WASHINGTON NATURAL HERITAGE PROGRAM

Sphagnum-dominated Peatlands in the Puget Lowlands: Ecology and Response to Adjacent Land Use.

Implications for Conservation, Management, and Restoration

Prepared for

U.S. Environmental Protection Agency
Region 10

Prepared by

F. Joseph Rocchio, Tynan Ramm-Granberg,
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January 03, 2023

Natural Heritage
Report 2023-01

WASHINGTON STATE DEPARTMENT OF
NATURAL RESOURCES

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ON THE COVER: Top left (Kings Lake Bog NAP); Top right: Covington Creek 12; Bottom left: Trossachs Bog; Bottom right: Cranberry Marsh 2 (All photographs by Joe Rocchio).

TABLES

FIGURES

ACKNOWLEDGEMENTS

This project was conducted with financial support from a U.S. Environmental Protection Agency, Region 10 Wetland Program Development Grant (CD-01J37601). We appreciate EPA's support and flexibility through the logistical challenges posed by staffing changes and the COVID-19 pandemic. We are very grateful for the ongoing collaboration with colleagues at the Washington Department of Ecology—especially Lauren Driscoll, Amy Yahnke, Patricia Johnson, Teri Granger, and Dana Hock—to improve the delivery of critical wetland data, guidance, and recommendations to those regulating, conserving, and managing Washington's wetland resources. Rebecca Niggemann, former Washington Department of Natural Resources, Natural Heritage Program (WNHP) database manager/GIS analyst, conducted the early remote sensing and GIS analysis to assist with study site selection and calculation of study site characteristics. Bec Braisted, former WNHP ecologist, provided critical data collection support during the shortened and crazy 2020 field season. Joshua Cohen, Senior Conservation Scientist/Lead Ecologist with the Michigan Natural Features Inventory, spent a week in the field with our project team, assisting with data collection and participating in excellent discussions comparing "bogiferous" ecosystems of Michigan with those in the Puget Lowlands. Most importantly, Joshua was our project liaison with 'Piezo', the resident bear at the Echo Falls study site. Piezo did not appreciate the placement of well nests in their play area and expressed this displeasure by repeatedly breaking open the 2.5" PVC pipes and gnawing on our data loggers. Two Colorado State University students, Jingwen Yang, Lin Pan and Ran Zang, dedicated time mining data from George Rigg's peat monograph to help our team understand historical impacts. Dan Gavin (University of Oregon), Kate Heckman (U.S. Forest Service, Northern Research Station), and John Hribljan (currently University of Nebraska, Omaha) provided much guidance, analysis, and discussion about the peat cores collected from eight of the study sites. Dan provided critical context on the historical vegetation and climate history of the region. Kate provided guidance on collecting samples for carbon analysis and offered her time and lab services for analyzing carbon from the peat cores. John was instrumental as the team expert in the laborious, cold, and brutal process of collecting the cores in the field. Although the peat core data were not used in this report, our project team benefited greatly from this effort and we hope to conduct future analyses of these peat cores. We appreciate the cooperation of Capitol Land Trust, City of Sammamish, Echo Fall Home Owners Association, Evans Creek Home Owners Association (particularly Bill Thurman), Green Diamond, Inc., King County Department of Natural Resources, SHADOW Lake Nature Preserve, Trossachs Home Owners Association, and the Washington Department of Natural Resources for allowing our project team to access our study sites. We hope this research will assist their efforts in managing these peatlands. Finally, we appreciate the work of our boggy forebears, who built the foundation of knowledge upon which our research stands. In particular, we want to recognize the work of George Rigg, whose research and writings in the early 20th Century not only opened the eyes of his international contemporaries to the unusual ecology of the *Sphagnum*-dominated peatlands found in the Pacific Northwest, but also provided a historical reference for this project. Linda Kunze's seminal work on the vegetation of *Sphagnum*-dominated peatlands in western Washington was critical for understanding vegetation patterns in our study. Finally, the excellent work by Louise Kulzer, Scott Luchessa, Sarah Cooke, Ruth Errington, and Fred Weinmann in their community profile of local *Sphagnum*-dominated peatlands of western Washington was immensely helpful for identifying critical research questions, sample site selection, and building a set of recommendations that we hope land managers find useful.

1.0 INTRODUCTION

1.1 PROJECT GOALS

The primary objective of the Clean Water Act is to "maintain and restore the chemical, physical, and biological integrity of the Nation's waters," including wetlands. Land use near wetlands affects their ecological integrity, especially through changes to water inputs and water chemistry, but regionally specific, quantitative data on these impacts is limited (Azous & Horner 1997; Bell 2002; Cooke Scientific Services 2005; Adamus 2014). Peatland types such as bogs and fens are typically distinguished based on their primary water sources. Understanding a peatland's primary water source is also critical to successful conservation, management, and restoration of these sensitive ecosystems. Although the term 'bog' is used to describe many peatlands in Washington State, only one published study has confirmed the presence of an ombrotrophic bog (i.e., rain-fed) in the state (Rocchio et al. 2021). Doubt remains as to how many of Washington's "bogs" are solely rain-fed. A better understanding of water source(s) and potential effects of adjacent land use on "bogs"—or *Sphagnum*-dominated peatlands—is needed to ensure that regulatory permitting, compensatory mitigation requirements and guidance, and voluntary restoration and conservation actions are effective in meeting the Clean Water Act's primary objective. Most current guidance is derived from quantitative studies about land use impacts to aquatic ecosystems, or logic-based models that presume likely impacts to wetlands. This project addresses a significant data gap by measuring differences in hydrological regime, water chemistry, and vegetation response in peatlands across a land use intensity gradient.

1.2 PEATLAND ECOSYSTEMS

Peatlands are wetlands with a surface substrate composed of organic matter accumulated *in situ* called peat. In the United States, a peat thickness of 40 cm is often used to distinguish peatlands from other wetland types (Rydin and Jeglum 2013). Peat forms when plant production exceeds decomposition. This occurs due to excessive primary plant production but largely due to slow decomposition from water logged soils and/or cool temperatures (Vitt et al. 1994, Rydin and Jeglum 2013). Peatlands occupy approximately 3% of the world's land surface and are globally significant for their role in regulating climate, supporting biodiversity, and providing other ecosystem services (Moore 2002, Parish et al. 2008). Peatland formation is closely tied to climatic conditions and local hydrogeomorphology (Gorham 1957, Moore and Bellamy 1974, Damman 1977, 1979, Parviainen and Luoto 2007). In areas where annual precipitation normally exceeds evapotranspiration, peatlands can form in a variety of landforms such as in depressions, on slopes, and flat terrain (Gorham 1957, Rydin and Jeglum 2013). In persistently wet regions, peatlands can blanket entire landscapes, such as blanket bogs in wet, cool northern climates and extensive, tropical peatlands in wet, warm climates (Moore 2002, Rydin and Jeglum 2013). As evapotranspiration approaches or exceeds precipitation, peatland development is limited to areas with a continuous supply of groundwater including seeps, springs, and also along the shorelines of some very stable and quiet water bodies (Gorham 1957).

1.2.1 Peatland Types

Peatlands vary significantly due to climate, water source, hydrological regime, topography, geology, soil and water chemistry, and biogeographic patterns (Gorham 1957, Gore 1983, Moore and Bellamy 1974, Glaser and Janssens 1986, Glaser 1992, Vitt et al. 1994, Bridgham et al. 1996; Wheeler and Proctor 2000, Parviainen and Luoto 2007). Peatland classification efforts have focused on one or a combination of these gradients (Tansley 1939, Sjörs 1950, Moore and Bellamy 1974; Malmer 1986, Vitt et al. 1994, Bridgham et al. 1996, National Wetlands Working Group 1997, Wheeler and Proctor 2000, Parviainen and Luoto 2007, Joosten et al. 2017a, Table 1). Importantly, peatland classification is also influenced by cultural perspective, regional ecological context, and purpose of the classification (Joosten et al. 2017a).

Bogs and fens are the most commonly recognized terms for describing variability of northern peatlands, and are applicable to peatlands around the world (Table 1; Gorham 1957, Moore 2002). However, these terms have been defined using a variety of ecological variables (Table 1). Many researchers restrict the definition of a bog to those areas where peat has accumulated deep enough that the plant rooting zone is not influenced by groundwater, thus limiting the water sources for plants to precipitation (i.e., ombrotrophic peatlands). In contrast, these same researchers consider fens to be limited to those areas where surface and groundwater occurs within the rooting zone of plants (i.e., minerotrophic peatlands). Additional types based on morphology, water chemistry, and vegetation have also been described (Sjörs 1950, Moore and Bellamy 1974, Gore 1983, Damman 1995, Moore 2002, Joosten et al. 2017b).

Vegetation composition has been another common means of differentiating bogs and fens, as vascular plants and bryophytes reflect underlying ecological variables (Bridgham et al. 1996, Wheeler and Proctor 2000). Because floristic similarity between ombrotrophic bogs and minerotrophic poor and acidic fens has been shown to be more similar than between poor and rich (alkaline) fens, floristic distinctions, without regard to water source, has been suggested as practical way to distinguish bog and fen (Gorham and Janssens 1992, Damman 1995, Bridgham et al. 1996, Wheeler and Proctor 2000, Moore 2002). In such a framework, bogs include acidic peatlands (i.e. bogs and poor fens *sensu* Sjörs 1950) dominated by peat mosses (*Sphagnum* spp.), low ericaceous shrubs, and/or conifers while fens include slightly acidic to alkaline peatlands dominated by graminoids, brown mosses, tall shrubs and/or various tree species (Rigg 1925, Damman 1995, Bridgham et al. 1996, Wheeler and Proctor 2000).

1.2.2 Ombrotrophic versus Minerotrophic Peatlands

The ombrotrophic – minerotrophic gradient is commonly used to distinguish bogs from fens in many regions (Gorham 1957, Damman 1995, Glaser 1987, 1992, Glaser et al. 1981, Rybníček and Yurkovskaya 1995, Økland et al. 2001). Ombrotrophic peatlands have hydrological and water chemistry characteristics that are distinct from other peatlands, as they are entirely dependent on precipitation for water and ion inputs (Gore 1983, Damman 1995, Proctor et al. 2009). Because precipitation is a relatively poor source of many ions, ombrotrophic peatlands are generally highly acidic and have low ion concentrations (Sjörs 1950, Ingram 1967). However, in near oceanic environments concentrations of Na+ and Cl may be moderately high. Minerotrophic peatlands are supported by groundwater or surface water flow that has had contact with mineral soils or bedrock (Ingram 1967, Moore and Bellamy 1974, Damman 1995). The chemical composition of minerotrophic peatlands varies along the pH gradient from acid to alkaline, with low to high ion content, depending on local geology and soils (Sjörs 1950, Ingram 1967). The ecological differences between ombrotrophic and minerotrophic peatlands have important implications for land managers, since successful conservation, management, and restoration actions need to be tuned to the predominant water source. Changes to the type or proportion of water sources flowing into a peatland can lead to significant changes to hydrological patterns, porewater chemistry, peat accumulation and decomposition rates, and biological composition.

Table 1. Peatland Classifications (table adapted from Kulzer et al. 2001)

<table>
<tr><td rowspan="3">Source</td><td colspan="11">Sphagnum moss ⟷ Brown moss</td></tr>
<tr><td colspan="11">Rain fed ⟷ Groundwater fed</td></tr>
<tr><td colspan="11">Very acidic ⟷ Alkaline</td></tr>
<tr><td>Weber (1908); Weber (1902) as cited in Couwenberg and Joosten (2002)
Central Europe</td><td colspan="2">Hochmoore (= raised bog)</td><td colspan="6">Ubergangsmoore (=transitional)</td><td colspan="3">Niedermoore (=fen)</td></tr>
<tr><td>Rigg (1925)
North American Pacific Coast</td><td colspan="7">Sphagnum bog
(Sphagnum-dominated peatland)</td><td colspan="4">Marsh, Swamp</td></tr>
<tr><td>DuRietz (1949, 1954)
Scandinavia</td><td colspan="2">Bog
(Sphagnum dominates; lack of ‘fen indicator’ species)</td><td colspan="6">Poor fen
(Sphagnum dominates; a few ‘fen indicator’ species present)
Mineral soil limit</td><td colspan="3">Rich fen
(Brown mosses dominate; ‘fen indicator’ species are abundant)</td></tr>
<tr><td>Kulczynski (1949)
Poland</td><td colspan="2">Ombrophilous
(rain-fed)</td><td colspan="6">Transition mires
(groundwater inputs from within immediate watershed)</td><td colspan="3">Rehophilous mires
(groundwater inputs external to immediate watershed)</td></tr>
<tr><td>Sjörs 1950
Scandinavia</td><td colspan="2">Moss
(pH 3.7 - 4.6)</td><td colspan="2">Extreme poor fen
(pH 3.7 – 5.2)</td><td>Transitional poor fen
(pH 4.5 – 6.5)</td><td colspan="3">Intermediate fen
(pH 4.5 – 6.5)</td><td colspan="2">Transitional rich fen
(pH 5.7 – 7.8)</td><td>Extreme rich fen
(pH 7.1 – 8.5)</td></tr>
<tr><td>Malmer et al (1992)</td><td colspan="2">Bog
(pH < 4.5)</td><td colspan="6">Poor Fen</td><td colspan="3">Rich Fen
(pH > 5.5)</td></tr>
<tr><td>Heinselman (1970)
Minnesota</td><td>Ombro-trophic Bog</td><td colspan="2">Semi-ombrotophic Bog</td><td colspan="3">Transitional Forested Bog / Weakly Minerotrophic Swamp</td><td colspan="5">Various fen types</td></tr>
<tr><td>National Wetland Working Group (1988)
Canada</td><td colspan="2">Bog
(ombrotrophic; pH<4.6; Ca + Mg < 5 mg/L</td><td colspan="9">Fens
(pH = 4.6 – 7.9; Ca +Mg 0.5 - 140 mg/L)</td></tr>
<tr><td>Gignac & Vitt (1990)</td><td colspan="7">Sphagnum-dominated peatlands
(bogs and poor fens)</td><td colspan="4">Rich fens</td></tr>
<tr><td rowspan="2">Vitt et al. (1994)
Western Canada</td><td colspan="2" rowspan="2">Bog
(Sphagnum dominated; pH < 4.0)</td><td colspan="5" rowspan="2">Poor fen
(Sphagnum dominated; pH = 4.0 – 5.5)</td><td colspan="4">Rich fens (pH > 5.5)</td></tr>
<tr><td colspan="2">Moderate rich fen
(pH = 5.5 – 7.0)</td><td colspan="2">Extreme rich fen
(pH = 7.0 – 8.5)</td></tr>
<tr><td>Proctor et al. (2009)
Scotland</td><td colspan="2">Ombrotrophic
(molar Ca:Mg < 1)</td><td colspan="9">Minerotrophic
(molar Ca:Mg > 1)</td></tr>
<tr><td>Rydin and Jeglum (2013)</td><td colspan="2">Bog
(ombrotrophic)</td><td colspan="9">Fen
(additional gradients defined)</td></tr>
</table>

The ombrotrophic – minerotrophic gradient is based largely on the work of Du Rietz (as cited in Sjörs 1948, 1950; Wheeler and Proctor 2000 and Kulcynski 1949). Attempting to identify the 'mineral soil water limit', or division between ombrotrophic and minerotrophic peatlands, Du Rietz recommended use of 'fen indicator species' as a practical measure of the mineral soil water limit in the field. This method assumes that the richness of 'fen indicator species' increases from being absent in ombrotrophic peatlands, to low in poor fens, and highest in rich fens (Sjörs 1948, Glaser 1992). This approach has been used to characterize the ombrotrophic to minerotrophic gradient in Scandinavia for many decades (Sjörs 1948, Jeglum 1991, Økland et al. 2001). Indicator species that have been verified against water source and water chemistry measures can be effective for indicating the mineral soil water limit (Sjörs 1950). However, shortcomings of this approach include: (1) the tolerance of individual species to the acidic and nutrient poor conditions found in ombrotrophic peatlands varies geographically, making the determination of 'fen indicator species' a regionally specific endeavor (Sjörs 1948, Sjörs 1950, Glaser 1992, Damman 1995); (2) some peatlands can be acidic and have low ion content for reasons not related to ombrotrophic conditions (Sjörs 1950; Gore 1983, Gorham and Janssens 1992, Cooper and Andrus 1994, Bridgham et al. 1996, Wheeler and Proctor 2000, Tahvanainen 2004, Proctor et al. 2009); (3) vegetation-based determinations of bog and fen don't always coincide with water chemistry measures (Sjörs 1950, Tahvanainen 2004, Proctor et al. 2009); and (4) the use of unverified indicator species to detect the mineral soil water limit can make the argument circular (Gorham and Janssens 1992, Wheeler and Proctor 2000).

Other approaches for detecting the mineral soil limit include the use of peatland morphology, pH, electric conductivity, and Ca^{2+} concentration. Peatlands that are raised above the surrounding terrain are inferred to be ombrotrophic based on the assumption that the biologically active portion of the peat is above the influence of minerotrophic waters entering at depth (Glaser and Janssens 1986, Vitt et al. 1994). However, ombrotrophic conditions are known to occur in peatlands without substantially raised topography (i.e. "flat bogs"), where ombrotrophic peat in the central part of the bog can extend below the mineral soil water limit in the lagg (Heinselman 1970, Damman 1986, Rydin et al. 1999, Proctor et al. 2009). Another scenario observed in flat bogs is when ombrotrophic peat may be thick enough to affect the *Sphagnum* ground layer, yet thin enough that some vascular plants penetrate far enough to access minerotrophic peat deeper in the profile (Proctor et al. 2009). Heinselman (1970) describes "semi-ombrotrophic bogs" which have semi-convex peat surfaces that receive little minerotrophic inputs. He noted that precipitation tended to flush these inputs, thus depleting ion content. Underlying protrusions of bedrock or large sediment deposits could elevate a peat body, as could strong upwelling groundwater (Wolf and Cooper 2015). A regional example of the latter is the Ebey Island Fen, a large peatland (over 300 hectares) which is elevated approximately 2.5 meters due to strong, upwelling groundwater associated with regional aquifers (Shaw et al. 2022).

Hydrologic patterns and water chemistry measures are helpful for determining the relative influence of precipitation and groundwater inputs into a peatland. Porewater chemistry and downward movement of water (recharge) are both strong indicators of ombrotrophic conditions (Ingram 1983, Damman 1986, Siegel and Glaser 1987, Glaser et al. 1997, Proctor et al. 2009). Because Ca^{2+} concentration is extremely low in precipitation, measured Ca^{2+} concentrations < 2.5 mg/L, or a Ca:Mg of 1.0, have been used to indicate ombrotrophic conditions (Malmer et al. 1992, Sjörs and Gunnarsson 2002, McHaffie et al. 2009, Proctor et al. 2009, Joosten et al. 2017b). A pH < 4.2 has been used as a threshold to separate bogs from fens in many parts of the world (Sjörs

1950, Glaser et al. 1981, Glaser et al. 1990). However, as noted above, very acidic conditions and low ion concentrations can occur for reasons not related to ombrotrophic conditions, for example fens supported by very dilute water from crystalline rocks (Sjörs 1950; Gore 1983, Gorham and Janssens 1992, Cooper and Andrus 1994, Bridgham et al. 1996, Wheeler and Proctor 2000, Tahvanainen 2004, Proctor et al. 2009). Atmospheric inputs of Ca^{2+}, N, P, and heavy metals into rain-fed bogs often result in pore water concentrations that overlap with ranges found in minerotrophic poor fens, making use of these variables as ombrotrophic indicators problematic, at least in some regions (Wheeler and Proctor 2000). Comparing the chemical composition of contributing hydrological sources relative to peatland pore water composition can be helpful for discerning primary water sources (Proctor et al. 2009). However, the 'mineral soil water limit' is rarely sharp, as hydrological and ion inputs can vary seasonally and across years (Glaser et al. 1997; Proctor et al. 2009, Siegel and Glaser 1997). Tahvanainen (2004) did not find a strong relationship between Ca^{2+} concentration and a poor-rich fen indicator metric. Malmer et al. (1992) argued that there are no universal chemical signatures of bog waters, with pH in bogs ranging from 3.5 to 4.5 and Ca^{2+} concentrations from < 1 mg/L to 2.5 mg/L. In Fennoscandian and British peatlands, bogs typically have a pH < 4.2, although it can be as high as 4.5 in oceanic areas where high rainfall washes organic acids from the peat (Gorham 1957, Sjörs and Gunnarsson 2002, Tahvanainen 2004, Proctor et al. 2009, Joosten et al. 2017b). Proctor et al. (2009) argue that the Ca:Mg of ombrotrophic peatland waters is similar to that found in local precipitation. Although Procter et al. (2009) recommend a Ca:Mg of 1 (with Ca^{2+} concentrations < 2 mg/L) to delimit the ombrotrophic boundary, Sjörs and Gunnarsson (2002) note that concentrations of Mg^{2+} in precipitation are higher closer to maritime coasts, leading to lower Ca:Mg in coastal ombrotrophic bogs. This may also be the reason many oceanic bogs, like those along the northern Pacific Coast of North America, have a higher pH and higher species diversity compared to ombrotrophic peatlands inland (Sjörs and Gunnarsson 2002). Thus, an approach using Ca:Mg needs to be calibrated against solute concentrations in local precipitation.

Regardless of the measure, another complicating factor is that the mineral soil water limit can be spatially and temporally variable within a given site (Proctor et al. 2009). Although precisely delimiting the mineral soil limit boundary can be difficult (Sjörs and Gunnarsson 2002, Moore 2002; Proctor et al .2009), determining whether ombrotrophic conditions exist—or whether precipitation is the predominant water source—is critical for identifying appropriate and effective management, restoration, and conservation goals. A multi-measure approach, based on a preponderance of evidence associated with peatland morphology, vegetation composition, water chemistry, and hydrological patterns, may be the most effective approach for determining the relative proportions of water sources into a peatland (Gore and Janssens 1992; Bridgham et al. 1996, Wheeler and Proctor 2000).

1.2.3 Global, Continental, and Regional Distribution of Ombrotrophic Peatlands

1.2.3.1 Global Distribution

Peatlands are found across the globe, but most are concentrated in cold, high latitudes, tropical forests, and in mountainous regions (Damman 1995, Rydin and Jeglum 2013, Charman 2002). Most peatland area is located within temperate zones, with the majority occurring in the northern hemisphere (Moore 2002). North America is estimated to support over 170 million ha, or about 41% of the world's peat area (Moore 2002). Canada alone contains 25% of the world's peatland area (Moore 2002). The distribution of peatland types is strongly associated with regional climate patterns (Moore and Bellamy 1974, Glaser and Janssens 1986, Vitt et al. 1994, Parviainen and Luoto 2007).

