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Can Analysis of Historic Lagg Forms Be of Use in the Restoration of Highly Altered Raised Bogs? Examples from Burns Bog, British Columbia

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Abstract: Natural bogs are generally surrounded by a zone of hydrologic, hydrochemical, and ecological gradients called a lagg. In laggs, large changes over short lateral distances result in distinctive ecological gradients and vegetation patterns. Part of the restoration planning challenge for Burns Bog involves recreating such water and chemistry gradients to establish and maintain conditions for appropriate plant and animal communities that reflect natural transitions from nutrient-poor bog to adjacent mineral-soil-influenced wetlands. We present a conceptual model inferred from historic air photos and vegetation maps from the margins of Burns Bog and theorize how particular vegetation represents the hydrological and hydrochemical gradients of the past that existed in transition to surrounding landscapes. Understanding lagg ecosystems and how they function is important not only to restoring the ecological integrity of Burns Bog, but also to developing a conceptual model useful for predicting and interpreting these gradients in other peatlands.

Résumé : Les tourbières naturelles sont en général entourées par une zone de gradients hydrologiques, hydrochimiques et écologiques nommée « lagg » (marécage bordier). Dans les laggs, de vastes changements sur de courtes distances latérales se traduisent par des groupements de végétation et des gradients écologiques particuliers. Une partie du défi entourant la planification de la régénération pour la tourbière Burns Bog implique le besoin de recréer de tels gradients hydrochimiques pour établir et maintenir des conditions propices aux communautés végétales et animales appropriées qui reflètent des transitions naturelles des tourbières pauvres en éléments nutritifs aux marais qui subissent l'influence des sols minéraux adjacents. Nous présentons un modèle conceptuel tiré de cartes de végétation et de photographies aériennes historiques des marges de la tourbière Burns Bog et nous élaborons la théorie selon

S.A. Howie[1,2], P.H. Whitfield[3,4,7], R.J. Hebda[5,6,7], R.A. Dakin[7], and J.K. Jeglum[7]

[1] Corporation of Delta, Delta, BC V4K 3E2
[2] Department of Geography, Simon Fraser University, Burnaby, BC V5A 1S6
[3] Environment Canada, Vancouver, BC V6C 3S5
[4] Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6
[5] Royal British Columbia Museum, Victoria, BC V8W 9W2
[6] Department of Biology and Schools of Earth and Ocean Sciences and Environmental Studies, University of Victoria, Victoria, BC V8W 2Y2
[7] Burns Bog Scientific Advisory Panel, Metro Vancouver, BC V5H 4G8

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laquelle la végétation particulière représente les gradients hydrologiques et hydrochimiques du passé qui existaient en transition par rapport aux paysages avoisinants. La compréhension des écosystèmes propres aux laggs et de leur fonctionnement est importante non seulement pour la restauration de l'intégrité écologique de Burns Bog, mais également pour la création d'un modèle conceptuel pouvant servir à la prédiction et à l'interprétation des gradients dans d'autres tourbières.

Introduction

An ombrotrophic bog is exclusively fed by precipitation and atmospheric particulate deposition and is characterized by a dense cover of *Sphagnum* mosses, sedges, and ericaceous shrubs (Hebda *et al.,* 2000; Rydin and Jeglum, 2006). The surface consists of a varying microtopography of hummocks, lawns, carpets, hollows, and pools (Bragazza *et al.,* 2003). The surface water contained in the bog peat has a low nutrient and mineral content (oligotrophic) and low pH usually around 4 (<4.2, Sjörs, 1950; <4.5, Gorham *et al.,* 1985) as a result of the 'perched' water table being remote from the surrounding and underlying mineral soil (Bridgham *et al.,* 1996). The primary structural features of a raised bog are: 1) a large dome or plateau that is rain fed and in which peat accumulation occurs; 2) a narrow transition zone (the 'rand') that often has a relatively steep slope; and 3) a discharge zone (the 'lagg') that is located at the edge of the bog and where the excess water from the bog meets mineral soil water from adjacent and underlying mineral soil, collects, and drains away (Hebda *et al.,* 2000). For a raised bog to be viable and maintain its integrity, all three of these structures must be present and functioning appropriately (Hebda *et al.,* 2000).

Rydin and Jeglum (2006) describe the lagg as "a narrow fen or swamp surrounding a bog, receiving water both from the bog and from the surrounding mineral soil". Thus, the lagg is typified by the mixing of acid, organic-rich, mineral-depleted water from the peat-dominated bog and less acidic mineral-influenced water from adjacent mineral soil. The lagg zone often includes a perimeter stream or drainage-way that drains water away from the bog (Godwin and Conway, 1939) during the wet seasons. This process contributes to the hydrologic isolation of a bog by intercepting and collecting mineral-enriched runoff from adjacent areas (Hebda *et al.,* 2000) because of the positive hydrologic gradient on the bog side. In summer, when the water table drops due to reduced precipitation inputs, the lagg may become stagnant and dry out (Hebda *et al.,* 2000).

In raised bogs surrounded by laggs, the elevation difference between the topographic surfaces of the bog (higher) and the lagg (lower) results in clear vegetational and ecological differences (Svensson, 1988). The lagg is minerotrophic and therefore supports a more eutrophic type of vegetation than the adjacent bog (Godwin and Conway, 1939). The border between bog and lagg correlates with differences in the hydrology and chemistry of the peat and mineral areas (Svensson, 1988). A lagg normally supports fen and swamp vegetation including sedges, shrubs, and trees (Hebda *et al.,* 2000).

The higher mineral content of the water in the lagg zone may impede the tendency of the raised bog to extend radially by inhibiting the upwards growth of *Sphagnum* and establishment of a continuous raised layer of ombrotrophic *Sphagnum* peat above underlying minerotrophic peat. This may be the case when the lagg is adjacent to a steep slope of the mineral soil basin. If the topographic slope at the edge of the bog is more gradual, the lateral growth outwards of the bog margin over adjacent minerotrophic peatland is more rapid (Korhola, 1992). The rate of lateral growth of a bog over adjacent non-bog surfaces is controlled generally by the balance between incoming precipitation and outputs, and probably by its stage of development, for example, young rapid-growing versus mature slow-growing.

