transect elevations were determined from LiDAR data (relative accuracy of 15 cm, absolute accuracy of 30 cm) collected in September 2008.

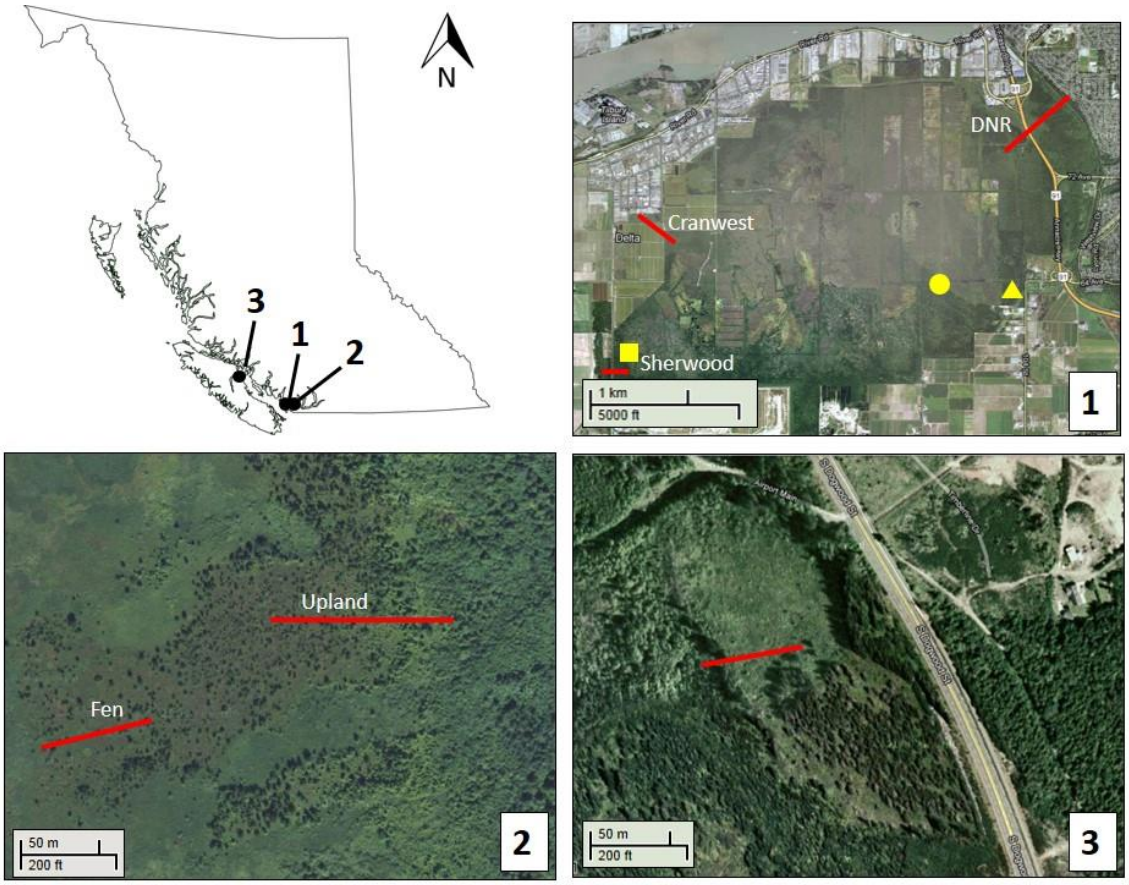

Figure 2. ***Location of three research sites in coastal British Columbia: 1) Burns Bog, 2) Blaney Bog, and 3) Campbell River Bog. Red lines represent the transect locations. Additional Burns Bog data are from PF-100 and PF-200 (yellow triangle), a piezometer near the Sherwood BG site (yellow square), and a piezometer and a well in the southeastern part of the bog (yellow circle). Air photos are from Google Earth.***

3.4. Methods

3.4.1. Field Methods

Piezometers were installed in hollows at each study location on the transects to determine the depth to water table. The piezometers were 1.5 m long, 2.5 cm diameter Schedule 40 PVC pipe with a 40 cm slotted length at the bottom, and were capped at both ends. The piezometers were installed in April/May 2010 in Burns Bog, in May 2010 in Campbell River Bog, and in June 2010 in Blaney Bog. The depth of the piezometers varied between 0.47 and 1.20 m below the surface and depended on the depth of the water table in the borehole during installation; mean depth was 0.85 m below the surface (standard deviation: 0.21 m). We aimed to install the piezometers as close to the surface as possible, while still ensuring a sufficient amount of water in the piezometers for sampling during low water table conditions in late summer. The piezometers acted as wells (i.e. the water level was at or below the top of the screening) in late summer (August-September) and as piezometers (i.e. the water level was above the top of the screening) from autumn to early summer (October-July).

The purpose of this study was not to monitor water level responses during precipitation events but rather to record the broad seasonal pattern in depth to water table (i.e. the hydroperiod) and how this varies across the bog expanse – bog margin transition. Shallow piezometers were used instead of wells in this study to avoid "short-circuiting" of water during rainfall events or flooding. Although wells should be used to measure the depth to water table, the error in determining the depth to water table from the water level in the shallow piezometers was likely small. Significant clay layers were not observed during installation of the piezometers in the peat (ash content at the locations of the piezometers was <15% for the BG, R1, R2, and LG sites), and rainfall intensities are generally very low in this coastal area so the measured heads are likely highly correlated to the position of the water table. Previous measurements in Burns Bog showed that shallow piezometers (i.e. screening <1.5 m below the surface) act similarly to wells. For example, a piezometer with screening at 0.6-1.5 m below the surface, and a well installed less than 1 m from the piezometer, showed similar water levels (Fig. 3a). The mean difference in geodetic water level elevation between the piezometer and the well was 0.8 cm (standard deviation: 1.3 cm). Furthermore, differences between the depth to the water level in the piezometer and the depth to surface water when ponding occurred (which would be identical if a well was used instead of a piezometer) were small (mean difference: 1.2 cm, standard deviation: 0.9 cm for 13 shallow piezometers, 2011 data not included in this study).

Even though the lagg is a discharge zone, and vertical head gradients thus affect the depth to water table determined from the water level measurements in the shallow piezometers, the relatively shallow depths at which the piezometers were installed caused these gradients to only have minor effects on the depth to water table determined from the water level measurements. Data from a piezometer nest in a lagg swamp in Burns Bog that is a relatively strong discharge zone (site not included in this study) for example showed that differences in the water level in a shallow (screening 0.38-1.28 cm below the surface) and deep (screening 0.85-1.75 m below the surface) piezometer were small and generally less than 2 cm (mean difference: 1.5 cm, standard deviation: 3 cm). We therefore assumed that the water levels measured in the shallow piezometers represents the seasonal and spatial patterns in the water table reasonably well, and that the uncertainty in the determination of the depth to the water table due to the use of shallow piezometers instead of wells is generally of the same order as the measurement accuracy (0.5 cm) and the uncertainty in determining the location of the bog surface (~1-3 cm).

The piezometers were purged twice 1-2 weeks prior to sampling, with the exception of the Campbell River Bog piezometers, which were only given one day in 2010 and four days in 2011 to recharge prior to sampling. One to two weeks is a relatively long interval between purging and sampling but this measurement schedule was necessary for this study due to the very slow recharge rate of some of the piezometers (e.g. the LG and MN sites). In order to determine the water chemistry at all sites along the transects on the same day, it was necessary to allow all piezometers to recharge prior to the measurements and sampling.

Depth to the water level in the piezometers was measured with an electronic water level probe (Heron Instruments Little Dipper). Table 1 lists the number and interval of the water level measurements for each transect. The measurement frequency for the Sherwood transect increased to weekly between August 2011 and December 2011 to monitor the change in water table in response to logging of the mature forest at the LG sites on the transect. Electrical conductivity and pH were measured directly in the piezometers with a WTW Multiline P4 water quality meter. The probes were rinsed with distilled water before each measurement. Electrical conductivity was compensated for H^+ concentrations using the following formula: $EC_{corr} = EC_{measured} - EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$, and 3.49×10^5 is the conversion factor for field measurements standardized to 25 ºC by a handheld meter (Rydin and Jeglum, 2006). At Campbell River bog, the field pH meter failed in 2011, so pH was measured in the laboratory. In order to be consistent between sites and different dates, regardless of the volume of water present in the piezometer, and to avoid any variation due to the potential effects of stratification of water inside the piezometers (which we did not observe), we measured pH and EC in the top 10-15 cm of the water column.

For Blaney Bog and Burns Bog DNR, sampling for Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, and acidity was only done once (June 2011). For the other two Burns Bog transects and Campbell River Bog, water chemistry samples were taken in May/June of 2010 and 2011. A low-flow peristaltic pump (Global Water SP200) was used to collect water samples into plastic HDPE bottles at the rate of recharge whenever possible. To avoid contamination of water samples, the plastic tubing of the peristaltic pump was rinsed with water from each site prior to sample collection and flushed prior to taking a sample. Samples were kept on ice and refrigerated until delivery to the Pacific Environmental Science Centre (North Vancouver, BC), where they were analyzed for: Ca^{2+}, Mg^{2+}, Na^{+}, SO_4^{2-}, and Cl^{-} concentrations, and acidity using inductively coupled plasma spectrometry. Replicate samples were taken at Campbell River bog (R1 site) in 2011 and the Sherwood transect in Burns Bog (R2 site) in 2010, which equates to one replicate for every 14.5 samples. Differences between the original and replicate samples were <0.5 mg/l (mean: 0.2 mg/l) for cations, <4 mg/l for Cl^{-} (mean: 2.1 mg/l), and <3 mg $CaCO_3$/l (mean: 2 mg/l) for acidity; sulphate was below the laboratory minimum detection limit at the sites where replicate samples were collected. For Burns Bog and Blaney Bog, pore-water concentrations were compared to 1986-1993 average concentrations in precipitation at Vancouver International Airport (Piteau Associates, 1994). For Campbell River Bog, pore-water concentrations were compared to 1978-1986 average concentrations in precipitation from Port Hardy (National Atmospheric Chemistry Database, 2012).

3.4.2. Statistical Methods

Analysis of variance (ANOVA) was used to determine whether the variation in the hydrochemical characteristics over time, or across the transects, was statistically significant. Tukey's Honestly Significant Difference (HSD) was calculated to determine which locations on the transects were significantly different in pH and EC_{corr}. Spearman rank correlation tests were performed between depth to water table, pH, EC_{corr}, and all other measured hydrochemical parameters. A significance level of 0.05 was used for all analyses.

Table 1. Description of the transects ("BG" sites) and frequency and dates of sampling.

Transect	Latitude	Longitude	Transect Length (m)	Maximum Elevation Difference on Transect (m)	Frequency of water level and EC/pH measurements (n=total number of EC/pH measurements)	Collection dates for water chemistry samples
Burns Bog – Sherwood	49° 6'26"N	123° 1'10"W	560	2.9	1-3 months[a] (n=9)	June 6, 2010; June 21, 2011
Burns Bog – Cranwest	49° 7'26"N	123° 0'36"W	830	1.6	1-3 months (n=9)	June 6 & 10, 2010; June 20, 2011
Burns Bog – DNR	49° 8'16"N	122°56'11"W	1000	1.4	4-6 months (n=4)	June 18, 2011
Blaney Bog – Upland	49°15'35"N	122°35'18"W	180	1.3	3 months (n=5)	June 25, 2011
Blaney Bog – Fen	49°15'33"N	122°35'24"W	100	1.5	3 months (n=5)	June 25, 2011
Campbell River Bog	49°57'60"N	125°14'34"W	100	1.5	Annually (2010/2011) (n=2)	May 24, 2010; May 31, 2011

[a]Depth to water table measurement frequency at this site increased to weekly between August and December 2011, and then monthly until December 2012.

Table 2. Precipitation and temperature data for the studied bogs. Data for Burns Bog are from Vancouver International Airport (YVR) (16 km from Burns Bog), for Blaney Bog from Haney UBC research forest weather station (1 km from Blaney Bog), and for Campbell River Bog from the Campbell River city weather station (6 km from Campbell River Bog) (source: Environment Canada, 2012).

Site	Annual Precipitation (mm)			Total Precipitation between April 1 and September 1 (mm)		Mean Air Temperature between April 1 and September 1 (°C)	
	30-year mean (1971-2000)	2010	2011	2010	2011	2010	2011
Burns Bog	1008	1207	1071	261	288	14.6	13.9
Blaney Bog	2194	2034	1989	474	644	14.2	12.8
Campbell River Bog	1452	1904	1378	304	246	13.7	12.7

3.5. Results

3.5.1. Spatial and Temporal Water Table Fluctuations

The depth to water table was generally smallest in the bog and increased toward the bog margin, although three of the lagg sites experienced flooding during the wet season (Table 3, Figs. 4 and 5). For comparison with a longer time series, Figure 3b shows the water level fluctuations from 2006-2012 for a piezometer located 330 m north of the Sherwood BG site, in the same plant community. Similar to all the BG sites, the water table at this piezometer dropped to 30-40 cm below the bog surface (average of 34 cm) each summer during the six-year monitoring period. The water level fluctuations increased across the transition from bog to forest for the Burns Bog and Blaney Bog transects (Table 3, Figs. 4 and 5). The average (and median) difference between the maximum measured depth to water table and the minimum measured depth to water table was 0.33 m (0.32 m) for the BG sites, 0.57 m (0.59 m) for the LG sites, and 0.61 m (0.64 m) for the MN sites (Table 3).

Table 3. ***Maximum (max), minimum (min), and mean (avg) depth to water table for all Burns Bog and Blaney Bog sites. Campbell River Bog was not included in this analysis because depth to water table was only measured in May. Negative values indicate that the water table was above the bog surface.***

	Water Table Depth Below Surface (m)																	
	BG			R1			R2			LG1			LG2			MN		
	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg	max	min	avg
Burns Bog – Sherwood	0.34	0.04	0.15	0.67	0.13	0.38	0.66	0.14	0.34	0.69	0.24	0.40	0.75	0.17	0.34	0.86	0.13	0.50
Burns Bog – Cranwest	0.40	-0.02	0.10	0.43	0.07	0.19	0.53	-0.13	0.07	0.52	-0.09	0.09	-	-	-	0.92	0.45	0.68
Burns Bog – DNR	0.32	0.00	0.14	-	-	-	-	-	-	0.58	-0.14	0.22	0.57	0.13	0.34	0.48	-0.17	0.17
Blaney Bog – Upland	0.37	0.11	0.19	0.50	0.17	0.27	0.58	0.17	0.32	0.69	0.07	0.29	-	-	-	0.94	0.15	0.37
Blaney Bog - Fen	0.52	0.18	0.28	0.46	0.08	0.18	0.48	0.08	0.22	0.47	-0.04	0.13	-	-	-	0.15	-0.26	-0.06
MEAN	0.39	0.06	0.17	0.52	0.11	0.26	0.56	0.07	0.24	0.59	0.01	0.23	0.66	0.15	0.34	0.67	0.06	0.33
MEDIAN	0.37	0.04	0.15	0.48	0.11	0.23	0.56	0.11	0.27	0.58	-0.04	0.22	0.66	0.15	0.34	0.86	0.13	0.37
STD. DEV.	0.08	0.08	0.07	0.11	0.05	0.09	0.08	0.14	0.12	0.10	0.15	0.12	0.13	0.03	0.00	0.35	0.28	0.29

3.5.2. "Watering Up" in Sherwood Forest

A portion of the mature forest on the western side of the Sherwood transect was unexpectedly cut in May/June 2011. Two piezometers on the Sherwood transect were affected by the logging: LG1 at the edge of the cutblock and LG2 in the middle of the cutblock (Fig. 4). The result of the logging was a pronounced "watering-up" effect. The mean water table rise between August-November of 2010 and 2011 (the period with available data for both years) was 8 cm for the clearcut LG2 site and 7 cm for the LG1 site at the edge of the cut block (Fig. 4). The mean water table between August-November was 6 cm, 16 cm, and 12 cm lower in 2011 than in 2010 for the undisturbed open bog (BG), pine-salal forest (R1, R2) (transitional between bog and lagg), and mineral (MN) sites on the Sherwood transect, respectively (Fig. 4). The lowest measured water table in late summer was 27 cm higher in 2011 than in 2010 for LG2 and 12 cm higher in 2011 than in 2010 for LG1. For the other sites on the Sherwood transect, the lowest measured water table in late summer was 0.5 cm lower (BG), 4 cm lower (mean for R1 and R2), and 0.5 cm lower (MN) in 2011 than in 2010.

The difference in water level in late summer-fall 2010 and 2011 for the logged LG2 site on the Sherwood transect was also larger than for any of the unlogged LG sites on the other transects (Fig. 4 and 5). The mean water table between August and November was 13 cm lower in 2011 than in 2010 for the Cranwest LG site and 8 cm lower for the DNR LG site. The lowest measured water table was 10 cm higher in 2011 than in 2010 for the Cranwest LG site and 0.5 cm lower for the forested DNR LG site.

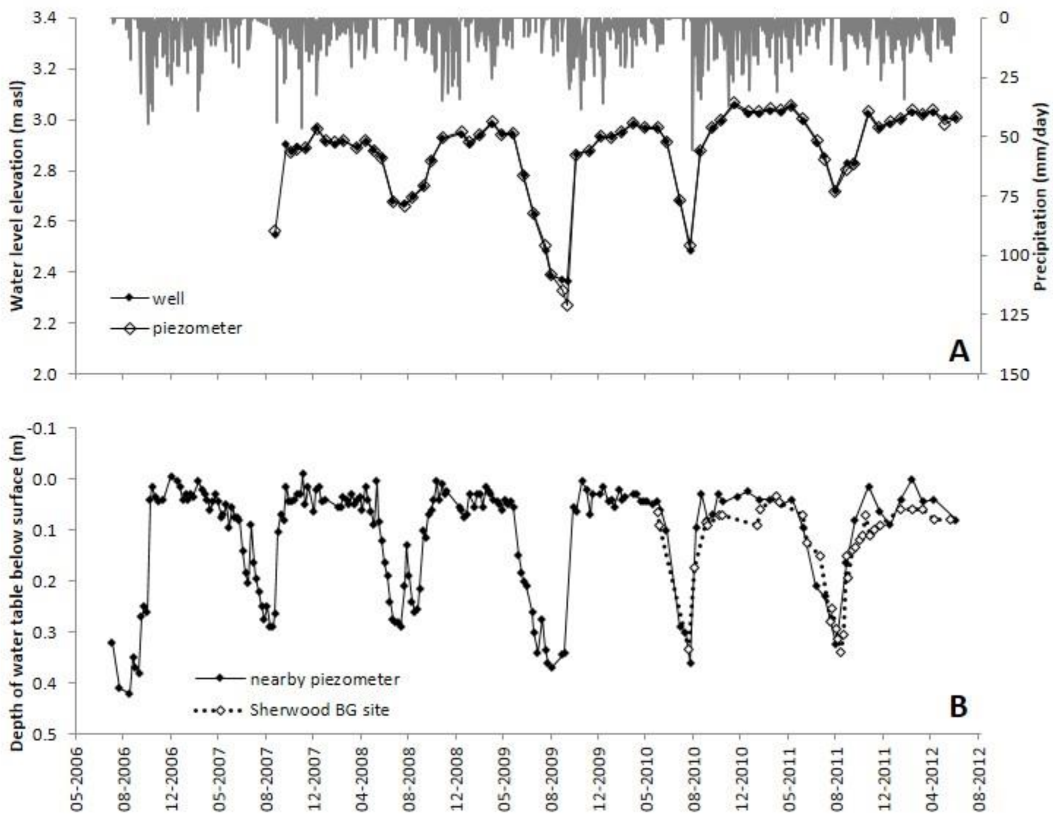

Figure 3. ***a) Water level measured in a piezometer and a well <1 m apart in the southeast area of Burns Bog, and b) Depth to water table at the "Sherwood BG" site and a nearby piezometer for the 2006-2012 period. See Figure 2 for locations. Precipitation (gray bars) was measured at Vancouver International Airport, 15 km from the Sherwood transect (source: Environment Canada).***

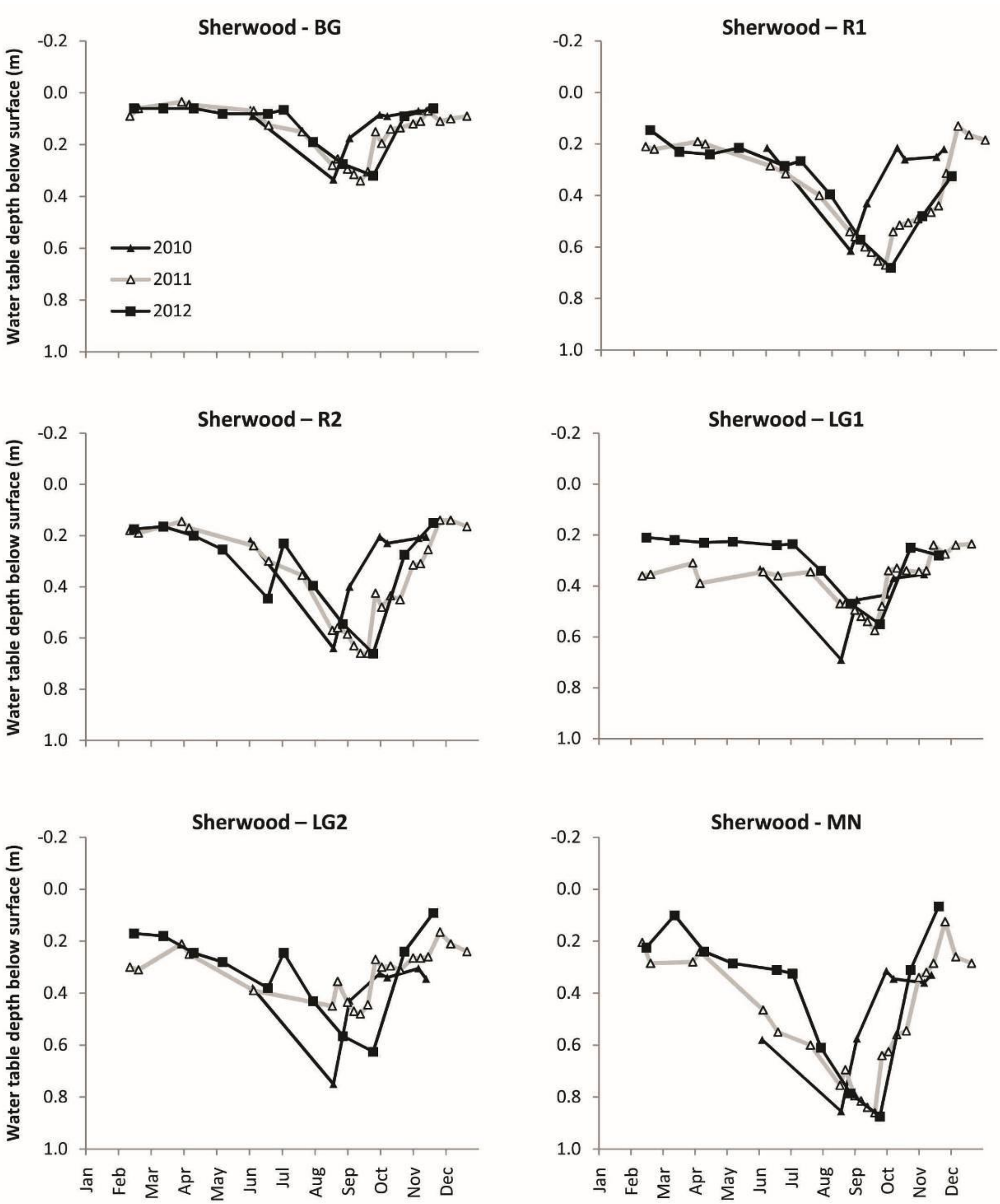

Figure 4. ***Time series of depth to water table along the Sherwood Forest transect from June 2010 to December 2012. In May/June 2011, logging occurred adjacent to the LG1 site; all trees were removed at the LG2 site. Longer time series for a shallow piezometer near the Sherwood BG site are given in Fig. 3b.***

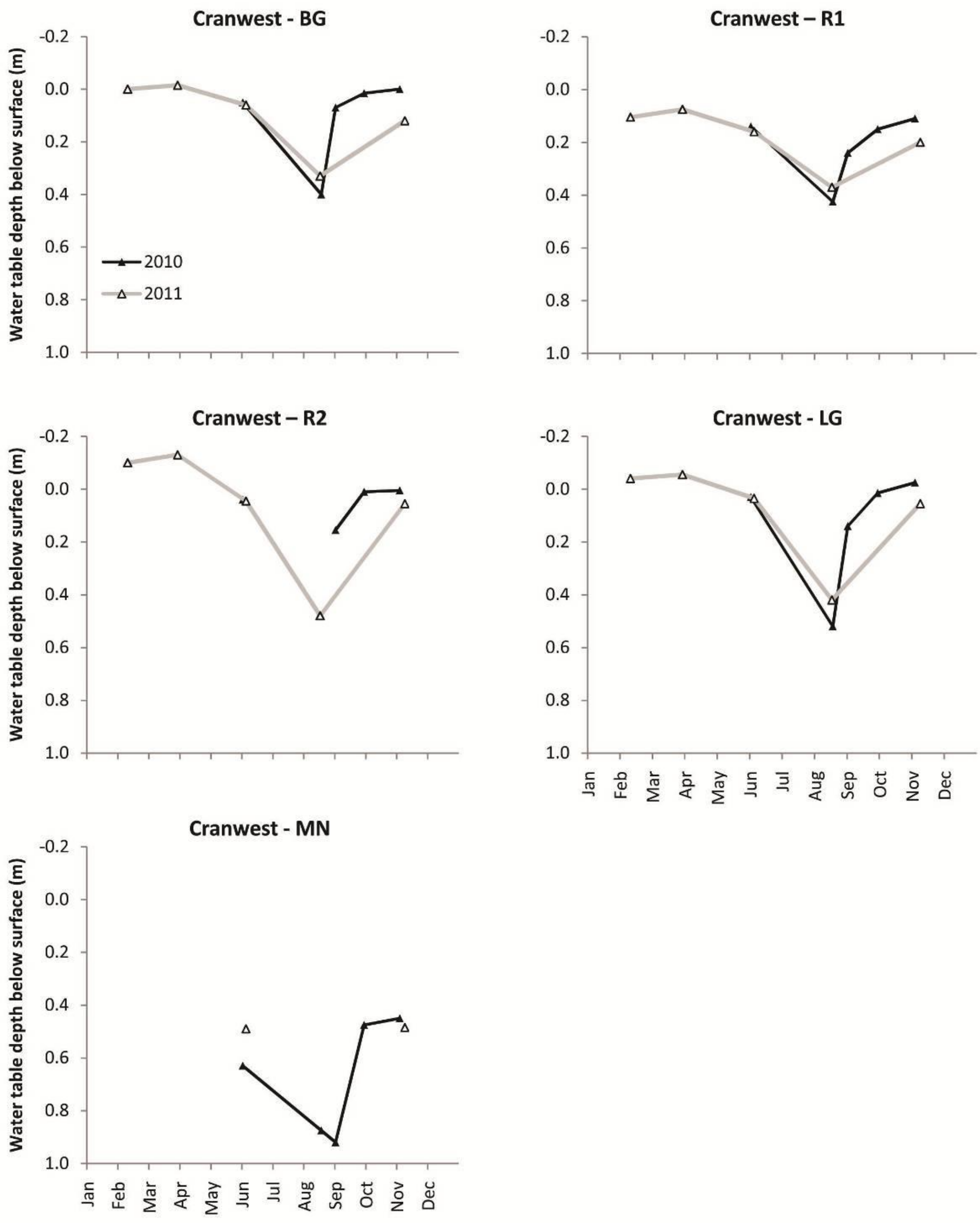

Figure 5. ***Time series of depth to water table along the Burns Bog Cranwest transect from June 2010 to December 2011. Negative values indicate that the water table was above the ground surface.***

3.5.3. *Spatial Variation in Water Chemistry*

Spatial differences in pH across the transects varied between the transects. For some transects, the pH increased across the transition from bog to forest (Blaney Bog Upland, Cranwest, DNR) (Fig. 6, Table 4). For other transects, the pH fluctuated across the transect without a clear spatial pattern (Sherwood, Blaney Bog Fen). ANOVA results indicate that the difference in pH along the transects was statistically significant ($p<0.05$) for all transects, except the Fen transect in Blaney Bog ($p=0.591$) (Appendix B). Results from Tukey's HSD calculations for each transect showed that the locations from which pH differed significantly from the other locations on the transect varied between the different transects. For example, on the Cranwest transect, pH at the LG site was significantly different from the BG site, and pH at the MN site was significantly different from all other locations on the transect (Table 4). For the Blaney UP transect, on the other hand, pH was significantly different from the other locations for most of the sites on the transect (Table 4).

EC_{corr} was generally lowest in the bog and highest towards the lagg and mineral sites, but not for all transects (Fig. 7). The ANOVA results showed that the variation in EC_{corr} along the transects from BG to MN was statistically significant ($p<0.05$) for all transects, except the Fen transect in Blaney Bog ($p=0.053$) (Appendix B). The Tukey's HSD results for EC_{corr} varied between the transects, similar to the results for pH. For the Sherwood transect, EC_{corr} at the LG and MN sites was significantly different from all other transect locations. For the Cranwest transect, EC_{corr} was significantly different only for the MN sites. For the other three transects, EC_{corr} was only significantly different for a single pair of locations (for the DNR transect, LG1 and MN were significantly different from one another; for the Blaney UP transect, BG and R2 were significantly different; for the Blaney FN transect, BG and MN were significantly different from one another).

Ca^{2+} and Mg^{2+} concentrations often increased across the transect from bog to forest, but not for all transects (Table 5). The Ca:Mg ratio did not follow a consistent trend across any transect, and was generally twice as high in Blaney Bog as in Burns Bog, with the exception of the DNR transect (Table 6). Ca^{2+} and Mg^{2+} concentrations, and the Ca:Mg ratio, were not significantly correlated with position on the transect.

There was no clear trend in concentrations of Na^+, Cl^-, SO_4^{2-}, or acidity across the transects (Table 5).

In the BG sites, concentrations of Na^+ and Cl^- in pore-water were, on average, four times higher than in precipitation (Table 7). Ca^{2+} and Mg^{2+} concentrations were, on average, 5 and 9 times higher, respectively, in BG site pore-water than in precipitation (Table 7). The ratio of the average concentration in pore-water and precipitation generally increased across the transect from bog to forest for all measured cations and anions. For example, Na^+ concentrations in pore-water samples were, on average, 4, 4, 5, 7, and 11 times higher than the average concentration in precipitation for the BG, R1, R2, LG, and MN sites, respectively. Ca^{2+} concentrations were, on average, 5, 6, 8, 9, and 16 times higher than the average concentration in precipitation for the BG, R1, R1, LG, and MN sites, respectively. SO_4^{2-} concentrations were generally below the 0.5 mg/l laboratory minimum detection limit in our water samples, but ranged from 0.7-1.8 mg/l in precipitation.

3.5.4. Seaonal Variation in Water Chemistry

There was relatively little variation in field-measured pH during the study period (Table 4, Fig. 6). For all sites, pH varied by less than 0.85 over time and measurements taken in June/July were all within 0.25 of the study average. On average, the temporal variation was lowest in the BG sites, and increased approaching the lagg (Table 4). However, this trend was not clear for the individual transects; variability in pH increased across one transect (Blaney Bog - Upland), decreased across one transect (Campbell River), and fluctuated across the remaining transects (Fig. 6). ANOVA results showed that the differences in pH for the different measurement dates were not statistically significant for any of the Burns Bog or Blaney Bog transects (Appendix B).

Temporal variation in pH-corrected electrical conductivity (EC_{corr}) generally followed the variation in pH (Fig. 7), although EC_{corr} was more variable. All measurements taken in June/July were within 65 µS/cm of the study average; 85% were within 25 µS/cm of the long term average. Average values from May are not reported here for EC_{corr} due to equipment malfunction in May 2010. The differences in EC_{corr} between the measurement dates were not statistically significant for any of the Burns

Bog or Blaney Bog transects (Appendix B). For the Burns Bog – Sherwood transect, temporal variation in EC_{corr} was highest in the bog and decreased across the transect; the opposite trend was found for the Cranwest and DNR transects in Burns Bog (Fig. 7). There was no clear spatial trend in temporal variability in EC_{corr} for the Blaney Bog transects.

Mg^{2+} and Na^{+} concentrations varied by less than 0.9 mg/l between years for all three multi-year transects (Table 5). Ca^{2+} concentrations were more variable over time, with the difference between years ranging from 0-4.2 mg/l (mean: 1.1 mg/l). Most SO_4^{2-} concentrations were less than the laboratory detection limit of 0.5 mg/l, so it is not possible to draw conclusions about its temporal variability, except that it was low in both years. Changes in Cl^{-} concentrations and acidity between years ranged from 0.5-8.1 mg/l (mean: 4.3 mg/l) and 1-34 mg $CaCO_3$/l (mean: 16.7 mg/l), respectively (Table 5). The relative change in concentration (=difference between the two years/mean) was lowest for Na^{+}, and increased in the following order: Na^{+}, Mg^{2+}, Ca^{2+}, Cl^{-}, and acidity. For the transects where we collected water samples in 2010 and 2011 (Sherwood, Cranwest, and Campbell River), we found that the differences in Ca^{2+} and Mg^{2+} concentrations in 2010 and 2011 generally increased across the transects from bog to forest; the other hydrochemical parameters did not display a trend in temporal variability across the transect.

Spearman rank correlation tests for all piezometers together revealed a significant positive correlation between depth to water table and EC_{corr} and Mg^{2+} concentrations (results not shown). There was also a significant positive correlation between pH and concentrations of Ca^{2+} and Na^{+}. However, these correlations were not significant for the individual transects.

Seasonal hydrochemical variations during a one-year monitoring period from March 2011 to March 2012 in another part of Burns Bog (pine-salal forest at 100 and 200 metres from edge of bog were similar to the variations observed along the study transects (Fig. 2). From March to August 2011, pH increased, corresponding with a decline in water table over spring and summer, and then decreased between August 2011 and March 2012 (Table 8). However, the maximum change in pH was less than 1, similar to the transects in Burns Bog and Blaney Bog that were monitored in June 2010 and June 2011 for this study. Ca^{2+} and Mg^{2+} concentrations also increased slightly as the water table declined in summer (Table 8). The relative change in concentration increased in the following order: SO_4^{2-}, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, similar to the results for the transects in Burns Bog and Blaney Bog in this study, except that SO_4^{2-} concentrations were frequently below the detection limit for the transects of this study. Spearman rank correlation tests for these two piezometers revealed a significant positive correlation between depth to water table and pH, as well as between depth to water table and concentrations of Ca^{2+} and Mg^{2+}. There was also a significant positive correlation between pH and Ca^{2+} and Mg^{2+} concentrations.

Table 4. ***Range in pH for all sites (May 2010-December 2011). See Table 1 for the frequency of the measurements. Different superscript letters indicate significant differences between locations on the transects using Tukey's HSD of the means.***

	pH range (minimum – maximum)					
	BG	**R1**	**R2**	**LG1**	**LG2**	**MN**
Burns Bog – Sherwood	3.71-4.30 [ac]	3.84-3.95 [a]	3.76-4.00 [a]	4.04-4.38 [b]	3.56-3.86 [c]	3.64-4.24 [ab]
Burns Bog – Cranwest	3.88-4.22 [a]	4.32-4.51 [ab]	3.90-4.75 [ac]	4.13-4.94 [bc]	-	5.10-5.41 [d]
Burns Bog – DNR	4.09-4.36 [a]	-	-	4.17-4.57 [a]	5.20-5.39 [b]	5.51-5.72 [c]
Blaney Bog – Upland	4.09-4.42 [a]	4.21-4.37 [a]	4.34-4.90 [b]	4.95-5.36 [c]	-	5.19-5.84 [d]
Blaney Bog – Fen	4.28-4.69 [a]	4.25-4.53 [a]	4.30-4.66 [a]	4.22-4.67 [a]	-	4.35-4.57 [a]
Campbell River Bog	4.23[*]	4.25-4.67	4.52[*]	6.08-6.29	-	6.49-6.68
MEAN	4.10	4.24	4.31	4.60	4.32	4.98
MEDIAN	4.09	4.30	4.33	4.43	3.82	5.19
STD. DEV.	0.27	0.24	0.36	0.54	0.83	0.79

[*]Measurements from May 2011 (May 2010 measurements are not included due to incomplete piezometer development)

Table 5. ***Pore-water concentrations for Burns Bog, Blaney Bog, and Campbell River Bog in May/June 2010 and May/June 2011. SW=Sherwood, DNR=Delta Nature Reserve, CW=Cranwest, BU=Blaney Bog Upland, BF=Blaney Bog Fen, CR=Campbell River Bog. Dates and locations for which water samples were not collected are indicated by "-". MDL=Minimum Detection Limit. Values in parentheses for SW - R2 and CR - R1 are the concentrations of the replicate samples.***

		Ca^{2+} (mg/l)		Mg^{2+} (mg/1)		Na^{+} (mg/l)		SO_4^{2-} (mg/l)		Cl^{-} (mg/l)		Acidity (mg $CaCO_3$/l)	
	MDL	0.1		0.1		0.1		0.5		0.5		1	
	Sample Location	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
Burns Bog	SW - BG	1.3	1.4	1.0	1.0	3.4	4.3	<0.5	<0.5	9.8	4.8	33	46
	SW - R1	1.1	1.1	1.6	1.5	2.7	2.7	0.8	<0.5	10.0	17.0	26	53
	SW - R2	1.5 (1.0)	1.1	1.5 (1.3)	1.5	2.8 (2.7)	2.4	<0.5 (<0.5)	<0.5	9.0 (5.0)	8.5	29 (30)	39
	SW- LG1	2.5	1.9	1.6	1.7	1.9	2.0	0.6	<0.5	7.9	16.0	18	34
	SW - LG2	2.4	-	1.8	-	4.1	-	2.9	-	10.8	-	59	-
	SW - MN	5.9	4.9	4.0	3.9	5.7	5.4	5.2	1.6	22.0	15.0	33	52
	DNR - BG	-	-	-	-	-	-	-	-	-	-	-	-
	DNR - LG1	-	3.8	-	0.7	-	5.5	-	<0.5	-	9.4	-	34
	DNR - LG2	-	2.6	-	0.8	-	16.6	-	<0.5	-	19.0	-	46
	DNR - MN	-	9.4	-	3.1	-	10.4	-	<0.5	-	11.2	-	21
	CW - BG	1.5	2.1	1.1	1.1	5.1	4.6	<0.5	<0.5	8.4	5.4	24	54
	CW - R1	2.1	1.5	1.0	1.0	5.7	5.7	<0.5	<0.5	11.5	9.4	13	47
	CW - R2	3.4	1.8	1.6	0.9	3.2	2.8	1.9	<0.5	9.1	3.7	24	31
	CW - LG	-	1.8	-	0.9	-	2.5	-	<0.5	-	3.7	-	27
	CW - MN	5.0	3.1	1.2	1.7	16.7	17.6	-	-	-	-	-	-
Blaney Bog	BU - BG	-	0.5	-	<0.1	-	0.8	-	<0.5	-	2.6	-	33
	BU - R1	-	0.3	-	<0.1	-	1.5	-	<0.5	-	2.7	-	37
	BU - R2	-	0.9	-	0.1	-	6.0	-	<0.5	-	4.4	-	45
	BU - LG	-	3.2	-	0.5	-	1.7	-	<0.5	-	2.6	-	19
	BU - MN	-	4.7	-	0.7	-	3.6	-	0.7	-	3.3	-	13
	BF - BG	-	1.2	-	0.3	-	0.9	-	<0.5	-	2.2	-	36
	BF - R1	-	2.0	-	0.8	-	0.8	-	<0.5	-	2.2	-	38
	BF - R2	-	2.5	-	0.6	-	0.8	-	<0.5	-	2.6	-	23
	BF - LG	-	1.3	-	0.2	-	0.9	-	<0.5	-	2.7	-	21
	BF - MN	-	2.0	-	0.7	-	2.3	-	<0.5	-	5.0	-	41
Campbell River Bog	CR - BG	-	1.7	-	0.7	-	4.8	-	<0.5	-	10.0	-	23
	CR - R1	3.6	2.5 (2.6)	1.0	1.0 (1.0)	5.3	4.8 (5.0)	<0.5	<0.5	12	8.1 (8.0)	18	28 (25)
	CR - R2	-	3.6	-	1.1	-	4.6	-	<0.5	-	6.8	-	30
	CR - LG	5.1	4.0	1.7	1.5	6.1	6.2	<0.5	<0.5	10	9.3	12	11
	CR - MN	6.7	2.5	1.4	1.0	5.7	5.5	-	<0.5	-	8.3	-	13

Table 6. Ca:Mg ratios for all transects in June 2011 (May 2011 for Campbell River).

	Ca:Mg ratio					
	BG	**R1**	**R2**	**LG1**	**LG2**	**MN**
Burns Bog – Sherwood	1.4	0.7	0.7	1.1	-	1.3
Burns Bog – Cranwest	1.9	1.5	2.0	2.0	-	1.8
Burns Bog – DNR	-	-	-	5.4	3.3	3.0
Blaney Bog – Upland	>5.0	>3.0	9.0	6.4	-	6.7
Blaney Bog - Fen	4.0	3.5	4.2	6.5	-	2.9
Campbell River	2.4	2.5	3.3	2.7		2.5

Table 7. ***Ratio of the average concentration in pore-water to the average concentration in precipitation. See Table 5 for transect codes and Table 1 for sampling dates. Precipitation chemistry data for Burns Bog and Blaney Bog are from YVR 1986-1993 (Piteau Associates, 1994), and for Campbell River Bog from Port Hardy 1978-1986 (National Atmospheric Chemistry Database, 2012).***

	Sample Location	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
Burns Bog	SW – BG	3.9	14.3	6.3	38.1	<0.3	6.1
	SW – R1	3.1	22.1	4.4	78.8	<0.4	11.3
	SW – R2	3.7	21.4	4.3	51.6	<0.3	7.3
	SW – LG1	6.3	23.6	3.2	57.2	<0.3	10.0
	SW – LG2	6.9	25.7	6.7	31.9	1.6	9.0
	SW – MN	15.4	56.4	9.1	30.0	3.8	15.4
	DNR – BG	-	-	-	-	-	-
	DNR – LG1	10.9	10.0	9.0	33.1	<0.3	7.8
	DNR – LG2	7.4	11.4	27.2	51.9	<0.3	15.8
	DNR – MN	26.9	44.3	17.0	21.3	<0.3	9.3
	CW – BG	5.1	15.7	8.0	23.4	<0.3	5.8
	CW – R1	5.1	14.3	9.3	8.1	<0.3	8.7
	CW – R2	7.4	17.9	4.9	28.1	<1.1	5.3
	CW – LG	5.1	12.9	4.1	30.0	<0.3	3.1
	CW - MN	11.6	20.7	28.1	42.5	-	-
Blaney Bog	BU – BG	1.4	<1.4	1.3	4.4	<0.3	2.2
	BU – R1	0.9	<1.4	2.5	3.1	<0.3	2.3
	BU – R2	2.6	1.4	9.8	7.5	<0.3	3.7
	BU – LG	9.1	7.1	2.8	3.8	<0.3	2.2
	BU – MN	13.4	10.0	5.9	5.0	0.39	2.8
	BF – BG	3.4	4.3	1.5	4.4	<0.3	1.8
	BF – R1	5.7	11.4	1.3	5.0	<0.3	1.8
	BF – R2	7.1	8.6	1.3	5.6	<0.3	2.2
	BF – LG	3.7	2.9	1.5	5.6	<0.3	2.3
	BF – MN	5.7	10.0	3.8	4.4	<0.3	2.8
Campbell River Bog	CR – BG	8.8	3.6	3.2	24.1	<0.5	3.8
	CR – R1	15.7	5.2	3.3	31.6	<0.5	3.8
	CR – R2	18.6	5.7	3.0	16.1	<0.5	2.6
	CR – LG	23.5	8.3	4.0	38.5	<0.5	3.6
	CR – MN	23.7	6.2	3.7	61.5	<0.5	3.1

Table 8. ***Data from piezometers PF-100 and PF-200 in Burns Bog (see Figure 2 for location of these piezometers). DTW = depth to water table; EC_{corr} = pH-corrected electrical conductivity.***

Parameter	March 8, 2011		June 28, 2011		August 29, 2011		March 21, 2012	
	PF-100	PF-200	PF-100	PF-200	PF-100	PF-200	PF-100	PF-200
DTW (m)	0.41	0.41	0.58	0.57	0.89	0.84	0.36	0.33
pH	3.79	3.85	4.27	4.15	4.62	4.45	3.73	3.71
EC_{corr} (µS/cm)	61	52	45	44	70	55	47	35
Ca^{2+} (mg/l)	0.9	0.8	1.6	1.5	2.9	2.6	1.1	1.3
Mg^{2+} (mg/l)	0.7	0.8	0.9	1.1	1.8	1.8	0.6	0.7
Na^{+} (mg/l)	2.1	2.1	2.0	1.9	2.4	2.2	2.5	3.3
SO_4^{2-} (mg/l)	1.0	0.9	0.7	0.6	<0.5	<0.5	<2.5	<2.5
Cl^{-} (mg/l)	1.9	3.0	0.9	0.7	8.6	7.1	4.2	3.5

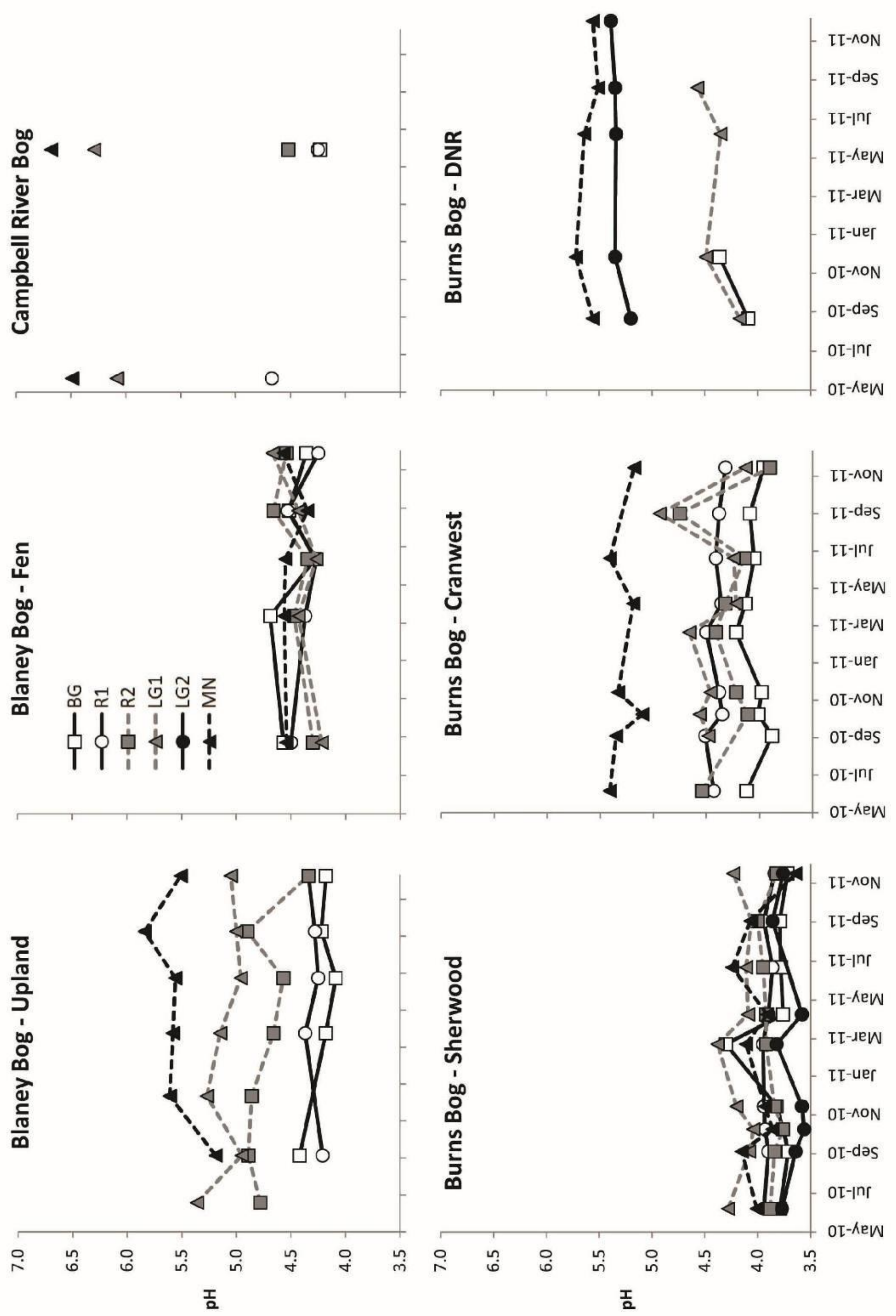

Figure 6. pH across the six study transects from May 2010-December 2011.

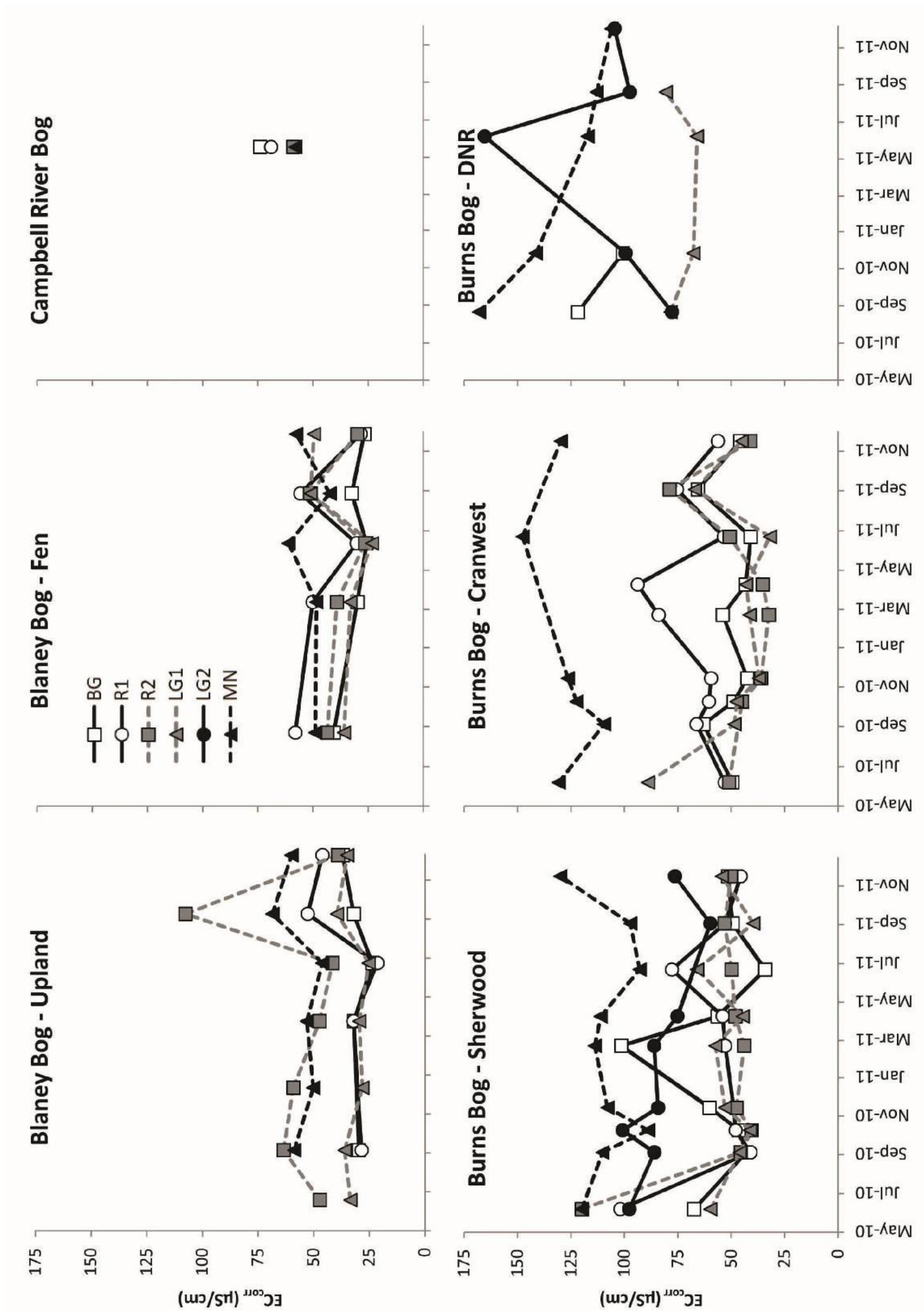

Figure 7. ***pH-corrected electrical conductivity (EC$_{corr}$, µS/cm) across the six study transects from June 2010-December 2011.***

3.6. Discussion

3.6.1. Spatial and Temporal Variation in Depth to Water Table

The water table in bogs often fluctuates in a spatially and temporally consistent manner (Økland et al., 2001) because seasonal water table fluctuations in bogs are closely linked to precipitation (e.g. Malmer, 1986; Dubé et al., 1995). The annual hydroperiod (i.e. the repeating and predictable cycle of water table fluctuations over time) for Burns Bog and Blaney Bog agreed with those observed by Howie et al. (2009) and Golinski (2004). The measurements in Burns Bog and Blaney Bog also confirmed that bogs generally have a smaller annual fluctuation in the water table compared to the laggs and adjacent minerotrophic sites (Table 3, Fig. 4; Schouten, 2002; Damman, 1986; Malmer, 1986). In general, the water table was at its highest and most stable position near the bog surface between October and March, and declined from April onwards in response to decreased precipitation and increased evapotranspiration. It reached a low point in late August or September, and increased rapidly to the high winter water level in response to rainfall in September or October (Figs. 4, 5; Table 3). The depth of the low point of the water table was variable between years and dependent on the extent of the summer drought period, but was generally 30-40 cm below the bog surface, and thus within the range for a healthy bog (Schouwenaars and Vink, 1992). Similar annual fluctuations have also been recorded for bogs in Europe (e.g. Egglesmann et al., 1993). This suggests that depth to water table measurements during key phases of the hydroperiod (e.g. wet season, spring transition, end of dry season) may be sufficient to obtain a general sense of the annual maximum and minimum depth to water table. The low point of the water table at the end of the dry season is the most critical measurement in ecological terms, because, in general, the depth to the water table is closely linked to species composition and *Sphagnum* survival (Rydin and Jeglum, 2006).

The water table (and heads) in bogs can fluctuate rapidly in response to precipitation. A single measurement is not likely to capture the maximum or minimum water level in a given year. However, the goal of this study was to describe the hydroperiod of bogs and laggs in coastal BC, which follows a similar pattern each year. Although water levels fluctuate in response to rainfall events, these fluctuations average out to a certain mean high point of the water table during winter and early spring (i.e. a high base level near the bog surface with increases due to rainfall) and an average low point of the water table during late summer. Depth to water table measurements during key periods will provide a general idea of the seasonal fluctuation in the water table and whether the water table fluctuates within the general range for undisturbed bogs in the region, or whether the water table is lower so that *Sphagnum* regeneration may be hindered and the bog may require restoration.

3.6.2. Spatial Variability in Water Chemistry Across the Transects

The four hydrochemical parameters that varied with position on the transect across the bog expanse – bog margin transition were pH, EC_{corr}, and Ca^{2+} and Mg^{2+} concentrations. However, the increase in these hydrochemical parameters from bog to lagg was not consistent. We observed an increase from bog to lagg for pH (67% of the transects) and Mg^{2+} (83% of the transects), whereas Ca^{2+} and EC_{corr} only showed this trend for 50% and 33% of the transects, respectively. Vitt et al. (1995) found that pH, EC_{corr}, and Ca^{2+} and Mg^{2+} concentrations increased along a bog – rich fen gradient, and were highly correlated with one another. Bragazza et al. (2005) observed that Ca^{2+} and Mg^{2+} concentrations and pH in pore-water were higher at the mire margin (lagg) than in the mire expanse for an Italian and a Swedish bog. Similarly, Bubier (1991) found higher Ca^{2+} and Mg^{2+} concentrations at a lagg stream compared to the bog centre. While we found similar gradients across the bog expanse – bog margin transition when all transects were combined, the results of this study show that these gradients do not occur across each individual transect. For the bogs that we studied, the Ca:Mg ratio did not appear to be a useful indicator of the mineral soil water limit either. Since both pH and Mg^{2+} concentrations displayed the most consistent increase across the transects, these parameters may be more useful for locating the mineral soil water limit. However, pH did not always increase significantly at the transition between bog and lagg, and Mg^{2+} concentrations were low (<4 mg/l) so that it may not be a dependable indicator of the location of the lagg or mineral soil water limit either. Thus, while there are broad hydrochemical gradients across the bog expanse – bog margin transition, hydrochemical gradients vary between the different transects and hydrochemical parameters are not necessarily uniformly useful for determining the location of the mineral soil water limit across individual transects in coastal BC bogs.

3.6.3. *Temporal Variation in Water Chemistry*

Observations in Burns Bog and Blaney Bog suggest that although there is some seasonal variability in pH, the variation is relatively limited (e.g. generally within 0.5 pH units) and large deviations from the average are not common (Table 4, Fig. 6). Accordingly, pH can be considered a seasonally stable parameter. Vitt et al. (1995) also found that pH was relatively constant between May and October in Alberta peatlands, and suggested that a one-time sampling event would be adequate for these parameters. Wieder (1985) found subsurface pH (at 30 cm depth) to be relatively constant during the growing season (April – December) in a West Virginia bog.

EC_{corr} was generally also consistent over time, although it did occasionally spike above the average values (Fig. 7). There was no consistent increase or decrease in variability in EC_{corr} from bog to forest. The maximum change over time was 88 µS/cm. The largest "spike" in EC_{corr} (an increase of 66 µS/cm, compared to the previous measurement in December 2010) was observed in Burns Bog (DNR transect, LG2) in June 2011. There is no clear explanation for this increase, as EC_{corr} did not change considerably at the other sites on the transect but it could be caused by groundwater movement from the adjacent upland in response to a large rainfall event. Another increase above the average was observed for all sites on the Burns Bog Cranwest transect in September 2011. This increase may have been due to concentration of ions in the peat during dry weather, deposition of dust from the surrounding agricultural fields, or highway construction; pH was also higher at some sites on this transect on this date (Fig. 6). EC_{corr} was 58 µS/cm higher than the average in Blaney Bog (upland transect, R2) in September 2011. EC_{corr} and pH both increased across this transect on this date, but it is unclear why EC_{corr} at the R2 site increased more than at the other sites. Vitt et al. (1995) found only small changes (<50 µS/cm) in weekly measurements of corrected electrical conductivity of bog water in central Alberta during the ice-free season.

Pore-water chemistry is buffered against changes in precipitation chemistry due to ion exchange with the peat (Proctor, 2003; Worrall et al., 2003); the buffering effect likely becomes greater with depth because new rainfall moves slowly through the peat and most water movement is (laterally) through the poorly decomposed, porous upper peat. However, the observed spikes in EC_{corr} occurred for piezometers at various depths (0.58-1.10 m below the surface; average: 0.89 m), not only the shallowest piezometers. Ion concentrations are expected to be higher during periods of intense evaporation (concentration effect), and lower during periods of high rainfall (dilution effect). We found a statistically significant correlation with depth to water table only for EC_{corr} and Mg^{2+} concentrations.

There was also little variation in Mg^{2+} and Na^{+} concentrations between the two years. Ca^{2+} was more variable at the R2 and MN sites of the Cranwest transect, and at the MN site in Campbell River Bog, but changed little on the Sherwood transect; samples were only taken in 2011 for the DNR and Blaney Bog transects. The relatively small change in ion concentrations in bog water over time is caused by ion exchange with the peat (Proctor, 2003). Wieder (1985) also found that major cation and Cl^{-} concentrations were fairly constant during the growing season. Adamson et al. (2001) also found little change in pH and EC_{corr} over time, except during drought conditions. The increase during drought periods was attributed to an increase in H^{+} concentration due to evaporative concentration and aerobic conditions, which resulted in oxidation of H_2SO_4 to SO_4^{2-} and H^{+}. The increased availability of H^{+} resulted in cation exchange that subsequently increased concentrations of Na^{+}, Mg^{+}, and Ca^{2+} (Adamson et al., 2001). Vitt et al. (1995) found that Ca^{2+}, Mg^{2+}, and Na^{+}, concentrations in an Alberta bog were highest in spring, declined in early summer, and then increased gradually over the summer, but, despite this seasonal pattern, the concentrations of these cations were low (<5 mg/l) throughout the growing season and generally stable.

Na^{+} and Cl^{-} are not biologically limiting in oceanic bogs, and consequently accumulate in peat and drainage water (Damman, 1986). Concentrations of Na^{+} and Cl^{-} in pore-water were, on average, four times higher than in precipitation (Table 7). Ca^{2+} and Mg^{2+} concentrations were also higher (5 and 9 times, respectively) in pore-water at the BG sites than in precipitation (Table 7), so also do not appear to be biologically limiting in this region. SO_4^{2-} may be the only parameter measured in this study that is potentially biologically limiting; SO_4^{2-} was generally below the 0.5 mg/l detection limit in our water samples, but ranged from 0.7-1.8 mg/l in precipitation. Gorham et al. (1985)

reported that SO_4^{2-} concentrations are lower in bogs than in precipitation, particularly in oceanic regions, and attributed this to plant uptake and microbial reduction. Upon entering the peat surface, much of the SO_4^{2-} from precipitation is reduced to sulphides (Proctor, 1995).

