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

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Abstract

The laggs of three raised bogs in coastal British Columbia were studied in 2010–2012 to determine the temporal variation in depth to water table and hydrochemistry. The lagg is an integral, but rarely studied, part of a raised bog that helps to maintain the water mound in the bog and provides a buffer for runoff from adjacent mineral areas. Depth to water table measurements in 25 piezometers displayed similar annual fluctuations, with the highest water table in winter and the lowest at the end of summer. The smallest fluctuations in depth to water table were recorded closest to the bog centre, and the largest fluctuations in the laggs and adjacent mineral soil sites. 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 increased by 8 cm from 2010 to 2011, and by up to 27 cm during the driest time of the year. pH, pH-corrected electrical conductivity, and Na^+ and Mg^{2+} concentrations varied little during the study period, whereas Ca^{2+}, K^+, Cl^-, and DOC concentrations and acidity were more variable.

1 Introduction

Raised bogs form where precipitation is relatively evenly distributed throughout the year, and where annual precipitation exceeds potential evapotranspiration in most years (Schouten, 2002). Due to the dependence on precipitation, hydrological processes in raised bogs are closely linked to the amount, intensity, and distribution of precipitation. While discharge from the bog is strongly influenced by precipitation in the wet season, evapotranspiration is a major control on water in the acrotelm during the dry season (Wheeler et al., 1995). During moderate to large rainfall events, water levels in raised bogs tend to rise rapidly (Malmer, 1986). Correspondingly, water levels often decrease rapidly during dry periods due to evapotranspiration and relatively rapid lateral discharge through acrotelmic peat with a high hydraulic conductivity near the bog surface (Damman, 1986; Malmer, 1986; Holden, 2005). This repeating and predictable

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cycle of water level fluctuations over time is known as the "hydroperiod" (Rydin and Jeglum, 2006). In undisturbed raised bogs, the annual fluctuation of the water table is about 30 cm, which is much smaller than in the adjacent mineral soils where the fluctuations can be closer to 50–150 cm (Schouten, 2002).

In temperate coastal regions, the highest water table in raised bogs occurs in winter, during periods of heavy rainfall, and the lowest in summer when there is little precipitation (Damman, 1986; Egglesmann et al., 1993). In contrast, bogs that experience extended periods of freezing in winter have the lowest water levels near the end of winter, because snow accumulates on the frozen bog surface and the bog continues to drain until spring snowmelt (Damman, 1986). In both climates, evapotranspiration losses are largest during summer. The standard annual hydroperiod in southern coastal British Columbia (BC), Canada, has been established for Burns Bog (Howie et al., 2009a) and five eastern Vancouver Island bogs (Golinski, 2004). In general, the water table is at its highest and most stable level near the bog surface between October and March, and declines from April onwards in response to decreased precipitation and increased evapotranspiration. It reaches a low point in September, and increases rapidly to the high winter water level in response to rainfall in September or October (Howie et al., 2009a; Golinski, 2004). The depth of the low point of the water table is variable between years and dependent on the extent of the summer drought period, but is generally 30–40 cm below the bog surface for a healthy bog (Schouwenaars and Vink, 1992). Similar annual fluctuations have been recorded for bogs in Europe (e.g. Egglesman et al., 1993).

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). 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). If the summer water table

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frequently drops more than 40 cm below the surface, non-bog species such as *Betula* may outcompete *Sphagnum*, the main peat-forming species in raised bogs, due to their ability to tolerate a more widely fluctuating water table (Price et al., 2003). A high water table supports the soil moisture and soil-water pressure required for survival of *Sphagnum* colonies. Most *Sphagnum* colonies grow in places where volumetric soil moisture 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). 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).

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 of a raised bog is often the first damaged by conversion to other land uses (e.g. agricultural, industrial). 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 of the bog by reducing the outward hydraulic gradient (Wheeler and Shaw, 1995). 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. The seasonal water level fluctuation is often smallest in the bog, greater in the outwardly-sloping rand forest at the bog margin, and greatest in the lagg fen (Damman, 1986). However, 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

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areas, may display a smaller water table fluctuation than laggs that are topographically constrained and experience frequent flooding (Howie and Tromp-van Meerveld, 2011).

The water table in peatlands is also affected by vegetation. 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 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 the 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 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.

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 the sole source of nutrients (Damman, 1986). Concentrations in bog water are most similar to precipitation during times of heavy 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 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

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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 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 located in a drier climate. The few studies on the temporal variability in water chemistry in bogs usually have 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 weather patterns.

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 bogs, and higher in marginal lagg fens (Bubier, 1991; Bragazza et al., 2005). 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 $mg\,L^{-1}$; Type II (lagg/transitional water), pH 4.5–6.0, Ca^{2+} 3–10 $mg\,L^{-1}$; Type III (terrestrial/minerotrophic water), pH $>$ 5.0–8.0, Ca^{2+} $>$ 10 $mg\,L^{-1}$. 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*. For example, the lagg water type (Type II) classified by Balfour and Banack (2000) was often characterized by a dense thicket of *Spiraea douglasii*. 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),

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although the exact value varies depending on the chemical composition and amount of precipitation (Waughman, 1980; Shotyk, 1996).

The objectives of this study were: (i) to improve the knowledge of the temporal variation in depth to water table and pore-water chemistry in coastal raised bogs in BC, and in particular how these changes relate to the rarely-studied marginal lagg, and (ii) to determine whether a single sampling event is sufficient to characterize the hydrochemistry of bogs and their associated laggs in coastal BC. More frequent measurements in a large number of bogs are often not feasible; if bog hydrochemistry can be approximated by a single sample, a larger number of sites can be surveyed. This would help with establishing restoration plans for these bogs, as many of them are impacted by drainage or land use changes around the margins of the bog. Our hypothesis was that the water table in bogs follows a broadly similar pattern each year due to the close association between depth to the water table and precipitation (Malmer, 1986) and that the lagg of raised bogs has a similar hydroperiod as the adjacent open bog area. With respect to hydrochemistry, our hypothesis was that hydrochemical analysis in early summer would be representative for the entire year because this time of year has neither extended dry periods nor high rainfall, which can cause concentrations to spike or drop (Vitt et al., 1995). Unexpected logging at one of the study sites allowed us to also study the effect of vegetation changes on the depth to water table.

2 Study sites

Raised bogs are a common feature 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 – NWWG, 1988). In the Fraser River delta, 10–25 % of the land area is covered by wetlands; the surrounding Fraser River lowland contains 5–10 % wetlands. On Vancouver Island, wetlands make up less than 5 % of the landscape. Further north along the coast, higher annual rainfall and lower temperatures results in wetlands in

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up to 75 % of the land area (NWWG, 1988). Golinski (2004) developed a regional vegetative classification for Vancouver Island peatlands, and compared the hydrology and chemistry of disturbed and undisturbed peatlands. However, apart from this study, a few local studies by university classes (e.g. Trinity Western University), and monitoring programs by wetland management agencies (e.g. Burns Bog, Delta, BC), little is known about seasonal water level and hydrochemical changes in bogs in southwestern BC. Therefore, Burns Bog (Delta, BC) was studied from June 2010–December 2012, Blaney Bog (Maple Ridge, BC) from June 2010–December 2011, and Campbell River Bog (Campbell River, BC) in May 2010 and May 2011 (Fig. 1).