Ombrotrophic peatlands have a narrow distribution tightly associated with specific climatic conditions. These peatlands are generally found in cool climates where precipitation exceeds evapotranspiration (Charman 2002, Glaser and Janssens 1986, Damman 1995, Vitt et al. 1994, Parviainen and Luoto 2007, Moen et al. 2017). In the northern hemisphere, ombrotrophic peatlands are most common in temperate maritime or humid, snowy, continental climates with cool-to-warm summer temperatures and little seasonality in precipitation (Gignac et al. 2000, Kottek et al. 2006, Parviainen and Luoto 2007). This includes northwest Europe, the Baltic coast, northeast Europe (to central Siberia), and northern portions of North America (Heinselman 1970, Damman 1979, Eurola et al. 1984, Damman 1986, Glaser and Janssens 1986, Malmer et al. 1992, Vitt et al. 1994, Damman 1995, Charman 2002, Masing et al. 2010, Moen et al. 2017).

Wet, maritime climates with modest temperature extremes support blanket bogs and raised plateau bogs, like those found on the southern coast of Finland (Vasander 1996). Snow-dominated continental climates, with wide temperature extremes and greater seasonality, support raised domed bogs and slightly raised or flat bogs (Damman 1995, NWWG 1997, Kottek et al. 2006). Climate envelopes developed for Fennoscandia peatlands showed that ombrotrophic peatlands in that region develop in areas where mean annual temperatures range from 1.6º to 7.0º C and mean annual precipitation is > 49 cm/yr.; however, growing degree days (a measure of average heat accumulation) was the most significant variable predicting the presence of ombrotrophic peatlands in Fennoscandia (Parviainen and Luoto 2007). On the other hand, ombrotrophic peatlands have been documented in areas exposed to extreme droughts and with minimal moisture surplus. Groundwater recharge is thought to be a mitigating factor for bog persistence in areas that experience periodic summer droughts (Glaser et al. 1997), as well as regions with a distinct wet and dry season (Hebda and Biggs 1981, Howie et al. 2016). Ombrotrophic peatlands are also found in the southern hemisphere and in the tropics (Rydin and Jeglum 2013).

1.2.3.2 Continental Distribution

In North America, ombrotrophic peatlands have been documented across much of Canada (National Wetlands Working Group 1997) and in northern sections of the United States (Gajewski et la. 2001). In northeastern Canada and Maine, a variety of ombrotrophic peatlands have been described (Damman 1977, 1979, 1986, Damman and French 1987, Foster and Glaser 1986, Jeglum 1991, Glaser 1992, Glaser and Janssens 1986, National Wetlands Working Group 1997). In this region, the southern boundary of ombrotrophic bogs runs from northeastern Vermont to northern New Hampshire and southwestern Maine (Damman and French 1987). Flat, ombrotrophic bogs have been noted in upstate New York (Andrus 1980), Vermont (Sorenson et al. 2016), and as far south as the Allegheny Mountains of West Virginia (Darlington 1943, Rigg and Strausbaugh 1949). Further south, ombrotrophic peatlands (regionally known as pocosins) occur on the coastal plain of North Carolina (Richardson 2003). In the Midwest, ombrotrophic peatlands are widespread in Minnesota (Heinselman 1970, Glaser et al. 1990, 1997) and southwest Ontario (National Wetlands Working Group 1997). Small ombrotrophic bogs have been reported in Wisconsin and lidar data indicate that at least one site appears to be slightly raised (Epstein 2017, Ryan O'Connor, Wisconsin Dept. of Natural Resources, personal communication). Michigan has an abundance of semi-ombrotrophic to weakly minerotrophic peatlands (Gates 1942), but ombrotrophic peatlands are also reported (Kost et al. 2007). The modeled distribution of

Sphagnum-dominated peatlands within the United States (includes both ombrotrophic bogs and acidic fens) across North America includes the north Pacific Coast, the Central Rocky Mountains, and the upper Midwestern and Northeastern regions (Gignac et al. 2000).

1.2.3.3 Regional Distribution

Ombrotrophic peatlands in western North America are reported for Alaska (Osvald 1933; Rigg 1937, Neiland 1971, Viereck et al. 1992), continental western Canada (Vitt et al. 1990), coastal British Columbia (Vitt et al. 1994, Hebda and Biggs 1981, National Wetlands Working Group 1997, Golinski 2004, Howie and van Meerveld 2013, Howie et al. 2016), and the Olympic peninsula of Washington State (Rocchio et al. 2021). Low elevation, *Sphagnum*-dominated peatlands are also found along the Oregon coast, though hydrologic and water chemistry data are needed in order to make a determination of ombrotrophic conditions at these sites (Christy 2001). The vegetation composition of these acidic peatlands does not suggest that they are ombrotrophic, but they are floristically unique from other regional *Sphagnum*-dominated peatlands, so further investigation may be warranted. *Sphagnum*-dominated, minerotrophic peatlands are found in many of the mountain ranges of the Pacific Northwest (Chadde et al. 1998; Rocchio and Crawford 2015b).

Ombrotrophic bogs form in the extremely wet and mild climate patterns associated with coastal British Columbia (Vitt et al. 1994, Golinski 2004, Kottek et al. 2006; Howie and van Meerveld 2013, Howie et al. 2016). The climate of this region is somewhat different from other maritime regions where ombrotrophic bogs develop; annual precipitation is higher than maritime regions in Europe and winters are milder than in eastern North America (Malmer et al. 1992). For example, ombrotrophic peatlands in extreme southwest British Columbia, occur within a warm, summer dry climate region (Hebda and Biggs 1981, Howie and van Meerveld 2013, Kottek et al. 2006). Only one published study has demonstrated ombrotrophic conditions in a Washington peatland (Rocchio et al. 2021).

In Washington State, "bogs" and "*Sphagnum*-dominated peatlands" have been widely reported (Osvald 1933; Dachnowski-Stokes 1936, Rigg 1925, 1940, 1951, 1958, Osvald 1933, Hofstetter 1983). Rigg (1925) defined bogs as areas with nearly continuous cover of living *Sphagnum* spp., with *Sphagnum* peat soil, and a flora dominated by ericaceous shrubs, trees, and distinctive herbaceous species. Early literature about Washington's peatlands (Rigg 1940; 1951; 1958) noted that two types of bogs were found in the state: (1) flat bogs and (2) raised bogs. Raised bogs are noticeably elevated above the level of the surrounding area (Rydin and Jeglum 2013). The process of peat accumulation creates a conspicuous raised surface that develops above the surrounding topography and isolates the bog surface from surface and/or groundwater influence. This creates ombrotrophic conditions (meaning the bog only receives water and nutrients from precipitation). Flat bogs are also known as "raised, level bogs" (Gawler and Cutko 2010), "gently convex bogs" (Davis and Anderson 2001), and "flat and basin bogs" (NWWG 1997). In Washington, flat bogs are not perceptibly raised relative to their outer margins. In the Puget Lowlands, these ecosystems have a distinct hummock/hollow pattern in their centers, except those that border ponds, which generally consist of *Sphagnum* lawns or carpets (*sensu* Sjörs 1948). Except for a single known site, all *Sphagnum*-dominated peatlands in Washington are either flat bogs or acidic fens (Rigg 1940; Rigg 1958; Kulzer et al. 2001; Rocchio et al. 2021). Rigg (1919) described regional bogs not as "typical raised bogs", rather they are "slightly higher in the center than at the margin, but the differences in level is at most 1 meter or less". Rigg (1940, 1951, 1958) did note that a "few

Sphagnum bogs in western Washington are, however, sufficiently raised so that their convexity can be recognized by merely looking at them. Some are 5 or 6 feet higher in the center than at the margins, but the slopes are gentle." Dachnowski-Stokes (1936) noted that several peatlands, which "may be characterized as raised bogs", were found in the lower Snoqualmie River valley, but these may represent the large groundwater mound fens reported by Shaw et al. (2022). In all of these cases, no hydrological or water chemistry data were collected to confirm ombrotrophic conditions. Given Rigg's definition of a *Sphagnum* bog, it is important to keep in mind that his "flat bog" concept includes ombrotrophic bogs and acidic, minerotrophic fens. To avoid confusion, local researchers have suggested using the term "*Sphagnum*-dominated peatlands", rather than bogs, to avoid the complicated determination of whether a site meets a strict, ombrotrophic definition (Kulzer et al. 2001). This concept matches the bog definition used by Rigg in his research (Rigg 1925, 1940, 1951, 1958).

1.3 Peatland Conservation Values

Peatlands occupy about 3% of the world's land surface (over 400 million ha) and are globally significant for their role regulating climate, supporting biodiversity, and providing other ecosystem services (Joosten and Clarke 2002, Moore 2002, Parish et al. 2008). Peatland biodiversity is distinct from other wetland types and in many regions they support numerous rare and unusual species (Gorham 1990, Warner and Asada 2006, and Rydin and Jeglum 2013).

Peatlands support endemic beetles (Lane 1938, Johnson 1979, LaBonte et al. 2001, Bergdahl 2020), dragonflies (Warner and Asada 2006), fungi (Filippova and Thormann 2014), butterflies (Pyle and Hammond 2018), spiders (Kupryjanowicz et al. 1997, Crawford, 2022), and a distinct flora (Gignac et al. 1991, Wheeler 1993, Gignac et al. 2004). Each peatland type has unique chemical composition, hydrological patterns, landscape settings, and vegetation structure, all of which provide different filters for biodiversity (Noss, 1990, Wheeler 1993, Vitt et al. 1995, Sjörs and Gunnarsson 2002, Rochefort et al. 2012). Floristic diversity, composition, and life forms also vary across continental and regional gradients (Glaser et al. 1990, Gignac et al. 1991, Gignac et al. 2004, Warner and Asada 2006, Rydin and Jeglum 2013, Howie et al. 2016). Bogs have more diverse lichens, liverworts, dwarf shrubs, and trees while fens have higher diversity of herbs, ferns, and true mosses (Warner and Asada 2006). Vascular plant species richness in North American raised bogs is highest near the coast and decreases inland (Glaser 1992, Howie et al. 2016). Peatlands contain many obligate vascular plant and bryophyte species found in no other habitats, plus numerous relict species occurring at the southern extent of their range (Minayeva et al. 2017).

The Washington Natural Heritage Program (WNHP) considers lowland *Sphagnum*-dominated peatlands to be a State Threatened ecosystem type due to natural rarity, significant direct loss to urbanization, historical peat mining, conversion to agriculture, and ongoing degradation of ecological integrity in extant occurrences (Table 2; Rocchio & Crawford, 2015a, 2015b; DNR 2022). At least 17 state sensitive, threatened, or endangered plant communities are associated with Puget Lowland *Sphagnum*-dominated peatlands (Table 2). These plant communities provide habitat for 29% of the state's rare wetland plants (13% of all rare plants; Rocchio et al. 2015). In a survey of carabid beetles in Puget Lowland wetlands, Bergdahl (2020) found 18 species to be restricted to *Sphagnum*-dominated peatlands. These included the State Candidate Beller's ground beetle (*Agonum belleri*), a regional endemic, and the State Candidate Hatch's click beetle (*Eanus hatchi*), which is only found in Puget Lowland *Sphagnum*-dominated peatlands (Bergdahl 1997;

WDFW 2015). Two butterflies, the Makah copper (*Lycaena mariposa makah*) and June's copper (*Lycaena mariposa junia*), have extremely narrow ranges and are only found in coastal *Sphagnum*-dominated peatlands of the Olympic peninsula (WDFW 2015; Pyle and Hammond 2018). During the course of this project, the first North American record of a bog potworm (*Cognettia sphagnetorum*) was found at one of the project study sites (Reeves et al. 2021). There are at least 34 spiders that are restricted to, or primarily found in, *Sphagnum*-dominated peatlands in Washington State, including the globally imperiled Georgia Basin bog spider (Bennet et al. 2006, Crawford 2022, NatureServe 2022). The Subarctic Bluet (*Coenagrion interrogatum*) is found in *Sphagnum*-dominated fens in northeastern Washington. Washington's 12 populations of northern bog lemming (*Synaptomys borealis*), a species known to inhabit *Sphagnum*-dominated peatlands, are mostly in the northeastern portion of the state, but one was recently located in the Puget Lowlands (WDFW 2015). The State Sensitive Olympic mudminnow (*Novumbra hubbsi*) is found in pools and slow moving streams associated with *Sphagnum*-dominated peatlands in the lowlands of western Washington.

Peatlands play a vital role in the global carbon cycle. Although they cover only 3% of the Earth's terrestrial surface, they hold 550 gigatons of carbon in their peat (Joosten 2008). This translates to 30% of the world's soil carbon stock, the equivalent of 75% of all atmospheric carbon, or as much as all the carbon stored in terrestrial biomass and twice the carbon stored in global forests (Joosten 2008). Living *Sphagnum* species and *Sphagnum*-derived peat have been estimated to cover over 1.5 million km^2 in boreal regions across the world (Clymo and Hayward 1982). This translates to approximately 150 Gt of carbon, suggesting *Sphagnum* has a greater ability to store carbon than any other genus in the world (Clymo and Hayward 1982, Rydin and Jeglum 2013). However, peatlands may also *release* copious amounts of methane and carbon dioxide when stressors trigger negative carbon balances (Moore, 2002; Rydin & Jeglum, 2013). Protecting intact peatlands and restoring degraded ones are important actions that can help mitigate ongoing climate change.

1.4 Threats to Peatlands

1.4.1 Land Use

Agriculture, urbanization, timber harvest, water use, transportation, recreation, mineral extraction, grazing, and other human land uses can negatively impact wetland integrity (Laine et al. 1995; Gunnarsson et al. 2000; Minayeva et al. 2017; Lachance and Lavoie 2004; Ireland and Booth 2012; Pasquet et al. 2015; Sheldon et al. 2015), but sensitivity to human-induced stressors can vary between wetland types (Hruby 2014). Historical and contemporary land use practices have impacted hydrologic, geomorphic, and biotic structure and function of peatlands in western Washington. Urban development has been demonstrated to have negative impacts on chemical, physical, and biological integrity of wetlands in the Puget Sound region (Azous and Horner 1997). Conversion of peatlands for agriculture has resulted in significant loss of peatland extent. Many coastal peatlands, especially along the southwest coast of Washington, have been converted to cranberry production. Puget Lowland peatlands have been lost to development and conversion to agriculture. An estimated 31% of all wetland area has been lost statewide (Dahl, 1990). A recent estimate of *Sphagnum*-dominated peatlands identified by Rigg (1958) indicated that 13.5% have been lost across the lowlands of western Washington, and 17% within the Puget Lowland ecoregion have been extirpated (Rocchio, *unpublished data*). On an area-basis, Bell (2002) concluded that 69% of *Sphagnum*-dominated peatlands in King County were lost or degraded due to agricultural conversion, peat mining, and/or urban development over a 50-year period. Peatlands in other portions of the Puget Lowlands have been drained, cleared, and/or mechanically disturbed via these same stressors (Rigg, 1958; Bell, 2002). Stressors affecting extant peatlands have changed over time. In the past 50-75 years, development has increased dramatically around Puget Lowland peatlands while stressors associated with peat mining, pastures, and agriculture have declined (Figure 1; Pan and Shaw 2019). However, during the same timeframe, the proportion of sites with surrounding natural land cover has not changed significantly over the past 60-100 years and remains nearly 80%.

Direct alteration of hydrologic regimes (i.e., channeling, draining, damming) or indirect alteration (i.e., roads or vegetation removal on adjacent slopes) can change species composition and wetland extent. Water diversions and ditches can have a substantial impact on the hydrology as well as biotic integrity of peatlands. If stressors reduce water table depth, peat oxidization and subsequent decomposition occur. Decomposition can lead to reduced peat body depth, altered hydrological patterns, and increased nutrient flux, all of which can result in a change in species composition. Conversely, *increased* surface flow into a bog can result in conversion to a new wetland type, like a marsh, that reflects the new hydrology (Ireland and Booth 2012). As such, it is important to understand whether a site functions as an ombrotrophic peatland (i.e., bog) or is primarily maintained by groundwater and surface water inputs (i.e., fen). Vegetation type, productivity, and overall peatland structure are influenced by pH, mineral ion concentrations, available nutrients, and cation exchange capacity. Changes in water table level, increased water fluctuations, increased nutrient/cation-loading, and changes to composition and abundance of plant species have all been identified as useful measures for documenting stressor-induced change in peatlands (Lachance & Lavoie, 2004; Ireland & Booth, 2012; Rydin & Jeglum, 2013). Additionally, peat core data (e.g., pollen and macrofossil data) provide a temporal perspective of these changes, helping discern natural variation from human-induced changes (Ireland & Booth, 2012).

Landscape stressors can cause significant ecosystem changes, such as potentially converting acidic peatlands to intermediate fens, forested or shrub swamps, or marshes (Ireland and Booth 2012; Kulzer et al. 2001). Such wetland type conversions may be driven by increased water flow into or decreased water drainage away from peatlands. Indeed, studies outside of Washington have demonstrated the sensitivity of peatland floristic composition to adjacent drainage or altered upland hydrology (Pasquet et al. 2015), as well as nutrient loading from non-point sources such as agricultural-derived, dust deposition (Ireland and Booth 2012). Numerous stressors may increase flow into peatlands, including roads, channelized flow, and logging-related drops in precipitation interception and transpiration rates (Adamus 2014). Such impacts can have negative consequences for hydrological regimes of peatlands, resulting in changes in decomposition and species composition. Besides impacting the hydrological regime, roads in a peatland's watershed also increase sediment, contaminant, and nutrient inputs. Increased nutrients (whatever the source) can alter species composition and, in *Sphagnum*-dominated peatlands, result in the loss of *Sphagnum* or a shift in *Sphagnum* composition. Surrounding land use can directly or indirectly

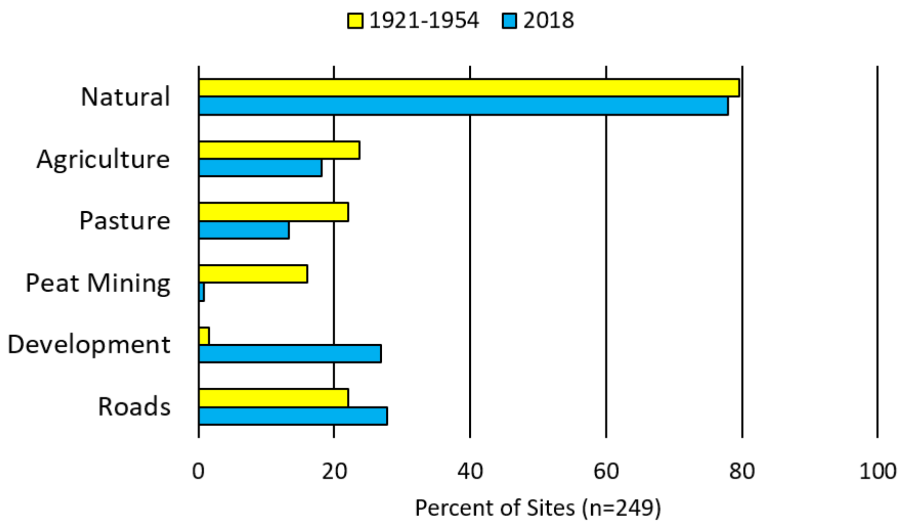


Figure 1. Land Use Change in Puget Lowland Peatlands. Proportions are number of sites with stressor detected relative to total sites (n=249); site could be counted toward multiple stressors. (Pan and Shaw 2019)

affect water quality of peatlands and down-gradient surface waters. Runoff in urbanized watersheds may increase pH in peatlands, particularly where cement surfaces are abundant (Kulzer et al. 2001). Increased ions (especially Ca^{2+}, Mg^{2+}, or CO_3^{2-}) can raise source water pH, alter nutrient dynamics, and increase decomposition rates (Ireland and Booth 2012; Pasquet et al. 2015, Moore 2002). When a peatland's carbon balance shifts from net gain to net loss of organic matter, there may be an associated nutrient release to downstream ecosystems (Kulzer et al. 2001). If downstream ecosystems include more peatlands, excess nutrients may cascade throughout the watershed.

When ditching or upstream restrictions lower a peatland's water table, increased oxidation, decomposition, and land subsidence can lead to reduced peat depth, altered hydrological patterns, and increased nutrient flux, in turn causing species composition changes. A mere 15 cm water table drop may result in carbon loss of 4-157 g cm^{-2} yr^{-1} (Alm et al. 1999). When summer water tables remain below a depth of 40 cm for long intervals, woody species may increase, initiating a positive feedback on drawdown by increasing evapotranspiration (Damman and French 1987; Verry 1997). Shading by dense woody species may in turn decrease *Sphagnum* cover (Rigg 1958). That said, many *Sphagnum* species—especially hummock species—are well-adapted to survive periods of drought due to their high moisture-retention qualities (Clymo 1997). The elastic hydrological properties of such species may contract the acrotelm (the portion of the peat body near the surface) during droughts, allowing the bog to persist until wetter conditions return (Moore 2002, Waddington et al. 2015). However, long-term reductions in water table may exceed the temporal threshold of these buffering processes.

Localized peat mining has clear impacts on the physical integrity of peatlands (Moore 2002). Additionally, localized peat removal may alter subsurface water storage capacity and channelize surface flow, further degrading the 'intact' portion of the peatland. Peat mining can also alter nutrient cycles and species composition in these 'intact' remnant areas. Given the slow accumulation rates of peat, once it is mined (i.e. removed) the peatland cannot be restored to historical conditions in a time frame relevant to management activities. In western Washington, Rigg (1958) estimates a peat accumulation rate of ~1 inch per 40 years (2.5 cm per 40 years, or 0.60 mm/yr). Peat cores collected as part of this project suggested similar estimates of 2.3 inches per 100 years (5.8 cm per 100 years, 0.58 mm/yr). This estimate is also similar to rates of 2.6 in. per 100 years (6.67 cm per 100 years, 0.67 mm/yr) determined for *Sphagnum* peat layers at Burns Bog (Hebda 1977).

