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Ecohydrological characteristics of a newly identified coastal raised bog on the western Olympic Peninsula, Washington State, USA

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Abstract

In western North America, ombrotrophic bogs are known to occur as far south as coastal regions of British Columbia. A recent discovery of a peatland with a raised peat surface on the western Olympic Peninsula in Washington State (Crowberry Bog), USA, suggested that the distribution range of this ecosystem type extends further south along the coast. To confirm if the site was an ombrotrophic peatland, we analysed its topography, hydrologic regime, water chemistry and vegetation. LiDAR data indicated that the peatland is elevated nearly 3 m above the surrounding landscape. Water table variations in the plateau were strongly associated with seasonal and daily precipitation events, indicating ombrotrophy. The hydraulic gradient on the plateau is downward through most of the year, demonstrating that precipitation is percolating vertically into deeper peat layers. In the rand, the hydraulic gradients are horizontal over much of the year, indicating that the plateau is draining through the rand to the lagg. Calcium, magnesium and potassium occur in very low concentrations, and the only ions in higher concentration are sodium and chloride, suggesting inputs of precipitation influenced by Pacific Ocean sea spray. Distinct vegetation composition and structure are associated with the plateau, rand and lagg zones of the site. These multiple lines of evidence indicate that Crowberry Bog is an ombrotrophic peatland, the first of its type identified in the conterminous western USA and the most southerly occurrence of its type in western North America.

KEYWORDS
bog, fen, hydrology, ombrotrophic, peatland, plateau bog, water chemistry

1 | INTRODUCTION

Bogs and fens are two commonly recognized types of peatlands (Gorham, 1957; Moore, 2002). Bogs are solely dependent on precipitation for their input of water and nutrients (ombrotrophic) resulting in distinct hydrologic regimes and water chemistry characteristics (Damman, 1995; Proctor et al., 2009). Because precipitation is a poor source of ions, bogs have very low concentrations of cations and anions other than hydrogen (Ingram, 1967; Sjörs, 1950). In contrast, fens are supported by surface and groundwater inputs (minerotrophic) which provide ions leached from bedrock, surficial deposits and soils of their watershed (Damman, 1995; Ingram, 1967; Moore & Bellamy, 1974).

In the Northern Hemisphere, bogs are most common in temperate maritime or cold continental climates with cool-to-warm summer temperatures, little seasonality in precipitation, and where annual precipitation exceeds evapotranspiration (Gignac et al., 2000; Kottek et al., 2006; Parviainen & Luoto, 2007). However, in northern Canada, continental bogs occur in areas with relatively low annual precipitation (Vitt et al., 1994), only marginal moisture surpluses, and distinct seasonal precipitation patterns (Glaser et al., 1997; Hebda & Biggs, 1981). In western North America, bogs are known to occur in coastal British Columbia as far south as Vancouver, British Columbia, a maritime region with a summer dry climate (Hebda & Biggs, 1981; Howie & van Meerveld, 2013; Kottek et al., 2006). However, a recent discovery of a raised peatland on the western Olympic Peninsula in Washington State, USA, prompted our investigation to determine whether this site is ombrotrophic. Although the term bog is applied to many wetlands in the Pacific Northwest region (Osvald, 1933; Rigg, 1937, 1958), no published research has demonstrated the presence of an ombrotrophic peatland in Washington State. This determination is critical because ombrotrophic bogs are not known to exist in the continental western USA (Cooper et al., 2012), and the presence of a new ecosystem type at its southern range limit requires important conservation and management steps.

Confirming ombrotrophy can be difficult using easily measurable variables such as vegetation composition, pH and electrical conductivity as these variables do not always exhibit abrupt differences between bogs and fens and thus are not reliable on their own as indicators of ombrotrophic conditions (Damman, 1977; Proctor et al., 2009; Sjörs, 1950). Investigating additional variables such as morphology, hydrologic process and water chemistry provides a more robust determination of ombrotrophy (Bridgham et al., 1996; Wheeler & Proctor, 2000). Therefore, a comprehensive evaluation of numerous ecohydrological characteristics was conducted to confirm if our study site was ombrotrophic. Moss growth, short-term peat accumulation and structural patterns of woody vegetation were also measured to provide insight into the bog's ecological integrity.

Peatlands that are elevated above the surrounding terrain may be ombrotrophic because the peat surface, and plant-rooting zone are raised above the influence of minerotrophic water (Glaser & Janssens, 1986; Vitt et al., 1994). However, some fens may be raised due to underlying bedrock or very strong localized groundwater flow that produces large peat mounds (Wolf & Cooper, 2015). Conversely, peatlands without conspicuously raised surfaces may also be ombrotrophic (Damman, 1986; Proctor et al., 2009; Rydin et al., 1999). Coastal bogs often form lagg, rand and plateau ecological zones. A lagg is the wet zone around the perimeter of the bog and can receive water from the bog and adjacent upland or wetlands (Howie & Meerveld, 2013). As such, it is more minerotrophic and may contain plants typical of fens or swamps. The rand is the upward-sloping margin of the bog, and the plateau is a generally flat-topped expanse of the bog (Damman & French, 1987; Osvald, 1933; Rydin & Jeglum, 2006).

Quantification of hydrologic processes and water chemical content can help determine the relative influence of precipitation and groundwater inputs in a peatland. Downward hydrological gradients (recharge) and chemical similarities between peatland waters and local precipitation are both strong indicators of ombrotrophic conditions (Damman, 1986; Glaser et al., 1997; Ingram, 1983; Proctor et al., 2009; Siegel & Glaser, 1987). Because Ca^{2+} concentrations are extremely low in precipitation, Ca^{2+} concentrations <2.5 mg/L or a Ca^{2+}/Mg^{2+} ratio of 1.0 have been used to indicate ombrotrophic conditions (Joosten et al., 2017; Malmer et al., 1992; McHaffie et al., 2009; Proctor et al., 2009; Sjörs & Gunnarsson, 2002). However, these thresholds may not apply to coastal peatlands influenced by sea spray.

In western North America, bogs have been reported in Alaska (Neiland, 1971; Rigg, 1937; Viereck et al., 1992), continental Canada (Vitt et al., 1994) and coastal British Columbia (Golinski, 2004; Hebda & Biggs, 1981; Howie & van Meerveld, 2013; Vitt et al., 1990). In Washington State, 'bogs' and '*Sphagnum*-dominated peatlands' have been widely reported, including mentions of 'raised bogs' (Dachnowski-Stokes, 1936; Hofstetter, 1983; Osvald, 1933; Rigg, 1925, 1940, 1951, 1958). Rigg (1958) noted that while raised bogs are not characteristic in Washington, a few *Sphagnum* bogs in western Washington are 'sufficiently so raised that their convexity can be recognized by merely looking at them.' Previous reports of raised bogs in Washington lack hydrogeochemical information and were based solely on visual assessment of topography or vegetation composition.

We worked at 'Crowberry Bog,' a site first recognized in 2011 during a statewide analysis of ecologically significant wetlands for its conspicuously raised peat surface, a feature distinctive from other peatlands in the western USA. Heusser (1974) noted that Crowberry Bog was 'slightly domed', but no data were provided to support this observation. Our research focused on using multiple data sets to determine whether Crowberry Bog is ombrotrophic and to compare its morphology, ecological characteristics and associated climate to other coastal ombrotrophic peatlands in the Northern Hemisphere. We address the following questions: (1) Are there significant periods of the year when the movement of groundwater is primarily downward, (2) are the concentrations of pore water ions within the range reported for ombrotrophic peatlands, (3) is the vegetation composition limited to species tolerant of nutrient poor conditions, (4) is the topography consistently raised above the adjacent land area, (5) is the peatland currently accumulating peat, (6) how is woody vegetation distributed currently distributed across the bog and (7) has the surrounding land cover and tree cover on the bog changed over time?

2 | STUDY AREA

Crowberry Bog is located on the western Olympic Peninsula in Jefferson County, Washington State, USA (Figure 1). The peatland occurs on a Fraser Age glacial terrace just south of the Hoh River and is 0.19 km^2 in area (Heusser, 1974). The site is approximately 135 m above mean sea level (MSL) and 18 km east of the Pacific Ocean.

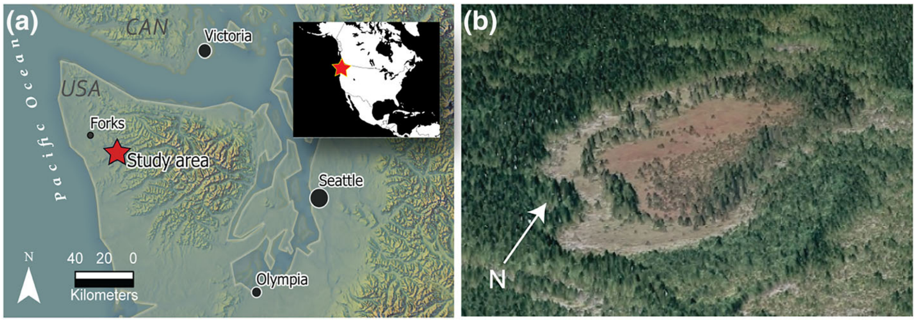

FIGURE 1 (a) Location of the Crowberry Bog study area in northwestern Washington State, USA, on the Olympic Peninsula. (b) Oblique view of aerial image draped over LiDAR-derived digital terrain model of study site. The plateau surface is ~450 m long in the north to south direction

The nearest climate stations are (1) Spruce, approximately 11 km to the east of site along the Hoh River and (2) Forks 1 E, WA, about 19 km to the northwest of the study site (Western Regional Climate Center, 2018). Temperature data are not available for the Spruce station. At the Forks station, the average annual maximum temperature is 14.7°C and average annual minimum temperature is 4.8°C. July and August are the warmest months, December through February are the coldest. Average annual precipitation is 2995 mm at Forks and 3134 mm at Spruce, with most precipitation falling between October and March. July is typically the driest month with a mean monthly total of 58 mm at Forks and 71 mm at Spruce. Average annual snowfall is 330 mm at Forks and 584 mm at Spruce.