Burns Bog is a 3000 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 harvesting 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 undisturbed; 2450 ha of the bog were purchased by the local, regional, provincial, and federal government in 2004 as an ecological conservancy area. 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 laggs areas remain relatively undisturbed. Three of these remnant laggs were studied from June 2010–December 2011: Sherwood Forest (slough boundary), Cranwest (outwash to delta), and the Delta Nature Reserve (DNR) (upland) (Howie et al. 2009b) (Fig. 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 ($\sim 500\,\text{stems}\,\text{ha}^{-1}$) of western red-cedar (*Thuja plicata*) 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 three other piezometers in Burns Bog are reported here as well. For comparison of water table data, we include data from a piezometer that was installed in 2006 in an open bog site near the Sherwood transect (Fig. 1). For water chemistry, we present data from

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two piezometers (PF-100 and PF-200) installed in 2010 in the southeastern corner of Burns Bog. PF-100 and PF-200 are located in a bog forest dominated by *Pinus contorta* and *Gaultheria shallon*, 100 and 200 m from the bog margin, respectively (Fig. 1).

Blaney Bog is a 130 ha bog/fen complex in the Pitt River valley and is 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 matrix (Gebauer, 2002). The entire lagg of the developing bog remains intact, providing a unique opportunity to study two undisturbed lagg transition features: upland forest and spring fen (Fig. 1).

The Campbell River site contains a complex of open bog, bog forest, fen, and 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 upland lagg on the west side of the bog appears to be relatively undisturbed.

Annual precipitation at Vancouver International Airport (YVR) (16 km from Burns Bog) was 1207 mm in 2010 and 1071 mm in 2011 (source: Environment Canada). For Blaney Bog (Haney UBC research forest weather station, approx. 1 km from Blaney Bog), annual precipitation was 2034 mm in 2010 and 1989 mm in 2011. Annual precipitation in Campbell River was 1904 mm in 2010 and 1378 mm in 2011. Total precipitation at YVR between 1 April and 1 September was 261 mm in 2010 and 288 mm in 2011. At Blaney Bog, 1 April–1 September total precipitation was 474 mm in 2010 and 644 mm in 2011. For the same time period, total precipitation in Campbell River was 304 mm in 2010 and 246 mm in 2011. Between 1 April and 1 September, mean air temperature at YVR was 14.6 °C in 2010 and 13.9 °C in 2011, 14.2 °C in 2010 and 12.8 °C in 2011 at Blaney Bog, and 13.7 °C in 2010 and 12.7 °C in 2011 in Campbell River.

Transects

There were five sampling locations across each of the six studied lagg transects: (1) inside the bog ("bog"), (2) between the bog and lagg (closer to bog; "trans1"), (3) between the bog and lagg (closer to lagg; “trans2”), (4) approximate centre of the lagg (“lagg”), and (5) outside the bog (“mineral”). These five locations were determined in the field based on vegetation characteristics that indicated the position along the transect. “Bog” was defined as *Sphagnum*-dominated heath, “lagg” was defined either as *Spiraea*-dominated or containing larger shrubs and trees than the bog, and “outside” was defined as the forest surrounding the bog. In Burns Bog, there were two exceptions to this transect configuration: the Sherwood Forest transect contained a second “lagg” study location due to changes in vegetation across the lagg, and the Delta Nature Reserve transect contained two “lagg” locations (due to the presence of two different vegetative lagg types) and no study location between the bog and lagg (due to the influence of a highway).

All locations were recorded with an Oregon 300 handheld GPS unit, accurate to 5 metres. 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 collected in September 2008.

3 Methods

3.1 Field methods

Piezometers were installed 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. 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 piezometers were purged twice 1–2 weeks prior to each 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. Depth to water table was measured in the piezometers with an electronic water level probe (Heron Instruments Little Dipper). Table 1 lists the frequency of the depth to water table

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measurements for each transect. Depth to water table measurement frequency in the Sherwood transect increased to weekly between August 2011 and December 2011 to monitor the water table change in response to logging of the mature forest between the "lagg1" and "mineral" sites on the transect.

Electrical conductivity, pH, and temperature were measured directly in the piezometers (top 10–15 cm of water column) 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 °C 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.

For Blaney Bog and Burns Bog DNR, sampling for cations, chloride, sulphate, acidity, dissolved organic carbon (DOC) was only done once (June 2011). For the other two Burns Bog transects and at Campbell River Bog, water chemistry sampling was carried out 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. 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^+, K^+, SO_4^{2-}, Cl^-, and DOC concentrations, and acidity. For Burns Bog and Blaney Bog, pore water concentrations were compared to 1986–1993 average concentrations in precipitation from YVR (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).

3.2 Statistical methods

Analysis of variance (ANOVA) was used to determine whether the variation in the hydrochemical characteristics over time, or across the transects, were statistically significant. 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.

4 Results

4.1 Spatial and temporal water table fluctuations

The depth to water table fluctuations increased across the transition from bog to forest for the Burns Bog and Blaney Bog transects. The fluctuation of the depth to water table between June 2010 and December 2011 in the "bog" sites ranged from 0.26–0.42 m, compared to 0.33–0.66 m in the transition sites between bog and lagg, 0.45–0.72 m in the lagg, and 0.41–0.79 m in the mineral sites (Table 2, Figs. 2, 3). Campbell River Bog was not included in this analysis because depth to water table was only measured in May. For comparison with a longer time series, Fig. 4 shows the water level fluctuations from 2006–2012 for a piezometer located 330 m north of the Sherwood forest "bog" site, in the same plant community. Similar to all the "bog" sites, the water table at this piezometer dropped to a maximum of approx. 30–40 cm below the bog surface over the six-year monitoring period.

4.2 "Watering up" in Sherwood Forest

A portion of the mature forest on the western side of the Sherwood transect was unexpectedly cut part way through the study period in May/June 2011. Two piezometers on the Sherwood transect were affected by the logging: "lagg1" and "lagg2" (Fig. 2). The result of this logging was a pronounced "watering-up" effect. The lowest measured

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water table at the “lagg2” site, in the middle of the Sherwood clearcut, was 27 cm higher in 2011 than in 2010, whereas it was 10 cm higher in 2011 than in 2010 for the Cranwest “lagg” site and 0.5 cm lower for the DNR forested “lagg” site. The clearcut site showed a mean water table increase of 8 cm between August and November compared to the pre-logged condition in 2010, whereas the mean water table was 13 cm lower in 2011 than in 2010 for the Cranwest lagg and 8 cm lower for the DNR forested lagg. The “lagg1” site, which was located at the edge of the cutblock, displayed a moderate water table increase of 11 cm in August 2011 compared to August 2010; the August–November mean water table increase compared to pre-logged conditions in 2010 was 4 cm. In 2012, the late summer water table in the “lagg2” site was lower than in 2011, which may partly be attributed to the regeneration of a salal (*Gaultheria shallon*) shrub layer and resulting increased evapotranspiration in the clearcut site in 2012. Mean air temperature at YVR for July and August was the same between 2011 and 2012 (18 °C), but there was less precipitation during this period in 2012 (31 mm) than in 2011 (57 mm), which may in part also account for the lower water table in 2012.