A special type of peat mining occurred in the early 20th century where live *Sphagnum* (specifically *S. papillosum*) was harvested for surgical dressing during World War I (Nichols 1920). The mining occurred as community activities called "moss drives" and often resulted in 2,000 sacks of moss being gathered per day (Nichols 1920). Although this activity did not disrupt underlying peat deposits, the impact this *Sphagnum* harvesting has had on peat accumulation or vegetation composition is not known.

1.4.2 Fire

Fire can be an important natural disturbance in some peatland types. The frequency and severity of fire is dictated by regional climatic conditions, human activities, and hydrological and vegetation patterns of the peatland. Fire is likely to be a recurring and influential disturbance process in peatlands exposed to seasonal and/or inter-annual variation in temperature, precipitation, and humidity due to those peatlands typically having a higher density of shrub and/or tree cover which can carry fire more effectively than herbaceous sites (Rydin and Jeglum 2013, Waddington et al. 2015).

Fire can have a significant effect on the short- and long-term successional trajectory of *Sphagnum*-dominated peatlands (Osvald 1933, Rigg 1958, Hebda and Biggs 1981, Benscoter and Vitt 2008). Osvald (1933) recognized the significant role fire plays in the development and succession of *Sphagnum*-dominated peatlands in the Georgia Basin and Puget Lowlands, also noting the summer dry season as a key reason for fire's prevalence. Forested swamps may convert to *Sphagnum*-dominated peatlands when fires kill trees and decrease evapotranspiration (Asada et al. 2004). This is apparent in some of the peat profiles investigated by Rigg (1958), where woody-peat is succeeded by *Sphagnum* peat. At some sites, these patterns repeat over time, indicating dynamic, non-linear successional trajectories. Very large, fire-scarred, western redcedar (*Thuja plicata*) snags are occasionally observed in *Sphagnum*-dominated peatlands in western Washington. Such large trees are not found in *Sphagnum*-dominated peatlands, indicating that these sites were previously forested swamps before fire-induced conversion to *Sphagnum*-dominated peatlands. Some of these fires may have been the result of intentional burning of adjacent, upland areas subsequent to logging.

Native Americans and early European settlers intentionally set fire to bogs in the Upper Midwestern United States to encourage growth of blueberries (Crum 1992). Native peoples on the western portion of the Olympic peninsula intentionally burn peatlands to maintain and encourage growth of usable plants (Anderson 2009). The extent to which tribes used fire in Puget Lowland *Sphagnum*-dominated peatlands is not known. Presumably fire would have provided similar utility as documented on the Olympic peninsula. Early European settlers routinely used fire to clear

Sphagnum-dominated peatlands prior to attempting to drain and then convert them for cultivation (Rigg 1958).

Fire frequency in *Sphagnum*-dominated peatlands of the Pacific Northwest presumably varies by size and location of the peatland, though we are not aware of any published research documenting fire frequency intervals. With non-human ignitions, small peatlands likely burn when fires move into the site from adjacent forests. Thus, such sites likely have fire frequency similar to adjacent forests. Human ignitions could have resulted in more frequent fires (Anderson 2009). Large peatlands may have fire frequencies that are different from the surrounding landscape. For example, Burns Bog near Vancouver, British Columbia is an extremely large bog (3,000 hectares or 11.5 sq. miles) that is thought to have historically burned every couple of hundred years. Today, it burns more frequently due to increased accidental human ignitions. Signs of past fire are common in many *Sphagnum*-dominated peatlands of western Washington, including fire-scarred snags and downed wood. These fires may have resulted from post-logging burning of slash piles, as most of these sites occur in landscapes managed for timber resources.

1.4.3 Invasive Species

Invasive species are generally not a significant threat to *Sphagnum*-dominated peatlands of western Washington at this time. However, European birch (*Betula pendula*), highbush blueberry (*Vaccinium corymbosum*), and inflated bladderwort (*Utricularia inflata*) are currently the most concerning, as they occur in numerous sites and appear to be expanding in occupied peatlands. There are numerous nonnative species at Summer Lake in Skagit County that appear to have been intentionally planted, including Venus flytrap (*Dionaea muscipula*), purple pitcher plant (*Sarracenia purpurea*), yellow pitcher plant (*Sarracenia flava*), and white pitcher plant (*Sarracenia leucophylla*). The purple pitcher plant and yellow pitcher plant, which have also been found at other Washington locations, have expanded their footprint at the site, while the other species have either declined or remained very restricted over the years (Weinmann 2021). In particular, the yellow pitcher plant has expanded dramatically and is also abundant at another *Sphagnum*-peatland in Skagit County. The nonnative tawny cottongrass (*Eriophorum virginicum*) and Canadian rush (*Juncus canadensis*) are also found at Summer Lake and are thought to have inadvertently been introduced when the carnivorous species were planted (Weinmann 2021). Tawny cottongrass is an abundant nonnative species at Burns Bog where it was thought to have been introduced by contaminated peat extraction equipment (Sarah Howie, personal communication).

1.4.4 Climate Change

Peatlands are the largest terrestrial source of carbon in the world and thus play a significant role in the Earth's carbon cycle. Development and persistence of peatlands is controlled by the balance of water inputs and storage in relation to evapotranspiration. Increased temperatures may increase decomposition at the same time as productivity (Moore 2002, Valiranta et al. 2016, Oke and Hagar 2017, Rydin and Jeglum 2013). The balance between these two dictates whether a given peatland continues to accumulate peat or begins to lose its peat mass to decomposition. That said, a drop in the water table can override these changes, resulting in increased peat decomposition, a negative carbon budget, and, with enough time, conversion to a non-peat accumulating wetland type (Rydin and Jeglum 2013). The quantity and quality of water contributed to a peatland either via precipitation, groundwater discharge, or surface flow are the most important variables associated with peatland development and ecology. As such, distinguishing between ombrotrophic and minerotrophic peatlands is critical for understanding vulnerabilities to climate change.

Northern peatlands have spatially and temporally complex, positive and negative feedbacks associated with climate, making predictions about the direction and magnitude of climate-induced change difficult (Waddington et al. 2015). Numerous studies suggest that autogenic processes in ombrotrophic peatlands (e.g., hydrological self-regulation) provide some buffer against shifts in precipitation regime (Valiranta et al. 2016, Oke and Hagar 2017). "Mire breathing" is an example of this autogenic process in which the peat surface rises and falls with fluctuating water tables, thereby keeping the surface vegetation near the water table (Rydin and Jeglum 2013). Mire breathing may provide ombrotrophic peatlands with resilience against the initial effects of decreased precipitation and increased evaporation, but long-term drops in the water table would eventually override this autogenic response (Rydin and Jeglum 2013). In raised bogs, increased winter precipitation is unlikely to buffer against increased evapotranspiration during summer months. Once raised bogs are saturated, additional water inputs run off the bog and exit the wetland basin.

Development of Washington *Sphagnum*-dominated peatlands was initiated immediately following the recession of continental and alpine glaciation, about 12,000 to 16,000 years ago. In that time, *Sphagnum*-dominated peatlands have been exposed to climatic shifts. Peat profiles from many Washington *Sphagnum*-dominated peatlands demonstrate abrupt shifts to forested swamps or sedge-dominated fens, while other sites were able to persist despite periods of long-term drought and increased temperatures (Rigg 1958). While some of these changes seem to be consistent with expected climatic-induced change, modifications to the surrounding landscape (e.g., beaver dams, forest fires, landslides, etc.) could also have caused similar ecosystem shifts. Some studies suggest that increased temperatures may increase peat accumulation in bogs due to an increase in *Sphagnum* primary production, while other research indicates that increased warming would increase microbial activity and result in a net loss of peat (Oke and Hagar 2017). It is not clear what the balance might be in low-elevation *Sphagnum*-dominated peatlands in western Washington, but they may be susceptible to a switch towards negative carbon balance and subsequent cessation of peat accumulation. Peat loss would eventually shift the *Sphagnum*-dominated peatlands toward another wetland type, such as a marsh, shrub swamp, or forested swamp. However, pollen from peat cores taken from a raised, ombrotrophic bog near the Hoh River indicate that bog vegetation has persisted at those sites, without interruption, for the past 8,000 years (Heusser 1974, Rocchio et al. 2021). Additionally, peatland development in these sites began and persisted in a climate that was warmer and drier than the one currently experienced on the western Olympic peninsula (Heusser 1974, Gavin et al. 2013). Across the globe, tree cover is thought to be increasing in bogs (Moore 2002, Valiranta et al. 2016, Rydin and Jeglum 2013). Comparing notes from Rigg (1958) with recent aerial photography, Zong and Shaw (2019) showed that the presence of trees in *Sphagnum*-dominated peatlands has dramatically increased since 1921 (Figure 2). Some research suggests historical land use may be the culprit, while other research points to increasing temperatures and decreased precipitation (Valiranta et al. 2016, Edvardsson et al. 2015, Rydin and Jeglum 2013). Increased tree cover is presumed to increase evapotranspiration and lower the water table, ultimately leading to accelerated peat decomposition (Moore 2002, Valiranta et al. 2016, Edvardsson et al. 2015, Rydin and Jeglum 2013). Yet other studies have disputed these outcomes, instead suggesting that increased evapotranspiration from greater tree cover is offset by decreased evapotranspiration from shaded understory vegetation (Moore 2002, Limpens et al. 2014). If tree invasion occurs to the extent that canopies become closed, understory bog vegetation will likely be eliminated and peat accumulation will stall.

As noted previously, Native Americans frequently used fire to manage vegetation in *Sphagnum*-dominated peatlands on the Olympic peninsula. If increased fire were coupled with increased water table depth, significant changes in vegetation composition and structure, peat depth, water chemistry, and hydrology would likely occur, possibly shifting the peatland to another wetland type. However, the autogenic processes of the peat body are thought to maintain conditions that allow *Sphagnum* to eventually reestablish (Waddington et al. 2015). As noted above, the time frame for such recovery is unknown and may be beyond any practical management timeframe. The temporal dynamics of *Sphagnum*-dominated peatlands occur over a much longer time frame than changes in many other wetland types.

Based on climate change predictions for Washington State (Siemann and Warheit 2011), the following changes and potential outcomes may affect *Sphagnum*-dominated peatlands across the lowlands of western Washington:

- Predicted warmer winters may increase germination and survival of tree seedlings in *Sphagnum*-dominated peatlands, leading to an increased abundance of seedlings (Fitzgerald 1966)

- Prolonged summer drought could lead to extended low water tables providing a more competitive environment for the abundance of new tree seedlings, with an eventual outcome of excessive tree encroachment (Siemen and Warheit 2011; Barthelmes et al. 2015)

- Extreme heat events could kill tree seedlings and shrubs, as was observed in numerous Puget Lowland *Sphagnum*-dominated peatlands during the heat dome of 2021.

- Extreme heat events / increased solarization could scorch south-facing sides of hummocks, thereby reducing *Sphagnum* cover (Bragazza 2008).

- Shifts from snow- to rain-dominated precipitation regimes could expand potential locations for bog development at higher elevations (Barthelmes et al. 2015)

Abundant tree cover is a hallmark characteristic of coastal peatlands in western North America (Sjörs 1983). Coupled with the fact that Washington State is at the southern edge of the range of ombrotrophic peatlands in western North America (Rocchio et al. 2021; Gignac et al. 2000; Gajewski et la. 2001), it is possible that the tension between closed forests and open peatlands has been in play for centuries or longer. Climate change could swing this pendulum more permanently toward increased tree encroachment, which appears to be occurring in many peatlands in western Washington (Figure 2; Pan et al. 2019). This tension may also explain why Native Americans are known to have used fire in local peatlands to manage woody vegetation (Anderson 2009). Lack of fire and/or increasing effects of climate change are both possible causal factors for the increased tree cover in western Washington peatlands (Figure 2; Zong and Shaw 2019).

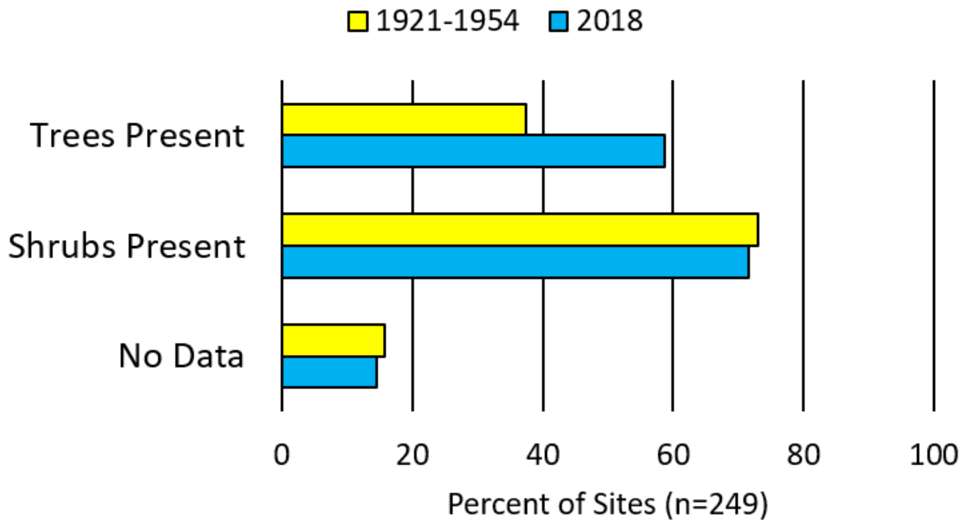


Figure 2. Change in Tree Presence in Lowland *Sphagnum*-dominated Peatlands of Western Washington since 1921. (Zong and Shaw 2019)

1.5 Existing Regulatory, Management, and Conservation Guidance

The unique biodiversity, ecosystem services, and sensitivity to human stressors associated with *Sphagnum*-dominated peatlands have long been recognized in Washington's academic, conservation, management, and regulatory communities (Rigg 1925, 1958; Osvald 1933, Dyrness et al. 1975, Kunze 1994, Chadde et al. 1998, Hruby 2004, Granger et al. 2005, Sheldon et al. 2005, Rocchio et al. 2021). Over the years, conservation plans, regulations, policies, and management guidance have been developed to explicitly or indirectly protect the critical ecological values provided by Washington's peatlands. Conservation organizations and state agency conservation programs have targeted protection of rare and high-quality *Sphagnum*-dominated peatlands for over 50 years (Dyrness et al. 1975, WDFW 2015, DNR 2022). The Washington Department of Ecology developed special wetland permitting and management guidance for peatlands (Hruby 2004, 2013, and 2014; Granger et al. 2005). Below is a brief description of known guidance related to the preservation, management, restoration, and regulation of *Sphagnum*-dominated peatlands in western Washington. In order to be effectively implemented, these efforts need the best available science regarding the ecological variability and sensitivity to human stressors of *Sphagnum*-dominated peatlands, along with assessment protocols and tools to help determine these characteristics.

1.5.1 Washington Department of Natural Resources, Natural Heritage Program

The Washington Natural Heritage Program (WNHP) uses methods shared by NatureServe and the network of natural heritage programs to catalogue Washington's rare plants and ecosystems, prioritize their conservation needs, and conduct surveys for their locations. This information helps guide funding toward critical areas for biodiversity conservation and provides the framework for the statewide system of natural areas. Information on priority species and ecosystems comes from a wide variety of sources, including government agencies, conservation organizations, consultants, and extensive fieldwork and research by WNHP staff. Site-specific and species/ecosystem information is maintained in Biotics, an integrated database used by WNHP that currently contains more than 7,000 records of rare species and rare/high-quality ecological communities. These data are essential to planners and landowners, helping them make land use decisions that balance economic growth and development with conservation of our state's natural heritage.

The WNHP uses the U.S. National Vegetation Classification (USNVC) to catalog and set conservation priorities for Washington's ecosystems. The USNVC, which classifies vegetation within an ecological context, is a comprehensive classification system for all vegetation types in the United States. The USNVC is an eight-level hierarchy with classification levels ranging from coarse to fine, reflecting the functional ecology of plant communities. *Sphagnum*-dominated peatlands of Washington State are included in three USNVC groups (USNVC 2022): (1) North Pacific Open Bog and Acidic Fen Group; (2) North Pacific Maritime Wooded Bog and Poor Fen Group; and (3) Rocky Mountain Acidic Fen Group. *Sphagnum*-dominated peatlands of lowlands of western Washington are part of the North Pacific groups. The WNHP has 225 records of USNVC *Sphagnum*-dominated peatland associations in its database, 138 of which are found within the Puget Lowlands. These records, also known as 'element occurrences' reflect the locations of rare and/or high-quality stands of USNVC associations that WNHP feels warrant some level of conservation action due to their rarity and/or excellent ecological integrity. These data inform many of the policies and guidance that are described below.

1.5.2 Statewide System of Natural Areas

In 1972, the State Legislature passed the Natural Area Preserves Act (Revised Code of Washington 79.70), recognizing the need for, and benefits of, permanently designating areas explicitly for conservation of biodiversity and geological features, research, and education. The Natural Area Preserves Act authorized the Washington State Department of Natural Resources (DNR) to establish and manage a statewide system of natural areas through cooperation with federal, state and local agencies, private organizations and individuals. In 1991, the Legislature passed the Natural Resources Conservation Areas Act, which established another critical conservation land use designation, to protect critical biodiversity resources, geological features, archaeological features, and scenic areas are also compatible with low-impact recreation uses. Collectively, these designated natural areas are intended to provide critical habitat for rare and vanishing species, conserve representative examples of the state's ecosystems, and ensure the availability of places for scientific research and education. Today, this system consists of lands managed by numerous federal and state agencies as well as private conservation organizations.

A primary goal of the statewide system of natural areas is to protect representative examples of the state's rare species and ecosystem types (Dyrness et al. 1975; DNR 2022). Selection of natural areas not only considers the presence of these targeted elements but also the ability of the site to sustain populations of those rare species or maintain ecological integrity of the targeted ecosystem type. Because of the degree of human-induced habitat loss, degradation of habitat quality and fragmentation of natural landscapes, the statewide system of natural areas contains some of the last places where rare species can survive, and some of the best remaining examples of the state's ecosystems, especially in landscapes where other conservation designations such as National Parks or Wilderness Areas are lacking.

Currently, 27 natural areas protect some type of *Sphagnum*-dominated peatland across the state, with 13 natural areas protecting examples of the North Pacific Open Bog and Acidic Fen Group, 11 natural areas protecting examples of the North Pacific Maritime Wooded Bog and Poor Fen Group, and 3 natural areas protecting examples of the Rocky Mountain Acidic Fen Group. Although the North Pacific Open Bog and Acidic Fen Group and the North Pacific Maritime Wooded Bog and Poor Fen Group are both considered ‘adequately represented’ in the Statewide System of Natural Area, many of the USNVC associations that are part of those groups remain high priorities for protection within the natural area system (DNR 2022).

1.5.3 Local Government and Land Trust Natural Areas

Many local governments and non-governmental organizations manage natural areas that, while potentially not meeting the criteria to be included in the statewide system of natural areas, still protect significant ecological resources, including *Sphagnum*-dominated peatlands.

The King County Department of Natural Resources protects *Sphagnum*-dominated peatlands as part of their natural areas system (King County 2022). In fact, two of this project’s study sites are King County Natural Areas. King County’s natural areas contain a “diversity of native vegetation that provides fish and wildlife habitat and embodies the beauty and character of our region's landscape” and are managed for these ecological values in balance with low-impact recreation activities.

There are 32 land trusts active in conserving Washington’s lands that sustain various economic and ecological values. Some land trusts protect native ecosystem types, including *Sphagnum*-dominated peatlands. Some of these sites are included in the statewide system of natural areas, while others are not, but still provide critical peatland conservation. Two of this project’s study sites are owned and managed by land trusts or similar organizations.

1.5.4 Washington Department of Natural Resources, Forest Practices

The Forest Practices Board is a Washington State agency that developed standards, or Forest Practices Rules, to regulate how timber harvesting, pre-commercial thinning, road construction, fertilization, forest chemical application and other forest practices are implemented (Title 222 WAC) to meet the goals of the Forest Practices Act (chapter 76.09 RCW) and Stewardship of Non-industrial Forests and Woodlands (chapter 76.13 RCW). Forest Practice Rules are designed to protect public resources such as water quality and fish habitat while maintaining a viable timber industry. Rules involving water quality protection are approved by the Washington Department of Ecology before adoption by Forest Practices Board.

In order to determine which wetland types require “wetland management zones” around them, Forest Practice Rules consider impacts to wetlands by first categorizing them into different types that reflect their ecological variation and associated sensitivity. Due to high sensitivity to the effects of timber harvesting, “all forested and nonforested bogs greater than 0.25 acres shall be considered Type A Wetlands” (WAC 222-16-035). Bogs are defined in this context as wetlands having organic soils 16 inches (40 cm) or more in depth and vegetation such as “*Sphagnum* moss, Labrador tea, bog laurel, bog rosemary, sundews, and sedges; bogs may have an overstory of spruce, western hemlock, lodgepole pine, western red cedar, western white pine, Oregon crabapple, or quaking aspen, and may be associated with open water.” This definition includes nutrient poor fens and is equivalent to how the term ‘*Sphagnum*-dominated peatlands’ is used in this report.

Type A wetlands have special rules to protect their sensitive nature. This includes developing a plan to harvest in the wetland buffer that ensures trees are not felled into or cable yarded across the wetland (WAC 222-08). Harvest is not allowed within bogs and roads are also not permitted to be constructed in bogs or low nutrient fens. Type A wetlands (including bogs) have larger Wetland Management Zones (WMZs) relative to Type B wetlands. WMZs have more restrictions on timber harvest activities than areas outside the WMZs.

1.5.5 Washington Department of Natural Resources, Habitat Conservation Plan

The Washington Department of Natural Resources, State Trust Lands Habitat Conservation Plan (HCP) is an ecosystem-based forest management plan that outlines a path to protect habitat for at-risk species, while also conducting forest management and other activities on state trust lands to generate revenue for public schools, universities, and other state institutions. The core element of the HCP outlines how DNR provides for:

- Habitat for northern spotted owls, marbled murrelets, and riparian-dependent species such as salmon
- Habitat for other animal and plant species listed as threatened or endangered by the federal or state governments
- Habitat for unlisted plant or animal species that might be declining in numbers or that could be listed at some future time
- Uncommon habitats and habitat elements (talus fields, caves, cliffs, oak woodlands, large snags, balds, mineral springs, and large, structurally unique trees) that support the various species that depend on them
- Old-growth forests in the five habitat conservation planning units in western Washington
- Unstable slopes

In addition to protecting bog-dependent species such as Beller's ground beetle and Hatch's click beetle, the HCP also affords special management considerations to bogs (larger than 0.1 acres), as defined by Forest Practice Rules. These considerations are implemented within a 100 to 150 ft. buffer around the bog.