A strict definition of the term 'lagg' refers to the region between a raised bog and the upland terrain (firm ground) of a valley side (Godwin and Conway, 1939). In more gentle terrain, such as a delta, a lagg may have several forms (Hebda *et al.,* 2000). It may be narrow and contain bodies of deep water in winter, or it may be wide and shallow, depending on whether the adjacent non-bog surface is flat or sloping (Hebda *et al.,* 2000). Often one side of a raised bog is limited by a river or stream, and the lateral growth of the bog is checked by alluvial flooding and mineral deposition. In such cases, a steep rand may develop against the floodplain of the river (Godwin and Conway, 1939). Similar steep bog rands are found in boreal peatlands throughout Canada, where spring flooding and directed flow of surface waters in minerotrophic water tracks cause sharp boundaries to form along raised bogs and bog islands (Glaser, 1992).

This paper describes different lagg configurations that naturally developed around Burns Bog. Understanding how these historic lagg forms developed contributes to improved predictions of proposed bog restoration and re-creation of these habitats.

Study Site

Burns Bog, in the Lower Mainland of British Columbia, occupies approximately 3,000 ha of the Fraser Lowland between the south arm of the Fraser River and Boundary Bay (Figure 1). Burns Bog formed in the mid-Holocene after regional sea levels stabilized. About 5,000 years ago, brackish marshes developed on the sand and silt delta at the mouth of the Fraser River (Hebda, 1977). As the delta surface built up, freshwater river marshes developed, forming peat which accumulated above flood levels. By about 3,500 years ago, the ground surface was high enough that shrubs, such as sweet gale (*Myrica gale*) and hardhack (*Spiraea douglasii*) could establish, and form woody peat (Hebda, 1977). As peat accumulated over the dense, poorly drained organic silts below, the surface of the ground was nearly sealed to the downward movement of water (Hebda *et al.,* 2000). At that point, the main source of water changed from nutrient-rich flood water and groundwater to nutrient-poor rainfall (Hebda *et al.,* 2000). The first true bog species, such as (*Ledum groenlandicum* and *Sphagnum* spp.), established on the acid peat, followed by other bog species (Hebda, 1977). *Sphagnum* peat accumulated to form the present ombrotrophic raised bog, with the typical two-layered peat deposit (acrotelm and catotelm). The acrotelm is the aerobic surface layer of a mire soil, generally 25-50 cm thick, in which the water table fluctuates seasonally; in Holarctic regions, live plant material (esp. *Sphagnum*) generally covers the surface of the acrotelm (Ingram, 1978; 1982) and extends somewhat below the surface. The catotelm is the anaerobic lower layer that can be many metres thick and generally remains saturated with water (Ingram, 1982).

The Burns Bog lagg historically supported three broad minerotrophic plant communities: herbaceous vegetation of grasses, rushes, reeds, and sedges (wet meadow or fen); shrub swamp thickets of hardhack (*Spiraea douglasii*), willow (*Salix* spp.), crab apple (*Malus fusca*), and rose (*Rosa* spp.); and swamp forest of western red-cedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and red alder (*Alnus rubra*) (Hebda and Biggs, 1981). The first two of these communities predominated in much of the lagg zone either separately or together in a mosaic.

According to an extensive ecosystem review carried out in 2000 (Hebda *et al.,* 2000), it appears that before strong disturbance excess water in Burns Bog drained by lateral flow and seepage via four drainage zones to a complex marginal lagg system of streams and wetlands. To the north and west, lagg drainage flowed southwest and joined with streams from non-bog lowlands and entered Crescent Slough (a flood channel of the Fraser River), which acted as a distinct drainage channel at the outer edge of the lagg zone along the bog's west margin. At the south central and southeast margins, discharge collected in a lagg zone and drained into well-defined sinuous channels that flowed to Boundary Bay. Another drainage system carried water from the southeast and much of the eastern bog, and the upland Cougar Creek, to join Big Slough and empty into Boundary Bay (Hebda *et al.,* 2000). In the northeast, water from a small portion of Burns Bog and from Panorama Ridge drained directly to the Fraser River (Hebda *et al.,* 2000). Remnants of an alluvial fan on the eastern edge, presumably from Cougar Creek prior to the construction of the drainage canal, likely introduced mineral water into Burns Bog during flood events. It is estimated that about 30% of the water drained to Boundary Bay and 70% drained to the Fraser River (Hebda *et al.,* 2000).

Burns Bog in the 1930s (Figure 1) appears to have mostly extended to its original natural boundaries. Farms were built up to the edge and clearing and drainage extended onto the margins of the peat (Hebda, 1977), especially in the south. We assume that the marginal features evident in Figure 1 are a reasonable representation of the original pre-disturbance lagg and include the transition to the uplands of Panorama Ridge, the levee of the Fraser River, the incised boundary of Crescent Slough, the low gradient topography with presumed beach features adjacent to Boundary Bay, and seepage across a flat delta surface expanse.