Crowberry Bog soils are mapped as Orcas peat derived from *Sphagnum* species (USDA, 1975). Peat cores indicate that *Sphagnum*-derived peat extends from the ground surface to a depth of 3.8 m, with muck from 3.8–4.8 m and muck and clay from 4.8 m to the basin bottom at 5.8 m depth (Heusser, 1974). Soil surrounding the peatland is the Lagitos–Klone–Tealwhit complex, consisting of clayey or fine-texture old alluvium (USDA, 1975, WADNR 2014). This complex consists of poorly drained and somewhat poorly drained silty loam over sand and gravel and well-drained gravelly loam derived from glacial outwash (WADNR, 2014).

Roosevelt elk (*Cervus elaphus ssp. roosevelti* Merriam 1897) and Columbian black-tailed deer (*Odocoileus hemionus spp. columbianus* [Richardson]) have been observed within the site throughout the year and have created trails across the peatland. Many human trails also exist throughout the peatland from the harvest of beargrass (*Xerophyllum tenax*) and salal (*Gaultheria shallon*) for the floral nursery trade. Commercial logging removed trees from portions of the lagg (outer zone of the peatland), starting in the 1960s. Today, the lagg has cut stumps and fire-scarred snags likely related to past logging activity.

3 | METHODS

3.1 | Topographic analysis

We analysed LiDAR data collected and processed by the Puget Sound LiDAR Consortium (Haugerud et al., 2003) and distributed through the Washington Department of Natural Resource's LiDAR portal (http://lidarportal.dnr.wa.gov/). Airborne LiDAR data were collected in April 2012 using a Leica ALS60 and Leica ALS50 Phase II laser system and a single pulse flight plan. Point cloud data were obtained in *.las format and used to produce 1 m digital surface models of site topography. The vertical accuracy of the LiDAR was 3.1 cm (Watershed Sciences, 2012). In addition, we produced digital canopy models to evaluate patterns of tree cover and height across the peatland.

3.2 | Weather and climate

Precipitation was measured at Crowberry Bog using a Hobo tipping bucket rain gauge (Onset, Inc.). Data were compared to historical climate data for the study region from the Forks 1 E, WA weather station. Because of wildlife damage to the on-site rain gauge, data were not available for the entire duration of the study. To provide context for our study, we obtained recent and historical climate data for several locations in the Northern Hemisphere known to support coastal ombrotrophic peatlands (Table 1). We used Global Historical Climate Network stations with at least 30 years of data from the Climate Data Online data portal (National Climatic Data Center (NCDC), 2020). From the daily record, we calculated daily means for temperature and precipitation by day of year and fit loess smooth lines to compare seasonal patterns among stations.

3.3 | Hydrologic regime

We measured water table levels and hydraulic heads from April 2016 through April 2019 using a network of 15 groundwater monitoring wells and 5 nested piezometers installed across the peatland. The wells were placed along transects spanning the bog ensuring that the edge (lagg), sloping margin (rand) and top (plateau) were represented. Wells were 1.25 m long, constructed from 3.175 cm inside diameter fully slotted schedule 40 PVC pipe installed by hand-augering boreholes. Wells were capped on the bottom, the borehole was backfilled with exhumed peat and the wells were developed by bailing. Bottom caps were perforated. We installed nonvented continuous recording Hobo U20L-04 data loggers, corrected for atmospheric pressure using data from an on-site barometric pressure data logger, in a subset of wells and recorded water level hourly for the entire study period. Wells without loggers were manually measured at least quarterly each year using an electronic tape. Piezometers were nested with

TABLE 1 Weather stations for representative sites supporting coastal ombrotrophic bogs in the northern hemisphere

Station	Name	Latitude	Longitude	Elevation (m asl)
USC00452914	Forks, USA	47.956	−124.354	106.7
CA001108395	Vancouver BC, CANADA	49.200	−123.183	4.0
CA001066482	Prince Rupert BC, CANADA	54.283	−130.450	35.0
SWE00139272	Avesta, SWEDEN	60.140	16.170	100.0
USW00014764	Portland, ME, USA	43.642	−70.304	13.7
SPE00119729	Santiago de Compostela Labacol, SPAIN	42.888	−8.411	370.0
EIM00003962	Shannon, IRELAND	52.702	−8.925	14.0
FIE00142080	Helsinki, FINLAND	60.327	24.960	51.0

monitoring wells and installed to 50, 100, 150 and 200 cm below the ground surface and water levels measured with an electronic tape. Piezometers were unslotted 1/2″ inside diameter PVC pipe, pushed to the desired depth with a rod inside the pipe then the rod was removed so the piezometers were open only at the bottom (Cooper & Merritt, 2012). All well and piezometer tops were covered to prevent precipitation inputs. The location and elevation of all monitoring wells and piezometers and ground surface topography were identified using LiDAR. Analysis of variance was used to determine if wells had significantly different ($p < 0.05$) water levels each month during our study period. We also used Tukey adjusted pairwise comparisons to contrast the continuous logger data for wells 1, 2 and 4 by month. We used functions in R and supporting packages (R core team, 2020; Wickham & Averick, 2019) for all statistical analyses and plotting.

3.4 | Water chemistry

Water samples were collected from monitoring wells 1 (lagg), 2 (rand), 3 (rand/plateau boundary), 4 and 5 (plateau) on 21 September 2016, 25 April 2017, 6 July 2018 and 18 January 2018 after first emptying the well volume three times using a bailer. The collection and use of water from wells is recommended by Tahvanainen and Tuomaala (2003), instead of sampling surface water, as it avoids diurnal and fine scale vertical and horizontal variation in surface water. We collected 100 ml of water from the top of the water table in 125 ml Nalgene bottles and samples were stored on ice and then frozen within 48 h. Samples were thawed and filtered (0.45 μ filter) prior to analysis at the Colorado State University Soil and Water testing laboratory for concentrations of Ca^{2+}, Mg^{2+}, Na^+ and K^+ using ICP; CO_3 using titration; and Cl, NO_3 and SO_4 using ion chromatography (Fritz, 1987). Using a calibrated Thermo Orion Star A325 pH/conductivity meter, pH and EC were measured in situ from water samples taken from the top of the water table in each well. EC was corrected to account for hydrogen ion using the procedures in Sjörs (1950) and Rydin and Jeglum (2006).

Analysis of variance was used to identify significant differences ($p < 0.05$) in ion concentration by landform (lagg, rand and plateau) and by well, followed by a Tukey pairwise comparison where significant differences existed (Appendix B).

3.5 | Vegetation

The composition of vegetation around each monitoring well was assessed in April 2016 to characterize the site vegetation. Trees and shrubs were documented in a 10 × 10 m plot, and herbaceous and nonvascular species were documented in a 2 × 2 m plot, offset from the well by approximately 1 m in a random direction to avoid the trampled area around the well. All vascular plants were identified to species or subspecies. Dominant bryophyte and lichen species were sent to Dr. Dale H. Vitt and Dr. Bruce McCune, respectively, for identification. Species nomenclature follows Hitchcock and Cronquist (2018) for vascular plants, Bryophyte Flora of North America (Flora of North America Editorial Committee, 2007, 2014) for mosses, and Esslinger (2019) for lichens.

3.6 | Short-term peat accumulation

We measured moss growth using the 'crank wire method' (Clymo, 1970), modified by adding horizontal plastic bristles at the bottom end (Gunnarsson & Rydin, 2000) to add extra stability in the peat and prevent movement during freeze–thaw events (Cooper et al., 2015). At wells 3, 4 and 5, we installed one transect of 20 wires spaced 20 or 50 cm apart. Wires were 15 cm long stainless steel and installed approximately 5 cm into the ground surface. At the time of installation in April 2016 and four times per year through April 2019, we measured distance from the ground surface to the top of the wire to develop a relative measure of moss growth. The initial wire length above the moss capitulum at the time of installation was the zero point, and all subsequent measures were used to record total growth during the period.

We excavated five *Pinus contorta var. contorta* individuals to measure the thickness of peat above their germination point using the 'pine method' (Ohlson & Dahlberg, 1991). The ground surface level on each tree was marked before excavation. Trees were removed, then dried and cut into disks to find the germination point or root crown, which as identified as the point where the pit originates (Birken & Cooper, 2006; Cooper et al., 2003). Peat accumulation rate was calculated as the stem age at the germination point divided by the peat thickness above the root crown. The study area has a strongly seasonal precipitation and temperature regime with a summer drought, and we assumed no false rings occurred.

3.7 | Tree cover and structure

To assess vegetation structure across the wetland, we used the RRQRR algorithm (Theobald et al., 2007) to develop a spatially balanced random sample of locations across the wetland. A 10 m circular buffer was placed around sample points and used to extract information from the LiDAR-derived digital surface model and canopy height model layers using zonal statistics in ArcGIS Pro (ESRI, Inc.) for further analysis of canopy cover characteristics across the wetland. To understand changes in surrounding land cover and dynamics of tree cover within the wetland, we evaluated historical aerial photographs from 1939, 1950, 1971, 1981, 1990 and 2016.