In agreement with our hypothesis for the second objective of this study, we thus found that pH and EC_{corr} did not change significantly over the 1.5-year sampling period for a given site and that a single measurement in June or July is reasonably representative of the average conditions (Appendix C). A single survey or measurement campaign will thus give a reasonable representation of the gradients in pH and EC_{corr} across the bog expanse – bog margin transition, but longer time series, and especially more frequent measurements during precipitation events are needed to validate this result and to determine if larger changes in EC_{corr} and pH occur during precipitation events.

We found that temporal variation of Ca^{2+} and Mg^{2+} concentrations generally increased across the transect from bog to forest. On average, temporal variation of pH similarly increased from bog to forest, but not for all individual transects (Table 4). There was no trend in the temporal variation of EC_{corr} across the transects. Similarly, Vitt et al. (1995) found that seasonal variability in Ca^{2+} and Mg^{2+} concentrations was increasingly greater in poor fen, moderately rich fen, and extremely rich fen sites, suggesting that the influence of groundwater determines the variation in cation concentrations over time in fens, whereas soil-water ion concentrations in bog peat are not affected by groundwater and buffered against changes in precipitation chemistry. As a result, pore-water chemistry in the bog is generally less variable. This indicates that a one-time sampling campaign may be adequate for bog sites, but not necessarily for the lagg or mineral sites that are influenced by minerotrophic groundwater. For lagg and mineral sites, samples taken during key hydrological phases (e.g. drought, flooding, heavy rainfall, stable weather conditions) will give a better estimate of the variability in pore-water chemistry in response to fluctuations in precipitation and evapotranspiration. Andersen et al. (2010) found smaller changes in major cation and Cl^- concentrations over time for a natural peatland in Quebec, compared to restored and unrestored blocks in an adjacent harvested peatland area. More frequent sampling may thus also be needed in disturbed sites.

3.6.4. *Effect of Logging*

The unexpected removal of large (10-40 m tall) trees due to clearcut logging on the Sherwood transect in Burns Bog resulted in a 27 cm higher late-summer water table in the clearcut in 2011 compared to the pre-logged condition in 2010, whereas the depth to water table was similar in late summer of 2010 and 2011 for the other sites (Fig. 4). The mean water table in the clearcut between August-November was 8 cm higher in 2011 than in 2010, compared to a 13 cm lower mean water table between August-November in 2011 than in 2010 for the sites on the Sherwood transect that were not affected by the logging. The rise in water table in the clearcut site can therefore be attributed to a reduction of interception and evapotranspiration losses (Dubé et al., 1995). Cheng (2011) observed a mean evapotranspiration rate of 0.9 mm/day and 1.1 mm/day in an open bog site and a forested site dominated by small pine trees (mean DBH: 15 cm) near the Sherwood transect, respectively, during the 2009 growing season (June-September). However, the area that was logged was dominated by large cedar and hemlock trees (mean DBH: 40 cm) rather than small pine trees. The site studied by Cheng contained only two large (mean DBH: 40 cm) hemlock trees, but their transpiration rates (on a per tree basis) were 10 times higher than for the small pine trees (Cheng, 2011). Differences in evapotranspiration losses between the clearcut and the lagg forest in this study are thus expected to be larger than the differences in evapotranspiration between the forested bog and open bog sites of Cheng (2011). Cheng (2011) found that canopy interception was 12% in the forested site and negligible in the open bog site due to the lack of trees. This would translate to 35 mm of interception loss between August and November 2011 (0.3 mm/day), but the large cedar and hemlock trees are expected to intercept more precipitation than the open pine forest studied by Cheng (2011). In a forested wetland with a similar tree basal area (~30 m^2/ha) as the pine forest studied by Cheng (2011), Roy et al. (2000) measured an average interception rate of 31%; their study area was characterized by cedar, spruce, and fir trees.

In 2012, the late summer water table in the logged LG2 site was lower than in 2011. This may partly be attributed to the regeneration of a shrub layer and resulting increased interception and evapotranspiration losses in 2012, as well by the lower summer precipitation. Mean air temperature at YVR in July and August was the same for 2011 and 2012 (18ºC), but there was less precipitation during this period in 2012 (31 mm) than in 2011 (57 mm),

Although the results of this study suggest a significant watering-up effect due to clearcut logging, only one piezometer (LG2) was located within the clearcut because the logging was not foreseen at the time this study was initiated. However, our results are similar to (or slightly larger than) those reported for other studies in Canada and Finland (e.g. Dubé et al., 1995; Heikurainen and Päivänen, 1970), which suggests that a water table rise of this order can be expected after tree removal. The watering-up effect in this study is, for example, similar to the mean water table rise of 7 cm, and a maximum rise of 15 cm, for a clearcut black spruce bog in the St. Lawrence lowland (Dubé et al., 1995) and larger than the average watering-up effect of 4 cm after clearcut logging in a forested wetland near Quebec City (Marcotte et al., 2008). Jutras et al. (2006) found a mean water level rise of 2.6 cm after pre-commercial thinning of forested wetlands in the St. Lawrence lowland, while Päivänen (1980) observed a water table rise of 6 cm for clearcut pine and spruce peatland sites in southeast Finland. While removal of large trees can be beneficial for restoring a higher water table in support of the restoration of open bog areas and *Sphagnum* colonies, it may be a detrimental activity in laggs that naturally contain large trees (e.g. the Sherwood and DNR laggs in Burns Bog). Tall trees in the Sherwood lagg forest provide important habitat and may benefit the bog by providing a barrier to dust blown from neighbouring farms and roads, although we did not observe a discernible change in pH or EC_{corr} in response to logging of the lagg forest on the Sherwood transect during the study period.

3.7. Conclusions

Peatlands cover large areas of coastal British Columbia. In order to characterize the hydrological, hydrochemical, and ecological conditions of a representative sample of peatlands to create restoration plans or set boundaries for conservation areas, it is necessary to characterize their ecohydrological status with relatively few measurements at each site. Depth to water table and near-surface pore-water chemistry are critical measurements in the assessment of peatland conditions, because peatland ecology is closely linked to these abiotic gradients. The marginal areas of bogs (i.e. the lagg) are often disturbed and drained for agricultural or other land uses due to shallow peat depths at the margins; however, a high water table at the bog margin is often integral to the hydrological system of a bog because it reduces the hydraulic gradient and helps to support the water mound of the bog.

The depth to water table in coastal BC bogs displays a similar pattern in response to annual cycles of precipitation and evapotranspiration each year, with water levels dropping further below the bog surface during dry years. Annual fluctuations of the water table were smallest in the bog sites, and increased toward the lagg and adjacent mineral forest. In the bog, the depth to water table was less than 40 cm; in the lagg, the depth to water table was less than 75 cm. These maximum depths to water table may be used to guide restoration in areas where the lagg has been damaged or lost. Logging on one transect changed the amplitude of the hydroperiod and led to a 27 cm increase in the lowest measured water level in late summer and an average increase of 8 cm for the August – November period.

Spatial variation in EC_{corr} and pH across the transects from the bog to mineral sites was statistically significant and larger than the temporal variability in pH and EC_{corr}. pH-corrected electrical conductivity, pH, and Na^{+} and Mg^{2+} concentrations varied little during the study period; spatial gradients across the bog expanse – bog margin transition can thus be determined by a one-time sampling campaign. On the other hand, Ca^{2+} and Cl^{-} concentrations and acidity varied significantly between years at some sites and may be too variable to be confidently estimated with a one-time sampling campaign. Mg^{2+} concentration and pH increased most frequently from bog to forest, but did not increase consistently at the vegetative transition from bog to lagg for each individual study transect.

4. Small scale spatial variability in depth to water table, hydrochemistry, and peat properties in Burns Bog, Delta, BC

4.1. Abstract

Depth to water table, pH, and electrical conductivity measurements at a single point are often assumed to be representative of the area surrounding the measurement site, but this generalization has not been demonstrated for bogs of coastal BC. Microtopography in peatlands may result in a wide range of depth to water table readings, and pore-water chemistry may vary depending on living vegetation and peat properties. Depth to water table, pore-water chemistry (pH, electrical conductivity), peat properties (humification and ash content at 10, 50, and 100 cm below the surface), and soil moisture at 0-30 cm below the surface were measured at 25 points in a 4 x 4 m study area in an open bog heath area to determine the small scale spatial variability of these parameters. Depth to water table and soil moisture measurements were consistent when measured only in hollows. Water content of peat samples varied little (standard deviation <4%) at all sample depths. There was very little variation in pH throughout the study area (mean: 3.65; standard deviation: 0.03), and slightly more variation in electrical conductivity (mean: 84 µS/cm; standard deviation: 7.5 µS/cm). The level of humification was generally within 1-2 points on the von Post scale for samples from a given depth. Ash content decreased with depth below surface, and was less variable at 50 and 100 cm below the surface than at 10 cm below the surface. Thus, most of the tested variables appear to be generally representative of the surrounding area, but there were statistically significant differences in depth to water table and soil moisture between hummocks and hollows.

4.2. Introduction

In peatland studies, it is common to assess the depth to water table and hydrochemistry by taking point measurements along a transect or on a large-scale (e.g. 100 x 100 m) sampling grid (e.g. Rydin and Jeglum, 2006; Schouten, 2002; Bragazza and Gerdol, 1999; Tahvanainen and Tuomaala, 2003). Depth to water table, residence time of water in the rooting zone, and seasonal fluctuations in the water table strongly influence species composition, distribution, and structure of plants (Rydin and Jeglum, 2006). Depth to water table is therefore one of the most frequently measured parameters in peatlands studies. When water levels are measured at several locations across a peatland, and surveyed relative to a common datum, it is possible to also gain an understanding of lateral water movement through the system. Measurements in piezometers installed at different depths below the surface help to determine vertical hydraulic gradients.

Chemistry of peat and pore-water is often determined for the purpose of peatland classification (McNamara et al., 1992), assessment of nutrient cycling (Vitt and Chee, 1990), understanding the relation between peat and hydrochemical properties relative to the volume and chemical composition of precipitation (Gorham et al., 1985; de Mars and Wassen, 1999), or delineation of regional patterns in peatland chemistry related to oceanic influences and atmospheric pollutants (Gorham et al., 1985; Vitt et al., 1990; Malmer et al., 1992). Peat and pore-water chemistry in the rooting zone are often correlated with certain plant communities, whereby low-nutrient, low-pH ombrotrophic conditions promote the establishment of *Sphagnum* and ericaceous shrubs, and mineral-enriched fen peat provides conditions more suitable for brown mosses and sedges, grasses, and reeds (National Wetlands Working Group, 1988; Bridgham et al., 1996; Wheeler and Proctor, 2000; MacKenzie and Moran, 2004).

A number of studies have looked at how depth to water table and hydrochemistry change from the bog centre to the bog margin. Bubier (1991) found that pH, electrical conductivity, and cation concentrations were higher at the bog margin compared to the adjacent open bog in Vermont. Similar results were found by Bragazza et al. (2005) for an Italian and a Swedish raised bog. Depth to water table generally increases across the transition from the bog centre to margin (Damman, 1986). When studying these gradients, it is important to know whether the observed differences in depth to water table and hydrochemistry are related solely to the changing conditions across the bog margin (e.g. increasing surface slope, greater influence from adjacent or underlying mineral soils) or whether some of the observed differences are related to inherent small scale variability in depth to water table, pore-water chemistry, and peat properties.

Measurements at a single point in a peatland are usually assumed to be representative of the general area around the sampling site. Due to financial and time constraints, it is usually necessary to minimize replication in studies on depth to water table and the hydrochemical gradients across the bog expanse – bog margin transition. However, depth to water table measurements on the same day in different parts of a bog can vary by as much as 40 cm, depending on whether the measurement is taken in a hummock or hollow (Bragazza et al., 1998). The hummock-hollow sequence of bog topography can cause difficulties for surveying and determination of the “depth below the surface” of the water table. In addition, hummocks may experience more pronounced water table fluctuations, due to drainage of hummock water into adjacent low-lying areas during dry periods (Bragazza and Gerdol, 1999). Hummock height can be highly variable (e.g. 5-50 cm), and therefore it has been recommended to measure depth to water table in hollows (Verry, 1984; Almerdiger, 1986; Whitfield et al., 2009). Even in relatively flat sites, it is important to know whether the water table measured in hollows is uniform within a given area.

Hydrochemical characteristics of near-surface pore-water may vary between hummocks and hollows as well, due to differences in vegetation (specifically nutrient uptake by plants), redox reactions, biological activity (e.g. by microorganisms), rate of decomposition, cation and anion exchange, and vertical and horizontal variability in peat properties, such as hydraulic conductivity and bulk density (Naucke et al., 1993; Schouwenaars and Vink, 1992; Tahvanainen et al., 2002). Biogeochemical “hot spots” can form due to spatially variable water movement through uneven subsurface conditions that are a result of surface micro-topography (Frei et al., 2012). Rydin and Jeglum (2006) noted that there are differences between hummock, lawn, and carpet peat, and that groundwater chemistry is a better indicator of the chemical conditions of the area than peat chemistry. Bragazza and Gerdol (1999) found lower pore-water pH in hummocks compared to hollows in an Italian bog, which they attributed to the greater cation exchange capacity of the hummock Sphagna. Cation concentrations (Ca^{2+}, Mg^{2+}) were slightly higher in surface water in a hummock than a hollow, but the difference was generally not significant; the opposite was found in water samples from piezometers 25 cm below the surface, where Ca^{2+} and Mg^{2+} concentrations were slightly higher in hollows during both the wet and dry season. Bragazza et al. (1998) observed significant differences in pH, Na^{+}, K^{+}, and Mg^{2+} between hummocks and hollows. Cation concentrations except Mg^{2+} were higher and also temporally more variable in hummocks. Gerdol et al. (2011) on the other hand found no significant differences in pH or Ca^{2+} and Mg^{2+} concentrations between hummocks and hollows. It is important to characterize the magnitude of the differences in pore-water chemistry between hummocks and hollows in order to ensure that measurements in different places in a peatland are representative and comparable.

For studies on gradients in depth to water table, hydrochemistry, and peat characteristics across a single bog, or studies on regional gradients in chemistry and peat properties, it is critical to know whether a point sample on a transect or grid is representative of the area around the measurement point, and what range of variability can be expected for each parameter as a result of natural heterogeneity and small scale variability. The objectives of this study were therefore i) to determine whether point measurements can be used as representative samples of a general area; ii) to determine which parameters, if any, would require spatial replication, and if so, what level of replication would be necessary to ensure representative measurements; iii) to quantify the differences in depth to water table, soil moisture, pH, electrical conductivity, peat properties, and vegetation between hummocks and hollows; and iv) to determine whether the measured abiotic variables and percent cover of the dominant plant species were correlated.

4.3. Study site

This study took place in a 4 x 4 m study grid in the undisturbed, southwest corner of Burns Bog in spring 2012 (Fig. 8, 9). Burns Bog is a 3,000 ha raised bog located in Delta, British Columbia (BC), Canada. Dominant plant species in the undisturbed area of Burns Bog include *Pinus contorta* var. *contorta*, *Ledum groenlandicum* Oeder, *Cladina* *portentosa* (Dufour) Follmann, *Vaccinium uliginosum* L., *Andromeda polifolia* L., *Kalmia occidentalis* Small, *Rhynchospora alba* (L.) Vahl., and *Sphagnum* spp. There is one main hummock on the north side of the grid, and several smaller hummocks near the edges of the study grid (Figs. 9-10). There is a slight gradient in hummock height from the north side (somewhat hummocky) to the south side (less hummocky) of the study grid (Table 9).

Figure 8. ***Study location (white star) in Burns Bog, Delta, British Columbia, Canada. Inset shows location of Burns Bog in southwest British Columbia (BC).***

Figure 9. Photograph of the study grid (facing southeast).

4.4. Methods

Twenty-five piezometers were installed at a 1-metre interval in the study site in April 2012. The piezometers were 1.5 m long, 2.5 cm diameter Schedule 40 PVC pipe with a 40 cm slotted length at the bottom. All piezometers were installed 66 cm below the surface based on past knowledge of the range of the annual water table fluctuation in this area of the bog; the goal was to keep the piezometer screening near the bog surface while still ensuring a minimum volume of water for sampling. 48% of the piezometers were installed in hummocks, and 52% in hollows. Trampling of hummocks was minimized by only walking in the hollows or by walking on a tarp. The elevation of the study grid was surveyed on September 19, 2012 with a Leica GS12 Netrover antenna and Leica C515 controller GPS unit with survey-grade accuracy.

The piezometers were purged once on April 20, 2012, and twice on May 4, 2012. At this time of year, the water table in Burns Bog has usually just begun to decline from the wet season (October to March) high point, but in years with a wet spring the high water table can extend into May (Howie et al. 2009b, Howie and van Meerveld 2012). The early spring of 2012 was only slightly wetter than normal (93 mm precipitation from April 1-May 1) compared to the long-term average for 1971-2000 (84 mm from April 1-May 1) (data from Vancouver International Airport; source: Environment Canada). There were scattered showers on May 4 (1.4 mm), but there was no additional precipitation between purging and the measurements. Depth to water table in the piezometers was measured to the nearest 0.5 cm on May 9, 2012 with an electronic water level probe (Heron Instruments Little Dipper, Dundas, Ontario, Canada). It was assumed that the water level in the shallow piezometers represented the water table because previous measurements during a 5-year period in another part of Burns Bog had shown that the difference between the water levels measured in a well and in a piezometer were small (mean: 0.8 cm) (Chapter 3) and similar to our water level measurement accuracy (0.5 cm) and the uncertainty of determining the ground surface in uneven terrain.

On May 11, 2012, a WTW Multiline P4 water quality meter (College Station, Texas, USA) was used to measure electrical conductivity (EC), and a WTW Multi 3430 water quality meter (College Station, Texas, USA) was used to measure pH. The probes were inserted directly into the piezometers; pH and EC measurements were taken in the top 10-15 cm of the water column. The probes were calibrated prior to use, and were rinsed with distilled water prior to insertion into the piezometers and between each measurement. Electrical conductivity was corrected for pH (EC_{corr}) using the following formula: $EC_{corr} = EC_{measured} – EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$, and 3.49×10^5 is the conversion factor for field measurements standardized to 25 ºC by a handheld meter (Rydin and Jeglum 2006). Soil moisture (volumetric water content at 0-30 cm below the surface) was measured 5 cm east of each piezometer with a Moisture Point 917 single diode 30 cm TDR probe (Sidney, BC, Canada) on the same day. The Moisture Point probe is factory-calibrated for mineral soils; therefore, our field measurements were adjusted using the calibration of Cheng (2011) for a peat core from Burns Bog.

Prior to piezometer installation, peat cores were collected at 10, 50, and 100 cm below the surface from each location. The 10-point von Post scale was used to determine level of humification (decomposition) by squeezing a sample of peat in a closed fist to see if water of different colouration and turbidity (in various quantities) was expressed between the fingers; H1 represents undecomposed peat and H10 completely decomposed peat (Egglesmann et al., 1993; Rydin and Jeglum, 2006; Damman and French, 1987). 5 cm samples of peat were collected from 10 cm, 50 cm, and 100 cm below the surface. The peat samples were enclosed in plastic wrap, sealed in plastic bags, and frozen until analysis in May 2012. In the lab, the peat samples were weighed, dried at 105 ºC for 24 hours and re-weighed to determine gravimetric water content, and then dry-ashed at 550 ºC for 24 hours and re-weighed to determine loss on ignition (ash content).

The vegetation at each piezometer was photographed from above in April and September, covering an area of approximately 0.8 m x 1.0 m with the piezometer in the centre. Using these photographs, percent cover was estimated for each of the eight dominant plant species: *Pinus contorta* var. *contorta*, *Ledum groenlandicum*, *Cladina portentosa*, *Vaccinium uliginosum*, *Andromeda polifolia*, *Kalmia occidentalis*, *Rhynchospora alba*, and *Sphagnum* spp. Species nomenclature follows Hitchcock and Cronquist (1973).

Pearson linear correlation tests were performed to determine significant correlations between the measured abiotic variables. Spearman rank correlations were used to determine the correlations between percent cover of the dominant plant species and the measured abiotic parameters. Students t-tests were used to determine differences in abiotic variables between hummocks and hollows. A significance value of 5% was used for all analyses. Canonical Correspondence Analysis (CCA) was used in PC-ORD (McCune and Mefford, 2011) to determine which environmental variables were most strongly related to species variance. Multiple regression was used to determine which environmental variables were most strongly correlated with percent cover of each of the dominant species. Maps were created in Matlab® using linear distance interpolation.

4.5. Results

4.5.1. Depth to Water Table, Soil Moisture, and Hydrochemistry

Depth to water table ranged from 5 to 27 cm below the surface (mean: 10.7 cm; standard deviation: 5.2 cm; Fig. 10), and was positively correlated with surface elevation (Table 10, Fig. 11). Depth to water table was significantly greater for hummocks than hollows. The water table elevation was less variable (mean: 2.73 m above sea level; range: 9 cm; standard deviation: 2 cm) than the depth to water table. However, these measurements are somewhat uncertain because surface elevation was measured in late summer (19 weeks after the depth to water table measurements) when the water table and surface elevation can be expected to be lower than in May (Whitfield et al., 2006).

Volumetric soil moisture content at 0-30 cm ranged from 45 to 75% (mean: 68%; standard deviation: 7.5%). Mean soil moisture was 64% (standard deviation: 8.5%) for the hummocks and 73% (standard deviation: 1.5%) for the hollows; the difference between hummocks and hollows was statistically significant. The spatial pattern of soil moisture closely matched that of depth to water table (Fig. 10). Soil moisture in the upper 30 cm of the peat was negatively correlated with depth to water table (r^2=0.87) and surface elevation (r^2=0.66) (Table 10; Fig. 11).

The average pH was 3.65 (range: 3.59-3.70; standard deviation: 0.03). Field-measured EC ranged from 70 to 98 µS/cm (mean: 84 µS/cm; median: 84 µS/cm; standard deviation: 7.5 µS/cm). EC_{corr} ranged from 0 to 14 µS/cm (mean: 6 µS/cm; median: 5 µS/cm; standard deviation: 5 µS/cm) and was highest in the southeast of the study grid (Fig. 12). EC_{corr} and pH were not significantly correlated with surface topography; their spatial distribution was not significantly correlated with any of the other measured parameters either (Fig. 12, Table 10).

Table 9. ***Elevation, depth to water table measured to the nearest 0.5 cm, volumetric soil moisture content at 0-30 cm, and peat properties across the study grid.***

Site #	Grid Coordinates		Elevation (metres above sea level)	Hummock Height (cm)	Water table depth below surface (cm)	Soil Moisture (%)	von Post humification			Ash content (%)		
	X	Y					10 cm depth	50 cm depth	100 cm depth	10 cm depth	50 cm depth	100 cm depth
1	5	5	2.88	25	15.5	62	H3	H4	H2	4.0	0.4	1.0
2	4	5	2.85	0	8.0	72	H3	H3	H2	1.7	1.0	0.5
3	3	5	2.84	0	8.5	72	H3	H3	H2	3.2	1.0	0.0
4	2	5	2.89	10	14.5	64	H3	H4	H2	4.2	4.1	0.8
5	1	5	2.92	25	20.5	50	H3	H5	H2	4.0	0.6	0.8
6	5	4	2.86	5	9.0	68	H4	H5	H2	1.4	1.4	0.0
7	4	4	2.82	0	8.0	70	H2	H5	H3	3.4	1.8	0.5
8	3	4	2.97	30	27.0	45	H4	H5	H2	4.2	0.9	0.6
9	2	4	2.85	0	9.5	73	H4	H3	H2	1.2	1.1	0.0
10	1	4	2.79	5	7.0	73	H4	H3	H2	0.4	0.0	0.0
11	5	3	2.87	10	13.0	68	H3	H4	H2	2.5	0.0	0.7
12	4	3	2.86	0	10.5	74	H4	H3	H2	1.0	1.3	0.6
13	3	3	2.86	10	11.0	63	H4	H3	H2	0.8	0.0	0.6
14	2	3	2.87	10	11.5	66	H4	H3	H2	2.4	0.5	0.8
15	1	3	2.83	0	9.0	72	H4	H3	H2	0.0	0.0	1.2
16	5	2	2.96	15	18.0	62	H4	H6	H2	5.1	0.9	0.0
17	4	2	2.81	0	7.0	71	H4	H5	H2	8.6	0.0	0.9
18	3	2	2.80	0	6.5	74	H4	H3	H3	6.3	1.2	0.8
19	2	2	2.79	0	7.5	74	H4	H3	H2	6.4	1.8	0.8
20	1	2	2.81	0	6.5	72	H4	H3	H5	4.2	0.0	1.1
21	5	1	2.84	2	11.5	72	H4	H3	H3	9.1	1.1	0.5
22	4	1	2.76	0	4.5	74	H4	H3	H4	6.6	0.3	1.3
23	3	1	2.78	0	5.0	75	H4	H3	H4	9.1	0.8	1.0
24	2	1	2.83	5	10.5	69	H4	H3	H5	8.9	0.8	0.7
25	1	1	2.83	0	8.0	73	H4	H3	H3	8.1	0.7	0.8

Table 10. ***Pearson linear correlation coefficients (r^2) (top half of table) and Spearman rank correlation coefficients (r_s) (bottom half of table) for all measured variables. Only statistically significant ($p<0.05$) correlations are shown. Elev. = elevation (masl). DTW = depth to water table (cm). SM = volumetric soil moisture (%) at 0-30 cm. AC = ash content (%) at 10, 50, and 100 cm below surface. VP = von Post humification at 10, 50, and 100 cm below surface. %S = percent cover of Sphagnum spp. %LG = percent cover of Ledum groenlandicum. %KM = Percent cover of Kalmia occidentalis. %RA = percent cover of Rhynchospora alba.***

	Elev.	DTW	SM	AC10	AC50	AC100	VP10	VP50	VP100	pH	EC_{corr}	%S	%LG	%KM	%RA
Elev.		0.85	0.67	-	-	-	-	0.40	0.24	-	-	-	0.31	-	0.37
DTW	0.93		0.87	-	-	-	-	0.34	-	-	-	-	0.20	-	0.24
SM	-0.81	-0.81		-	-	-	-	0.39	-	-	-	-	0.16	-	0.20
AC10	-	-	-		-	-	-	-	0.31	-	-	-	0.35	-	0.46
AC50	-	-	-	-		-	-	-	-	-	-	-	-	-	-
AC100	-	-	-	-	-0.40		-	-	0.18	-	-	-	-	-	0.30
VP10	-	-	-	-	-	-		-	-	-	-	-	-	-	0.17
VP50	0.56	0.49	-0.69	-	-	-	-		-	-	-	-	-	-	0.19
VP100	-0.58	-0.51	0.41	0.63	-	-	-	-		-	-	-	0.20	-	0.60
pH	-	-	-	-	-	-	-	-	-		-	-	-	-	-
EC_{corr}	-	-	-	-	-	-	-	-	-	-		-	-	-	-
%S	-0.40	-	0.46	0.40	-	-	-	-	0.51	-	-		0.29	-	0.18
%LG	0.61	0.55	-0.47	-0.70	-	-0.49	-	-	-0.69	-	-	-0.64		-	0.30
%KM	-	-	-	-0.44	-	-	-	-	-	-	-	-	-		-
%RA	-0.70	-0.56	0.55	0.58	-	0.56	0.44	-0.45	0.76	-	-	0.68	-0.79	-	

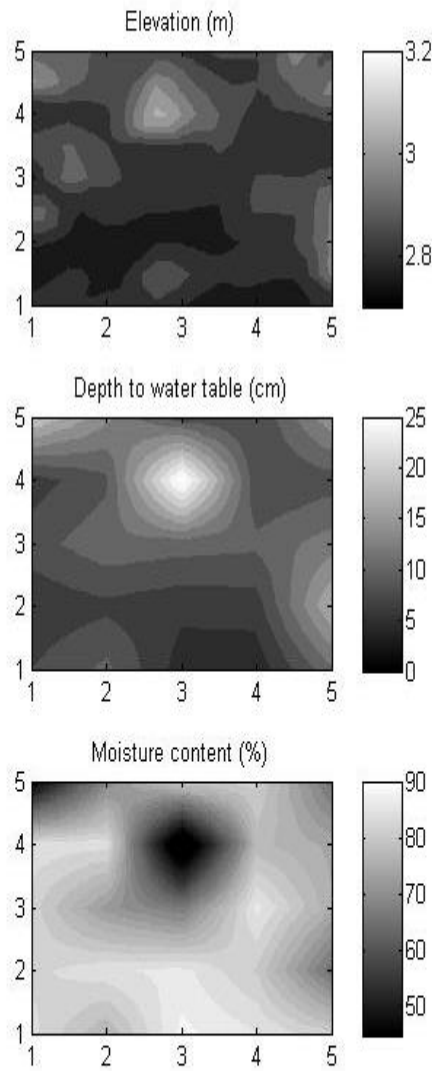

Figure 10. ***Spatial distribution of surface elevation above sea level, depth to water table, and volumetric soil moisture content at 0-30 cm. X and Y axes are distances in metres; location 1, 1 represents the southwest corner of the study grid.***

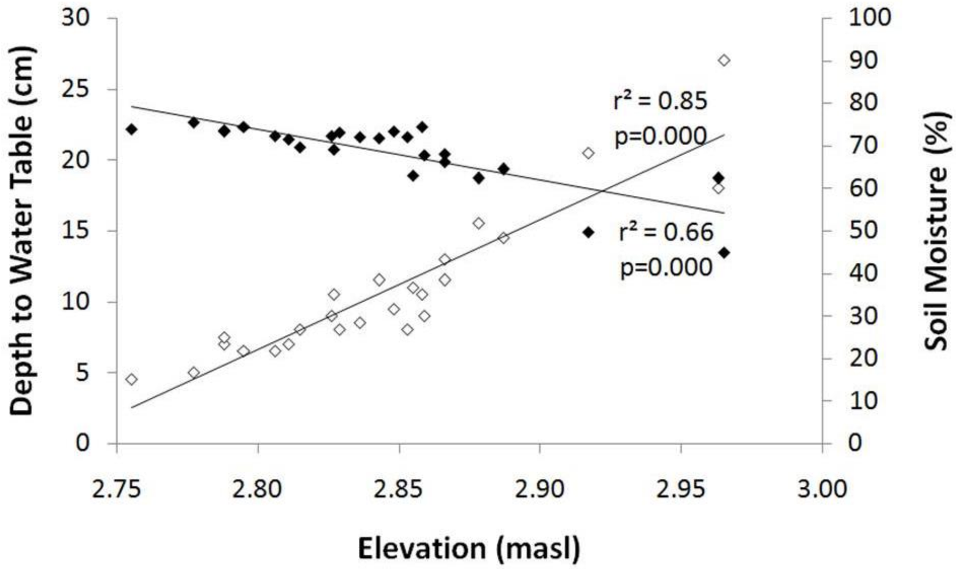

Figure 11. ***Relation between surface elevation (metres above sea level) and: 1) depth to water table (open diamonds) and 2) volumetric soil moisture content at 0-30 cm (solid diamonds).***

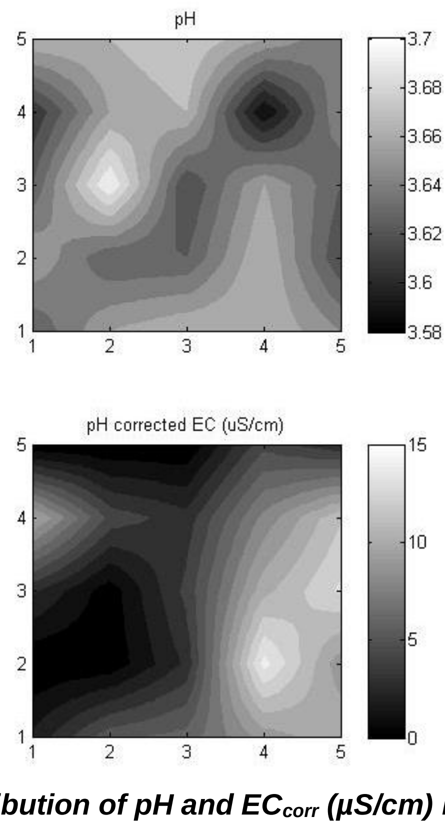

Figure 12. ***Spatial distribution of pH and EC_{corr} (µS/cm) in near-surface pore-water across the study grid. X and Y axes are distances in metres; location 1, 1 represents the southwest corner of the study grid.***

4.5.2. Peat Properties

At 10 cm depth, the von Post humification was usually either H3 (24%) or H4 (72%) (Table 9). Samples from 50 cm depth were more variable: H3 (64%), H4 (12%), H5 (20%), and one sample was H6. At 100 cm depth, most of the samples were H2 (68%), but many of the samples from the southern part of the study area were more decomposed (H3 to H5). At 50 cm depth, most samples from hollow sites were H3, whereas the samples from the hummock sites ranged from H3 to H6; there was no clear difference in humification between hummock and hollow sample locations at 10 cm and 100 cm depths. Gravimetric water content of the peat samples from 10, 50, and 100 cm below the surface averaged 87% (standard deviation: 4%), 93% (standard deviation: 2%), and 94% (standard deviation: 2%), respectively.

All peat samples contained less than 10% mineral material. Ash content was highest at 10 cm depth (mean: 4.3%; standard deviation: 2.9%), and decreased at 50 cm depth (mean: 0.9%; standard deviation: 0.9%) and 100 cm depth (mean: 0.6%; standard deviation: 0.4%) (Fig. 13, Table 9). Ash content and von Post humification appear to be related because humification was also highest near the surface. There was a significant linear correlation between ash content and humification when the samples for the three depths were combined. However, for each of the three depth groupings individually, only the samples from 100 cm below the surface showed a significant (positive) linear correlation between ash content and humification (Table 10). At 100 cm depth, both ash content and von Post humification were highest in the southern part of the study grid. Ash content of dry peat samples was significantly (negatively) correlated with gravimetric water content at both the 10 cm and 50 cm depths.

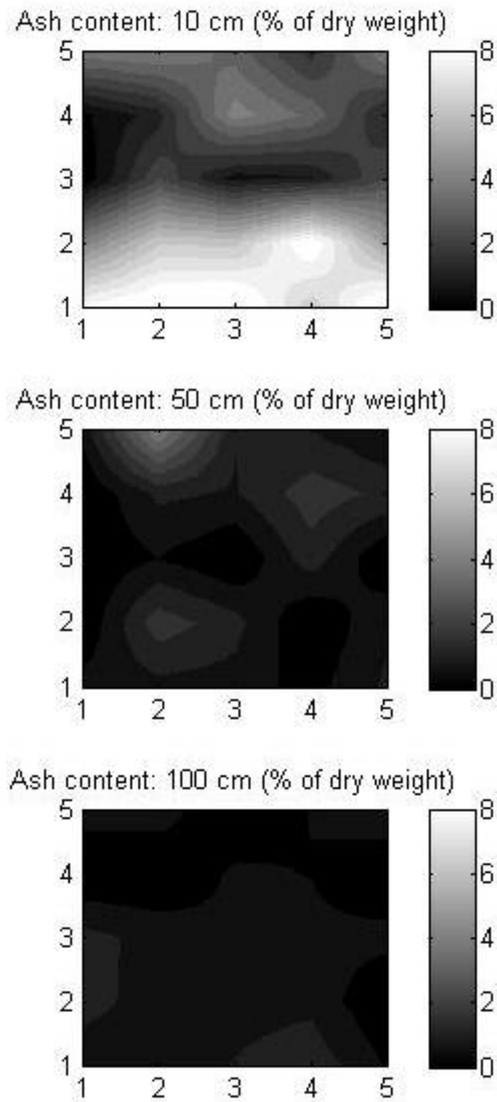

Figure 13. ***Spatial distribution of ash content (% of dry weight) at: a) 10 cm depth, b) 50 cm depth, c) 100 cm depth. X and Y axes are distance in metres; location 1, 1 represents the southwest corner of the study grid.***

4.5.3. Vegetation

The ground surface was more hummocky in the northern half, and flatter in the southern half, of the study area (Fig. 10). Cover of *Ledum groenlandicum* was highest on the hummocky side of the study area, whereas *Sphagnum* spp. and *Rhynchospora alba* were predominant on the flatter southern side of the study area (Fig. 14). Cover of *Ledum groenlandicum* was significantly negatively correlated with cover of *Sphagnum* spp. and *Rhynchospora alba*. Since hummock height (elevation) and depth to water table are correlated, the changes in plant species cover across the study grid suggests that cover of these species is related to depth to water table and soil moisture. Spearman rank correlation tests showed that cover of *Ledum groenlandicum* increased significantly with increasing depth to water table and decreased with soil moisture at 0-30 cm (Table 9). Cover of *Sphagnum* spp. and *Rhynchospora alba* increased significantly as soil moisture increased. Cover of *Rhynchospora alba* also increased significantly with decreasing depth to water table. Cover of *Ledum groenlandicum* and *Kalmia occidentalis* were significantly negatively correlated with ash content at 10 cm depth; cover of *Sphagnum* spp. and *Rhynchospora alba* were significantly positively correlated with ash content. These statistically significant correlations, however, do not necessarily equate to causation or mean that species cover is influenced by ash content. Ash content was negatively correlated to gravimetric water content, but the species that generally tolerate the wettest conditions (*Sphagnum* and *Rhynchospora*) were most abundant in areas with higher ash content at 10 cm depth. However, ash content was not correlated with volumetric soil moisture at 0-30 cm (Table 10). There was no significant correlation between cover of the dominant plant species and pH or EC_{corr} (Table 10).

CCA results showed that surface elevation explained 22% of species variance, depth to water table and ash content at 10 cm explained 25% of species variance; and soil moisture explained 21% of species variance. These dependencies were tested using separate runs of the CCA analysis because the variables were correlated with one another. Multiple regression results showed that cover of *Ledum groenlandicum* and *Sphagnum* spp. were most closely linked to soil moisture and ash content at 10 cm depth, and cover of *Kalmia occidentalis* and *Rhynchospora alba* were most closely linked to ash content at 10 cm depth.

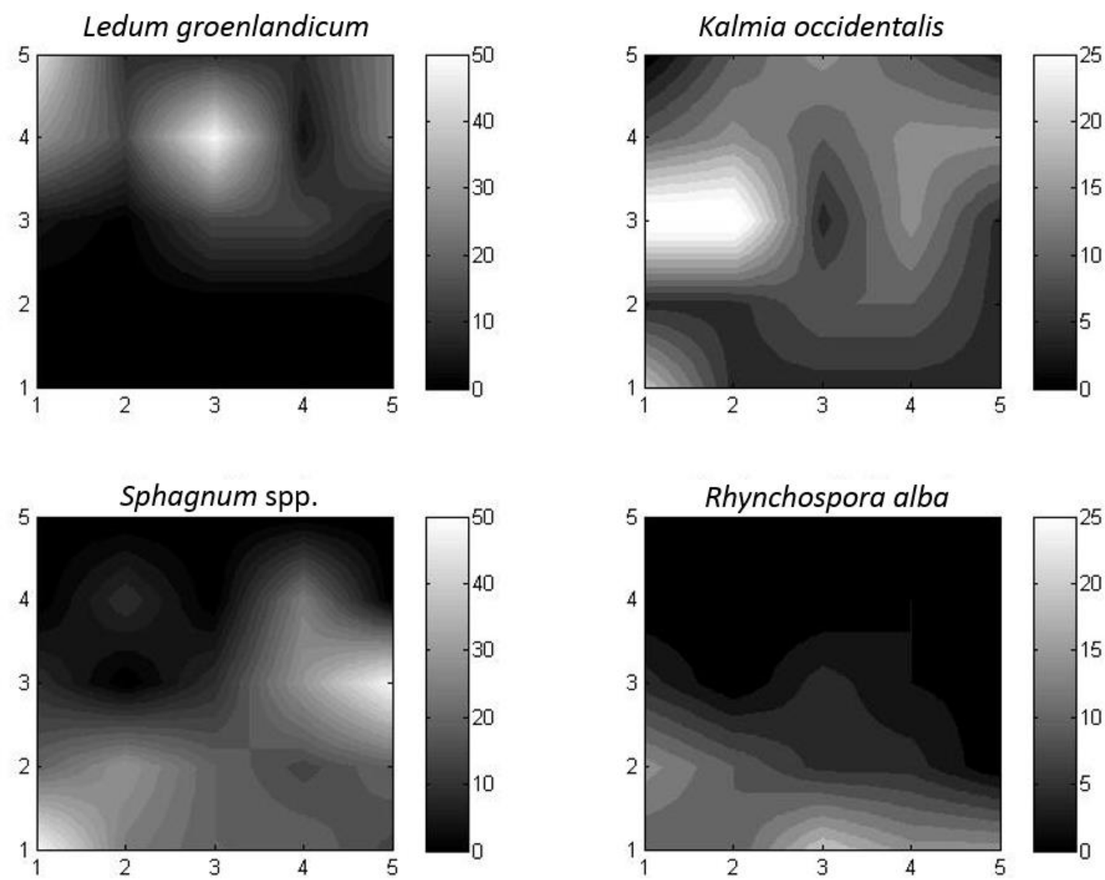

Figure 14. Percent cover of Ledum groenlandicum, Kalmia occidentalis, Sphagnum spp., and Rhynchospora alba in the study grid. X and Y axes are distance in metres; location 1, 1 represents the southwest corner of the study grid.

4.6. Discussion

The depth to water table was rather variable (standard deviation: 5.2 cm) for such a small study area. This variation, however, was systematic in that half of the piezometers were installed in hummocks and half in hollows. Depth to water table was less variable (standard deviation: 1.7 cm) in the piezometers installed only in hollows, compared to hummock sites (standard deviation: 5.5 cm). This indicates that depth to water table measurements in hollows can be expected to represent the position of the water table more reliably, assuming the piezometers have been installed properly and fully recharged. Depth to water table results are more consistent if measured only in hollows because hollow bottoms vary less in elevation than hummocks (Verry, 1984; Table 9). Whitfield et al. (2009) note that depth to water table and hummock height are usually referenced to the average surface elevation of hollows, but that these measurements are not very precise due to the uneven topography and difficulty in determining the actual "surface" of a peatland.

The water table elevation (surface elevation minus depth to water table) varied (range: 9 cm) throughout the study site. The undulation of the water table elevation may be related to the hummock-hollow sequence and variation in density and hydraulic conductivity of the peat. The moderate level of humification in the surface peat samples suggests a relatively low hydraulic conductivity (Schouwenaars and Vink, 1992; Price and Whitehead, 2001) compared to peat from 50 and 100 cm depths. Ingram (1983) noted that the water table will be flat in sites where the top layer of peat is permeable, but when the surface peat is less permeable, evaporation may differ between hummocks and hollows and result in an undulating water table. Ingram (1983) reported a water table depression below datum of approximately 5 cm below tall hummocks of *Sphagnum fuscum* (Schimp.) Klinggr.. Our data suggest that the water table was depressed below the main hummock in the study grid, which agrees with these findings. However, an elevated water table has also been found in hummocks (Moore and Bellamy, 1973). The undulation of the water table may change during the year in response to precipitation and evapotranspiration, as a result of changes in moisture demand of the hummock and hollow *Sphagnum* species or woody plants in the hummocks, and vertical and horizontal variability in peat density and hydraulic conductivity.

The volumetric soil moisture content at 0-30 cm was also less variable for just the hollows: 70-75%. Cheng (2011) found that soil moisture content in a similar open bog site near our study site was lower for hummocks than for hollows. Gravimetric water content of the peat samples was very similar throughout the study area, with a standard deviation of less than 4% for all depths. Thus, the gravimetric water content of a given peat sample, at a given depth, can be expected to fall within 4% of the average if samples are collected on the same day.

Peat decomposition is generally thought to increase with depth (Schouten 2002; Rydin and Jeglum, 2006). Levrel et al. (2009) observed consistently increasing humification from 0 (H1-H2) to 1 m (H7) below the surface. However, others have found that this trend is not as consistent as often assumed (e.g. Baird et al., 2008). Approximately two thirds of our von Post values for each sample depth were the same, i.e. H4 was the predominant level of decomposition at 10 cm, H3 at the 50 cm depth, and H2 at 100 cm depth. This depth profile of von Post humification is opposite of the typical pattern of increasing humification with depth, as described above. Regardless, a single von Post sample point from a given depth can be expected to be accurate (i.e. similar to the surrounding peat) two thirds of the time; the level of humification may be slightly higher or lower than average, but is likely still within 1 or 2 points on the von Post scale most of the time.

Ash content at each sample depth was only somewhat consistent across the study grid, with coefficients of variation of 68%, 100%, and 61% at 10, 50, and 100 cm below the soil surface, respectively. Ash content of peat samples changed similarly with depth as von Post humification. Ash content of bog peat is usually less than 5% (Brooks and Stoneman, 1997); 66 of our 75 peat samples (88%) were within this range, while the remainder were between 5-10% ash content. The results suggest that the surface peat in the study site is more decomposed (due to oxidation in more aerated conditions) and possibly denser because it contains more mineral material. Historic drainage for peat mining within 1 km of the study site that began in the 1930s and continued for five decades may have caused the water table to drop even in undisturbed areas such as where the study grid was located, and may have lead to oxidation and decomposition of the surface peat. Atmospheric deposition of pollutants and dust, caused by anthropogenic activities, may also have increased the mineral content of the surface peat (West et al., 1997); the increased dustfall could have, in turn, increased biological activity which further lowered the water table and increased oxidation and decomposition of the surface peat.

The most consistent hydrochemical parameter was pH, with a standard deviation of 0.03; thus, one can expect pH of near-surface pore-water around a given measurement location to be highly spatially stable. In a similar study in a moderately rich fen, Tahvanainen and Tuuomala (2003) measured pH just below the water table on a 38 m long transect of PVC wells located in alternating hummocks and hollows. They found very little variation in pH along the transect, with a range of 0.3 pH units for unaerated samples, and noted that pH was consistent regardless of the hummock-hollow sequence on the transect. Our results for a smaller grid that contained both hollows and hummocks show an even narrower range of variation (0.11). In contrast, Bragazza et al. (1998) found that pH was slightly lower in hummocks (mean: 4.17) compared to hollows (mean: 4.36). We found no difference between hummocks (mean: 3.65) and hollows (mean: 3.65), although our study site was located in an area with relatively little topographic variation and only small (<30 cm, mean 13 cm high) hummocks.

EC varied more than pH, but was fairly stable with a standard deviation of 7.5 µS/cm. There was no significant difference in EC_{corr} between hummocks and hollows. Howie and van Meerveld (2012) found that EC_{corr} and pH were generally temporally stable as well. Although locally stable, EC_{corr}, pH, and depth to water table often vary approaching the bog margin (e.g. increasing pH and calcium concentrations), and may change abruptly over a short distance (Howie and Tromp-van Meerveld, 2011; Howie and van Meerveld, 2012). Caution should therefore be used when interpreting measurements at the margin of a bog, such that results from one point at the bog margin are not incorrectly assumed to be representative of another nearby but different site.

Species distribution was not significantly related to pH or EC_{corr}, but percent cover for some species was correlated with depth to water table, soil moisture, and ash content at 10 cm depth. Visual cover estimates of plant species in this study contain a degree of uncertainty, as cover was estimated from photographs. A more detailed method of determining percent cover is to use a sampling quadrat with a small grid size. For example, a detailed study on trends in cover of *Sphagnum* mosses and other common bog species using 1 m x 1 m quadrats with a 10 cm x 10 cm grid size has been underway in Burns Bog since 2005 (Munsen, 2012; Howie et al. 2009b). A finer resolution vegetation study would be required to more accurately correlate plant species cover with environmental gradients such as depth to water table, soil moisture, and ash content of the peat within the rooting zones of the species surveyed.

4.7. Conclusion

Depth to water table should be measured using piezometers installed in hollows, not hummocks, because hummocks are higher in elevation, variable in height, and artificially increase the "depth below the surface" measurements. The surface elevation survey and depth to water table measurements suggest that the water table beneath the study site was not flat, but undulated with the lowest point beneath the main hummock; however, the accuracy of these data is uncertain because the survey was conducted several months after the water level measurements. Soil moisture was related to percent cover of some species, so this parameter should be measured in a representative number of hummocks and hollows within a vegetation plot. Humification at a given depth below the surface appears to be somewhat stable spatially, such that one point measurement represented the average level of humification about 67% of the time, and revealed a level of humification within 1-2 von Post points of the average most of the time. We found an opposite trend to what was expected for the von Post measurements, with decreasing humification with depth. Ash content also decreased with depth, and was somewhat consistent across the sample grid (<10% at 10 cm, <5% at 50 cm, and <1.5% at 100 cm depth). Both pH and electrical conductivity were spatially consistent enough to warrant a single point measurement. Vegetation in raised bogs is patchy, even within a relatively small area; multiple plots should be surveyed for percent cover of plant species to gain a representative sample.

5. Regional and local patterns in depth to water table, hydrochemistry, and peat properties of bogs and their laggs in coastal British Columbia

5.1. Abstract

In restoration planning for damaged raised bogs, the lagg at the bog margin is often not given considerable weight and is sometimes disregarded entirely. However, the lagg is critical for the proper functioning of the restored bog, as it supports the water mound in the bog. In order to include the lagg in a restoration plan for a raised bog, it is necessary to understand the hydrological characteristics and functions of this transition zone. To this end, we studied 13 coastal British Columbia (BC) bogs and identified two different gradients in depth to water table, hydrochemistry, and peat properties: 1) a local bog expanse – bog margin gradient, and 2) a regional gradient related to climate and proximity to the ocean. Depth to water table generally increased across the transition from bog expanse to bog margin, but did not differ regionally. In the bog expanse, pH was above 4.2 in the Pacific Oceanic wetland region (cooler and wetter climate) and below 4.3 in the Pacific Temperate wetland region (warmer and drier climate). Both pH and pH-corrected electrical conductivity increased significantly across the transition from bog expanse to bog margin, though not in all cases. Na^+ and Mg^{2+} concentrations were generally highest in exposed, oceanic bogs and lower in inland bogs. Ash content in peat samples increased across the bog expanse – bog margin transition, and appears to be a useful abiotic indicator of the location of the bog margin. These gradients highlight both local and regional diversity of bogs and their associated laggs. If undisturbed bogs are used as reference ecosystemss for the restoration of damaged raised bogs, knowledge of these gradients is important.

5.2. Introduction

One of the most extensively-studied topics in peatland research is the poor-rich gradient (i.e. the continuum from ombrotrophic raised bogs to minerotrophic rich fens) in both vegetation and water chemistry (e.g. Sjörs, 1950; Moore and Bellamy, 1974; Glaser, 1992; Tahvanainen et al., 2002). Only a few studies have looked at the related hydrochemical transition from the bog expanse to the bog margin (e.g. Sjörs, 1950; Bubier, 1991; Blackwell, 1992; Mitchell et al., 2008; Richardson et al., 2010). This research often specifically concerns the mineral soil water limit, which is the boundary between water from only atmospheric sources and mineral soil water. This boundary is often (but not always) associated with a distinct change in plant communities (Ivanov, 1981; Damman, 1986). The variable topography around the margins of raised bogs, results in a diverse set of transition forms, even around a single bog. Where a topographic depression forms at the margin of a bog, a well-defined lagg ecotone may develop due to a higher groundwater table and mixing of bog water with non-bog water. In other cases, the topographic transition outward from the bog may be less distinct, and vegetation may change from open bog to forest without a clear lagg ecotone (Howie and van Meerveld, 2011).

The majority of bog studies focus on the central bog expanse; few studies have included a detailed investigation of the lagg, which is the transition zone at the bog margin where water from the bog and the surrounding mineral soil mix and form a vegetative ecotone, or have focussed specifically on the bog margin, with the exception of literature related to the development and structure of raised bogs (e.g. Ivanov, 1981; Damman and French, 1987). The lagg is an integral part of the hydrological system of a raised bog because it supports the water mound of the bog and buffers the bog from surrounding minerotrophic water (Schouten, 2002; Damman, 1986). However, marginal zones, such as the lagg, tend to be disturbed first for agriculture or other development, and are frequently disturbed even for bogs that are in a (near) natural condition in their central parts. A greater understanding of this transition zone, however, is critical for the delineation of conservation boundaries and development of ecological restoration plans (Howie and Tromp-van Meerveld, 2011). For example, in the Fraser River delta of British Columbia (BC), government agencies are developing management and restoration plans for several raised bogs; the few small lagg areas that remain in the delta are therefore studied to ensure that this important transition zone is included in restoration planning for the local bogs. Delineation of the boundary of a potential lagg conservation zone requires an understanding of the hydrology, hydrochemistry, peat properties, and vegetation in the lagg. Increased knowledge about local lagg characteristics also aids in the development of a list of measurable lagg indicators (e.g. pH, calcium concentration, ash content of the peat) to be used in restoration strategies or as restoration goals.

Depth to water table is closely linked to plant community composition and varies across the bog expanse – bog margin transition. The characteristic raised bog vegetation patterns from the bog to the margin consist of 1) central open heath, where a consistently high water table supports *Sphagnum* and ericaceous shrubs, 2) marginal rand forest, where a lower water table supports tall shrubs and trees, and 3) lagg fen/swamp, where a highly fluctuating water table and mineral soil support fen or swamp species (Damman, 1986). Water level measurements across the bog expanse – bog margin can also provide information about groundwater flow patterns. Outward flow towards the lagg suggests an ombrotrophic raised bog, whereas a minimal gradient may indicate a flat bog or poor fen environment.

Hydrochemical characteristics also vary across the transition from the bog to the margin. Chemical characteristics are a key parameter in the Canadian System of Wetland Classification because chemical conditions in peatlands are directly related to precipitation chemistry (oligotrophic peatlands) and groundwater chemistry (eutrophic peatlands) (National Wetlands Working Group (NWWG), 1988). Hydrochemistry also has a strong influence on vegetative composition (Bridgham et al., 1996; Wassen and Joosten, 1996). For example, Glaser et al. (1990) found increasing species richness along the gradient from ombrotrophic bog to rich fen, and that bog and fen indicator species fell within specific ranges of pH and calcium concentrations. Hydrochemical parameters such as pH, alkalinity, electrical conductivity, and calcium and bicarbonate concentrations are therefore sometimes used to determine the boundary between ombrotrophic and minerotrophic conditions at the bog margin (Bragazza and Gerdol, 2002; Bourbonniere, 2009), although this may be a gradual change over several tens of metres without a discrete boundary (Sjörs and Gunnarsson, 2002; Howie and Tromp-van Meerveld, 2011). Cation concentrations (particularly calcium and magnesium), electrical conductivity, and pH generally increase from the bog centre to the bog margin (Bubier, 1991; Bragazza et al., 2005; Richardson et al., 2010), which indicates the increasing influence of minerotrophic water towards the bog margin. The Ca:Mg ratio may also be used to locate the mineral soil water limit, whereby a ratio less than 1 is often taken as an indication of ombrotrophy (Waughman, 1980; Naucke et al., 1993); however, the specific Ca:Mg ratio at the transition from ombrotrophic to minerotrophic conditions varies regionally and is related to distance from the ocean and annual precipitation (Waughman, 1980; Lähteenoja et al., 2009). This proxy for determining the mineral soil water limit may therefore only be useful where the ratio has been determined for several bogs in the region, as well as for precipitation (Shotyk, 1996).

Closely related to the hydrochemical conditions of a site is the ash content of the peat. The ash content of a peat sample is the amount of non-organic (i.e. mineral) material in the peat and generally indicates the degree of influence of minerotrophic water (e.g. deposition of sediment from flooding or upland runoff). It may therefore be possible to delineate the lagg by mapping the ash content of near-surface peat (Bridgham et al., 1996; Rydin and Jeglum, 2006). However, this variable has been cited far less frequently as an indicator of the mineral soil water limit than gradients in hydrochemistry and vegetation.

In addition to these local environmental gradients, there are also regional gradients in vegetation and water chemistry. Regional gradients are largely caused by climate, but are also related to differences in precipitation chemistry between exposed, oceanic environments and more sheltered, inland regions. For example, Vitt et al. (1990) identified a clear gradient in surface water chemistry from the outer islands of northern BC to the mainland, where the more oceanic islands were characterized by higher concentrations of Na^+ and Cl^-. Riley (2011) observed a positive correlation between pH and distance from the Hudson Bay in central-eastern Canada. In contrast, Glaser et al. (1997) studied raised bogs across northwestern Minnesota (a relatively arid, continental region with no oceanic influences) and found no apparent correlation between the westward gradient in precipitation/evapotranspiration and hydrology or water chemistry. Malmer (1986) concluded from a literature review that regional variation in bog vegetation cannot be attributed to differences in precipitation chemistry, as previously thought, but rather is caused by differences in hydrology, whereby annual precipitation is higher and drought periods are shorter in coastal regions. These wetter conditions result in a higher water table and the establishment of plant species that tolerate wet conditions, compared to a lower water table and longer drought periods in continental regions, which support tree growth (Malmer, 1986).

Even though peatlands are common in coastal BC, Canada, due to the cool-moist maritime climate that supports dense vegetation and slows decomposition (NWWG, 1988), research on laggs has been limited to a study of peatlands on Vancouver Island (Golinski, 2004) and Burns Bog in the Fraser River delta (Howie et al., 2009a). Little information exists about regional gradients in bog hydrology and hydrochemistry in coastal BC. The objective of this study was therefore to improve our understanding of the environmental gradients across bog margins, and to determine whether these gradients are consistent for bogs throughout coastal BC. Understanding regional differences in lagg characteristics is needed to ensure an accurate understanding of ecohydrological functioning and sound management of the bogs, and bog restoration. As noted by Bragazza et al. (2005), it is not appropriate to compare bogs in geographically distinct regions because they are “not necessarily equivalent from an ecological point of view”.

5.3. Study Locations

The 13 studied bogs are situated along the BC coast between 49º and 54º north, within 20 km of the Pacific Ocean (including inlets), and are located less than 100 m above sea level. The bogs are located on Haida Gwaii (Graham Island), in the Prince Rupert area, on Vancouver Island, and in the Fraser Lowland area (Fig. 15, Table 11) and were studied in June and July of 2010 and 2011, with the exception of Campbell River and Port McNeill bogs, which were studied in late May 2011 (Table 12).

Three of the studied bogs are located near Prince Rupert (Diana Lake, Oliver Lake, and Butze Rapids). Across Hecate Straight on Graham Island (Haida Gwaii), research was conducted at three bogs (Mayer Lake, Drizzle Lake, and Tow Hill). These six north coast bogs are underlain by acidic basaltic and sedimentary bedrock (NWWG, 1988). Further south on Vancouver Island, studies took place at one bog on the west coast (Shorepine Bog) and two bogs on the east coast (Port McNeill and Campbell River). Shorepine and Campbell River bogs are underlain by sand, whereas Port McNeill bog is underlain by the same basaltic and sedimentary bedrock as the north coast bogs. Four additional bogs were studied in the Fraser Lowland region of southwestern BC. Three of the bogs (Burns Bog, Surrey Bend, and Langley Bog) were formed on Fraser River deltaic deposits. The fourth bog (Blaney Bog) is located in the Pitt River valley wetland complex. Although each Fraser Lowland bog has its own unique characteristics and set of past disturbances (e.g. peat mining in Burns Bog and Langley Bog; sewer and road construction in Surrey Bend), they are similar in terms of original form and historic plant communities. The Fraser Lowland bogs represent the southernmost extent of *Sphagnum*-dominated raised bogs on the west coast of Canada (Vitt et al., 1999).

Canada's wetland regions are based on broad climatic and vegetation zones, following a north-south temperature gradient and an east-west precipitation gradient (NWWG, 1988). Wetlands on the Pacific coast of BC fall within two of the seven Canadian wetland regions: Pacific Oceanic and Pacific Temperate (Fig. 15). Haida Gwaii and the Prince Rupert area are located within the North Coast subregion of the Pacific Oceanic wetland region. The west coast of Vancouver Island is located in the South Coast subregion of the Pacific Oceanic wetland region. The North Coast Pacific Oceanic wetland subregion receives the most precipitation (Table 11), resulting in wetlands covering up to 75% of the landscape; common bog types in this region are slope bogs, basin bogs, and shore bogs (NWWG, 1988). The South Coast Pacific Oceanic wetland subregion is warmer and most bogs are flat bogs or basin bogs. The remainder of the studied bogs are located in the Pacific Temperate wetland region (Fig. 15). Less than 5% of the landscape in this region is covered by wetlands (NWWG, 1988). The most common types of bog in the Pacific Temperate region are basin bogs and domed bogs.