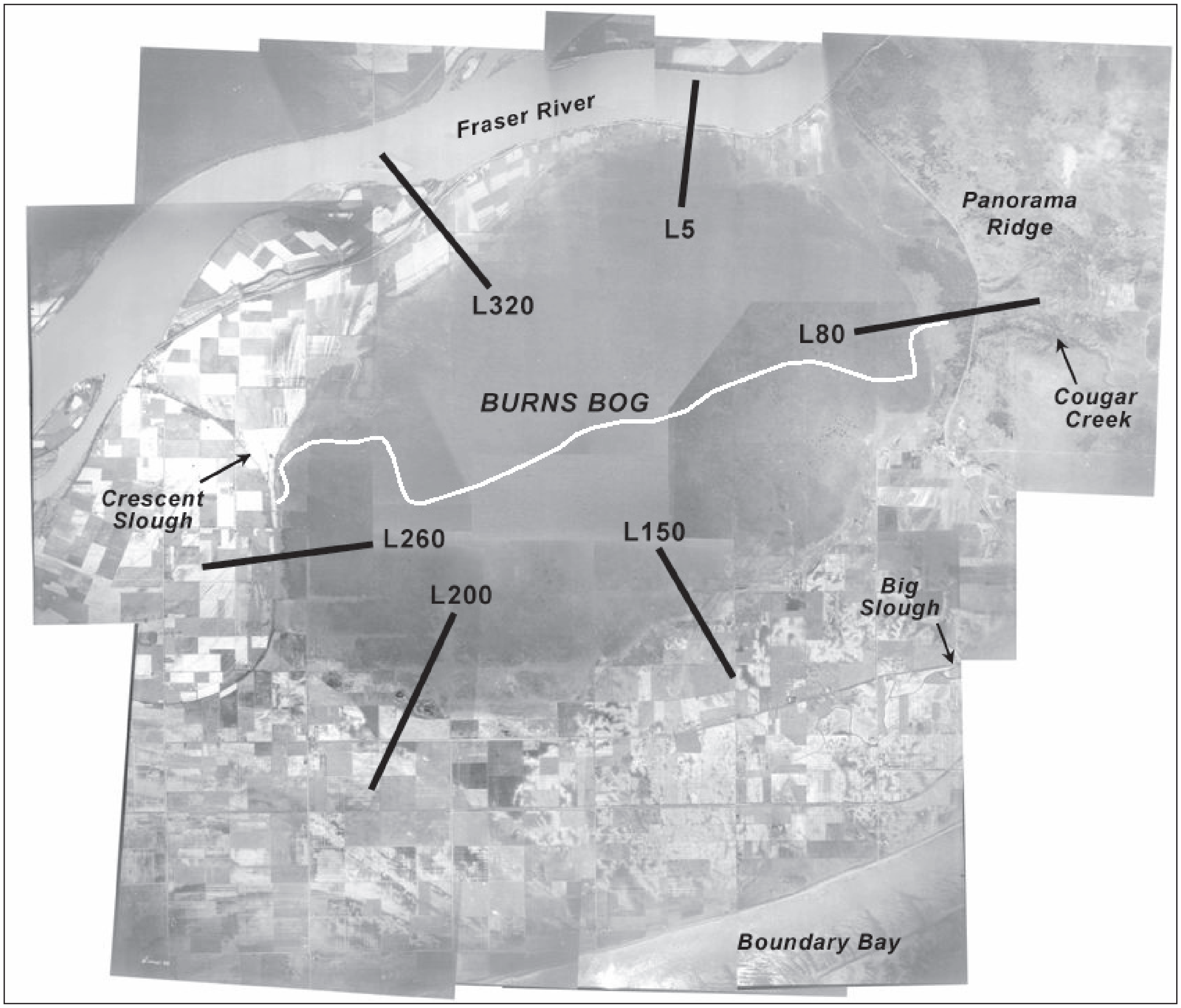


Figure 1. 1930 aerial photo mosaic showing Burns Bog and associated landscape features in Delta, BC. Transects used in the air photo analysis are shown. These transects are perpendicular to the bog/lagg interface and the numeric portion indicates the angle of the transects with respect to the centre of the bog. The white line indicates the inferred historic drainage divide from Hebda *et al.* (2000).

Lagg Conceptual Model

Whitfield *et al.* (2006) developed a conceptual framework of how these lagg transitions might have looked in cross-section. These conceptual sketches of the lagg transitions with descriptions are shown in Figure 2. The model presented here is based on that framework, coupled with gradients expected to be present in the ecotone. This contribution supports the conceptual framework with a detailed analysis of historic (1930/1954) air photos and with 1873-74 survey notes (Hebda and Biggs, 1981). This paper illustrates how the model has been refined based on study of the historic aerial photographs, topography, and stratigraphic cross-sections; the refinements move the concepts presented in Whitfield *et al.* (2006) toward a predictive model of lagg forms.

The original concepts shown in Figure 2 principally described geomorphologic lagg forms and an indication of flow direction (hydrology). Two other elements, hydrochemistry and ecology, are integral to the hydrological gradients of the lagg. The varying water table and chemical properties of the transition from bog to minerotrophic soil result in a specific