4 | RESULTS

4.1 | Topographic and terrain analyses

LiDAR-derived digital surface models revealed that the peatland has a distinct raised form in north–south and east–west directions (Figure 2). The cross-sections illustrate a topographic low in the outer edge or lagg (Howie & van Meerveld, 2013); rising through the rand to a relatively level top, which we call the plateau (Damman & French, 1987; Osvald, 1933; Rydin & Jeglum, 2006). At the highest point, the relative elevation difference between the lagg and plateau is nearly 3 m, and the plateau is completely composed of *Sphagnum*-derived peat that extends to a depth of 3.8 m (Heusser, 1974).

4.2 | Weather and climate

On-site precipitation data are highly correlated with the Forks 1 E, WA (Forks) weather station ($R^2 = 0.75$, $F = 1498$, $p < 0.0005$). Rain events align temporally, but the Forks station on average has higher daily totals (Figure 3). Comparative climate analyses indicated that Forks was distinct from other regions with coastal ombrotrophic bogs (Figure 4). Temperature patterns are all similar seasonally, with the warmest temperatures in July through September. Forks temperatures fit well with the annual temperature pattern for all sites, but along with the Spain, Maine and Vancouver sites are warmer in winter than the other sites. Summer precipitation at Forks is nearly as low as the Mediterranean climate site in Spain and Vancouver in July and August. Forks receives approximately three times more winter precipitation than the other sites.

4.3 | Hydrologic regime

Water levels in all monitoring wells were highest during the winter and spring from November through April and into June. Significant water table decline occurred in late summer each year due to the seasonal lack of precipitation. Water levels were deepest in the late summer, July through September. Three wells with continuous loggers illustrate the water table response to both seasonal and daily weather patterns (Figure 5). Water levels were above the ground surface in the lagg (well 1) and on the plateau (well 4) during October through March 2016 and during rainy periods in October through May 2018 and 2019. Water levels in the lagg, rand (well 2) and plateau had almost identical patterns of water level rise and fall in response to precipitation events and seasonal variation. The water level in wells was significantly different ($p < 0.05$) from each other in most months of the year, but well 2 in the rand and 4 on the plateau were not different in April and June (Appendix A).

All wells declined more than 40 cm in the dry season and then rose and fell up to 20–30 cm in response to short-term precipitation patterns. Interestingly, water levels declined sharply between precipitation events indicating that the peatland water source was precipitation and it drained rapidly. For example, a 1-week rainless period in February 2017 produced a water level decline of almost 25 cm in all three wells and was most dramatic in the rand, with an

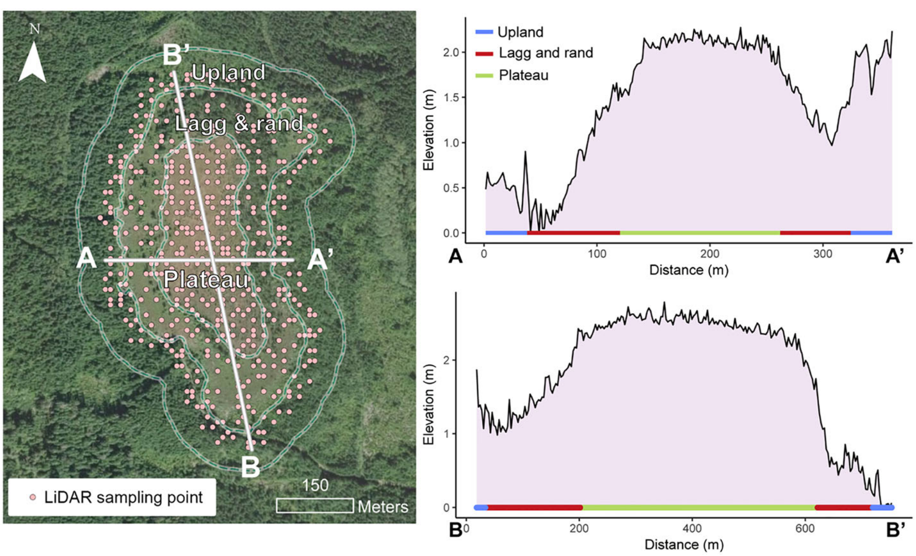

FIGURE 2 Overview of sample points and cross-sections used in analysis of LiDAR data. Elevation cross-sections A-A′ and B-B′ extracted from LiDAR-derived digital terrain model of wetland showing upland, lagg and rand and plateau

average daily decline of more than 3 cm/day. Similar rates of decline also occurred during the summers of 2016, 2017 and 2018. Clearly, the maintenance of water table levels near the soil surface requires regular precipitation. Rainless periods of several weeks to 1–2 months resulted in a ground water level decline of 40–80 cm.

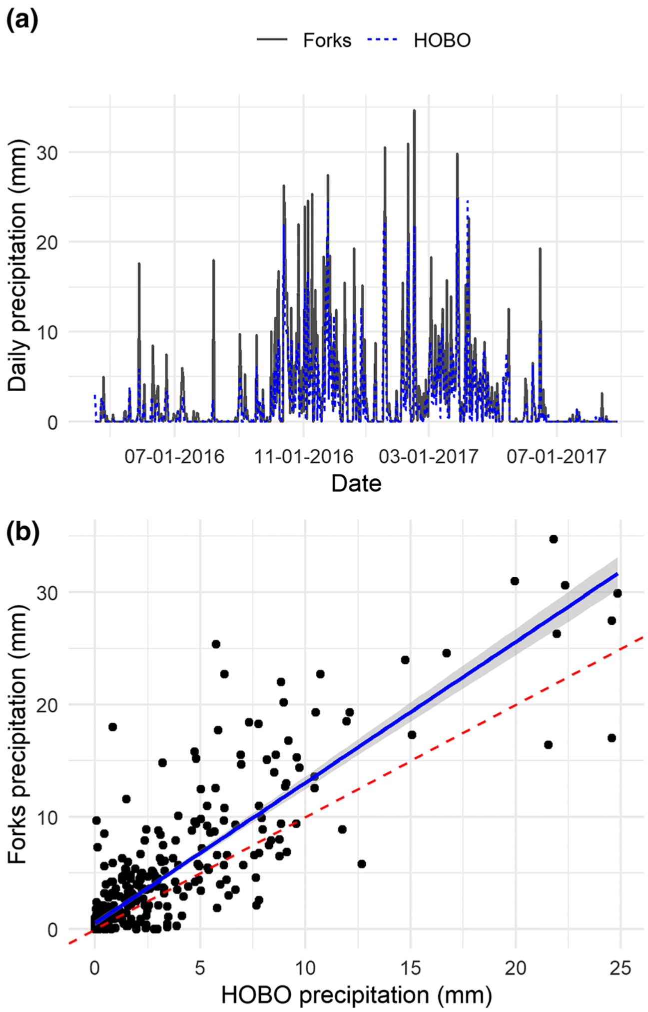

FIGURE 3 (a) Daily precipitation (mm) for on-site HOBO rain gauge and precipitation from the Forks, WA, weather station. (b) Comparison of daily precipitation data from the on-site HOBO rain gauge and Forks, WA, data with 1:1 line (red) and least squares regression line (blue)

Water levels in the lagg recorded in wells 1 and 7 were at or above the soil surface in the wet season but dropped to more than 30 cm below the soil surface and went dry in summer (Figure 5). The lagg has thinner peat soils than the rand and plateau over dense mineral or rocky substrate. Water levels in the rand, at wells 2, 6, 9, 13 and 14, were near the soil surface during the wet season but dropped to 60 to 80 cm below the soil surface in the late summer and the ground surface was dry. On the plateau water levels in wells 4, 5 and 12 remained near the surface for much of the year but dropped to 40 cm or more below the ground surface in late summer.

Hydraulic gradients in the well and piezometer nest in the rand (well 2) were nearly equal in 2016 and the first half of 2017 indicating horizontal flow. However, the hydraulic head in the monitoring well and the 50 cm piezometer of well 2 declined in the summer of 2017, while the deeper piezometers had higher heads indicating upward gradient into the shallow peat layers (Figure 6). At wells 3, 4, 5 and 6 the flow direction was downward during the wet season and the gradient reversed in the dry season during August through October 2017 but never reached the soil surface. During the dry season, the head in all piezometers declined but remained higher than the water table.