1.5.6 Washington Department of Ecology, Wetland Rating System

Washington's wetlands are ecologically variable and consequently differ in their functions and values. While all wetlands provide some level of ecosystem services, many have ecological characteristics that result in unique or highly valued ecosystem functions. These unique wetlands may be rare on the landscape, relatively undisturbed, or support rare species. Managers, planners, and citizens need tools to understand the resource value of individual wetlands in order to protect them effectively. The Washington Department of Ecology developed the Wetland Rating System to provide managers, planners, and citizens a tool to differentiate between wetlands based on their sensitivity to disturbance, their significance, their rarity, our ability to replace them, and the functions they provide (Hruby 2014). The Wetland Rating System assigns a wetland to one of four categories, ranging from Category 1 (rare or irreplaceable) to Category 4 (heavily impacted and providing low levels of ecological function). The rating categories are intended to assist in developing standards for protecting and managing wetlands to reduce further loss of their value as a resource. The categories are often used by decision makers to determine the buffer width needed to protect a wetland from adjacent development, the amount of mitigation needed to compensate for impacts to the wetland, and permitted uses in the wetland.

Bogs are typed as Category 1 wetlands within the Wetland Rating System "because they are sensitive to disturbance and impossible to re-create through compensatory mitigation." (Hruby 2014). The Wetland Rating System defines a bog as (1) having organic soil horizons that are 16 inches (40 cm) or more of the first 32 inches (81 cm) of the soil profile (less if on bedrock or floating on water); (2) have more than 70% cover of mosses at ground level and have at least 30% cover of "bog" species (listed in Hruby 2014). This definition is essentially equivalent to how the term '*Sphagnum*-dominated peatlands' is used in this report.

Washington's Growth Management Act (GMA) requires all cities and counties adopt development regulations that protect critical areas. These regulations help to preserve the natural environment, maintain fish and wildlife habitat, and protect drinking water. Wetlands, including bogs, are one of five 'critical areas' defined in this legislation. The Wetland Rating System is used by many local governments as a framework for protecting wetlands as part of their Critical Areas requirements (Ecology 2016; Commerce 2018). Within these requirements, Category 1 wetlands like bogs are generally afforded wider buffer widths, more stringent mitigation requirements, and more limited use relative to other wetland types.

1.5.7 Washington Department of Ecology, Wetland Mitigation Guidance in Washington State

The Washington Department of Ecology, U.S. Army Corps of Engineers, and U.S. Environmental Protection Agency have developed guidance to improve the quality and effectiveness of compensatory wetland mitigation in Washington State. Bogs are explicitly noted in many portions of the guidance. The guidance defines bogs as (1) wetlands with peat, (2) a pH < 5, and (3) with plants and animals adapted to such conditions. Avoidance is strongly emphasized as the preferred action for bogs due to their rarity, sensitivity, and the difficulty to replace them through restoration actions (Ecology 2021). When avoidance is not feasible, the guidance notes that preservation is the only viable option with which to compensate for impacts (Ecology 2021) and that a preservation ratio should start at 24:1. The guidance also notes that preservation should include provisions to "minimize stormwater inputs that could adversely affect the water chemistry of these wetland types. This could include providing additional upland buffer as part of the compensatory mitigation proposal." Recommended buffer widths around these preserved bogs vary according to the level of impact in the buffer, with 100 ft. recommend for relatively undisturbed buffers (e.g., open space), 190 ft. for moderately impacted buffers, and 250 ft. for highly impacted buffers (Ecology 2021).

1.5.8 Washington Department of Ecology, State of Wetland Science in Washington

The Washington Department of Ecology and Washington Department of Fish and Wildlife completed a two volume report on the status of wetland science to assist local governments in meeting Growth Management Act requirements (Granger et al. 2005; Sheldon et al. 2005). These publications provide a thorough overview of issues related to wetland management, conservation, and regulation. Both volumes address bogs in a variety of contexts.

1.5.9 Washington Department of Fish and Wildlife, State Wildlife Action Plan

Washington's State Wildlife Action Plan (SWAP) outlines a comprehensive approach for conserving the state's fish and wildlife species and the natural habitats on which they depend (WDFW 2015). The SWAP is part of national effort by all 50 states and five U.S. territories to develop conservation action plans and participate in the State and Tribal Wildlife Grants (SWG) Program. The SWG Program is intended to support state actions that benefit wildlife and their habitats, but particularly "Species of Greatest Conservation Need (SGCN)" as identified by each individual state. The SWAP assesses the status of the state's wildlife and habitats, identifies key threats and challenges, and recommends actions needed to conserve SGCN and their habitats over the long term. An overall goal of the SWAP is to identify actions needed to conserve wildlife and their habitats before species become too rare and restoration efforts too costly. The intent of the SWAP is to inform conservation priorities and actions statewide, and provide tools and informational resources to support collaborative conservation initiatives across a range of organizations and entities.

The North Pacific Bog and Fen Ecological System (Rocchio and Crawford 2015b) is considered a Habitat of Greatest Conservation Need in the SWAP, as some SGCN are dependent on this ecosystem type (WDFW 2015). The North Pacific Bog and Fen Ecological System includes all peatland types in western Washington and thus describes a concept broader than *Sphagnum*-dominated peatlands. However, a few SGCN identified in the SWAP (Hatch's click beetle and Beller's ground beetle) are associated with *Sphagnum*-dominated peatlands.

A state conservation goal of the SWAP is to identify occurrences of the North Pacific Bog and Fen Ecological System and then (1) protect key sites through acquisition, easement, low intensity land uses, and protection of hydrology; (2) support creation of Growth Management Act-based Voluntary Stewardship Plans; and (3) build resilience for added stress of climate change by addressing existing stressors

1.5.10 Draft Management Guidance for Low Elevation, Sphagnum-dominated Peatlands of Western Washington

Draft management guidance for low elevation, *Sphagnum*-dominated peatlands was provided in Kulzer et al. (2001) The guidance generally focused on preventing or mitigating for potential stressors in a peatland's watershed and was based on best available science, as well as best professional judgement (Kulzer et al. 2001). The guidance was described as "preliminary" due to the lack of data describing pathways by which human activity could impact acidic peatlands. However, given the rate of human population growth and subsequent human-induced stressors affecting acid peatlands, they noted an urgent need for a more comprehensive set of management guidelines.

The guidance was organized around (1) physical factors, (2) chemical factors, and (3) biological factors. The specific recommendations are summarized below. Additional details are found in Kulzer et al. (2001).

<u>Physical Factors:</u>

- Prevent or reduce peat extraction/mining.
- Maintain existing forest cover in the peatland's watershed.
- If logging or land-use conversion occurs in the peatland's watershed, route excess flows to an area downstream of the *Sphagnum* areas in the peatland, avoiding backwater effect that could flood those areas.
- If land use is predicted to increase water table drawdowns, consider engineered infiltration trenches or gravel-filled reservoirs to augment summer flows.

- Keep flows dispersed to the extent possible; if flows are concentrated, do not introduce them into a *Sphagnum*-dominated peatland in a piped discharge. Design a flow dispersal system at the edge of a 200-foot wetland buffer.
- If possible, avoid routing roads though a *Sphagnum*-dominated peatland's watershed.
- Road runoff should be dispersed and treated through a properly sized filter strips.
- Trampling from human foot traffic within a *Sphagnum*-dominated peatland can be addressed by building either a low-impact trail (using non-alkaline building materials that allow light penetration) through a portion of the peatland or building a viewing platform above the peatland.

Chemical Factors

- Treat any surface runoff before it enters the peatland so that over 90% of the total settleable solids and as much of the nutrient context of the water as possible.
- Avoid use of calcium-containing materials (e.g., Portland cement, whitewash, cement structures, etc.) in *Sphagnum*-dominated peatland's watershed.
- Avoid fertilization of forests and lawns within the watershed of *Sphagnum*-dominated peatlands.
- Restrict any land disturbing activities in the watershed, including logging, during the rainy season.
- Dry season land disturbances should be revegetated before rainy season begins to avoid sediment transport into the peatland.

Biological Factors

- Prevent shading of *Sphagnum* mosses by maintaining conditions that prevent shrub growth, such as a high summer water table and the avoidance of nutrient enrichment.
- Maintain stable water table levels and prevent mineral-rich water from entering the peatland to avoid invasion of the *Sphagnum*-dominated zone by marsh species such as cattail (*Typha* spp.).
- Place interpretative signs at all trail access points into a *Sphagnum*-dominated peatland, advising people to clean their footwear of plants seeds (especially those of reed canarygrass (*Phalaris arundinacea*) before entering the peatland.

1.6 PROJECT OBJECTIVES

Past and ongoing land uses within and adjacent to *Sphagnum*-dominated peatlands have resulted in loss and degradation of peatland biodiversity in many areas of the world, including Washington State (Kulzer et al. 2001, Joosten and Clarke 2002, Rocchio and Crawford 2015b). Effective conservation and management of peatland biodiversity and other ecological values requires an understanding of their landscape setting, hydrological processes, water chemistry, associated biotic patterns, and response to human stressors. However, despite the fact that some of the earliest research of *Sphagnum*-dominated peatlands in the United States occurred in the Pacific Northwest West (Rigg 1917, 1919, 1925, 1937, 1940, 1951, 1958; Osvald 1933), there has been limited quantitative study of the hydrological, chemical, and biological characteristics of Washington's *Sphagnum*-dominated peatlands (Lebednik and del Moral 1976; Kulzer et al. 2001; Rocchio et al. 2021) and especially how these peatlands respond to human-induced stressors (Kulzer et al. 2001).

Current guidance for buffers, mitigation avoidance measures, watershed planning, and conservation site selection applicable to *Sphagnum*-dominated peatlands is primarily derived from research addressing stressors in other wetland types (Azous and Horner 1997; Kulzer et al. 2001, and Adamus 2014). Because of the unique ecological characteristics of *Sphagnum*-dominated peatlands, there is a need to understand how adjacent land use may affect their ecological integrity. Protection, management, and regulatory actions need to be tailored to the specific requirements of *Sphagnum*-dominated peatlands to mitigate impacts and help protect these rare and valuable wetlands.

For example, many existing regulations and management guidance do not explicitly consider water source(s), which could result in undesirable outcomes for the long-term management of Puget Lowland peatlands. A better understanding water source(s) and potential effects of adjacent land use on *Sphagnum*-dominated peatlands is needed to ensure that regulatory permitting, compensatory mitigation requirements and guidance, and voluntary restoration and conservation actions are effective in preventing, managing, or mitigating stressors induced by adjacent land use activities. Understanding a peatland's hydrological patterns and water chemistry are integral to developing protection strategies, mitigation scenarios and restoration actions.

This research is intended to address significant data gaps, update existing guidance, and potentially inform new guidance to improve the effectiveness of regulatory, conservation, and management actions seeking to protect, preserve, and restore Washington's peatlands. Specifically, this research attempts to quantify impacts to peatland ecological integrity and relate them to surrounding land use.

Many of the policies, regulations, and conservation actions previously described depend on ecological assessment tools that can be employed in an efficient and cost-effective manner, but that also provide reliable results. This project tested the utility of multiple rapid assessment methods against hydrological, chemical and vegetation quantitative measures.

This project focused on low elevation, *Sphagnum*-dominated peatlands, all of which are very acidic, low in nutrients, and may be ombrotrophic. *Sphagnum*-dominated peatlands also occur in montane regions of the state, but those are acidic to circumneutral, minerotrophic peatlands (fens) dominated by various sedges (*Carex* spp.), willows (*Salix* spp.), and bog birch (*Betula glandulosa*). Such peatlands were not the focus of this research.

Low elevation, *Sphagnum*-dominated peatlands were chosen because of their significant conservation value, sensitivity to anthropogenic stressors, and the long time-scales required for their development and potential restoration (Hruby, 2014; Rocchio & Crawford, 2015a, 2015b; Minayeva et al., 2017). In this study, we quantified variation in hydrology, water chemistry, and vegetation across gradients of land use intensity, precipitation, watershed size, and connectivity with adjacent uplands. Peat monoliths were collected from the surface peat layers at three sites to explore patterns of pollen and macro/microfossils and whether they correspond with initiation of adjacent land uses, abrupt shifts in the peat profile, and/or tree encroachment. These data have been used to address the following questions and hypotheses:

1. What are the biotic and abiotic patterns of Puget Lowland, *Sphagnum*-dominated peatlands as they relate to climate, hydrology, water chemistry, watershed conditions, and adjacent land use?

2. Do ombrotrophic bogs exist in western Washington?

3. How do rapid ecological assessments correlate to quantitative measures of ecological integrity?

Another question we initially sought to address was the extent to which tree encroachment in low elevation, *Sphagnum*-dominated peatlands in western Washington is a local (site) or widespread (regional) phenomenon. However, limited funding and staffing capacity prevented the level of investigation needed to address this question. This is an area of inquiry that needs to be explored in order to determine whether tree encroachment is a result of climatic and/or local stressors and/or a natural successional dynamic.

2.0 Study Area – Puget Lowland Ecoregion

This study focused on acidic, *Sphagnum*-dominated peatlands within the EPA Level 3 Puget Lowland ecoregion (EPA 2013; DNR 2022). The ecoregion is a broad rolling landscape that primarily occupies a continental glacial trough (from Thurston County to the Canadian border) and includes many islands, peninsulas, and bays in the Puget Sound area. From the lowlands surrounding the Puget Sound, the ecoregion extends south to include the upper basin of the Chehalis River and the Cowlitz river valley and the Portland Basin in Clark County (Figure 3).

2.1 Geology and Topography

This ecoregion lies in a topographic and structural trough between the Cascade Range to the east and the Olympic Mountains and Willapa Hills (e.g., Coast Ranges) to the west. The region is relatively broad but narrows considerably in the southern end (Figure 3). Other than a few areas in the San Juan Islands, most of the region occurs below 500 feet in elevation. Much of the region's topography is a result of glaciation that began in the early Pleistocene with four periods of extensive glaciation. Glaciation ceased between 200,000 to 740,000 years ago and then reinitiated during the late Pleistocene. Contemporary landscapes are primarily the result of the last continental glacier (the Cordilleran Ice Sheet) that moved through the region about 18,000 years ago and began to recede around 12,000 years ago. The ice advanced from what is now British Columbia to just south of Olympia. Surface runoff from the Cascades was dammed by the ice sheet and/or diverted south along the flanks and around the terminus of the glacier south of Olympia and out to the Pacific through the Chehalis River valley. These events left a landscape almost entirely derived from glacial deposition or erosion. South of the outwash areas in the Chehalis River valley, the topography is mostly a result of stream erosion. However, alpine glaciers and their associated outwash deposits are found in the Cowlitz River valley and into the Columbia River (Pringle 2008). Some post-glacial alluvial erosion and deposition has modified the landscape in riverine settings. Kettle holes, glacial till, moraines, glacial scours, meltwater outwash, compacted till, proglacial lake deposits, and contemporary alluvial and shoreline landforms affect the distribution of wetland types and distribution across the Puget lowlands.

2.2 Climate

The ecoregion is characterized by a mild, maritime climate. Prevailing wind directions are from the south to southwest during the wet season and from the northwest during the summer dry months. Factors such as distance from Puget Sound, rolling terrain, and influx of oceanic air through the Straits of Juan de Fuca and the Chehalis River valley result in variation in temperature, growing season duration, fog, rainfall, and snowfall (WRCC 2022). The growing season in the ecoregion generally lasts from the middle of April until the middle of October.

The majority of precipitation (>70%) falls between October and March. Annual precipitation ranges from 82 to 96 cm (32 to 38 inches) in the northern portion of the ecoregion (from Seattle to the Canadian border) while increasing in the southern portion to 127 cm (~50 inches) in Olympia and ~48 inches (122 cm) in Centralia (WRCC 2022). Issaquah, which occurs near the eastern edge of the ecoregion at the base of the Cascades, receives 53 inches (135 cm) per year. Precipitation approaches 254 cm (100 inches) per year on the western edge of the ecoregion, in Mason County. Precipitation mostly falls as rain but an average of 25 to 50 cm (10 to 20 inches) of snow intermittently falls throughout the area. Snowfall and rain increase with elevation and distance

Figure 3. Puget Lowland Ecoregion

from Puget Sound. Snowfall melts relatively quickly and depths rarely exceed 15 to 38 cm (6 to 15 inches). The rain shadow cast by the Olympic Mountains results in drier conditions in the northeastern portion of the Olympic peninsula, northern Kitsap peninsula, the San Juan Islands, and the western portions of Whatcom and Skagit counties. For example, Sequim, on the north end of the Olympic peninsula, receives only 43 cm (17 inches) per year.

As one moves further from Puget Sound, winters become colder and summers become warmer. Average annual minimum and maximum temperatures in the ecoregion range from 44.1°F to 59.2°F (6.7°C to 15.1 °C) in Bellingham, 46.7°F to 59.2°F (8.2°C to 15.1 °C) in Seattle, 41.1°F to 60.0°F (5.2°C to 15.5 °C) at Snoqualmie Falls, 40.9°F to 61.2°F (4.9°C to 16.2 °C) in Olympia, and 39.8°F to 61.2°F (4.3°C to 16.2 °C) in Matlock (WRCC 2022).

2.3 VEGETATION

2.3.1 Puget Lowland Vegetation Patterns

Historically, old-growth forest stands of Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) covered much of the ecoregion. Most of this original forest has been logged, often numerous times. Contemporary forests are still dominated by the same species, but most stands lack the structural complexity found in late-mature and old-growth forests. Bigleaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*) are common forest co-dominants that tend to increase in abundance in more disturbed forests. Pacific madrone (*Arbutus menziesii*) and Oregon white oak (*Quercus garryana*) can co-occur with Douglas-fir on shallow or coarse-soils. Prior to conversion to agriculture or development, dry upland prairies and Oregon white oak woodlands covered extensive areas of coarse glacial outwash, especially in the southern portion of the ecoregion. Historically, frequent fire kept these prairies from being invaded by forest species. These fires were primarily a result of intentional ignitions by Native Americans in recent centuries (Norton 1979, Whitlock 1992, Agee 1996, Tveten and Fonda, 1999). Very little of this prairie ecosystem remains on the landscape today. Estuaries are found along some of the inlets of Puget Sound. Marshes, swamps, riparian areas, and peatlands are very abundant across the landscape, especially in previously glaciated regions and along valley bottoms. Large, low-gradient rivers begin in adjacent mountains and flow through the ecoregion, terminating in Puget Sound in the northern portion of the ecoregion and the Chehalis River or Columbia River in the southern extent of the ecoregion. Small streams often originate at lower elevations. Lakes are numerous in the areas affected by past glaciation.

2.3.2 Vegetation of Puget Lowland Sphagnum-dominated Peatlands

Sphagnum-dominated peatlands in the Puget Lowlands are characterized by ericaceous shrubs, typically less than 50 cm in height and open enough to allow for a nearly continuous ground cover of *Sphagnum* and certain feathermosses (e.g. *Pleurozium schreberi*). Labrador tea (*Rhododendron groenlandicum*), bog laurel (*Kalmia microphylla*), and salal (*Gaultheria shallon*) are the most common shrubs. Native small cranberry (*Vaccinium oxycoccos*) sprawls across *Sphagnum* carpets, lawns, and hummocks. In the driest and/or recently disturbed sites, Labrador tea and bog laurel can be dense and tall (often > than 1 m) to the extent that they exclude other species—including *Sphagnum* spp., cranberry, and sundews (*Drosera rotundifolia*)—from growing beneath their canopy. In relatively wet areas, Labrador tea and bog laurel are typically well-spaced and exhibit a short-statured, stunted growth form (often < 50 cm high). *Sphagnum fuscum* and *S. capillifolium* are common hummock-forming species. *Pleurozium schreberi* is also common on top of hummocks and tends to become more dominant as tree cover (and thus shade) increases. *Sphagnum rubellum* is often present in oligotrophic hummocks or lawns. *Sphagnum angustifolium* is a common peat moss in hollows while *S. miyabeanum* and *S. mendocinum* are common in pools or very wet hollows. Reindeer lichens (*Cladonia* and Cladina spp.) can be abundant, sometimes to the extent that they outcompete *Sphagnum* species. Some researchers believe these lichens proliferate following fire (Hebda 1977, Hebda & Biggs, 1981), while others note a recurring cycle between lichen and *Sphagnum* dominance (Foster & Glaser 1986). Bracken fern (*Pteridium aquilinum*) is common in many bogs, sometimes forming dense stands that may indicate recent disturbance such as fire. Soaks and wet hollows are often dominated by cottongrass (*Eriophorum chamissonis*), three-way sedge (*Dulichium arundinaceum*), and white beakrush (*Rhynchospora alba*). Skunkcabbage (*Lysichiton americanus*) sometimes forms "wells" or deep holes that these plants appear to inhabit for decades, if not longer (Turesson 1916; Osvald 1933). When present, trees—most commonly shore pine (*Pinus contorta* var. *contorta*) and western hemlock (*Tsuga heterophylla*)—are most often represented by relatively short, stunted, bonsai-like growth forms with rounded or flat tops. Often these trees are of small diameter and stature, but exhibit the furrowed bark of older trees. Western white pine (*Pinus monticola*) is also common, and Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*) and Douglas-fir (*Pseudotsuga menziesii*) are occasionally found.

Laggs occur around the outer perimeter of most *Sphagnum*-dominated peatlands and act as mixing zones where water from the interior peatland mixes with water from adjacent uplands or wetland habitats (Crum 1992, Howie and van Meerveld 2011, Howie and van Meerveld 2013, Langlois et al. 2015). Lagg development is most pronounced in raised bogs, but can occur in slightly convex flat bogs (Crum 1992; Howie and van Meerveld 2011), but is not present in Continental bogs in Alberta, Canada (Vitt et al. 1994). Laggs typically have distinct water chemistry and vegetation composition relative to the interior portion of the peatland (Howie and van Meerveld 2011). Paradis et al. (2015) suggest that the lagg must be influenced by drainage from the peatland center, thus excluding large areas surrounding a bog that are relatively unaffected by bog drainage. Some laggs have been shown to have lower hydraulic conductivity than peatland centers, thereby serving to help retain water tables in the interior portion of the bog (Baird et al. 2008). Most Puget Lowland *Sphagnum*-dominated peatlands have outer zones that match these characteristics. Rigg (1925) referred to this zone as the 'marginal ditch' surrounding regional bogs, while Osvald (1933) referred to them as wet margins or laggs. Rigg (1958) noted that most of Washington's "*Sphagnum* bogs" had a marginal ditch between the margin of the *Sphagnum* area and "the bordering hard land". Rigg described these marginal ditches as having standing, shallow water, at least in the rainy season, with vegetation dominated by marsh or swamp species. Laggs in Puget Lowland peatlands are often dominated by western hardhack (*Spiraea douglasii*), Pacific crabapple (*Malus fusca*), willows (*Salix* spp.), and various sedges (*Carex obnupta*, *C. utriculata*, *C. aquatilis* var. *sitchensis*) (Kunze 1994).