4.3 Seasonal variation in water chemistry

There was little variation in field-measured pH during the study period from May 2010 to December 2011 (Table 3, Fig. 5). For all sites, pH varied by less than 0.85 over time. At 21 % of the sites pH varied by more than 0.5; at 46 % of the sites pH varied by 0.25–0.5. All pH measurements taken in June/July were within 0.25 of the long term average. On average, the temporal variation was lowest in the “bog” sites, and increased approaching the lagg (Table 3). 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. 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.

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Temporal variation in pH-corrected electrical conductivity (EC_{corr}) generally followed the variation in pH (Fig. 6), although EC_{corr} was more variable. At 28 % of the sites EC_{corr} varied by 0–25 $\mu S\,cm^{-1}$ during the study period, at 44 % of the sites it varied by 25–50 $\mu S\,cm^{-1}$, and at 28 % of the sites it varied by 50–100 $\mu S\,cm^{-1}$. All measurements taken in June/July were within 65 $\mu S\,cm^{-1}$ of the long term average; 85 % were within 25 $\mu S\,cm^{-1}$ of the long term average. Average values from May are not reported here for EC_{corr} because this parameter was not measured in May 2010 due to equipment malfunction. The differences in EC_{corr} between the measurement dates were not statistically significant for any of the Burns Bog or Blaney Bog transects. 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. There was no clear spatial trend in temporal variability in EC_{corr} for the Blaney Bog transects.

Table 4 shows the results of the laboratory analyses for all six transects. Magnesium and sodium concentrations were low and varied by less than 0.9 $mg\,L^{-1}$ between years for all three multi-year transects. Calcium and potassium concentrations were more variable over time, with the difference between years ranging from 0–4.2 $mg\,L^{-1}$ and 0.4–14.8 $mg\,L^{-1}$, respectively. Most sulphate concentrations were less than the laboratory detection limit of 0.5 $mg\,L^{-1}$, so it is not possible to draw conclusions about its temporal variability, except that it was low in both years. Changes in chloride concentrations, dissolved organic carbon concentrations, and acidity between years ranged from 0.5–8.1 $mg\,L^{-1}$, 0.9–16.6 $mg\,L^{-1}$, and 1–34 mg $CaCO_3\,L^{-1}$, respectively. The relative change in concentration (= difference/mean) was lowest for sodium, and increased in the following order: Na^+, DOC, Mg^{2+}, Ca^{2+}, Cl^-, acidity, K^+. Spearman rank correlation tests for all piezometers together revealed a significant positive correlation between depth to water table and: EC_{corr}, Mg^{2+}, and K^+ concentrations. There was also a significant positive correlation between pH and concentrations of Ca^{2+} and Na^+. However, we did not consistently find these correlations to be significant for individual transects ($n = 5$). For the transects where we collected water samples in both 2010 and 2011

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(Sherwood, Cranwest, and Campbell River), we found that the difference in calcium and magnesium concentrations between 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.

In another part of Burns Bog (Pine-salal forest at 100 and 200 m from edge of bog, Fig. 1), there was also little variation in hydrochemistry during a 1-yr monitoring period from March 2011 to March 2012 (Table 5). From March to August 2011, pH increased, corresponding with the decline in water table over spring and summer, and then decreased between August 2011 and March 2012. However, the maximum change in pH was less than 1, similar to the transects in Burns Bog and Blaney Bog that were monitored in 2010–2011 for this study. Calcium and magnesium concentrations also increased slightly as the water table declined in summer. The relative change in concentration changed from lowest to highest in the following order: DOC, SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-. Spearman rank correlation tests for these two piezometers revealed a significant positive correlation between depth to water table and: pH and concentrations of Ca^{2+} and Mg^{2+}. There was also a significant positive correlation between pH and Ca^{2+} and Mg^{2+} concentrations.

Sodium and chloride are not biologically limiting in oceanic bogs, and consequently accumulate in peat and drainage water (Damman, 1986). In the ombrotrophic "bog" sites on the study transects, concentrations of Na^+ and Cl^- in pore water were, on average, four times higher than in precipitation (Table 6). Nitrogen, phosphorus, and potassium are assumed to be the biologically limiting nutrients in peatlands (Vitt and Chee, 1990; Bridgham et al., 1996); however, our measured K^+ concentrations were, on average, 29 times higher in pore water than in precipitation in Burns Bog and Campbell River Bog, but only 4 times higher in Blaney Bog. Calcium and magnesium concentrations were, on average, 5 and 9 times higher, respectively, in "bog" pore water than in precipitation (Table 6), so also do not appear to be biologically limiting in this region. 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,

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except K^+. 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 "bog", "trans1", "trans2", "lagg", and "mineral" sites, respectively. Ca^{2+} concentrations were, on average, 5, 6, 8, 9, and 16 times higher than the average concentration in precipitation for the "bog", "trans1", "trans2", "lagg", and "mineral" sites, respectively. Sulphate may be the only parameter measured in this study that is biologically limiting; sulphate was generally below the 0.5 $mg\,L^{-1}$ detection limit in our water samples, but ranged from 0.7–1.8 $mg\,L^{-1}$ in precipitation. Gorham et al. (1985) reported that sulphate 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 sulphate from precipitation is reduced to sulphides (Proctor, 1995).

4.4 Spatial variation in water chemistry

Spatial differences in pH across the transects were generally persistent over time for all Burns Bog and Blaney Bog transects, but the pattern varied between the transects. In some cases, pH consistently increased across the transition from bog to forest (Blaney Bog Upland, Cranwest, DNR) (Fig. 5, Table 3). In other cases, pH fluctuated across the transect without a clear spatial pattern (Sherwood, Blaney Bog Fen). ANOVA results indicate that the difference in pH across the transects was statistically significant for all transects, except the "fen" transect in Blaney Bog ($p = 0.591$). EC_{corr} was generally lowest in the bog and highest towards the lagg and mineral sites, but not in all cases (Fig. 6). Variation in EC_{corr} across the transects was statistically significant for all transects, except the "fen" transect in Blaney Bog ($p = 0.053$).

Calcium and magnesium concentrations often increased across the transect from bog to forest, but not in all cases (Table 4). 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 7). Calcium and magnesium

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concentrations, and the Ca : Mg ratio, were not significantly correlated with position on the transect.

5 Discussion

5.1 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). Depth to water table measurements in Burns Bog and Blaney Bog confirm that bogs generally have a smaller annual fluctuation in water table compared to their laggs and adjacent minerotrophic sites (Schouten, 2002; Damman, 1986; Malmer, 1986). On average, the magnitude of the annual fluctuation in depth to water table increased across the transects from bog to lagg and mineral sites in Burns Bog and Blaney Bog (Table 2). The water table in Burns Bog displayed a relatively constant pattern between years, with the winter water table stabilizing at a maximum height between October and March, a gradual decline through spring/summer, and a low point at the end of summer determined by summer precipitation and evapotranspiration (c.f. Golinski, 2004; Howie et al., 2009a; Balfour, 2011). Seasonal water table fluctuations in bogs are closely linked to precipitation (e.g. Malmer, 1986; Dubé et al., 1995). These data suggest 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 the depth to the water table is closely linked to species composition and *Sphagnum* survival (Rydin and Jeglum, 2006).