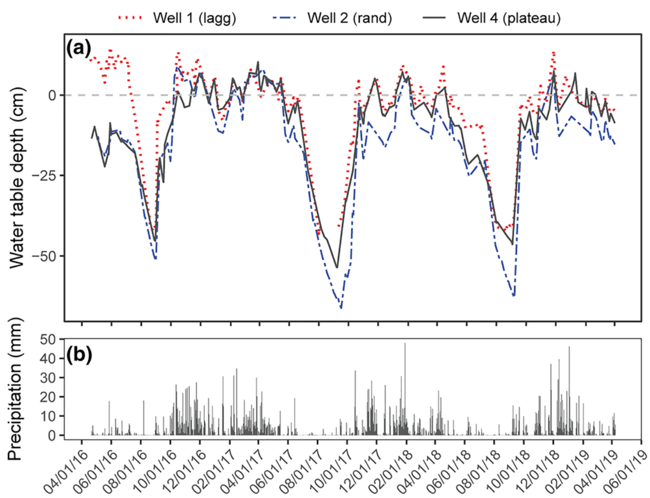

FIGURE 5 (a) Continuous depth to ground water in wells 1 (lagg), 2 (rand) and 4 (plateau) for April 2016 to April 2019. (b) Daily precipitation from Forks, WA

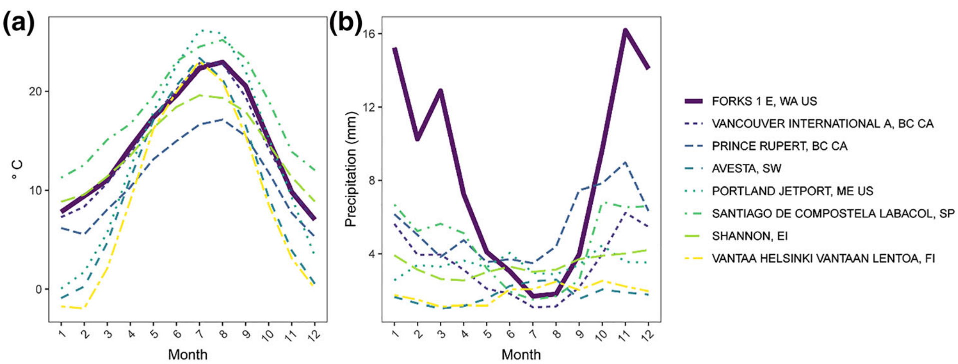

FIGURE 4 (a) Loess lines fit through annual time series, 1988–2018, of daily mean maximum temperature and (b) monthly precipitation (mm) for different regions supporting ombrotrophic peatlands. The site locations are in Table 1

When analysed across the entire study period, all wells had a similar monthly trend (Figure 7). Water tables were at or near the ground surface from approximately November through April, the wettest and coolest time of year. Water levels trended downward toward an annual minimum in August and September. For most months, median water table depth was highest in the lagg at well 1 and deepest in the rand at well 2. However, there was significant variability in all wells during the study period.

4.4 | Water chemistry

The pH of ground water in wells averaged 5.12 (sd = 0.18, n = 8)), 4.65 (0.25, *n* = 16)), 4.20 (0.14, *n* = 79) and 4.27 (0.22, *n* = 27) in the upland, lagg rand and plateau (Figure 8). Except for the plateau–rand comparison, the pH in each ecological zone was significantly different ($p < 0.05$) from each other (Appendix B). The lowest pH measured was 3.76 in well 5 (plateau) in August 2017. The highest pH measured within the peatland was 5.31 in well 7 (lagg) in July 2016. Across all ecological zones, the average pH measures were lowest during dry season (July through September) and highest during the wet months (January). Average pH in the lagg was always higher than the rand and plateau, regardless of sample date. The rand and plateau had similar average pH, although the rand was slightly lower (between 0.04 and 0.1). The highest pH in the upland well (#8) occurred during the driest sampling times (July and September).

EC^{corr} averaged 40.2 µS/cm in the lagg, 26.5 µS/cm in the rand and 23.2 µS/cm on the plateau (Figure 8). The highest EC^{corr} recorded was 125 µS/cm in well 1 (lagg) in July 2016. EC^{corr} was lowest across all ecological zones at the end of the rainy season in April and highest during dry season (July through September). EC^{corr} in the lagg was always higher than the rand and plateau, regardless of sample date. The rand had slightly higher EC^{corr} than plateau in all seasons except July.

Na^+ was the cation with the highest concentration, ranging from 2.0 to 10.8 mg/L and averaged 3.8 mg/L (Figure 9). Ca^{2+} occurred in very low concentrations, 0.1–0.2 mg/L, in most samples to a high of 0.8 at well 5 in January 2018 and averaged 0.3 mg/L across all sites and sample dates. Mg^{2+} had similar concentrations to Ca^{2+}, while K^+ was below the detection limit on most dates. Na^+ was the only cation to show significant differences across ecological zones (Appendix B). No other cations nor anions were found to be significantly different across ecological zones.

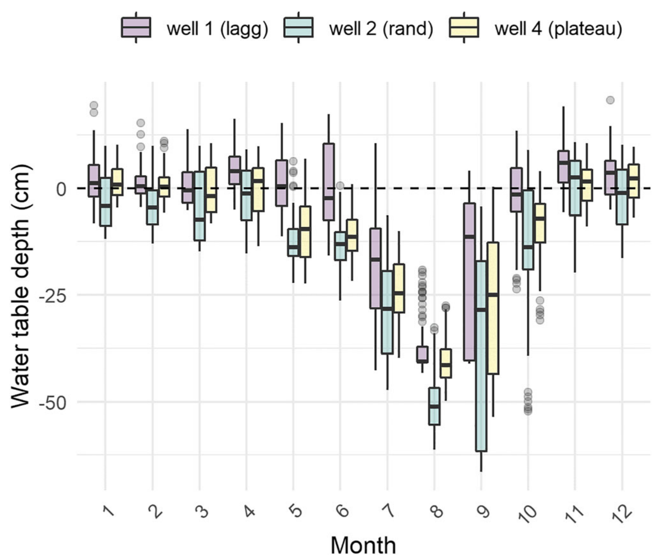

FIGURE 7 Boxplots of the 25th, 50th and 75th percentiles showing monthly water table depth across all years for well 1 (lagg), 2 (rand) and 4 (plateau). Grey dots are outliers

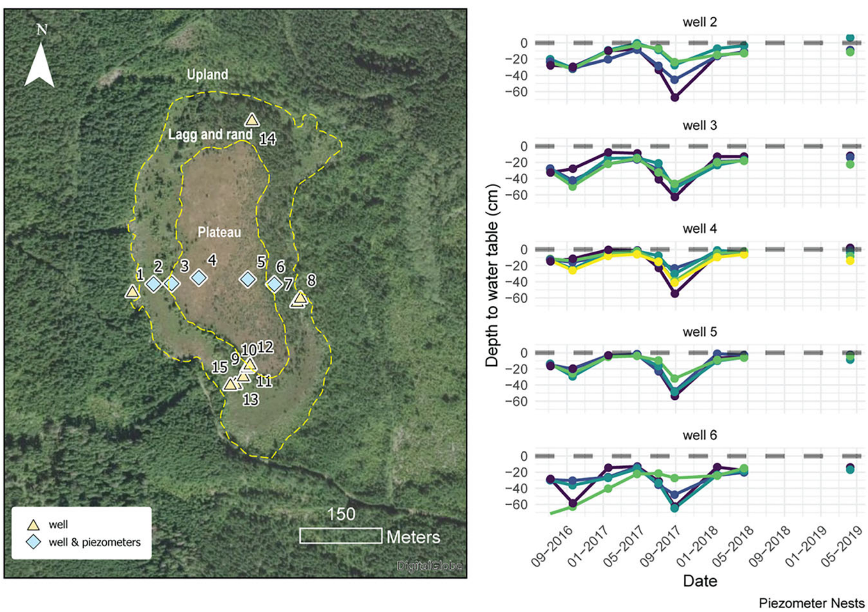

FIGURE 6 (Left) Locations of monitoring wells and field mapped boundaries of the plateau, rand, lagg and upland. (Right) Water level in monitoring wells (S) and piezometers completed at 50, 100, 150 and 200 cm at wells 2, 3, 4, 5 and 6

The anion in highest concentration was Cl- with an average concentration of 6.7 mg/L, and all four stations had concentrations exceeding 8.0 mg/L at some time with the highest concentration being 16.1 at well 2. SO_4 was the anion with the second highest concentration and an average of only 0.61 mg/L. HCO_3 was near the detection limit of the analytical technique and its concentration was negligible.

Proctor et al. (2009) suggest that a molar Ca^{2+}/Mg^{2+} ratio <1.0 is indicative of ombrotrophic conditions. The molar ratio of Ca^{2+}/Mg^{2+} was greater than 1.0 in all sample wells for all four sample periods on the plateau. These ratios suggest that all wells, and most strongly those on the plateau, do not meet the criterion for ombrotrophy suggested by Proctor et al. (2009). The relatively high concentration of Na^+ and Cl_ indicate transport of sea spray from the Pacific Ocean to Crowberry Bog.

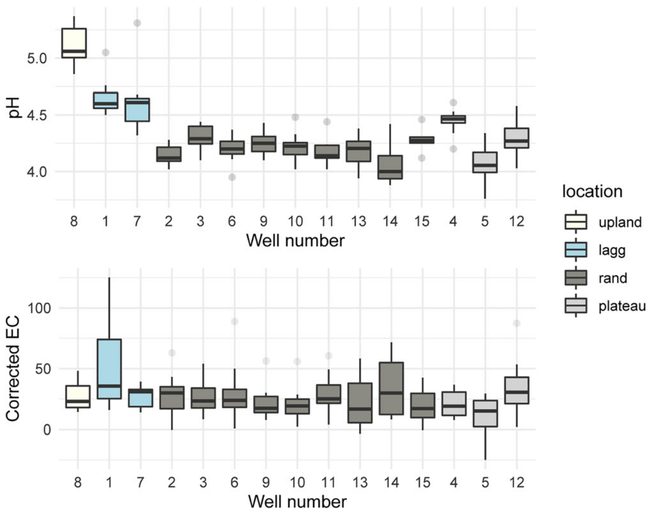

FIGURE 8 Boxplots of the 25th, 50th and 75th percentiles of all measurements during 2016, 2017 and 2018 for (a) pH and (b) corrected electrical conductivity (EC^{corr}) for study site wells. The wells are in the upland (well 8), lagg (wells 1 and 7) rand (wells 2, 3, 6, 9, 10, 11, 13, 14 and 15) and plateau (wells 4, 5 and 12)

4.5 | Vegetation

The plateau is dominated by short statured (<30 cm) *Rhododendron groenlandicum* and *Kalmia microphylla var. occidentalis*, along with *Vaccinium oxycoccos* and *Empetrum nigrum* (Table 2). A nearly continuous moss carpet formed by *Sphagnum fuscum* and *S. rubellum* occurs across the entire plateau. Small hummocks of *Sphagnum austinii* are scattered across the plateau, mostly near the transition to the rand. As is typical of many acid peatlands in the region, species of fruiticose lichens (*Cladonia* spp.) occur on the plateau with *Sphagnum*. *Cladonia rangiferina* is the most common lichen on the plateau along with *Cladonia albonigra*, *C. stricta*, and *C. uncialis*, which is rare in Washington (Bruce McCune, personal communication). *Xerophyllum tenax* and *Lysichiton americanus* are widespread on the plateau. Individuals of *Lysichiton americanum* form small 'wells' in many areas (Osvald, 1933; Turesson, 1916). *Sphagnum* is replaced by *Aulacomnium palustre* and *Dicranum scoparium* in these wells. Stunted *Pinus contorta var. contorta* and occasional *Tsuga heterophylla* are common in the central part of the plateau. *Eriophorum chamissonis*, *Rhynchospora alba* and *Triantha occidentalis ssp. brevistyla* dominate small hollows and water tracks.