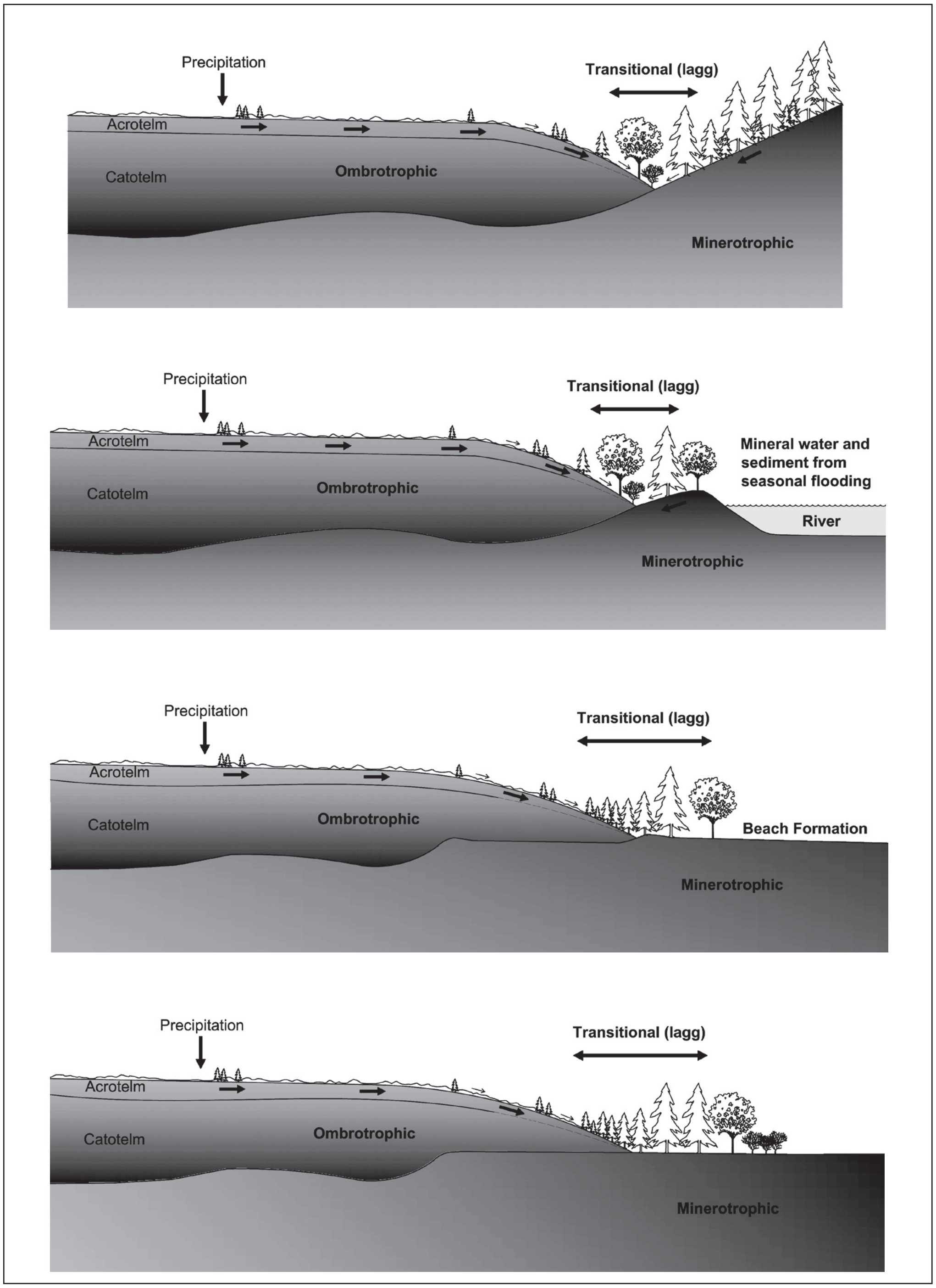


Figure 2. Conceptual lagg structure after Whitfield *et al.* (2006). The vertical scale has been greatly exaggerated. 1. Upland: At the eastern boundary where the bog meets Panorama Ridge, the lagg was structured as is typical of many upland bogs: a transition zone between a mineral upland and the peat upland of the bog. 2. River Levee: Along the northern and western boundaries, the lagg was a transition from bog to wet minerotrophic lagg and up onto the natural levee of the Fraser River, an area subject to periodic flooding and tidal fluctuations in the River. 3. Beach: Ancient beach formations may be responsible for the lagg positioning and structure south of the bog. 4. Outwash: At the southeastern edge, it is presumed that there was natural seepage from the bog across a flat delta surface expanse (Whitfield *et al.,* 2006).

pattern of vegetation structure (Godwin and Conway, 1939; Groenveld and Or, 1994). In a bog, there is a strong relationship between water level and tree height, with tree height increasing as the water table becomes deeper below the surface. Since plant communities can be correlated at the site level with measured water levels and chemistry (Hebda *et al.,* 2000), this information can be used to make predictions about the hydrological and hydrochemical conditions underlying the same plant communities at other locations in the past. Thus, plant community structure in archival aerial photographs and from earlier surveyors' notes provides key insight into historic lagg configurations (i.e., lagg conditions prior to anthropogenic interventions such as drainage, farming, and filling) where the hydrology and hydrochemistry are unknown today.

The conceptual model of the lagg structure and chemical and vegetation gradients for an upland lagg transition are presented in Figure 3. The two hydrological gradients Δh_1 and Δh_2 indicate the movement of water

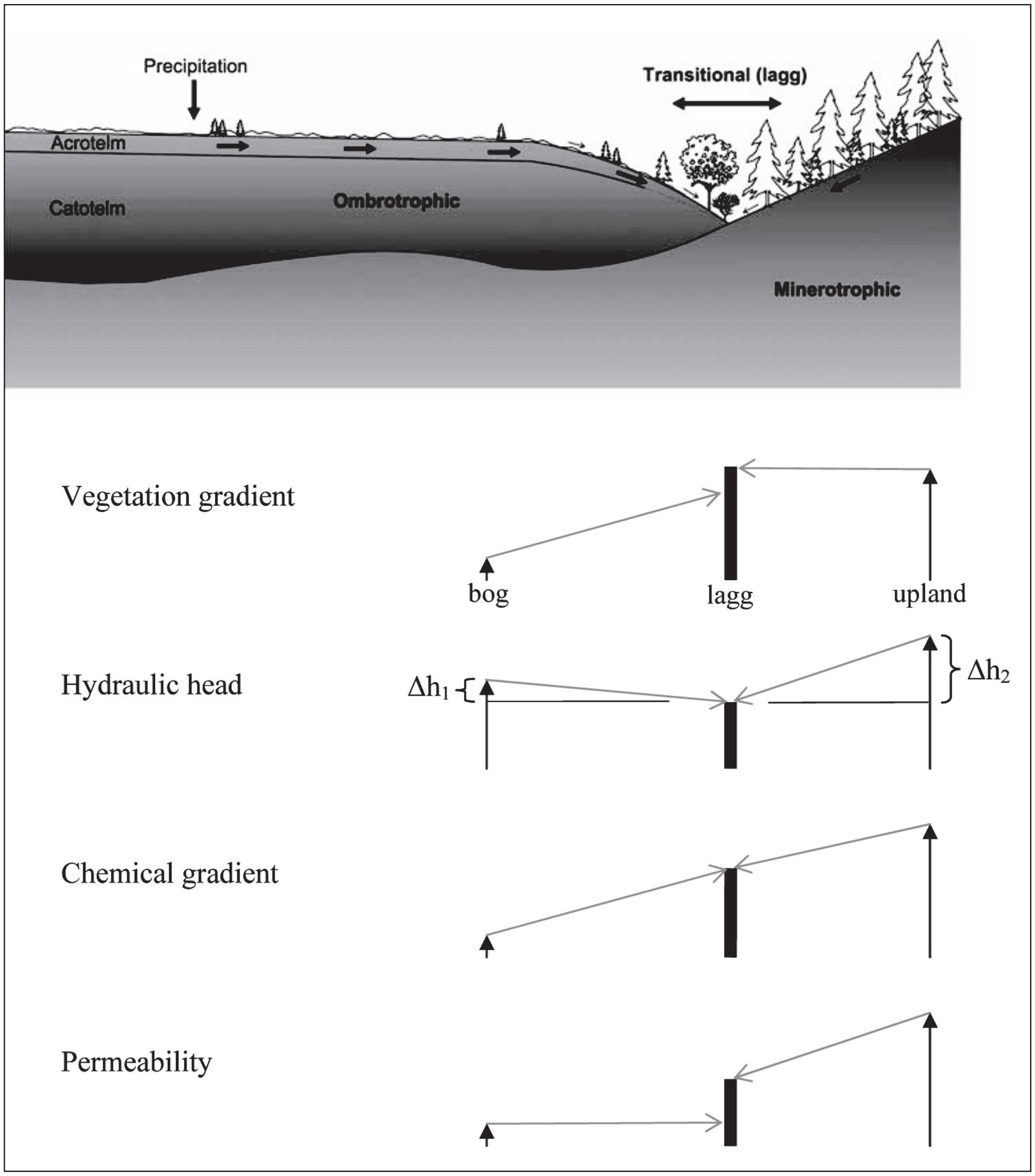


Figure 3. Conceptual model of an upland lagg vegetation transition and associated physical gradients (vegetation height, hydraulic head, chemical, and permeability). Other aspects such as plant community, pH, will be similar. Some gradients (e.g., vegetation height) will vary on either side of the lagg and will only mix upon entering the lagg; hence, some of the arrows do not meet at the same location on either side of the lagg symbol.