5.2 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 low (e.g. generally within 0.5 pH units)

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and large deviations from the average are not common, so that pH can be considered as a seasonally stable parameter in the bog, lagg, and mineral locations. Vitt et al. (1995) also found that pH and pH-corrected electrical conductivity were relatively constant between May and October in Alberta peatlands, and suggested that one-time sampling 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. The pH of deeper bog water may be buffered more from variations in rainfall by ion exchange with the peat (Proctor, 2003; Worrall et al., 2003).

EC_{corr} was generally also consistent over time, although it did occasionally spike above the average values. There was no consistent increase or decrease in variability in EC_{corr} from bog to forest. The maximum change over time was 88 $\mu S\,cm^{-1}$. The largest "spike" in EC_{corr} (an increase of 66 $\mu S\,cm^{-1}$, compared to the previous measurement in December 2010) was observed in Burns Bog (DNR transect, "lagg2") in June 2011. There is no clear explanation for this spike, as EC_{corr} did not change considerably at the other sites on the transect. Another increase is evident 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. 5). EC_{corr} was also higher in Blaney Bog (upland transect, "trans2") in September 2011. EC_{corr} and pH both increased across this transect on this date, but it is unclear why EC_{corr} at the "trans2" site increased more than at the other sites. Vitt et al. (1995) found only small changes ($< 50\,\mu S\,cm^{-1}$) in weekly measurements of corrected conductivity of bog water in central Alberta during the ice-free season.

There was also little variation in magnesium and sodium concentrations between the two years. Calcium was more variable at the "trans2" and "mineral" sites of the Cranwest transect, but changed little on the Sherwood transect. The relatively small change in ion concentrations in bog water over time is caused by ion exchange with the peat (Proctor, 2003). Vitt et al. (1995) found that calcium, magnesium, sodium, and

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potassium concentrations in an Alberta bog were highest in spring, declined in early summer, and then increased gradually over the summer. However, despite this seasonal pattern, the concentrations of these cations were low ($< 5\,mg\,L^{-1}$) throughout the growing season and generally stable. We found a statistically significant correlation between depth to water table and some hydrochemical parameters (EC_{corr}, Mg^{2+}, K^+) but not for the other parameters. Wieder (1985) also found that major cation and chloride concentrations were fairly constant during the growing season. Adamson et al. (2001) found little change 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). Andersen et al. (2010) found relatively small changes in major cation and chloride concentrations over time for a natural peatland in Quebec, compared to restored and unrestored blocks in an adjacent harvested peatland area.

On the other hand, Vitt et al. (1995) found that seasonal variability in calcium and magnesium 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 over time. Similarly, we found that temporal variation of calcium and magnesium concentrations generally increased across the transect from bog to forest. 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.

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Potassium concentrations differed significantly between June 2010 and June 2011. Proctor (2003) observed that K^+ concentrations peaked in late spring and declined through the summer, and attributed this trend to depletion by plant uptake during the growing season. Vitt et al. (1995) also suggested that inputs from spring snowmelt and vegetation uptake during the summer accounted for seasonal variation in K^+ concentrations. A decrease in K^+ concentrations from 2010 to 2011 was observed at 83 % of the studied sites. The only transect where this trend was not persistent was the Sherwood transect in Burns Bog; two of the sites ("trans1" and "lagg1") showed an increase in K^+ concentrations between 2010 and 2011 whereas the other sites showed a decrease. Chloride concentration displayed similar changes as K^+ between years, so it is unlikely that the changes in K^+ concentration between the two years is solely due to differences in plant uptake in 2010 and 2011, but also likely due to precipitation input and evapotranspiration.

Dissolved organic carbon (DOC) concentrations were somewhat stable between years at most sites ($< 8\,\mathrm{mg\,L^{-1}}$ change), but were more variable at other sites (12–17 $\mathrm{mg\,L^{-1}}$ change). For Burns Bog, DOC was higher in 2010 than 2011, but in Campbell River DOC was higher in 2011. This may be due to differences in precipitation; at YVR, there was 20 mm more rainfall in the week prior to sampling in 2010 (possibly causing the higher DOC compared to 2011), and in Campbell River, there was 7 mm more rainfall in 2011 (possibly causing the marginally higher DOC concentrations in 2011). Adamson et al. (2001) noted that DOC is an indicator of decomposition activity in the soil, and found that DOC correlated with air temperature (lowest concentrations in spring, and highest in late summer and autumn), but that seasonal fluctuations were only significant at 10 cm below the surface and that fluctuations were smaller at 50 cm below the surface and did not follow the same seasonal pattern as at 10 cm. Similarly, Fraser et al. (2001) observed a decrease in peatland DOC concentrations with depth, fairly constant DOC concentrations below 75 cm, and larger seasonal fluctuations in the upper 45 cm. They also showed that DOC was lowest ($\sim 40\,\mathrm{mg\,L^{-1}}$) during snowmelt, highest ($\sim 70\,\mathrm{mg\,L^{-1}}$) during the growing season), and increased in response to rainfall

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events (Fraser et al. 2001). Since these changes did not correlate with depth to water table, Fraser et al. (2001) attributed the variations in DOC concentrations to substrate availability, temperature, and “DOC partitioning through respiration and methanogenesis”. However, air temperatures at YVR and Campbell River in the two weeks prior to sampling did not appear to be correlated with the differences in DOC concentrations between 2010 and 2011; average air temperature was the same in Campbell River in 2010 and 2011, and higher in 2011 at YVR.

5.3 Spatial variability in water chemistry across the transects

The only hydrochemical parameters that varied with position on the transect were pH, pH-corrected electrical conductivity, and calcium and magnesium 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 magnesium (83 % of the transects), whereas calcium and EC_{corr} only showed this trend for 50 % and 33 % of the transects, respectively. Vitt et al. (1995) found that pH, EC_{corr}, Ca^{2+}, and Mg^{2+} increased along a bog-rich fen gradient, and were highly correlated with one another. We also found that Ca^{2+} concentrations were correlated with pH and Mg^{2+} concentrations, and that EC_{corr} was correlated with Mg^{2+} and Ca^{2+}concentrations. Bragazza et al. (2005) observed that pH, Ca^{2+}, and Mg^{2+} concentrations 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. For the bogs that we studied, the Ca : Mg ratio did not appear to be a useful indicator of the mineral soil water limit. 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 ($< 4\,mg\,L^{-1}$) so that it may not be a dependable indicator of the location of the lagg or mineral soil water limit.

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Thus, hydrochemical parameters are not necessarily uniformly useful for determining the location of the mineral soil water limit in coastal BC bogs.