Vegetation composition of the rand is similar to the plateau, but plant height, vigour and density are conspicuously greater, particularly

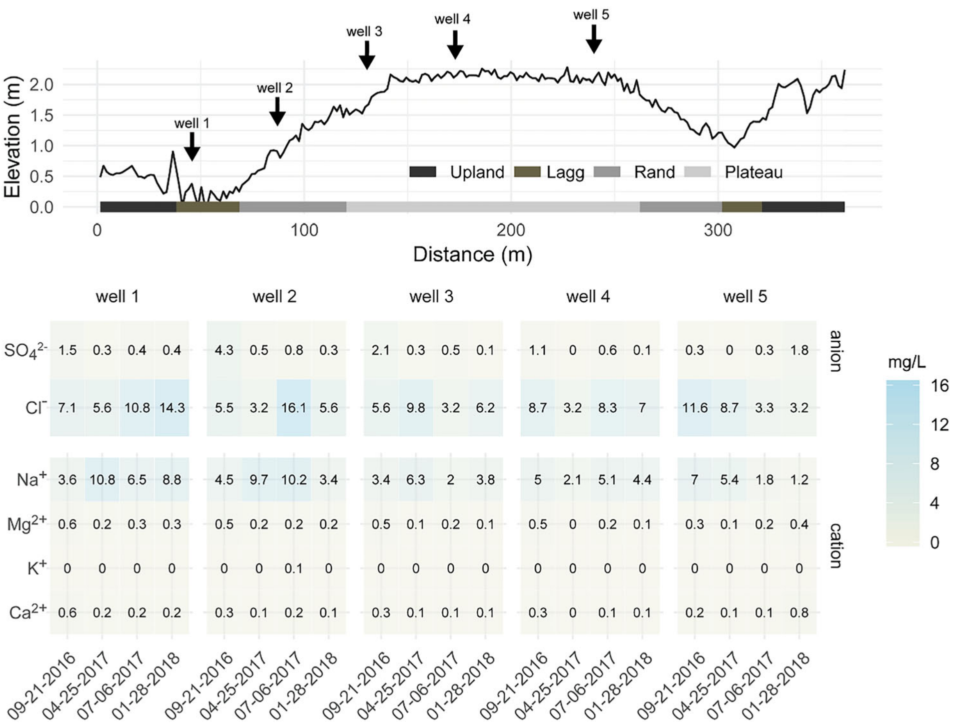

FIGURE 9 Anion and cation concentrations (mg/L) for four sample dates (21 September 2016, 25 April 2017, 6 August 2017 and 18 January 2018) at wells 1, 2, 3, 4 and 5, representing a transect from lagg to plateau. Well 1 is lagg, well 2 rand, well 3 on the boundary between rand and plateau and wells 4 and 5 on plateau. K^+ results reported as 0 were below the detection limits of instruments used

TABLE 2 Vegetation composition of the lagg, rand, plateau and upland areas of Crowberry Bog

Zone	Lagg	Rand	Plateau	Upland[a]	*Lysichiton americanum* 'wells'
Plot/Well #	**1, 7, 15**	**2, 6, 9, 10, 13, 14**	**3, 4, 5, 11, 12**	**8**	**n/a**
TREES					
Alnus rubra Bong.	X			X	
Picea sitchensis (Bong.) Carrière	X				
Pinus contorta Douglas ex Loudon var. *contorta*		X	X		
Tsuga heterophylla	X	X	X	X	
Thuja plicata Donn ex D. Don	X	X		X	
SHRUBS					
Empetrum nigrum L.			X		
Frangula purshiana (DC.) A. Gray ex J.G. Cooper	X	X			
Gaultheria shallon Pursh	X	X	X	X	
Kalmia microphylla (Hook.) A. Heller var. *occidentalis* (Small) Ebinge	X	X	X		
Malus fusca (Raf.) C.K. Schneid.	X				
Rhododendron groenlandicum (Oeder) Kron & Judd	X	X	X		
Vaccinium oxycoccos L.	X	X	X		
Vaccinium parvifolium Sm.	X	X			
HERBACEOUS					
Cornus unalaschkensis Ledeb.	X	X			
Drosera rotundifolia L.			X		
Eriophorum chamissonis C.A. Mey.			X		
Juncus hesperius (Piper) Lint	X				
Lysichiton americanum Hulten & H. St. John	X	X	X		X
Maianthemum dilatatum (Alph. Wood) A. Nelson & J.F. Macbr.	X	X			
Pteridium aquilinum (L.) Kuhn ssp. *pubescens* (Underw.) J.A. Thomson, Mickel & Mehlt.		X			
Rhynchospora alba (L.) Vahl			X		
Struthiopteris spicant (L.) Weiss	X				
Triantha occidentalis (*S. Watson*) R.R. Gates ssp. *brevistyla* (C.L. Hitchc.) Packer			X		
Xerophyllum tenax (Pursh) Nutt.	X	X	X	X	
BRYOPHYTES					
Aulacomnium palustre (Hedwig) Schwagrichen			X		X
Dicranum scoparium Hedwig					X
Hylocomium splendens (Hedwig) Schimper in P. Bruch and W. P. Schimper		X		X	
Kindbergia oregana (Sullivant) Ochyra		X			
Kindbergia praelonga (Hedwig) Ochyra		X			
Pleurozium schreberi (Willdenow ex Bridel) Mitten		X	X		
Rhytidiadelphus loreus (Hedwig) Warnstorf		X			
Sphagnum austinii Sullivant in C. F. Austin			X		
Sphagnum capillifolium (Ehrhart) Hedwig		X			
Sphagnum pacificum Flatberg	X				
Sphagnum henryense Warnstorf [a]	X				
Sphagnum fuscum (Schimper) H. Klinggraff			X		
Sphagnum papillosum Lindberg	X				X
Sphagnum rubellum Wilson	X	X	X		

(Continues)

TABLE 2 (Continued)

Zone	Lagg	Rand	Plateau	Upland[a]	*Lysichiton americanum* 'wells'
Plot/Well #	**1, 7, 15**	**2, 6, 9, 10, 13, 14**	**3, 4, 5, 11, 12**	**8**	**n/a**
LICHENS					
Cladonia cf *albonigra* Brodo & Ahti			X		
Cladonia ciliata var. ciliata (Flörke) Ahti	X	X	X		
Cladonia rangiferina (L.) F. H. Wigg.	X	X	X		
Cladonia cf *stricta* Stirton	X	X	X		
Cladonia cf. *transcendens* (Vain.) Vain.			X		
Cladonia uncialis (L.) F. H. Wigg.	X	X	X		

[a]Several vouchers were identified as *Sphagnum henryense*, but this species was not separated from *S. palustre* in the field.

of *Rhododendron groenlandicum*. *Empetrum nigrum*, *Eriophorum chamissonis*, *Triantha occidentalis spp. occidentalis* and *Rhynchospora alba* are absent from the rand and lagg (Table 2). Some areas of the rand are dominated by closed canopy forests of *Pinus contorta var. contorta* and *Tsuga heterophylla*. The understory of these forests varies from dense patches of *Xerophyllum tenax* to being sparsely vegetated. *Sphagnum capillifolium* and *Pleurozium schreberi* hummocks comprise the dominant mosses in the nonforested portions of the rand. *Hylocomium splendens*, *Kindbergia oregana*, *K. praelonga* and *Rhytidiadelphus loreus* are abundant mosses in the forested portions of the rand.

Vegetation in the lagg includes many of the species found in the plateau and rand but also species commonly found in shrub and forested swamps in western Washington such as *Thuja plicata*, *Malus fusca* and *Juncus hesperius* (Table 2, USNVC, 2019). *Sphagnum henryense*, *S. pacificum* and *S. papillosum* are common in the lagg. *Cladonia* species are scattered, usually on downed wood. Upland forests are dominated by dense stands of mostly *Thuja plicata*.