Montane to subalpine peatlands (all of which are fens) are primarily supported by groundwater discharge or occur along lake or pond shorelines. Species such as beaked sedge (*Carex utriculata*), Cusick's sedge (*C. cusickii*), mud sedge (*C. limosa*), woodrush sedge (*C. luzulina*), inflated sedge (*C. exsiccata*), mountain sedge (*C. scopulorum* ssp. *bracteosa*), tufted bulrush (*Trichophorum cespitosum*), elephant head (*Pedicularis groenlandica*), bog laurel, cottongrass (*Eriophorum angustifolium*), Sitka alder (*Alnus viridis* subsp. *sinuata*), speckled alder (*A. incana*), bog bilberry (*Vaccinium uliginosum*), and bog birch (*Betula glandulosa*) are common. Many of these also have a continuous cover of *Sphagnum* spp. These montane fens are not within this project's scope.

2.3.3 Classification of Puget Lowland Sphagnum-dominated Peatland Vegetation

The WNHP uses the USNVC to catalog and set conservation priorities for Washington's ecosystems. The USNVC is a comprehensive classification of all vegetation types in the United States (Faber-Langendoen et al. 2014). The USNVC classifies vegetation according to shared physiognomy, floristics, biogeography, and ecological relationships (Faber-Langendoen et al. 2014). USNVC is the only vegetation classification system for the United States providing a standardized framework for communication and cooperation on vegetation management issues that cross jurisdictional boundaries (FGDC 2008). Such properties make the USNVC ideal for characterizing regional vegetation types for conservation, restoration, and management objectives.

The top three levels of the USNVC (class, subclass, formation) are coarse and describe major structural categories on a global scale, such as temperate forest, cold desert, and temperate grassland. The middle levels (division, macrogroup, group) reflect distinctive combinations of species in the context of regional- to continental-scale climate, geology, and water cycles, and disturbance patterns of fire, wind, and flood. These mid-levels include ecosystem categories familiar to ecologists, like Douglas-fir – western hemlock forest, marshes, bogs, hardwood-conifer swamp, and shrub-steppe. The combination of species largely defines the lowest, most fine-scale levels (alliance, association). These levels distinguish between shrub- and herbaceous-dominated acidic peatlands, for example. The association is the finest unit of the USNVC and has been used by the WNHP as the primary focus for establishing ecosystem conservation priorities. The association is defined on the basis of a characteristic range of plant species composition, diagnostic plant species occurrence, habitat conditions and physiognomy. Associations reflect topo-edaphic climate, substrates, hydrology, and disturbance regimes.

WNHP ecologists have played a key role in the identification and development of association concepts for Washington State. This is accomplished through synthesis of various vegetation classification efforts conducted within or applicable to Washington, as well as firsthand collection and analysis of vegetation plot data over the past 45 years. WNHP staff have collected over 200 relevé plots that were used in the classification of *Sphagnum*-dominated vegetation types in Table 2 (USNVC 2022). Not listed in this table are a few aquatic vegetation associations that commonly dominate large pools or ponds within *Sphagnum*-dominated peatlands. These include *Brasenia schreberi* Western Aquatic Vegetation, *Nuphar polysepala* Aquatic Vegetation, *Schoenoplectus subterminalis* Aquatic Vegetation, and *Utricularia macrorhiza* Aquatic Vegetation.

2.4 Land Use

Conversion of the ecoregion's natural land cover to other uses has been rapid since Euroamerican settlement in the 1850s. Today, the majority of Washington's population lives in the ecoregion. As a result, over 50% of the ecoregion has been converted to urban or tilled agricultural uses, with most of the remaining area in active forestry rotation. The Puget Lowlands are by far the most highly developed of Washington's ecoregions. Human development of the ecoregion has resulted in numerous changes to marine and nearshore habitats, including shoreline modifications, bulkheading, dredging, diking, proliferation of invasive species, environmental contaminants, and filling, resulting in loss of native aquatic habitat. Terrestrial natural land cover has been lost to development and remaining areas show a high degree of fragmentation.

2.5 Peatland Distribution

There are an estimated 589 *Sphagnum*-dominated peatlands in the lowlands of western Washington, of which 399 are located within the Puget Lowland ecoregion (Figure 4). Kulzer et al. (2001) reported 247 *Sphagnum*-dominated peatlands, but their estimate did not include aerial photography interpretation. The updated tally of 589 is based on a compilation of data sources summarized in Table 3 (Rocchio, unpublished data). Data sources include known locations from the Washington Natural Heritage Program database, Rigg (1958), King County Bog Inventory (Cooke Scientific Services and Kulzer 1997), and Kulzer et al. (2001), and supplemented with aerial photography interpretation (Table 3).

Table 2. U.S. National Vegetation Classification Types Associated with Puget Lowland *Sphagnum*-dominated Peatlands. State Conservation Status is described in DNR (2022). Codes are those assigned by USNVC (CEGLXXXXXX) or WNHP (CWWAXXXXXX)

	M063 North Pacific Bog & Fen Macrogroup	State Conservation Status	Code
	G284 North Pacific Acidic Open Bog & Fen Group	**Threatened**	**G284**
Associations	*Carex* (*livida, utriculata*) / *Sphagnum* spp. Fen	Endangered	CEGL003423
	Carex cusickii - (*Carex aquatilis* var. *dives*) / *Sphagnum* spp. Fen	Endangered	CWWA000061
	Carex lasiocarpa / (*Sphagnum* spp.) Fen [Provisional]	Threatened	CWWA000261
	Eriophorum chamissonis / *Sphagnum* spp. Bog & Acidic Fen	Sensitive	CEGL003333
	Juncus balticus - *Comarum palustre* / *Sphagnum* spp. Fen [Provisional]	Endangered	CWWA000247
	Kalmia microphylla - *Ledum groenlandicum* / *Xerophyllum tenax* Shrub Bog	Endangered	CEGL003359
	Kalmia microphylla - *Vaccinium oxycoccos* / *Sphagnum* spp. Shrub Bog	Threatened	CWWA000224
	Ledum groenlandicum - *Gaultheria shallon* / *Sphagnum* spp. Shrub Bog	Threatened	CWWA000226
	Ledum groenlandicum - *Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive	CEGL003414
	Ledum groenlandicum / *Carex utriculata* / *Sphagnum* spp. Shrub Bog	Threatened	CWWA000229
	Rhynchospora alba - (*Vaccinium oxycoccos*) / *Sphagnum* spp. Herbaceous Bog	Threatened	CEGL003338
	Spiraea douglasii / *Sphagnum* spp. Fen	Threatened	CEGL003416
	G610 North Pacific Maritime Wooded Bog & Poor Fen Group	**Sensitive**	**G610**
Associations	*Pinus contorta* var. *contorta* - *Betula papyrifera* / *Ledum groenlandicum* Treed Bog [Provisional]	Endangered	CWWA000235
	Pinus contorta var. *contorta* / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Endangered	CEGL003337
	Pinus monticola / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Endangered	CEGL003360
	Tsuga heterophylla - (*Thuja plicata*) / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Threatened	CEGL003339
	Tsuga heterophylla - (*Thuja plicata*) / *Sphagnum* spp. Treed Bog	Endangered	CEGL003417

The majority of *Sphagnum*-dominated peatlands in the Puget Lowlands are associated with landforms of glacial origin (e.g., glacial scours, kettles, etc.), isolated oxbows, old lake beds, or in areas of groundwater discharge (Rocchio et al. 2014). Peatlands are also found in river valleys and along lake and pond shorelines (Kulzer et al. 2001). Many peatlands have been destroyed or degraded in the urbanized areas of King, Pierce, and Snohomish counties, but there are peatlands in less urbanized areas of the Puget Sound region that remain relatively intact (Bell 2002; Rocchio et al. 2014; Figure 4). Of the 247 *Sphagnum*-dominated peatlands reported by Kulzer et al. (2001) as occurring at low elevations in the western Washington, 18 were deemed extirpated. The most recent estimate indicates a total of 61 *Sphagnum*-dominated peatlands have been extirpated, with 58 of those in the Puget Lowland ecoregion (Table 3).

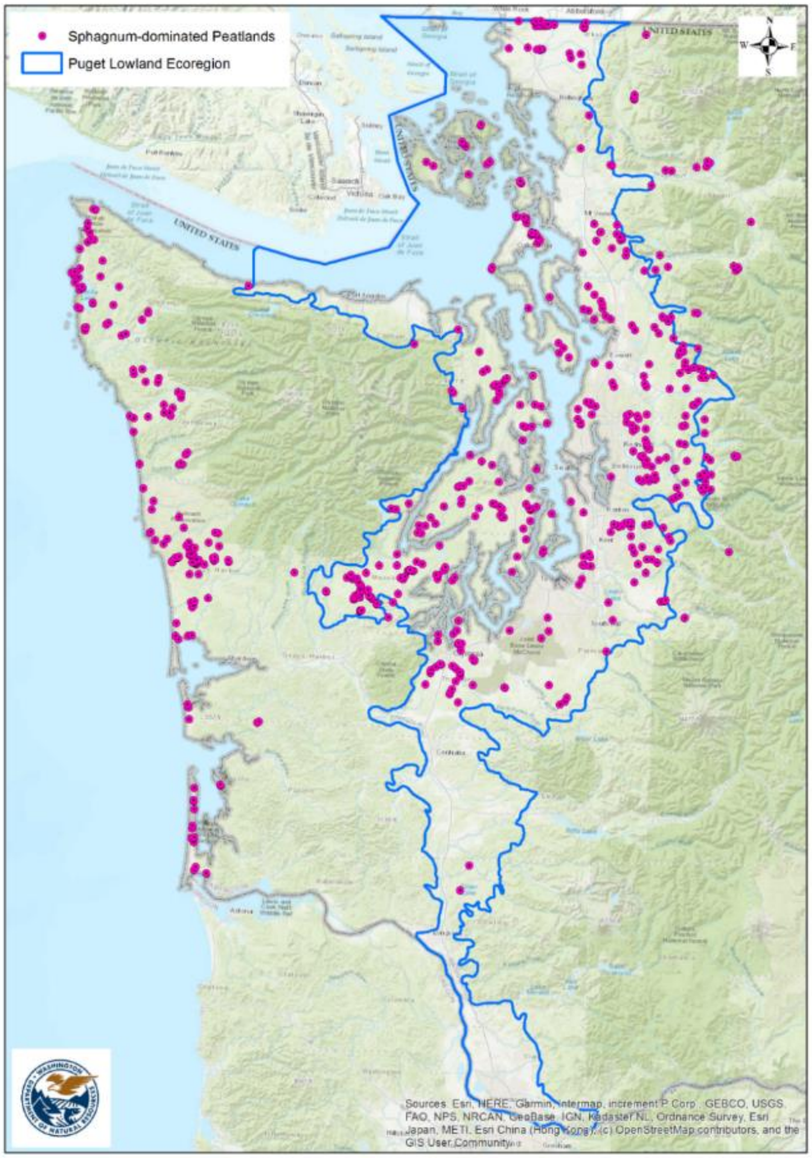


Figure 4. Distribution of Low Elevation, *Sphagnum*-dominated Peatlands of Western Washington. (Rocchio, *unpublished data*)

Table 3. Summary of Low Elevation, *Sphagnum*-dominated Peatlands of Western Washington. (Rocchio, unpublished data).

Ecoregion	Total Peatlands	Determination		Confidence		Current Status	
		Field	Aerial Photographs	Confirmed	Uncertain	Extant	Extirpated
North Cascades	33	17	16	22	11	32	1
Northwest Coast	146	64	82	90	56	144	2
Puget Lowland	406	266	140	328	78	348	58
West Cascades	4	1	3	2	2	4	0
Total	**589**	**348**	**241**	**442**	**147**	**528**	**61**

3.0 METHODS

3.1 STUDY SITE SELECTION

This study focused on acidic, *Sphagnum*-dominated peatlands within the Puget Lowland ecoregion. Locally, the target peatlands are referred to as "bogs" and are generally dominated by ericaceous shrubs and *Sphagnum* species (or, if no living *Sphagnum* is present at the surface, then *Sphagnum* peat is found immediately below the surface; Rigg 1958; Kulzer et al. 2001). *Carex* spp. and deciduous shrubs are minor components in these sites, except around the outer perimeter where a distinct, more minerotrophic zone (lagg) often occurs. Almost all of these bogs have a tree component ranging from scattered to nearly closed canopy. The most common tree species in the bogs include western hemlock (*Tsuga heterophylla*) and shore pine (*Pinus contorta* var. *contorta*). Within the context of other classification of peatlands, acidic peatlands of the Puget Lowlands could range from being ombrotrophic bog to acidic fens (Sjörs 1950, Moore and Bellamy 1974, and Proctor et al. 2009).

Although these 'bogs' are also found in the lowlands of the western Olympic peninsula, that area was excluded from this study due to the natural climatic difference between those sites and the peatlands in the Puget Lowlands. Constraining this variation was necessary in order to test differences across stressor gradients. The targeted peatland types all occur within topographic depressions where water sources include precipitation, groundwater discharge, and surface flow/overland flows from adjacent uplands. These peatland basins are characterized by vertical water fluctuations. Ombrotrophic zones may occur or dominate within these depressions.

A database of potential sample sites within the Puget Lowlands was developed using peatland locations identified in Rigg (1958), WNHP's database, the King County Bog Inventory (Cooke Scientific Services & Kulzer, 1997), and expert input. Each site in the database was attributed with watershed size and percent impervious surface area within that watershed.

3.1.1 Watershed Size

Watershed size is used in our study as a proxy for potential surface inflows into the peatland. The greater the catchment, presumably the greater the risk of land use activities impacting the peatland. Local surface watersheds for each peatland were delineated using lidar-derived flow accumulation models in ArcMap (ESRI, 2018). The local surface watersheds related only to immediately adjacent areas that might contribute surface water into the bog. Since many bogs are isolated or not directly connected to a creek or river, readily available resources such as Washington's Watershed Resource Inventory Area (WRIA) boundaries or USGS hydrological units were not sufficient for delineating potential hydrological contributions into these peatlands.

3.1.2 Percent Impervious Surface Area

Peatland watersheds with greater impervious surface areas are presumably at higher risk of impacts from land uses activities within the watershed. Impervious surfaces eliminate infiltration of precipitation and convey surface water, along with potential pollutants, toward peatlands. The National Land Cover Dataset was used to quantify % impervious surface area within each bog's contributing watershed.

3.1.3 Final Site Selection

Seventeen *Sphagnum*-dominated peatlands were selected to quantify the effects of land use and watershed characteristics on wetland hydrologic regime and water chemistry (Figure 5; Table 4). These peatlands represent the range of variation in size and impervious surface area percentage of the contributing watersheds. Site accessibility, availability of existing monitoring data, and prior knowledge of a site's characteristics relative to study design needs also informed site selection. Appendix A shows aerial imagery depicting boundaries of each study site, along with the local watershed of each peatland.

The study sites are located on interfluves or in headwater valley segments where thick (>1 m) peat bodies have formed by terrestrialization of kettle ponds and the margins of larger lakes. All selected sites are in areas mapped as either till or outwash from late Pleistocene glaciations (Jones 1999) and peat coring at eight sites revealed localized glaciolacustrine clay underlying the peat. Small intermittent streams provide surface water inputs to four sites (Echo Falls, Evans Creek, Lake Dorothy, and Shadow Lake), while all sites are drained by outlet streams, most of which flow intermittently during the winter rainy season.

To minimize the effects of climate differences, sites with similar temperature and evapotranspiration regimes were selected. Annual mean and maximum daily temperatures of the study sites were derived from 800 m grids of 1981-2010 climate normals (PRISM Climate Group 2012), averaging 10.47 ± 0.07˚C and 15.19 ± 0.06˚C; (Table 5) respectively. Mean and maximum daily temperatures during the May-September dry summer period were also uniform, averaging 15.70 ± 0.07˚C and 21.54 ± 0.08˚C, with corresponding maximum vapor pressure deficits of 14.32 ± 0.12 hPa. Since site elevations in this regional analysis ranged from 290 to 960 m, mean annual precipitation did vary significantly across the sites, averaging 1,490 ± 97.9 mm, but with a range of 1,130 to 2,290 mm. However, mean precipitation during May-September was much less variable, averaging 285 ± 12.7 mm and ranging from 191 to 396 mm.

3.1.4 Reference vs Developed Sites

For the purposes of some analyses, sites were categorized as "reference" or "developed" based on the amount of impervious surface areas within 50 m of the peatland boundary, within their watersheds. Sites with no impervious surface area within 50 m were categorized as "reference" and all other sites were considered "developed". This follows the finding of Azous and Horner (1997) who found that wetlands with < 3% impervious surface in their watershed had few indicators of hydrological and water quality degradation.

3.2 Sample Locations within Study Sites

Within each study site, locations were selected in two distinct zones—peatland centers and laggs—for hydrological, porewater chemistry, and vegetation sampling. These two locations represent distinct ecological zones that commonly characterize regional *Sphagnum*-dominated peatlands. Peatland center locations represent the portion of the study site where vegetation indicative of bog or very acidic fens is prevalent. The lagg represents the outer perimeter of the peatland where water draining from the peatland center mixes with drainage from adjacent uplands, resulting in distinct hydrological patterns, porewater chemistry, and vegetation composition (Rigg 1958; Howie and van Meerveld 2011, 2012, 2013).

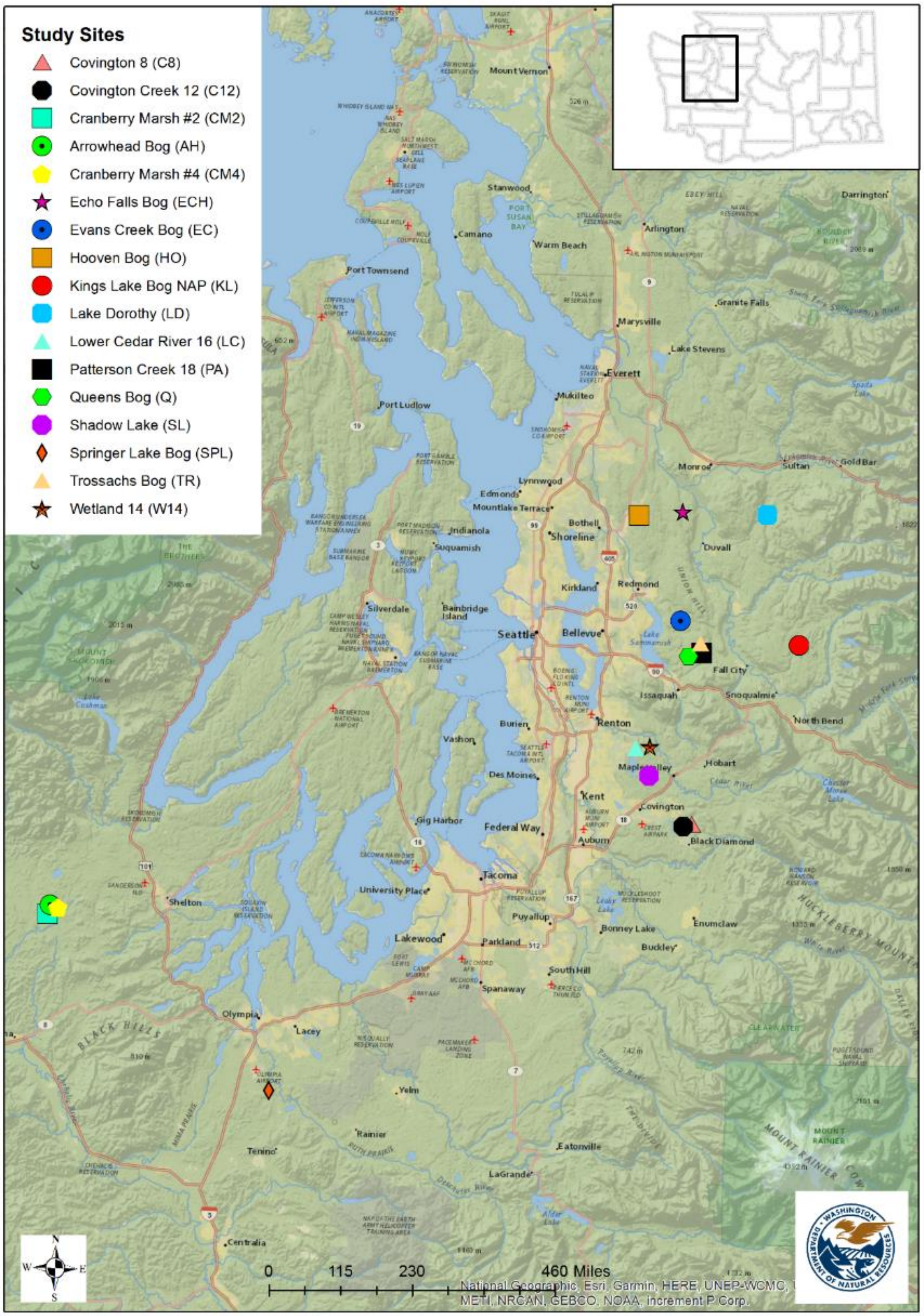


Figure 5. Study Site Locations

Table 4. Study Site Characteristics

Site Code	Site Name	County	Ownership	Minimum Elevation (m)	Maximum Elevation (m)	Watershed Size (ha)	% Impervious Surface (watershed)	% Impervious Surface (50 m)	Site Type
AH	Arrowhead Bog	Mason	Green Diamond Resources	117	135	16	16%	0%	Reference
C12	Covington 12	King	King County	174	185	23	8%	13%	Developed
C8	Covington 8	King	King County	205	229	16	12%	19%	Developed
CM2	Cranberry Marsh #2	Mason	Green Diamond Resources	118	126	17	1%	0%	Reference
CM4	Cranberry Marsh #4	Mason	Green Diamond Resources	124	135	15	4%	0%	Reference
ECH	Echo Falls	Snohomish	Private HOA	125	165	53	10%	1%	Developed
EC	Evans Creek	King	Private HOA	117	189	185	37%	38%	Developed
HO	Hooven Bog	Snohomish	Snohomish County	116	152	121	24%	19%	Developed
KL	Kings Lake Bog	King	WA DNR	291	321	77	9%	0%	Reference
LD	Lake Dorothy	King	WA DNR	150	204	56	7%	0%	Reference
LC	Lower Cedar	King	King County	152	207	50	35%	15%	Developed
PA	Patterson Creek	King	City of Sammamish	118	152	114	36%	22%	Developed
Q	Queen's Bog	King	City of Sammamish	121	143	63	31%	18%	Developed
SL	Shadow Lake	King	SHADOW Lake Nature Preserve	158	191	74	24%	17%	Developed
SPL	Springer Lake	Thurston	Capitol Land Trust	89	129	17	8%	3%	Developed
TR	Trossachs Bog	King	Private HOA	129	172	72	7%	11%	Developed
W14	Wetland 14	King	King County	154	230	29	26%	20%	Developed