into the lagg from both directions. The character of h_2 may be influenced by h_1 (water levels in bog). For example, on relatively flat terrain, the elevation of the water table in the bog could rise more than in the adjacent landscape at times of high precipitation, affecting movement of nutrients to the lagg. The chemical gradient for calcium indicates the mixing of low mineral content bog water and high mineral content upland water or mineral terrain water. For organic carbon (e.g., DOC, fulvic and humic acids) the gradient would generally be reversed. Conceptually, the differences in the rate of flow of water reflect the permeability differences between the bog side and the mineral side. Catotelmic peat has a very low permeability and is expected to differ greatly from the outside mineral area. The permeability of the underlying organic delta top silts may also be low. This conceptual diagram will be further refined when these elements are verified in the field.

The differences in the height of vegetation are indicated as being different on either contributing side. Different vegetative forms of lagg, such as those involving fens, are expected to have unique combinations of plant height gradients and/or transitions strongly influenced by nutrient flux and seasonal variation in the water table. Plant species composition and distribution is affected by water level (both height and fluctuation) and water chemistry (nutrient flux) in the acrotelm (de Mars and Wassen, 1999; Weirda *et al.,* 1997). While this may be true in a high flux lagg, in other low gradient/low relief laggs the nutrient flux and/or water flow may be much lower. In the conceptual model and in the data in Figure 4, the vegetation gradient varies across and between different lagg types. Although tree density data are not presented in this paper, analysis of old air photos shows that tree density is also affected by hydrology and hydrochemistry; increasing nutrient levels and a lower water table appear to facilitate increased tree density. It is acknowledged that vegetation height, density, and species composition may also be affected by other factors, such as height variation of mature trees between different species or previous natural disturbances (e.g., fire, wind, snow).

Methods

Historic aerial photographs (1930 and 1954) were reviewed to establish the past extent of Burns Bog and the various formations of the lagg around the perimeter before extensive peat excavation, draining, and filling on the margins. A stereoscope was used to assist in the examination of the height and density of trees along selected transects perpendicular to the bog margin. The location of the lagg was determined based on vegetation patterns in the photos, such as the transition from *Sphagnum*-heath communities to primarily woody vegetation, an indication of water movement or hydrochemical gradients (e.g., flooding, old beach formations, ponds, natural drainage courses). The location of the bog-lagg transition was generally interpreted to be where there was a marked increase in height of the trees. It was assumed that the dominant lodgepole pines grew better in the rand-lagg transition, or that increased nutrient availability favoured other tree species as in mixed conifer forest (Hebda and Biggs, 1981). The patterns detected in the historic air photos were compared with a map produced from the 1873-74 surveyors' notes from the area (Hebda and Biggs, 1981) to verify the inferred patterns. For each of the lines shown in Figure 1, the tree heights and forest density (defined in relative terms, e.g., dense, scattered) were determined from stereoscopic pairs of 1954 air photos on three parallel transects at approximately 50 m intervals; the location of distinct linear features were also determined. The 1950 ground elevation data presented in Hebda *et al.* (2000) were used for elevations. The results were compared to the inferred pattern as presented in the model in Figure 2.

Results

The historic drainage patterns evident in the 1930 and 1954 aerial photographs show that the series of topographic features surrounding Burns Bog (uplands, floodplain, river levee, and slough) gave rise to a variety of lagg forms. Based on the review of 1930/1954 air photos and stratigraphic cross sections, it appears that Burns Bog historically supported five variations of lagg transition.

1. Upland Complex (Transect L80 in Figure 1): At the eastern boundary where Burns Bog meets Panorama Ridge, the lagg occurred between steeply rising mineral upland and the peat dome of the bog with a sharp transition from minerotrophic to oligotrophic water. The vegetation was a swamp forest likely dominated by western red-cedar (*Thuja plicata*) and Sitka spruce (*Picea sitchensis*), and patches of wet meadow thicket dominated by hardhack (*Spiraea douglasii*). The strong upland hydrologic gradient resulting from discharge off Panorama Ridge either drove minerotrophic surface water into Burns Bog or caused minerotrophic groundwater to well up within the lagg, resulting in woody species and peat, but with little *Sphagnum* accumulation.

Approximately 1 km to the west, there was a second mineral-influenced zone within the body of the bog, where the mineral subsurface rose near the peat surface and groundwater upwelling likely occurred. Woody peat occurred in the subsurface, rather than *Sphagnum* peat. The mineral ridge acted as a subsurface hydrological and hydrochemical divide and a sort of "internal lagg zone" channelling subsurface discharge from the bog along its crest/length. Non-bog woody vegetation is clearly visible in the historic aerial photographs along this subsurface ridge, where the forested and hardhack communities abruptly change to bog vegetation. Tree height increased from less than 1 m in the bog to more than 5 m at this ridge; tree height then decreased east of the subsurface ridge before rising quickly to 15 m or more at the base of Panorama Ridge (Figure 4). Minerotrophic species grew along the ridge (Hebda and Biggs, 1981). The location of the subsurface ridge is shown in Figure 4; there is a depression of the bog surface at this location, presumably because less peat accumulated.