4.6 | Short-term peat accumulation

The net increase in moss height over the study period was greatest at wells 4 and 5 on the plateau. Mosses grew a mean total of approximately 3 cm or 1 cm/year (Figure 10). Much of the increase appeared to occur in the winter and spring, with growth stagnation or height loss in the summer. Asada et al. (2003) found slightly higher rates of annual moss growth in a coastal peatland in British Columba approximately 850 km northwest of Crowberry Bog. Their study area had slightly lower annual precipitation (2500 mm) but almost twice the amount of precipitation during the summer months as Crowberry Bog (Asada et al., 2003).

The five *Pinus contorta var. contorta* excavated near well 5 ranged from 25 to 75 years old and 1.5 to 38.0 cm in diameter at the ground surface (Table 3). The root crown was 25 to 48 cm below the ground surface and short-term peat accumulation ranged from 0.64 to 1.1 cm/year over the period covered by the excavated trees.

4.7 | Tree cover and structure

LiDAR canopy height models indicated distinct patterns of tree cover and height across the wetland. Closed canopy forest surrounded the site and extended along the margin of the rand (Figure 11). Scattered trees are found across the plateau, but density increases near the apex of the plateau. Tree cover and height are lowest on the plateau, but there are locally dense patches of trees. There is an abrupt decrease in tree height along the border of the rand and plateau.

A time series of vertical aerial photographs from 1939, 1950, 1971, 1981, 1990 and 2016 illustrate a distinct increase in tree abundance and cover on the rand and parts of the plateau (Figure 12). *Tsuga heterophylla* and *Thuja plicata* are the dominant tree species on the rand, while *Pinus contorta var. contorta* is most abundant on the plateau. The 1971 photo shows that the west side was logged, and a road built before this photo was taken. The 1981 photo shows logging had recently occurred on the east side of the bog.

5 | DISCUSSION

Crowberry Bog has many characteristics of an ombrotrophic peatland. It has a seasonally inundated lagg, a sloping rand and a relatively level plateau where *Sphagnum*-derived peat extends to a depth of 3.8 m (Heusser, 1974). Our hydrologic investigations clearly show that the peatland is supported solely by precipitation. The water table rapidly responds to precipitation events, with rises immediately following precipitation events and sharp declines if precipitation does not occur for more than a few days. The hydraulic gradient is downward through most of the year, indicating that precipitation is percolating vertically through the plateau supporting the deeper peat layers. In the rand, the hydraulic gradients are horizontal over much of the year, indicating that the plateau is draining through the rand to the lagg. The water chemistry strongly indicates the ombrotrophic nature of the site. Calcium, magnesium and potassium occur in very low concentrations, and the only ions in higher concentration are sodium and chloride, indicating the importance of precipitation recharged by Pacific Ocean

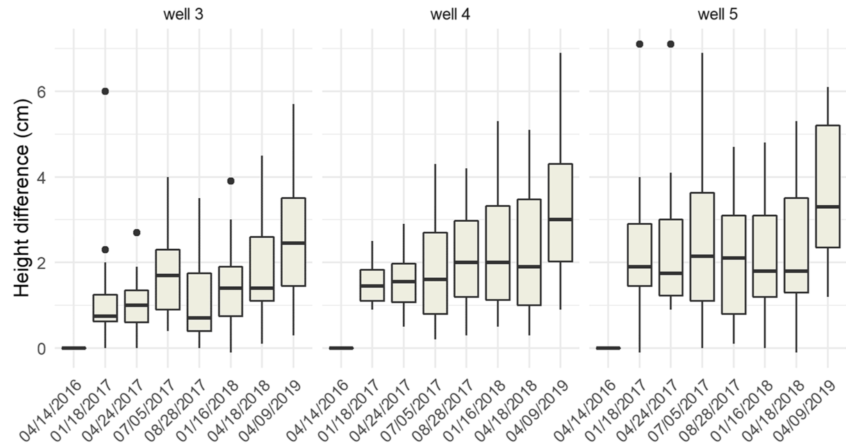

FIGURE 10 Boxplots of moss height growth at monitoring wells 3, 4 and 5 for the eight sample periods. Height is calculated relative to the zero point on the initial installation date

TABLE 3 Trunk diameter at ground, diameter at the root crown, depth of the root crown below the ground, age of the tree and peat accumulation rate for excavated *Pinus contorta* var. *contorta* near well 5

Tree number	Diameter at ground (cm)	Diameter at root crown (cm)	Root Crown depth (cm)	Age at root crown (year)	Peat accumulation cm/year
1	1.5	0.6	26	25	1.04
2	2.5	0.9	30	27	1.11
3	3.0	1.6	36	45	1.09
4	5.2	2.0	42	50	0.75
5	7.6	10.2	48	75	0.64

Note: Depth of the root crown is the distance from the ground surface to the root crown. Age at the root crown is the number of annual rings at the root crown. The rate of peat accumulation is calculated as the root crown depth divided by the age of the plant.

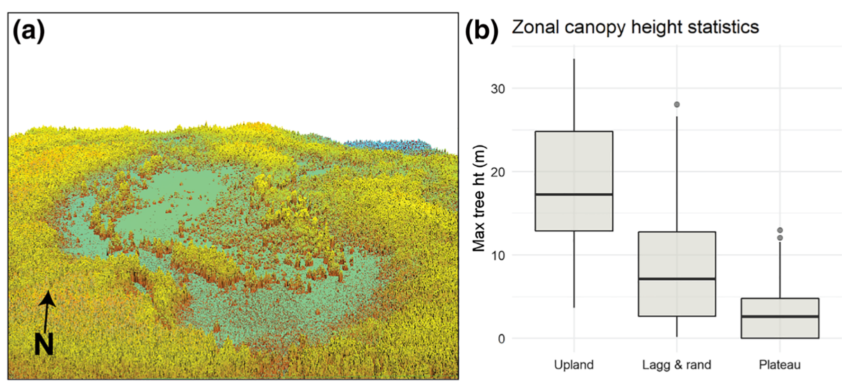

FIGURE 11 (a) Oblique view looking north of LiDAR-derived canopy height model illustrating patterns of tree cover and vertical structure across the site. (b) Boxplots of maximum tree height in the sample of points in the upland, lagg and rand and plateau

sea spray. In addition, the vegetation is dominated by species that are characteristics of ombrotrophic peatlands, especially *Sphagnum fuscum*, *S. rubellum*, *Rhododendron groenlandicum*, *Kalmia microphylla* and *Vaccinium oxycoccos*. These multiple lines of evidence strongly indicate that Crowberry Bog is an ombrotrophic peatland, the first ecosystem of its type identified in the conterminous western USA and the most southerly ecosystem of this type in western North America.

5.1 | Water chemistry

Pore water Ca^{2+} concentrations in Crowberry Bog were very low with 15 of 20 samples having concentration less than or equal to 0.2 mg/L. This is similar to ombrotrophic bogs on the north coast of British Columbia (Vitt et al., 1990) and plateau bogs in Nova Scotia (Damman, 1986). On the southern coast of British Columbia, Ca^{2+} occurred in slightly higher concentrations, ranging from 1.3 to 2.1 mg/L in Burns Bog, 0.5 to 1.2 mg/L in Blaney Bog and 1.7 mg/L at Campbell River bog (Howie & van Meerveld, 2012). The concentration of Ca^{2+} is lower than occurs in the bogs of northern Minnesota (Glaser et al., 1990) and Nova Scotia (Damman & Dowhan, 1981) and less than 1/10th of that found in the most oligotrophic fens on granite bedrock in California's Sierra Nevada (Wolf & Cooper, 2015) and the Wind River Range in the Rocky Mountains of Wyoming (Cooper & Andrus, 1994). A Ca^{2+} concentration of <2.0 mg/L has been used as one criterion to identify ombrotrophic bogs (Glaser et al., 1997, 1981), and Crowberry Bog is well below that level.

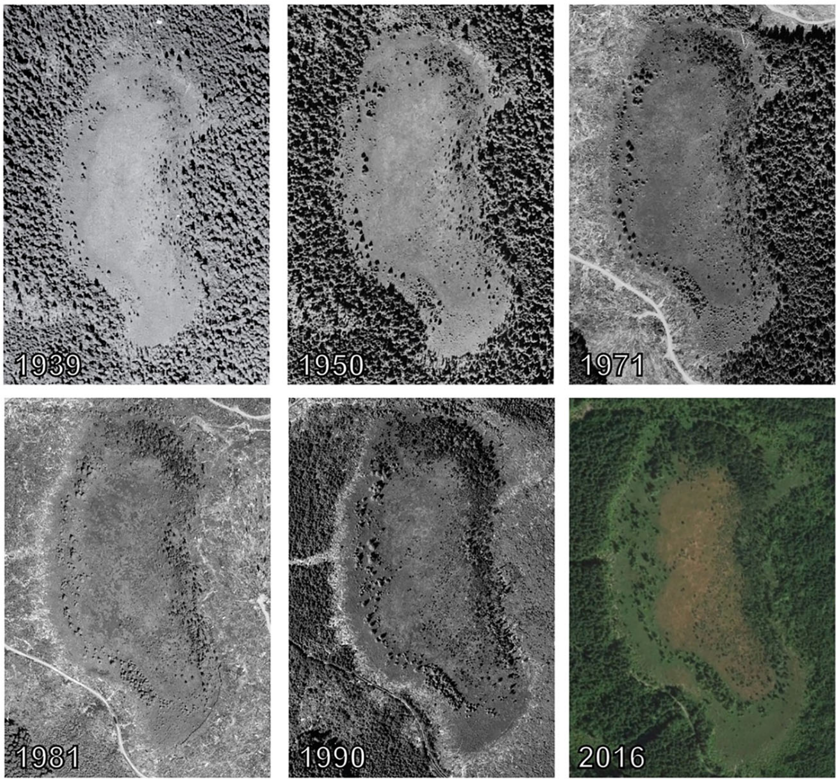

FIGURE 12 Aerial photographs of the Crowberry Bog study area illustrating changes in tree cover within and surrounding the wetland in 1939, 1950, 1971, 1981, 1990 and 2016