Table 11. ***Location and climate information for the 13 studied bogs. Bogs with more than one site code contained multiple study transects (one site code for each transect).***

Site Name	Site Code	Latitude (BG site)	Longitude (BG site)	Elev. (m above sea level)	Radius of bog (m)	Distance to Ocean (km)	Bog Type[b]	Average Annual Precip.[c] (mm)	Average July + August Precip.[c] (mm)	Precip. 30 days before measure-ments (mm)	Average Annual Temp.[c] (ºC)
Tow Hill Bog[a]	TH	54°03'53"N	131°48'50"W	19	405	0.1	Wb51	1508	141	87	8.2
Mayer Lake Bog[a]	ML	53°37'57"N	132° 04'7"W	40	433	9.1	Wb51	1508	141	88	8.2
Drizzle Lake Bog[a]	DT	53°55'41"N	132° 06'26"W	58	439	0.7	Wb51	1508	141	87	8.2
Butze Rapids Bog[a]	BR	54°18'01"N	130°15'34"W	28	30	0.3	Wb53	2594	270	86	7.1
Oliver Lake Bog[a]	OL	54°16'45"N	130°16'21"W	55	45	0.9	Wb52	2594	270	86	7.1
Diana Lake Bog[a]	DL	54°14'19"N	130° 09'22"W	36	73	8.2	Wb52	2594	270	86	7.1
Port McNeill Bog[a]	PM	50°34'20"N	127° 04'19"W	92	58	1.5	Wb50	1869	122	72	8.3
Campbell River Bog[a]	CR	49°57'59"N	125°14'35"W	81	70	2.1	Wb50	1452	89	88	8.6
Shorepine Bog	SPW, SPE	49°00'46"N 49°00'46"N	125°39'30"W 125°39'28"W	22	97	1.2	Wb51	3305	171	44 44	9.1
Burns Bog	CW, SW, DNR	49°07'27"N 49°06'26"N 49°08'16"N	123°00'36"W 123°01'11"W 122°56'11"W	4	3000	2.8	Wb50	1008	67	46 48 36	9.6
Surrey Bend Bog	SB	49°12'17"N	122°44'47"W	6	400	11.6	Wb50	1708	124	76	9.8
Langley Bog	LB	49°11'58"N	122°36'30"W	4	640	20.2	Wb50	1708	124	74	9.8
Blaney Bog	BU, BF	49°15'35"N 49°15'33"N	122°35'17"W 122°35'23"W	5	144	19.5	Wb50	2194	156	73 73	9.6

[a]Site name was created for this study based on nearby place name.

[b]Bog type is from MacKenzie and Moran (2004). Wb50 = *Ledum groenlandicum – Kalmia microphylla – Sphagnum*; Wb51 = *Pinus contorta* var. *contorta – Empetrum nigum – Sphagnum austinii*; Wb52 = *Juniper communis – Trichophorum cespitosum – Racomitrium lanuginosum*; Wb53 = *Pinus contorta – Chamaecyparis nootkatensis – Trichophorum cespitosum*.

[c]Environment Canada climate normals (1971-2000). Climate data for TH, ML, DT from Masset Inlet, BC; for BR, OL, DL from Prince Rupert, BC; for PM from Port Hardy, BC; for CR from Campbell River, BC; for SPW and SPE from Tofino, BC; for SW, CW, DNR from Vancouver International Airport; for SB and LB from Pitt Meadows, BC; and for BU and BF from Haney UBC Research Forest, BC.

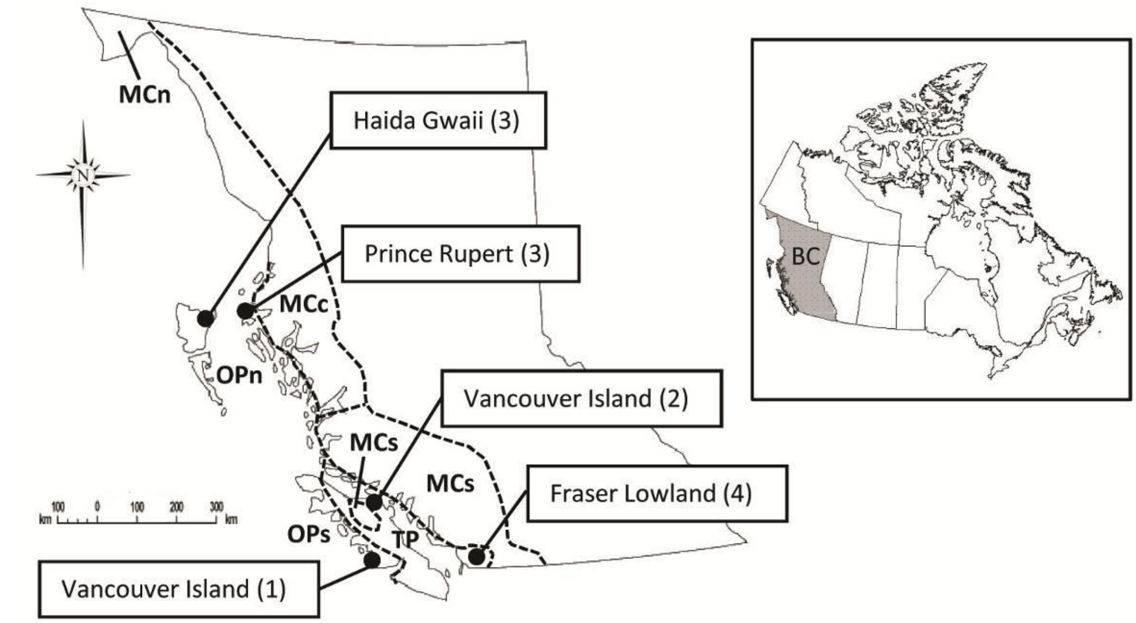

Figure 15. Location of the research sites in British Columbia (BC), with number of research sites in parentheses. Dashed lines represent the boundaries of the coastal wetland regions and subregions in this study: OPn = Pacific Oceanic, North Coast wetland subregion; OPs = Pacific Oceanic, South Coast wetland subregion; TP = Pacific Temperate wetland region. Other Pacific coast wetland subregions shown here but not included in this study: MCn = North Coastal Mountain wetland subregion, MCc = Central Coastal Mountain wetland subregion, MCs = South Coastal Mountain wetland subregion. Wetland region boundaries are from NWWG (1988). Inset: map of Canada.

5.4. Methods

We studied 17 transects consisting of five sampling locations across the laggs of the 13 bogs. Three of the bogs (Shorepine Bog, Burns Bog, and Blaney Bog) contained multiple study transects (Table 11). The five sampling locations on each transect were as follows: 1) inside the bog (“BG”), 2) between the bog and lagg (closer to the bog; “R1”), 3) between the bog and lagg (closer to the lagg; “R2”), 4) approximate centre of the lagg (“LG”), and 5) outside the bog (“MN”) (Fig. 16). Vegetative characteristics were used to determine the five transect locations. BG sites were defined as *Sphagnum*-dominated heath, LG sites as either *Spiraea*-dominated or containing larger shrubs and trees than the bog, and MN sites as the mineral forest surrounding the bog. The Burns

Bog DNR transect contained no sampling locations between the bog and lagg because of a highway in that transition zone; however, there were two sampling locations in the lagg in order to investigate the differences between two distinct lagg plant communities (a *Spiraea douglasii* swamp and a forest on deep peat), resulting in four sampling locations on the DNR transect. The Burns Bog SW transect also had two sampling locations in the lagg to study differences in lagg species composition, resulting in a total of six sampling locations on that transect. Butze Rapids bog is very small (60 m diameter), so the transect was shortened to four sampling locations, with only one sampling point between the bog and lagg. All locations were recorded with an Oregon 300 handheld GPS unit, accurate to 5 metres. All transects, except those in Burns Bog, were surveyed with a rod and level; the Burns Bog transect elevations were determined using LiDAR (Light Detection and Ranging) data from September 2008, accurate to 15 cm.

Piezometers were installed in hollows at each study location on the transects. The piezometers were 1.5 m long, 2.5 cm diameter Schedule 40 PVC pipe with a 40 cm slotted section at the bottom. The depth of installation was based on the observed water level in the bore holes that were dug prior to piezometer installation. We aimed to place the slotted section of the piezometers as close to the water table as possible, while still ensuring an adequate volume of water for sample collection. The average base of the piezometers was 0.53 m (standard deviation: 0.20 m) below the water table. The piezometers were purged twice and allowed to recharge for a minimum of 24 hours, but usually 3-7 days, prior to measuring the depth to water table using an electronic water level probe (Heron Instruments Little Dipper). It was assumed that the water level in the shallow piezometers represented the water table because previous measurements in another area of Burns Bog showed that the difference between the water levels in a well and in a piezometer were small (mean: 0.8 cm) (Chapter 3) and that this difference is similar to our water level measurement accuracy (0.5 cm) and the uncertainty of determining the ground surface in uneven terrain.

Electrical conductivity and pH were measured at the top 10-15 cm of the water column inside the piezometers with a WTW Multiline P4 water quality meter after allowing the piezometers to recharge after the second purging. Before each measurement, the probes were rinsed with distilled water. Electrical conductivity was compensated for the H^+ concentration using: $EC_{corr} = EC_{measured} - EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$ and 3.49×10^5 is the conversion factor for field measurements standardized to 25 ºC (Rydin and Jeglum, 2006).

Water samples were collected for laboratory analysis from all piezometers using a low-flow peristaltic pump (Global Water SP200) and plastic HDPE bottles. The tubing of the peristaltic pump was rinsed with water from each new site prior to sample collection in order to avoid contamination. Samples were filtered with a 0.45 μm filter within four hours of sample collection in 2010 and in the field in 2011. The water samples for cation analysis were preserved with nitric acid. Samples were kept on ice and refrigerated until delivery to the Pacific Environmental Science Centre (North Vancouver, BC) and were analyzed for the following parameters: Ca^{2+}, Mg^{2+}, Na^+, K^+ (using inductively coupled plasma spectrometry), acidity, and dissolved organic carbon (DOC).

At each study location along the transect, peat samples were collected at 10, 50, and 100 cm below the surface using an Eijkelkamp flag corer. For each depth, the von Post level of humification was determined in the field using the method described by Rydin and Jeglum (2006). Peat samples from the three depths were wrapped in plastic wrap and sealed in plastic freezer bags for laboratory analysis, transported in a cooler and refrigerated up to one month, or frozen, until laboratory analysis. In the lab, each sample was weighed, oven-dried at 105 ºC for 24 hours and re-weighed, and then dry-ashed in a 550 ºC oven for 24 hours and re-weighed a final time to determine the amount of mineral (i.e. non-organic) material in the sample. The depth of peat was determined at each coring location as well.

The measurements were taken in June/July (and late May at Campbell River and Port McNeill) because this was determined to be the most stable time of the year for sampling. Since ombrotrophic bogs receive most (or all) of their water from atmospheric sources, the fluctuation of the water table in bogs is closely linked to precipitation (Egglesmann et al., 1993). For coastal BC bogs, the seasonal rise and fall of the water table is quite similar between years; the water table is highest in winter, gradually declines through the spring and summer, and is lowest at the end of the summer (i.e. August/September), following the pattern of precipitation in this region (Golinski, 2004;

Howie et al. 2009b). Therefore, we measured depth to water table in each bog at roughly the same time of year (June/July) to ensure relatively comparable conditions.

Rainfall in coastal BC is generally lowest between May and August; thus, sampling in this period gives the highest probability of avoiding significant rainfall events between purging and sampling that could dilute near-surface pore-water and result in measurements that are not comparable to sites that did not experience the same precipitation prior to sampling (Appendix C). August is the driest month in this region, so sampling was avoided during this month to minimize the concentrating effect of evapotranspiration (Howie and van Meerveld, 2012). Electrical conductivity, pH, and the concentrations of major cations (e.g. sodium and magnesium) are generally fairly stable over time (Howie and van Meerveld, 2012). For example, in a 1.5-year study of bogs in southern coastal BC, Howie and van Meerveld (2012) showed that pH varied by less than 0.85 and EC_{corr} varied by less than 88 μS/cm. Measurements in June/July generally were within 0.25 of the average pH for the measurement period, and within 65 μS/cm of the average for EC_{corr} (85% of EC_{corr} measurements were within 25 μS/cm of the average) (Howie and van Meerveld, 2012). Bi-weekly and monthly measurements of near surface pore-water in an Alberta bog showed that the range in pH was less than 0.5, the range for pH-corrected electrical conductivity was less than 50 μS/cm, and the range was less than 5 mg/l for calcium concentration and less than 2 mg/l for sodium, potassium, and magnesium concentrations (Vitt et al., 1995). Therefore, it was assumed that a one-time sampling event was sufficient to characterize the hydrochemical gradients across the bog expense – bog margin transition.

Spearman rank correlations were used to test the correlation between depth to water table, the hydrochemical parameters, or ash content and location on the transect. Pearson linear correlations were used to determine the relation between pH and location on transect, peat depth, and calcium concentration. Spearman rank correlations were also used to determine the correlation between the hydrochemical parameters, peat depth, wetland region, latitude, and annual precipitation for the measurements in the BG sites. We used a two tailed t-test to determine if the differences between the two wetland regions were significant. Spearman rank correlations were not performed if the number of observations was less than five. All correlations described in the text are Spearman rank correlations, unless specifically noted as Pearson linear correlations. A significance level of 0.05 was used for all analyses, although tables 13 and 14 also show correlation results for other significance levels.

5.5. Results and Discussion

5.5.1. Depth to Water Table

Local Variation

In coastal BC, one can generally expect to find the water table in hollows in the bog expanse to be within 20 cm of the surface in June and July (Howie and van Meerveld, 2012). In this study, the water table was located within 25 cm of the surface for all studied BG sites. The depth to water table generally increased across the transition from bog to forest, except where there was a topographic depression that caused water to pond at the bog margin. Depth to water table was smallest for the BG sites (mean: 15 cm below the surface), slightly larger across the transition from bog to lagg (mean for R1, R2, and LG sites: 23 cm), and deepest in the MN sites (mean: 32 cm) (Table 12, Fig. 16a-b). The trend of increasing depth to water table towards the margin of raised bogs is well established (Ingram, 1983; Damman, 1986; Schouten, 2002). However, the variable topography of the individual bogs resulted in this trend being less clear on a site-by-site basis. Spearman rank correlation between depth to water table and position on the transect was significant for only four of 14 transects (three transects had less than five data points and were not included in the analyses) (Table 13). One of the significant correlations was negative (Blaney Bog FN); this transect is located adjacent to a frequently-flooded fen creek, which explains the high water table at the bog margin (Fig. 16c). In other locations (e.g. Mayer Lake, Surrey Bend), the water table was close to the surface in the lagg, due to the lagg being topographically constrained between the bog and an adjacent upland (Fig. 16d).

The (absolute) water table elevation declined from the bog outwards in some cases (10 out of 16 transects), but increased towards the lagg in other cases (6 out of 16 transects). The DNR transect was not included in this analysis because depth to water table was not measured at the BG site as the piezometer was vandalized, and there were no R1 or R2 sites on this transect. The hydraulic gradient between the R1 and LG sites ranged from 0.1-7.0 % (mean: 1.4 %, median: 0.5 %; standard deviation: 2.0%) (Table 12). The relatively large positive gradient from the bog to the lagg at one of the transects (Oliver Lake) may indicate that this bog is either a slope bog or a combination of a flat bog and a slope bog where the flat bog extends outwards from a basin up the adjacent slope; these types of bogs are common in this part of the study region due to high rainfall and relatively low temperatures (NWWG, 1988).

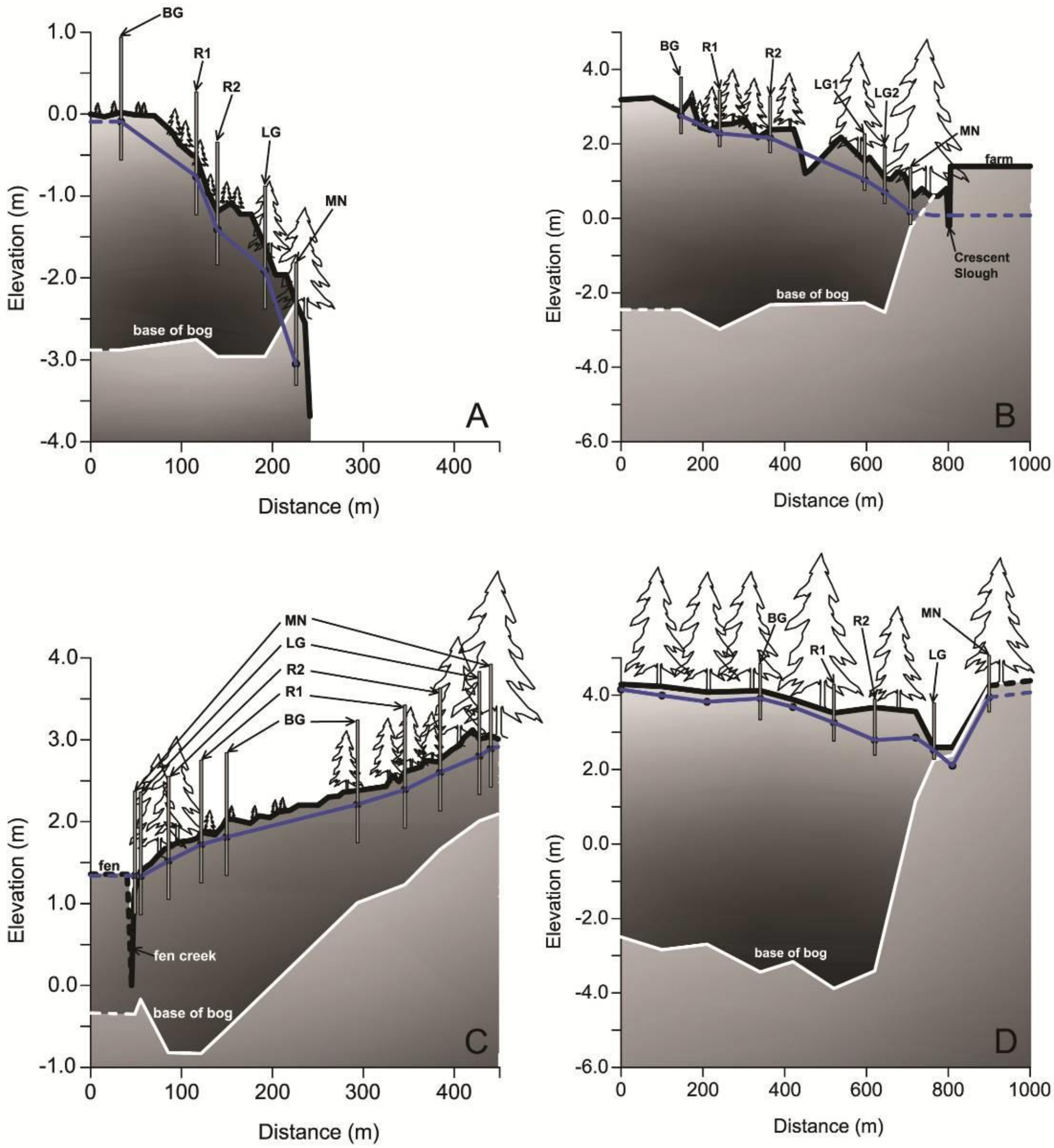

Figure 16. ***Topographic profiles for: A) Tow Hill bog, B) Burns Bog - SW, C) Blaney Bog (left = FN, right = UP), and D) Surrey Bend, with the locations of the sampling points. The thick black line represents the bog surface, the blue line with the piezometer symbols represents the water table, and the transparent bars represent the piezometers. Dashed lines are estimated values. Figure "D" includes six additional water level measurements from another study (Baird, 2011). Vertical exaggeration: 90x. Tree height is not to scale, but trees are scaled relative to one another for each profile.***

Regional Variation

There was no statistically significant difference in early summer depth to water table between the wetland regions (Table 12). Mean (and median) depth to water table for the BG sites was 14 cm (15 cm) and 16 cm (19 cm) for the Pacific Temperate and Pacific Oceanic wetland regions, respectively. The water table in bogs in the Pacific Temperate wetland region was closer to the surface, but this is likely because most of these bogs were surveyed in late May and June, whereas the bogs in the Pacific Oceanic wetland region were studied in July. In coastal BC, the water table in bogs can be expected to drop 5-10 cm over the month of June, depending on rainfall (Howie et al., 2009b; Howie and van Meerveld, 2012).

The water table was relatively high in MN sites in the Prince Rupert area (mean: 22 cm below the surface; median: 24 cm) compared to the other regions; the mean (and median) depth to water table was 41 cm (26 cm), 37 cm (40 cm), and 31 cm (33 cm) below the surface for the Haida Gwaii, Vancouver Island, and Fraser Lowland bogs, respectively). This may be partly explained by the forested slope bogs that are prevalent in the Prince Rupert area. This type of bog is able to persist in this region due to the high annual precipitation and relatively low temperatures (Table 11). The comparatively high water table in the MN sites of Butze Rapids and Diana Lake were likely due to the transects being installed across a transition from open bog to slope bog, instead of transitioning to a true minerotrophic forest. The piezometer in the Oliver Lake MN site was installed in a topographic depression on a slope above the bog, resulting in a water table close to the surface.

Table 12. Depth of the water table below the surface (cm) for all study transects. Negative values indicate that the water table was above the ground surface. For the DNR transect, the data shown under R2 are actually from the second LG site on this transect. Also shown is the hydraulic gradient (%) between the R1 and LG sites for all transects; positive values indicate that the water table at the LG site was higher than at the R1 site, and negative values indicate that the water table at the LG site was lower than at the R1 site.

Geographic Location and Bog Name	Depth to water table (cm)					Water Table Gradient: R1 to LG (%)	Date Measured
	BG	R1	R2	LG	MN		
Haida Gwaii							
Tow Hill	10.6	24.8	22.0	30.5	75.3	-1.5	July 9, 2010
Mayer Lake	21.6	25.5	27.5	7.0	20.5	-0.9	July 11, 2010
Drizzle Lake	22.0	24.9	11.0	37.5	26.0	0.4	July 10, 2010
Prince Rupert							
Butze Rapids	9.0	35.9	-	18.5	24.0	0.5	July 19, 2010
Diana Lake	18.0	36.0	47.5	21.0	23.5	-7.0	July 21, 2010
Oliver Lake[a]	9.5	16.5	44.5	50.0	18.0	5.6	July 20, 2010
Vancouver Island							
Port McNeill	19.0	23.0	58.5[b]	37.0	46.0	-0.6	May 30, 2011
Campbell River	1.0	0.5	-3.0	-2.0	40.0	-0.1	May 31, 2011
Shorepine West	19.0	41.0[b]	23.0	14.0	21.0	0.4	July 5, 2011
Shorepine East	19.5	25.0	21.0	37.5	39.0	-1.0	July 5, 2011
Fraser Lowland							
Burns Bog - SW	12.5	31.5	30.0	36.0	55.0	-0.4	June 21, 2011
Burns Bog - CW	5.0	18.0	5.0	7.5	66.5	-0.1	June 20, 2011
Burns Bog - DNR	-	-	8.5	28.5	22.5	-	June 18, 2011
Blaney Bog - UP	17.0	23.5	21.5	23.0	18.5	0.5	June 25, 2011
Blaney Bog - FN	25.0	14.0	13.5	3.5	-22.0	-0.7	June 25, 2011
Surrey Bend	25.0	19.5	13.0	2.5	44.0	-0.3	July 29, 2011
Langley Bog	11.0	11.0	16.5	40.5	-	-0.3	July 30, 2011
MEAN	15.3	23.2	22.5	23.1	32.4	-0.3	
MEDIAN	17.5	24.2	21.3	23.0	25.0	-0.3	

[a]This bog is located partly on a steep slope and thus appears to be a slope bog or a flat bog that has extended into a slope bog at its margin.

[b]It is possible that these piezometers had not fully recharged at the time of measurement, which resulted in water levels that were lower compared to the adjacent piezometers on the transects. For this reason, the hydraulic gradient for Shorepine West was calculated using the R2 water table elevation.

Table 13. ***Spearman rank correlation coefficients (r_s) for the relation between the measured parameters and position on the transect. Only correlations with $p<0.1$ are shown. For coefficients in bold, $p<0.01$; for plain text coefficients, $0.01<p<0.05$, and for coefficients in italics, $0.05<p<0.1$. $n=5$. n/a = not enough data ($n<5$). For site codes, see Table 11.***

Site Code	DTW (cm)	pH	EC_{corr} (µS/cm)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} / Mg^{2+} ratio	Na^{+} (mg/l)	AC10 (%)	AC50 (%)	AC100 (%)
TH	0.90	-	0.90	n/a	n/a	n/a	n/a	n/a	n/a	-
ML	-	-	-	n/a	n/a	n/a	n/a	n/a	-	n/a
DL	-	**1.00**	0.90	n/a	n/a	n/a	n/a	n/a	0.90	n/a
BR	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
DL	-	**1.00**	0.90	-	-	-	-	n/a	0.90	n/a
OL	-	-	*0.80*	-	-	-	**-1.00**	n/a	n/a	-
PM	-	*0.80*	-	*0.87*	-	-	-	-	0.90	0.90
CR	-	**1.00**	-	-	-	-	-	n/a	**1.00**	n/a
SPW	-	-	-	n/a	n/a	n/a	n/a	-	n/a	n/a
SPE	0.90	n/a	n/a	n/a	n/a	n/a	n/a	-	-	n/a
SW	0.90	**1.00**	-	-	0.97	n/a	-	-	-	-
CW	-	-	-	-	-	-	-	-	-	-
DNR	n/a	n/a	n/a	n/a	n/a	-	n/a	n/a	n/a	n/a
UP	-	**1.00**	*0.80*	0.90	0.97	-	-	-	n/a	n/a
FN	**-1.00**	-	-	-	-	n/a	-	-	**1.00**	*0.80*
SB	-	-	-	-	-	-	-	**1.00**	**1.00**	n/a
LB	n/a	n/a	n/a	n/a	n/a	-	n/a	-	-	n/a

DTW = depth to water table. AC = ash content at 10, 50, and 100 cm below the surface.

Table 14. Pearson linear correlation (r^2, top half of table) and Spearman rank correlation (r_s, bottom half of table) coefficients for parameters measured at the BG sites. For coefficients in bold, p<0.01; for plain text coefficients, 0.01<p<0.05, and for coefficients in italics, 0.05<p<0.1.

	Lat.	WR	PD	P	pH	EC_{corr}	Redox	Ca^{2+}	Mg^{2+}	Na^{+}	Acid.	DOC
Lat.		**0.83**	-	-	0.38	-	**0.47**	-	-	-	**0.84**	0.35
WR	**-0.63**		*0.23*	-	**0.62**	-	0.36	-	-	-	**0.77**	0.38
PD	-	0.51		0.26	**0.45**	-	-	-	-	-	0.33	*0.24*
P	-	-	-0.49		0.26	-	-	-	-	-	*0.28*	-
pH	*0.46*	**-0.84**	-0.61	*0.43*		-	-	-	-	*0.21*	**0.65**	**0.48**
EC_{corr}	-	-	-	-	-		-	-	*0.21*	*0.23*	-	-
Redox	0.54	-0.58	-0.55	-	*0.45*	-		-	-	-	0.42	-
Ca^{2+}	*-0.45*	-	-	-	-	-	-		-	-	-	0.35
Mg^{2+}	-	-	-	*-0.43*	-	**0.70**	-	-		**0.70**	-	-
Na^{+}	-	-	-	-	-	**0.80**	-	-	**0.83**		-	-
Acidity	**-0.95**	**-0.86**	**0.68**	*-0.47*	**-0.77**	-	-0.54	-	-	-		0.36
DOC	-0.65	**0.68**	-	-	**-0.75**	-	-	0.64	-	-	0.66	

WR = wetland region; PD = peat depth; P = mean annual precipitation (1971-2000 climate normals: Environment Canada)

5.5.2. Peat Characteristics

Local Variation

As expected, peat depth decreased from the centre of the bog to the margin for all regions (Fig. 17). There was a significant linear correlation between peat depth and position on the transect for the Haida Gwaii, Vancouver Island, and Fraser Lowland bogs, but not for the Prince Rupert bogs, when the transects were combined by region. The linear correlations were significant for 12 of the 17 individual transects. Some MN sites in the Prince Rupert and Fraser Lowland bogs were peaty, whereas all of the MN sites in the Haida Gwaii and Vancouver Island transects were located in mineral soil (Fig. 17). In the Fraser Lowland, this was due to the mineral soil adjacent to the bogs being too rocky to install a piezometer, so the MN study site was instead located in wet, partly organic soil at the margin of the bog. In one transect (Blaney Bog FN), the MN site was located in a large fen at the edge of the bog (Fig. 16c). In Prince Rupert, on the other hand, it is common for open bogs to transition into forested “slope bogs” (NWWG, 1988); the transect at Butze Rapids bog likely cut through this type of transition.

Bog peat normally contains less than 5% ash content by dry weight, whereas fen peat may have an ash content of up to 35% (Stoneman and Brooks, 1997; de Vleeschouwer et al., 2010). Our results for BG site peat samples from 10 cm depth generally agreed with these values, except for five bogs (from all regions, except Prince Rupert) that had ash contents between 5-10%. Peat samples from 50 and 100 cm showed similar results; BG site peat samples contained less than 6% ash content at 50 cm depth (except for Shorepine Bog) and less than 7% ash content at 100 cm depth (except for Shorepine Bog). The 50 and 100 cm samples from Shorepine Bog contained significant amounts of sand, which is the substrate beneath the shallow (25 and 60 cm) peat at the two BG sites.

Mean ash content increased across the transition from bog to forest for all regions (Fig. 18, Table 13). Peat samples from the LG sites contained less than 35% ash content at 10 cm depth, with the exception of Surrey Bend bog (50%), Campbell River bog (52%), and Drizzle Lake bog (58%). The mean ash content at 10 cm depth for all LG sites excluding Surrey Bend, Campbell River, and Drizzle Lake was 5% (standard deviation: 3%), which falls within the range of ash content of fen peat (Stoneman and Brooks, 1997; de Vleeschouwer et al., 2010). These results are similar to those of Gorham (1950), who found ash content at the outer minerotrophic edge of the lagg of a raised bog near Uppsala to be five times greater than the ash content closer to the centre of the bog.

Ash content was expected to increase with depth below the surface. However, this was only the case for 44% of the cores, mostly on Vancouver Island and in the Fraser Lowland. In many cases, ash content was relatively constant, or decreased with depth below the surface. Ash content increased with depth twice as often in the LG sites compared to the other locations on the transect. The lagg peat might have received greater amounts of sediment from adjacent upland areas during the accumulation of peat in the bog and lagg. The increasing ash content with depth in the lagg is likely also due to shallower peat in the lagg so that the deeper samples were influenced more by mineral soil. Laggs in which the ash content increased with depth had an average peat depth of 0.81 m, whereas laggs where ash content did not increase with depth had an average peat depth of 2.32 m. However, for the other (non-lagg) locations on the transects, depth of peat at the sample site was not related to whether the ash content of the peat cores increased with depth. The most consistent increase in ash content with depth was found for the Shorepine Bog transects; this bog is shallow (<0.8 m) so that the deeper samples were influenced by the sand beneath the peat.

It is generally thought that the level of humification of peat increases with depth below the bog surface (Schouten, 2002), although it has been shown (e.g. Baird et al., 2008) that this trend is not as clear or consistent as might be expected. Our von Post measurements showed a trend of increasing humification with depth in 72% of the cores, but no change (19%) or decreasing humification (9%) in the remainder of the cores (Fig. 19). Humification can also be expected to also increase across the transition from bog to lagg, because rand and lagg peat is generally more aerated due to a lower overall water table and more oxidation and decomposition. For example, Bubier (1991) observed that peat from the upper 40 cm of an open bog site was “non-humified”, whereas peat in the upper 20 cm of the adjacent rand forest was “moderately humified”. We found increasing von Post humification from the bog to the lagg in only 33%, 60%, and 47% of the transects at 10, 50, and 100 cm depth, respectively. Therefore, von Post humification displayed a more consistent increase with depth than with distance across the transect.

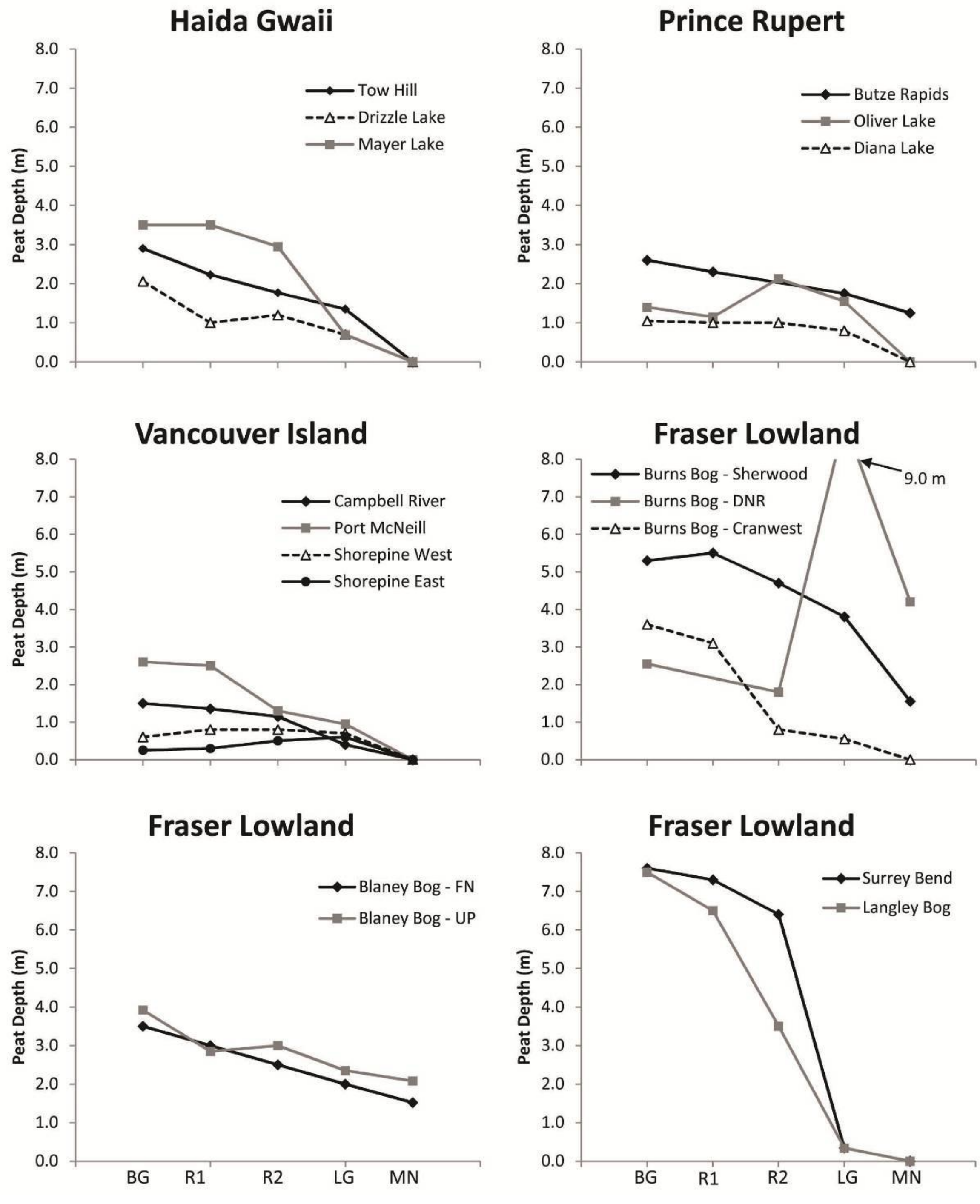

Figure 17. ***Peat depth (m) across the study transects from surface to mineral soil (e.g. silt, clay, sand).***

Regional Variation

There was a significant difference in peat depth between the Pacific Oceanic and Pacific Temperate wetland regions. Peat depth at the BG sites was <0.6 m in the South Coast Pacific Oceanic wetland subregion, and more variable in the North Coast Pacific Oceanic wetland subregion (1.1-3.5 m) and Pacific Temperate (1.5-7.6 m) wetland region. Average peat thickness at the BG sites in the Fraser Lowland bogs (4.9 m) was greater than in Haida Gwaii (2.8 m), Prince Rupert (1.7 m) and Vancouver Island (1.2 m).

Peat depth was significantly correlated with mean annual precipitation and mean annual temperature. The deepest bogs in our study are located where precipitation is lowest and temperature is highest. In general, the height of raised bogs increases as precipitation increases (Damman, 1979; Clymo, 1984; Ingram, 1983). Our results are thus not in agreement with this general observation. Bogs also increase in height with increasing mean annual temperature, as long as the water table is high enough that *Sphagnum* can access water during the growing season (Damman, 1979); our results do agree with this observation. However, the height of the peat dome does not only depend on climate, but is also related to the diameter of the bog (Hobbs, 1986; Clymo, 1984; Ingram, 1983). Most bogs in coastal BC are relatively small in comparison to those in other areas of Canada, in part due to topographic constraints in this mountainous region (NWWG, 1988). The large bogs of the Fraser Lowland, in contrast, formed on relatively flat fluvial material. Large bogs also cover a large part of the low-relief landscape of Graham Island, Haida Gwaii (NWWG, 1988). Despite receiving less precipitation than the Prince Rupert area or the west coast of Vancouver Island, the studied Fraser Lowland and Haida Gwaii bogs are larger than the other bogs (Table 11); the larger diameter of these bogs could bethe main contributing factor to their greater peat depths. We found a significant correlation between bog radius and peat depth ($r_s = 0.58$), and a non-significant correlation between bog radius and bog height above the lagg ($r_s = 0.50$, $p = 0.082$).

Peat depth is not only related to the rate of peat accumulation (which is influenced by climate) but also to the topographic setting of a particular bog. Bogs that are formed in a basin (e.g. Blaney Bog) will have greater peat depths than those that form on flatter surfaces (e.g. Shorepine Bog). Thus, the differences in peat depth between different geographic areas of this study can be explained by differences in the types of bogs that are most prevalent in each geographic area. Basin bogs and domed bogs are common in the Fraser Lowland; the underlying topography of the studied bogs in this area may be a contributing factor to the deep peat deposits in these bogs. Slope bogs and flat bogs often form on the north coast and on the west coast of Vancouver Island, which may partly explain the shallower peat deposits in some of the studied bogs in these areas.

Riley (2011) found that peat depth of Hudson Bay peatlands was related to time since glaciation and subsequent isostatic rebound. Coastal British Columbia was glaciated until the end of the Pleistocene (10,000 years BP); the Cordilleran Ice Sheet covered the mainland and Vancouver Island, whereas Haida Gwaii was covered by its own set of glaciers and large areas may have been ice free (Clague, 1989; Vitt et al., 1990). Some peat deposits in Haida Gwaii predate the end of the last glaciation, supporting the hypothesis that this area was not entirely glaciated (Mathewes and Clague, 1982). Deglaciation in the Prince Rupert area occurred around 12,700 ±120 BP (Mathewes and Clague, 1982). *Sphagnum* growth and bog development near Port McNeill occurred around 7000 BP as the climate became wetter (Hebda, 1983). The Fraser River delta formed between 7500 and 5000 BP (Clague et al., 1991), and formation of peat in the delta occurred between 5500 and 3500 BP (Hebda, 1977; Clague et al., 1991). Thus, time since last glaciation does not appear to be a primary factor for the observed differences in peat depth in this region.

There was no significant difference in mean ash content at any of the sampled depths for the BG or LG sites between the Pacific Oceanic and Pacific Temperate wetland regions. In all 50 and 100 cm LG site peat samples from Prince Rupert and Haida Gwaii, ash content was less than 35%, except for Drizzle Lake Bog which had 36% ash content at 50 cm depth (and no sample from 100 cm depth). In contrast, only 43% and 81% of deeper LG site samples from Vancouver Island and the Fraser Lowland, respectively, had less than 35% ash content. The laggs of north coast bogs contain more organic matter and appear to be less influenced by adjacent and underlying mineral soils, whereas some laggs on Vancouver Island and in the Fraser Lowland may have received greater amounts of sediment from adjacent upland areas and river floodplains (prior to dyking) during their development. There was no clear difference in level of von Post humification between the four study regions (Fig. 19).

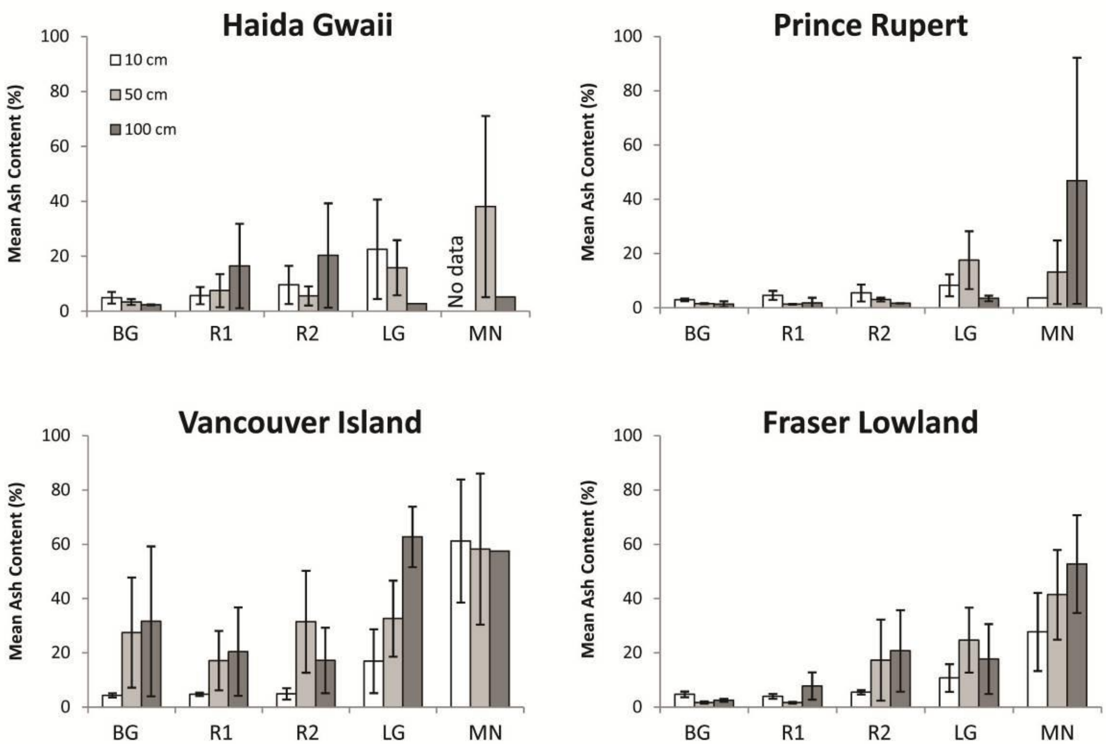

Figure 18. ***Mean ash content (% dry weight) in peat samples from three depths below the surface (10 cm, 50 cm, and 100 cm) for the four study regions. The samples from Shorepine Bog (a shallow bog: peat depth <0.8 m) explain the significantly higher mean ash content values shown for Vancouver Island. Whiskers represent one standard error. Bars with no whisker represent only one sample.***

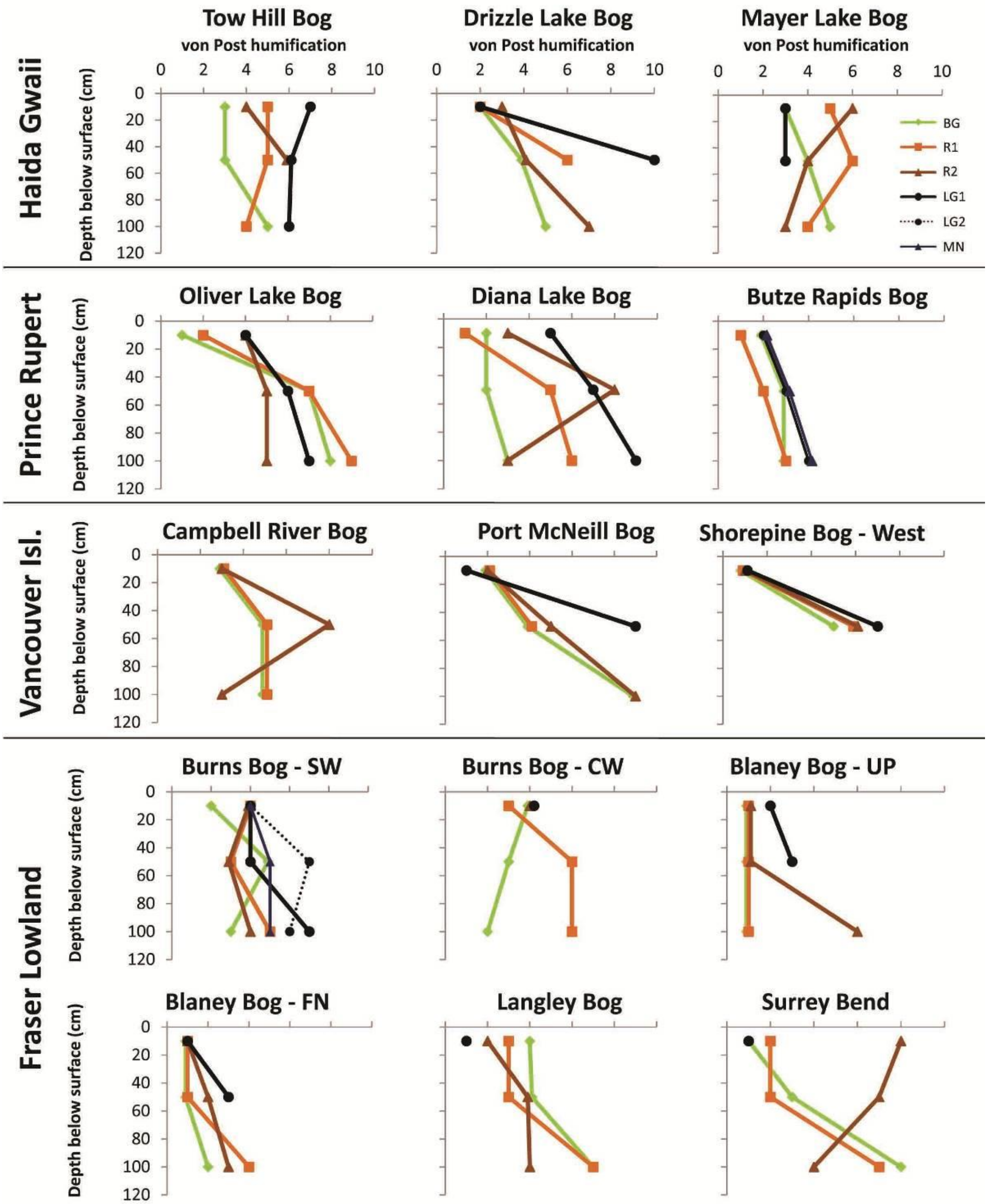

Figure 19. ***von Post humification as a function of depth below the surface for all transects. "Shorepine Bog - East" and "Burns Bog – DNR" are not included in this graph due to missing data points. Overlapping von Post values are offset by 0.1 to improve visual clarity of the figures.***

5.5.3. Hydrochemistry

Local Variation

Pore-water pH generally increased across the transects from bog to forest, with the lagg pH being transitional between the two ecosystems (Fig. 20). A significant linear correlation between pH and location on the transect was found for all regions when all bogs in a region were analyzed together, but not for all bogs individually. There was a significant correlation between pH and location on the transect for only 5 of the 17 transects (Table 13). Similar to pH, Ca^{2+} concentrations generally increased across the transition from bog to forest (Fig. 21). However, this correlation was not as consistent or clear as that of pH. The correlation between Ca^{2+} concentration and position on the transect was only significant for the Prince Rupert and the Fraser Lowland bogs when all bogs in a region were combined, and rarely (only 1 out of 9 tested transects) for individual transects (Table 13). Corrected electrical conductivity (EC_{corr}) also tended to increase across the transects from bog to forest (Fig. 22). There was a significant linear correlation between EC_{corr} and location on the transect when bogs were combined by region, except for Vancouver Island, but not often (only 3 out of 13 tested transects) for the individual transects (Table 13). Mg^{2+} and Na^{+} increased from bog to forest for 47% and 35% of the transects, respectively, and did not appear to be related to position on the transect for the other transects (Table 13). Bubier (1991) found that pH, EC_{corr}, and Ca^{2+} and Mg^{2+} concentrations increased significantly along a transect from an open bog to a lagg creek in Vermont. Similarly, Bragazza et al. (2005) observed a higher pH and higher concentrations of Ca^{2+} and Mg^{2+} in the lagg fens of an Italian and a Swedish bog compared to the open bog expanse. Richardson et al. (2010) found a clear increase in pH at the topographic locations of the laggs derived using LiDAR data for four lagg transects in Ontario and Minnesota. While EC_{corr}, pH, and Ca^{2+} concentration may be useful indicators of the change from an ombrotrophic to minerotrophic environment for some bogs, the transition of these parameters from the bog to the lagg was neither sharp nor consistent in the coastal BC bogs studied here.

Calcium is frequently correlated with pH across the lagg transition due to cation exchange (Rydin and Jeglum, 2006; Adamson et al., 2001), and it is common for both indicators to be used when surveying the poor-rich gradient (Tahvanainen, 2004). Ca^{2+}

concentration and pH were not strongly correlated for the BG sites, but were significantly correlated when all sites on all transects were combined (Pearson correlation: $r^2 = 0.482$; Spearman correlation: $r_s = 0.635$). The water samples from the studied sites appear to group into two clusters: 1) pH<4.8, Ca^{2+}<5 mg/l, and 2) pH>5.0, Ca^{2+}>2.5 mg/l (Appendix D). Several other researchers have reported a bimodal distribution of pH, where bog pH is less than 4.5-5.0 and fen pH is higher than 5.5-6.0 (Wheeler and Proctor, 2000; Bourbonniere, 2009). "Cluster 1" is representative of typical bog chemistry, whereas "Cluster 2" is representative of fen or minerotrophic water (McKenzie and Moran, 2004; Bourbonniere, 2009). All of the water samples from the BG and R1 sites belong to Cluster 1, whereas the remainder of the transect points were split between Cluster 1 and Cluster 2: 71% of R2 samples, 53% of LG samples, and 27% of MN samples are part of Cluster 1. Due to the proximity of LG sites to adjacent and underlying minerotrophic soils, one would expect most of the LG sites to fall within Cluster 2, but in fact, about half of the LG sites fell within Cluster 1. A possible explanation is that the Cluster 1 LG sites were more affected by bog water than Cluster 2 LG sites. The topographic evidence for this hypothesis, however, is not strong; 4 out of 10 of the Cluster 1 laggs, and 5 out of 9 of the Cluster 2 laggs, were higher in elevation than the adjacent bog sites, so could not receive much surface runoff from the bog. The water table elevation at 8 out of the 10 LG sites in Cluster 1 was lower than at the BG sites on the same transect, suggesting subsurface flow towards the lagg. However, subsurface flow towards the lagg likely occurred in the other bogs at other times as well (e.g. in winter when the water table is higher). Another reason for the high number of LG sites in Cluster 1 could be that the peat was deeper in the Cluster 1 LG sites, which could result in lower pH and Ca^{2+} concentrations, but the peat depth data from the LG sites do not support this. A final explanation is that the LG peat in Cluster 2 was more influenced by minerotrophic soil than Cluster 1, regardless of topography or peat depth. Mean ash content of Cluster 1 LG peat was only 20% of the mean ash content of Cluster 2 LG peat at 10 cm depth, and 70% of the mean ash content of Cluster 2 LG peat at 50 cm depth. Thus, it appears that ash content of the lagg peat may have a stronger influence on the chemical composition of pore-water during the summer months than topographic position or peat depth in the lagg. Ash content therefore appears to be a useful indicator of the change from ombrotrophic to minerotrophic conditions.

A Ca:Mg ratio greater than 1-2 has been proposed as a possible indicator of the mineral soil water limit (Waughman, 1980; Naucke et al., 1993; Bragazza and Gerdol, 1999). For example, Bragazza et al. (2005) found a sharp increase in the Ca:Mg ratio from the bog expanse to the minerotrophic margin in an Italian and a Swedish bog. In our study, the Ca:Mg ratio did not consistently indicate the mineral soil water limit; only 8 out of the 17 transects (47%) showed an increase in the Ca:Mg ratio from bog to forest. None of the correlations between the Ca:Mg ratio and position on the transect were statistically significant (Table 13).

Regional Variation

For the BG sites, pH of near-surface pore-water decreased significantly with increasing peat depth (Fig. 23); pH also increased with latitude and mean annual precipitation, but these trends were not significant (p=0.064 and 0.066, respectively). Acidity was also significantly correlated with peat depth and latitude, due to its correlation with pH (Table 13). Riley (2011) found a similar relation between pH and latitude for bogs of the Hudson Bay Lowlands, and noted that pH was above 4.0 in bogs with peat depths less than 1.5 m. Riley attributed the geographic variation in pH to isostatic rebound over the past 5500 years, whereby the land that emerged first has the deepest peat and the lowest pH. Shallower bogs are thought to have a higher pH due to a greater contribution of water from the mineral substrate (Riley, 2011). Similarly, in our study sites, the Fraser Lowland bogs had the greatest peat depths and the lowest pH (Fig. 23).

A number of researchers have reported a bimodal distribution in the pH of peatlands, with bog pH below 4.5–5.0 and fen pH above 5.5–6.0 (Wheeler and Proctor, 2000; Bourbonniere 2009), although a bimodal distribution is not found in all cases (e.g., Økland et al., 2000). For the eight transects in the Pacific Oceanic wetland region (north and south coast subregions), pH in the BG sites was above 4.2; for the nine transects in the Pacific Temperate wetland region, pH was below 4.3 (Fig. 23). The difference in pH between the Pacific Oceanic and Pacific Temperate wetland regions is statistically significant. This difference may be explained by the differences in peat depth, as described above. Another possible explanation is the difference in mean annual rainfall between the two wetland regions: average of 2117 mm/year for the Pacific Oceanic region and 1044 mm/year for the Pacific Temperate region (NWWG, 1988). In July and August, the studied Pacific Oceanic bogs receive, on average, ~60% more rainfall than the studied Pacific Temperate bogs (Table 11). The studied bogs in the Pacific Oceanic wetland region received, on average, 76 mm (standard deviation: 19 mm) of rainfall in the month preceding sampling; the bogs in the Pacific Temperate wetland region received 65 mm (standard deviation: 17 mm) in the month prior to sampling. Higher rainfall in the Pacific Oceanic wetland region may dilute near-surface pore-water so that it is less acidic and more similar to rainwater, even in summer. The drier and warmer conditions of the Pacific Temperate wetland region likely result in greater evapotranspiration and concentration of bog water, thereby lowering the pH of near surface pore-water. Measurements were taken on different dates and under a variety of weather conditions, leading to some variability due to the time of sampling. However, pH of near-surface pore-water tends to have a high temporal stability in bogs and measurements were taken in May-July when the concentration effect due to evapotranspiration isn't as pronounced as it is in later summer (Howie and van Meerveld, 2012; Vitt et al., 1995; Wieder, 1985). Howie and van Meerveld (2012) showed for two bogs in the Fraser Lowland that pH measured in June was within 0.25 of the mean pH.

EC_{corr} was generally higher in the Haida Gwaii and Vancouver Island bogs than the Prince Rupert and Fraser Lowland bogs. Na^+ and Mg^{2+} concentrations were lowest in the Prince Rupert bogs and highest in the Haida Gwaii bogs (Fig. 24). Since bogs in the Prince Rupert area receive approximately 1000 mm more precipitation annually than those in Haida Gwaii, the low ionic concentrations could be a result of the high rainfall but are likely also caused by differences in precipitation chemistry. Vitt et al. (1990) studied bogs on Haida Gwaii (Graham Island) and in the Prince Rupert area, and similarly found that Na^+ and Cl^- (and, to a lesser extent, Mg^{2+}) concentrations were much higher for bogs on Haida Gwaii than bogs in the Prince Rupert area and on islands to the south of Prince Rupert. They attributed this variation to a coastal-inland gradient of decreasing concentrations of cations and anions, particularly Na^+ and Cl^-, with distance from the coast. Malmer et al. (1992) reported a similar gradient in surface water chemistry of peatlands across western Canada, including Haida Gwaii and the Prince Rupert area. He found that Na^+, Mg^{2+}, and Cl^- concentrations were approximately 9, 8, and 7 times higher, respectively, in Haida Gwaii bogs than in Prince Rupert bogs. In the BG sites of our study, average Na^+ and Mg^{2+} concentrations were 5 and 3 times higher, respectively, in Haida Gwaii bogs than in Prince Rupert bogs; water samples from these bogs were not tested for Cl^- concentrations. It is well established that the ionic concentrations in surface water of ombrotrophic bogs reflect local precipitation (Gorham, 1955; Proctor, 1995), so the clear difference in ion concentrations between the Haida Gwaii and Prince Rupert bogs can most likely be attributed to higher ion concentrations in precipitation and increased dry deposition at the exposed, hyperoceanic bogs on Haida Gwaii, compared to the more sheltered bogs on the mainland near Prince Rupert. The Fraser Lowland bogs are located further from the open ocean than the other bogs (Table 11), which may result in lower Na^+ and Cl^- concentrations. For example, mean annual precipitation chemistry data from 1978-1985 showed that Na^+, Mg^{2+}, and Cl^- concentrations were all 2.3 times higher in Port Hardy (exposed to open ocean) than at Vancouver International Airport (sheltered by Vancouver Island) (National Atmospheric Chemistry Database, 2012).

The Ca:Mg ratio for the BG sites ranged from 0.4 to 10.0, and showed a distinct regional pattern: the Ca:Mg ratio was lowest in Haida Gwaii (mean: 1.0) and highest in Prince Rupert (mean: 5.3). This pattern was mainly influenced by the Mg^{2+} concentrations; Ca^{2+} concentrations did not display a similar regional pattern. 82% and 59% of the BG sites had a Ca:Mg ratio greater than 1 and 2, respectively, which is often taken as the mineral soil water limit. The Ca:Mg ratio in the BG sites of the Fraser Lowland (ratio: 4.6) and Vancouver Island bogs (ratio: 2.7) as well as that of Haida Gwaii were all higher than 2, so a Ca:Mg of 1 or 2 as an indicator of the mineral soil water limit is clearly too low for some areas in the coastal BC region. Due to the variable oceanic influence on coastal BC bogs, the Ca:Mg ratio would vary for each location based on local precipitation chemistry. The average Ca:Mg ratio in precipitation between 1978-1985 was 1.0 at Port Hardy and 5.4 at Vancouver International Airport (National Atmospheric Chemistry Database, 2012), indicating regional patterns in precipitation chemistry. Munger and Eisenreich (1983) compiled several precipitation chemistry datasets for North America and noted that Ca^{2+} concentrations were lowest in the Prince Rupert area and increased moving southeast; Mg^{2+} concentrations followed a similar pattern and were correlated with Ca^{2+} concentrations (r=0.83).