5.4 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 rise in the lowest measured late-summer water table in the clearcut in 2011 compared to the pre-logged condition in 2010, whereas the depth to water table at the other sites was similar in late summer of 2010 and 2011. The mean water table rise in the clearcut between August–November 2010 and 2011 (the period with available data for both years) was 8 cm, compared to a mean water table decline of 13 cm for the sites on the Sherwood transect that were not affected by the logging. The undisturbed open bog and pine-salal sites on the Sherwood transect (transitional between bog and lagg) showed a mean decrease in water table of 6 cm and 16 cm, respectively, between August–November 2010 and 2011. The rise in water table in the clearcut site can therefore be attributed to a reduction of interception and evapotranspiration due to the removal of large trees (Dubé et al., 1995). Cheng (2011) observed mean evapotranspiration rates of 0.9 mm day^{-1} and 1.1 mm day^{-1} in an open bog site and a forested site 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 (mean DBH: 16 cm in this study, and 15 cm in Cheng, 2011). The site studied by Cheng contained only two large (mean DBH: 40 cm) hemlock trees, but their transpiration rates were 10 times higher than the small pine trees (Cheng, 2011). Differences in evapotranspiration between the clearcut and the lagg forest are thus expected to be larger than the differences in evapotranspiration between the forested bog and open bog sites of Cheng (2011). Canopy interception was 12 % in the forested site and negligible in the open bog site due to the lack of trees in the study of Cheng (2011). This would translate to 35 mm of interception loss between August and November 2011 (0.3 mm day^{-1}), but the large cedar and hemlock trees are

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expected to intercept more precipitation than the open pine forest studied by Cheng (2011).

Although the results suggest a significant watering-up effect due to clearcut logging, only one piezometer was located within the clearcut because we were not aware of the logging at the time that this study was initiated. Therefore, it is not possible to confidently state on the basis of this single data point that removal of trees in other areas will result in a similar water table increase. 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 (when the water table in the control site was 10 cm below the surface) 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, it may be a detrimental activity in laggs that naturally contain large trees (e.g. Sherwood and DNR laggs). For example, tall trees in the Sherwood lagg forest may benefit the bog by providing a barrier to dust blown from neighbouring farms and roads. In this study, we did not observe a discernible change in pH or EC_{corr} in response to logging of the lagg forest on the Sherwood transect.

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6 Conclusions

The wet, temperate climate of coastal British Columbia provides ideal conditions for peatland development so that wetlands cover large areas of the landscape. In order to characterize the hydrological, hydrochemical, and ecological conditions of a representative sample of peatlands in order to create restoration plans or setting boundaries for conservation areas, it is necessary to characterize their ecohydrological status with relatively few measurements at each site. Annual hydroperiods for coastal BC bogs display a similar pattern in response to annual cycles of precipitation and evapotranspiration, with water levels dropping further below the bog surface in dry years. We suggest that the hydroperiod can be broadly approximated by taking measurements during key times of the year, such as winter (but not during freezing conditions), spring (May/June), and late summer (August/September). Annual fluctuations of the water table were lowest in the bog sites, and increased toward the lagg and adjacent mineral forest. In the bog, the depth to water table was always less than 40 cm; in the lagg, the depth to water table was always less than 75 cm. These maximum depth to water table values 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.

Spatial variation in EC_{corr} and pH across the transects from the bog to mineral sites was statistically significant. Temporal variability in pH and EC_{corr} was, however, not significant. Corrected electrical conductivity, pH, Na^+, and Mg^{2+} concentrations varied little during the study period and can thus be determined by a one-time sampling campaign. On the other hand, Ca^{2+}, K^+, Cl^-, and dissolved organic carbon concentrations and acidity varied significantly between years and are likely too variable over time 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.

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Table 1. Coordinates of the transects ("bog" sampling point) and sampling dates.

Transect location	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* (n = 9)	6 Jun 2010; 21 Jun 2011
Burns Bog – Cranwest	49° 7′ 26″ N	123° 0′ 36″ W	830	1.6	1–3 months (n = 9)	6 & 10 Jun 2010; 20 Jun 2011
Burns Bog – DNR	49° 8′ 16″ N	122° 56′ 11″ W	1000	1.4	4–6 months (n = 4)	18 Jun 2011
Blaney Bog – Upland	49° 15′ 35″ N	122° 35′ 18″ W	180	1.3	3 months (n = 5)	25 Jun 2011
Blaney Bog – Fen	49° 15′ 33″ N	122° 35′ 24″ W	100	1.5	3 months (n = 5)	25 Jun 2011
Campbell River Bog	49° 57′ 60″ N	125° 14′ 34″ W	100	1.5	Annually (2010/2011) (n=2)	24 May 2010; 31 May 2011

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

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Table 2. Difference (Δ) between the maximum and minimum depth to water table for all sites.

	Δ water table depth below surface (m)					
	"bog"	"trans1"	"trans2"	"lagg1"	"lagg2"	"mineral"
Burns Bog – Sherwood	0.31	0.54	0.52	0.46	0.59	0.74
Burns Bog – Cranwest	0.42	0.36	0.66	0.61	–	0.47
Burns Bog – DNR	0.32	–	–	0.72	0.45	0.64
Blaney Bog – Upland	0.26	0.33	0.41	0.63	–	0.79
Blaney Bog – Fen	0.34	0.38	0.40	0.51	–	0.41
MEAN	0.33	0.40	0.50	0.59	0.52	0.61
MEDIAN	0.32	0.37	0.47	0.61	0.52	0.64
STD. DEV.	0.05	0.07	0.09	0.08	0.06	0.14

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Table 3. Range in pH for all sites (May 2010–December 2011). See Table 1 for the frequency of the measurements.

	pH range (minimum–maximum)					
	"bog"	"trans1"	"trans2"	"lagg1"	"lagg2"	"mineral"
Burns Bog – Sherwood	3.71–4.30	3.84–3.95	3.76–4.00	4.04–4.38	3.56–3.86	3.64–4.24
Burns Bog – Cranwest	3.88–4.22	4.32–4.51	3.90–4.75	4.13–4.94	–	5.10–5.41
Burns Bog – DNR	4.09–4.36	–	–	4.17–4.57	5.20–5.39	5.51–5.72
Blaney Bog – Upland	4.09–4.42	4.21–4.37	4.34–4.90	4.95–5.36	–	5.19–5.84
Blaney Bog – Fen	4.28–4.69	4.25–4.53	4.30–4.66	4.22–4.67	–	4.35–4.57
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).

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Table 4. 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 "–".