Coastal bogs influenced by sea spray transported inland by onshore winds (Gorham, 1955) typically have Na^+ and Cl- as their most abundant ions, as occurs at Crowberry Bog, even though it is 18 km from the Pacific Ocean. The concentration of Mg^{2+} is more than three times that of Ca^{2+} in the Pacific Ocean (Tsunogai et al., 1968), and sea spray influenced precipitation would deposit more Mg^{2+} than Ca^{2+} in Crowberry Bog. In addition, Ca^{2+} is more readily leached from peat than Mg^{2+} (Gorham, 1955). These processes combine to produce pore water with equal or higher concentrations of Mg^{2+} than Ca^{2+}. As a result the Ca^{2+}/Mg^{2+} ratio, calculated using their molar ratio, not ionic mass, was >1.0 in all Crowberry Bog water samples placing Crowberry Bog outside the range that Proctor et al. (2009) suggested was indicative of ombrotrophic conditions. It is unlikely that the Ca^{2+}/Mg^{2+} ratio can be used as an objective indicator of ombrotrophic conditions in coastal bogs influenced by sea spray, but comparing the Ca^{2+}/Mg^{2+} ratio in the peatland pore water with local precipitation might be a more useful comparison. Proctor et al. (2009) did suggest that the Ca^{2+}/Mg^{2+} ratio of 1.0 as the cutoff between ombrotrophic and minerotrophic was somewhat arbitrary, and a broader interpretation of this chemical signature may be warranted.

A pH < 4.2 has been used as a threshold to separate bogs from fens in many parts of the world (Glaser et al., 1981; Glaser et al., 1990; Sjörs, 1950). Water in only two of the Crowberry Bog wells had a pH that averaged less than or equal to 4.2, and many were higher than 4.5, the upper end of what is typically considered characteristic of bogs (Proctor et al., 2009). The same occurred in northern British Columbia (Vitt et al., 1990) although pH was <4.2 for bogs in southern British Columbia (Howie et al., 2012) and southeastern Alaska (Bisbing et al., 2015). The higher pH values we measured may have been a result of the influx of salt in precipitation. In Sweden, the pH of maritime-influenced ombrotrophic sites ranged up to 4.8 and was attributed to higher Mg^{2+} concentrations (Sjörs & Gunnarsson, 2002). Raised oceanic bogs in Newfoundland had pH ranging from 4.1 to 4.5 with relatively high Mg^{2+}concentrations (Glaser, 1992).

5.2 | Hydrologic processes

The western Olympic Peninsula has a strongly seasonal precipitation regime. November through January averaged more than 400 mm of precipitation per month, while July and August receive less than 70 mm per month. The water table on the plateau is several meters higher than the lagg and remains close to the ground surface from October through May, although even in this season it can decline after just a few days without precipitation. This sensitivity is likely due to the relatively small size of the bog, the steep slope of the rand that facilitates drainage and evapotranspiration in warm sunny periods. The water table also responds rapidly to precipitation inputs even when the water table is below the ground surface (Fitzgerald et al., 2003). The water table on the plateau and rand drops to 40–70 cm deep during August and September, and the surface dries out for many weeks. The lagg was dry in summer and even for periods during the winter and spring wet season.

Long periods when the water table is deeper than 40 cm are reported to result in *Sphagnum* death (Lavoie et al., 2003). However, *Sphagnum* on the Crowberry Bog plateau recovered each fall after the long summer with deep water tables and resumed growth once precipitation occurred and the water table rose to the ground surface. Crowberry Bog receives dew associated with morning fog on many days during the summer that is significant enough to wet the ground. This could positively influence the survival of *Sphagnum* when the water table is deep. *Sphagnum* growth was greatest in the wet season and stagnated in the dry season, but we noticed no moss death. *Sphagnum* growth was also greater on the plateau than the rand, which is likely due to the higher water tables in the plateau throughout the growing season.

In many regions where plateau and raised bogs occur, precipitation is more evenly distributed through the year and the water table has little variance. For example, the water table in southern Nova Scotia plateau bogs varied by only approximately 10 cm during the year (Damman & Dowhan, 1981), similar to a bog complex near Prince Rupert, British Columbia (Fitzgerald et al., 2003), and a blanket bog near Juneau, Alaska (Bisbing et al., 2015).

On the west coast of British Columbia, the water table in bogs averaged 15 cm below the ground surface (Howie & van Meerveld, 2013) and was never more than 40 cm deep (Golinski, 2004; Howie & van Meerveld, 2012), but differences occurred between wetter and drier years. At Crowberry Bog, the rand and plateau water table dropped to approximately the same depth each summer, but the duration of the dry period varied and was much shorter in 2016 than 2017 and 2018.

The hydraulic head on the Crowberry Bog plateau was downward during the wet season as occurs in other bogs where the water table mound forces a component of flow vertically downward (Ingram, 1983). The head reversed during the dry season and the plateau and rand were areas of ground water discharge. However, the dry season water table was deep enough that water never reached near the soil surface. This upward head during the summer may stabilize the water table, as it does in Minnesota (Glaser et al., 1997; Siegel & Glaser, 1987) and allows bog formation and persistence in seasonally dry climates such as northern Minnesota and the Olympic Peninsula.

5.3 | Crowberry Bog in relation to other bogs

Climate patterns are the primary determinant of the type of ombrotrophic peatland that forms in any region (Damman, 1995, Damman & French, 1987, Glaser & Janssens, 1986, Vitt et al., 1994, National Wetlands Working Group, 1997). These patterns develop due to climate differences ranging from maritime to continental and result in the development of different peat body forms including domed bogs, plateau bogs, eccentric bogs, and concentric bogs (Moore, 2002; National Wetlands Working Group, 1997; Vasander, 1996). Wet, maritime climates with modest temperature extremes support blanket bogs and raised plateau bogs. Snow-dominated continental climates with wide temperature extremes and greater seasonality support raised domed bogs and slightly raised or flat bogs (Damman, 1995; Gignac et al., 2000; Kottek et al., 2006; Malmer et al., 1994; NWWG, 1997; Vitt et al., 1990).

Crowberry Bog exhibits characteristics described for plateau bogs including (1) relatively steep marginal slopes, (2) flat or plateau-like interior (e.g. bog expanse) with little hummock/hollow patterning, (3) close proximity to the open ocean and (4) species limited to coastal peatlands (Damman, 1977). Globally, plateau bogs are known to occur along the coast of southern Finland, southeast Sweden, and the eastern Baltic region (Damman, 1977; Moore & Bellamy, 1974; Vasander, 1996). These locations, as well as Crowberry Bog, share the climate characteristics of (1) high precipitation, (2) relatively long-growing season, (3) summer fog and (4) salt spray influenced precipitation chemistry. Coastal plateau bogs are very limited within North America and are documented along a narrow coastal strip in Maine, New Brunswick, Nova Scotia and the western coast of Newfoundland (Damman, 1977; Damman & French, 1987).

Burns Bog, a large raised bog approximately 30 km^2 in area and approximately 180 km northeast of Crowberry Bog, near Vancouver, British Columbia, has been described as both a domed bog (Hebda & Biggs, 1981; Vitt et al., 1999) and a plateau bog (Hebda et al., 2000, Howie, Whitfield, Hebda, Dakin et al., 2009). Crowberry Bog and Burns Bog share many characteristics including:(1) being raised above the surrounding landscape, (2) having lagg, rand, and a central bog features, (3) occurring in a region with strongly seasonal precipitation and a pronounced summer dry period and (4) supporting similar dominant and characteristic plant species (Hebda et al., 2000; Hebda & Biggs, 1981; Howie, Whitfield, Hebda, Dakin, & Jeglum, 2009). A distinct difference between the two bogs is that Crowberry Bog receives nearly three times the total annual precipitation as Burns Bog, approximately 300 cm versus 111 cm, respectively (Howie, Whitfield, Hebda, Munson, et al., 2009). While Burns Bog was previously noted as the southernmost raised bog in western North America, Crowberry is located approximately 145 km further south (Hebda et al., 2000; Vitt et al., 1999).

5.4 | Short-term peat accumulation and tree encroachment

Consideration of features such as peat thickness clearly indicates millennial scale stability in wetland processes. Our measures of moss growth as well as 20th century peat accumulation using the pine method suggest that Crowberry Bog has been accumulating peat. However, our analyses of historical air photos show *Pinus contorta* var. *contorta* invading the wetland and tree cover accelerating in recent decades. The *Pinus contorta* var. *contorta* woodlands now abundant on Burns Bog were not mentioned during land surveys in the late 1800s. Hebda and Biggs (1981) found that no individuals of *Pinus contorta* var. *contorta* at Burns Bog were found to be older than 70 years. The senior author has observed tree encroachment in numerous *Sphagnum*-dominated peatlands across the lowlands of western Washington. In some of these peatlands, tree establishment and growth have advanced to the point of canopy closure, which has limited or eliminated *Sphagnum* due to shading. This has significant implications for bog vegetation and continued peat accumulation (Bonnett et al., 2010; Ohlson et al., 2001). The drivers of tree encroachment are unknown but could be related to a changing climate that favours trees. Annual mean temperature in the Pacific Northwest warmed +0.7°C and the average frost-free season increased by 35 days between 1895 and 2011 (Dalton et al., 2013). However, there has been no significant change in precipitation patterns over the same period (Dalton et al., 2013). Fitzgerald (1966) demonstrated that survival of *Tsuga heterophylla* seedlings increased with warmer winter temperatures in a peatland in King County, WA. The lengthening of the summer dry season could provide a competitive advantage to conifer seedlings. It is possible that warmer winter temperatures, rather than lower water tables, are a causal factor of observed tree encroachment. However, *Pinus contorta* var. *contorta* naturally occurs in peatlands on the west coast of North America as far as Juneau, Alaska, nearly 1500 km to the north (Bisbing et al., 2015) and the abundance of trees in coastal peatlands of western North America has been noted as a distinguishing characteristic from coastal peatlands of Atlantic Europe (Sjörs, 1983). More research is needed to understand the mechanisms driving tree establishment and survival to better understand the long-term carbon dynamics at Crowberry Bog.