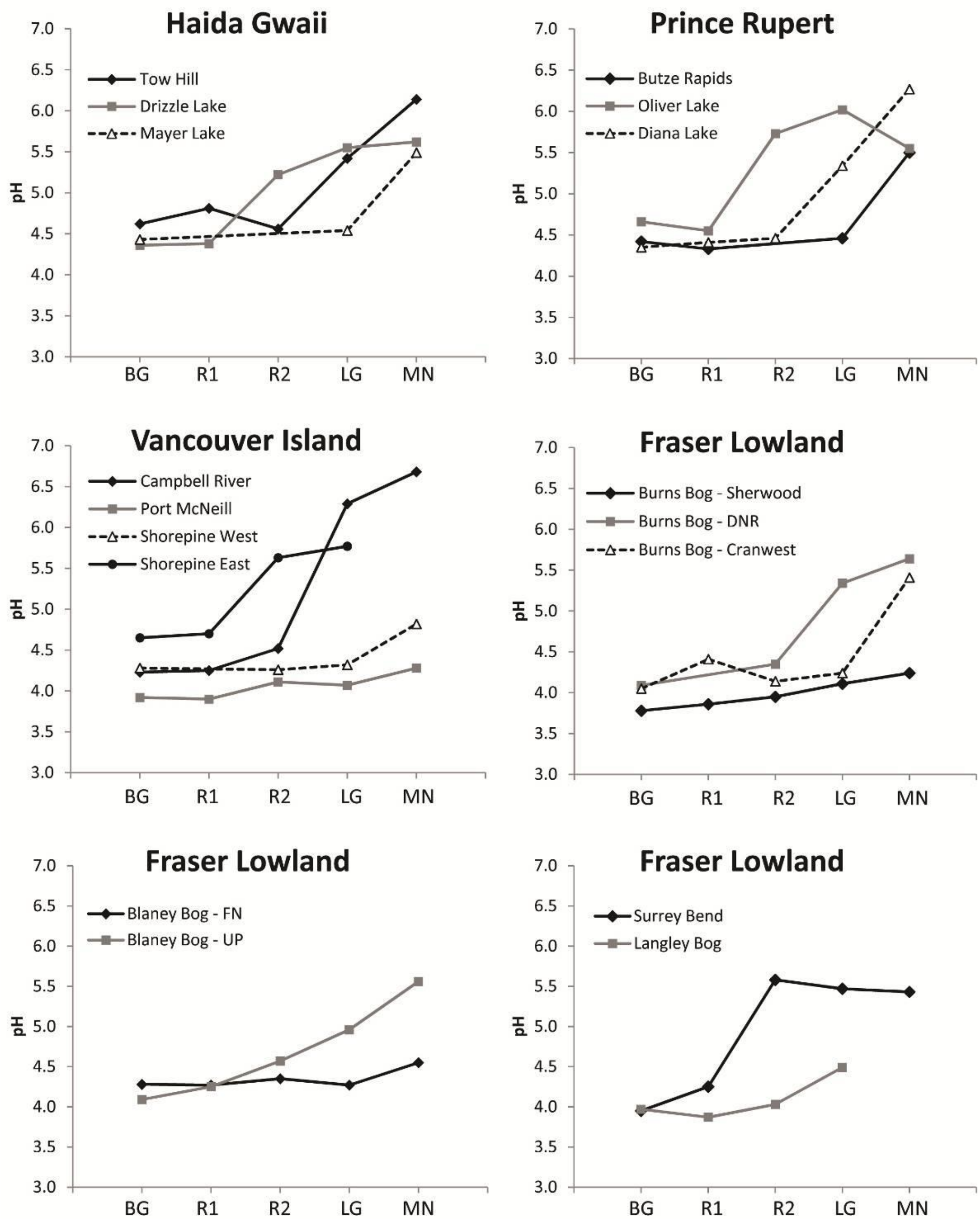

Figure 20. ***Variation in pH across the study transects.***

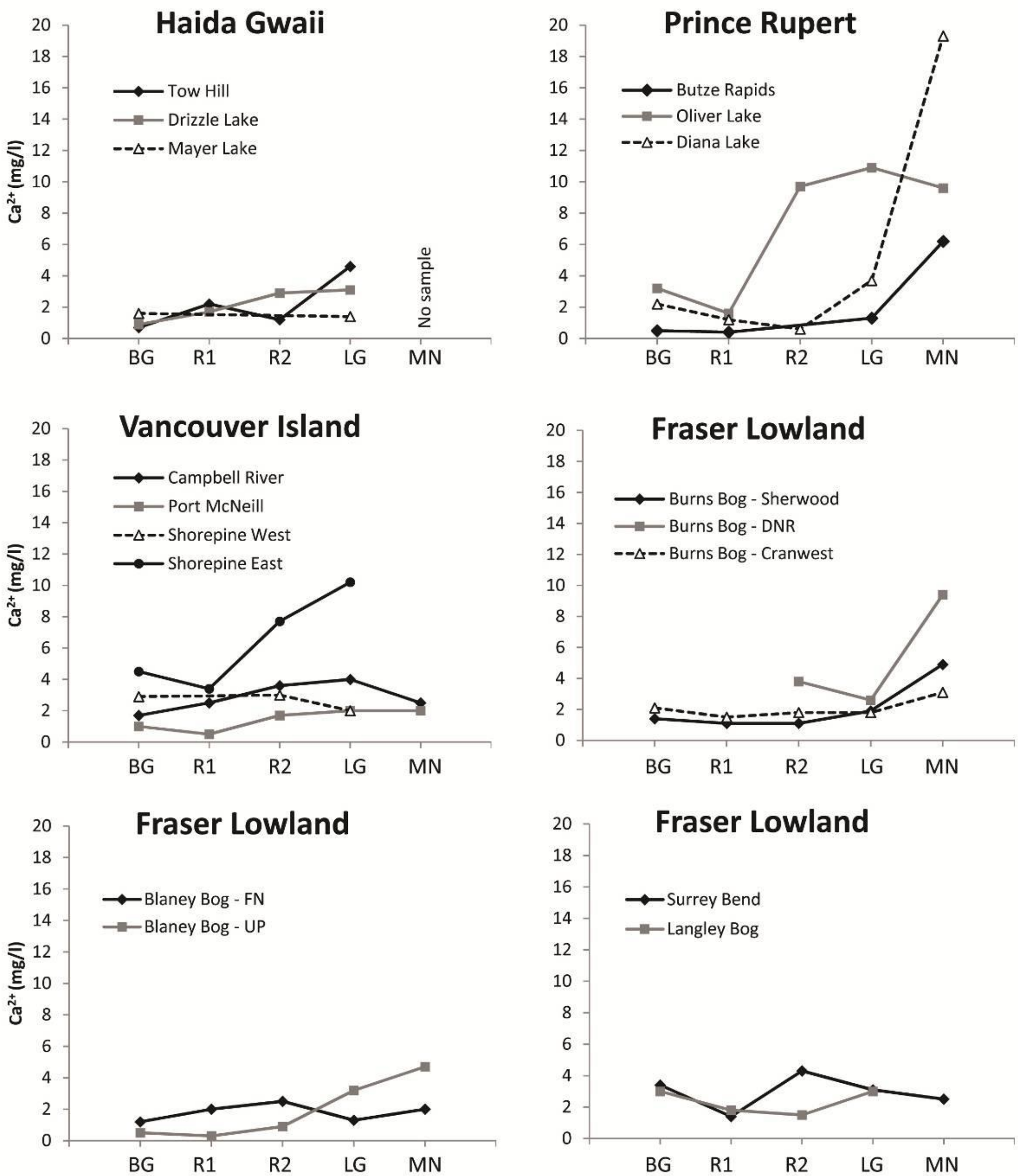

Figure 21. ***Variation in calcium concentrations across the study transects.***

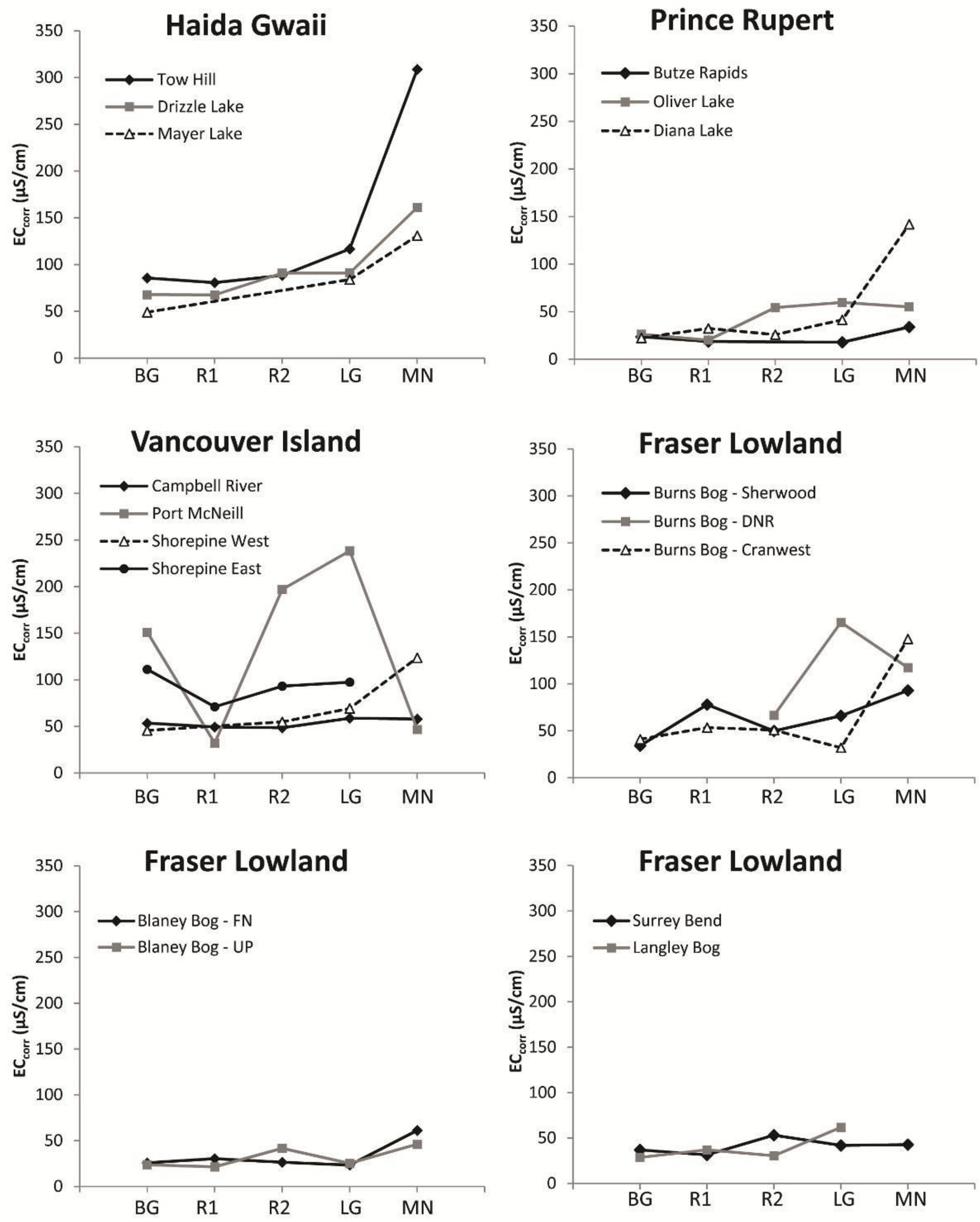

Figure 22. ***Variation in pH-corrected electrical conductivity (EC_{corr}) across the study transects.***

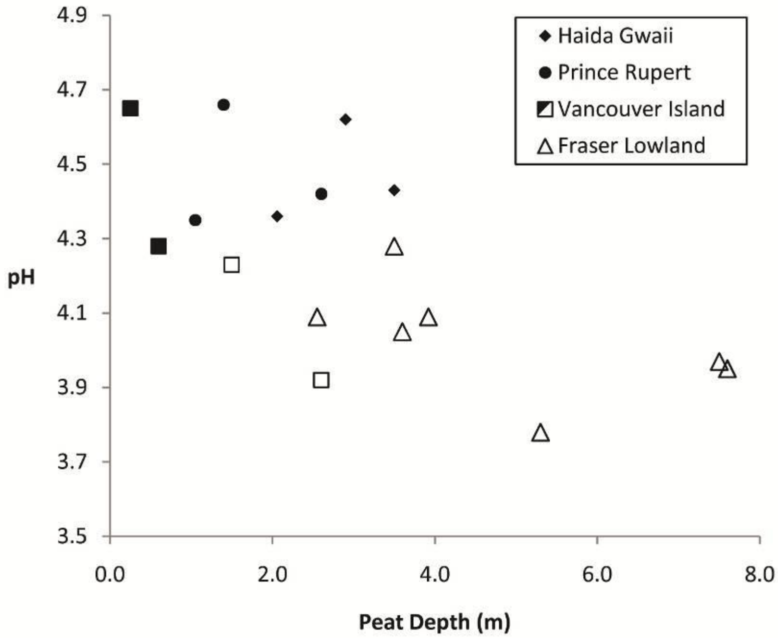

Figure 23. ***Relation between pH and peat depth for the BG sites (Pearson linear correlation: r^2 = 0.42, p=0.005; Spearman rank correlation: r_s = -0.61, p=0.009). Legend shows the four study regions in coastal British Columbia. Solid symbols represent bogs in the Pacific Oceanic wetland region; open symbols represent bogs in the Pacific Temperate wetland region.***

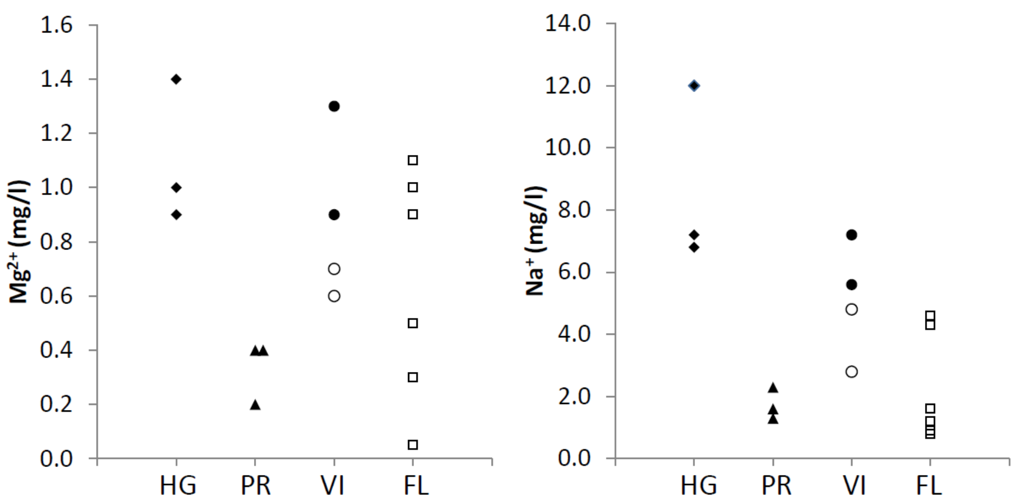

Figure 24. ***Magnesium and sodium concentrations for BG sites in the four study regions: Haida Gwaii (HG), Prince Rupert (PR), Vancouver Island (VI), and Fraser Lowland (FL). Solid symbols represent bogs in the Pacific Oceanic wetland region; open symbols represent bogs in the Pacific Temperate wetland region.***

5.6. Conclusion

Clear gradients were identified across the bog expanse – bog margin transition, particularly for depth to water table, pH, Ca^{2+} concentrations, and corrected electrical conductivity. Depth to water table, pH and ion concentrations generally increased from the bog expanse to the bog margin. However, the gradients for the hydrochemical parameters were not consistent for all bogs. For example, pH and Ca^{2+} concentrations increased consistently from the bog centre to the bog margin for only 14 and 12 of the 17 studied transects, respectively. The mineral content of peat samples usually increased across the bog expanse – bog margin transition; ash content in near-surface peat (10 and 50 cm depth) appears to be the most useful abiotic measure for determining the location of the lagg.

Regional variability in bog hydrochemistry was related to the wetland regions defined by NWWG (1988), latitude, annual precipitation, and oceanic influence. Specifically, pH increased with latitude and mean annual precipitation, and decreased with increasing peat depth. Na^{+} and Mg^{2+} concentrations, and EC_{corr}, were highest in the Haida Gwaii bogs and lowest in the Prince Rupert bogs, which suggests a coastal-inland gradient of decreasing cation concentrations.

Local gradients across the transition from bog to forest were larger than regional gradients for depth to water table, pH, EC_{corr}, Ca^{2+} concentration, peat depth, and ash content. Regional gradients were larger than local variability across the bog expanse – bog margin transition for Mg^{2+} and Na^{+} concentrations, and acidity. Further work is required to survey bogs in latitudes not covered by this study (e.g. from 50º34' N to 53º37' N) and at locations more than 20 km inland.

Despite the apparent similarities in climate and vegetation throughout coastal BC, bogs on islands, sheltered inland locations, and extreme northern or southern locations differ significantly from one another. These regional gradients must be taken into consideration when comparing different bogs and laggs, especially when contemplating the use of data from one bog as a reference ecosystem for the restoration of another bog. For example, a bog or lagg restoration project on Vancouver Island should only use data from other nearby bogs in the same wetland region and at a similar distance from the coast or exposure to the ocean, with the same climatic conditions, to develop a hydrological, hydrochemical, and ecological reference ecosystem for the restoration of the disturbed bog. With this knowledge, one can create an appropriate hydrological and hydrochemical gradient across the lagg using information about the topographic condition at the bog margin and local rainfall data. One can also attempt to re-create appropriate hydrochemical conditions for the restoration of lagg plant communities by using examples of laggs at other local bogs as a guideline.

6. Regional vegetation patterns in bogs and their laggs in coastal British Columbia, Canada.

6.1. Abstract

Thirteen bogs in coastal British Columbia were studied to determine whether or not there were regional patterns in plant communities. Data from 168 vegetation plots and 84 tree plots confirmed regional differences in both bog and lagg plant communities between bogs located in the Pacific Oceanic and Pacific Temperate wetland regions. These differences were related to climate, specifically precipitation and temperature. The climate in the Pacific Oceanic wetland region is cooler and wetter than the Pacific Temperate wetland region. Species richness was significantly higher in the Pacific Oceanic wetland region bog and lagg sites than in the Pacific Temperate wetland region bog and lagg sites. Shannon and Simpson diversity were also significantly higher in the lagg sites of the Pacific Oceanic wetland region sites; there was no significant difference in these diversity indices for the bog sites. Beta diversity analyses showed that bogs in the Pacific Oceanic wetland region had at least one species in common with their respective laggs, while half of the bogs in the Pacific Temperate wetland region had no species in common with their laggs, suggesting that lagg ecotones in the Pacific Temperate wetland region are more distinct from bog plant communities. Cover of *Sphagnum* spp. increased significantly with increasing mean annual precipitation. Cover of *Ledum groenlandicum* and *Pinus contorta* var. *contorta* increased significantly with increasing mean annual temperature. The number of vascular plant species per plot increased significantly with increasing pH and sodium concentrations. Ordination of bog and lagg vegetation plots revealed clusters of species groups that were associated with the different geographic regions in the study area.

6.2. Introduction

Four key gradients in peatland vegetation have been identified by European and North American ecologists: 1) the hummock-hollow sequence, 2) the bog expanse – bog margin gradient, 3) the poor-rich gradient between ombrotrophic and minerotrophic peatlands, and 4) regional gradients related to climate and proximity to the ocean (Malmer, 1986; Rydin et al., 1999; Tahvanainen et al., 2002; Sottocornola et al., 2009; Riley, 2011). The first three gradients are observed at the site level (i.e. across a single peatland), whereas the fourth gradient occurs on a larger scale and is influenced by differences in climate, particularly precipitation and temperature. These gradients shape the variation in peatland plant communities and the controlling environmental factors that influence plant species composition, particularly the depth to water table and the chemical properties of the peat and pore-water.

Regional variation in peatland vegetation is well-established for the Northern Hemisphere. Ingram (1983) observed that fens are more common in areas with low rainfall, that raised bogs form in wetter locations, and that the wettest climates promote the formation of blanket bogs. Riley (2011) found that differences in plant species composition and abundance in wetlands in the Hudson Bay were primarily correlated with depth to water table and pore-water pH; these characteristics vary across a series of adjacent ecoregions, the boundaries of which were determined by climatic patterns (mean annual precipitation, temperature, and relative humidity). Damman (1977) observed regional differences in plant communities of raised bogs in the Bay of Fundy in eastern Canada and the USA, specifically between inland and coastal bogs, which were attributed to the high fog frequency and intermittent snow cover of coastal bogs compared to inland bogs. Damman (1977) noted that regional patterns in plant species composition were most recognizable for large bogs, because bog size is related to the i) depth of peat, which determines the influence of minerotrophic water from the surrounding area, and ii) the buffering effects of the surrounding forest on weather (e.g. wind speed, snow drift). A similar oceanic-continental gradient in bog plant communities has been reported for Sweden, which appears to be the result of higher ion concentrations in precipitation, higher mean relative humidity, and shorter drought periods in oceanic areas (Rydin et al. 1999). In contrast, Glaser et al. (1997) found that species richness, species dominance, and assemblages of plants in bogs were essentially invariable in a regional survey of peatlands across northern Minnesota, despite a pronounced east-west climatic gradient. Glaser et al. (1997) attributed this to a “high degree of buffering from changes in moisture stress”, noting that most of the bogs in their study area were influenced by groundwater recharge, which reduced the precipitation-dependence of these bogs.

An aspect of spatial variation in plant communities that is less commonly studied is the difference in species composition between the bog expanse and the bog margin, or “lagg”. The lagg is defined as a “transition zone at the margin of a (usually raised) bog receiving water from both the bog and surrounding mineral ground, characterized by fen or swamp species, transitional water chemistry, and shallow peat of relatively low hydraulic conductivity” (Howie and Tromp-van Meerveld, 2011). The lagg may be clearly defined by a vegetative ecotone between the bog and forest where there is a topographic depression at the bog margin that allows water to pool. Where the bog and surrounding forest are relatively flat, or where the ground slopes away from the bog, the lagg may not be visually evident in the field. In a study of BC, Washington, and Oregon bogs, Rigg and Richardson (1938) observed that marginal lagg swamps were characterized by sedges (*Carex* spp.) or hardhack (*Spiraea douglasii* Hook.). Field researchers examining the transition from bog center to margin rarely extend their study beyond the bog margin into the surrounding minerotrophic ecosystem (e.g., forest), and therefore tend to ignore the variable chemical composition of runoff from the adjacent landscape (Howie and Tromp-van Meerveld, 2011). Since peat is generally shallow at the bog margin, the lagg of a bog is often disturbed (e.g. for agriculture or other land uses), even for bogs that are otherwise relatively undisturbed.

Where a lagg ecotone is present at the bog margin, the cause of regional variation in lagg plant communities may be more difficult to determine than for the adjacent bog. In ombrotrophic bogs, water and nutrients are almost entirely supplied by an atmospheric source (i.e. precipitation and dustfall), so regional variations in plant communities are controlled by climate and precipitation chemistry. In the lagg, it is also necessary to consider the varying degrees of influence from minerotrophic water from areas outside the bog. Damman (1977) noted that plant species composition at the bog margin is most strongly influenced by the topography and the surrounding minerotrophic soils, and that differences in plant communities caused by climate are less evident than in central bog areas.

Knowledge of these regional and local patterns in bog and lagg plant communities is useful for management and restoration of bogs. In order to manage a bog for conservation purposes, it is important to have a record of the vegetation characteristics of similar undisturbed bogs. Regional gradients in bog plant communities therefore have to be documented to ensure that the undisturbed bog that is used as a reference ecosystem for restoration has suitable vegetative characteristics for the restoration site. An inventory of relatively undisturbed laggs in a given area may also assist lagg restoration; a list of common lagg species and their preferred range in depth to water table, pH, and nutrient concentrations can help management agencies to develop restoration targets for disturbed laggs. This type of inventory can also be useful in determining whether a lagg is in a natural condition or has been impacted by human activities, e.g. the presence of invasive species would indicate a disturbed condition.

The purpose of this study was to determine whether regional patterns exist in the plant communities of bogs and laggs in coastal British Columbia (BC), and to link these patterns to regional environmental gradients such as climate, and local environmental gradients such as depth to water table and hydrochemical characteristics. Regional gradients in bog plant communities have previously been documented for coastal BC. During an extensive study of 78 bogs in the Pacific Northwest (encompassing Alaska, British Columbia, Washington, and Oregon), Rigg (1925) made numerous observations of plant species that were distributed according to latitude. For example, *L. glandulosum var. columbianum* (Piper) Hitchc. was most abundant in Washington and Oregon bogs, whereas *L. palustre* was most common in Alaska. *Kalmia occidentalis* Small was found in the northern bogs, but was absent from the Oregon bogs. Vitt et al. (1990) found that plant species composition in *Sphagnum*-dominated peatlands of the hyperoceanic north coast of BC was most strongly correlated with surface water chemistry; concentrations (esp. sodium and chloride) decreased with distance from the Pacific Ocean. Golinski (2004) found four floristically distinct groups of peatlands on Vancouver Island, which were related to differences in mean annual precipitation, mean annual temperature, and elevation. This study includes bogs in these previously studied subregions, but also widens the scope to a more representative sample of bogs along the BC coast and looks at plant community gradients in the lagg, which is a rarely-studied ecotone.

6.3. Methods

6.3.1. Study Area

The west coast of BC has a mild climate that supports a wide variety of ecosystems. These ecosystems have been classified into "biogeoclimatic zones" on the basis of their climax plant communities. The two most common low-elevation biogeoclimatic zones on the west coast of BC are Coastal Western Hemlock (CWH) and Coastal Douglas Fir (CDF). The CWH zone is the wettest and most productive biogeoclimatic zone in the province, resulting in the development of organic soils in the wetter areas. The organic matter build-up often promotes the formation of bogs, particularly on the north coast. Characteristic tree species of these bogs include stunted western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), shore pine (*Pinus contorta* var. *contorta*), western red cedar (*Thuja plicata* Donn.), and yellow cedar (*Chamaecyparis nootkatensis* D. Don) (Jones and Annas, 1978). The CDF zone is warmer and drier than the CWH zone, as a result of its more southern location in the rainshadow of the Olympic Peninsula and Vancouver Island mountains. The CDF zone is dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) (Jones and Annas, 1978), but bogs in this zone are characterized by stunted shore pine (Hebda et al., 2000).

Wetlands on the Pacific coast of BC fall within two of the seven Canadian wetland regions: Pacific Oceanic and Pacific Temperate. Canada's wetland regions are based on broad climatic and vegetation zones following a north-south temperature gradient and an east-west precipitation gradient (NWWG, 1988). Mean annual precipitation is 2117 mm in the Pacific Oceanic wetland region and 1044 mm in the Pacific Temperate wetland region (NWWG, 1988). The Pacific Oceanic wetland region is divided into two subregions: North Coast and South Coast.

Thirteen bogs within 20 km of the Pacific Ocean and less than 100 m above sea level were studied between May and August of both 2010 and 2011 to assess the variation in bog and lagg plant communities in this region. Six bogs were studied on the north coast: three bogs near Prince Rupert (Diana Lake, Oliver Lake, and Butze Rapids) and three bogs on Haida Gwaii (Tow Hill, Mayer Lake, Drizzle Lake). These bogs are located in the North Coast subregion of the Pacific Oceanic wetland region and are dominated by yellow cedar, shore pine, western red cedar, evergreen ericaceous shrubs, sedges, and *Sphagnum* species (Banner et al., 1988).

Three bogs were studied on Vancouver Island: one on the west coast (Shorepine Bog) and two on the east coast (Port McNeill and Campbell River) of the island. Shorepine Bog is located within the South Coast subregion of the Pacific Oceanic wetland region; bogs in this area are dominated by *Sphagnum* and *Carex* species, Labrador tea (*Ledum groenlandicum* Oeder), crowberry (*Empetrum nigrum* L.), cottongrass (*Eriophorum angustifolium* L.), cloudberry (*Rubus chamaemorus* L.), great burnet (*Sanguisorba officinalis* L.), and stunted shore pine and yellow cedar (Wade, 1965; MacKenzie and Moran, 2004). The Port McNeill and Campbell River bogs are located in the Pacific Temperate wetland region and are characterized by Labrador tea, sweet gale (*Myrica gale* L.), western bog-laurel (*Kalmia occidentalis* Small), bog cranberry (*Vaccinium oxycoccos* L.), hummock-forming *Sphagnum* mosses, and stunted shore pine (MacKenzie and Moran, 2004).

Four bogs were studied in the Fraser Lowland region: Burns Bog, Surrey Bend, Langley Bog, and Blaney Bog. Burns Bog is the only bog in this study that is located in the CDF biogeoclimatic zone; the other bogs are all located in the CWH biogeoclimatic zone (Fig. 25). The Fraser Lowland bogs are all located in the Pacific Temperate wetland region and are dominated by Labrador tea and *Sphagnum* spp., with abundant shore pine, western bog laurel, and bog cranberry. The Fraser Lowland bogs represent the southernmost extent of *Sphagnum*-dominated raised bogs on the west coast of Canada (Vitt et al., 1999). The most common *Sphagnum* species include *S. fuscum* (Schimp.) Klinggr., *S. capillifolium* (Ehrh.) Hedw., and *S. papillosum* Lindb. (MacKenzie and Moran, 2004). All four Fraser Lowland bogs have been disturbed in some way (e.g. peat mining, utility and road construction, drainage, conversion to agriculture), but they contain enough remnant natural parts to allow a comparative vegetation study.

Table 15. ***Location of the BG sites, associated climate data, and transect length for the studied bogs and species richness, evenness, and diversity for the BG and LG sites. Bogs with more than one site code contained multiple study transects (one transect for each site code). Climate data source: Environment Canada climate normals (30-year average, 1970-2000).***

Site Name	Site Code	Average Annual Precip. (mm)[b]	Average Annual Temp. (^{o}C)[b]	Transect Length (m)		Average Species Richness		Average Evenness		Average Shannon diversity		Average Simpson diversity	
				BG to LG	LG to MN	BG	LG	BG	LG	BG	LG	BG	LG
Tow Hill Bog[a]	TH	1508	8.2	150	23	22.0	11.5	0.6	0.6	1.9	1.3	0.8	0.6
Mayer Lake Bog[a]	ML	1508	8.2	145	96	17.0	11.0	0.5	0.7	1.4	1.7	0.6	0.8
Drizzle Lake Bog[a]	DT	1508	8.2	100	11	16.5	18.0	0.6	0.7	1.7	2.1	0.7	0.8
Butze Rapids Bog[a]	BR	2594	7.1	14	6	17.5	16.5	0.8	0.8	2.2	2.1	0.9	0.8
Oliver Lake Bog[a]	OL	2594	7.1	40	24	22.0	16.0	0.7	0.8	2.1	2.1	0.8	0.8
Diana Lake Bog[a]	DL	2594	7.1	41	7	18.5	14.5	0.7	0.7	2.0	1.8	0.8	0.8
Port McNeill Bog[a]	PM	1869	8.3	52	7	10.0	13.0	0.6	0.6	1.4	1.5	0.7	0.7
Campbell River Bog[a]	CR	1452	8.6	87	19	7.0	9.0	0.8	0.6	1.5	1.3	0.7	0.7
Shorepine Bog	SPW	3305	9.1	38	12	15.5	16.5	0.8	0.7	2.2	2.1	0.9	0.8
	SPE			75	16	17.0	12.5	0.7	0.7	1.9	1.7	0.8	0.8
Burns Bog	CW	1008	9.6	203	635	14.0	8.0	0.9	0.8	2.3	1.7	0.9	0.8
	SW			471	92	11.0	7.5	0.8	0.7	1.9	1.4	0.8	0.7
	DNR			658	359	6.5	6.0	0.6	0.6	1.2	1.1	0.6	0.6
Surrey Bend Bog	SB	1708	9.8	422	115	12.5	5.5	0.8	0.7	2.0	1.0	0.8	0.6
Langley Bog	LB	1708	9.8	272	26	12.5	10.0	0.9	0.6	2.3	1.3	0.9	0.7
Blaney Bog	BU	2194	9.6	151	28	7.5	10.0	0.9	0.9	1.7	2.0	0.8	0.8
	BF			98	6	12.5	9.0	0.7	0.7	1.7	1.4	0.7	0.7

[a]Site names created for this study based on nearby place names.

[b]Environment Canada climate normals (1971-2000). Climate data for TH, ML, DT from Masset Inlet, BC; for BR, OL, DL from Prince Rupert, BC; for PM from Port Hardy, BC; for CR from Campbell River, BC; for SPW and SPE from Tofino, BC; for SW, CW, DNR from Vancouver International Airport; for SB and LB from Pitt Meadows, BC; and for BU and BF from Haney UBC Research Forest, BC.

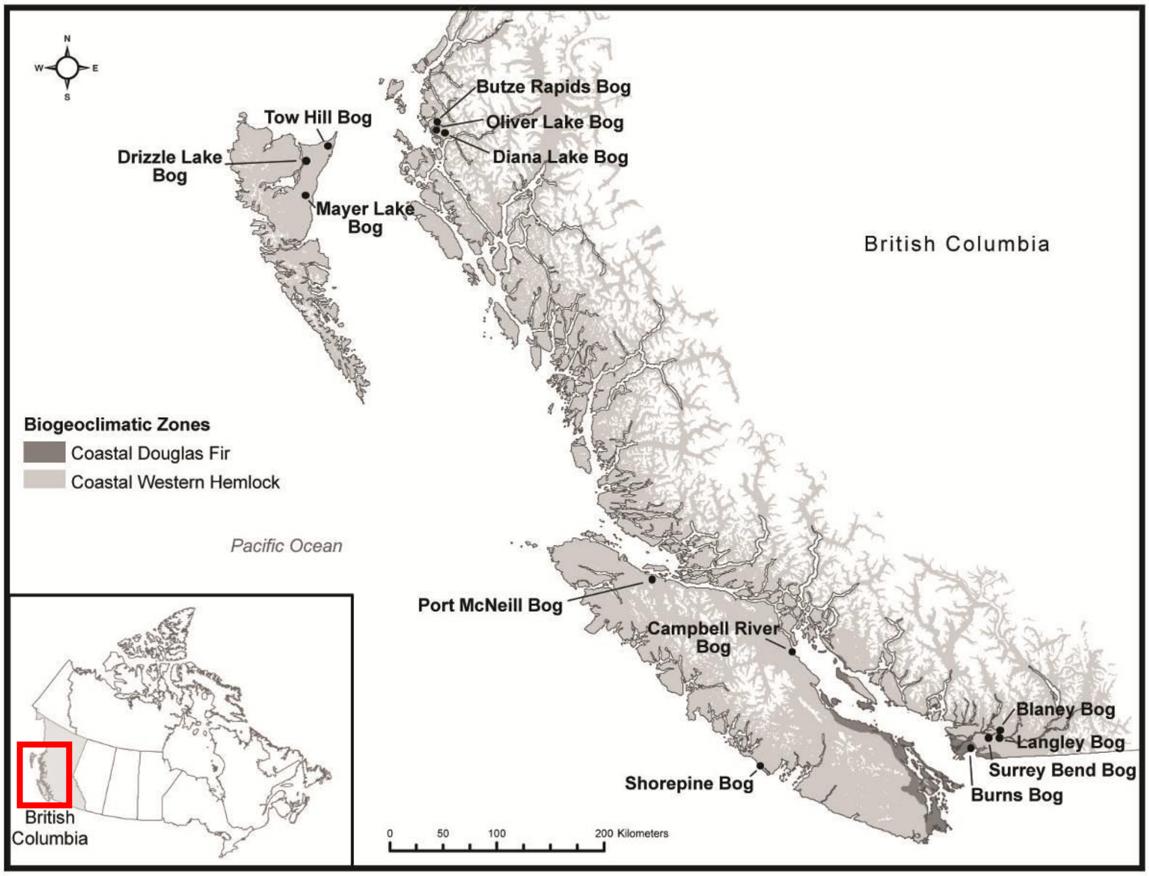

Figure 25. Location of research sites in British Columbia. Inset: map of Canada. Red box indicates area of larger map.

6.3.2. Field Measurements

At each bog, a transect comprising five study points was laid out perpendicular to the bog margin. Most of the thirteen studied bogs contained only one study transect, but two bogs had two study transects (Shorepine Bog and Blaney Bog), and one bog had three study transects (Burns Bog). The five study points across each transect were determined in the field based on the dominant plant communities. One point was located in the *Sphagnum*- and heath-dominated “central bog” area (BG), two points were located in the transition from bog expanse to bog margin (one closer to the bog (R1) and one closer to the margin (R2)), the fourth point was located in the lagg, as determined by an obvious change in plant species composition at the bog margin (LG), and a fifth point was located in the mineral forest adjacent to the bog (MN). The DNR transect in Burns Bog had only four points, due to the presence of a highway between the bog and lagg.

The SW transect in Burns Bog had six points (two in the lagg) to account for differences in plant species composition across the relatively wide lagg on this transect.

At each study point on the transects, we recorded the cover of all species in a 5 m by 5 m plot using the Braun-Blanquet scale of cover and abundance: “r”=solitary with small cover, “+”=few with small cover, “1”=numerous but <5% cover, “2”=5-25% cover, “3”=25-50%, “4”=50-75%, “5”=≥75% (Mueller-Dombois and Ellenberg, 1974). Species nomenclature for vascular plants followed Hitchcock and Cronquist (1973), and for bryophytes followed Klinkenberg (2012). For *Sphagnum* spp., we recorded the cover of up to four of the most abundant species in the plot. A parallel transect of 5 m by 5 m vegetation plots was studied 20 m from each transect for replication. In a 10 m by 10 m plot at each point on the main transect, we determined species, height, and diameter of all trees, except for seedlings shorter than 20 cm. On short transects with less than 10 m between study points (Table 15), the tree plots were shortened to 5 m by 10 m (27 out of 84 plots). Diameter was measured at 1.4 m (DBH) unless trees were shorter than 2 m, in which case, diameter was measured mid-way along the stem. Many small trees (<0.5 m in height) were less than 1 cm in diameter; in these cases, the trees were assigned a diameter of 0.5 cm for analysis purposes. We surveyed a total of 168 vegetation plots and 84 tree plots.

Piezometers were installed in hollows at the five transect points in each bog, and were used to measure depth to water table and collect samples of near-surface pore-water for analysis of pH, electrical conductivity, and concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}. Peat depth was determined at these locations as well. For a detailed description of depth to water table measurements and hydrochemical sampling methods, see Chapter 5.

6.3.3. Data Analysis

Spearman rank and Pearson linear correlations were used to determine the correlation between plant species presence/abundance and environmental parameters. Two-tailed Student’s t-tests were used to determine if there was a significant difference in percent cover of the dominant plant species between the Pacific Oceanic and Pacific

Temperate wetland regions, and between northern sites (>53^{0}N) and southern sites (<51^{0}N). A significance level of 0.05 was used for all analyses.

Ordination (multivariate) analyses were performed using PC-ORD (McCune and Mefford 2011) to evaluate more complex relationships. Ordination techniques are commonly used in the analysis of ecological communities because they can help to identify the factors that have the greatest effect on species composition, separate the most important patterns from less important ones, and reveal patterns that would be difficult to find using univariate or bivariate analysis (McCune and Grace, 2002). More specifically, we used these analyses to search for ecological and regional vegetative groups in the studied BG and LG plots using hierarchical agglomerative cluster analysis and non-metric multidimensional scaling (NMS). For the cluster analysis, we used Euclidean distance and Ward's linkage method. For NMS, we used Sorensen (Bray-Curtis) distance, a maximum of 200 runs, 100 iterations, and a stability criterion of 0.0005. The test parameters listed above for the cluster analysis and NMS ordination were used because they were determined to be effective in the ordination of bog and lagg plant communities on Vancouver Island (Golinski, 2004). Canonical correspondence analysis (CCA) was performed to determine how much of the species variance could be explained by latitude, mean annual precipitation, and mean annual temperature. A second CCA was performed to test the extent to which species variance was related to site-scale properties, namely hydrochemical characteristics, depth to water table, and peat depth. CCA was used because we wanted to determine whether some portion of the plant community composition was more strongly related to the measured environmental variables than expected by chance, and because this method can be considered a "direct gradient analysis" (McCune and Grace, 2002). For ordination, correlations, and tests of significance, Braun-Blanquet cover values for plant species were converted to percent cover values by using the mean of each percent class: "r"=0.25%, "+" = 0.5%, "1" = 2.5%, "2" = 15%, "3" = 37.5%, "4" = 62.5%, "5" = 87.5%.

The Sörensen Index was used to determine Beta Diversity between the BG vegetation plots and the other vegetation plots on the transects: Sörensen Index = 2a/(2a+b+c), where "b" = the number of species in the BG plot, "c" = the number of species in another plot, and "a" = the number of species shared between "b" and "c".

Beta Diversity was used because it is a well-known measure of diversity, which allows for a comparison of the change in species diversity and composition between different ecosystems. We also calculated the following indices for the vegetation plots with PC-ORD (McCune and Mefford, 2011): species richness (S = total number of species); evenness:

$$E = H' / \ln(S)$$

Shannon's diversity index:

$$H' = -\sum_{i}^{S} p_i \log p_i$$

and Simpson's diversity index:

$$D = 1 - \sum_{i}^{S} p_i^2$$

where p_i = importance probability for each species, relative to the total species for each vegetation plot. Species richness was used to determine whether there was a difference in the number of species in BG and LG sites regionally (e.g. between the Pacific Oceanic and Pacific Temperate wetland regions, or between northern and southern bogs). A goal of this study was to determine regional and local differences in dominant species assemblages; thus, the Shannon and Simpson diversity indices were chosen because they account for both the abundance and evenness of the species in the plots; both diversity indices were used because the Simpson diversity index emphasizes common species while rare species have little effect on the measure of diversity, whereas the Shannon diversity index also includes the species that are relatively rare (Hill, 1973).

6.4. Results

6.4.1. Regional Variation in Plant Species Composition

BG Plots

We recorded a total of 146 species in the 168 vegetation plots (100 vascular plants and 46 bryophytes) (Appendix E); 76 of these species (52%) were located in the BG plots. Species richness in BG plots was relatively high in the Prince Rupert bogs (17-24 species per plot), the Haida Gwaii bogs (16-23 species), and Shorepine Bog on the west coast of Vancouver Island (15-18 species). Species richness was lower in the BG plots of the bogs on the east coast of Vancouver Island (6-11 species), and in the Fraser Lowland bogs (5-15 species). The difference in the number of species in the BG plots between the Pacific Oceanic wetland region (mean: 16.3 species) and the Pacific Temperate wetland region (mean: 9.7 species) was statistically significant. Mean species evenness, the relative abundance of different species, was significantly higher in the BG plots in the Pacific Temperate wetland region (0.77) than the Pacific Oceanic wetland region (0.67); there was no significant difference in the mean Shannon diversity (Pacific Temperate: 1.78, Pacific Oceanic: 1.94) or mean Simpson diversity (Pacific Temperate: 0.77, Pacific Oceanic 0.78) indices for the BG plots in the two wetland regions.

Overall, the most common understory species in the BG plots were: *Ledum groenlandicum*, *Kalmia occidentalis*, *Vaccinium uliginosum*, and *Sphagnum capillifolium* (Table 16). However, the Haida Gwaii bogs were different as they were dominated by *Sphagnum austinii* and *Juniperus communis*. The Haida Gwaii and Prince Rupert bogs contained a relatively large cover of *Empetrum nigrum* (mean Braun-Blanquet cover: 2) compared to the other bogs (mean Braun-Blanquet cover: 0). The difference in cover of *Ledum groenlandicum* in the BG plots in the southern bogs (<51^{0}N) and the northern bogs (>53^{0}N) was significant. While cover of *Ledum* was variable in the southern bogs (Braun-Blanquet cover: 0-5; median: 5), it was always low in the Haida Gwaii and Prince Rupert bogs (Braun-Blanquet cover: ≤2; median: 1). Cover of *Ledum groenlandicum* was also significantly higher in bogs of the Pacific Temperate wetland region than in bogs of the Pacific Oceanic wetland region. Similarly, cover of *Kalmia occidentalis* was significantly higher in the southern bogs and in the Pacific Temperate wetland region. Conversely, *Juniperus communis* was only present in the northern bogs, *Empetrum nigrum* was only present in the bogs of the Pacific Oceanic wetland region, and cover of *Rubus chamaemorus* was significantly higher in the northern bogs (Braun-Blanquet cover: 0-3) and in the bogs of the Pacific Oceanic wetland region (Braun-Blanquet cover: 0-3) (Table 16).

The most common species of *Sphagnum* in the BG plots varied by region (Table 17). In Haida Gwaii, *S. austinii* was the most common species, creating a relatively flat lawn on the bog surface. In the Prince Rupert bogs, *S. papillosum* was the most common lawn species. The bogs on the east and west coasts of Vancouver Island had different dominant species of *Sphagnum* (*S. lindbergii*, *S. mendocinum*, and *S. pacificum* on the east coast, and *S. capillifolium* and *S. papillosum* on the west coast). In the Fraser Lowland, hummock-forming species *S. capillifolium and S. fuscum*, and lawn species *S. magellanicum* and *S. pacificum*, were most common. *S. papillosum* (mean Braun-Blanquet cover of 3 for the Prince Rupert bogs and Shorepine Bog) and *S. austinii* (mean Braun-Blanquet cover of 4 for the Haida Gwaii bogs) were the most common species in the bogs in the Pacific Oceanic wetland region, whereas *S. capillifolium* was the most common species in the Pacific Temperate wetland region (mean Braun-Blanquet cover: 3, Table 16). Cover of *S. papillosum* and *S. austinii* were significantly higher in the Pacific Oceanic wetland region; cover of *S. capillifolium* was not significantly different between the two wetland regions, but was significantly higher in the southern bogs than the northern bogs (Table 16).

There were also clear regional patterns in tree species composition in the BG tree plots. Although the dominant tree species (pine, cedar, and hemlock) were the same for all studied bogs, their relative abundance in the plots differed by region. Pine was the dominant tree in the Haida Gwaii, eastern Vancouver Island, and Fraser Lowland bogs, whereas cedar (*Chamaecyparis nootkatensis* and *Thuja plicata*) was dominant in the Prince Rupert and western Vancouver Island bogs (Fig. 29a). Some of the bogs in the Fraser Lowland contained deciduous species (i.e. birch, cascara), while there were only coniferous trees in the other bogs (Fig. 29a).

The distribution of the plant species in the study area seems to be related to climate. Percent cover of *Sphagnum* (all species combined) in the BG plots was significantly positively correlated with mean annual precipitation (r_s = 0.422). Some of the other abundant species in BG plots were significantly correlated with mean annual temperature: percent cover of *Ledum groenlandicum* (r_s=0.501) and *Pinus contorta* var. *contorta* (r_s=0.407) were higher in warmer sites, whereas *Carex* (r_s=-0.639) was less common in the warmer sites. In the CCA ordination for latitude, mean annual precipitation, and mean annual temperature, Axis 1 (correlated with latitude (r^2=-0.904) and mean annual temperature (r^2=-0.758)) explained 11% of species variance in the BG plots and Axis 2 (correlated with mean annual precipitation (r^2=-0.762)) explained 7% of species variance. Axis 3 was not well correlated with any variable, and explained 6% of the variance.

Cluster analysis for the BG plots showed that the bog plant communities can be grouped into the two coastal BC wetland regions (Fig. 30a). Using NMS ordination, these regional distinctions became more clear; bog plant communities were grouped into four main regions: Haida Gwaii, Prince Rupert, west coast of Vancouver Island, and Georgia Basin (east coast of Vancouver Island and the Fraser Lowland) (Fig. 31a). Only two outliers out of the 34 BG vegetation plots did not fit this classification; the BG plot on the main SW transect was classified as being similar to Shorepine Bog on the west coast of Vancouver Island, and the BG plot on the parallel DT transect (in Haida Gwaii) was classified as being more similar to the Prince Rupert bogs.

6.4.2. Local Variation in Plant Species Composition

Species richness varied across the study transects. For the Prince Rupert and Haida Gwaii study sites, species richness declined across the transition from bog to forest (Fig. 26). For the Vancouver Island and Fraser Lowland bogs, there was no clear trend in species richness across the transects (Fig. 26). Average species richness was lowest in the LG plots in both the Pacific Oceanic and Pacific Temperate wetland regions, but this trend was not clear for the individual transects (Fig. 26; Table 15). Average values for evenness, Shannon diversity index, and Simpson diversity index for all bogs in the two wetland regions combined were lowest for the LG plots in the Pacific Temperate wetland region, but not for the Pacific Oceanic wetland region. The average

Shannon and Simpson diversity indices for all bogs in the Pacific Temperate wetland region combined decreased across the transect from BG to LG, and were either the same as LG (Simpson) or slightly higher (Shannon) in the MN sites. There was no trend in these diversity indices across the transects for the bogs in the Pacific Oceanic wetland region. The Beta Diversity analysis revealed a difference between the Pacific Oceanic and Pacific Temperate wetland regions in terms of species similarity between the plots on the transects. All of the Pacific Oceanic LG and MN plots had species in common with the BG plots on their respective transects (Fig. 27). Only 12 out of 22 LG plots and 7 out of 20 MN plots of the bogs in the Pacific Temperate wetland region had species in common with the BG plots (Fig. 28).

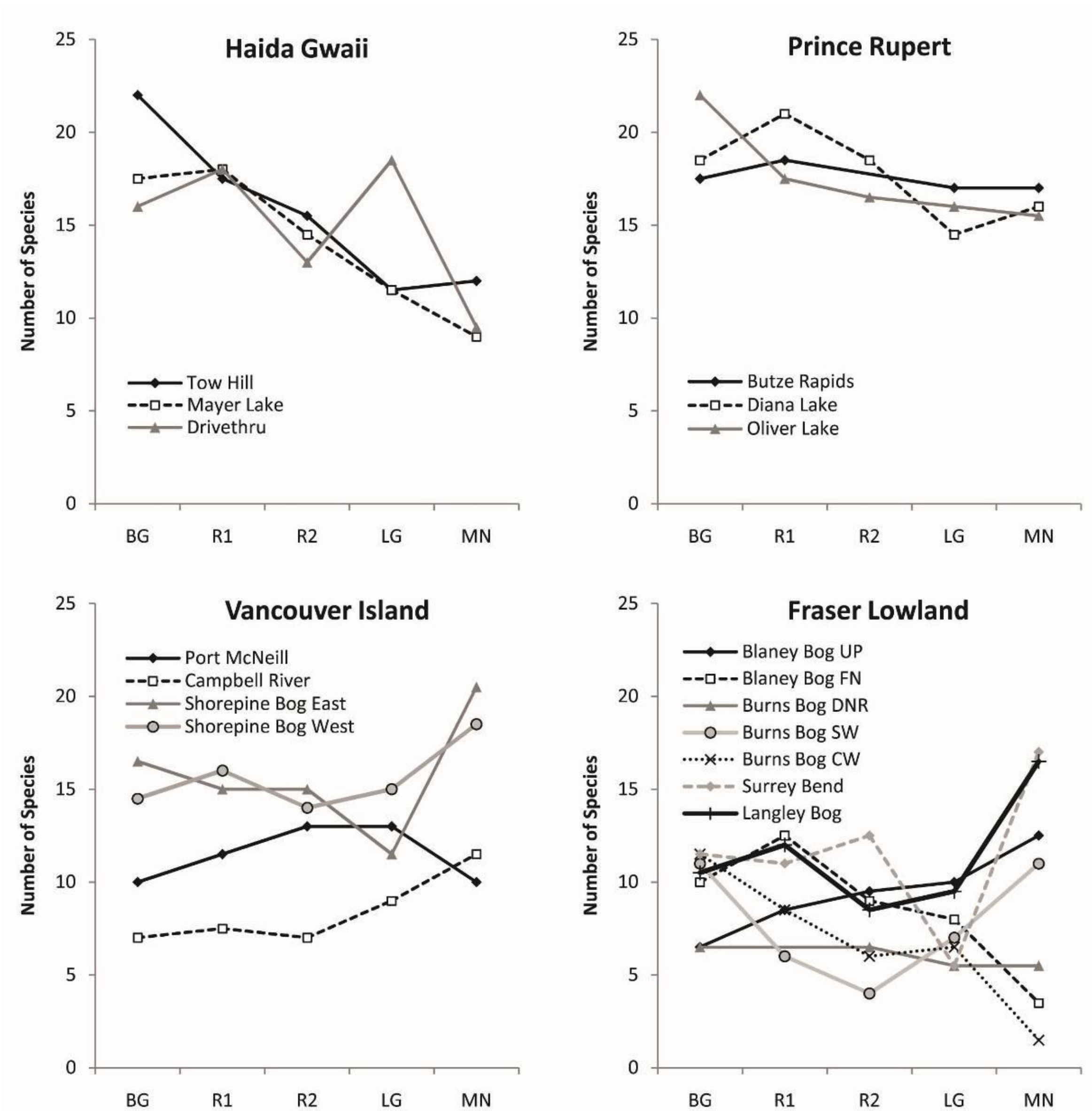

Figure 26. ***Number of species in the vegetation plots along the study transects in each geographic region: Haida Gwaii, Prince Rupert, Vancouver Island, and Fraser Lowland. Graphs display the average of the two parallel vegetation transects for each bog.***

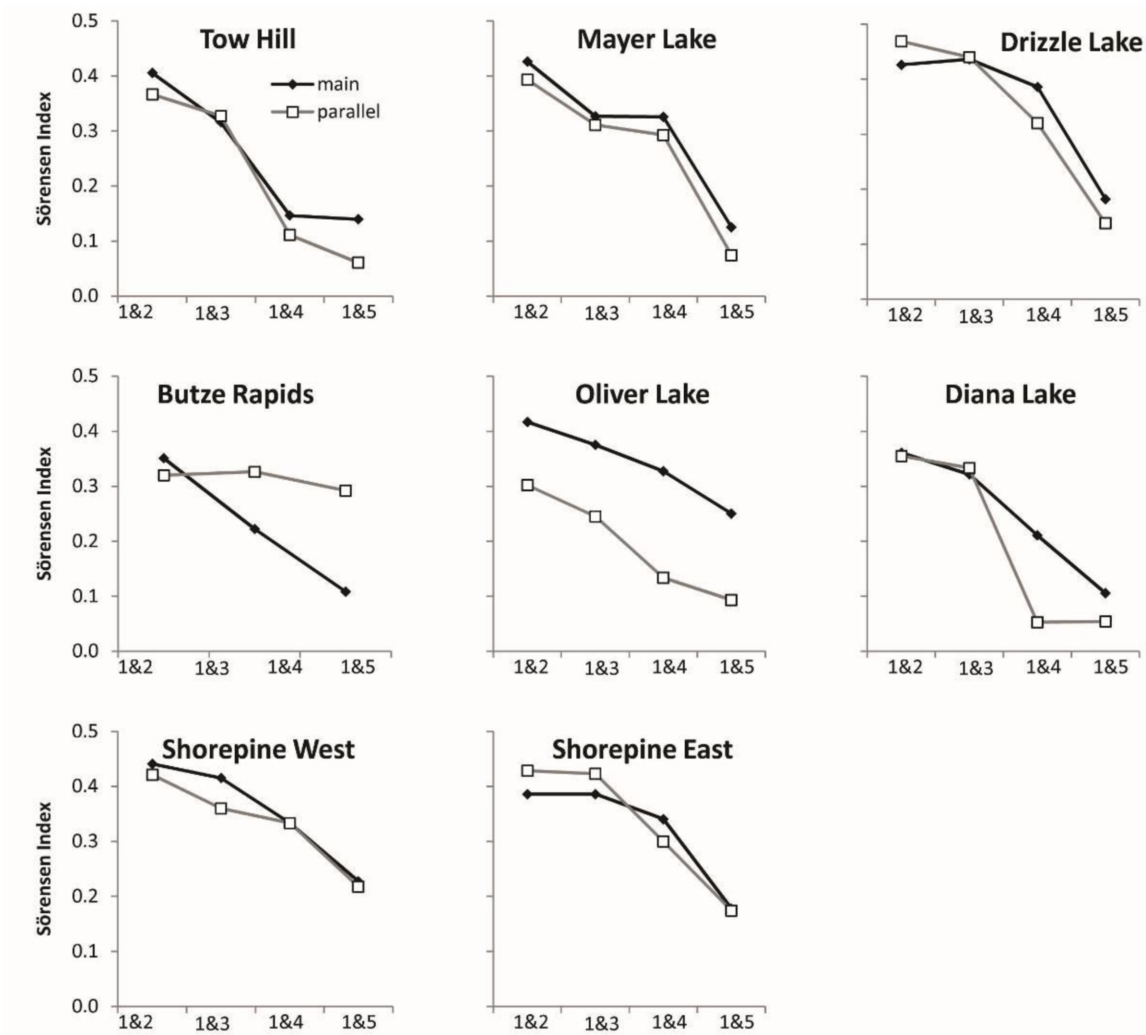

Figure 27. ***Sörensen Index of Beta Diversity for vegetation plots from the Pacific Oceanic wetland region. "Main" = the vegetation plots on the main study transect; "parallel" = the parallel vegetation transect 20 m from the main study transect. A value of zero means that paired plots had no species in common with each other. X-axis labels: 1 = BG, 2 = R1, 3 = R2, 4 = LG, and 5 = MN plots.***

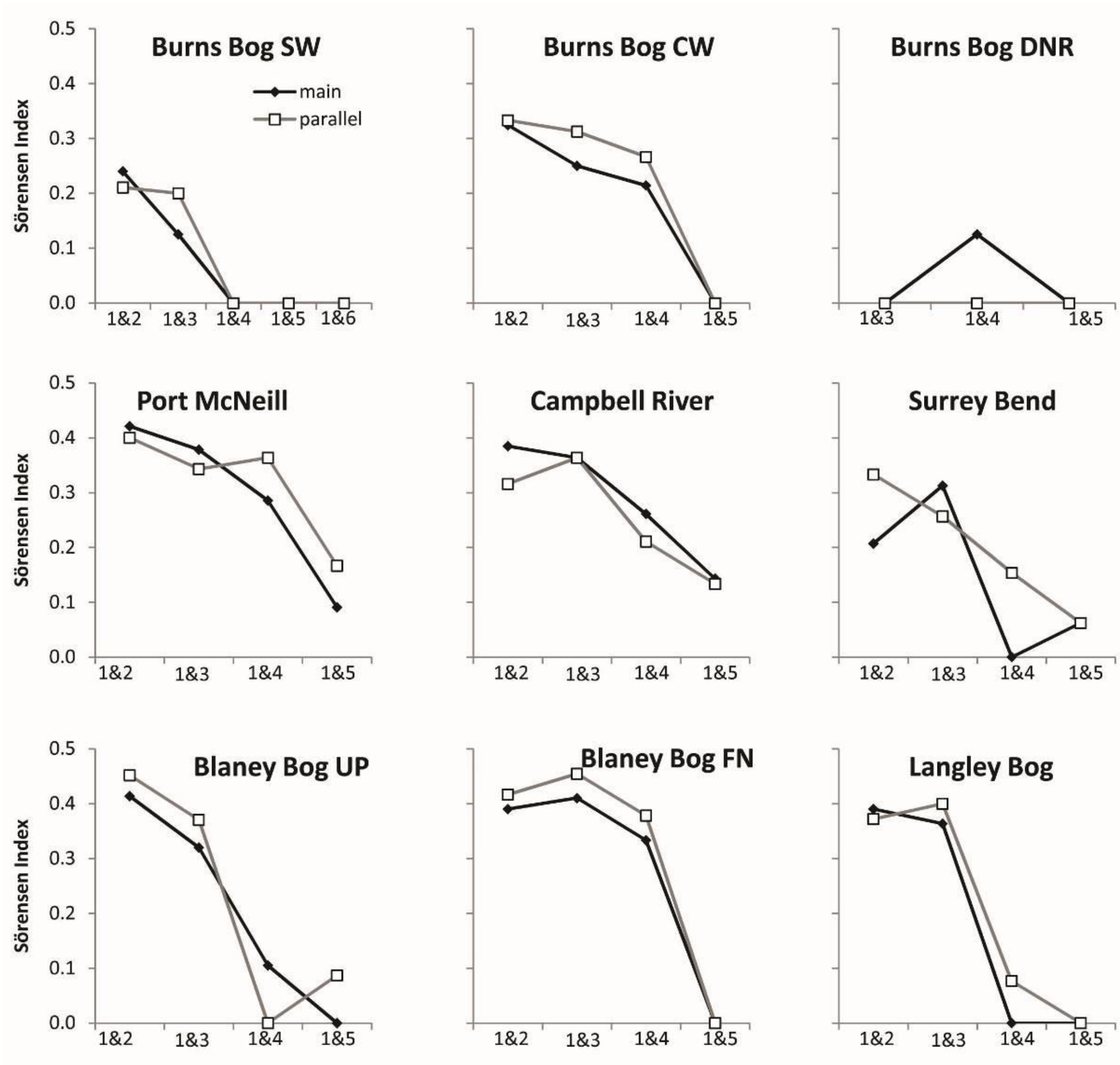

Figure 28. Sörensen Index of Beta Diversity for vegetation plots in the Pacific Temperate wetland region. "Main" = the vegetation plots on the main study transect; "parallel" = the parallel vegetation transect 20 m from the main study transect. A value of zero means that paired plots had no species in common with each other. X-axis labels: 1 = BG, 2 = R1, 3 = R2, 4 = LG, and 5 = MN plots. For the Sherwood transect, "4" and "5" are the two LG plots, and "6" is the MN plot. For the DNR transect, "3" and "4" are the two LG plots. For Burns Bog and Blaney Bog site codes, see Table 15.