	Sample location	Ca^{2+} ($mg\,L^{-1}$)		Mg^{2+} ($mg\,L^{-1}$)		Na^{+} ($mg\,L^{-1}$)		K^{+} ($mg\,L^{-1}$)		SO_4^{2-} ($mg\,L^{-1}$)		Cl^{-} ($mg\,L^{-1}$)		Acidity ($mg\,CaCO_3\,L^{-1}$)		DOC ($mg\,L^{-1}$)	
		2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
Burns Bog	SW "Bog"	1.3	1.4	1.0	1.0	3.4	4.3	7.6	4.6	< 0.5	< 0.5	9.8	4.8	33	46	71.6	65.7
	SW "Trans1"	1.1	1.1	1.6	1.5	2.7	2.7	5.2	20.0	0.8	< 0.5	10.0	17.0	26	53	57.4	58.3
	SW "Trans2"	1.5	1.1	1.5	1.5	2.8	2.4	10.5	6.0	< 0.5	< 0.5	9.0	8.5	29	39	71.0	54.4
	SW "Lagg1"	2.5	1.9	1.6	1.7	1.9	2.0	2.4	15.9	0.6	< 0.5	7.9	16.0	18	34	64.8	61.1
	SW "Lagg2"	2.4	–	1.8	–	4.1	–	5.1	–	2.9	–	10.8	–	59	–	100.0	–
	SW "Mineral"	5.9	4.9	4.0	3.9	5.7	5.4	7.0	2.6	5.2	1.6	22.0	15.0	33	52	95.2	90.8
	DNR "Bog"	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	DNR "Lagg1"	–	3.8	–	0.7	–	5.5	–	5.3	–	< 0.5	–	9.4	–	34	–	84.0
	DNR "Lagg2"	–	2.6	–	0.8	–	16.6	–	8.3	–	< 0.5	–	19.0	–	46	–	79.5
	DNR "Mineral"	–	9.4	–	3.1	–	10.4	–	3.4	–	< 0.5	–	11.2	–	21		65.3
	CW "Bog"	1.5	2.1	1.1	1.1	5.1	4.6	4.5	3.0	< 0.5	< 0.5	8.4	5.4	24	54	84.5	77.4
	CW "Trans1"	2.1	1.5	1.0	1.0	5.7	5.7	1.5	1.1	< 0.5	< 0.5	11.5	9.4	13	47	63.9	60.3
	CW "Trans2"	3.4	1.8	1.6	0.9	3.2	2.8	6.8	2.2	1.9	< 0.5	9.1	3.7	24	31	81.8	69.5
	CW "Lagg"	–	1.8	–	0.9	–	2.5	–	4.8	–	< 0.5	–	3.7	–	27	–	59.8
	CW "Mineral"	5.0	3.1	1.2	1.7	16.7	17.6	7.2	6.4	–	–	–	–	–	–	–	–
Blaney Bog	BU – "Bog"	–	0.5	–	< 0.1	–	0.8	–	0.7	–	< 0.5	–	2.6	–	33	–	37.1
	BU – "Trans1"	–	0.3	–	< 0.1	–	1.5	–	0.5	–	< 0.5	–	2.7	–	37	–	52.5
	BU – "Trans2"	–	0.9	–	0.1	–	6.0	–	1.2	–	< 0.5	–	4.4	–	45	–	123.0
	BU – "Lagg"	–	3.2	–	0.5	–	1.7	–	0.6	–	< 0.5	–	2.6	–	19	–	33.4
	BU – "Mineral"	–	4.7	–	0.7	–	3.6	–	0.8	–	0.7	–	3.3	–	13	–	23.8
	BF – "Bog"	–	1.2	–	0.3	–	0.9	–	0.7	–	< 0.5	–	2.2	–	36	–	42.6
	BF – "Trans1"	–	2.0	–	0.8	–	0.8	–	0.8	–	< 0.5	–	2.2	–	38	–	41.5
	BF – "Trans2"	–	2.5	–	0.6	–	0.8	–	0.9	–	< 0.5	–	2.6	–	23	–	48.3
	BF – "Lagg"	–	1.3	–	0.2	–	0.9	–	0.9	–	< 0.5	–	2.7	–	21	–	37.6
	BF – "Mineral"	–	2.0	–	0.7	–	2.3	–	0.7	–	< 0.5	–	5.0	–	41	–	61.1
Campbell River Bog	CR "Bog"	–	1.7	–	0.7	–	4.8	–	2.1	–	< 0.5	–	10.0	–	23	–	55.8
	CR "Trans1"	3.6	2.5	1.0	1.0	5.3	4.8	4.9	0.6	< 0.5	< 0.5	12	8.1	18	28	50.5	51.6
	CR "Trans2"	–	3.6	–	1.1	–	4.6	–	1.4	–	< 0.5	–	6.8	–	30	–	81.2
	CR "Lagg"	5.1	4.0	1.7	1.5	6.1	6.2	5.6	1.1	< 0.5	< 0.5	10	9.3	12	11	21.6	28.3
	CR "Mineral"	6.7	2.5	1.4	1.0	5.7	5.5	9.6	1.1	–	< 0.5	–	8.3	–	13	–	11.9

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Table 5. Data from two piezometers (PF-100 and PF-200) in Burns Bog (see Fig. 1 for location of these piezometers). DTW = depth to water table; EC_{corr} = corrected electrical conductivity; DOC = dissolved organic carbon.

Parameter	8 Mar 2011		28 Jun 2011		29 Aug 2011		21 Mar 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} ($\mu S\,cm^{-1}$)	61	52	45	44	70	55	47	35
Ca^{2+} ($mg\,L^{-1}$)	0.9	0.8	1.6	1.5	2.9	2.6	1.1	1.3
Mg^{2+} ($mg\,L^{-1}$)	0.7	0.8	0.9	1.1	1.8	1.8	0.6	0.7
Na^{+} ($mg\,L^{-1}$)	2.1	2.1	2.0	1.9	2.4	2.2	2.5	3.3
K^{+} ($mg\,L^{-1}$)	< 0.1	0.8	4.0	2.9	4.3	2.2	2.9	< 2.0
SO_4^{2-} ($mg\,L^{-1}$)	1.0	0.9	0.7	0.6	< 0.5	< 0.5	< 2.5	< 2.5
Cl^{-} ($mg\,L^{-1}$)	1.9	3.0	0.9	0.7	8.6	7.1	4.2	3.5
DOC ($mg\,L^{-1}$)	82.0	68.0	81.9	69.9	79.6	54.0	66.2	70.5

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Table 6. Ratio of the average concentration in pore water to the average concentration in precipitation. See Table 4 caption for transect codes and Table 1 for sampling dates. Precipitation chemistry sources: (a) Burns Bog and Blaney Bog: YVR 1986–1993 mean (Piteau Associates 1994), (b) Campbell River Bog: Port Hardy 1978–1986 mean (National Atmospheric Chemistry Database, 2012).

	Sample location	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	SO_4^{2-}	Cl^{-}
Burns Bog	SW "Bog"	3.9	14.3	6.3	38.1	< 0.3	6.1
	SW "Trans1"	3.1	22.1	4.4	78.8	< 0.4	11.3
	SW "Trans2"	3.7	21.4	4.3	51.6	< 0.3	7.3
	SW "Lagg1"	6.3	23.6	3.2	57.2	< 0.3	10.0
	SW "Lagg2"	6.9	25.7	6.7	31.9	1.6	9.0
	SW "Mineral"	15.4	56.4	9.1	30.0	3.8	15.4
	DNR "Bog"	–	–	–	–	–	–
	DNR "Lagg1"	10.9	10.0	9.0	33.1	< 0.3	7.8
	DNR "Lagg2"	7.4	11.4	27.2	51.9	< 0.3	15.8
	DNR "Mineral"	26.9	44.3	17.0	21.3	< 0.3	9.3
	CW "Bog"	5.1	15.7	8.0	23.4	< 0.3	5.8
	CW "Trans1"	5.1	14.3	9.3	8.1	< 0.3	8.7
	CW "Trans2"	7.4	17.9	4.9	28.1	< 1.1	5.3
	CW "Lagg"	5.1	12.9	4.1	30.0	< 0.3	3.1
	CW "Mineral"	11.6	20.7	28.1	42.5	–	–
Blaney Bog	BU – "Bog"	1.4	< 1.4	1.3	4.4	< 0.3	2.2
	BU – "Trans1"	0.9	< 1.4	2.5	3.1	< 0.3	2.3
	BU – "Trans2"	2.6	1.4	9.8	7.5	< 0.3	3.7
	BU – "Lagg"	9.1	7.1	2.8	3.8	< 0.3	2.2
	BU – "Mineral"	13.4	10.0	5.9	5.0	0.39	2.8
	BF – "Bog"	3.4	4.3	1.5	4.4	< 0.3	1.8
	BF – "Trans1"	5.7	11.4	1.3	5.0	< 0.3	1.8
	BF – "Trans2"	7.1	8.6	1.3	5.6	< 0.3	2.2
	BF – "Lagg"	3.7	2.9	1.5	5.6	< 0.3	2.3
	BF – "Mineral"	5.7	10.0	3.8	4.4	< 0.3	2.8
Campbell River Bog	CR "Bog"	8.8	3.6	3.2	24.1	< 0.5	3.8
	CR "Trans1"	15.7	5.2	3.3	31.6	< 0.5	3.8
	CR "Trans2"	18.6	5.7	3.0	16.1	< 0.5	2.6
	CR "Lagg"	23.5	8.3	4.0	38.5	< 0.5	3.6
	CR "Mineral"	23.7	6.2	3.7	61.5	< 0.5	3.1