5.5 | Conservation and Management Implications

As the first documented ombrotrophic peatland in the mainland western USA, Crowberry Bog merits special protection, restoration, management and long-term monitoring. The site has numerous users who harvest plants, creating trails and trampling vegetation. Management of users could reduce damage to the site. Like many peatlands that are dry in the summer, trampling at this time can be most damaging to plants, particularly mosses and lichens. The area near Crowberry Bog has experienced extensive commercial tree harvesting. Slash from previous logging near the bog's lagg has left debris piles that block water flow in the lagg. This material could be removed where it blocks flow pathways in the lagg. Ombrotrophic peatlands are important sites for monitoring climate changes because they are completely dependent on atmospheric inputs of water and nutrients. Crowberry Bog is the southern extent of documented raised bogs in western North America and could be an important location for research addressing climate change effects on peatlands in western North America. Long-term monitoring of water table depth, moss growth and tree encroachment is important for understanding the persistence of this unique ecosystem.

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DATA AVAILABILITY STATEMENT

Supporting data from the Washington Department of Natural Resources (DNR) are not currently available online. DNR data sharing resources are currently under development with the goal to make all data publically available in the future. Data are available on request from the corresponding author or from DNR, Natural Heritage Program.

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APPENDIX A

Statistical Analysis of Water Level Data

TABLE A1 Analysis of variance for water level ~ well number

Month	Term	Df	Sumsq	Meansq	Statistic	*p* value
1	wellNo	2	1404.872	702.436	25.892	<0.001
1	Residuals	258	6999.436	27.13		
2	wellNo	2	1342.311	671.155	35.327	<0.001
2	Residuals	249	4730.633	18.999		
3	wellNo	2	1373.095	686.548	18.622	<0.001
3	Residuals	276	10175.51	36.868		
4	wellNo	2	1729.226	864.613	24.41	<0.001
4	Residuals	219	7757.142	35.421		
5	wellNo	2	9407.465	4703.733	109.331	<0.001
5	Residuals	276	11874.31	43.023		
6	wellNo	2	9694.506	4847.253	102.405	<0.001
6	Residuals	267	12638.26	47.334		
7	wellNo	2	5228.599	2614.299	21.947	<0.001
7	Residuals	255	30375.25	119.119		
8	wellNo	2	7909.883	3954.941	98.541	<0.001
8	Residuals	267	10716.08	40.135		
9	wellNo	2	16259.46	8129.732	24.004	<0.001
9	Residuals	258	87381.04	338.686		
10	wellNo	2	6141.8	3070.9	23.932	<0.001
10	Residuals	276	35415.94	128.319		
11	wellNo	2	1573.763	786.882	21.217	<0.001
11	Residuals	267	9902.517	37.088		
12	wellNo	2	1564.029	782.015	22.52	<0.001
12	Residuals	276	9584.311	34.726		

Note: ANOVA models for all months were statistically significant at α = 0.05.

TABLE A2 Tukey adjusted pairwise comparisons for different wells (AOV: water level [cm] ~ location)

Month	Contrast	Estimate	Confidence Interval (low)	Confidence Interval (high)	Adj. *p* value
1	well2-well1	−5.077	−6.938	−3.215	0
1	well4-well2	4.75	2.888	6.612	0
1	well4-well1	−0.327	−2.188	1.535	0.91
2	well2-well1	−5.13	−6.715	−3.544	0
2	well4-well2	4.623	3.037	6.208	0
2	well4-well1	−0.507	−2.093	1.079	0.732
3	well2-well1	−5.174	−7.272	−3.075	0
3	well4-well2	4.026	1.928	6.124	0
3	well4-well1	−1.148	−3.246	0.951	0.403
4	well2-well1	−6.535	−8.844	−4.226	0
4	well4-well1	−5.006	−7.315	−2.697	0
4	well4-well2	1.529	−0.78	3.838	0.264
5	well2-well1	−13.405	−15.672	−11.139	0
5	well4-well1	−10.821	−13.087	−8.554	0
5	well4-well2	2.585	0.318	4.851	0.021
6	well2-well1	−13.721	−16.138	−11.304	0
6	well4-well1	−11.374	−13.791	−8.957	0
6	well4-well2	2.347	−0.07	4.764	0.059
7	well2-well1	−10.98	−14.904	−7.057	0
7	well4-well1	−6.367	−10.291	−2.443	0
7	well4-well2	4.613	0.69	8.537	0.016
8	well2-well1	−12.591	−14.817	−10.365	0
8	well4-well2	9.892	7.666	12.118	0
8	well4-well1	−2.699	−4.925	−0.473	0.013
9	well2-well1	−19.29	−25.868	−12.712	0
9	well4-well2	10.767	4.19	17.345	0
9	well4-well1	−8.523	−15.1	−1.945	0.007
10	well2-well1	−11.317	−15.231	−7.403	0
10	well4-well1	−7.392	−11.307	−3.478	0
10	well4-well2	3.925	0.01	7.839	0.049
11	well2-well1	−5.612	−7.751	−3.472	0
11	well4-well1	−4.422	−6.562	−2.282	0
11	well4-well2	1.19	−0.95	3.329	0.391
12	well2-well1	−5.63	−7.666	−3.594	0
12	well4-well2	4.02	1.984	6.057	0
12	well4-well1	−1.61	−3.646	0.427	0.152

Note: Separate models were fit to each month.

APPENDIX B

Statistical Analysis of Ion Concentrations in Wells by Date

TABLE B1 Analysis of variance for water chemistry value ~ location (e.g. lagg, plateau and rand)

Species	Term	Df	Sumsq	Meansq	Statistic	*p* value
Ca^{2+}	location	2	0.041	0.021	0.552	0.586
	Residuals	17	0.637	0.037		
Cl-	location	2	25.253	12.627	0.896	0.427
	Residuals	17	239.537	14.09		
HCO_3^-	location	2	0.003	0.001	1.133	0.345
	Residuals	17	0.023	0.001		
K^+	location	2	0.002	0.001	2.267	0.134
	Residuals	17	0.008	0		
Mg^{2+}	location	2	0.053	0.027	0.913	0.42
	Residuals	17	0.497	0.029		
Na^+	location	2	50.503	25.252	4.097	**0.035**
	Residuals	17	104.787	6.164		
NO^{3-}	location	2	131.048	65.524	1.7	0.212
	Residuals	17	655.23	38.543		
SO_4^{2-}	location	2	2.425	1.213	1.207	0.324
	Residuals	17	17.087	1.005		

Note: Chemical species in bold are significant at α = 0.05. Each pair of rows represent a separate ANOVA model.

TABLE B2 Analysis of variance for water chemistry value ~ well number

Species	Term	Df	Sumsq	Meansq	Statistic	*p* value
Ca^{2+}	wellNo	4	0.113	0.028	0.75	0.573
	Residuals	15	0.565	0.038		
Cl-	wellNo	4	26.08	6.52	0.41	0.799
	Residuals	15	238.71	15.914		
HCO_3^-	wellNo	4	0.008	0.002	1.714	0.199
	Residuals	15	0.018	0.001		
K^+	wellNo	4	0.002	0	1	0.438
	Residuals	15	0.007	0		
Mg^{2+}	wellNo	4	0.06	0.015	0.459	0.765
	Residuals	15	0.49	0.033		
Na^+	wellNo	4	50.725	12.681	1.819	0.178
	Residuals	15	104.565	6.971		
NO^{3-}	wellNo	4	131.048	32.762	0.75	0.573
	Residuals	15	655.23	43.682		
SO_4^{2-}	wellNo	4	2.637	0.659	0.586	0.678
	Residuals	15	16.875	1.125		

Note: ANOVA models for none of the chemical species were statistically significant at α = 0.05.

TABLE B3 Analysis of variance for pH by landform

Term	Contrast	Location 1	Location 2	Null value	Estimate	Confidence Interval (low)	Confidence Interval (high)	Adj. *p* value
location	plateau-lagg	plateau	lagg	0	−0.3790	−0.5358	−0.2222	0.0000
location	plateau-rand	plateau	rand	0	0.0722	−0.0381	0.1824	0.3250
location	rand-lagg	rand	lagg	0	−0.4511	−0.5876	−0.3147	0.0000
location	upland-lagg	upland	lagg	0	0.4686	0.2528	0.6844	0.0000
location	upland-plateau	upland	plateau	0	0.8476	0.6473	1.0478	0.0000
location	upland-rand	upland	rand	0	0.9197	0.7349	1.1045	0.0000

Note: Each comparison was significant at α = 0.05 except for the plateau-rand comparison.