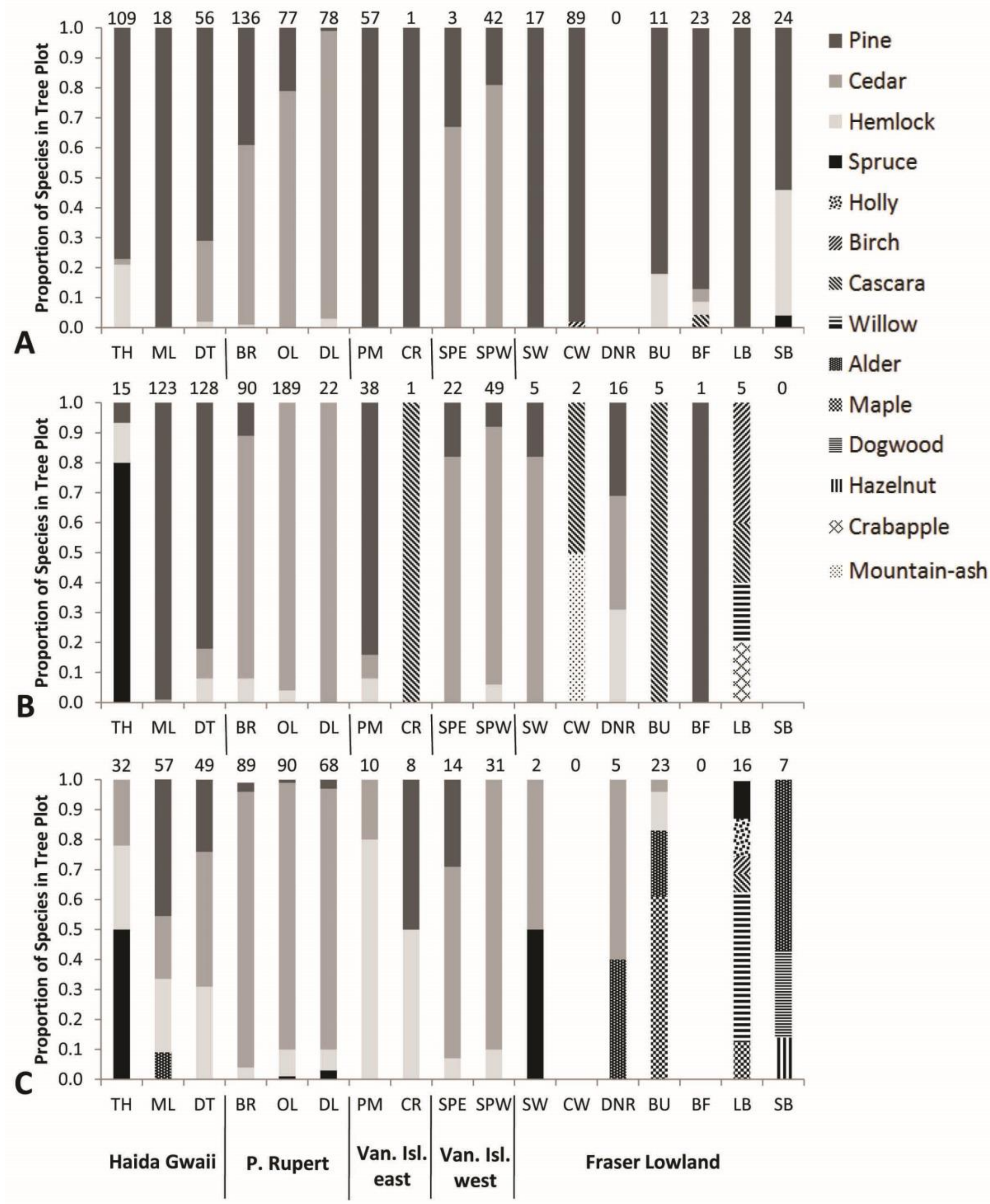

Figure 29. ***Proportion of tree and tall shrub species in the tree plots at: a) BG sites, b) LG sites, and c) MN sites on each transect, grouped by region. Sites with no data contained no trees taller than 20 cm. Numbers above bars represent the sample size (n) for each plot.***

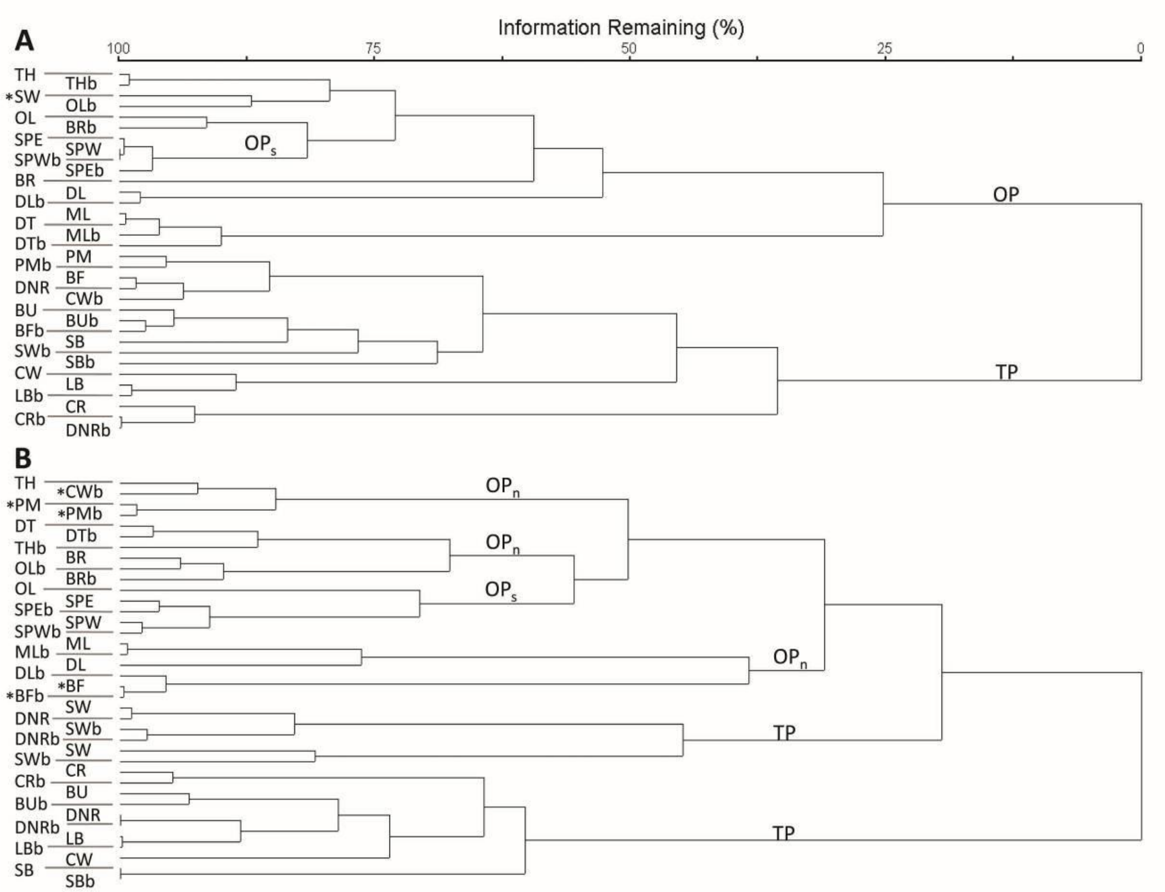

Figure 30. ***Dendrogram from hierarchical agglomerative cluster analysis showing regional clustering of vegetation in: a) BG plots and b) LG plots. OP_n = Pacific Oceanic wetland region, North Coast subregion; OP_s = Pacific Oceanic wetland region, South Coast subregion; TP = Pacific Temperate wetland region. "*" represents outliers that were classified in the wrong wetland region.***

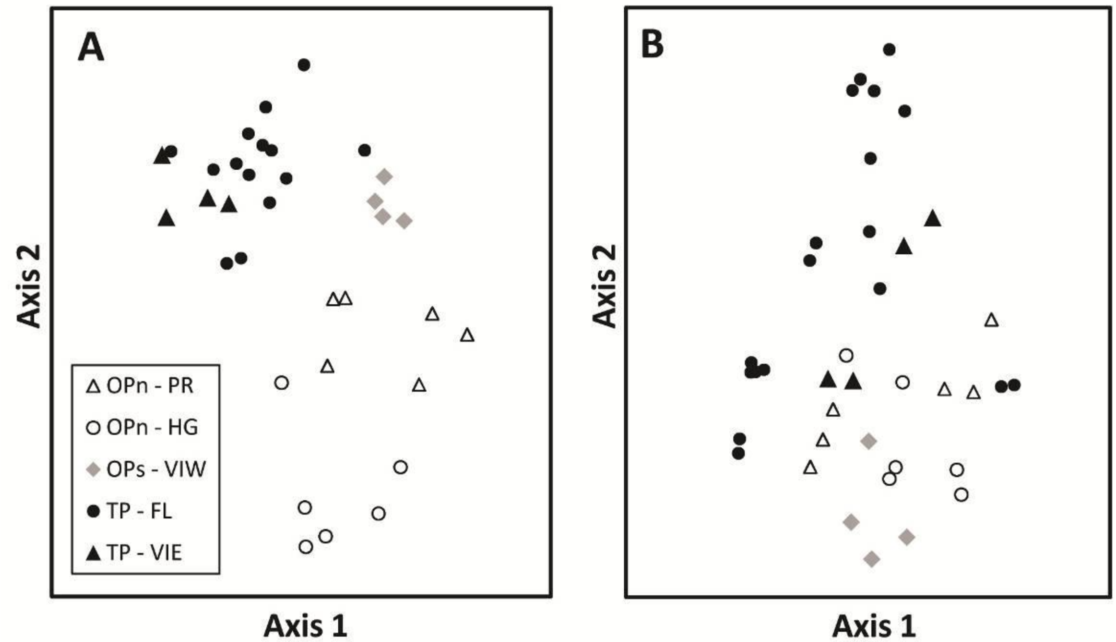

Figure 31. ***NMS ordination showing regional clustering of vegetation in a) BG plots and b) LG plots. OPn = Pacific Oceanic wetland region, North Coast subregion; OPs = Pacific Oceanic wetland region, South Coast subregion; TP = Pacific Temperate wetland region; PR = Prince Rupert area; HG = Haida Gwaii; VIW = west side of Vancouver Island; VIE = east side of Vancouver Island; FL = Fraser Lowland.***

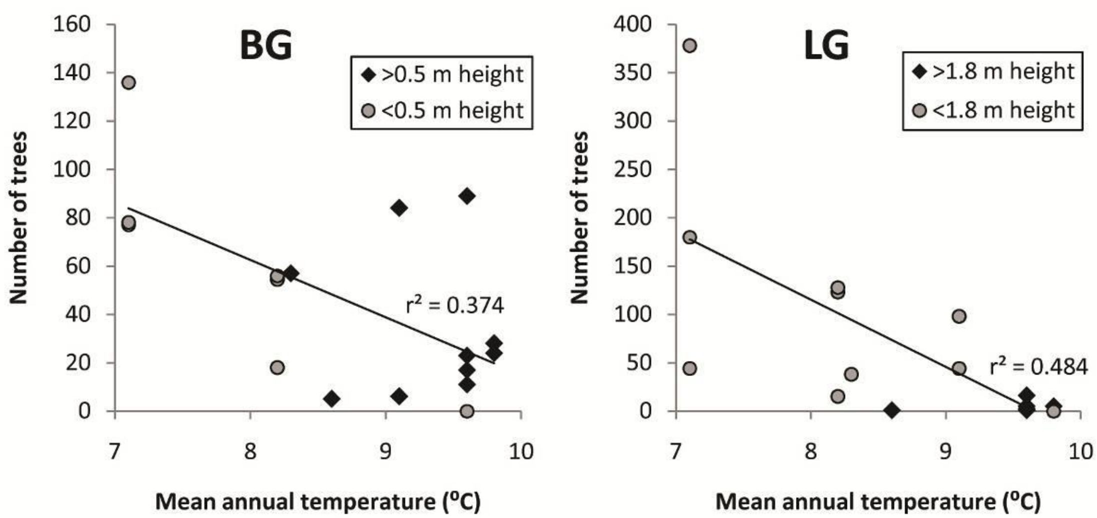

Figure 32. ***Correlations between mean annual temperature and the number of trees in BG and LG tree plots. Black diamonds represent trees that are taller than 0.5 m and 0.8 m for the BG and LG tree plots, respectively; grey circles represent trees that are shorter.***

Table 16. ***Braun-Blanquet cover values ("0" = not present in plot; "r"=solitary with small cover, "+"=few with small cover, "1"=numerous but <5% cover, "2"=5-25% cover, "3"=25-50%, "4"=50-75%, "5"= >75%) on the main (first value) and parallel (second value) vegetation plots for each study site. See Table 15 for site codes. Only those species that were found with Braun-Blanquet cover ≥2 in at least 3 bogs are included.***

	Haida Gwaii			Prince Rupert			Van. Isl. East		Van. Isl. West		Fraser Lowland						
BG plots	**TH**	**ML**	**DT**	**BR**	**OL**	**DL**	**PM**	**CR**	**SPE**	**SPW**	**SW**	**CW**	**DNR**	**BU**	**BF**	**LB**	**SB**
Cladina portentosa	1,1	0,+	+,+	5,3	1,1	2,2	+,+	0,0	1,2	0,0	2,4	0,1	1,0	0,0	0,+	0,0	0,0
Empetrum nigrum	+,+	1,+	1,3	3,2	1,2	+,2	0,0	0,0	1,1	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Juniperus communis	1,1	2,2	3,2	2,1	1,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Kalmia microphylla	0,+	1,1	1,1	2,2	1,1	1,1	2,1	0,0	1,+	2,2	2,2	2,0	2,0	3,3	2,3	2,2	0,0
Ledum groenlandicum	+,+	+,+	0,2	2,2	1,1	1,2	4,5	3,5	1,0	1,1	+,4	3,5	5,5	4,5	5,5	2,2	5,3
Pinus contorta v. contorta	+,1	+,+	+,3	2,2	+,+	0,+	2,2	2,0	2,2	2,2	+,3	2,1	0,0	2,4	3	2,2	4,2
Rhynchospora alba	0,0	0,0	0,0	0,0	2,2	+,1	0,0	0,0	0,0	0,0	2,1	2,0	0,0	0,0	0,0	2,3	0,0
Rubus chamaemorus	+,+	r,+	2,2	1,3	0,2	2,2	+,1	0,0	0,0	0,0	0,1	0,0	0,0	0,0	+,1	0,0	0,0
Sphagnum austinii	3,2	5,4	5,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Sphagnum capillifolium	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,3	3,3	2,2	3,2	0,0	3,3	2,2	0,0	3,3
Sphagnum fuscum	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,2	0,0	0,0	0,3	3,3	0,0
Sphagnum magellanicum	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,3	2,3	3,3	0,0
Sphagnum pacificum	0,0	0,0	0,0	0,0	0,0	0,0	5,4	0,0	0,0	0,0	0,0	3,2	0,0	0,0	2,3	3,3	0,0
Sphagnum papillosum	0,0	0,0	0,0	4,3	4,0	2,0	0,0	0,0	3,3	3,3	0,0	0,2	0,0	0,0	0,0	0,0	0,0
Vaccinium oxycoccos	+,+	0,0	1,+	0,0	+,+	0,0	0,0	0,0	+,+	1,0	+,1	2,3	0,0	2,2	2,2	2,2	1,+
Vaccinium uliginosum	+,+	+,0	1,1	0,0	0,+	0,0	0,0	5,5	r,1	0,0	3,3	2,0	2,5	0,0	0,0	2,3	1,0
LG plots	**TH**	**ML**	**DT**	**BR**	**OL**	**DL**	**PM**	**CR**	**SPE**	**SPW**	**SW**	**CW**	**DNR**	**BU**	**BF**	**LB**	**SB**
Carex sitchensis	1,1	4,5	0,0	0,0	0,0	2,5	0,0	5,4	0,0	0,0	0,0	0,0	0,0	0,0	2,0	0,0	0,1
Chamaecyparis nootkatensis	0,0	0,0	3,4	3,4	0,2	0,0	0,0	0,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Empetrum nigrum	1,5	3,2	3,4	0,1	1,0	0,1	0,0	0,0	1,+	2,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Fauria crista-galli	0,0	0,0	+,+	0,2	1,2	2,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Gaultheria shallon	3,2	0,0	2,2	4,3	1,3	1,1	3,5	0,2	+,1	1,2	4,4	2,2	0,0	4,3	0,0	0,0	0,0

	Haida Gwaii			Prince Rupert			Van. Isl. East		Van. Isl. West		Fraser Lowland						
Kalmia microphylla	0,0	1,+	1,1	0,+	1,0	0,0	0,1	0,0	+,2	1,2	0,0	0,0	0,0	0,0	1,2	0,0	0,0
Ledum groenlandicum	3,2	1,2	2,4	2,2	2,0	1,0	4,5	2,2	+,1	1,2	0,0	4,5	0,0	0,0	2,3	0,0	0,0
Lysichiton americanum	0,0	0,0	0,0	0,0	0,0	2,2	1,r	0,0	0,0	1,2	0,0	0,0	0,0	2,2	0,0	+,0	0,0
Myrica gale	0,0	0,0	0,0	0,0	2,0	5,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	5,5	0,0	0,0
Pinus contorta v. contorta	0,0	4,3	4,4	4,0	0,4	0,0	1,1	0,0	2,0	0,2	0,0	0,0	0,0	0,0	0,r	0,0	0,0
Sphagnum pacificum	0,0	2,3	0,0	0,0	0,0	0,0	4,4	0,0	3,3	2,3	0,0	0,0	0,0	0,0	2,0	0,0	0,2
Sphagnum papillosum	0,0	0,0	0,0	2,1	0,0	3,1	0,0	0,0	3,3	2,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Spiraea douglasii	0,0	0,0	0,0	0,0	0,0	0,0	0,0	5,5	0,0	0,0	0,0	5,2	5,5	5,3	0,0	5,5	5,5
Thuja plicata	0,0	0,0	0,0	3,0	1,2	2,1	1,0	0,0	2,0	3,4	3,3	0,0	0,0	0,2	0,0	0,0	0,0
MN plots	**TH**	**ML**	**DT**	**BR**	**OL**	**DL**	**PM**	**CR**	**SPE**	**SPW**	**SW**	**CW**	**DNR**	**BU**	**BF**	**LB**	**SB**
Chamaecyparis nootkatensis	1,2	2,0	3,4	3,2	5,3	0,0	0,0	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Gaultheria shallon	5,5	5,+	5,5	2,3	2,4	2,3	4,5	4,4	2,2	3,3	0,0	0,0	0,0	0,0	0,0	3,3	0,0
Hylocomium splendens	1,1	2,1	2,2	0,0	0,2	0,0	1,1	0,0	0,1	1,3	0,0	0,0	0,0	1,1	0,0	0,1	0,0
Kindbergia oregana	0,0	2,1	2,2	2,2	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Ledum groenlandicum	0,0	0,0	1,0	0,3	2,0	0,0	0,1	0,0	1,2	2,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Maianthemum dilatatum	+,+	0,0	0,0	+,+	0,0	0,0	0,0	0,0	1,+	+,+	5,4	0,0	0,0	0,1	0,0	5,0	3,2
Menziesia ferruginea	0,0	0,0	0,0	2,1	2,2	1,1	1,2	0,0	0,2	2,2	5,3	0,0	0,0	2,2	0,0	0,0	0,0
Picea sitchensis	4,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,5	0,0	0,0	0,0	0,0	3,3	0,0
Pinus contorta v. contorta	0,0	2,0	3,2	0,0	+,0	2,0	0,3	2,2	3,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Pleurozium schreberi	0,0	0,0	0,0	2,2	2,2	0,0	1,2	0,0	1,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Rubus spectabilis	0,0	0,0	0,0	0,0	0,0	2,0	0,0	5,3	0,0	0,0	0,0	0,0	0,3	2,2	0,0	2,2	5,5
Thuja plicata	0,0	0,0	0,0	3,2	1,1	5,5	4,1	0,0	4,4	5,5	5,0	0,0	2,0	2,4	0,0	0,0	0,0
Tsuga heterophylla	2,0	0,0	0,0	2,0	1,1	+,3	5,3	2,0	0,0	2,2	0,0	0,0	0,0	2,4	0,0	0,0	0,0
Tsuga mertensiana	0,0	4,5	2,4	0,0	0,1	0,0	0,0	0,0	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Vaccinium parvifolium	0,0	1,0	2,2	2,0	0,0	0,1	2,2	1,4	0,0	0,0	3,2	0,0	0,0	2,3	0,0	0,2	0,0

Table 17. Presence (✓) of the most commonly occurring Sphagnum species in the BG plots (white rows) and LG plots (grey rows) for each studied bog. See Table 15 for site codes. Samples identified by Karen Golinski; "✓♦" indicates samples that were tentatively identified by S. Howie and are not confirmed.

		S. angustifolium	*S. austinii*	*S. capillifolium*	*S. fuscum*	*S. lindbergii*	*S. magellanicum*	*S. mendocinum*	*S. pacificum*	*S. palustre*	*S. papillosum*	*S. quinquefarium*	*S. rubellum*	*S. tenellum*
Haida Gwaii	TH		✓♦											
	ML		✓											
					✓				✓					
	DT		✓♦										✓	
			✓♦											
Prince Rupert	BR										✓♦			
											✓♦			
	OL										✓♦	✓		✓♦
		✓												
	DL									✓♦	✓			
											✓♦			
Van. Island East	PM					✓			✓					
									✓					
	CR							✓						
Van. Island West	SPE			✓							✓			
									✓		✓			
	SPW			✓							✓			
		✓							✓		✓		✓	
Fraser Lowland	SW			✓										✓
	CW			✓	✓				✓		✓			
				✓						✓				
	DNR													
	BU			✓			✓							
	BF	✓		✓	✓		✓		✓					
				✓			✓		✓					
	LB				✓		✓		✓					
								✓	✓					
	SB	✓		✓										
								✓						

LG Plots

Species richness in the LG plots was significantly higher in the Pacific Oceanic wetland region (mean: 14.6 species) than the Pacific Temperate wetland region (mean: 8.3 species) (Table 15). The Shannon and Simpson diversity indices were both also significantly higher for the LG plots in the Pacific Oceanic wetland region; there was no significant difference in evenness between the two wetland regions (Table 15). The most common understory species in the LG plots were *Gaultheria shallon* and *Ledum groenlandicum* (Table 16). However, *Spiraea douglasii* was the dominant lagg species in the Fraser Lowland bogs. The LG plots contained fewer *Sphagnum* species than the BG plots, and 14 out of 38 LG sites contained no *Sphagnum* at all (Table 17). The most common *Sphagnum* species in the LG plots were *S. pacificum* and *S. papillosum*. Regional differences in *Sphagnum* species were less clear in the LG plots than in the BG plots. For example, cover of *S. pacificum* in LG plots was not significantly different between the Pacific Oceanic and Pacific Temperate wetland regions, but cover of *S. papillosum* was significantly higher in LG plots of the Pacific Oceanic wetland region than in the LG plots of the Pacific Temperate wetland region (Table 16).

Regional patterns in tree species were also not as clear for the LG plots as for the BG plots. Similar to the BG plots, cedar was dominant in the Prince Rupert and western Vancouver Island LG plots (Fig. 29b). Half of the Fraser Lowland LG plots contained only deciduous trees, as did the LG plots of Campbell River bog. The lagg sites with deciduous trees are all located in the Pacific Temperate wetland region, which is relatively warm (mean annual temperature: 9.6 ^{0}C) and experiences relatively low rainfall (mean annual precipitation: 1044 mm). The laggs that are dominated by coniferous trees are located in the Pacific Oceanic wetland region, which is cooler (mean annual temperature: 8.2 ^{0}C) and experiences more rainfall (mean annual precipitation: 2117 mm) (NWWG, 1988). The number of trees in the BG and LG plots was significantly lower for the warmer sites (Fig. 32); the BG and LG plots of the northern bogs (cooler, wetter climate) in particular contained a significantly larger number of small trees (<0.5 m and <1.8 m for the BG and LG plots, respectively) compared to the southern bogs. Basal area, however, was not significantly correlated with either precipitation or temperature, and was not significantly different between the Pacific Oceanic and Pacific Temperate wetland regions for either the BG or LG plots.

Cluster analysis for the LG plots showed that the lagg plant communities were generally divided into the Pacific Oceanic and Pacific Temperate wetland regions, with the exception of: i) Port McNeill Bog, which is located near the boundary of the two wetland regions, ii) the BF transect of Blaney Bog, which was different from most of the other studied transects in that the MN site was a fen creek instead of a forest, and iii) the parallel LG plot of the CW transect, which is considered an outlier (Fig. 30b). Using NMS ordination, we found that plant species composition in LG plots was generally separated into the two main wetland regions, and that the South Coast region of the Pacific Oceanic wetland region formed a distinct cluster, but that unlike the results for the BG sites, the plant communities of the LG sites did not separate well into the different geographic areas (i.e. Prince Rupert, Haida Gwaii, Vancouver Island, Fraser Lowland) (Fig. 31b).

CCA results showed that latitude, mean annual precipitation, and mean annual temperature were correlated with one another, which resulted in all of these parameters being well correlated with Axis 1 and not to the other two Axes. However, Axis 1 explained only 6.6% of species variance, Axis 2 explained 4.9%, and Axis 3 explained 3.5%. Thus, climate explains some of the regional differences in lagg species composition, but does not appear to be the main factor.

MN Plots

Similar to the other locations on the transect, the number of species in the MN plots was significantly higher in the Pacific Oceanic wetland region (mean: 14.8 species) than the Pacific Temperate wetland region (mean: 9.9 species). The Shannon diversity index was significantly higher in the MN plots of the Pacific Oceanic wetland region (mean: 1.9) than the Pacific Temperate wetland region (mean: 1.5) as well, but there was no significant difference in evenness (mean for both the Pacific Oceanic wetland region and the Pacific Temperate wetland region: 0.7) or the Simpson diversity index (mean for the Pacific Oceanic wetland region: 0.8; mean for the Pacific Temperate wetland region: 0.7) for the two wetland regions. The most frequently occurring understory species in the MN plots were: *Gaultheria shallon*, *Vaccinium parvifolium*, *Rubus spectabilis*, and *Menziesia ferruginea* (Table 16). The tree plots at the MN sites displayed a similar pattern in tree species variation as the LG plots. The MN sites in the

Prince Rupert area and on western Vancouver Island were dominated by cedar; the Fraser Lowland MN sites were dominated by deciduous trees (Fig. 29c). Cascara and birch were less common in the MN sites (mean proportion of cascara and birch in MN tree plots: 0.00 and 0.00, respectively) than in the LG sites (mean proportion of cascara and birch in LG tree plots: 0.15 and 0.02, respectively). The MN site on the SW transect in Burns Bog contained a non-native tree species, English holly (*Ilex aquifolium*).

6.4.3. The Influence of Depth to Water Table and Hydrochemistry on Plant Species Composition

Plant species composition in peatlands is strongly related to depth to water table when the water table is located within the rooting zone (50-60 cm below surface) (Jeglum, 1971; Egglesman et al., 1993). We expected to find a relation between depth to water table and cover of *Sphagnum* because survival of this genus is closely tied to depth to water table and pore-water pressure (Price et al., 2003). As expected, extensive cover (Braun-Blanquet cover: ≥3) of *Sphagnum* was only found in plots with a June/July water table depth within 50 cm of the surface (Fig. 33). Some species appear to depend more on a high water table than others; for example, *S. capillifolium* was only found in sites with a June/July water table within 25 cm of the surface. *Vaccinium uliginosum* had a low cover (Braun-Blanquet cover: ≤1) in sites with a June/July water table more than 20 cm below the surface. Other frequently occurring species (e.g. *Pinus contorta* var. *contorta*, *Ledum groenlandicum*, *Carex* spp.) appeared to be limited to sites with a June/July water table within 40-50 cm of the surface. A high cover of *Gaultheria shallon* (Braun-Blanquet cover: ≥3) was only found in plots with a depth to water table >18 cm below the surface in June/July (Fig. 33).

Species diversity is also related to hydrochemistry in the rooting zone. Nelson et al. (2011) found higher species diversity at sites with higher cation concentrations and lower acidity. The Haida Gwaii bogs, which had the highest species richness, were characterized by higher concentrations of Mg^{2+} and Na^{+} than the other bogs (Fig. 34e,h). Both Prince Rupert and Haida Gwaii bogs had a higher pH (>4.2) than the more southern bogs (<4.3) (Chapter 5), which had a lower species richness. The positive linear correlations between the number of vascular plant species in the BG plots and both pH (r^2=0.681) and Na^{+} concentrations (r^2=0.298) in pore-water were significant (Fig.

34a,d). The linear correlation between number of vascular species and pH was strongest for the BG plots and generally decreased across the transect from bog to forest: for R1, r^2=0.335; for R2, r^2=0.242; for LG, r^2=0.042) and for MN, r^2=0.163 and were only significant for the BG and R1 sites. The correlation between number of vascular plant species and Na^+ concentration was only significant for the studied BG plots. The Na^+ concentration differed between the Pacific Oceanic and Pacific Temperate wetland region; this clustering influenced the regressions (Fig. 34d,e).

We tested the correlation between pH and the percent cover of the most frequently occurring species in our study sites (*Sphagnum capillifolium*, *Ledum groenlandicum*, *Vaccinium uliginosum*, *Gaultheria shallon*, *Pinus contorta* var. *contorta*, *Carex* spp., and *Spiraea douglasii*), but found no significant positive or negative correlation with pH. *Sphagnum* species overall covered a relatively large pH range (3.8-6.3). Three species were found within a more limited pH range: *Sphagnum capillifolium* (pH 3.8-4.7), *Sphagnum fuscum* (pH 4.0-4.5), and *Vaccinium uliginosum* (pH 3.8-4.6) (Fig. 35). Cover of *Ledum groenlandicum* was highest (Braun-Blanquet cover ≥3) in the pH 3.5-5.5 range.

There was no significant correlation between *Sphagnum* cover and any of the other hydrochemical parameters. There was a significant negative correlation between cover of *Ledum groenlandicum* and both Mg^{2+} (r_s = -0.581) and Na^+ = (r_s = -0.676) concentrations for the BG sites, but not for the other locations on the transects. However, this correlation is influenced by thegeographic differences in Mg^{2+} and Na^+ concentrations. The highest concentrations of these ions were found in the Haida Gwaii bogs (Fig. 34); the northern bogs also had a lower cover of *Ledum groenlandicum* compared to the southern bogs (Table 16).

In the CCA analysis for the BG plots using the hydrochemical parameters, depth to water table, and peat depth, Axis 1 (correlated with pH (r^2 = 0.629) and Na^+ concentrations (r^2 = 0.560)) explained 14.4% of species variance. Axis 2 (correlated with pH (r^2 = -0.560) and peat depth (r^2 = 0.578)) explained 10.4%, and Axis 3 (correlated with depth to water table (r^2 = -0.830)) explained 8.5% of species variance in the BG sites. For the LG plot, Axis 1 explained 9.6% of species variance and was most strongly correlated with peat depth (r^2 = 0.614), but also with most of the hydrochemical parameters; the strongest hydrochemical correlations with Axis 1 were for Mg^{2+} concentrations (r^2 = 0.479) and pH (r^2 = -0.479). Axis 2 explained 7.9% of species variance and was correlated most with depth to water table (r^2 = 0.639) and Ca^{2+} concentrations (r^2 = 0.610). Axis 3 explained 7.6% and was not strongly correlated with any of the tested parameters.

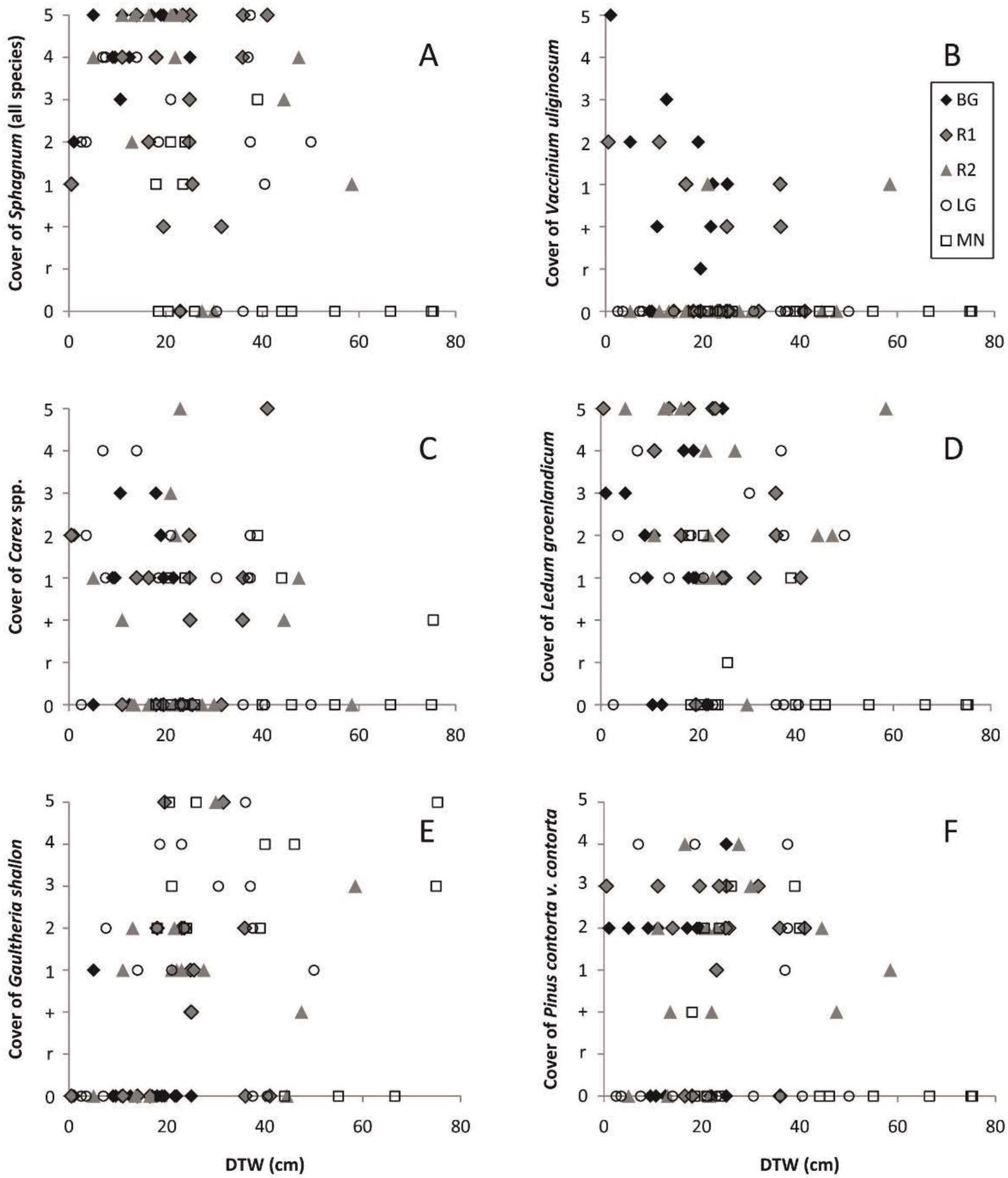

Figure 33. ***Relation between depth to water table (DTW) measured in June/July and Braun-Blanquet cover values for: a) Sphagnum spp., b) Vaccinium uliginosum, c) Carex spp., d) Ledum groenlandicum, e) Gaultheria shallon, and f) Pinus contorta var. contorta. A value of "0" means that the species was not present in the plot.***

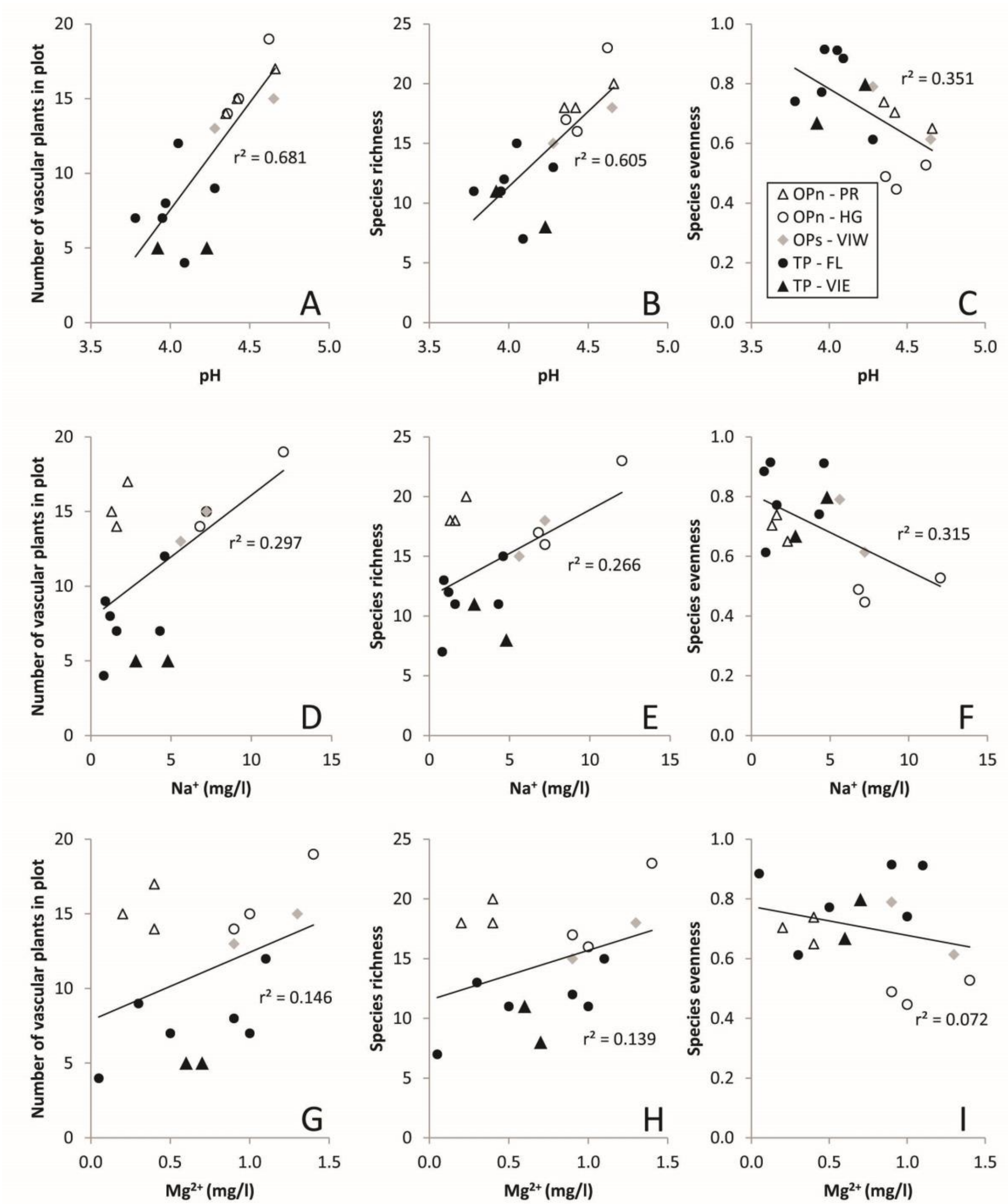

Figure 34. ***Correlations between the number of vascular plant species, species richness, and species evenness in BG plots and pH, Na^+, and Mg^{2+} concentrations in pore-water. OPn = Pacific Oceanic wetland region, North Coast subregion; OPs = Pacific Oceanic wetland region, South Coast subregion; TP = Pacific Temperate wetland region; PR = Prince Rupert area; HG = Haida Gwaii; VIW = west side of Vancouver Island; VIE = east side of Vancouver Island; FL = Fraser Lowland.***

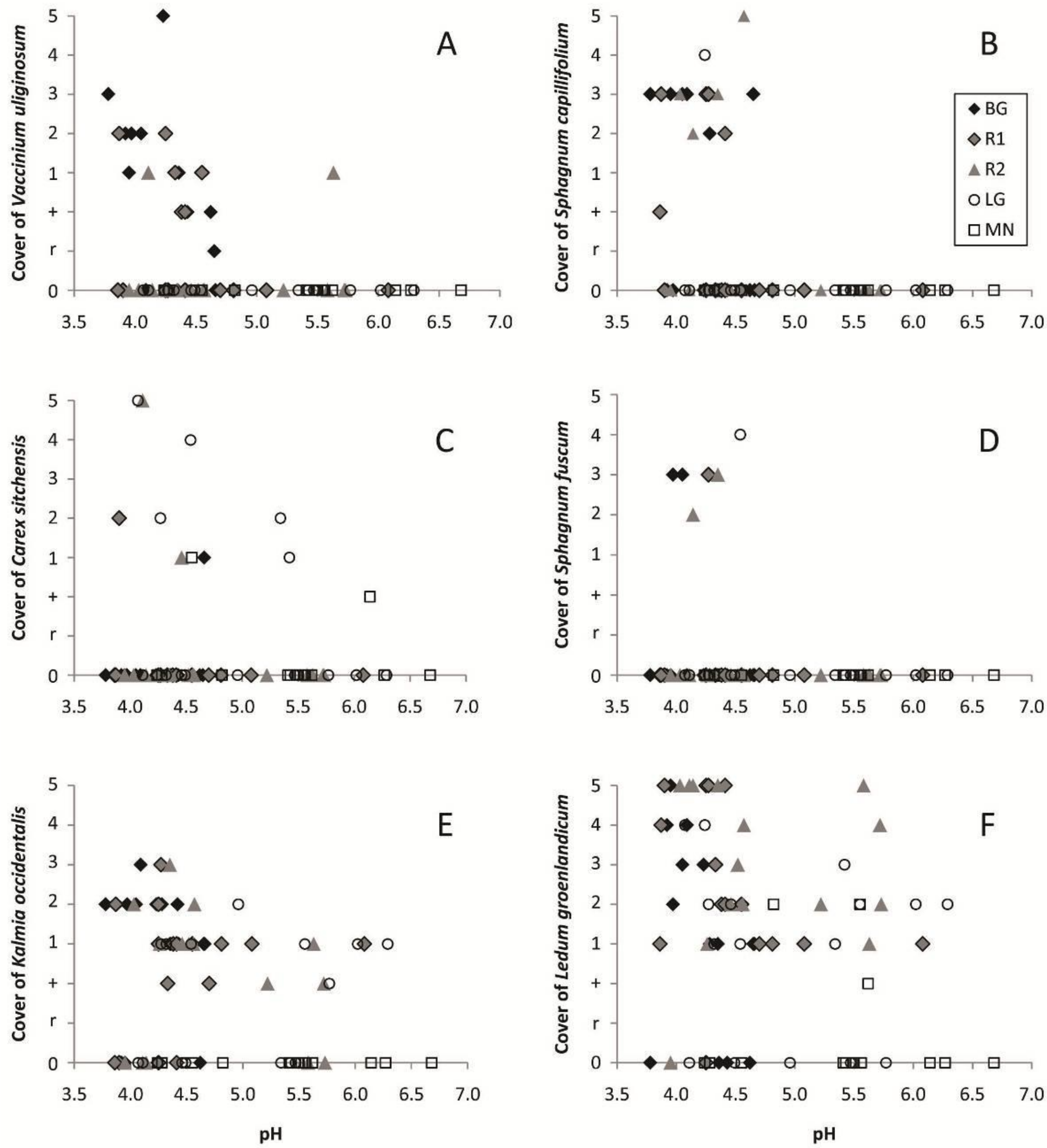

Figure 35. ***Relation between pH and Braun-Blanquet cover values for: a) Vaccinium uliginosum, b) Sphagnum capillifolium, c) Carex sitchensis, d) Sphagnum fuscum, e) Kalmia occidentalis, and f) Ledum groenlandicum. A value of "0" means that the species was not present in the plot.***

6.5. Discussion

6.5.1. Regional Variability

Bogs

The goal of this study was to determine whether regional patterns exist in bog and lagg plant communities on the west coast of British Columbia, and if so, to determine the factors involved. Species richness in BG plots was significantly higher in the Pacific Oceanic wetland region than in the Pacific Temperate wetland region. This may partly be due to these bogs being less disturbed than the studied bogs in the Pacific Temperate wetland region, but may in part be due to differences in climate, peat properties, and the geomorphology of the surrounding area.

Regional patterns in plant species composition and abundance are related to climate (Purves et al., 1992), specifically annual rainfall, precipitation intensity, amount of rainfall in the growing season, length of the summer drought period, and precipitation chemistry (Jeglum, 1971; Ivanov, 1981; Wheeler and Shaw, 1995). Temperature is also an important factor because evapotranspiration lowers the water table during long periods without rain (Price et al., 2003; Waddington et al., 2009). We found that the relative abundance of plant species in the different plant communities in BG plots could be grouped into the two studied wetland regions: Pacific Oceanic (cooler, wetter climate) and Pacific Temperate (warmer, drier climate) (Figs. 30a, 31a). In a study of peatlands on Vancouver Island, Golinski (2004) similarly found that bog plant communities fit into these two regional categories. She also found that bog species composition on the outer west coast of Vancouver Island (South Coast subregion of the Pacific Oceanic wetland region) was different from the northern bogs (North Coast subregion of the Pacific Oceanic wetland region). The cluster analysis (Fig. 30a) and the NMS ordination (Fig. 31a) results showed that the BG plots in Shorepine Bog (our only study site in the South Coast subregion) were more similar to each other than to the plant communities in the other bogs. Species distribution may also be related to regional differences in precipitation chemistry; we found differences in pore-water pH and Na^+ concentrations between the Pacific Oceanic and Pacific Temperate wetland regions. The number of vascular plant species was correlated with pH and Na^+ concentrations (Fig. 34).

British Columbia is divided into fourteen biogeoclimatic zones, each of which has a unique climax plant community; these zones are essentially determined by various combinations of temperature, rainfall, elevation, and degree of continentality (Meidinger and Pojar, 1991). Generally, in coastal BC, the elevation at which a given species or plant community occurs decreases as one moves north (Pojar and MacKinnon, 1994). This may explain why certain species in our study were not found at all latitudes, since all of our study sites are located at a low elevation (<100 m). For example, *Cladonia* spp. and *Vaccinium myrtilloides* were only found in the southern bogs (<50.4 ^{0}N). *Dodecatheon jefferi* spp. *jefferi* was only found at Tow Hill Bog, *Coptis trifolia* and *Drosera anglica* were only found at Diana Lake Bog, and *Gentiana sceptrum* was found only at Shorepine Bog. However, our species lists from the 5 x 5 m vegetation plots were obviously not exhaustive of all species in the bogs and these species may have been present elsewhere as well. Species distribution in the region is also related to historic factors such as presence or absence of glaciation; for example, *Spiraea douglasii* is mostly absent from Haida Gwaii (Ricklefs and Schluter, 1993).

The dominance of cedar trees (*Thuja plicata* and *Chamaecyparis nootkatensis*) in the Prince Rupert and western Vancouver island sites suggests that soil moisture conditions are more suitable for these species than for *Pinus contorta* var. *contorta*, which was the dominant bog tree in the other study areas (Fig. 29a). Klinka et al. (1998) reported that cedar trees in coastal BC are more tolerant of the wettest soil conditions than *Pinus contorta* var. *contorta*. Malmer (1986) notes that oceanic bogs tend to have higher rainfall and shorter drought periods, resulting in a more stable and higher water table, compared to continental bogs and, therefore, that regional patterns in peatland plant communities are more likely caused by variation in hydrology than by differences in the chemical composition of atmospheric inputs. Although less pronounced than the oceanic-continental precipitation gradient, this same pattern in precipitation is evident in coastal BC, as reflected by the wide range in mean annual precipitation (<1000 to >5000 mm/year) (Pojar and MacKinnon, 1994). While there was no significant difference in early summer depth to water table between the BG sites in the different geographic areas of our study, there were clear differences in plant communities. This suggests that seasonal precipitation patterns and related differences in depth to water table, temperature, or hydrochemistry also influence regional species variability; the CCA results support this inference. Based on the CCA results, it appears that bog and lagg species distribution is determined by a combination of interrelated factors (latitude, climate, and hydrochemistry) at both the regional and local scale

The bogs in this study were located either above 53.3 ^{0}N or below 50.4^{0}N, with no study sites in between. Therefore, it is difficult to determine whether the regional patterns in plant species composition represent a gradient (with some species gradually becoming more abundant and others less abundant with increasing latitude, mean annual precipitation, or mean annual temperature), or whether some species are limited to certain regions. Further study in bogs at intermediate latitudes is recommended in order to answer this question.

A number of indicator species have been established for coastal BC bogs on the basis of depth to water table and nutrient status: *Andromeda polifolia*, *Carex* spp., *Drosera rotundifolia*, *Eriophorum angustifolium*, *Fauria crista-galli*, *Kalmia occidentalis*, *Ledum groenlandicum*, *Rhynchospora alba*, *Sphagnum* spp., and *Vaccinium oxycoccos* (Klinka et al., 1989; Pojar and MacKinnon, 1994; MacKenzie and Moran, 2004), although some of these species also occur in poor fens and wet meadows in this region. These bog indicator species were all found in at least three bogs (and up to 17 bogs) of this study. With the exception of *Carex* spp., these species were generally found in greatest abundance in our BG plots (pH 3.78-4.66), and became less common across the transition from bog to forest, as pH generally increased and the water table usually declined across this transition (Howie and van Meerveld, 2012; Chapter 5). In addition, there appear to be bog indicator species that are specific to the various geographic regions (Prince Rupert, Haida Gwaii, Vancouver Island east and west, and the Fraser Lowland). *Fauria crista-galli* was only found in the northern bogs. *Carex* spp. were present in BG plots of the northern bogs and Vancouver Island bogs, but only in or near the LG plots of the Fraser Lowland bogs. *Vaccinium oxycoccos* and *Rhynchospora alba* were most abundant in the Fraser Lowland bogs, and generally had a lower cover in the other sites.

Laggs

The lagg plant communities in our study also displayed regional patterns. Overall, species richness was lowest in the LG plots compared to the other transect locations; Shannon and Simpson diversity were lowest in the LG plots of the bogs in the Pacific Temperate wetland region, but not the Pacific Oceanic wetland region. The LG plots in the Pacific Temperate wetland region were often dominated by only a few species. *Spiraea douglasii* was the dominant lagg species in the Fraser Lowland bogs and Campbell River bog (Pacific Temperate wetland region), along with *Rhamnus purshiana* and *Salix sitchensis*. In the Pacific Oceanic wetland region, there was either no vegetative ecotone to indicate a lagg, or the lagg was dominated by *Myrica gale*, *Carex sitchensis*, and *Lysichiton americanum*. Regional grouping of plant communities in LG plots was less clear than for the BG plots (Figs. 30b, 31b). Climate explained 18% of species variance in BG plots, but less than 7% of species variance in LG plots. Thus, the regional differences in lagg species may be less dependent on climate than bog plant species composition, and more related to bog form, topography, and substrate in the lagg.

Water chemistry in the lagg, as well as the proportion of bog water, depends on the degree of mixing of water from the bog and the surrounding areas. The bogs in the Fraser Lowland are relatively large, domed bogs that have developed over river sediments. Since the dome of these bogs tends to be higher in elevation than the surrounding land, a topographic depression is present at the bog margins. These topographic depressions on relatively impermeable silty deposits cause ponding of water, so that the water table is at or above the surface during the wet season and lower during summer drought periods (Howie et al., 2009a; Howie and van Meerveld, 2012). The greater amplitude in water table fluctuation (Chapter 3), as well as the higher sediment content of the lagg peat (Chapter 5), likely promotes the establishment of swamp species such as *Spiraea douglasii*, which was found in 50% of the LG sites in the Fraser Lowland with a Braun-Blanquet cover of 5. However, these measured site-level properties (depth to water table in June/July, hydrochemistry, and peat depth) explained more of the species variance in the BG plots (33%) than in the LG plots (25%), so the variation in lagg plant communities is likely also affected by other factors that were not included in this study. For example, nutrient concentrations and nutrient fluxes in the peat and pore-water were not studied. The availability of nutrients is related to both the concentration of the nutrients in water and the rate at which the water moves through the site, whereby faster-moving water delivers more nutrients per unit time than slowermoving water with the same nutrient concentrations. *Myrica gale*, for example, is strongly flux-related (R. Hebda, personal communication) and was found in this study on relatively steep slopes and near flowing water. Furthermore, only the depth to water table in June/July was studied, not the depth of the water table at the end of the dry season.

The northern bogs have generally developed over bedrock. Although these bogs initially form in topographic depressions, the high annual rainfall contributes to a high water table in these bogs, which allows them to grow out from the depressions and expand into surrounding areas. Due to the variable topography of these sites and the often flat bog surface, topographic depressions at the bog margin are uncommon, and a complete lagg ecotone around the entire bog perimeter is rare (Allan Banner, personal communication). The expansion of bogs out of depressions and onto slopes in this wet climate often results in the formation of “bog forest” environments, where peaty, near-ombrotrophic conditions are present in the forest (Banner, 1986). These low-nutrient conditions allow bog species to extend into adjacent forested areas, and thus the “true lagg” ecotone seen in the Fraser Lowland is rare for these northern bogs. The Beta Diversity analysis confirmed this and showed that all vegetation plots on the transects in the Pacific Oceanic bogs had at least one species in common with the BG plots, whereas about half of the LG and MN plots in the Pacific Temperate bogs shared no species with the BG plots.

6.5.2. Local Variability

At the site level, the composition and relative abundance of plant species are correlated with environmental gradients, particularly the soil moisture regime and peat/pore-water chemistry. We found that some species were present only within relatively narrow ranges in depth to water table (e.g. *Sphagnum capillifolium*, *Vaccinium uliginosum*), but our CCA results showed that depth to water table only explained a small part (<10%) of species variance in both the bog and lagg. However, Asada et al. (2003) reported that the lowest groundwater level was most strongly related to the bog – upland plant community gradient at Diana Lake Bog. In this study, the depth to water table was measured in June/July; if measured in late summer, which is the typically the time with the lowest water table in this region (Howie and van Meerveld, 2012), the differences in depth to water table between the studied bogs might be more pronounced and more strongly correlated with species distribution.

At sites with a permanent high water table, water chemistry can exhibit a strong control over species composition (Wierda et al., 1997). Jeglum (1971) developed a list of indicator species for Saskatchewan peatlands based on their affinity for various classes of surface water and near-surface peat pH, fertility, and depth to water table. The pH/fertility classes were: very oligotrophic (pH 3.0-3.9), oligotrophic (4.0-4.9), mesotrophic (5.0-5.9), eutrophic (6.0-6.9), and very eutrophic (7.0-7.9). A classification was also developed for depth to water table (moisture class): >80 cm (very moist), 60-79 cm, 40-59 cm (wet), 20-39 cm, 0-19 cm (surface water level), (-1)-(-19) cm, (-20)-(-39) cm (shallow water depth), (-40)-(-59) cm, and >-60 cm (medium water depth) (Jeglum, 1971). For both classifications, Jeglum (1971) found that many species fell within a certain range of pH and depth to water table. For example, *Ledum groenlandicum* was most abundant in pH class “3.0-3.9”, and depth to water table class “60-79 cm”. In a similar study, Bragazza et al (2005) found a correlation between plant community distribution (e.g. hummocks, lawns, carpets, and minerotrophic sites) and both pH and depth to water table in an Italian and Swedish bog. Riley (2011) observed that a number of bog species in the Hudson Bay lowlands occurred within ‘optimal’ pH ranges (e.g. *Rubus chamaemorus*, *Eriophorum spissum*, *Kalmia angustifolia*, *Cladina* spp.). We found that only a few species occurred within relatively small pH ranges (e.g. *Sphagnum capillifolium*, *Sphagnum fuscum*, *Vaccinium uliginosum*), while the other dominant species (e.g. *Ledum groenlandicum*, *Gaultheria shallon*, *Pinus contorta* var. *contorta*, *Empetrum nigrum*, *Rubus chamaemorus*, *Spiraea douglasii*) were able to a tolerate larger pH range (e.g. pH 4.0-6.5). The ten most abundant species in our study (apart from *S. capillifolium*, which was the 9th most abundant species) were not limited to bog conditions; *Ledum groenlandicum* (most abundant species), *Gaultheria shallon* (2nd most abundant), *Pinus contorta* var. *contorta* (3rd), *Thuja plicata* (4th), *Sphagnum papillosum* (5th), *Spiraea douglasii* (6th), *Empetrum nigrum* (7th), *Chamaecyparis nootkatensis* (8th), and *Sphagnum pacificum* (10th) were all found in at least one transect point and generally within the 3.9-6.1 pH range. We did not find a narrow pH range for any of the ten most abundant lagg indicator species. Narrower pH ranges for less dominant species that were limited to the BG or LG sites, however, may still exist; for example, *Sphagnum fuscum*, which was observed in only 13 out of 168 plots, was found in the relatively narrow pH range of 4.0-4.5.

6.6. Summary and Conclusions

Thirteen raised bogs and their laggs were surveyed in coastal British Columbia to determine if there are regional patterns in plant species composition and abundance in bogs and laggs in coastal BC, and to link these patterns to environmental gradients. The regional patterns that we found were related to the two main wetland regions in coastal BC: the cooler, wetter Pacific Oceanic wetland region, and the warmer, drier Pacific Temperate wetland region. Cluster analysis and non-metric multidimensional scaling of the open bog vegetation plots revealed that bog plant communities could be divided into the two wetland regions and also into the four main geographic regions of the study area (Prince Rupert, Haida Gwaii, Vancouver Island, and Fraser Lowland). The lagg species could also be grouped by wetland region, but the divisions were not as distinct and they did not group by geographic region. Differences in plant species composition between the different geographic regions of the study area were linked to differences in climate, specifically mean annual precipitation and mean annual temperature, as well as latitude, which is related to mean annual temperature, daylight, and length of the growing season. Some species (e.g. *Juniperus communis*, *Sphagnum austinii*, *Sphagnum papillosum*) were more prevalent in the cooler, wetter northern bogs and bogs on the outer west coast, whereas other species (e.g. *Polytrichum strictum*, *Sphagnum magellanicum*, *Vaccinium myrtilloides*) were limited to warmer, drier areas in the rainshadow of Vancouver Island and the Olympic Peninsula. Pine was the dominant tree species in the Haida Gwaii, eastern Vancouver Island, and Fraser Lowland bogs, whereas cedar was dominant in the bogs with the highest mean annual rainfall (Prince Rupert and western Vancouver Island). In the BG vegetation plots, cover of *Sphagnum* spp. increased with mean annual precipitation; cover of *Ledum groenlandicum* and *Pinus contorta* var. *contorta* increased, and cover of *Carex* spp. decreased, with mean annual temperature. The number of trees in both the BG and LG plots declined with increasing mean annual temperature. However, canonical correspondence analysis of the vegetation data showed that mean annual precipitation, mean annual temperature, and latitude explained less than 25% of species variance.

Species richness was highest in the Haida Gwaii and Prince Rupert bogs, and declined across the transect from bog to forest in these bogs, but not in most other locations. At the site level, plant species distribution and species richness were related to pore-water pH and depth to water table. Some species (e.g. *Sphagnum capillifolium*, *Vaccinium uliginosum*) were limited to a narrow range in depth to water table (<25 cm below the surface in June/July) and pore-water pH (3.8 - 6.3). The number of vascular plants in BG plots increased significantly with increasing pH and Na^+ concentration; however, a significant correlation was not found for the LG plots.

The Fraser Lowland area in the southwest of BC contained the most well-developed lagg ecotones, dominated by *Spiraea douglasii*. In contrast, the northern and outer west coast bogs were generally flatter (Chapter 5) and often lacked a true lagg ecotone; in these areas, bog plant communities blended into wet forest environments without a clear transitional lagg ecotone. All of the LG and MN plots in the Pacific Oceanic bogs shared at least one species with the BG plots on their respective transects, whereas half of the LG and MN plots in the Pacific Temperate region shared no species with the BG plots; this supports the observation that the Pacific Temperate bogs tend to develop lagg ecotones that contain distinctly different plant species from the adjacent bogs. Knowledge of these regional and local patterns in bog and lagg plant communities is useful for development of bog restoration plans and delineation of conservation boundaries.

7. Hydrotopographic Lagg Forms and Vegetative Lagg Types in Coastal British Columbia Bogs: Vegetation Response to Environmental Gradients

7.1. Abstract

A "lagg" is the transition zone along the outside margin of a raised bog. It is an important landscape element for maintaining a high water table within the peat mass of a bog, but has received little research attention. A greater understanding of the hydrotopographic lagg forms and vegetative lagg types will improve designation of appropriate conservation sites and development of restoration plans for (damaged) raised bogs. We therefore examined the hydrological, hydrochemical, vegetative, and peat characteristics of laggs of bogs in coastal British Columbia, Canada. Under the influence of variable topography, climate, and adjacent mineral soils, laggs within this region vary widely. The 17 studied lagg transects fall within two hydrotopographic forms: a) Marginal Depression or b) Flat Transition, which are divided into four vegetation types: [1] Spiraea Thicket, [2] Carex Fen, [3] Peaty Forest, and [4] Direct Transition (without a lagg ecotone). High water tables were associated with Spiraea Thicket and Carex Fen laggs, which were associated with a topographic depression at the bog margin; in contrast, the water table decreased gradually from the bog towards the lagg in the Peaty Forest and Direct Transition lagg types. Tree basal area was low in the Spiraea Thicket and Carex Fen lagg depressions, but increased from the bog outwards in the other lagg types. Spiraea Thickets laggs were common in the Fraser Lowland bogs of southwestern BC (warmer, drier climate), and Carex Fen laggs were more common in the north coast bogs (cooler, wetter climate). Ash content of peat samples was higher in lagg sites compared to bog sites and was used to differentiate the Flat Transition lagg form into the Peaty Forest (ash content <5%) and Direct Transition to Forest (higher ash content) lagg types. Pore-water chemistry (pH, electrical

conductivity, and concentrations of Ca^{2+}, Mg^{2+}, and Na^{+}) was not significantly different between the four lagg types.

7.2. Introduction

The most frequently-used definition of a lagg is “a transition zone at the margin of a raised bog, receiving water from the bog and surrounding mineral soil” (Damman and French, 1987; Schouten, 2002). A vegetative ecotone is often the visual evidence of this subsurface mixing of the two water types, usually taking the form of fen or swamp plant communities. However, the topographic conditions required for this type of mixing of water are not always present around the entire margin of a raised bog (e.g. in cases where the adjacent minerotrophic landscape is topographically lower than the bog), so that there may be no visual evidence of a lagg, but rather an abrupt transition from bog to adjacent forest or other minerotrophic plant community. In order to capture the true variation in conditions at the bog margin, the lagg is defined in this study as “the hydrological, hydrochemical, and/or vegetative transition zone at the margin of a bog”, regardless of whether a vegetative ecotone is present.

The lagg is an integral part of the hydrological system of a bog and can be strongly (hydrologically and hydrochemically) influenced by runoff from the bog (Howie and Tromp-van Meerveld, 2011). Low hydraulic conductivity in lagg peat (Baird et al., 2008), and the presence of a mineral soil layer of low permeability below the lagg peat, may cause water to pool in the lagg. This groundwater is directly connected to the water mound of the bog. A high water table in the lagg can therefore minimize the hydraulic gradient from the bog, thereby sustaining a high water table in the bog (Schouwenaars, 1995). Artificial lowering of the water table in the lagg, by drainage or for conversion to another land use (e.g. agriculture), may result in increased drainage from the bog and a lower water table in the bog. Drainage has been shown to cause detrimental and irreversible changes to bogs in the form of increased oxidation, peat compression, reduced ability for *Sphagnum* mosses to access water by way of capillary action, and establishment of trees and tall shrubs that outcompete bog species and increase interception and evapotranspiration losses (Eggelsmann et al., 1993; Money and Wheeler, 1999; Price et al., 2003). For conservation of raised bogs, it is therefore critical to protect not only the bog itself, but also the adjacent lagg (Schouwenaars, 1995; Schouten, 2002).