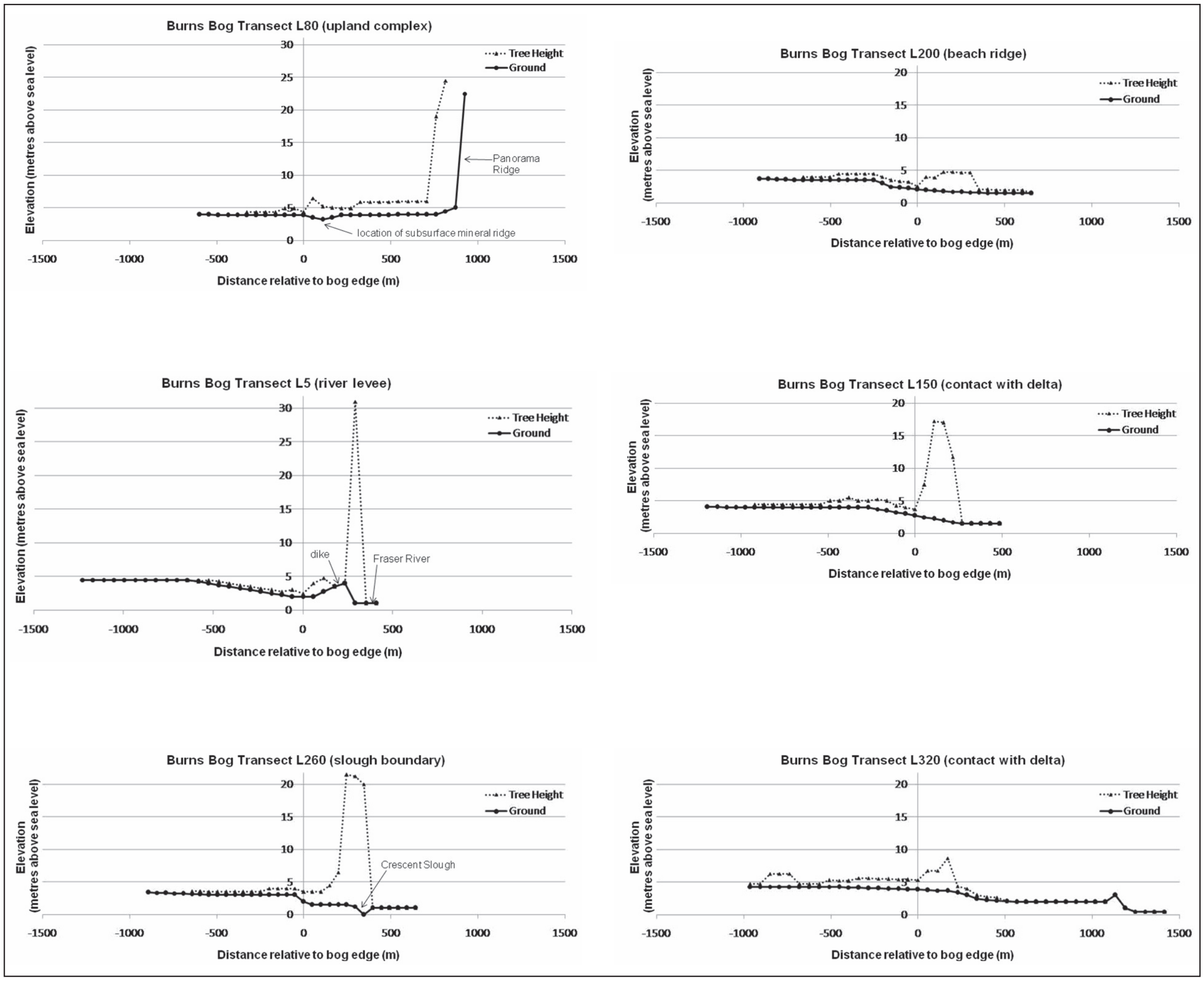
The area between this subsurface ridge zone and Panorama Ridge may have been a large wetland that originally formed in a basin (unlike the rest of Burns Bog, which formed on the flat delta surface), eventually filling with swamp peat and then being engulfed by expansion of *Sphagnum* peat-forming vegetation of the main bog from the west (Hebda, 1977). By the time of the 1930 aerial photograph, the raised bog vegetation had expanded over the ridge and ancient swamp to the east, but the north-south drainage axis and associated vegetation remained because the subsurface minerotrophic influence prevented the development of a true acrotelm and catotelm, which would require an adequate depth of *Sphagnum* peat accumulation.

Also complicating the eastern lagg zone is the ancient Cougar Creek fan. This alluvial structure appears to have played an important role in bringing mineral material into this area and certainly influenced the positioning of the lagg relative to the bog. This hydrological and hydrochemical pattern was modified by the construction of the Northeast Interceptor Canal cutting north-south through this area and diverting the flow from the Cougar Creek fan north to the Fraser River. The presence of mineral material in the subsurface area continues to influence local plant communities.

2. River Levee (Transect L5 in Figure 1): Along the northern edge of Burns Bog there was a sharp lagg transition from bog to minerotrophic lagg developed against the natural levee of the Fraser River. The physical constraints of the river in this lagg zone induced a narrow fen between a steep rand and levee. The lagg fen was characterized by wet grass prairie vegetation including grasses, rushes, reeds, and sedges (Hebda and Biggs, 1981), reflecting abrupt changes in lagg gradients.

Between the lagg and the river was a riparian spruce forest with crab apple, willow, and alder. In some sections of this margin there appears to have been no distinguishable fen zone and the bog discharged directly to the riparian zone of the Fraser River. Tree height was less than 1 m in the bog and rand, and did not increase until reaching the mineral-influenced levee of the river (Figure 4). Presumably, this reflects a bog margin dominated by steep bog water hydrological and hydrochemical gradients.

3. Slough Boundary (Transect L260 in Figure 1): At the west margin of Burns Bog, the peat mound met with Crescent Slough, a weak flood channel of the Fraser River. The outer limits of the bog here were likely flooded with mineral water from the Slough during the spring freshet in the Fraser River. In this zone, the lagg consisted and still consists of swamp forest dominated by western red cedar, Sitka spruce, western hemlock, and red alder (only immediately adjacent to the Slough). This forest likely reflects the influence of mineral water from floods and possibly mineral-rich groundwater. Tree height rose from less than 1 m in the bog to about 3 m along the narrow rand and then increased to about 20 m in the lagg zone between the bog and the Slough (Figure 4). Supplies of nutrient-rich water on the slough side of this zone are essential to this pattern of vegetation.


Burns Bog Transect L80 (upland complex)

Burns Bog Transect L200 (beach ridge)

Burns Bog Transect L5 (river levee)

Burns Bog Transect L150 (contact with delta)

Burns Bog Transect L260 (slough boundary)

Burns Bog Transect L320 (contact with delta)

Figure 4. Structure of laggs determined from 1954 air photographs for transects shown in Figure 1: an upland complex (L80), river levee (L5), slough boundary (L260), beach ridge (L200), and contact with delta (L150 and L320). Vertical axis is located at the presumed inner (bog) edge of the lagg, determined by topography and tree height. Tree height measurement error is relative to tree height (e.g., 2-3 m bog trees would have a small error of approximately 0.5 m, whereas taller trees of 15-30 m in height would have a larger error of approximately 2 m). Bog surface elevation as shown does not account for seasonal fluctuation of the bog

4. Beach Ridges (Transect L200 in Figure 1): Repetitive linear vegetation features in the 1954 air photos suggest low relief paleo-beach ridges resulting from previous slightly higher than present sea level stands or shoreline constructional features as marine waters abandoned the southwest periphery of the bog area. These ridges would have been topographically subtle and eventually might have been overtopped by the expanding peat mound. Tree height was approximately 1 m or less in the bog, increasing to 2-3 m beyond the outer edge of the rand as the underlying material became more minerotrophic (Figure 4). In this situation, the growth of the bog relative to these geomorphic structures results in a complex pattern of gradients, as is evident by a weakly defined bog margin and drainage system in the 1930 air photo (Hebda *et al.*, 2000). The presumed beach ridges do not show up in the topographic section of Figure 4 due to the low resolution of the elevation data; recently collected LiDAR data will provide a more detailed digital elevation model, which can be of use in verifying or invalidating this hypothesis.