Table 5. Climate Summaries of Study Sites

Site	Name	Mean Annual Temperature (Celsius)	Average Maximum Annual Temperature (Celsius)	Mean May - September Temperature (Celsius)	Average Maximum May - September Temperature (Celsius)	Mean Annual Precipitation (mm)	Mean May - September Precipitation (mm)	May - September Vapor Pressure Deficits (hPa)
AH	Arrowhead Bog	10.2	15.2	15.4	21.7	2287	311	14.1
C12	Covington 12	10.4	15.2	15.6	21.6	1334	298	15.1
C8	Covington 8	10.2	15.0	15.4	21.4	1420	327	14.9
CM2	Cranberry Marsh #2	10.2	15.3	15.5	21.9	2233	306	14.3
CM4	Cranberry Marsh #4	10.2	15.2	15.4	21.7	2254	309	14.1
ECH	Echo Falls	10.7	15.0	15.9	21.3	1256	282	13.2
EC	Evans Creek	10.9	15.4	16.1	21.7	1176	250	14.4
HO	Hooven Bog	10.8	15.1	16.0	21.3	1125	241	13.3
KL	Kings Lake	9.7	14.5	14.9	20.7	1758	396	14.4
LC	Lower Cedar	10.6	15.2	15.8	21.4	1239	253	14.1
LD	Lake Dorothy	10.4	15.0	15.6	21.3	1696	389	14.1
PA	Patterson Creek	10.8	15.4	15.9	21.7	1259	258	14.5
Q	Queen's Bog	10.7	15.3	16.0	21.7	1235	256	14.5
SL	Shadow Lake	10.5	15.2	15.7	21.5	1277	275	14.5
SPL	Springer Lake	10.5	15.7	15.7	22.2	1257	191	15.2
TR	Trossachs Bog	10.7	15.3	15.9	21.6	1256	251	14.5
W14	Wetland 14	10.6	15.3	15.8	21.5	1220	256	14.4

3.3 HYDROLOGIC AND CHEMICAL VARIABILITY OF STUDY SITES

3.3.1 Installation and Monitoring of Groundwater Wells

Well nests, consisting of one shallow groundwater monitoring well and nested piezometers, were established in the peatland center and lagg of each study site to characterize the range of hydrologic variability in *Sphagnum*-dominated peatlands of the Puget Lowlands. Peatland center well nests were located at the topographically highest point and/or at the center-most point within that zone. Groundwater levels were monitored from May 2018 to September 2021. Monitoring wells (5 cm slotted PVC) were installed to approximately 130 cm depth at each site, in hand-augered holes. Well locations within each study site are shown in Appendix A. At sites where significant inflows from surface water or stormwater management facilities occurred, an additional well was installed within the area receiving the inflow. Water levels were recorded every two hours using automated pressure transducers (Hobo U20L-04 Water Level Logger, Onset), corrected for barometric pressure using a nearby above-ground barometric pressure logger. Water levels were verified with manual measurements during March and August/September each year. After removing observations affected by bailing and water sample collection during site visits, the resulting data were aggregated to daily mean water table elevations relative to the ground surface, producing 45,131 daily mean values for the monitoring period.

Seasonal patterns in vertical hydraulic gradients (VHGs) were analyzed to determine the direction and relative magnitude of saturated flow in peatland centers and laggs (Rydin and Jeglum 2013). Nested piezometers (1.3 cm unslotted PVC) were installed near monitoring wells at depths of 50, 100, 150, and 200 cm. The deeper piezometers (e.g., 150 or 200 cm) could not be installed at some sites where thick clay or tephra layers were encountered. Water levels were measured by hand with an electronic tape in piezometers during spring (March) in 2019 and 2020, and at the end of the summer dry season (August/September) in 2019-2021. Vertical hydraulic gradients ($n = 215$) were calculated for each depth increment and for the entire instrumented profile as $\partial h/\partial z$, where 'h' is total hydraulic head and 'z' is elevation (Fetter 2001).

3.3.2 Water Chemistry Sampling

Seasonal porewater chemistry was characterized during spring and late summer. The spring sample was intended to capture water chemistry at high-water levels during the growing season. The late summer collection event targeted low water levels during the growing season. After bailing at least three well casing volumes (i.e., 3x the volume of water present in the pipe), pH and specific conductivity were measured in the field for a collected sample (Orion Star A325 pH/conductivity meter, Thermo Scientific). Additionally, 250 ml water samples were collected and filtered using a Nalgene Reusable Filter Unit (Model 300-4050) with 45 μm filters under vacuum. Water samples were stored in Nalgene bottles and kept frozen until analysis of major ion concentrations (Pfaff 1993, EPA 1994) at the University of Washington Analytical Service Center. Measured ions included major anions (Cl and SO_4^{2-}), cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+), and nutrients (NO_3^-, NH_4^+, and PO_4^{3-}). Anion concentrations were measured with a DX-120 Ion Chromatograph (Thermo Scientific) and cation concentrations were measured with a Jarrell-Ash ICAP 61E Inductively Coupled Plasma Spectrometer (Thermo Scientific). Specific conductivity was corrected for H^+ ion concentrations (EC_{corr}) following Rydin & Jeglum (2006).

3.4 VEGETATION COMPOSITION AND STRUCTURE OF STUDY SITES

Vegetation data were collected within 100 m^2 and 400 m^2 relevé plots surrounding each well nest. These data were used to analyze relationships between vegetation and wetland position, hydrology, land use variables, and to calculate Floristic Quality Assessment indices for each well nest. Plot size varied depending on physiognomy of the vegetation: Herbaceous and shrub strata were sampled within 100 m^2 plots while 400 m^2 plots were used to document canopy and subcanopy trees. Sampling occurred in late May to early June of 2019 and 2020.

Vascular plant species and nonvascular physiognomic group composition and abundance were recorded within each plot. All vascular plants were identified to species, subspecies, or variety when possible. Unidentifiable plants were documented at the finest possible taxonomic level. All plants rooted within a given relevé were recorded. Species were keyed using the Flora of the Pacific Northwest, 2nd Edition (Hitchcock & Cronquist, 2018) and Field Guide to the Sedges of the Pacific Northwest, 2nd Edition (Wilson et al., 2014). Identifications were then matched to the current taxonomy used in the University of Washington Burke Herbarium Washington Flora Checklist (Weinmann et al., 2002). The U.S. National Vegetation Classification vegetation units for each relevé were determined in the field using keys from Rocchio et al. (2022) and Rocchio and Ramm-Granberg (*In preparation*).

Cover values for vascular plants were recorded by visually estimating a circle around the outermost area covered by each plant. Estimates were made separately for each stratum in which a plant occurred: canopy (>10 m tall), subcanopy (5-10 m), shrub (0.5-5 m), and herb (<0.5 m). Discussion concerning "herb composition" or "shrub composition" below includes tree species occurring within those strata. The following cover classes were used: 0-1, 1-2, 2-5, 5-10, 10-25, 25-50, 50-75, 75-95, and 95+ percent (Peet et al., 1998). Cover classes were converted to midpoints and species occurring in fewer than two relevé plots were excluded from subsequent analyses.

Nonvascular species were not identified to species, limiting inferences about these taxa in this study. However, nonvascular species were recorded as the following "physiognomic groups": *Sphagnum* (*S. capillifolium*, *S. fuscum*, *S. rubellum*, etc.) feathermoss (*Pleurozium schreberi*, *Hylocomium splendens*, *Rhytidiadelphus* spp., *Ptilium* spp., etc.), other moss (*Dicranum* spp., *Aulacomnium* spp., *Polytrichum* spp.), lichen (primarily *Cladonia* spp.), and liverwort (primarily *Ricciocarpos natans*).

Besides the relevé, nonvascular physiognomic groups were more precisely recorded along 50 m transects centered on each well nest. Physiognomic group and hummock microposition (top, middle, toe, or hollow) were recorded at 1 m intervals. Species were noted, but only when field-identifiable. No data were collected directly next to the well nest, where trampling by field staff was most severe. Data were summarized as relative cover of each physiognomic group.

Tree stem counts were recorded within peatland center relevé plots (400 m^2) and tallied by species, stratum (canopy >10 m; subcanopy 5-10 m; shrub 0.5-5 m; and herb < 0.5 m) and diameter at breast height (DBH; < 2.5 cm, 2.5-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-25 cm, 25-30 cm, 30-35 cm, 35-40 cm, 40-45 cm, 45-50 cm, and > 50 cm). Stem density was summarized by stem height classes (total stem count divided by height class) and diameter classes (total stem count divided by diameter at breast height, or DBH). Because of the extremely limited tree flora in the peatland centers—four total canopy/subcanopy species at peatland center—most tree analyses below focus on tree density and size measures.

3.5 Watershed Characteristics

To clarify the effects of climate and landscape context on the physical functioning of peatlands in the Puget Lowlands, we examined the effects of watershed characteristics on hydrologic regimes and porewater chemistry. Mean annual precipitation was estimated from an 800 m grid of 30-year (1980-2010) climate normals (PRISM Climate Group 2012). Watershed area was calculated using flow accumulation grids derived from 1 m digital elevation models. The presence of natural surface water inflows such as intermittent tributaries was determined from aerial imagery, flow accumulation grids, and site reconnaissance.

3.6 Land Use Characteristics

Land use was quantified using four variables, (1) the proportion of impervious surface area within various buffered distances from the wetland boundaries; (2) the proportion of impervious surface area within various buffered distances *within the peatland's watershed*; (3) a Land Use Index within watersheds; and (4) the presence of stormwater management facilities discharging to the wetlands.

Impervious surface areas were estimated from a composite spatial data set consisting of the LANDFIRE U.S. National Vegetation Classification Groups raster (LANDFIRE 2016) superimposed with four additional data sets: Washington State Department of Transportation Roads and Highways (WSDOT 2020), Washington Department of Natural Resources Roads (DNR 2020), Washington Department of Fish and Wildlife High Resolution Change Detection (HRCD; WDFW 2018), and NOAA's Coastal Change Analysis Program data (C-CAP; NOAA 2016). Data sets were scaled to 30 m pixels and superimposed in order from oldest to newest. All roads were considered 100% impervious, including hardened gravel roads. The HRCD, C-CAP, and LANDFIRE impervious map classes were converted from ranges to midpoints (e.g., LANDFIRE "Developed, Low Intensity" was converted from 20-49% impervious to 34.5%). These composite data were used to calculate the proportion of impervious surface areas within each watershed and within 50 m buffer increments from the wetland boundaries to a distance of 500 m.

The Land Use Index (LUI) is a remotely sensed measure of land use intensity (Hauer et al. 2002; Mack 2006; Comer & Faber-Langendoen 2013; Rocchio et al. 2020a, 2020b) derived from the previously mentioned spatial data sets plus recent timber harvests documented in the Washington Forest Practices data set (DNR 2020). The percentage of different land use types within a peatland's watershed was calculated. Each land use type has been assigned a coefficient ranging from 0 (roads and high intensity development) to 1.0 (natural vegetation), with intermediate coefficients assigned to lower intensity land uses such as recent clearcuts (0.3), pastures/hay fields (0.4), and ruderal vegetation (0.5) (Table 6). The LUI for each site was calculated as the average weighted sum of land use type coefficients within the watershed.

The presence of stormwater management facilities discharging to the wetlands was visually inspected using GIS data from applicable municipalities (where available) and by field inspection.

Table 6. Land Use Index Calculation Example

Land Use Categories	Land Use Coefficient	% Area (0 to 1.0)	Score
Paved roads / parking lots	0		
Domestic, commercial, or publicly developed buildings and facilities (non-vegetated)	0	.25	0
Gravel pit / quarry / open pit / strip mining	0		
Unpaved roads (e.g., driveway, tractor trail, 4-wheel drive, logging roads)	0.1		
Agriculture: tilled crop production	0.2		
Intensively developed vegetation (golf courses, lawns, etc.)	0.2		
Vegetation conversion (chaining, cabling, roto-chopping, clearcut)	0.3		
Agriculture: permanent crop (vineyard, orchard, nursery, hayed pasture, etc.)	0.4	.25	0.1
Intense recreation (ATV use / camping / popular fishing spot, etc.)	0.4		
Military training areas (armor, mechanized)	0.4		
Heavy grazing by livestock on pastures or native rangeland	0.4		
Heavy logging or tree removal (50-75% of trees > 30 cm DBH removed)	0.5		
Commercial tree plantations / holiday tree farms	0.5	0.5	0.25
Recent old fields and other disturbed fallow lands dominated by ruderal and exotic species (includes clearcuts that have regenerated with young native trees)	0.5		
Dam sites and flood disturbed shorelines around water storage reservoirs and motorized boating	0.5		
Moderate grazing of native grassland	0.6		
Moderate recreation (high-use trail)	0.7		
Mature old fields and other fallow lands with natural composition (includes former clearcuts with mature native forests)	0.7		
Selective logging or tree removal (< 50% of trees > 30 cm DBH removed)	0.8		
Light grazing or haying of native rangeland	0.9		
Light recreation (low-use trail)	0.9		
Natural area / land managed for native vegetation	1.0		
Total Land Use Index (sum of scores)			**0.35**

3.7 POLLEN ANALYSIS

Understanding the effects of past land use on peatlands is important for setting appropriate management, conservation, and restoration objectives (Ireland and Booth (2012). This project sought to use pollen analysis to detect recent changes (~100-200 years) in vegetation patterns of each site. This information was intended to help discern historical vs more recent changes in peatland vegetation. Peat samples were collected from three of the study sites (Evans Creek, Kings Lake, and Shadow Lake). Peat samples were extracted from monoliths extracted from hummocks. The bottom of the monolith corresponded to the bottom of hummocks (thus the hollows). Hummock monoliths were assumed to be a better record of recent history than peat cores as the cores likely corresponded to ages older Euro-Asian settlement of the region (~1850). Additionally, the monoliths were not affected by compaction and decomposition and did not have the additional depth distortion from compaction that inevitably happens with extraction via the Russian corer. The peat monoliths were extracted in single continuous pieces (~10 cm x 10 cm x length of profile) and packaged into roof gutter sections for transport. In the lab they were frozen and sectioned on a band saw.

Samples for pollen analysis were collected every 3 cm along each site's monolith profile. A total of 20 samples were collected along the 53 cm Evans Creek monolith, 23 samples along the 61 cm Kings Lake monolith, and 35 samples along the 96 cm Shadow Lake monolith.

All pollen was extracted from those 78 samples following standard methods (Fægri and Iversen, 2000). Processed samples were stained and pollen was examined at 400X magnification. Pollen was identified to the lowest taxonomic level possible based on published keys (Fægri and Iversen, 2000; Kapp et al., 2000) and the modern pollen reference collection at the Paleoecology and Biogeography Laboratory at the University of Oregon. *Pinus* (pine) grains were differentiated into *Pinus* and *Strobus* subgenera-types based upon the presence or absence of verrucae on the leptoma. A minimum of 350 terrestrial pollen grains in each sample were identified. Pollen zones are based on a constrained cluster analysis (Grimm, 1987) using the total sum of squares method (based on percentages of tree, shrub and herbaceous taxa).

Continuous sediment sub-samples (1 cm^3) were extracted from each of the three monoliths (n=213). Charcoal particles were counted in each of the sediment sub-samples at two different size fractions (>250 µm and >125 µm) and expressed as a charcoal accumulation rate (CHAR, pieces/cm^2/year).

3.8 Rapid Ecological Assessments

Three rapid assessment and measurement techniques were tested for their ability to provide rapid, surrogate measures of peatland ecological integrity or function. Such techniques may be invaluable when intensive hydrological sampling is not practical.

3.8.1 Ecological Integrity Assessment

Ecological Integrity Assessments (EIA) were conducted at each peatland study site. EIA is a rapid ecological condition assessment method developed by NatureServe and the Natural Heritage Network, providing an estimate of the current ecological integrity of each site (Faber-Langendoen et al. 2019; Rocchio et al. 2020a,b). Protocols followed Rocchio et al. (2020a), with assessment areas (AA) defined by the extent of bog vegetation that occurred in the peatland centers. Vegetation occurring in the outer margins (lagg) were not included in the AA.

3.8.2 Floristic Quality Assessment

Floristic Quality Assessment (FQA)-based index scores were calculated for each well nest using the vascular species composition data from relevé plots collected in this project (Rocchio and Crawford, 2013). Correlation between FQA indices and abiotic variables and stressors (water level, water chemistry, percent impervious surface area, etc.) were assessed using linear regression.

3.8.3 Rapid Measure of Shallow Water Levels

PVC tape is known to discolor at the boundary between aerobic/anaerobic conditions, perhaps providing an inexpensive and rapid measure of water table levels (Bragazza, 1996; Belyea, 1999; Booth et al., 2005; Navrátilová & Hájek, 2005). Bamboo garden stakes mounted with strips of polyvinyl chloride (PVC) electrical tape were inserted in hollows (low points between hummocks) near well nests. Individual stakes were left in the ground for periods of either 6 or 12 months to represent different time periods: winter (= the rainy season, stake in the ground from fall to spring); summer (= the dry season, stake in the ground from spring to fall); or one calendar year. Most well nests had three total stakes inserted for separate 6-month periods, plus one inserted for a 12-month period. A variety of colors were used (white, blue, red, green, yellow, and black), but all were PVC-based. Colors were selected randomly for each stake. Stakes were approximately 180 cm long. A portion of each stake was left above ground (stickup height) to aid in relocation and to capture anticipated water level increases above the soil surface. Installed stickup heights generally varied between 15 and 45 cm, though some were as high as 110 cm (in lagg sites with particularly impenetrable shallow soil layers).

The height of the stake above the peatland surface was measured at installation and at the time of collection (to ensure that the stake had not been disturbed). After retrieving the stake, a field measurement was made from the top of the stake to the first visible discoloration (hypothetically the highest level that the water level reached over that time period). A field measurement to the point of full PVC discoloration was also made (the hypothesized lowest water level over the time period), as in Belyea (1999). An independent observer later repeated both sets of measurements in the laboratory, where muck and other obscuring material could be removed more thoroughly. This also provided the opportunity to make measurements under a consistent light source and to compare like-colored stakes side-by-side. All measurements were made to the nearest 0.5 cm and the observer did not have access to the field measurements. Stickup heights (from the time of collection) were subtracted from all measurements.

3.9 Determining Ombrotrophic Conditions of Study Sites

Ombrotrophic conditions were determined based on the preponderance of topographic, hydrologic and chemical evidence collected from each site. At a subset of the study sites lateral hydraulic gradients (between the peatland and lagg) and vertical hydraulic gradients (within the peat body) were analyzed to determine the direction of groundwater flow as an indicator of water source. Porewater chemistry was compared to published values for ombrotrophic and minerotrophic peatlands in other regions, as well as to regional precipitation and groundwater chemistry. Water flow from the peatland center toward the lagg is suggestive of ombrotrophic conditions, while a water table draining in the reverse direction (from lagg to peatland center) likely indicates minerotrophic water sources, in this case the dominance of lateral ground water inputs from the wetland margin.

Topography of peatland centers and laggs were determined using lidar. A subset of eight sites were surveyed with a laser level, using the ground surface at wells in peatland centers as a common datum. The latter eight sites were used to investigate lateral hydraulic gradients by comparing daily mean water table hydrographs between peatland center and lagg wells. Four of these sites occur within a managed timber landscape (Arrowhead, Cranberry Marsh 2, Cranberry Marsh 4, and Kings Lake), while four were surrounded by various degrees of suburban development (Echo Falls, Evans Creek, Queens Bog, and Springer Lake).

Ombrotrophic conditions can also be indicated by negative vertical hydrologic gradients (VHGs), which describe the direction and potential magnitude of vertical groundwater fluxes. Negative gradients indicate gravitational drainage downward through the peat profile and typically reflect ombrotrophic conditions. Large positive gradients indicate upward groundwater flow and are usually associated with partially confined aquifers, or rapid macropore flow through a low-permeability matrix that creates higher water potentials at depth. Negligible VHGs occur where groundwater movement is horizontal or nonexistent due to ponding, which could occur under ombrotrophic conditions or not. As such, negligible VHGs are not clear indicators of ombrotrophic conditions.

Porewater chemistry is also commonly used to distinguish between ombrotrophic and minerotrophic peatlands. Porewater pH is often useful for separating ombrotrophic bogs from poor fens, and exhibits less seasonal variability than ionic concentrations (Wheeler and Proctor 2000, Bourbonniere 2009). Bogs in the northern hemisphere have pH values less than 5.0 and often less than 4.5. Hard thresholds for electric conductivity measures in ombrotrophic peatlands are uncommon in the literature, but Vitt et al. (1995) identified a threshold of < 39 μS/cm for ombrotrophic bogs but we used 50 μS/cm for this analysis. Relative to poor fens, ombrotrophic peatlands also generally have lower concentrations of most major cations, but higher concentrations of Cl, SO_4^{2-}, and Na^+, although ranges overlap considerably (Bourbonniere 2009). Since Ca^{2+} is scarce in precipitation, Ca^{2+} concentrations can be a very useful indicator of ombrotrophic conditions. Molar Ca:Mg in ombrotrophic peatlands are also typically less than 1.0 (Proctor et al. 2009). Other researchers have noted that < 2.5 mg/L of Ca^{2+}, or a Ca^{2+}/Mg^{2+} ratio of 1.0 are also indicative of ombrotrophic conditions (Malmer et al. 1992, Sjörs and Gunnarsson 2002, McHaffie et al. 2009, Joosten et al. 2017b).