In recent years, the importance of the lagg to proper functioning of raised bogs has been recognized in some bog management programs. For example, efforts to restore raised bogs in Northeast Germany involve a “hydrological protection zone” (HPZ) that encompasses the historic lagg area, regardless of whether the lagg area is in a natural or disturbed condition (Bönsel and Sonneck, 2012). The purpose of the HPZ is to maintain a high water table in the lagg, in order to retain rainwater and reduce lateral flow from the bog (Bönsel and Sonneck, 2012). The restoration includes ditch blockages and construction of embankments to reduce discharge at the bog margin. The hydrological restoration of the HPZ must be complete (i.e. there cannot be any ditches that continue dewatering the bog), or the high water table will not be restored. At two raised bogs undergoing this type of restoration, one with a properly blocked HPZ and the other with an incomplete restoration of the HPZ, Bönsel and Sonneck (2012) observed ten years after restoration commenced that the bog with the fully blocked HPZ had a higher water table, decreased tree cover, and increased species diversity (incl. *Sphagnum* spp.). In contrast, the bog with the incomplete HPZ had a lower water table, greater water table fluctuations, lower diversity of *Sphagnum* species, and a lower cover of submerged or emersed plants or mosses. The concept of a hydrological protection zone has also been adopted in the UK (Morgan-Jones et al., 2005) and The Netherlands (Schouwenaars, 1993; Tomassen et al., 2010).

In order to properly delineate the extent of a hydrological protection zone, i.e. the historic lagg area of a raised bog, a clear understanding of the characteristics of laggs (i.e. in terms of hydrology, hydrochemistry, peat properties, and vegetation) and the regional variation in these characteristics is required. This information is particularly critical for using the lagg of one bog as the reference ecosystem for the restoration of another bog. However, in comparison to the large number of studies on raised bogs in North America and Europe, and despite the recent interest in hydrological protection zones, laggs of raised bogs have received relatively little research attention. Only a limited number of studies have reported observations about the gradients in hydrology, hydrochemistry, vegetation, and peat properties across the bog expanse – bog margin transition. As the ground surface slopes toward the margin of a raised bog, the water table tends to decline, resulting in increased tree growth and fewer bog species (Damman, 1986; Bubier, 1991; Howie et al., 2009b). Because the influence of minerotrophic water increases towards the bog margin, pH, electrical conductivity, and concentrations of Ca^{2+} and Mg^{2+} typically increase towards the bog margin (Bubier, 1991; Bragazza et al., 2005; Richardson et al., 2010; Howie and van Meerveld, 2012). Peat at the bog margin is generally denser and more decomposed, partly due to oxidation as a result of the lower or more widely fluctuating water table, and partly due to the higher mineral content of the peat (Gorham, 1950; Baird et al., 2008; Levrel et al. 2009). These site-level abiotic gradients, as well as precipitation and temperature, influence the plant community composition at the bog margin. Meiczan et al. (2012) observed significantly higher microbiological species diversity in the lagg of a bog in Eastern Poland compared to the adjacent bog and forest sites, suggesting that the lagg ecotone is important in terms of the biological diversity of a raised bog ecosystem. Ecotones are generally high in biodiversity and productivity (Risser, 1995) due to their structural diversity and relatively sharp changes in environmental gradients over a relatively short distance (Gosz, 1992).

To develop a better understanding of the characteristics of laggs of bogs in coastal BC and create a classification of laggs in coastal BC, we studied 17 laggs of 13 bogs, specifically looking at early summer depth to water table, hydrochemistry, vegetation, and peat characteristics. In this paper, we describe how varying topography relates to depth to water table, pore-water chemistry, tree basal area, and the presence, abundance, and assemblages of plant species and propose a classification of laggs in coastal BC. We also discuss how hydrochemistry and ash content of peat varied across the lagg transects.

7.3. Methods

7.3.1. Study Sites

Thirteen bogs within 20 km of the Pacific Ocean (including inlets) and less than 100 m above sea level were studied along the BC coast between 49^0 and 54^0 N (Fig. 36). Six of these bogs are located in the Pacific Temperate wetland region, which includes eastern and southern Vancouver Island, the Fraser Lowland, the Gulf Islands, and the mainland coast south of 51^0 N (Table 18). The other seven bogs are located in the Pacific Oceanic wetland region, which includes western and northern Vancouver Island, the Haida Gwaii islands, and the mainland coast north of 51^0 N. The Pacific Oceanic wetland region is divided into two subregions: North Coast (mainland and Haida Gwaii) and South Coast (Vancouver Island). These wetland regions have been classified based on precipitation and temperature gradients (NWWG, 1988). Mean annual precipitation is 1044 mm in the Pacific Temperate wetland region, and 2117 mm in the Pacific Oceanic wetland region (NWWG, 1988). The mean annual temperature is 9.6 ^{0}C and 8.2 ^{0}C for the Pacific Temperate and Pacific Oceanic wetland regions, respectively (NWWG, 1988). The 13 studied bogs belong to four different bog site associations: Wb50 (*Ledum groenlandicum* – *Kalmia microphylla* – *Sphagnum*), Wb51 (*Pinus contorta* var. *contorta* – *Empetrum nigum* – *Sphagnum austinii*), Wb52 (*Juniper communis* – *Trichophorum cespitosum* – *Racomitrium lanuginosum*), and Wb53 (*Pinus contorta* – *Chamaecyparis nootkatensis* – *Trichophorum cespitosum*) (MacKenzie and Moran, 2004). These bog site associations have been classified using diagnostic or dominant plant species, species distribution, landscape position, depth to water table, soil moisture and nutrient regimes, and acidity/alkalinity. The Wb50 bog site association is generally found in the Pacific Temperate wetland region; the Wb51-53 bog site associations are more common in the Pacific Oceanic wetland region (MacKenzie and Moran, 2004).

Four bogs were studied in the Fraser Lowland region of southwestern BC (Table 18, Fig. 36). Three of the bogs (Burns Bog, Surrey Bend, and Langley Bog) were formed on Fraser River deltaic deposits. The fourth bog (Blaney Bog) is located in the nearby Pitt River valley wetland complex. Although each Fraser Lowland bog has its own unique characteristics and set of past disturbances (e.g. peat mining in Burns Bog and Langley Bog; sewer and road construction in Surrey Bend), they are similar in terms of original form and historic vegetative composition. The Fraser Lowland bogs belong to the Wb50 bog site association and are situated at the southernmost extent of *Sphagnum*-dominated raised bogs on the west coast of Canada (Vitt et al., 1999). Mean annual precipitation is 1008 mm for Burns Bog (Vancouver International Airport weather station), 1708 mm for Surrey Bend and Langley Bog (Pitt Meadows Airport weather station), and 2194 mm for Blaney Bog (Haney UBC Research Forest weather station) (data source: Environment Canada 30-year averages).

On the north coast, three bogs were studied near Prince Rupert (Diana Lake, Oliver Lake, and Butze Rapids) and another three on Haida Gwaii (Mayer Lake, Drizzle Lake, and Tow Hill). All of the Haida Gwaii bogs belong to the Wb51 bog site association; two of the Prince Rupert area bogs belong to the Wb52 bog site association (Oliver Lake and Diana Lake) and one belongs to the Wb53 bog site association (Butze Rapids) (Table 18). These six bogs are underlain by acidic basaltic and sedimentary bedrock (NWWG 1988).

On Vancouver Island, studies took place on the west coast (Shorepine Bog) and the east coast (Port McNeill and Campbell River). Port McNeill and Campbell River bog belong to the Wb50 bog site association, similar to the Fraser Lowland bogs, whereas Shorepine Bog belongs to the Wb51 bog site association, similar to the Haida Gwaii bogs. Shorepine and Campbell River bogs are underlain by sand; Port McNeill bog is situated on the same basaltic and sedimentary rock as the north coast bogs. Mean annual precipitation is 1508 mm for the Haida Gwaii bogs (Masset Inlet weather station), 2594 mm for the Prince Rupert bogs (Prince Rupert weather station), 1452 mm for Campbell River Bog (Campbell River weather station), 1869 mm for Port McNeill Bog (Port McNeill weather station), and 3305 mm for Shorepine bog (Tofino weather station) (Data source: Environment Canada 30-year averages).

Table 18. ***Location information for the 13 studied bogs. Bogs with multiple site codes contained more than one study transect (one transect per site code).***

Site Name	Side Code	Month studied	Elev. (masl)	Distance to Ocean (km)	Bog Site Association[b]	Wetland Region[c]	Lagg Type[d]
Tow Hill Bog[a]	TH	July 2010	19	0.1	Wb51	OP_n	PF
Mayer Lake Bog[a]	ML	July 2010	40	9.1	Wb51	OP_n	CF
Drizzle Lake Bog[a]	DT	July 2010	58	0.7	Wb51	OP_n	DT
Butze Rapids Bog[a]	BR	July 2010	28	0.3	Wb53	OP_n	PF
Oliver Lake Bog[a]	OL	July 2010	55	0.9	Wb52	OP_n	DT
Diana Lake Bog[a]	DL	July 2010	36	8.2	Wb52	OP_n	CF
Port McNeill Bog[a]	PM	May 2011	92	1.5	Wb50	TP	DT
Campbell River Bog[a]	CR	May 2011	81	2.1	Wb50	TP	ST
Shorepine Bog	SPW, SWE	July 2011	22	1.2	Wb51	OP_s	DT DT
Burns Bog	SW, CW, DNR	June 2011	4	2.8	Wb50	TP	PF ST ST/PF
Surrey Bend Bog	SB	July 2011	6	11.6	Wb50	TP	ST
Langley Bog	LB	July 2011	4	20.2	Wb50	TP	ST
Blaney Bog	BU, BF	June 2011	5	19.5	Wb50	TP	ST CF

[a]Unofficial site name based on nearby place name.
[b]Bog site associations from MacKenzie and Moran (2004).
[c]OP_n = Pacific Oceanic wetland region, North Coast subregion; OP_s = Pacific Oceanic wetland region, South Coast subregion; TP = Pacific Temperate wetland region (NWWG, 1988).
[d]Lagg type abbreviations: CF = Carex Fen, ST = Spiraea Thicket, PF = Peaty Forest, DT = Direct Transition

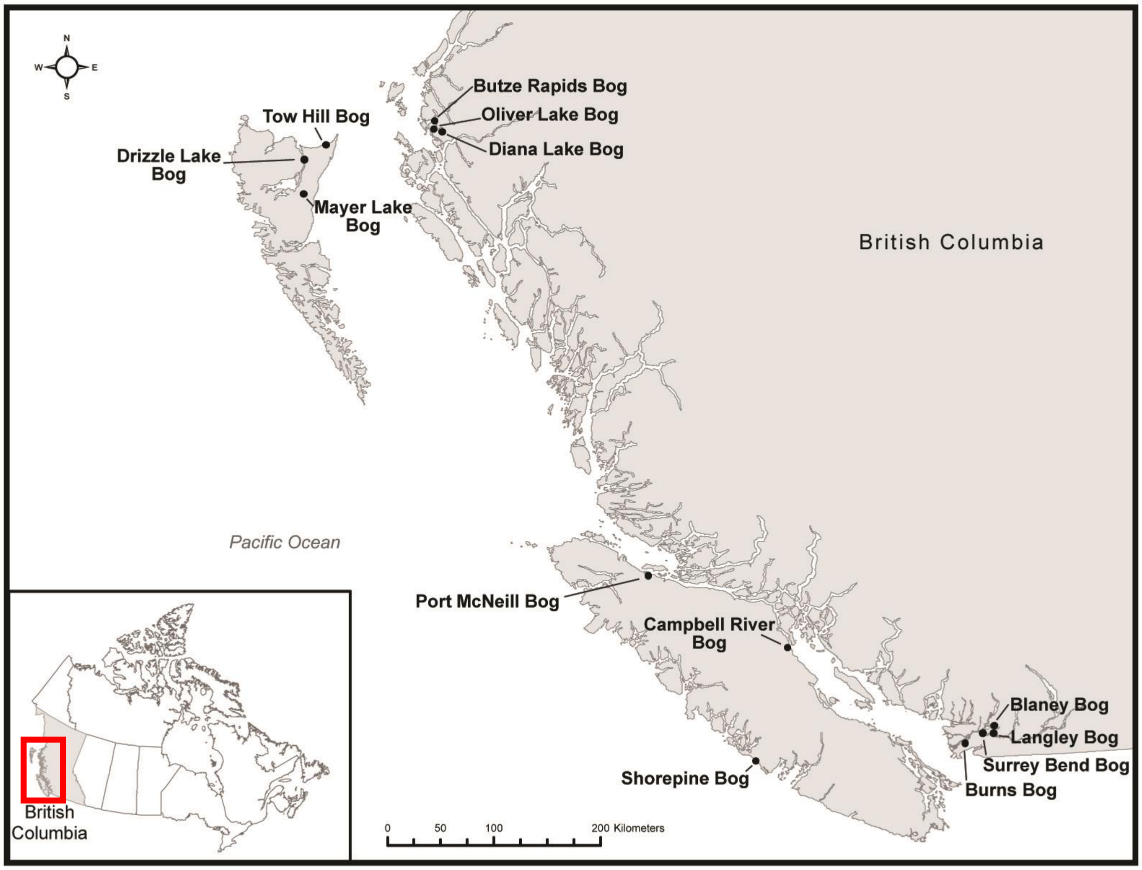

Figure 36. Location of research sites in British Columbia. Inset: map of Canada. Red box shows area of large map.

7.3.2. Field Methods

Each of the 13 bogs was studied during a several-day period in June or July of 2010 or 2011. Early summer in this region represents relatively average climate conditions, with a low likelihood of heavy rainfall or high evapotranspiration, which can both influence bog pore-water chemistry, although previous research has shown that some hydrochemical variables, such as pH, electrical conductivity, and Ca^{2+}, Na^{+}, and Mg^{2+} concentrations, tend to have fairly good temporal stability (Wieder, 1985; Vitt et al., 1995; Howie and van Meerveld, 2012). Campbell River Bog and Burns Bog were studied in both years to account for differences in weather patterns between the two years that might affect depth to water table and pore-water chemistry. For consistency, we used only the 2011 data for these sites.

At each bog, a transect was installed starting at or near the bog centre, running radially out to the bog edge through the rand (outward-sloping margin of the bog) and lagg, and into the surrounding minerotrophic land (usually forest). Most bogs contained one study transect, but Blaney Bog and Shorepine Bog had two study transects, and Burns Bog three (Table 18). It was assumed that a single measurement point for depth to water table and hydrochemical parameters at each study site would be representative of the immediate surroundings because these variables are relatively stable within a small area (Chapter 4). The transects were surveyed with a rod and level, and GPS, except for the three Burns Bog transects for which the elevation was derived from LiDAR data from 2008, accurate to 15 cm. The depth of the peat was determined using an auger.

Five 25 mm diameter PVC piezometers were installed along each of the 17 transects in the following locations: bog (BG), rand (two piezometers; R1 and R2), lagg (LG), and mineral (MN) soils. The locations were chosen according to their vegetative characteristics. BG sites were defined as *Sphagnum*-dominated, containing stunted ericaceous shrubs, LG sites as either an obvious vegetative ecotone between the bog and surrounding forest or the zone at the bog margin where the vegetation transitioned from open bog to forest, and MN sites as the forest surrounding the bog. Two transects contained more than one LG site: the SW transect of Burns Bog had two LG sites to account for subtle changes in plant species composition across the wide lagg area; the DNR transect had two LG sites to account for two different lagg types, one that was dominated by large trees, and one that was dominated by *Spiraea douglasii* Hook. The Butze Rapids Bog transect had only four study sites (no R2 site) due to the small size of the bog. The piezometers were 1.5 m long, slotted along the bottom 40 cm, and inserted at an average depth of 53 cm into the peat.

The piezometers were purged twice after installation with a low-flow peristaltic pump. After 3-7 days, the water level was measured with an electronic water level meter, and pH and electrical conductivity were measured with a WTW Multiline P4 hand-held meter. Because previous water level measurements in a well and a piezometer were similar (average difference <0.8 cm) (Chapter 3), it was assumed that the water level measured in the shallow piezometer represented the water table position. Electrical conductivity values were compensated for H^+ concentrations using: EC_{corr} =

$EC_{measured} - EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$ and 3.49×10^5 is the conversion factor for field measurements standardized to 25 ^{0}C (Rydin and Jeglum, 2006). Water samples were collected from the piezometers for laboratory analysis using a low flow peristaltic pump and HDPE plastic bottles. The samples for base cation analysis were filtered with a 0.45 µm filter, preserved with nitric acid, and refrigerated; anion samples were refrigerated unfiltered. Samples were analyzed for Ca^{2+}, Mg^{2+}, and Na^+ concentrations by the Pacific Environmental Science Centre (Environment Canada). For more details on depth to water table measurements and water chemistry sampling, see Chapter 5).

Peat samples were collected at 10, 50, and 100 cm below the surface with an Eijkelkamp flag corer at the locations of the piezometers. Samples from each depth were wrapped in plastic wrap, sealed in a plastic bag, and frozen up to 6 months until analysis. In the lab, samples were thawed and weighed, dried in an oven at 105 ^{0}C for 24 hours, weighed again and placed in a 550 ^{0}C oven for 24 hours and re-weighed to determine loss on ignition (ash content).

Percent cover of all plant species was measured in 5 x 5 m plots at each piezometer and 20 m from each piezometer. Cover of each species was recorded using the Braun-Blanquet scale: “r” = solitary, with small cover; “+” = few, with small cover; “1” = numerous or scattered, but <5%; “2” = 5-25% cover; “3” = 25-50% cover, “4” = 50-75% cover, and “5” = ≥75% cover (Mueller-Dombois and Ellenberg, 1974). Tree height and diameter at 1.4 m were measured in 10 x 10 m plots at each piezometer, except when the distance between piezometers was less than 10 m, in which case the tree plots were 5 x 10 m (Chapter 6). Only trees taller than 20 cm were included in the survey; for trees less than 2 m in height, diameter was measured at the mid-point of the stem. Trees with a diameter less than 1 cm were assigned a diameter of 0.5 cm for analysis purposes. For more details on the vegetation measurements, see Chapter 6.

7.3.3. Data Analysis

Spearman rank correlation was used to determine the correlations between vegetation (i.e. species cover; tree basal area, mean tree height and diameter, and tree density) and environmental conditions (i.e. depth to water table, pH, EC, cation concentrations). Two-tailed Students t-tests were used to determine if differences in the measured parameters between the hydrotopographic lagg forms were significant (see below). Analysis of variance (ANOVA) was used to test for significant differences in depth to water table, tree characteristics, peat depth, ash content, and hydrochemical conditions between the four different vegetative lagg types (see below). A significance level of 0.05 was used for all analyses.

Ordination (multivariate) analyses were performed in PC-ORD (McCune and Mefford, 2011) to search for ecological and regional vegetative groups in the studied LG plots using hierarchical agglomerative cluster analysis (specifications: Euclidean distance and Ward's linkage method). This clustering method is a "bottom up" approach where pairs of clusters are merged moving up the hierarchy. This method has been shown to be useful for classifying peatland plant associations in coastal BC (Golinski, 2004) and was chosen because our goal was to determine whether species presence/absence and cover data could be statistically classified into different vegetative types. Canonical correspondence analysis (CCA) (Hill's method) was used to determine how much of the species variance in the LG plots could be explained by climate (latitude, precipitation, and temperature), hydrochemical conditions, depth to water table, and peat properties (peat depth and ash content of peat at 10 and 50 cm below the surface). CCA was used because we wanted to determine whether a portion of the plant community structure was more strongly related to the measured environmental variables than expected by chance, and because this method can be considered as a "direct gradient analysis" (McCune and Grace, 2002). For these analyses, the Braun-Blanquet cover values were converted to percent cover values by using the mid-point of each percent class range: "r"=0.25%, "+" = 0.5%, "1" = 2.5%, "2" = 15%, "3" = 37.5%, "4" = 62.5%, "5" = 87.5%.

7.4. Results

Precipitation and temperature were similar between the two study periods. There were no large rainfall events (>25 mm) in the 30 days prior to sampling at either of the two bogs (Campbell River Bog and Burns Bog) that were sampled in both 2010 and 2011. Mean air temperature between April 1 and July 31 at Vancouver International

Airport (16 km from Burns Bog) was 13.7 ^{0}C in 2010 and 12.8 ^{0}C in 2011, and 11.0 ^{0}C in 2010 and 10.3 ^{0}C in 2011 in Campbell River. Depth to water table in the Campbell River Bog LG site was 4 cm lower in May 2010 than in May 2011 (Howie and van Meerveld 2012). Depth to water table in the LG sites of the SW and CW transects in Burns Bog differed by less than 1 cm between the 2010 and 2011 measurements. pH differed by 0.34 and 0.81 in the LG sites of the SW and CW transects of Burns Bog, respectively, and by 0.21 in the LG site of the Campbell River Bog transect for the 2010 and 2011 measurements (Howie and van Meerveld, 2012). EC_{corr} differed by 26 and 57 µS/cm for the SW and CW LG sites, respectively, for the 2010 and 2011 measurements; EC was only measured in 2011 in Campbell River Bog. Ca^{2+}, Mg^{2+}, and Na^+ concentrations varied by less than 1.1 mg/l between the 2010 and 2011 measurements for the SW and Campbell River Bog LG sites; samples for hydrochemical analyses at CW were only taken in 2011 (Howie and van Meerveld, 2012). This comparison between the measurements in the two different years confirms that the measurements at the other bogs can be considered representative, and are not expected to vary considerably between years.

7.4.1. Hydrotopographic Lagg Forms

The topographic surveys and depth to water table results for the transects revealed two general hydrotopographic lagg forms. Half of the studied transects (9 out of 17) contained laggs that were situated in a topographic depression at the bog margin; in this study, this kind of lagg is termed a "Marginal Depression" (MD) lagg (Fig. 37a,b; Fig. 38). The water table was usually high (mean: 12 cm below surface; standard deviation: 12 cm) in this lagg form because water tends to pool in this topographic depression at the bog margin (Fig. 39). For seven of the nine MD transects, the lagg was lower in elevation than the bog (Fig. 38). There were two exceptions to this (DNR and BU transects). The DNR lagg was higher in elevation than the bog because Burns Bog was mined for peat in the past, resulting in a lower surface elevation in much of the central bog area. Also, the current lagg is constrained by a highway, which may have enhanced ponding of water in this area. The Blaney Bog (BU) lagg was also higher than the bog, but a small ridge of peat at the margin of the bog appears to have resulted in a localized depression between the bog and adjacent mineral upland forest, allowing upland runoff to collect and a lagg ecotone to develop. The Marginal Depression form is a "true lagg" according to the conventional definition of lagg: a transition zone at the margin of a (usually raised) bog receiving water from both the bog and surrounding mineral ground.

For the other lagg sites (8 out of 17), the topographic gradient from bog to forest was relatively smooth (Fig. 37c,d). This kind of lagg is termed "Flat Transition" (FT). In seven of FT nine transects, the lagg was higher in elevation than the bog (Fig. 38). In two cases, the bog was higher than the lagg (Fig. 38 – SW, TH), but in these cases the MN site was lower in elevation than the bog, so runoff from the bog was not impeded by an upland. The water table gradually declined across the bog margin (Fig. 39), and the depth to water table in the lagg was greater (mean: 31 cm below surface; standard deviation: 12 cm) than for the MD form. The difference in mean depth to water table in the LG sites between the MD and FT lagg forms was statistically significant.

Two transects did not fit into these two main topographic forms. The DNR transect of Burns Bog contained both lagg forms. Whereas most bogs were adjacent to a minerotrophic forest, the MN site in the Blaney Bog FN transect is a creek with a large hardhack swamp on the other side of the creek that surrounds the south and west edges of the bog, resulting in a high water table not only in the lagg but also in the relatively flat rand. Thus, even though the topographic data suggests that this LG site is an FT lagg form, the shallow depth to water table is more characteristic of the MD lagg form.

Basal area was significantly lower in MD laggs (0.0-7.2 m^2/ha) than the FT laggs (9.6-67.2 m^2/ha) (Fig. 40). There was also a significant difference in mean tree diameter at breast height between the MD (0.5-21.0 cm) and FT lagg forms (0.5-60.0 cm). Average tree height and total number of trees in the LG plots were, however, not significantly different between the two hydrotopographic lagg forms. The number of trees increased significantly with increasing depth to water table for the LG sites (r_s = 0.550) and all sites on the transects (r_s = 0.236). There was a also significant correlation between depth to water table and basal area for the LG sites (r_s = 0.584), as well as for all transect sites combined (r_s = 0.474). There was no significant correlation between depth to water table and mean tree height or diameter.

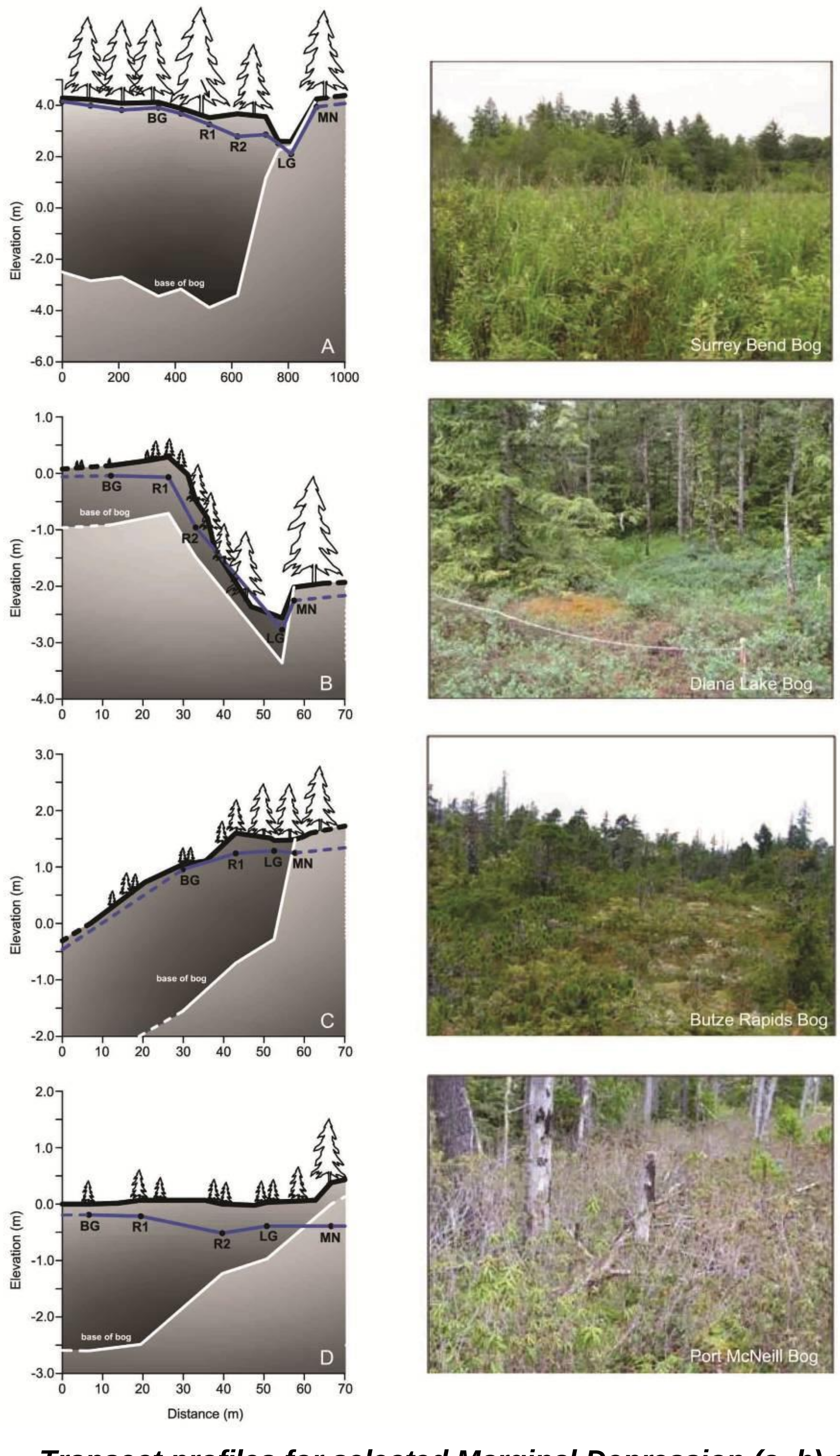

Figure 37. ***Transect profiles for selected Marginal Depression (a, b) and Flat Transition (c, d) lagg forms (left column) and photographs of the corresponding lagg sites (right column). Vertical exaggeration: a) 90x and b-d) 14x. The blue line with the symbols represents the water table, the white line the base of the peat. Dashed lines are estimated values.***

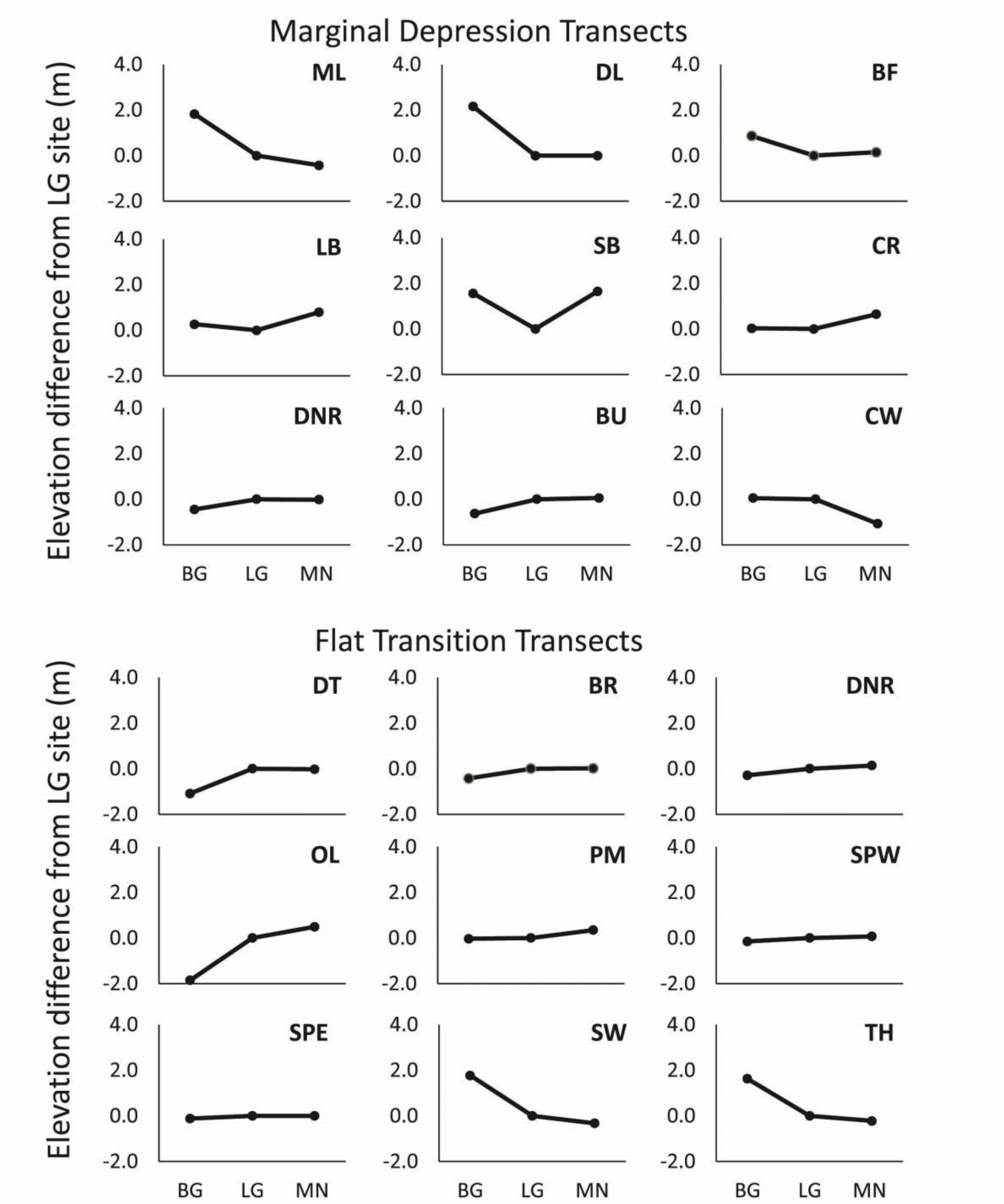

Figure 38. ***Elevation difference from LG sites to BG and MN sites for the Marginal Depression (MD) and Flat Transition (FT) transects. DNR is shown for both MD and FT lagg forms because this transect contained both forms of lagg.***

7.4.2. Vegetative Lagg Types

The MD laggs, with a high water table and comparatively low tree basal area (Figs. 38, 39), were dominated by two main plant communities: *Carex sitchensis-Sphagnum* or *Spiraea douglasii-Sphagnum*. Therefore, we named these two vegetative lagg types: Carex Fen (where *Carex sitchensis* Prescott was dominant in the lagg; mean Braun-Blanquet class: 3) and Spiraea Thicket (where *Spiraea douglasii* was dominant in the lagg; mean Braun-Blanquet class: 5) (Fig. 41; Appendix F)). Other common species in the Carex Fen lagg type included *Myrica gale* L. (Braun-Blanquet class 0-5), *Lysitchiton americanum* Hultén & H. St. John (Braun-Blanquet class: 0-2), *Sphagnum spp.* (Braun-Blanquet class 1-4), *Ledum groenlandicum* Oeder (Braun-Blanquet class 0-3), and *Vaccinium oxycoccos* L. (Braun-Blanquet class 0-1), although these species were not observed in all Carex Fen lagg sites. The *Spiraea douglasii-Sphagnum* sites were dominated by a dense thicket of *Spiraea douglasii,* although *Carex* was present in half of the sites with cover ranging from sparse (Braun-Blanquet class 1; <5%) to abundant (Braun-Blanquet class 5; >75%), depending on the openness of the *Spiraea* canopy. Other common species in the Spiraea Thicket laggs included *Ledum groenlandicum* (Braun-Blanquet class 0-5), *Gaultheria shallon* Pursh (Braun-Blanquet class 0-4), *Sphagnum* spp. (Braun-Blanquet class 0-5), *Rhamnus purshiana* DC. (Braun-Blanquet class 0-3, and *Salix sitchensis* Sanson (Braun-Blanquet class 0-2), although these species were not observed in all Spiraea Thicket lagg sites. *Spiraea douglasii* was not observed in the LG sites of the other vegetative lagg types. The difference in depth to water table and basal area between the Carex Fen and Spiraea Thicket lagg types was not statistically significant (Table 19).

In general, the FT laggs contained mostly ericaceous shrubs (e.g. *Gaultheria shallon, Ledum groenlandicum*, *Empetrum nigrum* L.*, Vaccinium spp.* (Braun-Blanquet class 0-5 for each of these species) and stunted trees (e.g. *Thuja plicata* Donn. (Braun-Blanquet class 0-5)*, Picea sitchensis* (Bong.) Carr. (Braun-Blanquet class 0-5)*, Tsuga heterophylla* (Raf.) Sarg. (Braun-Blanquet class 0-5), *Chamaecyparis nootkatensis* (D. Don) Spach (Braun-Blanquet class 0-5), and *Pinus contorta* var. *contorta* (Braun-Blanquet class 0-4). Even though the plant communities of the two FT lagg types were not as visually distinct from one another as for the MD types, they were divided into two lagg vegetation types: Peaty Forest, where the lagg is a forest (or scrub forest) over deep peat, and Direct Transition to forest, where there is no visible lagg ecotone between the bog and mineral forest based on plant community structure alone. Cover of *Sphagnum* was generally low in the Peaty Forest laggs (Braun-Blanquet cover range: 0-2; mean: 0) and higher in the Direct Transition laggs (Braun-Blanquet cover range: 0-5; mean: 3) (Fig. 42). *Gaultheria shallon* (Braun-Blanquet class 2-5) and *Thuja plicata* (Braun-Blanquet class 0-5) were dominant in the Peaty Forest laggs, while the Direct Transition sites contained a lower cover of these species (*Gaultheria shallon*: Braun-Blanquet class 0-5; *Thuja plicata*: Braun-Blanquet class 0-4), nearly twice as many occurrences of *Ledum groenlandicum* (observed in 9 of 10 Direct Transition plots vs. 4 of 8 Peaty Forest plots) and *Empetrum nigrum* (observed in 7 of 10 Direct Transition plots vs. 3 of 8 Peaty Forest plots), more than twice as many occurrences of *Chamaecyparis nootkatensis* (observed in 6 of 10 Direct Transition plots vs. 2 of 8 Peaty Forest plots) and *Pinus contorta* var. *contorta* (observed in 6 of 10 Direct Transition plots vs. 2 of 8 Peaty Forest plots), and no *Picea sitchensis*. The Direct Transition lagg type had significantly higher species richness than the other three lagg types (average of 15.2 species for Direct Transition vs. average of 8.2-11.5 species; Table 19). There was no significant difference in depth to water table or basal area between the Peaty Forest and Direct Transition lagg types (Table 19).

The Peaty Forest and Direct Transition LG sites were different not only in their vegetative composition, but also in ash content of the peat samples. In the Peaty Forest lagg type, peat samples at 50 cm depth contained little mineral material (<5% ash content; mean: 2%) (Fig. 43). Where the bog transitioned directly to forest (Direct Transition lagg type), the LG peat samples contained more mineral material at 50 cm (2 - 36% ash content; mean: 19%). This difference was smaller at 10 cm depth (mean ash content: 4% and 15% in the Peaty Forest and Direct Transition LG sites, respectively) and larger at 100 cm depth (mean ash content: 2% and 48% in the Peaty Forest and Direct Transition LG sites, respectively). The difference in mean ash content between the Direct Transition and Peaty Forest samples was significant at 50 and 100 cm depth using one-tailed t-tests, but not for two-tailed t-tests; this result may have been affected by the small sample size (n=5).

The two FT lagg forms also had different mean tree heights; mean tree height in the Peaty Forest lagg type was 10.4 m, whereas mean tree height was 0.9 m in the

Direct Transition lagg type (Table 19). In all cases but one, the LG sites with ash content <5% were classified as a Peaty Forest lagg type. The lagg of Oliver Lake Bog had an ash content <5% at 50 cm depth, but is considered a Direct Transition lagg on the basis of tree height; mean tree height was <0.7 m in the Oliver Lake lagg, compared to mean tree height >1.3 m in the Peaty Forest LG sites. It should be noted that “forest” is generally defined as a stand dominated by trees greater than 5-10 m in height at maturity; however, the Peaty Forest lagg type includes both forest (trees >5 m in height) and scrub forest (defined here as trees > 1.3 m in height).

The cluster analysis for the lagg vegetation plots (Fig. 44) generally agreed with our grouping of lagg types based on dominant plant species composition. The dendrogram shows that lagg plant communities in the studied bogs can be divided into four categories: Carex Fen, Spiraea Thicket, Peaty Forest, and Direct Transition. Two LG sites that we classified as Peaty Forest (Tow Hill bog and Butze Rapids bog) were classified as Direct Transition lagg type in the cluster analysis. The most likely explanation is that we classified the lagg types of the FT lagg form using vegetative criteria (species presence/abundance, tree height) and ash content (Appendix F). Thus, if laggs are classified based on species presence/abundance alone, these two bogs would be classified in the Direct Transition category.

Regional variation in lagg plant species composition is evident in the dendrogram; laggs in the Fraser Lowland and eastern Vancouver Island (i.e. the Pacific Temperate wetland region) belong (except for the CW outlier and the BF lagg) to either the Peaty Forest or Spiraea Thicket type (lower half of the dendrogram), whereas laggs on the north coast, and northern and western Vancouver Island (i.e. the Pacific Oceanic wetland region, but also Port McNeill Bog near the boundary of the two wetland regions), are either Carex Fen or Direct transition lagg types (upper half of the dendrogram).

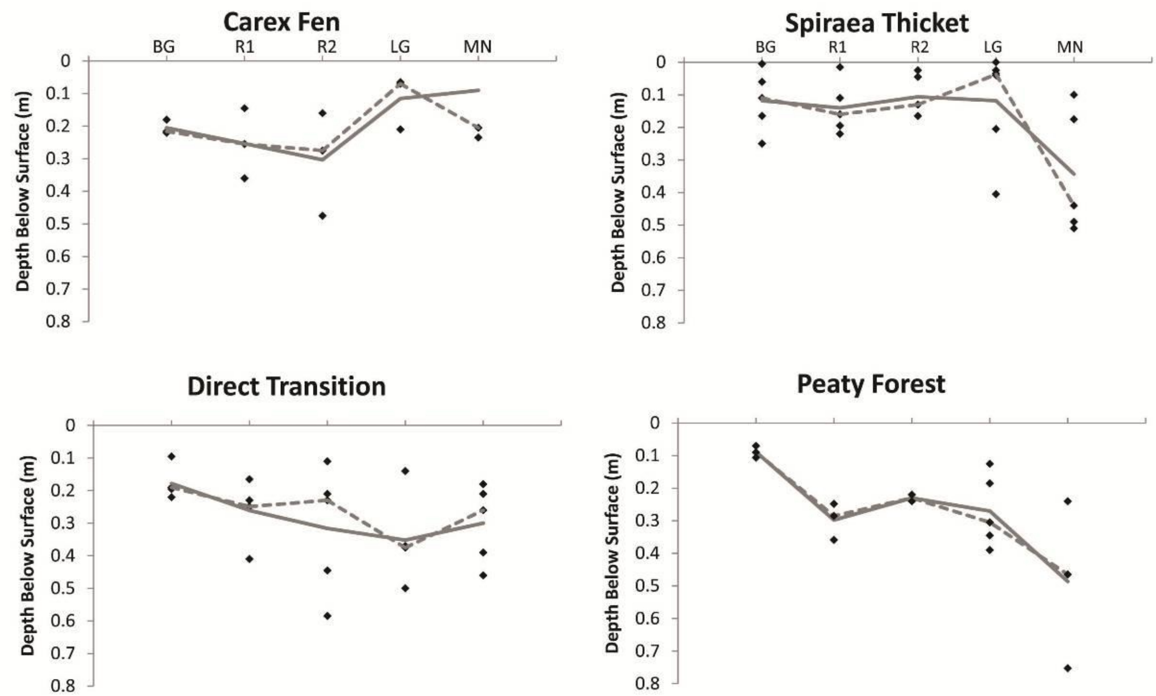

Figure 39. ***Depth of the water table below the surface as a function of location along the study transects for the four lagg types. The top row graphs are the Marginal Depression laggs, the bottom row graphs are the Flat Transition laggs. The solid grey line is the mean; the dashed grey line is the median.***

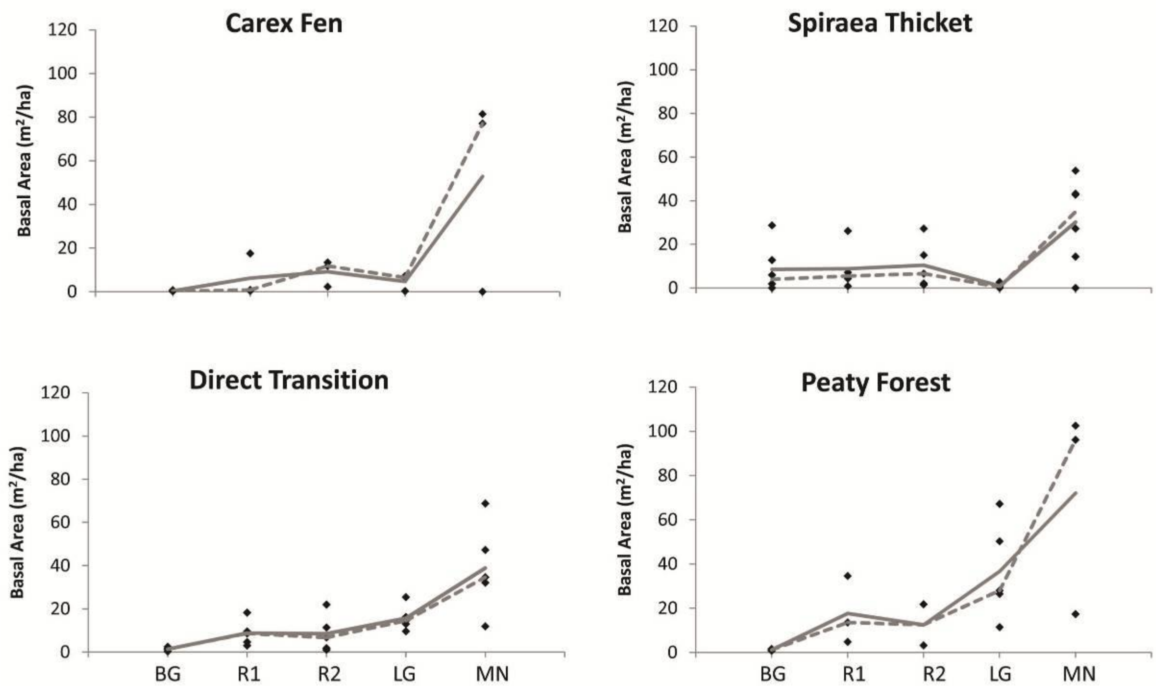

Figure 40. ***Tree basal area across the study transect for the four lagg types. The top row graphs are the Marginal Depression laggs, the bottom row graphs are the Flat Transition laggs. Solid grey line is the mean; dashed grey line is the median.***

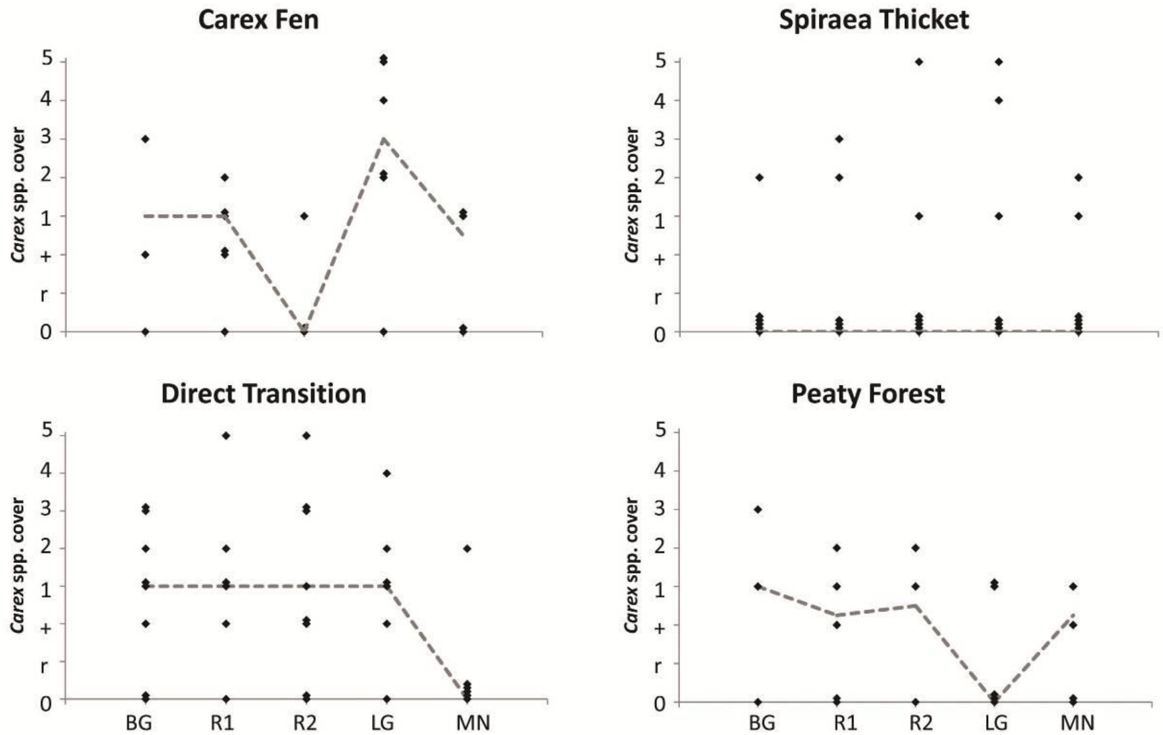

Figure 41. ***Braun-Blanquet cover of Carex spp. across the transects for the four lagg types. Dashed grey line is the median; to calculate the median, "r" was assigned a value of 0.25, and "+" was assigned a value of 0.5. The Carex Fen data point showing zero cover of Carex spp. in the lagg was the parallel vegetation plot for the Blaney Fen transect; the main LG vegetation plot on this transect had a Braun-Blanquet cover of "2" for Carex spp. The high cover values for Carex spp. in the Spiraea Thicket graph are from the two lagg plots at Campbell River Bog; this lagg had a high cover of both Spiraea douglasii and Carex spp., but was classified as a Spiraea Thicket lagg because it had a slightly higher cover of Spiraea douglasii, on average, than Carex sitchensis, and because it contained species that were also common in the other Spiraea Thicket LG plots (i.e. Rhamnus purshiana, Gaultheria shallon).***

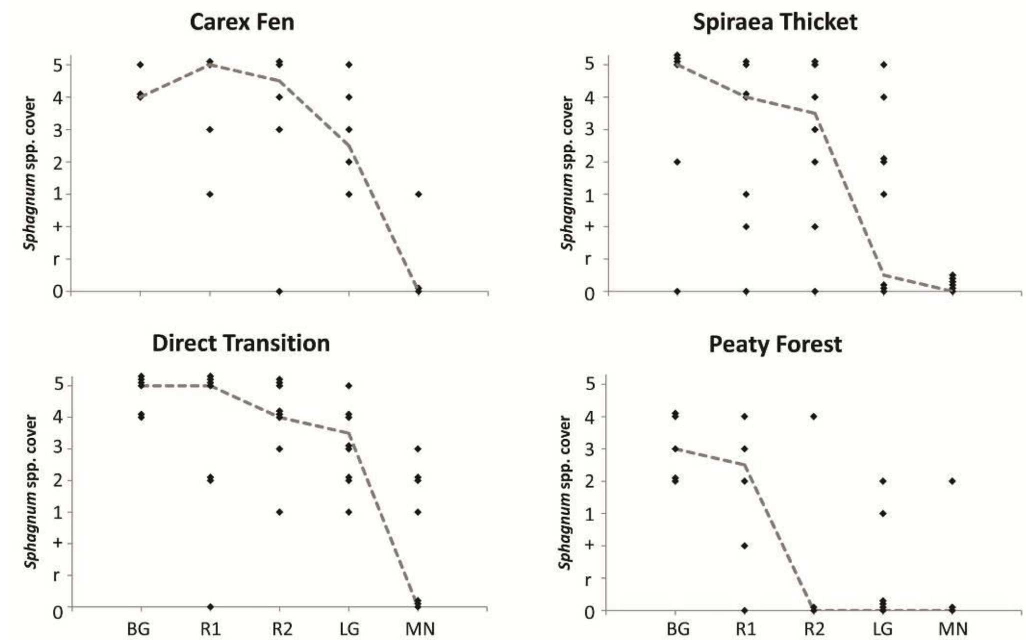

Figure 42. ***Braun-Blanquet cover of Sphagnum spp. across the study transects for the four lagg types. The top row graphs are the Marginal Depression laggs; the bottom row graphs are the Flat Transition laggs. The dashed grey line is the median; to calculate the median, "r" was assigned a value of 0.25, and "+" was assigned a value of 0.5.***

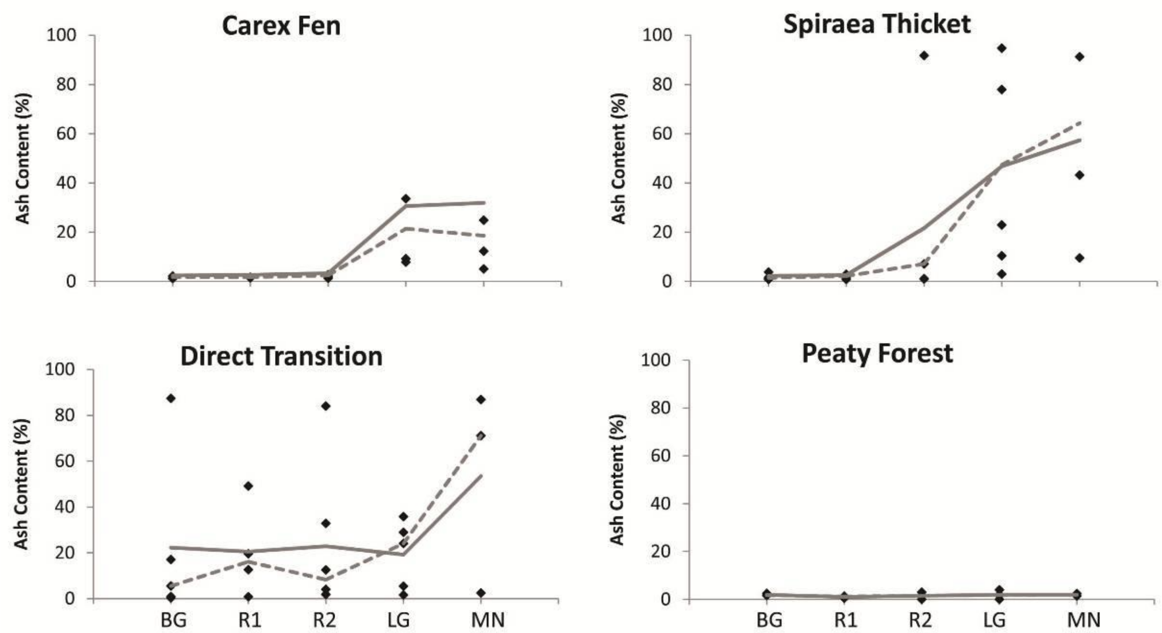

Figure 43. ***Ash content (% dry weight) in peat samples from 50 cm depth across the study transects for the four lagg types. The top row graphs are the Marginal Depression laggs; the bottom row graphs are the Flat Transition laggs. Solid grey line is the mean; dashed grey line is the median.***

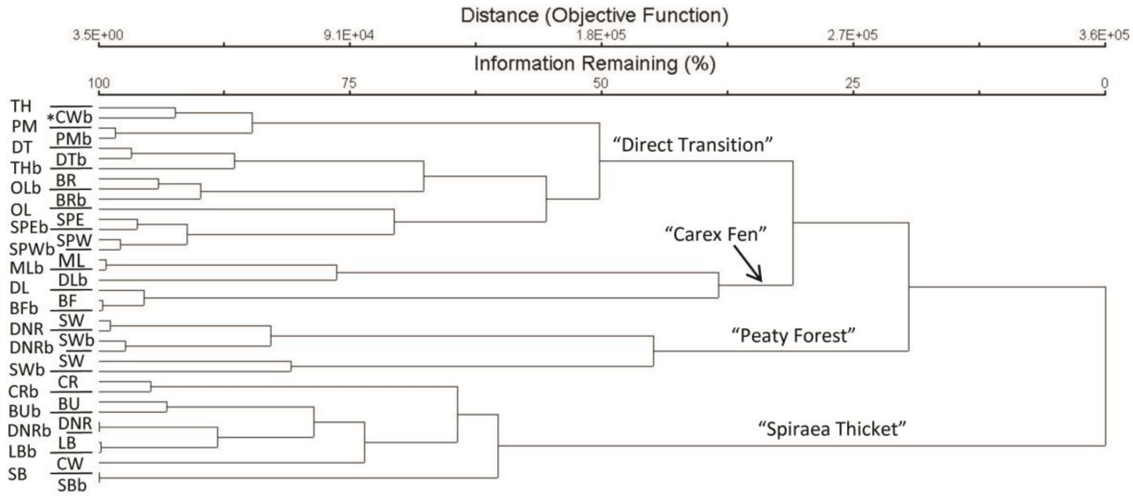

Figure 44. ***Dendrogram of the hierarchical agglomerative cluster analysis results showing the classification of lagg vegetation into four types. See Table 18 for site codes. Suffix "b" represents the parallel vegetation plot for each site. "CWb" is considered an outlier (*) as it was classified as the Direct Transition lagg type, whereas the "CW" plot was classified as Spiraea Thicket. "TH", "THb", "BR" and "BRb" were classified in this cluster analysis under the Direct Transition lagg type, but were classified by us as Peaty Forest based on the low ash content in the peat samples.***

7.4.3. Influence of Environmental Conditions on Lagg Vegetation

Hydrochemical differences between the lagg types were not very clear. Concentrations of Ca^{2+}, Na^{+}, and Mg^{2+} (and, consequently, pH-corrected electrical conductivity) were generally higher in the FT laggs, but were not significantly different from the MD laggs (Table 19). The Direct Transition laggs had higher EC_{corr} and Ca^{2+} concentrations compared to the other three lagg types (Table 19), but this difference was not significant either. We did not find a significant difference between the four lagg types for any of the hydrochemical parameters, ash content at any depth, or peat depth (Table 19). There was a significant correlation between cover of *Empetrum nigrum* and EC_{corr} (r_s=0.598) and Na^{+} concentration (r_s=0.630), and between cover of *Myrica gale* and Mg^{2+} (r_s=-0.595) and Na^{+} (r_s=-0.656) concentrations. Cover of the other most abundant understory lagg species (i.e. species with the greatest overall cover): (*Gaultheria shallon*, *Spiraea douglasii*, *Ledum groenlandicum*, *Carex sitchensis*, *Sphagnum pacificum* Flatb.) were not significantly correlated with any of the hydrochemical parameters.

The CCA test showed that all environmental parameters (latitude, mean annual temperature, mean annual precipitation, depth to water table, hydrochemical characteristics, peat depth, and ash content at 10 and 50 cm below the surface) together accounted for only 28% of the species variance. Axis 1 was most strongly correlated with ash content at 50 cm depth (0.614), depth to water table (-0.494), and peat depth (-0.458) and explained 11.5% of species variance. Axis 2 explained 8.8% of species variance and was most strongly correlated with the climate-related variables (mean annual temperature (0.728), mean annual precipitation (-0.680), and latitude (-0.656)), but also with hydrochemical parameters (pH (-0.492) and Ca^{2+} (-0.575) and Mg^{2+} (0.491) concentrations). Axis 3 explained 7.9% of species variance and was also correlated with latitude (0.370) and mean annual temperature (-0.321).

Table 19. Measurement range (and mean) for the LG sites on the transects of the four vegetative lagg types in coastal British Columbia. Superscripts letters denote that the parameter was significantly different from a lagg type with another superscript letter; parameters without a superscript letter were not significantly different between the four vegetative lagg types.

Parameter	Marginal Depression		Flat Transition	
	Carex Fen	**Spiraea Thicket**	**Peaty Forest**	**Direct Transition**
Number of sites (n)	3	6	4	5
Dominant plant species	*Carex sitchensis*, *Sphagnum* spp., *Myrica gale, Lysichiton americanum,*	*Spiraea douglasii, Sphagnum* spp., *Gaultheria shallon*, *Rhamnus purshiana*	Ericaceous shrubs, *Thuja plicata*, *Tsuga heterophylla*, *Picea sitchensis*	Ericaceous shrubs, *Thuja plicata*, *Chamaecyparis nootkatensis*, *Pinus contorta* v. *contorta*
Species richness (# of species in 5 x 5 m plot)	7-17 (11.5)^{a}	3-11 (8.2)^{a}	5-17 (9.7)^{a}	12-18 (15.2)^{b}
Water table depth below surface (m)	0.07 – 0.21 (0.12)^{a}	0.00 – 0.41 (0.12)^{a}	0.19 – 0.47 (0.33)^{ab}	0.14 – 0.50 (0.35)^{b}
Tree basal area (m^2/ha)	0.2 - 7.2 (4.6)^{a}	0.0 – 2.7 (1.0)^{a}	11.5 – 67.2 (36.7)^{b}	9.6 – 25.4 (15.8)^{b}
Tree height (m)	0.7 – 4.0 (2.2)^{ab}	2.4 - 8.4 (4.7)^{a}	1.4 - 20.2 (10.4)^{ab}	0.7 – 1.2 (0.9)^{b}
Number of trees in plot	1-123 (56)	0-5 (2)	5-180 (44)	38-378 (137)
Peat depth (m)	0.7-2.0 (1.2)	0.3-2.4 (1.0)	1.4-9.0 (4.0)	0.6-1.6 (0.9)
Ash content of soil (%) at 10 cm depth	2.2 – 14.2 (6.6)	4.5 – 52.0 (22.6)	2.4 – 5.4 (3.6)	1.8 – 58.5 (15.2)
Ash content of soil (%) at 50 cm depth	7.8-33.6 (16.9)	3.0-94.7 (46.8)	0.0-4.0 (1.9)	1.6-35.8 (19.2)
Ash content of soil (%) at 100 cm depth	5.1-10.4 (7.7)	4.6-94.6 (35.7)	1.4-3.4 (2.2)	2.0-83.4 (47.6)
EC_{corr} (μS/cm)	23 – 84 (49)	25 – 78 (50)	18 – 117 (69)	60 – 238 (111)
Ca^{2+} (mg/l)	1.3 – 3.7 (2.1)	1.8 – 4.0 (3.2)	1.3 – 4.6 (2.7)	2.0 – 10.9 (5.6)
Mg^{2+} (mg/l)	0.2-1.0 (0.5)	0.5-1.5 (0.8)	0.2-1.8 (1.2)	0.4-1.7 (1.0)
Na^{+} (mg/l)	0.9-8.6 (3.6)	1.6-6.2 (3.2)	1.4-16.6 (7.4)	1.3-8.5 (5.8)
K^{+} (mg/l)	0.8-3.8 (1.8)	0.6-10.8 (3.9)	2.4-8.3 (4.6)	2.2-88.7 (21.7)
pH	4.27 – 5.34 (4.72)	4.17 – 6.29 (4.94)	3.64 – 5.42 (4.56)	4.07 – 6.02 (5.15)

7.5. Discussion

7.5.1. Classification of Laggs into Hydrotopographic Forms and Vegetative Types

Two main hydrotopographic lagg forms were found in the studied coastal BC bogs: Marginal Depression and Flat Transition. These two distinct hydrotopographic forms were alluded to by Damman (1977), who reported for eastern North America that flatter bogs tend to blend into forest at the bog margin without a distinct lagg ecotone, whereas domed bogs have a pronounced slope at their margins, adjacent to which a "lagg moat" develops. Godwin and Conway (1939) described Osvald's (1937) observations of bogs that extend up the sides of a valley, where the lagg was "feebly developed". This condition is similar to some of the bogs in our study (e.g. Butze Rapids, Oliver Lake) where peat was found in the forest adjacent to the bogs. The National Wetlands Working Group (NWWG) (1988) reported that raised bogs in southern coastal BC generally have a well-defined lagg at (at least part of) the bog margin, whereas raised bogs on the north coast often blend into slope and basin bogs, so that the bog margin or lagg is difficult to delineate. The two hydrotopographic lagg forms can be difficult to distinguish visually in the field; for example, the MD LG sites in our study were 0.63 m higher to 2.16 m lower (mean: 0.61 m lower) in elevation than the BG sites on the transect; the FT LG sites were 1.85 m higher to 1.63 m lower (mean: 0.09 m higher) in elevation than the BG sites. Furthermore, there was not a significant difference in surface gradient or hydraulic gradient from bog to lagg for our study sites between the MD and FT lagg forms (Chapter 5), although the lagg was generally lower than the bog in MD laggs and higher than the bog in FT laggs (Fig. 38). In bogs with short vegetation, the depression at the bog margin may be visually evident; in other cases, the gradient can be subtle or may be obscured by tall vegetation and require a detailed topographic survey or LiDAR data. Differences in plant communities are easier to identify in the field (e.g. the presence of fen or swamp species at the bog margin) than subtle topographic changes.