Table 7. Ca : Mg ratios for all transects in June 2011 (May 2011 for Campbell River).

	Ca : Mg ratio					
	"bog"	"trans1"	"trans2"	"lagg1"	"lagg2"	"mineral"
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

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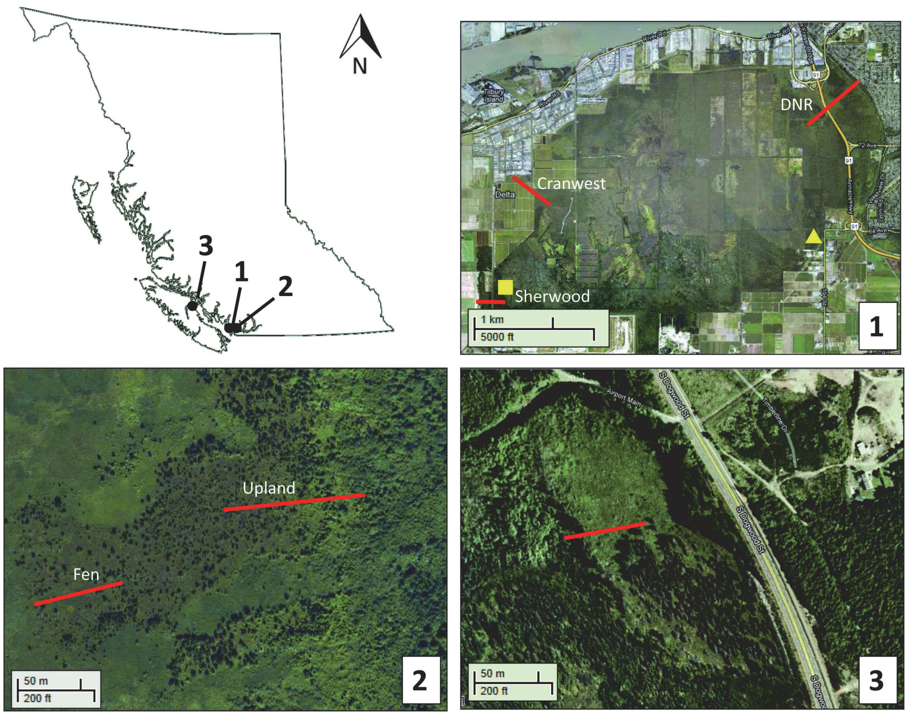

Fig. 1. Location of three research sites in coastal British Columbia: (1) Burns Bog, (2) Blaney Bog, and (3) Campbell River Bog. Red lines represent the transect locations. Additional Burns Bog data are from PF-100 and PF-200 (yellow triangle) and a piezometer near the Sherwood "bog" site (yellow square).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

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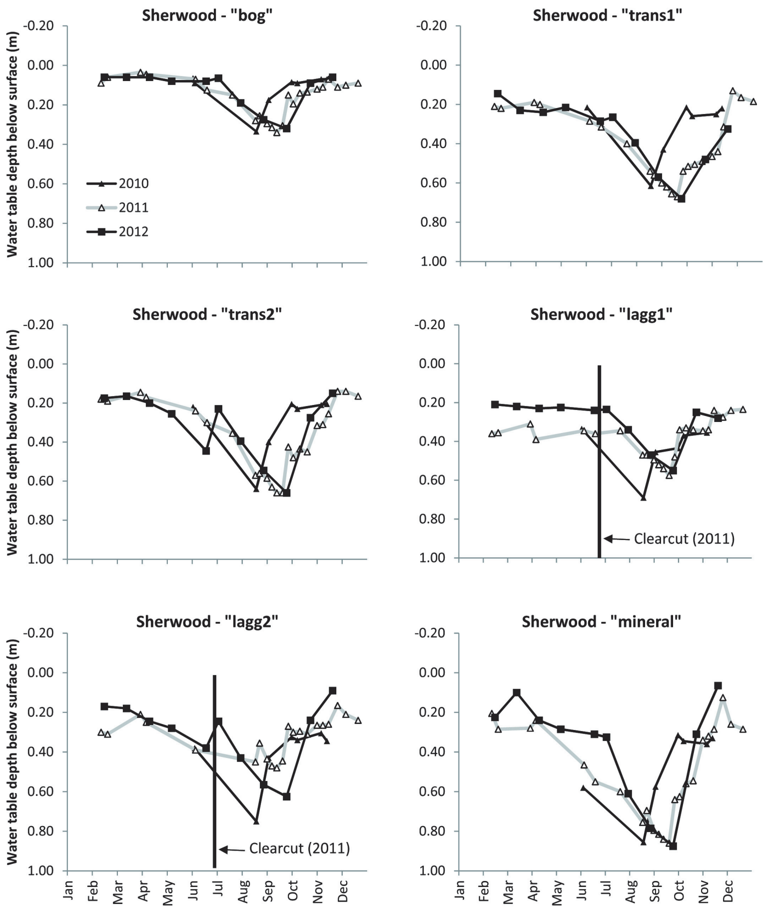

Fig. 2. Time series of depth to water table along the Sherwood forest transect from June 2010 to December 2012. In May/June 2011, logging occurred adjacent to the "lagg1" site; all trees were removed at the "lagg 2" site.