5. Inactive Delta (Transects L150 and L320 in Figure 1): A gradual and expansive lagg zone is seen to the south and northwest of Burns Bog in historic air photos, where natural seepage from the bog discharged over the now inactive delta surface (Whitfield *et al.,* 2006). This broad transitional zone was characterized by a mixture of shrub thickets and fens. It is presumed that these areas were undergoing succession to *Sphagnum* bog and that the gradual lagg zone was a precursor of *Sphagnum* bog as proposed by Hebda (1977). Tree height was less than 1.5 m in the bog, increasing to 3-5 m through the rand and increasing again to 10-15 m at the outer perimeter (Figure 4).

Discussion

The water mound of a natural raised bog does not exist in isolation, but structurally includes the transitional rand and marginal lagg zones (Hebda *et al.,* 2000). To ensure the ecological integrity and long-term viability of a raised bog, it is necessary to maintain the hydrological conditions of the lagg zone (Schouten, 2002). In many North American and European raised bog restoration initiatives, the lagg structure has not been considered in restoration efforts, perhaps because the restoration site comprises only a portion of the entire raised bog system, the lagg having been previously destroyed. It may not be necessary (or possible) in many situations to re-create the lagg in its historic form and position, but it is necessary to recreate some of the lagg functions (e.g., high water level at the bog perimeter) to restore a raised bog ecosystem in its entirety. For example, the water table in part of a lagg zone in an Irish bog was restored by blocking perimeter ditches (Schouten, 2002). Maintaining a high water table in perimeter ditches is an appropriate solution where feasible; however, this is not necessarily possible when the bog in question is surrounded by other land uses that could be flooded by such an action (see below).

Burns Bog is an urban bog that is entirely surrounded by drainage ditches, which both drain the bog and serve as storage features during the rainy season to minimize flooding of adjacent properties. In this case, a lagg is essential because it acts as a buffer between the bog and adjacent land uses and their potentially negative impacts on the bog ecosystem, such as mineral-rich runoff from industrial/residential uplands and farms, invasive species, and fire. Maintaining a high water level in the lagg will assist in holding precipitation within the bog, thereby promoting restoration of natural bog hydrology. Thus, it is essential to maintain a high water level at the perimeter of the area of Burns Bog that we hope to restore. In most cases, a simple perimeter ditch cannot perform lagg-related functions, largely because it is too narrow, sometimes too deep, and cannot maintain hydrological and hydrochemical gradients appropriate to healthy raised bogs. In the case of Burns Bog, it will be necessary to re-create the functions of a natural lagg to promote these gradients and ecological functions. An additional value of a forested lagg zone, if it is sufficiently high and dense, is to act as an effective barrier to windblown transport of mineral material from agricultural fields, transportation corridors, and other land uses. Wind-blown nutrients can negatively impact the unique, nutrient-poor plant communities of bogs (Farmer, 1993).

In Burns Bog, few original drainage channels remain in a natural form and the lagg zone has been greatly modified or converted to other non-bog uses and ecosystems. The original lagg and transitional rand are now disconnected from the water mound, especially in the east and northwest (Hebda *et al.,* 2000). Instead of water seeping or flowing out into the lagg as was the case historically, ditches extend from the bog perimeter to the centre of the water mound and remove water rapidly or water gathers in old peat works and flows out through ditches to the margins. The ditches and their associated lagg-like processes slice deeply into the bog ecosystem, lowering the water table in the peat mass and generating extensive hydrologic edge effects (Hebda *et al.,* 2000). Decades of peat mining and ditching have contributed to loss of water storage and decline in the water table and bog surface, contributing to the continued advance of pine forest into the bog (Hebda *et al.,* 2000).

Modern-day transitions from bog to non-bog, though located in different places than in the past, are similar in form to some of the original lagg configurations. Landfills and industrial areas now create upland-like transition conditions adjacent to Burns Bog in some ways similar to the original configurations adjacent to Panorama Ridge. The ditches and berms bordering adjacent cranberry fields and agricultural lands create transitions similar to the historic boundary formed by Crescent Slough or the Fraser River levees. Due to potential influence of the Fraser River floods, the northern margin remains similar to the original river levee lagg but the industrial lands do not function like ancient levees. Their high elevations create much stronger flows of mineral rich water toward the bog than was originally the case.

The transition to the Panorama Ridge upland also remains broadly similar to the past configuration, but the foot of the ridge is now strongly drained to the Fraser River by the Northeast Interceptor Canal. During times of intense precipitation, water overtops the canal and flows westward over the bog surface as it did before the canal was built.

It is important to emphasize that in the past much of Burns Bog was surrounded by a very broad zone of discharge through wide transitional plant communities (Hebda and Biggs, 1981). In general, the broad, gradual lagg transition zones have been lost to agriculture and industrial development. Little opportunity remains to restore this form of lagg zone. However, because sharp transitions (e.g., upland and levee) existed in the past, it is feasible that the lagg of Burns Bog can be restored with some possibility of success to accommodate desired bog processes using the historic lagg configurations as models. It may be that the gradual lagg form where it once occurred adjacent to much of the margin is not necessary for the ecological viability of the bog. The long-term success of such a narrow-lagg strategy remains to be seen and more hydrochemical, hydrological and ecological data are required before any models are fully implemented.

An innovation of this paper was the use of tree height as a reflection of the various types of lagg models for Burns Bog. Weirda *et al.* (1997) demonstrated that vegetation distribution on semi-natural grasslands with peat soils is mainly determined by how high the water table rises and how much it fluctuates. De Mars and Wassen (1999) report that hydrochemistry affects the vegetation; there is a correlation between the redox potential of mires at 15 cm below the peat surface and the water level. Plant species composition and distribution are affected by water level and chemistry. The plant community composition changes (hence also the peat composition) approaching the lagg, with much less *Sphagnum* and more woody material. Simple and traditional techniques (e.g., stereoscope) were used to examine old air photos, but newer technologies (e.g., Cardinal Systems VrTwo) are available that have the potential to significantly increase the accuracy and quantity of data.