The topographic depression at the bog margin of the MD laggs causes water to pool, which promotes a relatively high water table. Comparatively better drainage in the FT laggs results in a lower water table, although the June/July water table was only significantly lower in the Direct Transition laggs, not the Peaty Forest laggs. The vegetative response to the high water table in the MD laggs included a significantly lower tree diameter and basal area compared to the FT laggs, and dominance of fen and swamp species such as *Carex* spp. and *Spiraea douglasii*. The number of trees in the plots increased significantly with increasing depth to water table. There were fewer trees in the Spiraea Thicket laggs compared to the other lagg types (Table 19), but the difference was not significant, possibly due to the small number of LG tree plots (n=19). There was also a significant negative correlation between the number of trees in the lagg and mean annual temperature; laggs in warmer locations contained few large trees, whereas laggs in cooler locations had many small trees (Chapter 6). The greater number of (small) trees in the northern laggs may be related to nutrient fluxes. The northern laggs were often situated on a slope between bog and forest, and the mean annual precipitation is greater at these sites. These conditions could allow water to move more quickly through the lagg compared to sites with a Marginal Depression, thereby increasing the availability of dissolved nutrients per unit time (Ballard and Cole, 1974).

The two hydrotopographic lagg forms were classified into four vegetative lagg types: Carex Fen, Spiraea Thicket, Peaty Forest, and Direct Transition (with no lagg ecotone). Étienne Paradis (Ph.D. candidate, Université Laval, personal communication 2012) found four lagg types in a study of raised bogs on the east coast of Canada, which have similar characteristics to those described in this paper, including a shrubby swamp (similar to Spiraea Thicket), a graminoid-dominated fen (similar to Carex Fen), a peaty forested swamp (similar to Peaty Forest), and no ecotone (similar to Direct Transition). This suggests that these four main vegetation lagg types may be the most common lagg types at the margins of undisturbed bogs in coastal areas of the North America. However, there will be exceptions, such as where conditions at the bog margin are different from those studied here. For example, the outward growth of a bog could be limited by a watercourse and regular flooding (Wheeler and Shaw 1995), so that a "riparian lagg" ecotone could develop, which was not observed for the 13 bogs studied here.

The Direct Transition laggs are different from the other lagg types in that they do not represent a visually-evident ecotonal plant community, but rather an abrupt transition between bog and forest that correlates with an increase in ash content in the peat at the bog margin. A possible explanation for the lack of an obvious ecotone in the lagg is that the studied Direct Transition bogs are in an earlier stage of development. Theoretically, if peat continued to accumulate in these bogs, the lagg would eventually be lower than the bog and a Marginal Depression lagg could form. This could occur, for example, at Drizzle Lake Bog, Shorepine Bog, and Port McNeill Bog where the gradient from bog to forest is low (Chapter 5). The bogs of the north coast have a greater number of herbaceous plants compared to bogs in the south, which may indicate that these bogs are indeed at an earlier stage of development (NWWG, 1988). However, in other cases, such as Oliver Lake bog, the bog extended up a slope and the transition from bog to forest was 1.9 m higher than the main area of the bog. Thus, some of the Direct Transition laggs may be bogs at an early stage of development, where lagg ecotones could develop if peat accumulation raised the bog higher than the lagg, but there are other instances (e.g. slope bogs) where this may not occur.

The proposed classification of the forms and types of laggs (Appendix F) based on topography, depth to water table, vegetation, and ash content of the peat may assist land managers in delineating representative and functional conservation areas that include the critical lagg transition for bogs by providing a list of lagg indicators, namely: 1) topography, 2) depth to water table, 3) tree basal area, 4) dominant plant species, and 5) ash content of the peat. These results also establish measurable parameters and an initial range of expected values (Table 19) for each lagg type to guide the restoration of laggs. Knowledge of these ranges may aid in the development of reference ecosystemss for restoration using the lagg indicators, and help managers to determine the appropriate lagg type for a restoration site based on climate, wetland region, and topography. Finally, this information may also be useful in an initial assessment of the ecological health of a given lagg site. Further work is required in the form of additional data collection in laggs throughout coastal BC, particularly in the latitudes not covered by this study (i.e. between $50^{0}34'$ N and $53^{0}37'$ ^{0}N), to confirm these results and refine the ranges of the hydrochemical parameters and peat properties for each lagg type.

7.5.2. Regional Variation

The clear regional difference in lagg plant communities between the bogs of 1) the north coast and northern/western Vancouver Island (Pacific Oceanic wetland region), and 2) those of eastern Vancouver Island and the Fraser Lowland (Pacific Temperate wetland region), appear to be driven by climate although the CCA results show that mean annual temperature, mean annual precipitation, and latitude explain only a small part of the observed species variance. Asada et al. (2003) determined that the summer moisture deficit, which determines the lowest level of the water table and the residence time of the water table at various depths, had the greatest effect on species composition in Diana Lake Bog. This measure was not included in this study, but may have a strong influence on lagg plant community development. The Pacific Oceanic wetland region is cooler and wetter than that of the Pacific Temperate wetland region. In general, the Pacific Oceanic wetland region supports the Carex Fen and Direct Transition lagg types, whereas the Spiraea Thicket and Peaty Forest lagg types were more common in the Pacific Temperate wetland region, although there were exceptions to this division (e.g. the FN transect in Blaney Bog was classified as Carex Fen, but is located in the Pacific Temperate wetland region). Golinski (2004) recommended that Port McNeill Bog be included in the South Coast subregion of the Pacific Oceanic wetland region, instead of the Pacific Temperate wetland region, on the basis of its vegetation. The results of our cluster analysis of the LG sites agree with this recommendation; however, the plant communities of the BG sites were more similar to those in the Pacific Temperate wetland region (Chapter 6).

Depth to water table and climate appear to be key factors determining whether a MD lagg will develop a Carex Fen or Spiraea Thicket plant community, although the early summer depth to water table wasn't significantly different between the two types. In *Carex sitchensis*-*Sphagnum* fens, the water table is near the surface most of the time (measured on the BF transect of Blaney Bog), whereas the sites dominated by *Spiraea douglasii* thickets (i.e. Langley Bog, Surrey Bend, Campbell River Bog, and the DNR and CW transects of Burns Bog) experience flooding in the wet season but have a water table below the surface for much of the growing season (Howie and van Meerveld, 2012; MacKenzie and Moran, 2004). The warmer, drier climate of the Pacific Temperate wetland region may partly explain the dominance of the Spiraea Thicket lagg type in this geographic area as less precipitation and higher temperatures in the summer (Chapter 5) likely results in a larger fluctuation in the water table and a lower water table at the end of summer than in the Pacific Oceanic wetland region. *Spiraea douglasii* may be more tolerant of a fluctuating water table than the species that characterize the Carex Fen lagg type (e.g. *Carex sitchensis*, *Myrica gale*, *Lysichiton americanum*; Table 19) (MacKenzie and Moran 2004, Hebda et al. 2000).

CCA ordination showed that latitude and climate-related factors (mean annual temperature, and mean annual precipitation) explained only 15% of the species variance in lagg plant community composition (Chapter 6), which suggests that climate is not the main factor influencing vegetation at the bog margin. All of the parameters combined explained only 28% of species variance, which suggests that there are other key factors (e.g. inter-specific competition, shading, water level in winter or late summer, mean, minimum, and maximum volumetric soil moisture content in the rooting zone) that we did not measure affect species composition in the lagg. One of the challenges with this type of analysis is that the tested variables were correlated with each other so that it is difficult to determine which of the correlated factors has the greatest influence on plant community composition. Another confounding factor is the influence of geographic distinctiveness in dominant lagg species, meaning that all species are not equally available for all sites and regions; for example, *Empetrum nigrum* was widespread in the northern bogs, but was less common in the southern bogs (Chapter 6). In addition, many of the lagg sites in this study may have been influenced by minerotrophic water from the adjacent MN sites, the properties of which may be highly variable even around a single bog. For example, pH and Ca^{2+} concentrations in the MN sites ranged from 4.24-6.68 and 2.0-19.3 mg/l, respectively (Chapter 5); however, there was no significant difference in any hydrochemical parameter or ash content between the Marginal Depression and Flat Transition MN sites, or between the Pacific Oceanic and Pacific Temperate wetland region MN sites.

7.6. Conclusion

Topographic surveys and depth to water table measurements revealed that there are two hydrotopographic lagg forms for the coastal BC bogs that we studied: Marginal

Depression (MD) and Flat Transition (FT). A topographic depression, high water table, and low tree basal area are indicative of the MD lagg form. MD lagg sites were characterized by a dense cover of *Carex* spp. (especially *Carex sitchensis*) and *Sphagnum* spp. (=Carex Fen lagg type), or *Spiraea douglasii* and *Sphagnum* spp. (= Spiraea Thicket lagg type). These lagg types represent 50% of the studied laggs and fit the classic definition of lagg, i.e. a transition zone at the margin of a (usually raised) bog receiving water from both the bog and surrounding mineral ground. On the other hand, tree basal area gradually increased across the transition from bog to forest for the Flat Transition lagg form. Because differences in plant community composition were less clear for the FT laggs, the lagg types were classified on the basis of ash content of dry peat samples at 50 cm depth and tree height. Laggs with ash content >5% at 50 cm depth were classified as a Direct Transition lagg type, for which there is no ecotone at the bog margin. Laggs with ash content <5% were separated using tree height; those laggs with an average tree height >1.3 m were classified as Peaty Forest, while those with an average tree height <1.3 m were also classified as Direct Transition.

Most of the laggs in the Pacific Oceanic wetland region were classified as either a Carex Fen or Direct Transition lagg type, whereas most of the laggs in the Pacific Temperate wetland region were classified as a Spiraea Thicket or Peaty Forest lagg type. These regional differences appear to be related to climate and depth to water table in the lagg, although early summer depth to water table was not significantly different between the two wetland regions and CCA results showed that climate and depth to water table explain only a small part of the observed variation in species. Hydrochemical characteristics were not significantly different between the four lagg types. The MD laggs had lower cation concentrations and electrical conductivity than the FT laggs (Table 18), but this difference was not statistically significant. The proposed classification for the forms and types of laggs in coastal BC based upon topography, early summer depth to water table, vegetation, and ash content of peat may be useful for delineating bog conservation areas that include the lagg by providing a list of lagg indicators.

8. Characteristics of lagg remnants of Burns Bog in British Columbia, Canada, and recommendations for lagg restoration

8.1. Abstract

The lagg is an integral part of the hydrological system of a raised bog. Conservation and restoration of raised bogs should therefore involve consideration of the hydrological, hydrochemical, and ecological characteristics of this transition zone. Undisturbed parts of the lagg of Burns Bog, British Columbia, Canada, were studied with the objective of mapping the lagg remnants and developing a list of lagg indicators, in order to enhance our understanding of this transitional zone at the bog margin and assist management agencies in developing conservation and restoration strategies for Burns Bog and other local bogs. Much of the historic lagg of Burns Bog has been converted to agriculture and industry. Similar to laggs of other bogs in the Fraser Lowland, lagg remnants of Burns Bog could generally be separated into two vegetative lagg types: Spiraea Thicket (dominated by a dense cover of *Spiraea douglasii* with few trees; mean basal area: 0.1 m^2/ha) and Peaty Forest (with deep peat (>4 m) and tall trees; mean basal area: 58.7 m^2/ha). Electrical conductivity was higher in the Peaty Forest laggs, but there was no difference in pH or concentrations of Ca^{2+} and Mg^{2+} between the Peaty Forest and Spiraea Thicket lagg types. Analysis of historic maps shows that lagg plant communities have colonized parts of Burns Bog that were historically open bog or marginal forest. This suggests that it is possible to create the ecohydrological conditions of a lagg in areas that are currently occupied by bog species. To protect a representative sample of the rare bog-lagg transitional ecosystem in this region and maintain the ecohydrological integrity of the bog, conservation of historic lagg remnants that are currently under private ownership is recommended.

8.2. Introduction

Raised bogs often include a transitional zone with a distinct plant community at the bog margin called the “lagg”. This vegetative ecotone forms as a result of a hydrochemical gradient from ombrotrophic bog water to minerotrophic water in the surrounding area. These two types of water mix in the topographic low point at the bog margin, resulting in a transitional water type that supports fen or swamp species. In the field, the lagg is generally identified by this transitional plant community, but may also be based on gradients in key hydrochemical parameters such as pH and calcium concentrations (Balfour and Banack 1999) or ash content of the peat (Chapter 5, Chapter 7). Topography can be a clear indicator of the lagg location, but may be difficult to distinguish in the field. However, LiDAR elevation data can provide an accurate digital elevation model of the bog topography; for example, LiDAR-derived lagg locations at the margins of forested peatlands of Ontario and Minnesota were correlated with higher concentrations of pore-water methylmercury compared to the raised, central dome of the peatlands (Richardson et al., 2010).

It has been suggested that the low permeability of lagg peat helps to maintain a high water table in the lagg, thereby reducing the outward hydraulic gradient from the bog (Schouten, 2002). The lagg is also important for regional biodiversity, because the fen and swamp plant communities that develop in the lagg may be regionally uncommon or may provide important corridors for wildlife. Based on the understanding that the lagg is a critical element of the bog ecosystem, management agencies in Europe have begun to incorporate the lagg into raised bog conservation areas (Schouten, 2002; Morgan-Jones et al., 2005; Mawby and Brock, 2007). Studies on the lagg have been initiated in recent years on the east coast of Canada (Paradis and Rochefort, 2009, 2012) and in British Columbia (Howie et al., 2009a; Howie and Tromp-van Meerveld, 2011, 2012), suggesting increasing awareness of the importance of the lagg in Canada as well.

Clear gradients in depth to water table, hydrochemistry, peat properties, and vegetation have been observed across the transition from the bog expanse to the bog margin. Depth to water table generally increases from bog to lagg, except in cases where there is a topographic depression at the bog margin (Chapter 5; Damman, 1986). The water table generally fluctuates more in the lagg than in the bog expanse (Howie and van Meerveld, 2012). Concentrations of Ca^{2+} and Mg^{2+}, as well as pH, often increase from bog to lagg (Bubier, 1991; Bragazza et al., 2005; Richardson et al., 2010), although these pore-water properties may only increase gradually across the lagg transition and may not be clear indicators of the position of the lagg (Chapter 5). The temporal variability of ion concentrations (e.g. Ca^{2+} and Mg^{2+}) may be greater in the lagg than in the bog (Chapter 5), partly because the lagg is influenced by minerotrophic water from adjacent lands, and because bog peat is buffered from dilution caused by heavy rainfall, evaporative concentration, and temporal variations in precipitation chemistry due to its high cation exchange capacity. Ash content of near-surface (e.g. 0-50 cm below the surface) peat often increases from bog to lagg as well (Chapter 5), and may be several times higher in the lagg compared to the bog (Gorham, 1950). The lagg may have a distinct plant community (e.g. shrub thicket or graminoids-dominated fen) in some locations, but in other places, species composition may change gradually or abruptly from bog to forest without a distinct lagg ecotone (Chapter 7). Both climate and topography appear to influence the variation in lagg and bog plant communities (Chapter 6).

The goal of this study was to provide an analysis of the historic and current conditions of the lagg of Burns Bog, which will assist management agencies (The Corporation of Delta and Metro Vancouver) in carrying out the action items as described in the Burns Bog Ecological Conservancy Area Management Plan as they pertain to the lagg of Burns Bog. In 2005, the Burns Bog Scientific Advisory Panel was formed to provide scientific advice on the hydrological and ecological management of Burns Bog, Delta, BC. Early on, the Panel noted the importance of the lagg in the context of raised bog management and restoration. A workshop was held with local scientists at the University of British Columbia in 2006 to summarize the current extent of knowledge about laggs, and to develop a list of research priorities to improve the understanding of the lagg of Burns Bog (Peart, 2006). One of the high-priority management action items identified in the Burns Bog Ecological Conservancy Area Management Plan (2007) is to manage the lagg of Burns Bog, including delineation and study of existing lagg remnants, identification of additional lagg areas for protection, and development of lagg restoration plans. While this study focuses specifically on Burns Bog, the principles and results may also be applicable to other bogs.

8.3. Methods

8.3.1. Study Site

This study took place in Burns Bog, Delta, BC. Burns Bog is a 3,000 ha raised bog situated between the Fraser River and Boundary Bay. Burns Bog has a long history of disturbance, including a major peat mining operation in the centre of the bog between the 1930s and the 1980s, extensive fires (including a 200 ha fire in 2005 that burned for two weeks), and conversion to other land uses. The peat mining operation, as well as drainage and filling for other land uses (including a landfill) at the edge of the bog, have resulted in a network of drainage ditches throughout the bog centre and at the perimeter of the remaining bog area. The ditches have lowered the water table of the bog, particularly at the bog margin and in the lagg, resulting in peat subsidence and the establishment of pine and birch trees, which further lower the water table through increased interception and evapotranspiration (Hebda et al., 2000; Howie and van Meerveld, 2012). Large areas of the lagg have been destroyed in the conversion to farmland, highways, and industrial use. However, some portions of the lagg remain in a relatively undisturbed state, as do large areas of open bog and marginal forest.

8.3.2. Study Transects

Three lagg remnants in Burns Bog were studied (Fig. 45, 46). The “Sherwood” site contains a mature coniferous forest (dominated by *Thuja plicata* Donn., *Tsuga heterophylla* (Raf.) Sarg., and *Picea sitchensis* (Bong.) Carr.) growing on a thick layer of peat (>2.5 m); this lagg is located adjacent to a slough that was tidally-influenced prior to settlement and dyking of the area. The “Cranwest” lagg, which has been largely replaced by a cranberry farm, is characterized by a dense thicket of *Spiraea douglasii* Hook., *Ledum groenlandicum* Oeder, and *Sphagnum* mosses. The third studied lagg remnant, located in the Delta Nature Reserve (DNR), contains elements of the two other laggs: i) a dense thicket of *Spiraea douglasii* and ii) a coniferous forest on deep peat (>9 m) dominated by *Thuja plicata*, *Tsuga heterophylla*, and *Pinus contorta* var. *contorta*. Historically, the thicket of *Spiraea douglasii* on the DNR transect was part of the topographic low point between the bog and forest, where runoff from the bog and adjacent minerotrophic upland would collect and then flow north to the Fraser River and south to Boundary Bay. Extensive peat mining in Burns Bog has lowered the surface by 1-2 m (Hebda et al., 2000), and a highway constructed in 1986 through the original lagg drainage zone has created a barrier to water movement between the bog and lagg. Despite these major disturbances, the area to the east of the highway appears to be similar in form to historic conditions based on air photo interpretation, except that tall trees are now more widespread in the forest area between the *Spiraea douglasii* thicket and the minerotrophic upland.

Study transects were installed across each of the three lagg remnants (Fig. 45, Table 20). The Sherwood transect contained six monitoring sites, the Cranwest transect five, and the DNR transect four. On the Sherwood and Cranwest transects, one study site was located in the open bog (BG), two in the rand (the outward-sloping margin of a raised bog) (R1 and R2), one (Cranwest) or two (Sherwood) in the lagg (LG), and one in the mineral soil outside the bog (MN). The same points were studied on the DNR transect, except that there were no study sites in the rand due to impacts of peat mining and the highway in the zone between the bog and lagg. All locations were recorded with an Oregon 300 handheld GPS unit, accurate to 5 metres. Surface elevations along the transects were determined using LiDAR data from September 2008, accurate to 15 cm.

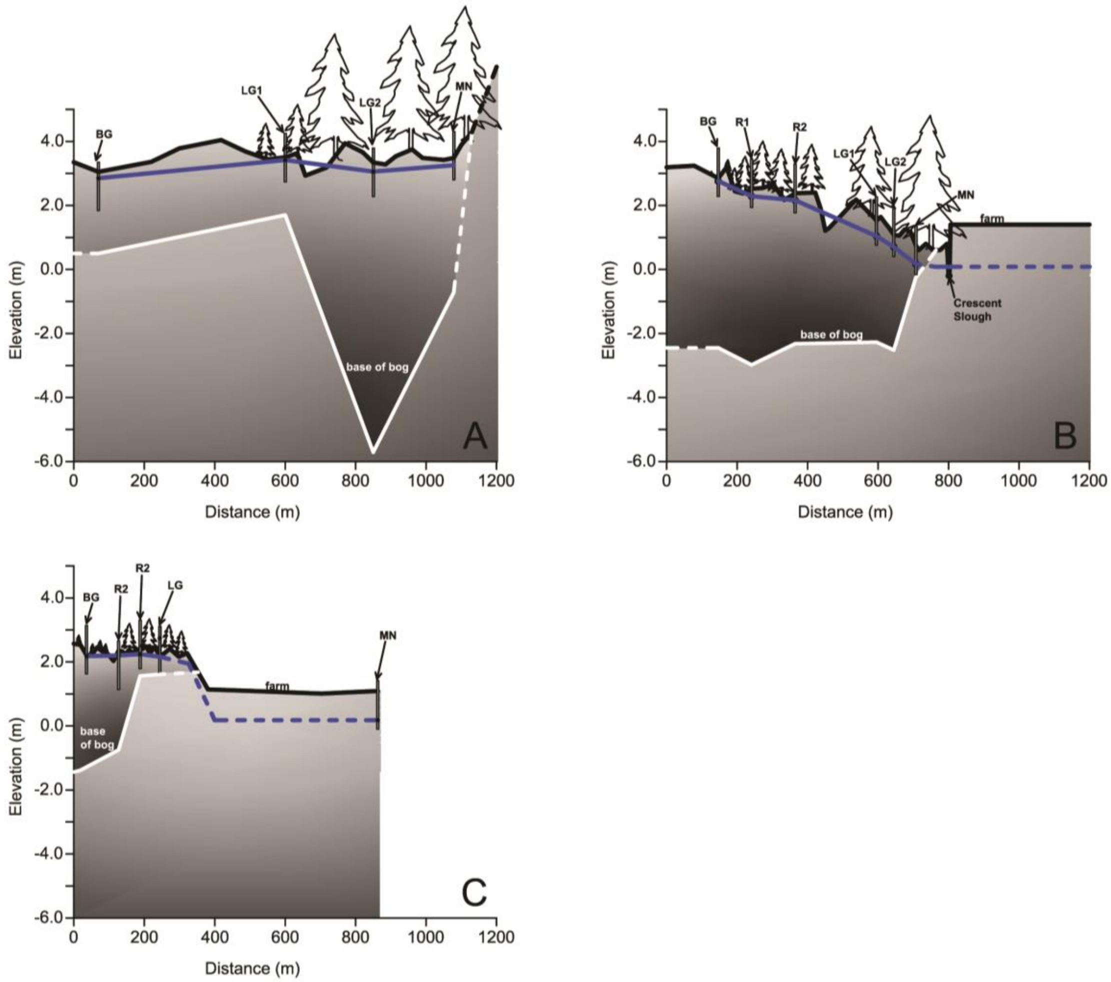

Figure 45. ***Transect profiles for the three study transects in Burns Bog: a) DNR, b) Sherwood, and c) Cranwest. Vertical exaggeration: 90x. The blue line with the symbols represents the water table, and the white line represents the base of the peat. Dashed lines are estimated values.***

8.3.3. Field Methods

Peat Sampling

At each of the sampling locations along the transects, peat samples were collected at 10, 50, and 100 cm below the surface with an Eijkelkamp flag corer. For each of the peat cores, the von Post scale of humification was determined in the field to record the various degrees of humification in the cores. Samples from the three depths were wrapped in plastic wrap and sealed in plastic freezer bags for later laboratory analysis. Core samples were transported from the field in a cooler and kept refrigerated up to one month, or frozen up to 9 months. In the lab, each 5-cm sample was weighed, oven-dried at 105 ºC for 24 hours and weighed, and then dry-ashed in a 550 ºC oven for 24 hours and weighed a final time to determine the amount of mineral (i.e. non-organic) material in the sample. In order to determine the depth of peat at each coring location along the transect, the same peat corer was used to auger down to the underlying mineral material.

Vegetation Survey

At each point on the study transects, we recorded cover of all species in a 5 x 5 m plot using the Braun-Blanquet scale of cover and abundance: "r"=solitary with small cover, "+"=few with small cover, "1"=numerous but <5% cover, "2"=5-25% cover, "3"=25-50%, "4"=50-75%, "5"=>75% (Mueller-Dombois and Ellenberg, 1974). In a 10 x 10 m plot at the same location, we determined the species, height, and diameter of all trees, except seedlings less than 20 cm tall. Diameter (DBH) was measured at 1.4 m unless trees were shorter than 2 m, in which case, diameter was measured mid-way along the stem. Trees less than 1 cm in diameter were assigned a diameter of 0.5 cm for analysis purposes. A parallel transect of 5 x 5 m vegetation plots was studied 20 m from each main transect for replication, leading to a total of 30 vegetation plots and 15 tree plots. Nomenclature followed Hitchcock and Cronquist (1973).

Depth to Water Table Monitoring

Piezometers were installed in April/May 2010 at each of the peat coring locations to determine depth to water table. The piezometers were 1.5 m long, 2.5 cm diameter PVC pipe with a 40 cm slotted length at the bottom. Prior to each sampling event, the piezometers were evacuated twice using a low-flow peristaltic pump. The piezometers were given 1-2 weeks to recharge before the water level was measured with an electronic water level probe (Heron Instruments "Little Dipper") every 1-2 months between June 2010 and December 2011 on the Sherwood and Cranwest transects and every 3 months on the DNR transect; measurement frequency on the Sherwood transect increased to weekly after unexpected clearcut logging in June 2011 in the lagg forest (Howie and van Meerveld, 2012).

Water Chemistry Monitoring

Water samples were taken at each piezometer after the water level measurements. The BG piezometer on the DNR transect was vandalized in spring 2011. Due to the loss of the piezometer and difficult site access, no further sampling or water level monitoring took place at this site after December 2010. In the field, pH and electrical conductivity were measured directly in the top 10-15 cm of the water column of the piezometers with a WTW Multiline handheld meter. The probes were rinsed with distilled water before every measurement to avoid contamination of the water in the piezometer. For samples with a pH lower than 5.0, conductance due to the hydrogen ions is a significant component of the measured electrical conductivity (Rydin and Jeglum, 2006). It was therefore necessary to subtract the hydrogen ion conductivity from the measured conductivity to get the corrected conductivity, using the following formula: $EC_{corr} = EC_{measured} - EC_{H^+}$, where $EC_{H^+} = 3.49 \times 10^5 \times 10^{-pH}$ and 3.49×10^5 is the conversion factor for field measurements standardized to 25 ^{0}C (Rydin and Jeglum, 2006).

A low-flow peristaltic pump was used to collect water samples into plastic bottles for laboratory analysis of Ca^{2+} concentrations using inductively coupled plasma spectrometry. To avoid contamination of the water samples, the tubing was rinsed with water from each site prior to collection. When possible, samples were delivered unfiltered and unpreserved to the Pacific Environmental Science Centre (Environment Canada) within 24 hours; otherwise, water samples were filtered in the field with a 0.45 micron filter (Waterra FHT-45), preserved with nitric acid, and delivered to the laboratory within 48 hours.

8.3.4. Additional Water Level and Chemistry Data

Additional water level and chemistry data from five other studies were used to augment the results of this study and fill in data gaps at lagg locations not included in this study:

1. The hydrochemical transition from bog to lagg was studied in 2009 at four additional transects by Hendry (2009); pH and EC were measured directly in shallow piezometers, or in a plastic cup into which water from the top of the water column in the piezometer was

pumped at the rate of recharge; water samples were analyzed for Ca_{2+} concentrations at a commercial lab (Exova, Surrey, BC) using inductively coupled plasma – atomic emission spectrometry (ICP-AES).

2. Water chemistry in shallow piezometers was monitored for another transect in the southwest corner of Burns Bog in 2011; pH and EC were measured in the field, and water samples were collected from the piezometers, field-filtered, preserved with nitric acid, and sent to ALS Environmental Laboratory (Burnaby, BC) for analysis of major cations using inductively coupled plasma – mass spectrometry (ICP – MS) (Golder Associates, 2011a).
3. Ten transects along the northern and western margins of Burns Bog were monitored as part of an environmental monitoring program for a highway construction project (Golder Associates, 2011b); this study used the same methodology as the study in the southwest corner of Burns Bog (#2).
4. Water chemistry was determined for one transect in the southeast corner of Burns Bog using the same methodology as this study in 2011 and 2012 (unpublished data provided by The Corporation of Delta). Water samples were analyzed by Exova (using ICP-AES) and ALS (using ICP-MS) labs.
5. Another study collected water level and water chemistry data in the northeast corner of Burns Bog; pH and EC were measured in the field, and water samples were analyzed by Maxxam Analytics, Burnaby, BC using ICP-AES (Enterprise Geosciences, 2006, 2011).

These data, along with newly collected data for this study, are summarized in Figs. 46, 47, and 48. A total of 99 piezometers were used to determine depth to water table; 63 winter samples and 75 summer samples were used to characterize pore-water chemistry.

Table 20. Coordinates of the sampling locations along the three Burns Bog transects.

Sample Location	Latitude N	Longitude W
Sherwood – BG	49°06’26”	123°01’10”
Sherwood – R1	49°06’26”	123°01’15”
Sherwood – R2	49°06’26”	123°01’22”
Sherwood – LG1	49°06’25”	123°01’32”
Sherwood – LG2	49°06’25”	123°01’35”
Sherwood – MN	49°06’24”	123°01’38”
Delta Nature Reserve – BG	49°08’16”	122°56’11”
Delta Nature Reserve – LG1	49°08’29”	122°55’54”
Delta Nature Reserve – LG2	49°08’31”	122°55’41”
Delta Nature Reserve – MN	49°08’36”	122°55’32”
Cranwest – BG	49°07’26”	123°00’36”
Cranwest – R1	49°07’29”	123°00’38”
Cranwest – R2	49°07’30”	123°00’40”
Cranwest – LG	49°07’32”	123°00’42”
Cranwest – MN	49°07’41”	123°01’09”

8.3.5. Maps

In the 1850s, surveyors visited Burns Bog and recorded their observations of the vegetation in the area. In 1979, North and Teversham (1984) used the historic surveyor’s notes to create a map of historic vegetation of the Fraser River delta, including the Burns Bog area. A detailed paleoecologic survey of Burns Bog resulted in an even more detailed map of the historic vegetation (Hebda and Biggs, 1981). I used the information in these maps to create a map of the historic lagg of Burns Bog (Fig. 46a).

In 1999, a map of the current lagg areas, as delineated by a *Spiraea douglasii* swamp thicket plant community and specific ranges for pH (4.5-6.0) and Ca^{2+} concentrations (3-10 mg/l) in near-surface pore-water was created as part of an ecosystem review for Burns Bog (Hebda et al., 2000). Based on the additional information collected in this study, we have updated this map to include other lagg forms, including a peaty forest lagg type and disturbed lagg sites that are dominated by invasive species such as reed canarygrass (*Phalaris arundinacea* L.) (Fig. 46b). This map of the current lagg areas was compared with the historic vegetation maps of North and Teversham (1984) and Hebda and Biggs (1981) to determine the changes in lagg vegetation.

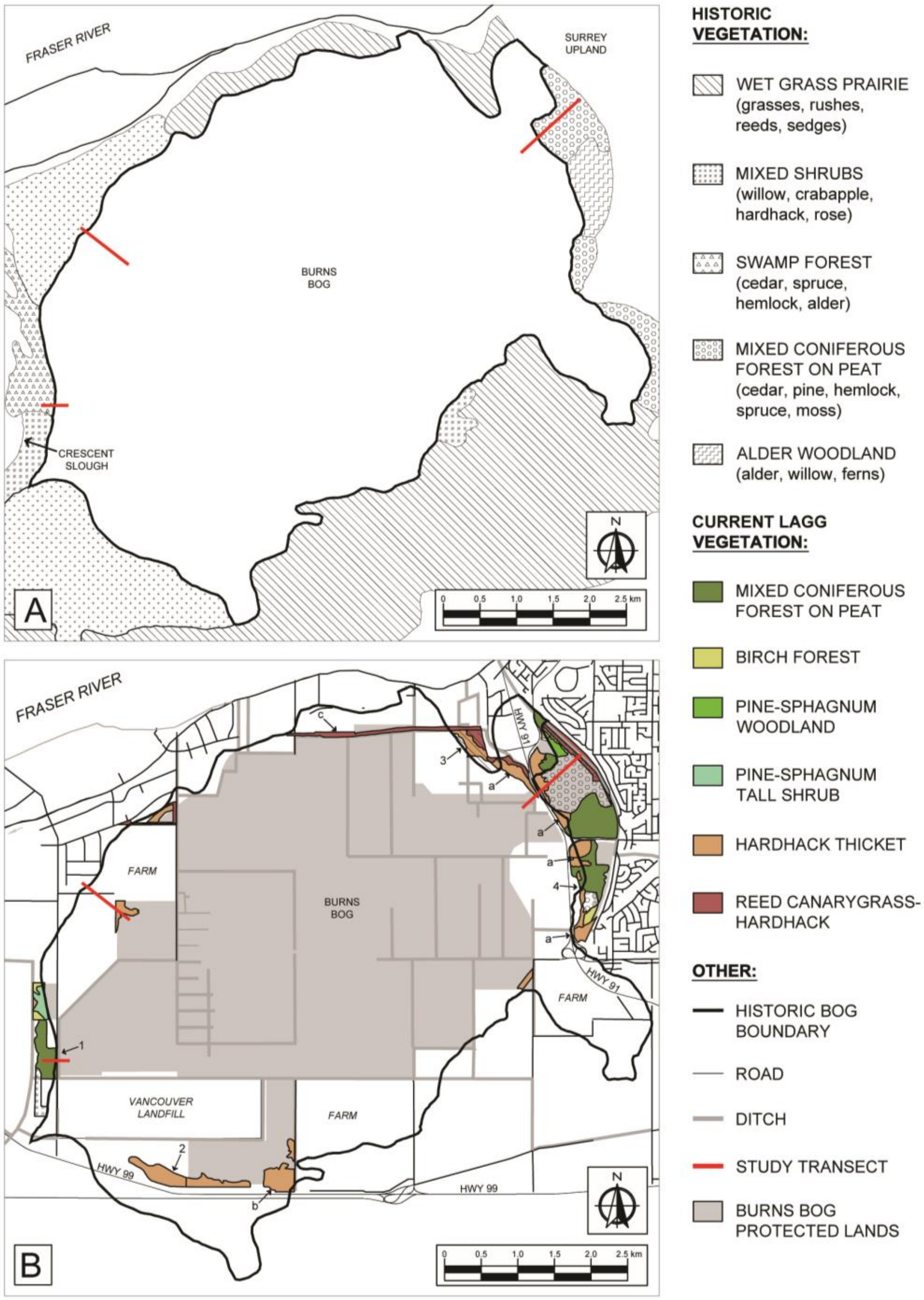

Figure 46. ***A) Historic lagg vegetation (modified from North and Teversham, 1984), and B) lagg remnants (modified from Hebda et al., 2000) of Burns Bog. Digital vegetation map files for "A" were provided by the Canadian Wildlife Service, and for "B" by the BC Environmental Assessment Office. Red lines represent the transect locations for this study. Numbers 1-4 in "B" delineate priority areas for conservation (see Appendix G). Letters a-c in "B" delineate newly-formed lagg sites.***

8.4. Results and Discussion

8.4.1. Water Mound and Water Chemistry in Burns Bog

Like a typical raised bog, Burns Bog contains a water mound within the peat mass that is several metres higher than the surrounding regional groundwater table. The high point of the water table ranges from 3.0 m above sea level (asl) in summer to 3.5 m asl in winter (Fig. 47). The elevation of the lagg is typically close to sea level, except on the eastern side of the bog where it borders the Surrey Uplands and is 3.5-4.5 m asl. The water mound expands outwards in winter (compare Fig. 47a and 47b) and is lower (by approx. 0.75-1.00 m) than its historical elevation, due to extensive drainage and loss of peat in the central part of the bog during the peat mining era (Hebda et al., 2000). An interesting feature of the water mound of Burns Bog is the secondary high point in the water table at the eastern edge of the bog. The high water table is supported by runoff from the upland area to the east. This area was also spared from peat extraction. It is likely that this eastern water mound was connected to the central water mound prior to peat mining, and that together they formed a high water ridge from east to west across the bog (Hebda et al., 2000). Prior to peat mining, drainage from the Bog was largely northwards and southwards from this central ridge (Hebda et al., 2000). The areas that were lowered by peat mining have created new drainage divides, such that a large portion of the bog now drains towards the northeast (Fig. 47).

As expected for a raised bog, pH was low (2.5-4.5) across most of the bog, and higher at the margin where there is a greater influence from minerotrophic runoff, though this was not true for all individual transects (e.g. the Sherwood transect) (Fig. 48a). Ca^{2+} concentrations were also lowest in the bog and increased outwards toward the lagg areas (Fig. 48b). In the northeastern part of the bog, pH and Ca^{2+} concentrations were higher than in the rest of the central bog area, suggesting a greater influence of minerotrophic water in this low-lying area, or possibly more dustfall from the industrial areas to the north. This area was mined for peat, so it is also possible that the higher pH and Ca^{2+} concentrations are a result of the piezometers being installed in older, more decomposed peat that remained at the bog surface after peat extraction. Vitt et al. (1995) reported increasing pH and electrical conductivity with depth (0-1.5 m below the surface) in a bog in central Alberta, Canada. Another reason may be that the deeper peat deposits in Burns Bog are composed of fen peat, which is higher in pH and ion concentrations. A large area of the bog further to the east burned in 1996, which may have increased Ca^{2+} concentrations in runoff that subsequently flowed in a northwest direction into the area where the higher pH and Ca^{2+} concentrations were measured. LiDAR data suggest that it is also possible that mineralized runoff from industrialized areas to the north could flow south into the low-lying areas of the bog. Ca^{2+} concentrations and pH were also higher at the eastern edge of the bog, corresponding with the eastern water mound, which may indicate the influence of upland runoff from the east.

In support of the Burns Bog Ecosystem Review (Hebda et al., 2000), Balfour and Banack (1999) developed a classification of water types in Burns Bog. Type I (pH: 3.5-5.5; Ca^{2+}: <3 mg/l) was termed “bog water”, Type II (pH: 4.5-6.0; Ca^{2+}: 3-10 mg/l) “transitional water” and was assumed to be the water type of the lagg, and Type III (pH: 5.0-8.0; Ca^{2+}: >10 mg/l) “non-bog” or minerotrophic water. We compiled all available pH and Ca^{2+} concentration data, and found that these divisions are not evident from the data (Fig. 49). There was a general positive correlation between pH and Ca^{2+} concentrations ($r_s = 0.608$, $p = 0.000$), but 38% of the data points fell outside (below) the pH ranges for the three water types. Also, 83% of the 12 pH measurements in laggs in Burns Bog identified on the basis of vegetation did not fit within the Type II category (67% of the samples had a lower pH than expected, and 42% of the samples had a lower Ca^{2+} concentration than expected). It is recommended to abandon this classification system or amend it to reflect the actual range in pH and Ca^{2+} concentrations in Burns Bog, and taking into consideration how these ranges are correlated with the dominant plant communities (Fig. 48). The Burns Bog lagg data also show that pH and Ca^{2+} concentrations were lower in summer compared to winter measurements (Fig. 49); these hydrochemical differences between summer and winter also need to be considered in any water type classification.

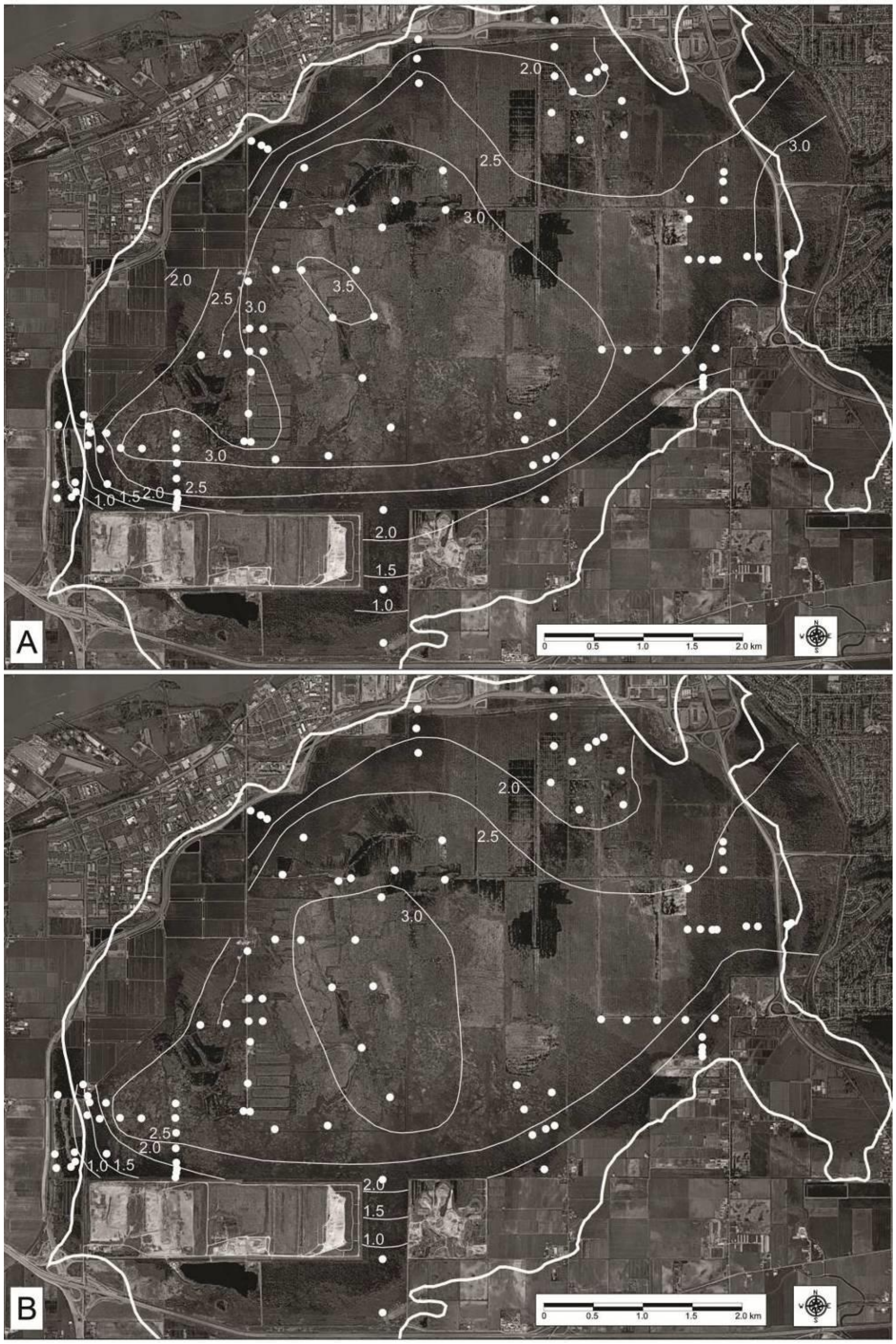

Figure 47. ***Water mound contours in Burns Bog for: a) February 2011 (wet season), and b) September 2011 (dry season). Data are from this study and studies by The Corporation of Delta (unpublished data), Golder Associates (2011b), and Enterprise Geosciences (2011). Contours were created by manually calculating the distance between adjacent points. The thick white line represents the historic bog boundary. Base image from The Corporation of Delta.***

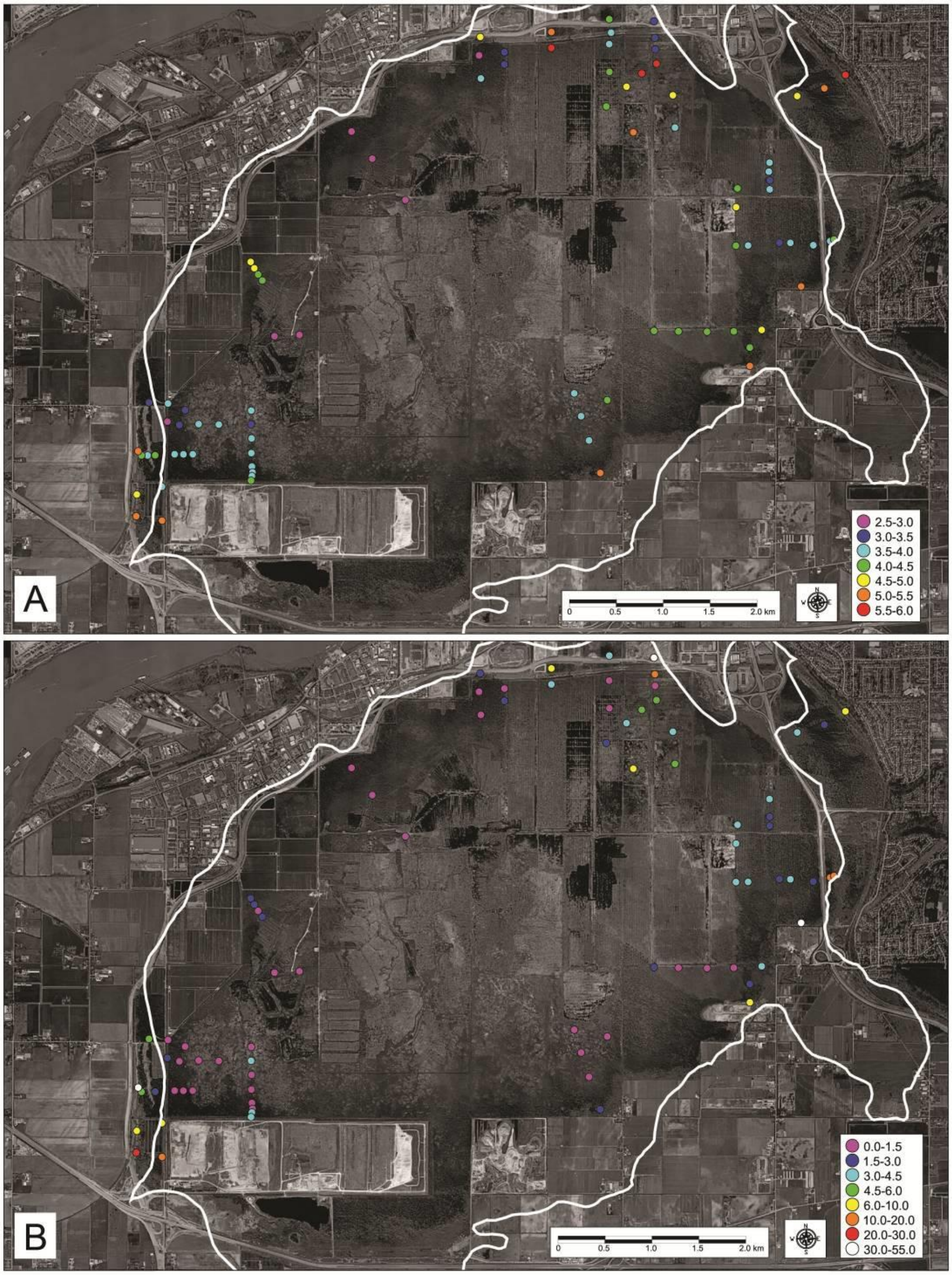

Figure 48. ***Dry season (July – September) shallow pore-water chemistry in Burns Bog: a) pH, and b) calcium concentrations. Data are from this study, The Corporation of Delta (unpublished data), Hendry (2009), Golder Associates (2011a, 2011b), and Enterprise Geosciences (2006, 2011). The thick white line represents the historic bog boundary. Base image from The Corporation of Delta.***

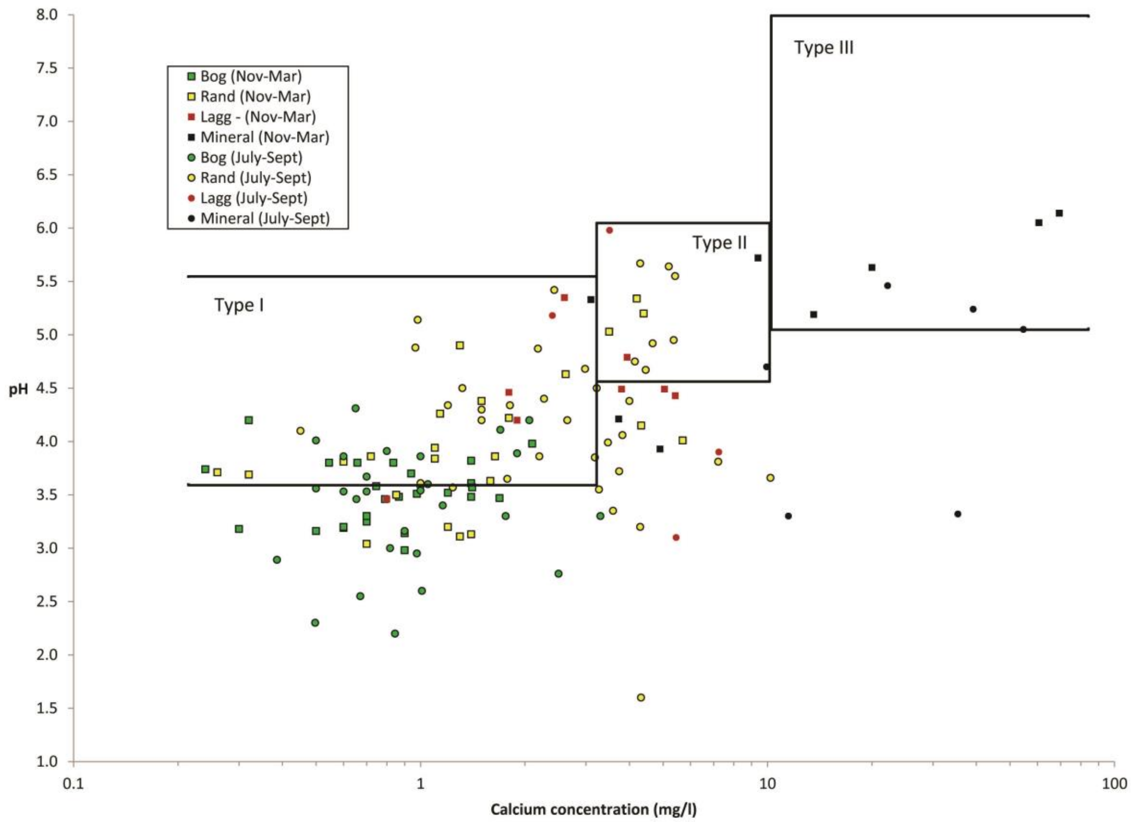

Figure 49. ***Relation between pH and calcium concentration (log scale) and the three "water types" identified by Balfour and Banack (1999) for Burns Bog: Type I (pH: 3.5-5.5; Ca^{2+}: <3 mg/l), Type II (pH: 4.5-6.0; Ca^{2+}: 3-10 mg/l), and Type III (pH 5.0-8.0; Ca^{2+}: >10 mg/l). Data sources: Hendry (2009), Golder (2011a, 2011b), Enterprise Geosciences (2006, 2011), this study, and unpublished data from The Corporation of Delta.***

8.4.2. Burns Bog Lagg

Historic Lagg

From the historic vegetation patterns (Fig. 46a), it is evident that the Burns Bog lagg was well-defined in topographically constrained areas along the base of the Surrey Upland to the east, the levee of the Fraser River to the north, and Crescent Slough to the west. This is in agreement with the commonly-used definition of the lagg as an ecotone plant community at the edge of the bog (Howie and Tromp-van Meerveld, 2011). In contrast, the flat deltaic deposits to the south of Burns Bog did not promote a well-defined lagg, but instead supported large areas of wet prairie grasses and shrubs such as willow, hardhack, and rose (Fig. 46a). The southern boundary of the bog provides us with a rarely-seen glimpse into historic vegetation patterns for deltaic raised bogs in locations that are not topographically constrained by an upland or river/watercourse. However, this broad expanse of swamp and prairie species may not be a useful reference ecosystem for lagg restoration because the physical constraints of the current boundaries of the bog would not allow for such a wide lagg formation; where bog plant communities extend to the conservation boundary, there is only a limited area available for lagg restoration. Development or construction of topographically-constrained lagg forms, e.g. the hardhack thicket which exists in very narrow (<20 m) strips at the margins of other local bogs (e.g. Langley Bog) (Chapter 6, and described below), is more feasible.

Remnant and Newly-Formed Lagg of Burns Bog

Very little remains of the original lagg of Burns Bog. A small remnant piece of "wet grass prairie", now classified as a hardhack thicket, remains in the northeast corner of the bog, adjacent to the Highway 91 interchange with Nordel Way (Fig. 46b). Two peaty forest remnants were logged: parts of Sherwood Forest were logged prior to 1930, in the 1960s, and in 2011, and the area east of Highway 91 was partially logged in the 1950s and 1960s). The contemporary forest communities in these two sites are somewhat altered from their historic form. Both logged forest areas are second-growth stands dominated by hemlock and cedar with scattered old-growth spruce trees that were not logged. These sites have also been disturbed by agriculture, filling, hydroelectric and sewer utilities, and a large peat processing plant, and contain some non-native species (e.g. *Ilex aquifolium* L., *Rubus discolour* Weihe & Nees, *Impatiens glandulifera* Royle). East of Highway 91, a large alder woodland existed historically where Cougar Creek met the lowland (North and Teversham, 1984). Due to the construction of an interceptor canal that now directs Cougar Creek to the Fraser River, as well as a railway and service road between the canal and the lagg, the historic alder woodland is now confined to the riparian zone near the canal and the forest has largely changed to a mixed coniferous forest on peat (Fig. 46b).

All other lagg plant communities identified in Fig. 46b have newly developed inside the original bog boundary. For example, a large hardhack thicket has formed around the Highway 91 interchange with Nordel Way, and along the eastern edge of the highway to 64th Avenue in areas that were, for the most part, historically classified as bog plant communities (letter “a” in Fig. 46b). This change in plant species composition is most likely a result of highway drainage ditches and road runoff altering the hydrological and hydrochemical characteristics of the area. Another large area of hardhack thicket has formed southeast of the Vancouver Landfill, where historic drainage patterns have been altered by Highway 99 and other small roads (letter “b” in Fig. 46b). The linear strip of a lagg plant community in the large east-west ditch at the current northern boundary of the bog (letter “c” in Fig. 46b) was dominated by hardhack and *Sphagnum* several decades ago (R. Hebda, personal communication), but has now been largely invaded by reed canarygrass, as a result of runoff from a landfill and industrial properties to the north (pH range in the ditch: 4.3-7.0; mean: 6.1) (unpublished data from EBA Engineering Consultants, 2010). An important conclusion from the comparison of the historic and contemporary vegetation maps is that lagg plant communities have naturally colonized historic bog areas where drainage has been impeded by road construction and filling. This suggests that it may be possible to restore or create a lagg in an area that was historically part of the bog.

Lagg Characteristics

The most common lagg type at the margins of the Fraser Lowland bogs is a Spiraea Thicket (Chapters 6, 7). In this lagg type, hardhack (*Spiraea douglasii*) forms dense thickets, and is often associated with *Ledum groenlandicum*, *Carex sitchensis* Prescott, *Rhamnus purshiana* DC., and *Sphagnum* species (Chapters 6, 7). In Burns Bog, other species in the Spiraea Thicket include *Myrica gale* L., *Gaultheria shallon* Pursh, *Malus fusca* (Raf.) C.K. Schneid., *Rosa* spp., and *Lysichiton americanum* Hultén & H. St. John (Table 21, Hebda et al., 2000). A related variety of the Spiraea Thicket, the reed canarygrass-hardhack plant community, was identified at the margin of Burns Bog during the Burns Bog Ecosystem Review (Hebda et al., 2000). This plant community is indicative of disturbance, and is dominated by invasive reed canarygrass (*Phalaris arundinacea*) with sparse hardhack, birch, and weedy shrubs, particularly blackberries. Fig. 46b delineates the current boundaries of these two varieties of the Spiraea Thicket lagg type.

The Spiraea Thicket lagg type forms where there is a topographic depression between the bog and an adjacent minerotrophic upland; this condition is present on the Cranwest and DNR study transects in Burns Bog. These sites are characterized by a high water table in winter (<6 cm below surface; mean: -3 cm; negative value indicates a water level above the surface and thus ponding) and a relatively high water table in late summer (<59 cm below surface; mean: 50 cm). There was a wider range in winter depth to water table in the other laggs in the Fraser Lowland (all <25 cm below surface), but the summer depth to water table in other laggs (<69 cm below surface) was generally similar to Burns Bog (Table 21) (Chapter 5). The high water table appears to limit tree growth; tree basal area was 0.14 m^2/ha and 0.05 m^2/ha in the Cranwest and DNR laggs, respectively. Basal area was generally higher than in other Spiraea Thicket laggs of the Fraser Lowland (range: 0-2.71 m^2/ha; mean: 1.61 m^2/ha) (Chapter 5). pH in June/July was 4.24 and 4.35 in the Cranwest and DNR laggs, respectively, which was lower than the Spiraea Thicket laggs of other Fraser Lowland bogs (range: 4.49-5.47; mean: 5.0) (Chapter 5). In comparison, pH in the undisturbed open heath areas of Burns Bog ranged from 3.71-4.36 (mean: 4.0); mean pH in the other Fraser Lowland bog sites was 4.16 (Chapter 5). June/July pH-corrected electrical conductivity in the Cranwest and DNR laggs was 32 μS/cm and 66 μS/cm, respectively, and similar or higher in the open bog (41-122 μS/cm; mean: 59 μS/cm) and other Spiraea Thicket laggs in the Fraser Lowland (Table 21). Despite a relatively high ash content in some Burns Bog lagg peat samples from 10 cm (mean: 10% ash) and 50 cm (mean: 53 % ash) below the surface, Ca^{2+} concentrations in Spiraea Thicket lagg water samples were below 3.8 mg/l (mean: 2.8 mg/l) and Mg^{2+} concentrations were always below 1.0 mg/l (mean: 0.8 mg/l). Ca^{2+} and Mg^{2+} concentrations were similar to those in other Spiraea Thicket laggs in the Fraser Lowland (Table 21).

The other main lagg type in the Fraser Lowland is a Peaty Forest (Chapter 7), which was found only on two transects at Burns Bog: DNR and Sherwood. This lagg forest is situated on a thick layer of peat (4-9 m). Despite little mineral material in the lagg peat (<5% ash content at 10 and 50 cm depth), large trees were present in this lagg type (mean basal area: 58.7 m^2/ha). The Peaty Forest lagg type was dominated by water-tolerant trees (*Thuja plicata*, *Tsuga heterophylla*, *Pinus contorta* var. *contorta*, *Picea sitchensis*) and *Gaultheria shallon* (Table 21). In this type of lagg, there is no marginal depression at the bog edge, but rather a relatively flat transition out from the bog. The Peaty Forest lagg sites were drier than the Spiraea Thicket laggs (winter and summer depth to water table: <37 cm (mean: 30 cm) and <76 cm (mean: 63 cm), respectively). pH in the Peaty Forest lagg sites of Burns Bog ranged from 4.1-5.3 (mean: 4.7), similar to the Spiraea Thicket lagg type. EC_{corr} in the Peaty Forest lagg sites ranged from 66-165 μS/cm (mean: 116 μS/cm), and was higher than in the Spiraea Thicket sites (Table 21). Major cation concentrations were similar in the Peaty Forest lagg (concentrations in lagg water samples: Ca^{2+} <3 mg/l; Mg^{2+} <2 mg/l) than in the Spiraea Thicket lagg sites. Cation concentrations in the studied laggs were relatively low compared to minerotrophic peatlands, but still within the range formoderately rich and rich fens in North America: Ca^{2+} 0.80-428 mg/l; Mg^{2+} 0.10-47 mg/l, Bourbonniere (2009).