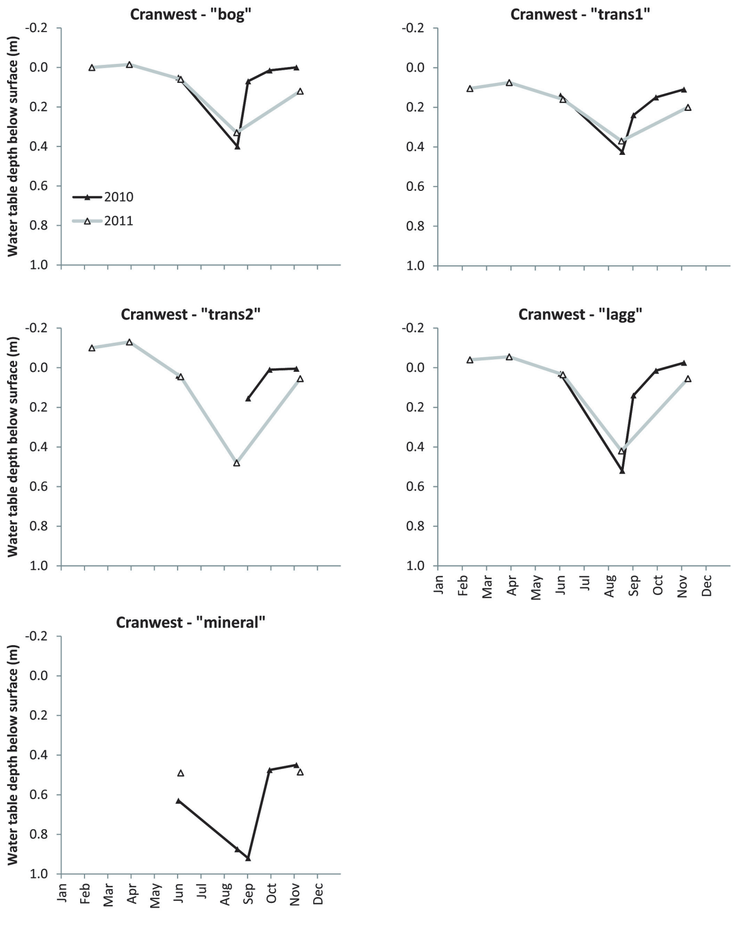

Fig. 3. Time series of depth to water table along the Burns Bog Cranwest transect from June 2010 to December 2011. Negative values indicate that the water table was above the ground surface.

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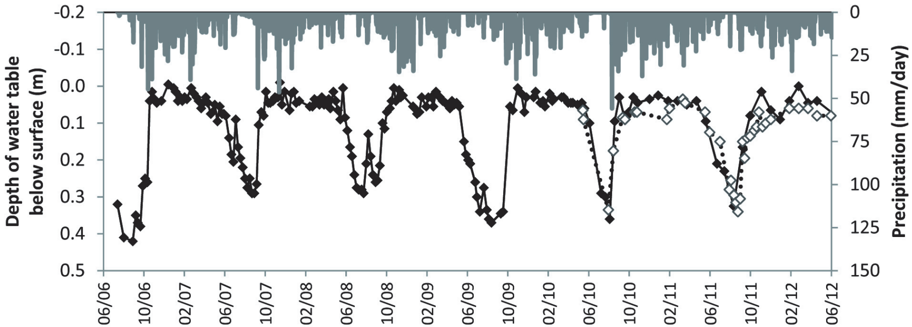

Fig. 4. Depth to water table at the "Sherwood bog" site (dashed line, open diamonds) for the 2010–2012 study period and a nearby piezometer (solid line, solid diamonds) for the 2006–2012 period. Precipitation (gray bars) was measured at Vancouver International Airport, 15 km from the Sherwood transect (source: Environment Canada, accessed online 25 July 2012).

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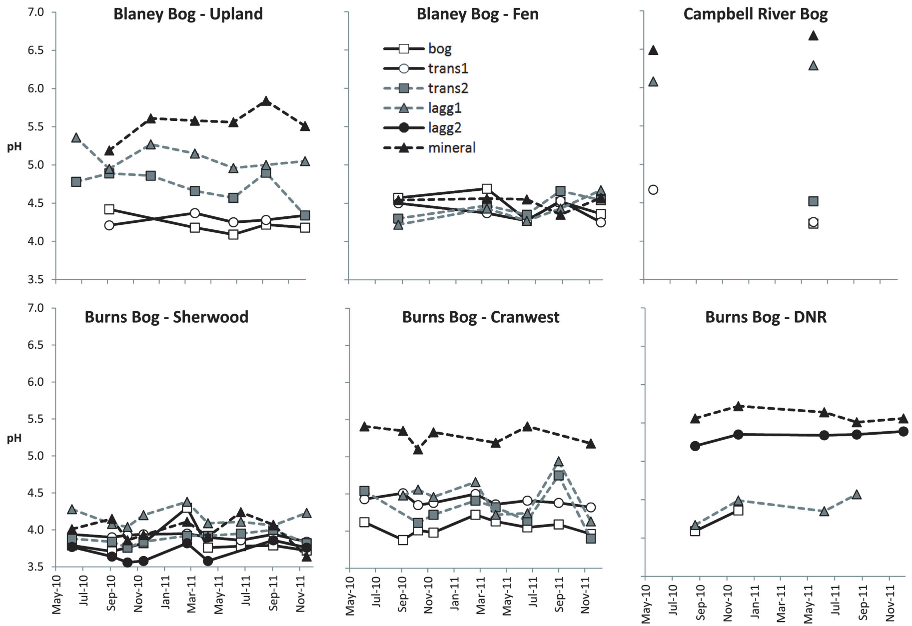

Fig. 5. pH across the six lagg transects from May 2010–December 2011.

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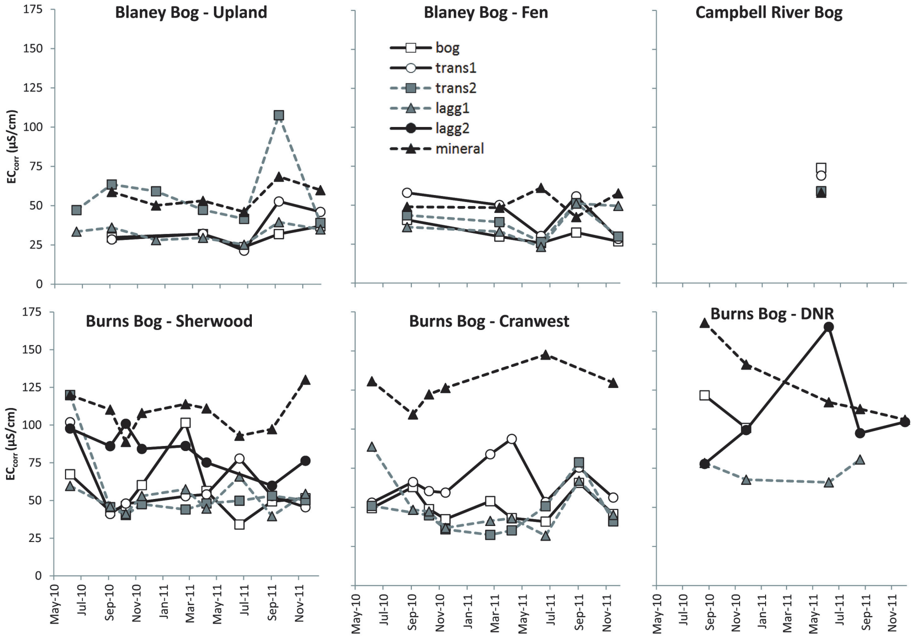

Fig. 6. Corrected electrical conductivity (µS cm^{-1}) across the six lagg transects from June 2010–December 2011.

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