It should be noted that changes in land use surrounding and within Burns Bog occurred before 1954, such as expanded farm encroachment at the bog perimeter, and peat harvesting and drainage within the bog itself. These impacts would have caused some alterations to the vegetative community, meaning that the conditions seen in the 1954 air photos are not necessarily representative of the exact historic conditions prior to European settlement of the area. Indeed, comparison between 1930 and 1954 air photos shows a slight increase in tree coverage at the margins of the bog. However, the purpose of this research is to illustrate that historic air photo interpretation is a useful tool for determining historic lagg configurations. In the case of Burns Bog, 1954 was the earliest date of clear air photos and it was decided that the 1954 conditions were close enough to the historic conditions (as described in historic surveyors' notes) to be useful for examining historic lagg features.

A lagg is a dynamic system that experiences seasonal variation and is always in the process of responding to ecologically relevant influence from abiotic conditions, adjacent plant communities, and natural disturbance; thus, it might be presumed that a lagg is in a constant state of flux. However, it was observed in the 1954 air photos that conditions in the lagg zone were similar around the entire bog perimeter. In addition, the air photo analysis transects were placed in triplicate at each site, and homogeneity was observed within the triplicates, suggesting that the conditions of the Burns Bog lagg forms were relatively stable. From this, it may be assumed that the 1954 air photos could be representative of a broader period of time.

Improved Predictability

In this paper, observations and analysis of historic air photos are used to move the conceptual model towards a more predictive model in which five distinct lagg transition forms are identified for Burns Bog. At least some of these forms can be expected to occur in the lagg zone of any raised bog, and perhaps at the margins of fens. The form that a given lagg transition will take is based on underlying and adjacent land forms and the natural successional series for wetland development in a region (Hebda, 1977). The results suggest that original lagg configurations for Burns Bog can be reconstructed through an analysis of historic vegetation data (Hebda and Biggs, 1981), 1954 air photos (Government of British Columbia), estimated 1950 elevation data (Hebda *et al.,* 2000), and draft stratigraphic cross-sections based on unpublished data from Golder Associates Ltd. (2007). While validation of the interpretation of the inter-relationships of the chemical, hydrologic, and ecological gradients continues, the conceptual framework may be applied to interpreting natural laggs in other situations, inferring the nature of gradients at the margins of bogs and perhaps fens.

The observations for Burns Bog inform predictions about lagg form and function at other raised bogs worldwide. The determination of original lagg form in a degraded or damaged raised bog ecosystem assists in identifying target conditions and designing the restoration plan to include the lagg. A key principle is the matching of past natural lagg configuration to current geomorphic conditions, even if the geomorphic conditions have changed. Assuming that within a region the same bog-lagg plant community patterns develop under similar conditions, an inventory of modern and past lagg zones and their hydrochemical, hydrological, and ecological characteristics provides a useful tool for choosing appropriate restoration designs for bog-lagg transitions, even those resulting as a consequence of recent disturbance.

The analysis of historic aerial photographs, as expected, demonstrates a link between the lagg form model and geomorphology for the conditions in Burns Bog and likely other bogs in the region. For Burns Bog, to verify that vegetation is a surface representation of the underlying hydrology and hydrochemistry and not the result of recent disturbance (i.e., a successional plant community), a more comprehensive investigation of the gradients is required from the few remnants in the bog and a wider sample of natural laggs in the region.

Thorough characterization of the gradients across the various lagg zones in a variety of bogs will provide useful information to the restoration of the lagg zone around Burns Bog. Preservation of the few remaining lagg fragments (such as Crescent Slough) is vital for continued study of natural lagg function. Monitoring of the condition of remaining lagg zones in response to current ditch blocking in the entire bog is also important. Considering that the present margins of Burns Bog are heavily altered, these conceptual models are expected to be particularly useful in creating or restoring laggs in areas such as the landfill uplands. It will be necessary to improve the understanding of the sharp lagg transition forms to determine whether it will be possible to recreate a functional lagg around the complete perimeter of Burns Bog using, for example, the upland transition model. The key is to fit the re-created lagg zone to the existing landscape setting, which in most places is altered from its original form.

To further refine the model and particularly the conceptual diagram presented in Figure 3, it will be necessary to examine if and how the acrotelm and catotelm change through the transition from bog to lagg. Presumably, at some point in the lagg the acrotelm/catotelm boundary ceases to exist, but some form of peat remains (Figure 3). Further research is required to understand how the acrotelm/catotelm boundary tapers out approaching the lagg, or the nature of the acrotelm/catotelm in the margins of the lagg if some form of this structure remains.

There is a difference in permeability between bog and mineral soils (Figure 3). For example, alluvial uplands may be much more porous than tills with cemented layers. A more detailed analysis of the permeability of soil across the various lagg forms of Burns Bog may lead to improved predictability of soil porosity for other bogs in the region.

It is proposed that the measurements described in this paper, if carried out at a variety of natural bogs in the same region, would help to move the conceptual model towards a predictive model. Research is underway to study lagg forms of natural raised bogs in coastal British Columbia, in hopes of developing a more refined understanding of lagg form and function in this region. This model, in turn, may prove useful in developing a restoration plan for the lagg of Burns Bog and other bogs in this region, and provide a useful framework for developing similar predictive models for other regions.

Conclusions

For raised bogs that have been altered from their original form, historical vegetation notes, vegetation patterns in old air photos, and a study of stratigraphy and topography can assist in determining natural lagg forms. The linking of pre-disturbance plant communities to underlying geomorphology, hydrology, and hydrochemistry is especially informative. This knowledge is useful for raised bog restoration, as it can assist in designing a proposal for lagg and concurrent bog restoration. One can also use this information to make predictions about lagg form and function in other disturbed bogs located in similar physiographic and climatic settings. The conceptual model proposed in Whitfield *et al.* (2006) has been refined here with respect to geomorphic form and tree height/density as a reflection of nutrient status and flux (hydrochemistry), as visible in old air photos. Further refinements are required in terms of the gradients proposed in this paper (geomorphology, permeability, and nutrient levels/flux) across the various lagg forms of Burns Bog.

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