3.10 Statistical Analyses

3.10.1 Hydrology and Water Chemistry Analyses

Variability in daily mean water levels was analyzed at annual, seasonl, and monthly timescales, while hydraulic gradients and water chemistry were analyzed at seasonal time scales (spring and late summer). Water level fluctuations (WLF) were analyzed as the range of daily mean water levels over the same timescales, following Azous and Horner (1997). Watershed and land use effects on porewater ionic concentrations were analyzed for a subset of representative ions. Chloride was used to represent anion variability, since it is unaffected by redox conditions that can alter SO_4^{2-} concentrations in wetlands. Calcium was used to characterize cation inputs to wetlands, and its concentrations were strongly correlated to those of magnesium ($r = 0.947$; $p < 0.001$) and sodium ($r = 0.754$, $p < 0.001$). Nitrate concentrations were negligible in most water samples and were not analyzed, but the major nutrients NH_4^+, and PO_4^{3-} were analyzed.

3.10.2 Watershed and Land Use Analyses

All analyses of the longitudinal data were done with linear mixed-effects models using sites as the repeated measures subjects. In these models, measured watershed and site characteristics were analyzed as fixed effects, while random effects were used to account for any unmeasured latent variables. The effects of watershed characteristics and land use metrics were analyzed separately for peatland centers and laggs to preserve degrees of freedom and simplify model interpretation.

For each analysis, we evaluated models consisting of all combinations of watershed and land use variables allowing for two-way interactions ($n = 189$), using the Akaike Information Criterion (AIC). This commonly used model comparison metric identifies the most parsimonious models (lowest AIC score) by weighing model fit against a penalty for model complexity (number of variables). However, since AIC and other model comparison methods do not distinguish between fixed and random effects, we used likelihood ratio tests to examine the significance of fixed effects for the ten models with the lowest AIC scores to obtain the most parsimonious explanatory model, and only models with statistically significant terms were considered. Independent variables were converted to z-scores prior to model fitting to account for autocorrelations and varying measurement scales, thereby allowing their relative importance to be assessed directly from the model coefficients. All mixed-effects model analyses were done with the R package 'lme4' version 1.1-26. Marginal r^2 values (variance explained by fixed effects) were calculated using the package 'MuMln' version 1.43.17, and post-hoc comparisons using Tukey-adjusted p-values were made using the package 'lsmeans' version 2.30-0. All other analyses were done with base functions in R version 4.0.3 (R Core Team 2020).

3.10.3 Vegetation Analyses

Nonparametric Multivariate Analysis of Variance (PERMANOVA; Anderson, 2001, 2017) was used with Bray-Curtis distance measures to test the hypothesis of significant vegetation compositional differences across factors. All analyses used raw species cover data. The use of log+1 transformations or Beal's smoothing did not meaningfully impact the interpretations.

Nonmetric Multidimensional Scaling (NMS) ordinations were used to illustrate the relationships demonstrated in the PERMANOVA results (Mather, 1976; Kruskal & Wish, 1978; McCune et al., 2002; McCune & Mefford, 2018). NMS analyses used the Sørensen (Bray-Curtis) distance measure, random starting configurations based on the time of day, 250 runs with real data, and a stability criterion of 0.000001. Only the number of dimensions beyond which additional axes provided only minimal reductions in stress were chosen, based on Monte Carlo tests (Metropolis & Ulam, 1949). Biplots used an r^2 cutoff of 0.20.

Indicator Species Analysis (ISA) (Dufrêne & Legendre, 1997) was used to identify diagnostic/differential plant species for reference and developed study sites, as well as other significant categorical hydrological and land use variables. ISA was performed using quantitative responses (Dufrêne & Legendre ISA eqn. 1), a randomization test, 4999 runs, and a 'time of day' starting seed. Tree stem density was analyzed using multiple linear regression.

All ordinations and non-PERMANOVA floristic analyses used PC-ORD v.7.08 (McCune & Mefford, 2018). All PERMANOVA analyses were performed using the Adonis function in the R package 'vegan' (Oksanen et al., 2020). Multiple linear regressions were performed using base functions in R version 4.1.3 (R Core Team, 2021) via RStudio (RStudio Team, 2022). Watershed and land use predictor variables were converted to z-scores prior to regression analysis.

3.10.4 Rapid Assessment Analyses

The EIA major ecological factor, primary rank factor, and overall scores were correlated with abiotic and land use variables using linear regression. The correlation between FQA indices and abiotic and land use variables (water level, water chemistry, % impervious surface area, etc.) were assessed using linear regression. FQA indices were also compared to EIA scores using simple linear regression. All EIA and FQA linear regressions were calculated in R (R Core Team, 2021; RStudio Team, 2022).

The accuracy and precision of PVC surrogate water table measures were tested using simple linear regressions. Water levels derived from the garden stakes were correlated with the daily mean water levels recorded by a data logger in the nearby shallow well. Since color changes may take up to a week to occur (Belyea, 1999; Booth et al., 2005), the beginning and end of each time series was trimmed by seven days. Regressions were fitted for the following variables: minimum, maximum, mean, 5th percentile, and 95th percentile daily mean water levels over the period of time in which the stake was in place. The data logger water levels were considered to be the dependent variable.

Table 7. PERMANOVA factors considered when analyzing vascular and nonvascular composition. Level 1 EIA is a GIS-based assessment while Level 2 EIA is a rapid-field based assessment.

Natural Factors	Hydrological & Hydrochemical Factors*	Land Use Factors
Mean annual precipitation	Mean August water level	Whether there are stormwater inflows
May-Sept precipitation	Minimum August water level	Land Use Index of watershed (WNHP Draft Level 1 EIA)
Whether there are natural inflows	Maximum August water level	Land Use Index of 100 m buffer (WNHP Level 2 EIA)
Watershed area	Mean January water level	Land Use Index of 500 m buffer (WNHP Level 2 EIA)
Whether or not the bog borders a lake	Minimum January water level	% impervious surface w/i the watershed
Minimum/maximum elevation of watershed	Maximum January water level	% impervious surface w/i 100 m buffer of wetland**
	Spring mean pH	% impervious surface w/i 150 m buffer of wetland**
	Spring mean EC_{corr}	% impervious surface w/i 200 m buffer of wetland**
	Summer mean pH	% impervious surface w/i 250 m buffer of wetland**
	Summer mean EC_{corr}	% impervious surface w/I 300 m buffer of wetland**
	Spring mean Ca	% impervious surface w/i 350 m buffer of wetland**
	Summer mean Ca	% impervious surface w/i 400 m buffer of wetland**
	Spring mean Mg	% impervious surface w/i 450 m buffer of wetland**
	Summer mean Mg	% impervious surface w/i 500 m buffer of wetland**
	Spring Ca:Mg	
	Summer Ca:Mg	

*May be impacted by surrounding land use (but are not themselves direct measures of land use).
**Assessed two ways: 1) simple buffer of wetland boundary and 2) buffer constrained by lidar-derived flow accumulation model of watershed.

Independent variables were the initial color change on the stake (estimated maximum water level), complete color change on the stake (estimated minimum water level), and the midpoint between the two (estimated mean water level). Analyses were subset by the following covariates: color of electrical tape used (light = yellow or white; dark = blue, red, green), peatland location (peatland center v. lagg), measurement type (field or lab), and the period of time that the stake was in the ground (summer, winter, or a full year). One-way ANCOVA was used to determine if the relationship between the data logger water levels and the surrogate water table measures varied significantly with these covariates. These analyses were performed using base functions in R version 4.1.3 (R Core Team, 2021) via R Studio (RStudio Team, 2022).

3.10.5 Pollen Analyses

For both the Evans Creek and Kings Lake peat cores a linear interpolation age model was used to assign ages for each sample depth based on the year the core was taken (2019) and the depth at which a modern age was returned from radiocarbon data (Evans Creek - 81 cm and Kings Lake - 65 cm). No other tie points could be determined based on charcoal abundance or changes in pollen.

The sedimentation rate for the Evans Creek was determined to be 1.42 cm/yr while the Kings Lake core sedimentation rate is 1.14 cm/yr

The ages for the Shadow Lake peat core were assigned using three different points, the year the core was extracted (2019), a peak in charcoal abundance occurring at 64 cm that likely dates to 1930 (a fire burned the area around the lake), and the youngest radiocarbon date (103 cm). Using these two tie points, the age model provided two sedimentation rates. The sedimentation rate at the base of the core (66 to 96 cm) is 0.24 cm/yr. The top third of the core (0-66 cm) has a higher sedimentation rate of 1.67 cm/yr.

All pollen data are represented as a percentage of the total pollen sum of the arboreal (tree and shrub taxa) and herbaceous taxa present.

4.0 RESULTS

4.1 ECOLOGICAL CHARACTERISTICS OF PUGET LOWLAND PEATLANDS

4.1.1 Hydrological Patterns of Puget Lowland Peatlands

Depending on the site, hydrological monitoring included the period from approximately August 2018 through spring or summer of 2021 (Table 8). Water levels within peatland centers and surrounding laggs had pronounced seasonal variability driven by precipitation (Figure 6). The annual maximum water level occurred in January and February in all sites, when evapotranspiration was minimal during the cool winter rainy season. The annual minimum water level occurred in August and September at all sites, at the end of the summer dry period. Hydroperiods were strongly synchronous between peatland centers and laggs, but water levels relative to the ground surface were consistently higher in laggs, where flooded conditions prevailed in all but the dry summer months (Figure 6, Figure 7). Water level fluctuations (WLF) were greatest during August-October, at the transition between dry and wet periods (Figure 8, Figure 9).

Peatland centers had mean water levels averaging 1.4 ± 2.3 cm (mean ± SE) during January, and declined to their lowest point in August when the average was -40.9 ± 4.9 cm. Mean annual water levels in reference peatland centers averaged -15.5 ± 2.8 cm and did not differ those in developed landscapes ($p = 0.40$), which averaged -13.3 ± 1.3 cm. Peatland center mean water levels also did not differ between reference and developed sites over seasonal ($p = 0.16$) or monthly timescales ($p = 0.19$), although water table depths were often deeper in some reference peatland centers during August and September. WLF within peatland centers did not differ between reference and developed landscapes on annual ($p = 0.13$) or seasonal timescales ($p = 0.59$), but monthly differences were apparent ($p = 0.067$). Reference peatland centers had larger WLFs during September and October ($p < 0.042$). Mean monthly water levels in developed area peatland centers were more variable than those in reference areas during October-June, while reference peatland center water levels demonstrated substantially larger variability during August-September, when some reference sites were dry. Laggs typically had standing water from November-June, with mean monthly water depths of 9.0 to 26.6 cm. Similar to the peatland centers, lagg water levels declined during the summer, falling to an average depth of -26.5 ± 7.3 cm during August, although some laggs remained inundated throughout the year. Mean annual water levels were lower in reference laggs than those in developed landscapes ($p < 0.001$), respectively averaging -3.1 ± 2.4 cm and 12.3 ± 2.4 cm, but these differences did not vary by season ($p = 0.97$) or month ($p = 0.97$). WLF in laggs did not differ between reference and developed landscapes on annual ($p = 0.63$), seasonal ($p = 0.29$), or monthly ($p = 0.61$) timescales.

Peatland center water tables were higher than lagg water levels at three of the four surveyed sites in developed landscapes (Figure 11). Water table elevations in peatland centers at Evans Creek and Queens Bog exceeded those in their laggs throughout the monitoring period, averaging 7.3 ± 0.01 cm and 8.2 ± 0.01 cm higher than laggs receiving stormwater inflow ($p < 0.001$). The peatland center water table at Echo Falls was also higher than in the lagg for 88.4% of the monitoring period, averaging 14.4 ± 0.02 cm higher ($p < 0.001$), but data from the stormwater inflow segment suggested that these inflows drove water table fluctuations across the site. Water levels in the stormwater inflow segment exceeded those in the peatland during 92.0% of the record and averaged 37.1 ± 0.01 cm higher ($p < 0.001$), and they were always higher than in the reference lagg. However, data were limited from the stormwater inflow monitoring well due to repeated damage from a resident bear. Peatland center water levels at Springer Lake were lower than in the lagg (-2.4 ± 0.01 cm; $p < 0.001$) and these tightly coupled water levels appeared to be driven by variation in the Springer Lake water level.

Table 8. Hydrologic records from 17 Puget Lowland *Sphagnum*-dominated peatlands.

Site	Well	Position	Record Period	Days in Record
Arrowhead	AH-1	Peatland	8/06/18 - 4/27/21	991
	AH-2	Lagg		993
Covington 8	C8-1	Peatland	5/11/18 – 8/31/21	1201
	C8-2	Lagg		1202
Covington 12	C12-2	Peatland	5/11/18 – 8/31/21	1201
	C12-1	Lagg		1185
	C12-3	Peatland “Edge”		1196
Cranberry Marsh #2	CM2-2	Peatland	7/30/18 – 4/27/21	997
	CM2-1	Lagg		971
Cranberry Marsh #4	CM4-1	Peatland	8/12/18 – 4/27/21	784
	CM4-2	Lagg		980
Evans Creek	EC-1	Peatland	5/12/18 – 7/08/21	1146
	EC-2	Stormwater inflow		1148
Echo Falls	ECH-1	Peatland	8/03/18 – 7/08/21	1044
	ECH-2	Lagg		1049
	ECH-3	Stormwater inflow		385
Hooven	HO-2	Peatland	5/13/18 – 7/07/21	1147
	HO-1	Lagg		1149
Kings Lake	KL-2	Peatland	5/12/18 – 7/27/21	1166
	KL-1	Lagg		1164
	KL-3	Natural inflow		1169
Lower Cedar River	LC-2	Peatland 2	5/11/18 – 9/16/21	1220
	LC-1	Lagg		1220
	LC-3	Peatland 1 (high point)		1222
Lake Dorothy	LD-2	Peatland	5/08/18 – 9/07/21	1216
	LD-1	Lagg		832
	LD-3	Stormwater inflow		1215
Patterson	PA-1	Peatland	5/09/18 – 8/08/21	1171
	PA-2	Lagg		1006
Queens	Q-2	Peatland	5/13/18 – 9/07/21	1211
	Q-3	Lagg		1210
	Q-1	Stormwater inflow		1209
Shadow Lake	SL-2	Peatland	5/11/18 – 9/17/21	1216
	SL-1	Lagg		1220
Springer Lake	SPL-1	Peatland	8/01/18 – 4/20/21	985
	SPL-2	Lagg		991
Trossachs	TR-1	Peatland	5/07/18 – 9/07/21	1036
	TR-3	Stormwater inflow		1208
	TR-2	Peatland “Edge”		1035
Wetland 14	W14-1	Peatland	5/11/18 – 9/16/21	1219
	W14-2	Stormwater inflow		1221

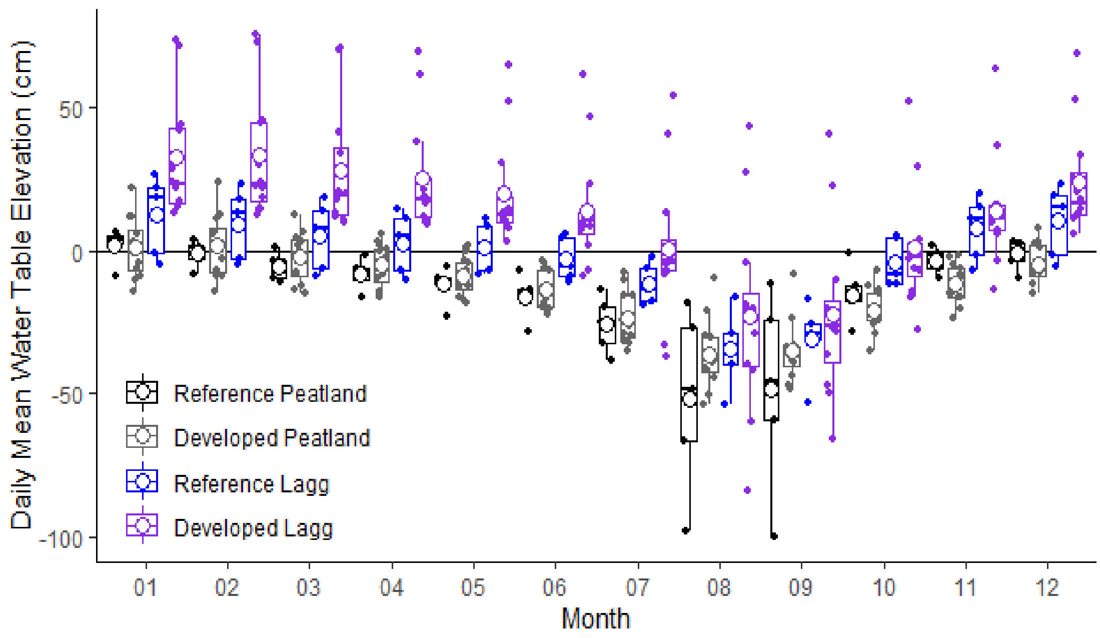


Figure 6. Mean monthly water levels relative to ground surface in peatland centers and laggs. Circles are means, boxplot centerlines are medians, shoulders are 25th and 75th percentiles, and whiskers are 5th and 95th percentiles. Jittered points are site means. Reference sites have no impervious surface within 50 m of the wetland.

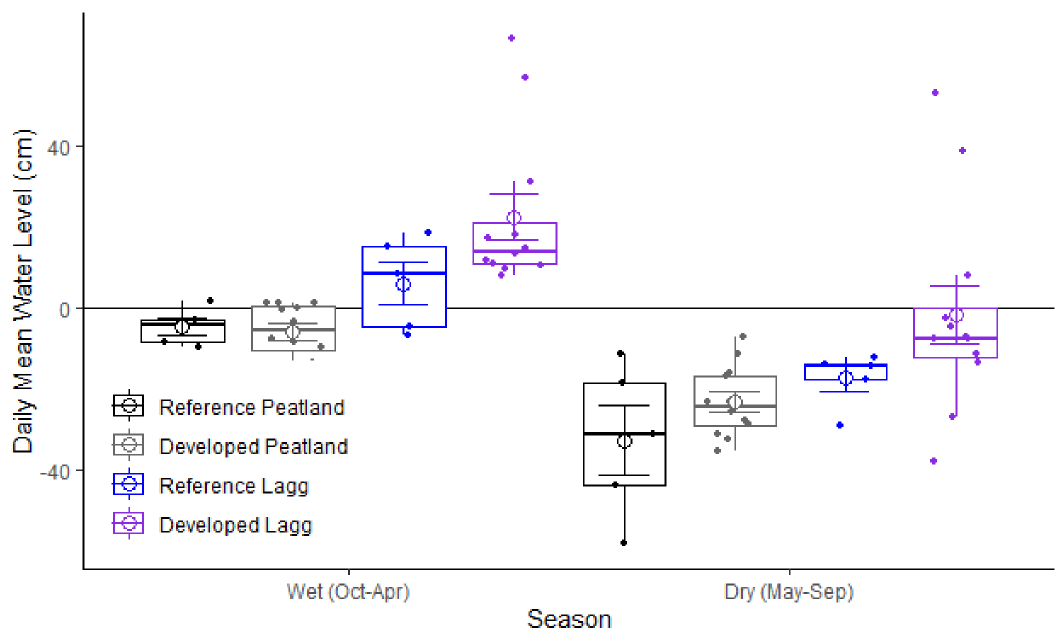


Figure 7. Mean seasonal water levels relative to ground surface in peatland centers and laggs.

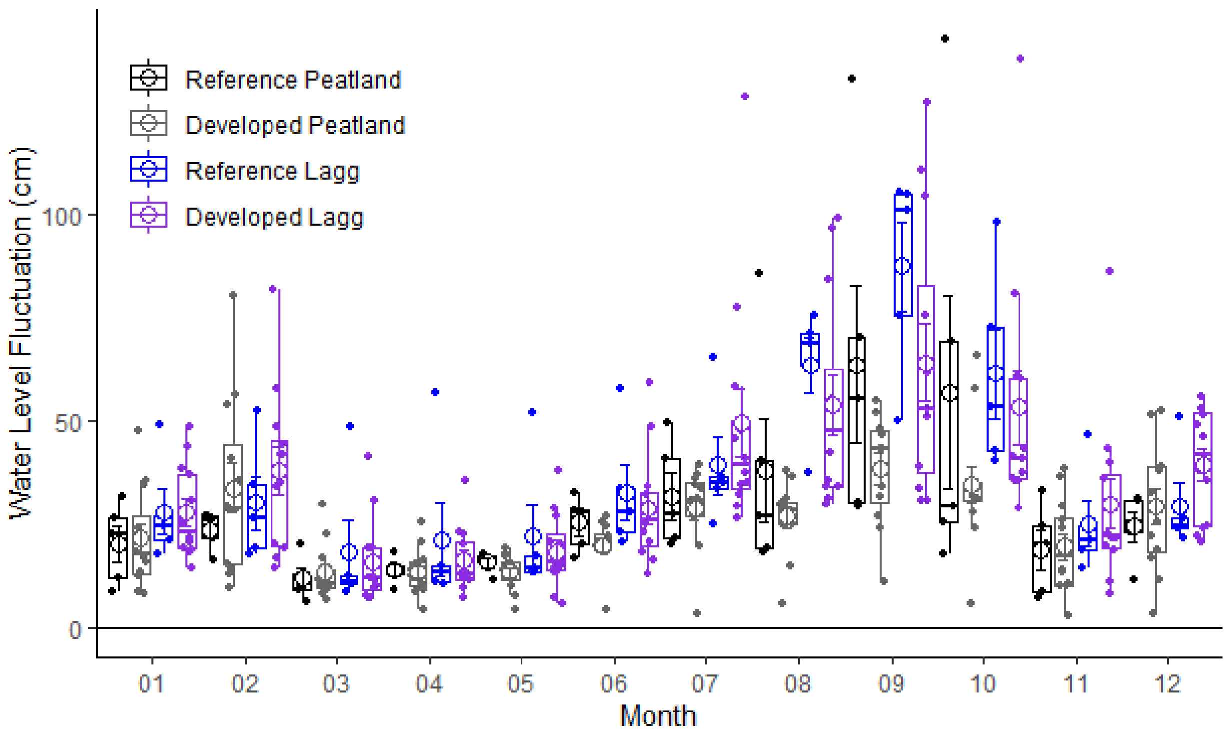


Figure 8. Mean monthly WLF relative to ground surface in peatland centers and laggs.