Table 21. ***Properties of lagg sites in Burns Bog and other Fraser Lowland bogs. Braun-Blanquet species cover values, separated by a comma, are for the main study transect (first) and the parallel vegetation transect (second). DTW = depth to water table; negative values indicate that the water table was above the bog surface. No other Peaty Forest laggs have been studied in the Fraser Lowland and therefore ranges for other Fraser Lowland bogs cannot be given for this lagg type.***

	Spiraea Thicket				Peaty Forest	
	CW	DNR	Other Fraser Lowland bogs		SW	DNR
			Range	Mean		
Braun-Blanquet species cover						
Spiraea douglasii	2,5	5,5	3-5	5	0,0	0,0
Ledum groenlandicum	4,5	0,0	0	0	0,0	0,0
Gaultheria shallon	2,2	0,0	0-4	1	5,5	5,5
Rhamnus purshiana	0,0	0,1	0-3	1	0,0	0,0
Myrica gale	0,0	0,0	0	0	0,0	0,0
Carex sitchensis	0,0	0,0	0-1	0	0,0	0,0
Sphagnum spp.	4,5	0,0	0-2	1	0,0	0,0
Thuja plicata	0,0	0,0	0-2	0	3,3	5,0
Tsuga heterophylla	0,0	0,0	0	0	4,0	2,5
Pinus contorta var. contorta	0,0	0,0	0	0	0,0	0,2
Picea sitchensis	0,0	0,0	0	0	0,5	0,0
Tree basal area (m^2/ha)	0.14	0.05	0-2.71	1.61	39.17	67.19
Max. DTW (cm)	52	58	41-69	55	75	57
Min. DTW (cm)	-9	-14	-2-7	2.5	17	13
June/July EC_{corr} (µS/cm)	32	66	25-62	43	66	165
Winter EC_{corr} (µS/cm)	45	68	35-42	39	54	105
June/July pH	4.24	4.35	4.49-5.47	5.0	4.11	5.34
Winter pH	4.13	4.49	4.12-5.05	4.59	4.23	5.39
June/July Ca^{2+} (mg/l)	1.8	3.8	3.0-3.2	3.1	1.9	2.6
June/July Mg^{2+} (mg/l)	0.9	0.7	0.5-0.8	0.6	1.7	0.8

8.4.3. *Options for Lagg Restoration in Burns Bog*

In some areas at the margin of Burns Bog, there is no remnant lagg, and lagg plant communities have not naturally developed inside the bog. The two most common plant communities that have developed in these areas are Birch Forest and Pine-salal Forest (Hebda et al., 2000). These forest plant communities are indicative of relatively dry conditions, resulting from many decades of drainage by adjacent ditches, and represent a loss of peat-forming bog species (e.g. *Sphagnum* spp.). If drying continues at the edges of the bog, which is enhanced by the higher evapotranspiration losses of these forests compared to bog species, it is possible for these forest communities to further encroach towards the bog centre, displacing additional bog plant communities, and halting *Sphagnum* peat formation in the affected areas (Freléchoux et al., 2004). It is therefore not only important to preserve the remaining lagg plant communities (see Appendix G and Fig. 46b for key areas), but to also actively restore a lagg community in the areas currently occupied by forests. In the area of Burns Bog that was subject to a large fire in 2005, and in which the water table was raised by lowering of the peat surface through burning and subsequently by ditch blocking, regeneration of *Sphagnum* has been observed in hollows. The regenerating *Sphagnum* in this burned area has spread over the roots of pine seedlings in some areas, which suggests that rewetting of these dry forests could return them to a *Sphagnum*-dominated plant community (i.e. the Pine-Sphagnum woodland community, which has naturally existed as the rand forest at the margin of the bog) (Fig. 46a).

The key elements that a lagg restoration must address relate to 1) depth to water table, 2) hydrochemistry of pore-water and surface water, and 3) plant community composition. For laggs in the Fraser Lowland, it has been observed that the water table fluctuates within 75 cm of the ground surface throughout the year and differs between the Peaty Forest and Spiraea Thicket lagg types (Table 21); this information provides a useful guideline for hydrological restoration of the lagg and suggests that lagg restoration can be encouraged by maintaining a high water table at the bog margin. The Peaty Forest and Spiraea Thicket lagg types also have specific ranges for pH, electrical conductivity, and Ca^{2+} and Mg^{2+} concentrations (Table 21), although additional research is required for the Peaty Forest lagg type to confirm the ranges for these parameters. In order to direct the hydrochemical conditions of the restoration site toward these restoration targets, it is important to control the flow of mineral water into the lagg, particularly from disturbed or developed sites, to ensure that the lagg is dominated by bog water runoff. If the hydrological and hydrochemical conditions of these two lagg types are met, it should allow the establishment of the dominant plant species that are characteristic of each lagg type (Table 21). Three restoration scenarios for the lagg of Burns Bog are given in Fig. 50 and described below. Each scenario represents a common condition at the margin of the bog.

Interface with filled properties

This condition is common along the southern boundary of Burns Bog, where the protected area borders deep drainage ditches that are shared with farms, and along the northern boundary where a large drainage ditch separates the bog from industrial land and a new highway (Fig. 50a). The ditches drain both the developed lands (which is necessary to avoid flooding in the low-lying areas) and the adjacent bog, resulting in the establishment of dry pine and birch forests along the ditches. Considerable peat subsidence (50-60 cm) has been observed along the edge of some of these ditches, indicating that drainage has lowered the water table and resulted in oxidation of the peat. To restore a high water table and lagg plant communities (e.g. Spiraea Thicket) in these areas, there are two recommendations; the choice will depend on the willingness of landowners to assist with restoration and the ability to purchase and protect additional land:

a) Work with landowners to install a drainage ditch further inside their property, leaving a berm between the two ditches, and then fill the large drainage ditch adjacent to the bog with peat, while maintaining a slightly lower elevation at the bog margin to allow for drainage during the wet season. This is the ideal condition, as it would not impact the protected lands of Burns Bog. However, landowners may require compensation for loss of arable or industrial land where the new ditch is installed.

b) Retain the existing drainage ditch for farm or industrial drainage, and construct a peat berm on the bog side of the ditch (Fig. 50a). Install overflow drains through the berm to minimize water pressure behind the berm. Install adjustable dams in the ditch to maintain a higher water level in summer, while allowing drainage in winter. Lagg species will likely establish naturally on the bog side of the new peat berm. This approach was used successfully at Raheenmoore Bog in Ireland (Schouten, 2008) (Fig. 51).

Undisturbed land

This condition exists in the northeast part of the bog where property lines cut through a contiguous piece of bog. The natural lagg exists well outside the property boundary of the protected area (Fig. 46a). The preferred condition would be to purchase this land for conservation, in order to protect the existing bog-lagg interface. However, if it is not possible to purchase this land and protect and maintain the existing lagg, an artificial lagg could be created inside the protected bog boundary. Since new laggs have naturally developed in the past on land that formerly contained bog plant communities (Fig. 46b), it should be possible to recreate the conditions for lagg development at these property boundaries.

In this scenario, it is recommended to create a double-ditch system similar to that surrounding the Vancouver Landfill in Burns Bog, but more similar to a natural configuration (Fig. 50b). In this system, the bog-side ditch is kept at a high level, to maintain a high water table in the bog, and to ensure that mineralized water from adjacent uplands cannot flow into the bog. The bog-side ditch is not meant to function as a ditch in the traditional sense (i.e. for drainage), but rather to maintain a high water table at the bog edge and to promote lagg fen or swamp plant communities. To ensure that the bog-side ditch doesn't drain the bog, the ditch should be intermittent, and not connected to any perimeter drainage system. The outer (development-side) ditch is maintained at a lower level through active drainage, to maintain an outward hydraulic gradient. The berm that separates the two ditches and maintains a high water level in the new lagg should be high enough to protect the developed property from flooding. The berm should be lined with an impermeable membrane on the bog side to prevent flow of mineralized water into the bog ditch. The berm area is compressed, lowering the permeability of the underlying peat, minimizing water movement through the berm, and slowing water loss from the bog. The double ditch and berm system requires maintenance, and the berm must be constructed of low-permeability material to minimize flow through the berm to the outer ditch.

Low-lying properties adjacent to the bog

In a few cases, such as adjacent to Cranwest Farms and some farms to the south of the bog, there is no ditch separating the bog from the developed land. This is an ideal situation for lagg restoration, because the water table is maintained near the surface. However, in some cases, these properties are flooded by bog runoff during the wet season, which may eventually encourage landowners to dig a drainage ditch to protect their property. An ideal solution is in place at the bog interface with Cranwest Farms between 72 St and 76 St; the farmer has constructed a single-lane gravel road adjacent to the bog, with just enough freeboard to withstand flooding from the bog in the wet season. In this situation, bog water collects in a narrow band along the road, and eventually drains slowly through the upper peat layers to the north. Bog and lagg species are present (i.e. *Sphagnum* spp., *Ledum groenlandicum*, *Spiraea douglasii*) at this interface, instead of the dry pine and birch forests in areas with large drainage ditches. It is recommended that this type of road or berm be constructed on private land at the edge of the bog whenever there are concerns about flooding (Fig. 50c). If (and only if) the bog surface and water table increase in elevation from the gravel road towards the bog, the mineral material in the gravel should cause little to no change to bog water chemistry.

Lagg areas dominated by reed canarygrass

Another situation that requires restoration consideration occurs where there is a lagg in the hydrological sense, but not in terms of its hydrochemical characteristics or plant community composition, such as the northern boundary ditch where reed canarygrass is predominant. In these areas, it is necessary to remove the invasive species and restore natural lagg species (e.g. hardhack, *Carex*, and *Sphagnum*). Reed canarygrass forms a monoculture and outcompetes native species, resulting in a loss of biodiversity. Despite an evapotranspiration rate similar to other riparian species per leaf surface area, evapotranspiration from reed canarygrass can be significantly larger due to a greater aboveground biomass and leaf surface area per square metre than other species (Gebauer et al., 2012).

Reed canarygrass is not found further inside the bog, suggesting that its ability to colonize and reproduce may be impaired if the hydrochemistry of the water in the restoration site becomes more similar to bog water (i.e. low pH and low ion concentrations). Restoration of a natural lagg ecotone in these situations would therefore involve blocking drainage water from fill material and agricultural and industrial properties to ensure that the water in the boundary ditch is not influenced by pollutants (e.g. nitrogen-rich water from urban runoff), and that seeds of non-native species are not transported via surface drainage. Thatch removal allows light to reach the soil surface and promotes germination of native plants (Thomsen et al., 2012). It is also important to damage (e.g. till) the underground rhizomes of reed canarygrass, which, if not addressed, may resprout after removal of the aboveground biomass (Annen, 2008). Replanting or seeding the site with the desired native species to discourage the regeneration of reed canarygrass may be required as well (Iannone and Galatowitsch, 2008). Paradis and Rochefort (2012) found that lagg species could be successfully reintroduced in cutover raised bogs with shallow residual peat (15-30 cm) in New Brunswick, Canada, by using shade to promote the establishment and growth of mosses and understory shrubs, although the use of shade as a restoration tool in coastal BC requires further study. Shade from tall shrubs such as willow (*Salix* spp.) may be beneficial in this case because reed canarygrass is shade intolerant (Kim et al., 2006).

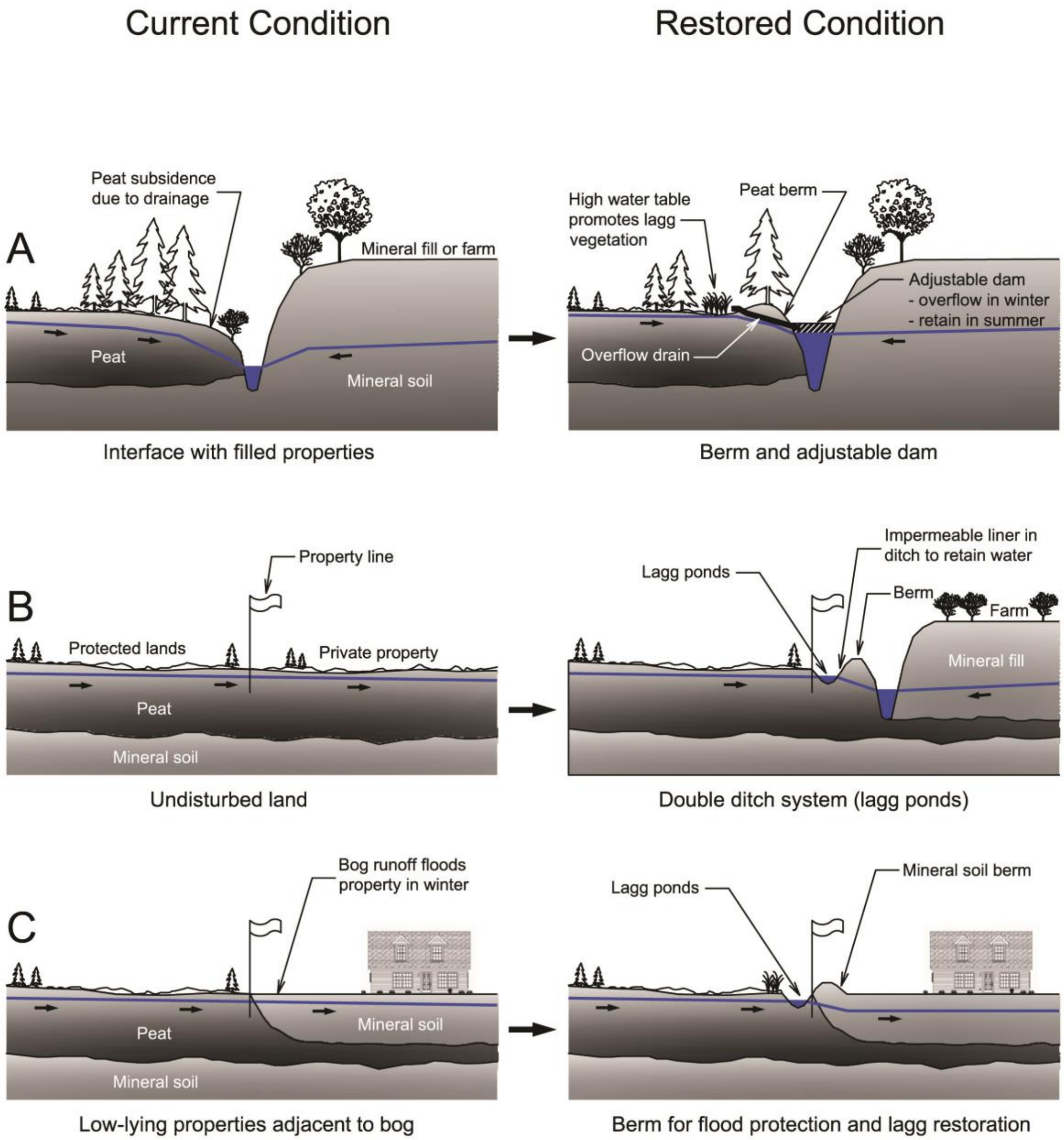

Figure 50. ***Restoration scenarios for the three most common lagg conditions at the boundary of the Burns Bog Ecological Conservancy Area. Blue line represents the water table.***

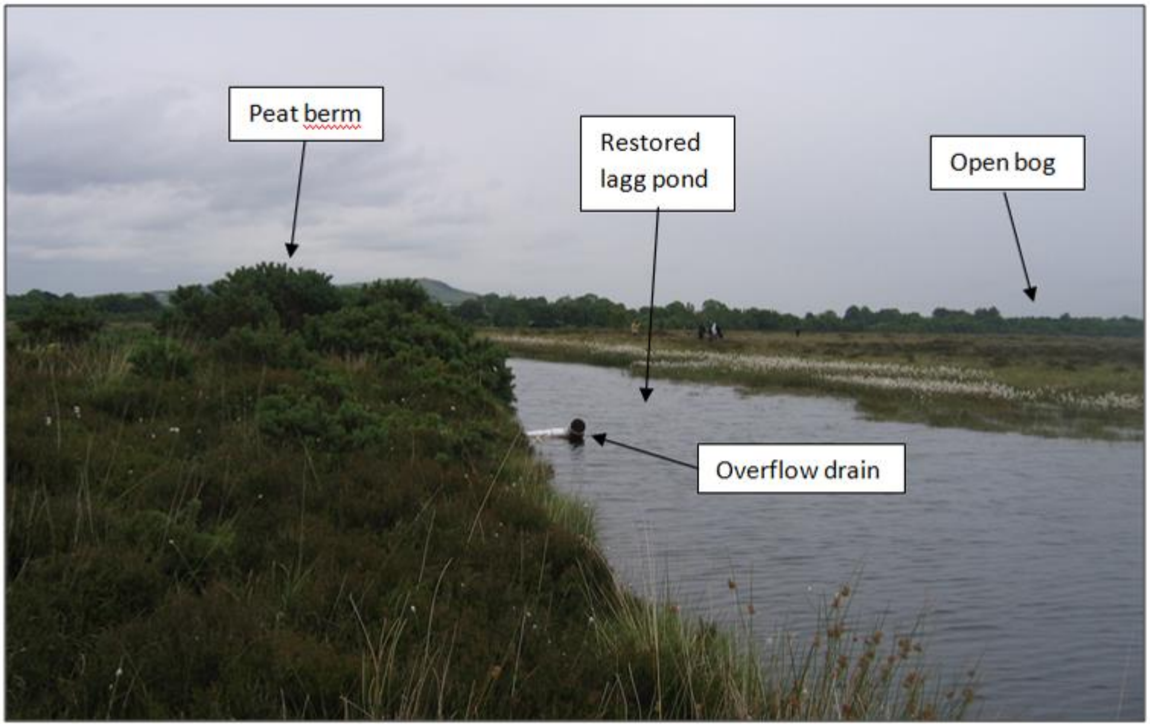

Figure 51. ***Lagg restoration using a peat berm at Raheenmoore Bog, Ireland (2008). The berm was built inside the historic bog boundary, and the lagg pond developed due to the impoundment of water behind the berm.***

8.5. Conclusions

The historic and current lagg conditions of Burns Bog were mapped to determine how the lagg of Burns Bog has changed since the 1850s. Three remnant lagg areas of Burns Bog were studied (Sherwood, Cranwest, DNR) and compared where possible to other laggs in the Fraser Lowland. Study parameters included depth to water table, hydrochemistry (pH, electrical conductivity, and Ca^{2+} concentrations), peat depth, ash content of the peat, and plant species cover. Data from five additional studies were used to supplement the depth to water table and hydrochemistry results of this study.

The water table in the Burns Bog lagg is typically near sea level (with the exception of the area east of Highway 91) and is approximately 3 m lower than the water table in the central bog area. pH and Ca^{2+} concentrations were typically higher in the lagg than in the bog. The water type classification developed for Burns Bog (Hebda et al., 2000) did not fit 38% of our data points and only 17% of the lagg samples fit the “transitional” water type for the lagg (pH: 4.5-6.0, Ca^{2+}: 3-10 mg/l), suggesting that this classification should be abandoned or a new system should be developed.

The lagg remnants at the margin of Burns Bog are characterized by two different natural lagg vegetation types: Spiraea Thicket and Peaty Forest. The Spiraea Thicket lagg type (found on the Cranwest and DNR transects) forms where there is a topographic depression at the margin of the bog and is dominated by a dense thicket of *Spiraea douglasii.* A disturbed variety of this lagg type is dominated by *Phalaris arundinacea*. Trees are generally absent in this lagg type, likely as a result of the high water table and flooding during the wet season. Pore-water pH was low (4.24 and 4.35) in the Spiraea Thicket lagg type, as were pH-corrected electrical conductivity (32 and 66 µS/cm) and Ca^{2+} concentrations (1.8 and 3.8 mg/l). The characteristics of these Burns Bog lagg remnants are generally similar to other studied laggs in the Fraser Lowland. The Peaty Forest lagg type (found on the Sherwood and DNR transects in Burns Bog) is characterized by large trees (basal area: 50 and 67 m^2/ha) and a lower water table due to better drainage than the Spiraea Thicket lagg type. The Sherwood Peaty Forest lagg differed from the DNR Peaty Forest lagg in that pH (4.11, compared to 5.34 in the DNR lagg) and EC_{corr} (66 µS/cm, compared to 165 µS/cm in the DNR lagg) were lower, but Ca^{2+} concentrations were similar for the two studied Peaty Forest laggs (2.5 and 2.6 mg/l for the Sherwood and DNR laggs, respectively). The Peaty Forest lagg type hasn’t been studied elsewhere in the Fraser Lowland, so it is not possible to compare the Burns Bog Peaty Forest laggs with other Peaty Forest laggs in the region.

Due to the rare nature of historic lagg remnants in the region, and the opportunity that these remnants present for detailed research on historic lagg development, it is advisable to conserve the remaining lagg fragments of Burns Bog. In other parts of the bog, lagg plant communities have naturally developed in areas that were historically bog and marginal forest plant communities, as a result of changes in drainage patterns and encroachment of mineral material. This suggests that lagg restoration (or creation) may be possible in other areas as well. Since these newly-developed lagg areas are functionally part of the Burns Bog ecosystem, it is important to protect these areas for conservation and research purposes. In some areas at the margin of the bog, where ditches have drained the peat, a dry forest vegetation type with a dense salal understory has developed instead of a lagg. To reverse the encroachment of these forests towards the centre of the bog, these dry forest areas should be rewetted to promote the growth of lagg swamp plant communities.

9. Conclusion

9.1. Summary of the Key Results

This thesis has explored the hydrological, hydrochemical, peat, and vegetative characteristics of laggs of bogs in coastal BC, and the gradients in these characteristics regionally (e.g. as a result of climate, proximity to the ocean) and locally (i.e. across the bog expanse - bog margin transition). This information was used to create a classification of hydrotopographic lagg forms and vegetative lagg types in this region, and to propose restoration options for Burns Bog in Delta, BC. This chapter presents a summary of the key findings of this research. This information may be of use for setting restoration targets in bogs locally, but is also instructive for restoration projects in other coasal areas outside this region.

9.1.1. Temporal Variation in Depth to Water Table and Hydrochemistry in Bogs and Laggs of Coastal BC

The annual fluctuation of the water table or "hydroperiod" measured in Burns Bog and Blaney Bog was similar to that measured in other coastal BC bogs (e.g. Howie et al., 2009b; Golinski, 2004), and closely follows the annual cycle in precipitation, with the water table dropping further below the surface in dry years. In the central bog areas, the water table remained within 40 cm of the bog surface, which is typical of undisturbed raised bogs (Schouwenaars and Vink, 1992). The studied laggs displayed a hydroperiod similar to the central bog areas, but the annual fluctuation in the water level (up to 75 cm below the surface) was greater than in the bog. It is possible to roughly characterize the hydroperiod of coastal BC bogs by taking depth to water table measurements at key points during the year: winter (but not during freezing conditions), spring (May/June), and late summer (August/September).

Hydrochemical conditions varied, on average, more in the lagg than in the bog. Electrical conductivity, pH, Na^+, and Mg^{2+} concentrations varied little during the study period. Temporal variations in these parameters at a single point were smaller than the spatial variability across the transect. Thus, a one-time survey can characterize the hydrochemical conditions of the bog and lagg, and the spatial variability in hydrochemical conditions across the bog margin reasonably well. The other studied parameters (Ca^{2+}, K^+, Cl^-, acidity, dissolved organic carbon) may be too variable to confidently describe their spatial variability across the bog margin with a one-time survey. We found relatively large differences in K^+ and dissolved organic carbon concentrations between duplicate samples (see Appendix A), so the variability in those two parameters could also be related to measurement uncertainty and the time between purging and sampling.

9.1.2. Representativeness of Measurements of Depth to Water Table, Hydrochemistry, and Peat Properties

A small grid of 25 sites was used to determine whether a measurement could be considered representative of the area around the sample site. von Post humification at a given depth below the surface appears to be somewhat spatially consistent over space, and can be expected to be within 1-2 von Post points of the average most of the time. Ash content was also somewhat consistent at the three sample depths: 10 cm (mean: 4.3%; standard deviation: 2.9%), 50 cm (mean: 0.9%; standard deviation: 0.9%), and 100 cm (mean: 0.6%; standard deviation: 0.4%). Depth to water table measured in hollows also varied little between sample sites (mean: 7.6 cm; standard deviation: 1.7 cm). Depth to water table should be measured using wells or piezometers installed in hollows, not hummocks, because the higher hummocks artificially increase the "depth the below surface" measurements. Water content of the peat samples was highly consistent for a given depth, so a single sample will suffice for this parameter. Both pH and electrical conductivity were spatially stable enough to warrant a single point measurement. Vegetation was heterogeneous, even within a relatively small area; multiple plots should be surveyed to obtain a more reliable estimate of plant species cover. All of the studied parameters varied across the study transects from bog to lagg

(Chapter 5), so a sample point should only be considered representative of their relatively small area.

9.1.3. Regional Variation in Bogs and Laggs of Coastal BC

Bog hydrochemistry varied according to wetland region, latitude, annual precipitation, and oceanic exposure. Specifically, pH increased with latitude and mean annual precipitation and decreased with increasing peat depth. Pore-water pH differed between the Pacific Oceanic and Pacific Temperate wetland regions. Na^{+} and Mg^{2+} concentrations, and electrical conductivity, were highest in the Haida Gwaii bogs and lowest in Prince Rupert bogs, which suggests a coastal-inland gradient of decreasing cation concentrations.

Differences in plant species composition in bogs and laggs within the study area were linked to variations in climate, specifically mean annual precipitation and mean annual temperature. Species richness was significantly higher in the studied bogs and laggs of the Pacific Oceanic wetland region than in the Pacific Temperate wetland region. Some species (e.g. *Juniperus communis*, *Sphagnum austinii*, *Sphagnum papillosum*) were more prevalent in the cooler, wetter northern bogs and bogs on the outer west coast, whereas other species (e.g. *Vaccinium myrtilloides*, *Polytrichum strictum*, *Sphagnum magellanicum*) were limited to warmer, drier areas in the rainshadow of Vancouver Island and the Olympic Peninsula. Half of the lagg plots in the Fraser Lowland, as well as the lagg plots at Campbell River bog contained only deciduous trees, whereas bogs on the north coast and western Vancouver Island were dominated by coniferous trees. Bogs in the Fraser Lowland area contained the most well-developed lagg ecotones, dominated by *Spiraea douglasii*. In contrast, the northern and outer west coast bogs were generally flatter and often lacked a true lagg; bog species blended into wet forest environments without a clear transitional lagg ecotone. All of the lagg plots in the Pacific Oceanic wetland region shared at least one species with the adjacent bog, whereas only half of the lagg plots in the Pacific Temperate wetland region shared species with the plots in the bog; this supports the observation that the Pacific Temperate bogs tend to develop lagg ecotones that contain distinctly different plant communities from the adjacent bogs.

9.1.4. *Environmental Gradients across the Bog Margin*

Clear gradients in measured abiotic parameters were identified across the bog expanse – bog margin transition. The water table generally declined from the bog expanse to the bog margin. pH, pH-corrected electrical conductivity, and Mg^{2+} and Ca^{2+} concentrations generally increased from the bog expanse to the bog margin. However, these hydrochemical gradients were not consistent for the individual transects and are thus not dependable indicators for determining the location of the mineral soil water limit at the bog margin. Some of the hydrochemical parameters (Na^{+}, Cl^{-}) fluctuated along the transect, or declined from bog expanse to bog margin for some individual transects. Mg^{2+} concentrations and pH increased most frequently from bog to forest, but did not increase consistently at the vegetative transition from bog to lagg. Peat depth decreased significantly from the bog expanse to the bog margin. Ash content of the peat samples usually increased across the bog expanse – bog margin transition; ash content in near-surface peat (0-50 cm depth) appears to be the most useful abiotic measure for determining the location of the lagg, except for the Peaty Forest lagg type.

9.1.5. *Hydrotopographic Lagg Forms and Vegetative Lagg Types of Coastal BC*

Laggs of bogs on the west coast of Canada can be classified based primarily upon topography, depth to water table, vegetation, and ash content of peat. Topographic surveys of the 17 studied lagg transects and water level measurements revealed two hydrotopographic lagg forms: Marginal Depression and Flat Transition. A high water table and low tree basal area were characteristic of the Marginal Depression lagg form. The Marginal Depression laggs were classified into two vegetative types: 1) Carex Fen (dominated by *Carex sitchensis* and *Sphagnum*) and 2) Spiraea Thicket (dominated by a thicket of *Spiraea douglasii*). The Carex Fen laggs were mainly found in the Pacific Oceanic wetland region; the Spiraea Thicket laggs were only found in the Pacific Temperate wetland region. The Flat Transition lagg form was characterized by a gradual increase in tree basal area across the transition from bog to forest. The difference in plant species composition between the two Flat Transition lagg types was not as clear as for the Marginal Depression lagg types, so ash content of peat samples at 50 cm depth and mean tree height were also used to differentiate them. The laggs with a very low ash content (<5%) and mean tree height >1.3 m were classified as Peaty Forest, while the laggs with a higher ash content and mean tree height <1.3 m were classified as Direct Transition. The Direct Transition lagg type generally had a higher percent cover of *Sphagnum* than the Peaty Forest lagg type, but not in all cases. Hydrochemical characteristics in the lagg were similar for the four vegetative lagg types.

One of the key observations in my research was that other lagg types exist in addition to the "textbook" lagg fen or swamp ecotone; the Peaty Forest lagg type was found in three of the studied bogs in coastal BC, and was also recently found in eastern Canada (Étienne Paradis, PhD student, Université Laval, personal communication, 2012), suggesting that the definition of lagg could be expanded to include other types of hydrological, hydrochemical, and vegetative transitions at the bog margin.

9.1.6. Implications for Bog and Lagg Restoration in Coastal BC

The comparison between historic and current lagg areas in Burns Bog revealed that lagg plant communities have developed in areas that historically had bog plant communities; this indicates that natural regeneration and active restoration of laggs may be possible for disturbed bogs. The classification of the hydrotopographic lagg forms and vegetative lagg types may assist land managers in delineating representative and functional conservation areas that include the critical lagg for bogs by providing a list of lagg indicators and characteristics, namely: 1) topography, 2) depth to water table, 3) tree basal area, 4) dominant plant species, and 5) ash content of the peat. These results also establish measurable parameters and an initial range of characteristics for each lagg type to guide the restoration of natural laggs in the region.

Regional and local gradients in bog hydrology, hydrochemistry, vegetation, and peat properties in coastal BC bogs must be taken into consideration when contemplating the use of data from one bog as a reference ecosystem for the restoration of another bog. For example, a bog restoration project on Vancouver Island should only use data from other nearby bogs with the same climatic and topographic conditions to develop a hydrological, hydrochemical, and ecological reference for the restoration of a disturbed bog. Using information from other geographic locations, even within the same coastal region, may result in the use of inappropriate targets (e.g. depth to water table, pore-water chemistry, plant communities) and incorrect restoration tools.

9.2. Recommendations for Further Research

The results of this study should be further validated by additional data collection in laggs throughout coastal BC, particularly in the latitudes not covered by this study (e.g. between $50^{o}34'$ N and $53^{o}37'$ N) and further from the coast. This would assist in confirming our results and refining the ranges of the hydrochemical, vegetation, and peat properties for each lagg type. The results from this study show that variation in species composition was only partly (28%) explained by climate, depth to water table, hydrochemistry, ash content, and peat depth. This suggests that other factors also influence vegetative composition, and that it thus may be useful to collect additional information at the studied sites (e.g. soil nutrient conditions, shading, late summer depth to water table and soil moisture, bulk density of the peat) to determine the other factors that cause the regional and local patterns in plant community composition.

It would be useful to test the lagg classification developed for this study for other bogs in coastal BC to confirm that laggs in this region fit within the classified hydrotopographic lagg forms and vegetative lagg types; the lagg classification could also be tested in other locations with different climates (e.g. Europe). The lagg classification developed in this study could also be expanded to include other types of laggs (e.g. a lagg in a riparian zone that is subject to frequent flooding) that were not included in this study.

It would also be instructive to study the fluctuations in pH, EC, major cation and Cl^- concentrations on a more frequent basis (e.g. daily or hourly) to determine the short-term response to precipitation events. The 25-site spatial study grid could be used to collect water samples for analysis of major cation concentrations and acidity to determine whether these parameters are as spatially stable as pH and electrical conductivity.

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Appendices

Appendix A. Error

Our methodology was designed to minimize error in this study. Piezometers were purged twice and generally left to recharge for a minimum of three days to ensure that the water level in the piezometers was representative of the water table in the surrounding soil. Water in the piezometers was usually sampled within one week of purging to minimize the amount of time that the water in the piezometer was exposed to the air. Piezometers were capped to minimize aeration, litter, and dustfall.

One in nine water samples were replicated to determine the accuracy and uncertainty of the measurements. Differences in Ca^{2+} concentrations of the replicates were less than 0.5 mg/l (mean: 0.3 mg/l = 3x the 0.1 mg/l minimum detection limit (MDL) of the lab). Differences in Mg^{2+} and Na^{+} concentrations were less than 0.2 mg/l (mean: 0.06 mg/l = similar to the 0.1 mg/l MDL of the lab). Differences for K^{+} concentrations were larger, with a maximum difference of 10.2 mg/l and a mean difference of 2.2 mg/l between replicates; the mean difference was 22 times larger than the MDL of the lab. Cl^{-} concentration had a maximum difference of 4.0 mg/l (mean: 2.0 mg/l = 2x the MDL of the lab). Acidity was relatively stable (maximum difference: 3.0 mg/$CaCO_3$; mean: 1.3 mg $CaCO_3$ = similar to the 1 mg/l MDL of the lab), but dissolved organic carbon (DOC) was more variable (maximum difference: 7.7 mg/l; mean: 2.6 mg/l = 5x the MDL of the lab).

For all parameters, the concentrations were lower than the original samples for 49% of the replicate samples, the same for 36% of the replicate samples, and higher for 16% of the replicate samples. It is possible that the replicate sample contained more "recharged" water from the peat, whereas the original sample was collected from water that had been in the piezometer for several days; this suggests that concentrations of the sampled hydrochemical parameters generally increased slightly while water sat in the pipe between purging and sampling and that the pore-water in the surrounding peat had slightly lower concentrations, although this applies for only half of the measurements.

Two vegetation plots were studied at each transect study site; the replicate plots generally contained similar plant assemblages, as shown in the cluster analyses (Chapter 6). Single peat cores were taken at each study site, but the results from the representativeness grid study (Chapter 4) indicate that von Post humification and ash content were spatially consistent within the sample site.

Parameter	**Difference (mg/l) between the original sample and the replicate sample**				**Percent of the time that the replicate sample was lower/higher or the same as the original sample**			**MDL (mg/l)**
	Minimum	Mean	Median	Maximum	Lower (%)	Same (%)	Higher (%)	
Ca^{2+}	0.0	0.3	0.1	1.2	71	14	15	0.1
Mg^{2+}	0.0	0.0	0.0	0.2	29	71	0	0.1
Na^{+}	0.0	0.1	0.1	0.2	43	29	28	0.1
K^{+}	0.0	2.2	0.1	10.2	43	43	14	0.1
Cl^{-}	0.1	1.7	1.4	4.0	100	0	0	1
DOC	0.0	2.6	1.1	7.7	60	20	20	1
acidity	0.0	1.3	1.0	3.0	60	20	20	0.5

Appendix B: ANOVA Results for Chapter 3

This table presents the results of the ANOVA tests of Chapter 3 for determining whether temporal and spatial variation in pH and EC_{corr} was statistically significant for each study transect.

	SS	df	MS	F	p-value
Variation in pH across the study transects					
	SS	df	MS	F	p-value
Burns Bog - Sherwood	1.07	5	0.21	12.84	0.000
Burns Bog – Cranwest	6.77	4	1.69	14.30	0.000
Burns Bog - DNR	4.96	3	1.65	111.83	0.000
Blaney Bog – Upland	5.96	4	1.49	55.27	0.000
Blaney Bog – Fen	0.06	4	0.01	0.72	0.591
Variation in EC_{corr} across the study transects					
	SS	df	MS	F	p-value
Burns Bog - Sherwood	22250.23	5	4450.05	14.86	0.000
Burns Bog – Cranwest	30347.39	4	7586.85	38.58	0.000
Burns Bog - DNR	7070.04	3	2356.68	3.83	0.039
Blaney Bog – Upland	3897.90	4	974.47	4.45	0.010
Blaney Bog – Fen	1196.43	4	299.11	2.81	0.053
Variation in pH during the 1.5-year sampling period					
	SS	df	MS	F	p-value
Burns Bog - Sherwood	0.33	8	0.04	1.18	0.335
Burns Bog – Cranwest	1.39	8	0.17	0.59	0.780
Burns Bog - DNR	0.76	4	0.19	0.48	0.750
Blaney Bog – Upland	0.10	4	0.02	0.08	0.988
Blaney Bog – Fen	0.09	4	0.02	1.15	0.361
Variation in EC_{corr} during the 1.5-year sampling period					
	SS	df	MS	F	p-value
Burns Bog - Sherwood	5739.09	8	717.39	1.03	0.427
Burns Bog – Cranwest	2020.26	8	252.53	0.23	0.983
Burns Bog - DNR	725.34	4	181.33	0.15	0.961
Blaney Bog – Upland	2192.56	4	548.14	1.80	0.168
Blaney Bog – Fen	580.74	4	145.18	1.06	0.403

Appendix C. Recommended Time of Year for Hydrochemical Sampling in Coastal BC

If it is only possible to collect hydrochemical measurements once at a research site, it is recommended that sampling takes place during average conditions, i.e. not immediately following heavy rainfall events or during an extended drought period. For coastal British Columbia, this "ideal" sampling period is June-July, possibly extending into May and August for some locations. Figure A1 shows the probability of not encountering a large precipitation event (>10 mm and >25 mm) in Burns Bog, Blaney Bog, and Campbell River bog on any given sampling day in a month, and the probability of no occurrence of a large precipitation event in the seven days prior to a given sampling date (seven days was usually the minimum time we allowed for piezometers to recharge between purging and sampling). These data show that May through August generally have the highest probability of no large rainfall events. The absence of large rainfall events is the preferred condition for water chemistry sampling, because it ensures that heavy rainfall does not influence the chemistry. In addition, August and early September are at the end of the dry season in coastal British Columbia, so this time generally corresponds with the lowest water table (Howie et al., 2009; Baird, 2012; Balfour, 2011). Extended drought periods in August and early September, however, should also be avoided if sampling for hydrochemistry, to avoid concentration of ions due to evapotranspiration and/or a lower water table (Prévost et al., 1999; Adamson et al., 2001). However, water level measurements during this drought period are crucial for tracking the seasonal water table fluctuations and their connection to hydrochemistry and vegetation (e.g. *Sphagnum*), and overall bog health.

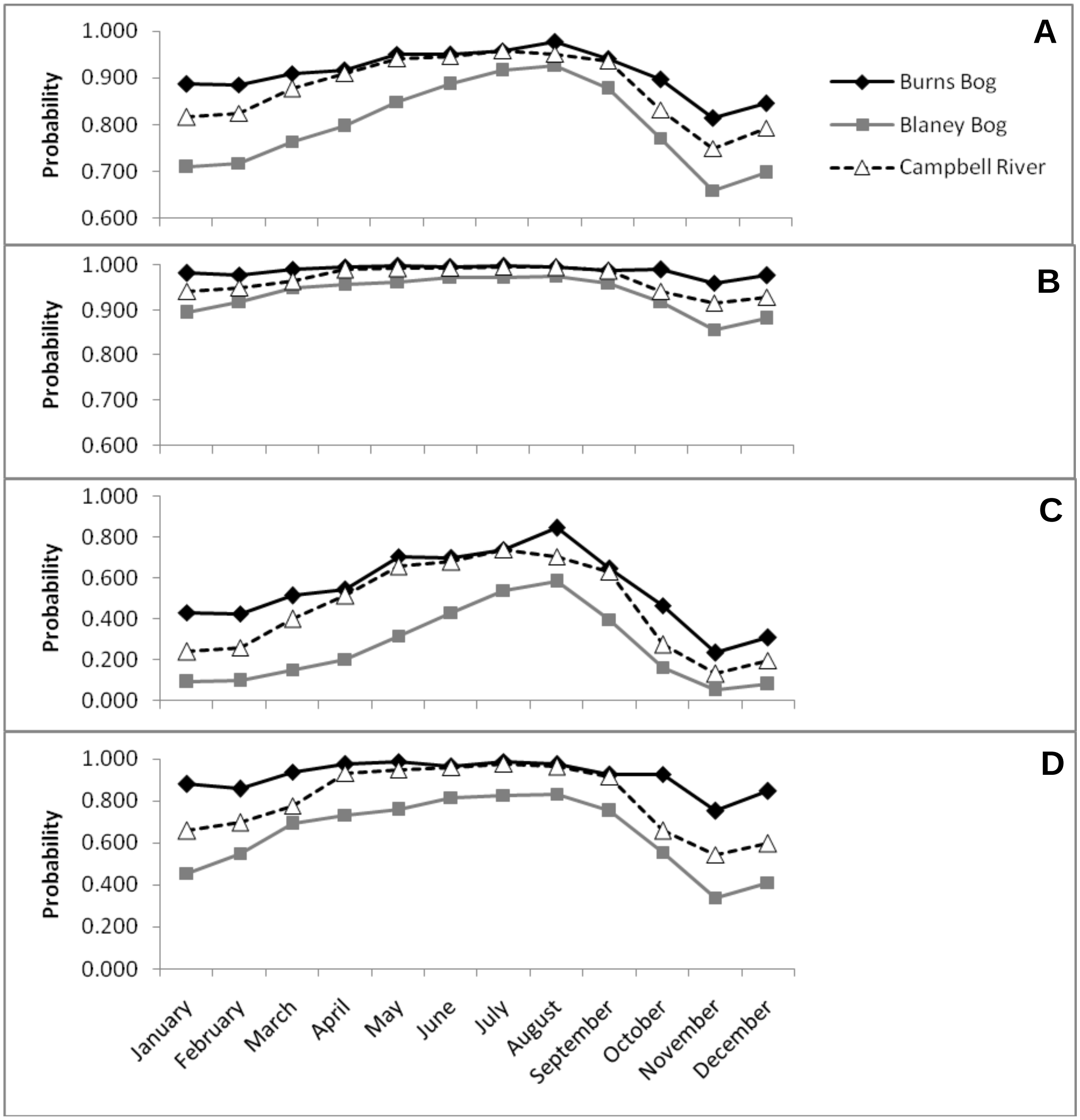

Figure A1. ***Probability of not encountering a large rainfall event in Burns Bog, Blaney Bog, and Campbell River Bog on 1) a given sampling day, a) >10 mm, b) >25 mm, and 2) for seven consecutive days, c) >10 mm, d) >25 mm. Calculated using 30-year average (1971-2000) rainfall values from Environment Canada.***

Appendix D. Correlation Between pH and Calcium Concentrations in the Studied Bogs

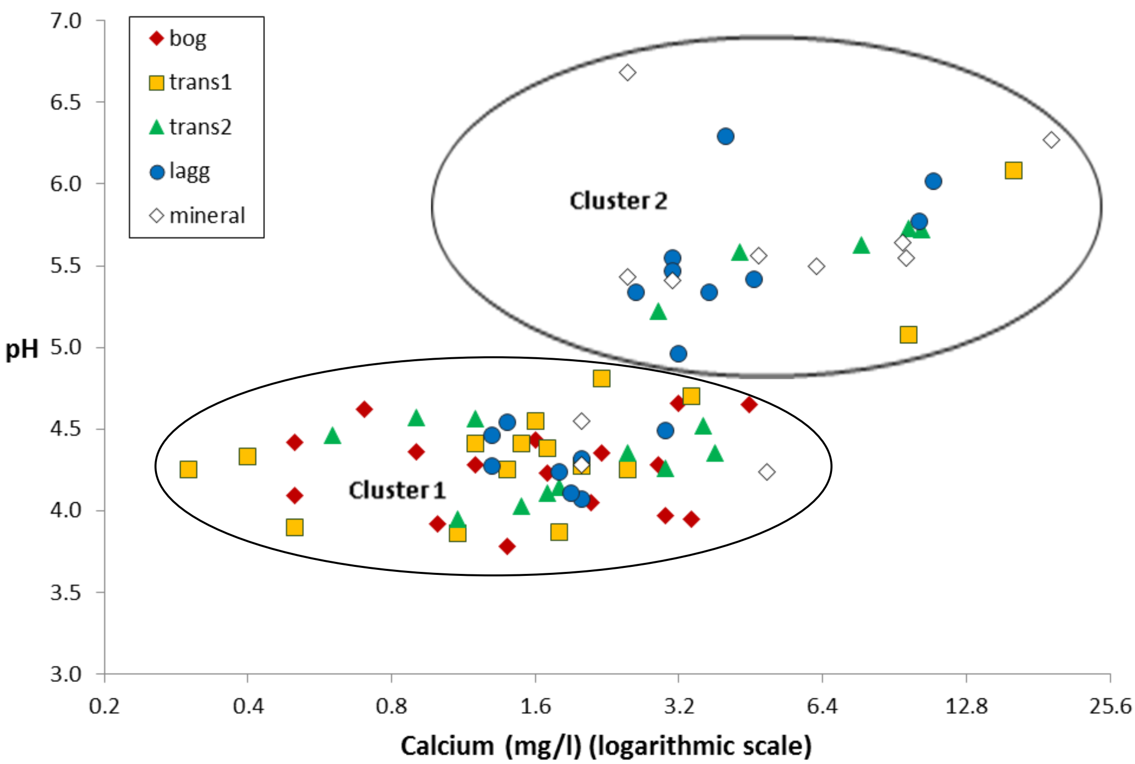

Figure A2. ***Relation between pH and calcium concentration for the studied bogs. The data group into two clusters: 1) generally representative of ombrotrophic bog water chemistry conditions, and 2) generally representative of sites influences by mineral groundwater.***

Appendix E. List of All Species Observed in this Study

The following tables contain the complete list of vascular and non-vascular species observed in vegetation plots in the BG (open bog heath), R1 (rand – transition between bog and lagg, closer to bog), R2 (rand – transition between bog and lagg, closer to lagg), LG (lagg), and MN (minerotrophic forest beyond the bog margin).

Vascular Species

	BG	R1	R2	LG	MN
Acer circinatum				x	x
Achlys triphylla					x
Agrostis aequivalvis	x	x	x	x	
Alnus rubra	x			x	x
Andromeda polifolia	x	x			
Athyrium filix-femina					x
Betula papyrifera	x	x	x	x	x
Betula pendula		x	x	x	
Blechnum spicant			x	x	x
Calamagrostis canadensis				x	x
Calamagrostis nutkaensis		x	x	x	x
Carex deweyana					x
Carex interior				x	
Carex obnupta	x	x	x	x	x
Carex pauciflora	x	x	x	x	
Carex phyllomanica	x	x	x		
Carex pluriflora	x	x	x	x	
Carex sitchensis	x	x	x	x	x
Carex spp.	x	x	x	x	
Chamaecyparis nootkatensis	x	x	x	x	x
Cicuta douglasii					x
Coptis trifolia	x		x		
Cornus canadensis	x	x	x	x	x
Corylus cornuta					x
Dodecatheon jeffreyi ssp. jeffreyi	x				
Drosera anglica	x				
Drosera rotundifolia	x	x	x	x	x
Dryopteris expansa				x	x
Empetrum nigrum	x	x	x	x	x
Eriophorum angustifolium	x	x	x		
Eriophorum virginicum	x	x	x	x	

	BG	R1	R2	LG	MN
Fauria crista-galli	x	x	x	x	x
Galium aparine					x
Gaultheria shallon	x	x	x	x	x
Gentiana douglasiana	x				
Gentiana sceptrum				x	x
Glyceria elata				x	
Ilex aquifolium				x	x
Impatiens glandulifera					x
Juncus effusus	x				
Juncus supiniformis	x				
Juniperus communis	x	x	x	x	
Kalmia microphylla	x	x	x	x	x
Lactuca muralis					x
Ledum groenlandicum	x	x	x	x	x
Ligusticum calderi		x		x	x
Linnaea borealis			x		
Lonicera involucrata				x	
Lysichiton americanum	x	x	x	x	x
Maianthemum dilatatum		x		x	x
Malus fusca			x		
Menziesia ferruginea		x	x	x	x
Microseris borealis	x	x	x	x	x
Myrica gale	x	x	x	x	x
Nuphar polysepalum	x				
Phalaris arundinacea					x
Physocarpus capitatus				x	x
Picea sitchensis		x	x	x	x
Pinus contorta	x	x	x	x	x
Polypodium glycyrrhiza				x	x
Polystichum munitum					x
Pseudotsuga menziesii					x
Pteridium aquilinium	x	x	x	x	x
Ranunculus uncinatus					x
Rhamnus purshiana	x	x	x	x	x
Rhizomnium glabrescens				x	
Rhynchospora alba	x	x	x		
Ribes lacustre			x		x
Rosa nutkana					x
Rubus chamaemorus	x	x	x	x	x
Rubus discolor					x

	BG	R1	R2	LG	MN
Rubus laciniatus					x
Rubus parviflorus					x
Rubus spectabilis				x	x
Rubus ursinus				x	x
Salix sitchensis				x	x
Sambucus racemosa					x
Sanguisorba officinalis	x	x	x	x	
Sorbus aucuparia		x	x	x	x
Spiraea douglasii	x	x	x	x	x
Symphoricarpos albus				x	x
Thelypteris phegopteris				x	x
Thuja plicata	x	x	x	x	x
Tofieldia glutinosa	x	x	x		
Trientalis arctica	x	x	x	x	x
Tsuga heterophylla	x	x	x	x	x
Tsuga mertensiana		x	x	x	x
Vaccinium corymbosum	x	x	x	x	
Vaccinium deliciosum	x				
Vaccinium membranaceum	x			x	x
Vaccinium myrtilloides	x	x	x		
Vaccinium ovalifolium	x	x	x	x	x
Vaccinium ovatum		x	x	x	x
Vaccinium oxycoccus	x	x	x	x	
Vaccinium parvifolium	x	x		x	x
Vaccinium uliginosum	x	x	x		
Vaccinium vitis-idaea	x	x	x	x	x
Viburnum edule					x
Veratrum viride				x	x

Non-vascular Species

	BG	R1	R2	LG	MN
Alectoria sarmentosa	x	x	x	x	x
Aulacomnium palustre		x			
Campylopus atrovirens	x				x
Cladina portentosa	x	x	x	x	x
Cladonia chlorophaea	x	x	x		
Cladonia macilenta	x	x			
Cladonia spp.		x			
Cladonia squamosa		x			

	BG	R1	R2	LG	MN
Climacium dendroides					x
Dicranoweisia cirrata					x
Dicranum scoparium	x	x	x	x	x
Dicranum spp.	x	x	x	x	x
Homalothecium fulgescens					x
Hylocomium splendens		x	x	x	x
Hypogymnia physodes				x	
Isothecium myosuroides	x	x	x	x	x
Kindbergia oregana		x	x	x	x
Kindbergia praelonga		x	x		
Lycopodium annotinum		x	x		
Lycopodium clavatum			x	x	
Lycopodium selago	x	x	x	x	x
Neckera douglasii				x	x
Oligotrichum parallelum					x
Orthrotrichum lyellii				x	
Peltigera neopolydactyla					x
Plagiomnium insigne				x	x
Plagiothecium undulatum		x		x	x
Pleurozium schreberi	x	x	x	x	x
Polytrichum strictum	x	x	x	x	
Porella navicularis				x	x
Racomitrium lanuginosum	x	x	x		x
Rhytidiadelphus loreus			x	x	x
Rhytidiadelphus triquetrus	x	x	x	x	x
Sphagnum angustifolium	x		x	x	x
Sphagnum austinii	x	x	x	x	
Sphagnum capillifolium	x	x	x	x	x
Sphagnum fuscum	x	x	x	x	
Sphagnum lindbergii	x		x		
Sphagnum magellanicum	x	x	x	x	
Sphagnum mendocinum	x	x	x	x	
Sphagnum pacificum	x	x	x	x	x
Sphagnum palustre	x	x		x	
Sphagnum papillosum	x	x	x	x	x
Sphagnum quinquefarium	x	x			
Sphagnum rubellum	x	x	x	x	
Sphagnum subnitens		x			
Sphagnum tenellum	x				

Appendix F. Dichotomous Key for Classification of Vegetative Lagg Types in Coastal British Columbia

1a. Tree basal area <8 m^2/ha..2

1b. Tree basal area >9 m^2/ha..3

2a. *Spiraea douglasii* present, cover ≥5%...Spiraea Thicket

2b. *Spiraea douglasii* absent, *Carex sitchensis* present..Carex Fen

3a. Ash content of peat at 50 cm depth >5%..Direct Transition

3b. Ash content of peat at 50 cm depth <5%...4

4a. Mean tree height <1.3 m..Direct Transition

4b. Mean tree height >1.3 m...Peaty Forest

Using this key, the laggs in this study were classified as follows:

Spiraea Thicket	**Carex Fen**	**Peaty Forest**	**Direct Transition**
Blaney Bog – UP	Mayer Lake	Butze Rapids	Drizzle Lake Bog
Burns Bog – CW	Diana Lake	Burns Bog – DNR (LG2)	Port McNeill Bog
Burns Bog – DNR (LG1)	Blaney Bog - FN	Burns Bog – SW (LG1)	Shorepine Bog East
Langley Bog		Burns Bog – SW (LG2)	Shorepine Bog West
Surrey Bend		Tow Hill Bog	Oliver Lake
Campbell River Bog			

This key was developed using data from 19 lagg study sites in coastal British Columbia. A larger data set is required to confirm that the ranges for basal area, tree height, species cover, and ash content are characteristic of most laggs in this region.

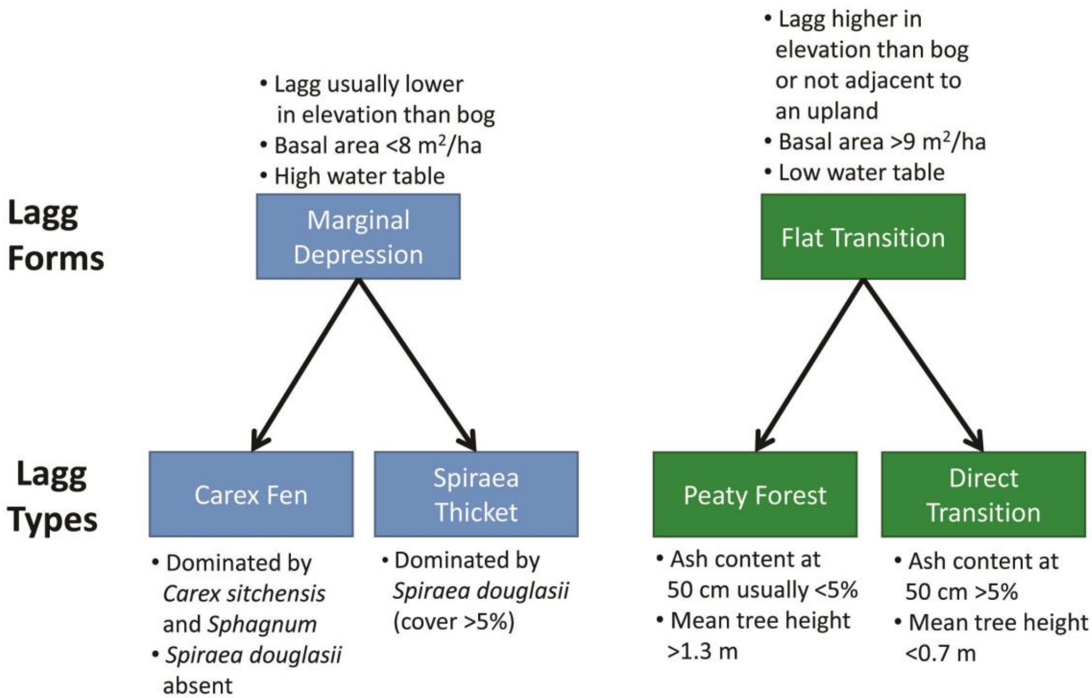

Figure A3. ***Proposed classification for lagg forms and types in coastal British Columbia.***

Appendix G. Recommendations for Conserving Additional Lagg Remnants of Burns Bog

Lagg Conservation

Identification and conservation of the lagg of Burns Bog is a priority item of the Burns Bog Ecological Conservancy Area Management Plan (Metro Vancouver 2007). Using the information from the historic and current lagg vegetation maps, aerial photographs, and field reconnaissance, we have identified four lagg remnants that are not currently protected in the conservation area (see Fig. 46b and descriptions below). These remnant and newly-formed lagg areas require protection not only because they are rare examples of this transition zone at the edge of the bog and are therefore important reference ecosystemss for restoration of the remainder of the Burns Bog lagg, but also because a high water table in the lagg supports the water mound of the bog. Conversion of these lagg areas to other land uses will undoubtedly require drainage of the lagg, which may negatively impact the water mound of the bog by increasing the outward hydraulic gradient and lowering the water table in the vicinity of the lagg. It is therefore recommended to map the remnant and newly-formed lagg areas with a detailed field-based assessment, and protect all existing lagg areas for conservation. Although the newly-formed lagg areas inside the historic bog boundary suggest that the bog has some capacity to naturally regenerate a lagg, it is not certain that the bog would continue to function in its current stable condition if the remaining areas of historic lagg that help to maintain the high water table in the peat mound were drained and converted to other land uses.

Sherwood Forest

This Peaty Forest lagg was logged 50-60 years ago, and a portion (4.7 ha) was logged again in 2011, but the peat was not removed and some old-growth spruce trees remain (#1 in Fig. 46b). Although this forested lagg appears to be a similar plant community to the large protected Peaty Forest lagg east of Highway 91, the Sherwood Forest lagg is unique in two ways. First, the Peaty Forest east of Highway 91 is separated from the bog by a highway, whereas the Sherwood Forest lagg is separated by a porous wood chip road. Second, and probably as a result of the porous nature of the wood chip road between the bog and the lagg, pH in the Sherwood Forest lagg (3.1-4.3) is very similar to pH in the bog centre (3.7-4.3), whereas pH in the Peaty Forest east of Hwy 91 (DNR transect) is higher (5.2-5.4). Since the only other undisturbed laggs in the Fraser Lowland bogs (outside of Burns Bog) are of the Spiraea Thicket type, it is not possible to compare the Sherwood Forest lagg to other Peaty Forests in the region outside of Burns Bog; however, two other Peaty Forest laggs on Haida Gwaii (Tow Hill Bog) and in Prince Rupert (Butze Rapids Bog) are also characterized by a pH within 0.8 of the pH in the adjacent bog.

Lagg Pond

A unique feature of the southern margin of Burns Bog is located south of the Vancouver Landfill. A lagg pond, approx. 100 m in diameter, is apparent in the earliest air photos from the 1930s, and appears to remain in a relatively undisturbed state, though somewhat drier than in the 1930s due to drainage in the area (#2 in Fig. 46b) as evidenced by a smaller area of open water in the more recent air photos. This pond is larger than the naturally-occurring ponds in the bog centre (typically approx. 20 m in diameter). This lagg pond appears to be a unique lagg formation in the region (i.e. large pond at the bog margin) and thus would be useful to conserve for research purposes and in order to protect this rare lagg feature.

Northeast Swamp

A rare portion of the historic lagg remains in a relatively undisturbed state in the northeast corner of the bog, adjacent to the Hwy 91/Nordel Way interchange (#3 in Fig. 46b). Although classified as “wet grass prairie” by land surveyors in the 1850s, this area now appears to be a dense hardhack swamp thicket. The change in plant community from the historic condition is most likely a result of the highway interchange (i.e. altered drainage and runoff from the highway and urban lands). This is the only large remnant of the wet grass prairie lagg, and so is an important site for lagg restoration research.

Panorama Swamp

A large, linear lagg swamp forest remains between Highway 91 and Panorama Ridge (#4 in Fig. 46b). Field observations in April 2010 showed that this swamp has a high water table in the wet season, and is dominated by lagg species, such as hardhack, willow, crabapple, skunk cabbage, and cascara. The presence of additional species that tend to develop in more minerotrophic, riparian settings (e.g. alder, cottonwood, salmonberry, elderberry, black twinberry) suggests that this site receives more runoff from areas outside the bog than the more common, hardhack-dominated lagg areas, although there is no evidence of a large contribution of surface runoff from aerial photos or LiDAR elevation data. This area was historically classified as “mixed coniferous forest on peat”, but appears to be a deciduous forest in air photos from 1930 and 1954. This area was either not mapped in detail in the 1850s, or developed between 1850 and 1930. This swamp represents a rare example of this lagg vegetation type at the margin of Burns Bog. Protection of this lagg swamp would provide the opportunity to study a rare lagg type in this region.