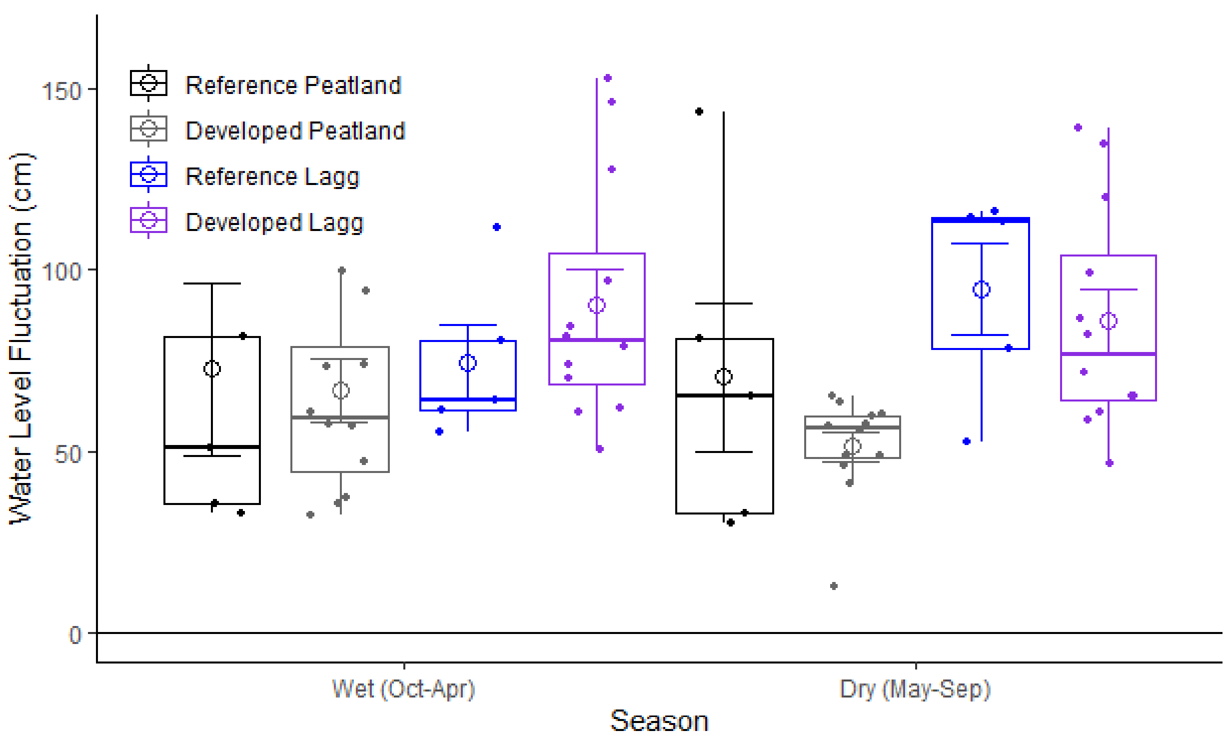


Figure 9. Mean seasonal WLF relative to ground surface in peatland centers and laggs.

Hydraulic gradients in peatland centers were highly variable and did not consistently indicate lateral flow from peatland centers toward the laggs. Of the eight sites surveyed for elevation, lateral hydraulic gradients between peatland centers and laggs reflected slightly raised water tables at five of the surveyed sites, including two out of four reference sites (Figure 10, Figure 11). Nine sites could not be surveyed due to dense vegetation cover, and available lidar point clouds were not dense enough to provide reliable elevations at the well locations. The water table in the peatland center was higher than in the lagg during 95.4% of the study period at Cranberry Marsh 2, averaging 4.6 ± 0.01 cm higher ($p < 0.001$). Similarly, the peatland center water table at Kings Lake exceeded that in the lagg during 99.1% of the monitoring period, averaging 10.4 ± 0.01 cm higher ($p < 0.001$). Water table levels during the rainy season were remarkably stable at Kings Lake, where the outflow appeared to control peatland center water levels. In contrast, lagg water levels equaled or exceeded those in the peatland centers at two reference sites (Arrowhead and Cranberry Marsh 4) during 100% and 92.2% of the monitoring period, suggesting that lateral inputs of surface water or groundwater from the lagg to the peatland center may be occurring in these wetlands.

Piezometer data collected during spring and late summer indicated considerable variation in vertical hydraulic gradients (VHGs) between sites, but means were similar across season, wetland position, and land use (Figure 12). Mean VHGs in the upper portions of peat bodies (50-100 cm depth) were generally more variable than those for the entire profile (to 200 cm depth) due to very small VHGs at greater depths. Peatland VHGs between 50 and 100 cm depth averaged -0.06 ± 0.03 cm/cm and did not vary between seasons ($p = 0.73$) or differ between reference and developed sites ($p > 0.46$). Lagg mean VHG at this depth was similar (-0.05 ± 0.04 cm/cm; $p > 0.53$) and did not vary with season ($p = 0.48$) or differ between reference and developed sites ($p > 0.33$). Similar patterns were apparent for VHGs over the full profiles, averaging -0.05 ± 0.02 cm/cm in peatland centers and -0.03 ± 0.04 cm/cm in laggs, although laggs in developed landscapes were the most variable.

Although the sample means indicated slight downward gradients within peatland centers, complex seasonal variation was apparent across sites (Table 9). Peatland centers at Arrowhead, Cranberry Marsh 4, Patterson, and Queens Bog showed strong downward gradients ($\leq$ -0.10 cm/cm) during spring and late summer. Evans Creek and Shadow Lake had negligible VHGs during spring, indicating that stable water levels or lateral flow prevailed during the rainy season, but downward drainage occurred during the dry late summer period. Shallow VHGs were also near zero at Covington 12 and Wetland 14 during spring, but strong positive gradients ($\geq$ 0.10 cm/cm) during late summer suggested that upward groundwater flow occurred between 50 and 100 cm depth at these sites. Springer Lake and Echo Falls had seasonal reversals in vertical flow direction, with upward flow during spring at the former and downward flow during summer at the latter. Vertical gradients between 50 and 100 cm depth were very small during both seasons at the remaining seven sites (Covington 8, Cranberry Marsh 2, Hooven, Kings Lake, Lake Dorothy, Lower Cedar, and Trossachs), suggesting that saturated flow was negligible or predominantly horizontal. Few site-level seasonal means were significantly different from zero due to large variability within small sample sizes.

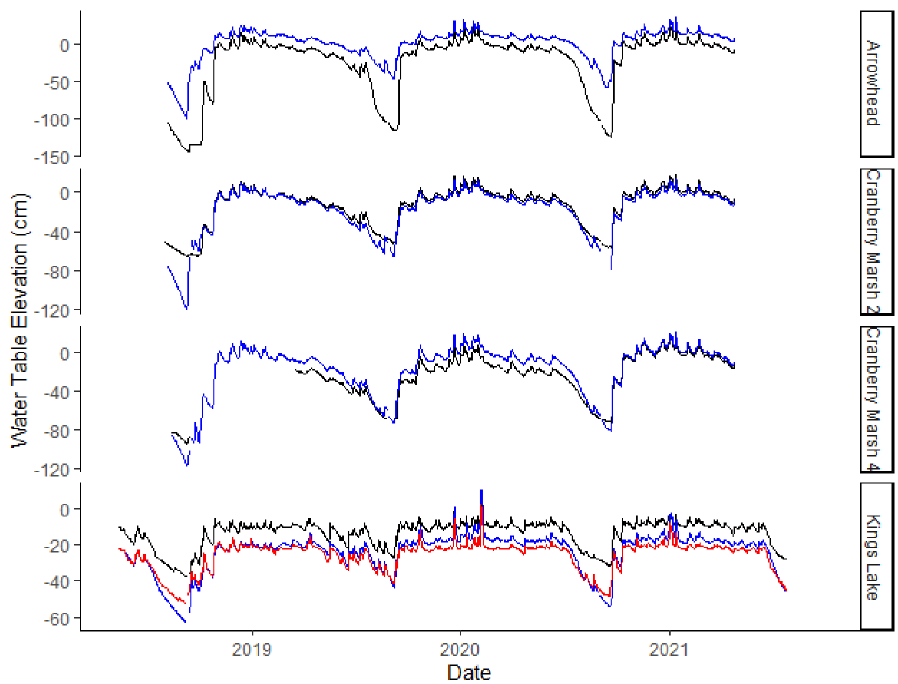


Figure 10. Daily mean groundwater levels at four reference sites. Black lines are wells in peatland centers, blue lines are wells in laggs, and red lines are wells in stormwater inflows. Note different scales on y-axis**.**

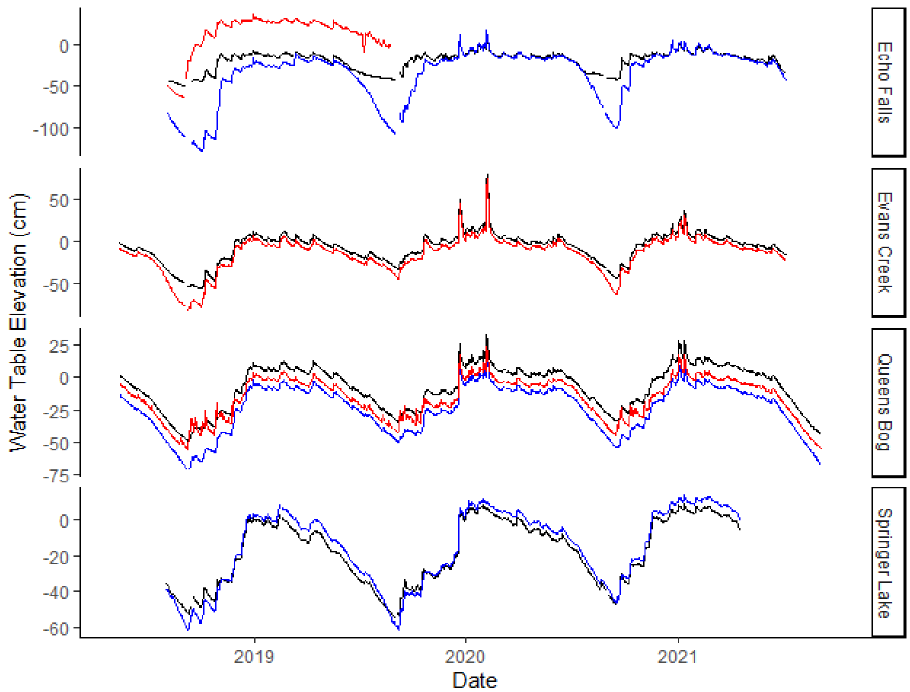


Figure 11. Daily mean groundwater levels at four developed sites. Black lines are wells in peatland centers, blue lines are wells in laggs, and red lines are wells in stormwater inflows. Note different scales on y-axis.

Table 9. Mean spring and summer vertical hydraulic gradients over 50-100 cm depth in peatland centers. P-value is from t-tests that means differ from zero. Grey cells: $p < 0.10$, bold text: $p < 0.05$. *n/a = small sample size or invariant values precluded t-test.

Site	Spring Mean±SE	p	Summer Mean±SE	p	Vertical Flow Direction
Arrowhead	-0.37±0.06	0.10	Dry	n/a	Downward
Covington 12	+0.06±0.05	0.44	+0.12±0.02	0.08	Upward
Covington 8	+0.04±0.00	NA*	+0.01±0.00	n/a*	Negligible
Cranberry Marsh 2	+0.07±0.02	0.14	+0.02±0.00	n/a*	Negligible
Cranberry Marsh 4	-0.12±0.01	0.05	Dry	n/a	Downward
Echo Falls	+0.22±0.16	0.40	-0.10±0.08	0.32	Upward
Evans Creek	-0.01±0.04	0.91	-0.25±0.17	0.24	Downward
Hooven Bog	-0.07±0.05	0.39	**-0.02±0.00**	**0.01**	Negligible
Kings Lake	-0.05±0.01	0.13	+0.01±0.03	0.67	Negligible
Lake Dorothy	+0.01±0.00	n/a*	+0.01±0.01	0.51	Negligible
Lower Cedar	+0.03±0.01	0.16	-0.02±0.01	0.18	Negligible
Patterson	-0.33±0.15	0.27	**-0.65±0.13**	**0.01**	Downward
Queens Bog	**-0.12±0.00**	**0.03**	**-0.14±0.01**	**0.001**	Downward
Shadow Lake	0.00±0.01	1.0	**-0.14±0.01**	**0.05**	Downward
Springer Lake	-0.10±0.03	0.19	+0.11±0.04	0.14	Upward
Trossachs	0.05±0.05	0.50	-0.04±0.04	0.46	Negligible
Wetland 14	-0.01±0.02	0.80	**+0.18±0.03**	**0.01**	Upward

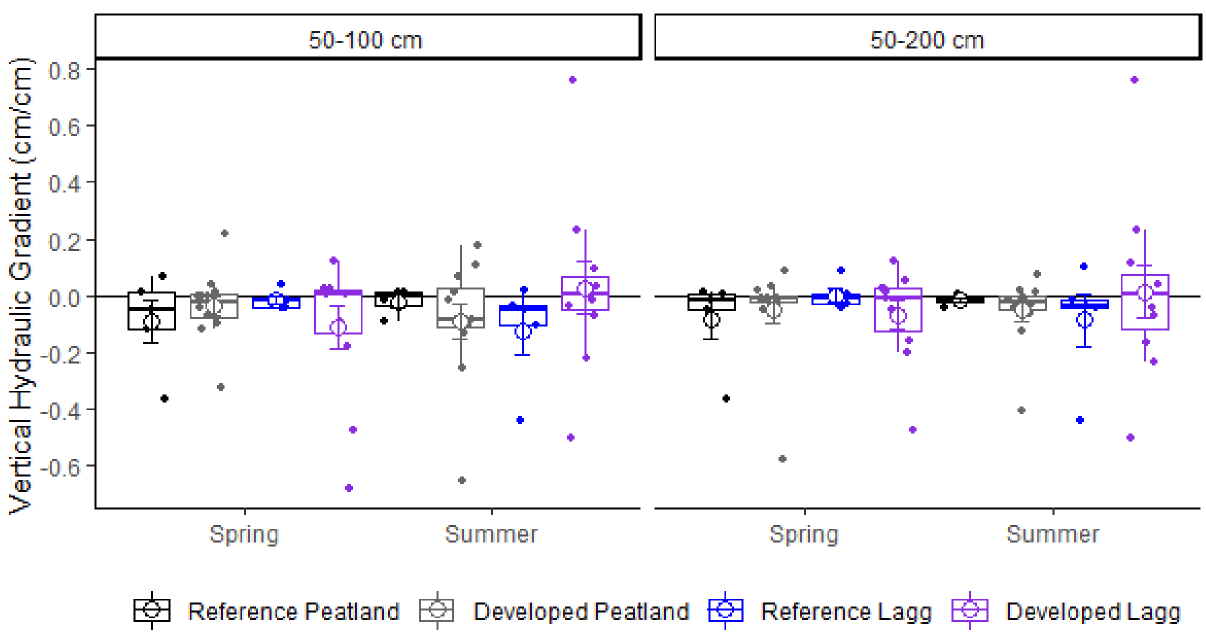


Figure 12. Mean seasonal vertical hydraulic gradients over 50-100 cm depth and the entire profile (to 200 cm depth) in peatland centers and laggs. Positive values reflect upward gradients, while negative values indicate downward gradients. See symbol description in Figure 6

4.1.2 Water Chemistry of Puget Lowland Peatlands

Porewater chemistry differed significantly between peatland centers and laggs, and many parameters showed pronounced seasonal variability. Mean pH in peatland centers was 4.22 ± 0.04 in spring, with a small but significant increase ($p = 0.008$) to 4.43 ± 0.04 by late summer (Figure 13). Mean peatland center pH did not differ between reference and developed sites in either season ($p > 0.94$). Porewater pH was significantly higher in laggs during spring and summer ($p < 0.001$), averaging 5.36 ± 0.11, but did not vary between seasons ($p = 0.77$). Reference lagg pH was lower than in developed sites during spring (5.02 ± 0.30 versus 5.66 ± 0.18; $p = 0.064$), but the means were similar during summer ($p = 0.12$). Mean EC_{corr} was lower in peatland centers than laggs ($p < 0.01$) and was lower in spring than late summer in both settings ($p < 0.001$; Figure 14). Mean EC_{corr} in peatland centers was 27.8 ± 2.7 μS/cm during spring and 47.2 ± 4.2 μS/cm during late summer. In laggs, mean EC_{corr} was 69.6 ± 14.0 μS/cm during spring and 136 ± 24.0 μS/cm by late summer. Mean EC_{corr} during spring was lower in reference sites than in developed landscapes for both peatland centers (16.6 ± 2.8 versus 31.6 ± 2.9 μS/cm; $p = 0.01$) and laggs (24.5 ± 5.2 versus 93.9 ± 18.2 μS/cm; $p = 0.02$), but differences were not detected in either setting during late summer ($p > 0.12$).

Porewater concentrations of major anions were lower in peatland centers than laggs and were generally higher during late summer in both wetland positions (Figure 15). Mean Cl^- concentration in peatland centers was 1.30 ± 0.13 mg/L during spring and 2.24 ± 0.26 mg/L during summer ($p = 0.003$). Seasonal mean Cl^- concentrations in peatland centers did not differ between reference and developed sites ($p > 0.12$). Mean Cl^- concentration in laggs was 3.85 ± 0.53 mg/L, and although this did not vary seasonally ($p = 0.77$), it exceeded concentrations in peatland centers during spring ($p = 0.002$) and summer ($p = 0.06$). Mean lagg Cl^- concentration in developed landscapes was 3.8 and 4.5 mg/L higher than in reference sites during spring and summer ($p < 0.004$). Mean SO_4^{2-} concentrations were also lower in peatland centers ($p < 0.002$), averaging 0.03 ± 0.00 mg/L during spring and 0.14 ± 0.30 mg/L during summer. Mean SO_4^{2-} concentrations in laggs were lower in spring, 0.44 ± 0.12 mg/L, than summer 1.62 ± 0.44 mg/L ($p = 0.01$). During spring, mean SO_4^{2-} concentrations were lower in reference sites for both peatland centers (0.01 ± 0.00 versus 0.03 ± 0.01 mg/L; $p = 0.03$) and laggs (0.11 ± 0.07 versus 0.61 ± 0.16 mg/L; $p = 0.04$), but reference sites were not distinguishable from developed sites in either setting during summer ($p > 0.40$).

Major cation concentrations did not vary seasonally in peatland centers ($p > 0.25$) and were generally lower than in laggs. Ca^{2+}, $Mg,^{2+}$ and Na^+ concentrations were higher ($p < 0.008$) during the growing season in laggs (Figure 15). Mean Ca^{2+} concentration was 1.08 ± 0.21 mg/L in peatland centers and did not differ between reference or developed sites ($p > 0.25$). Porewater Ca^{2+} concentrations were higher in laggs relative to peatland centers during both seasons ($p < 0.05$), increasing from 2.42 ± 0.45 mg/L in spring to 6.50 ± 1.13 mg/L in late summer. Mean Ca^{2+} was lower in reference laggs than laggs in developed landscapes during spring (0.79 ± 0.16 versus 3.31 ± 0.55 mg/L; $p = 0.004$), but differences were not significant during late summer ($p = 0.50$). Similar patterns were evident for Mg^{2+} and Na^+ concentrations, which averaged 0.52 ± 0.15 and 1.74 ± 0.16 mg/L in peatland centers and did not differ between reference and developed sites ($p > 0.21$). Mean lagg porewater Mg^{2+} concentration was 1.02 ± 0.20 mg/L in spring and 2.83 ± 0.60 mg/L in summer, while Na^+ concentration was 2.56 ± 0.43 mg/L in spring and 4.82 ± 0.68 mg/L in summer. Lagg Mg^{2+} and Na^+ concentrations were higher in developed landscapes during spring ($p < 0.01$) but not summer. In contrast to the other cations, porewater K^+ concentrations did not vary

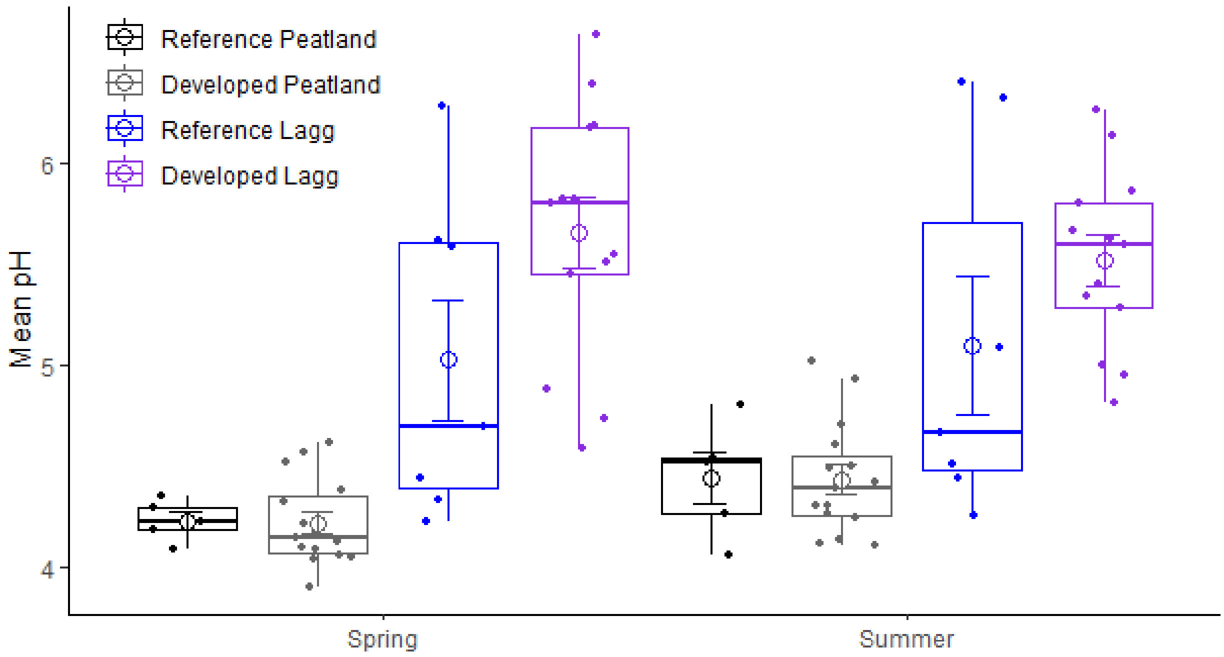


Figure 13. Mean seasonal pH of porewater in peatland centers and laggs.

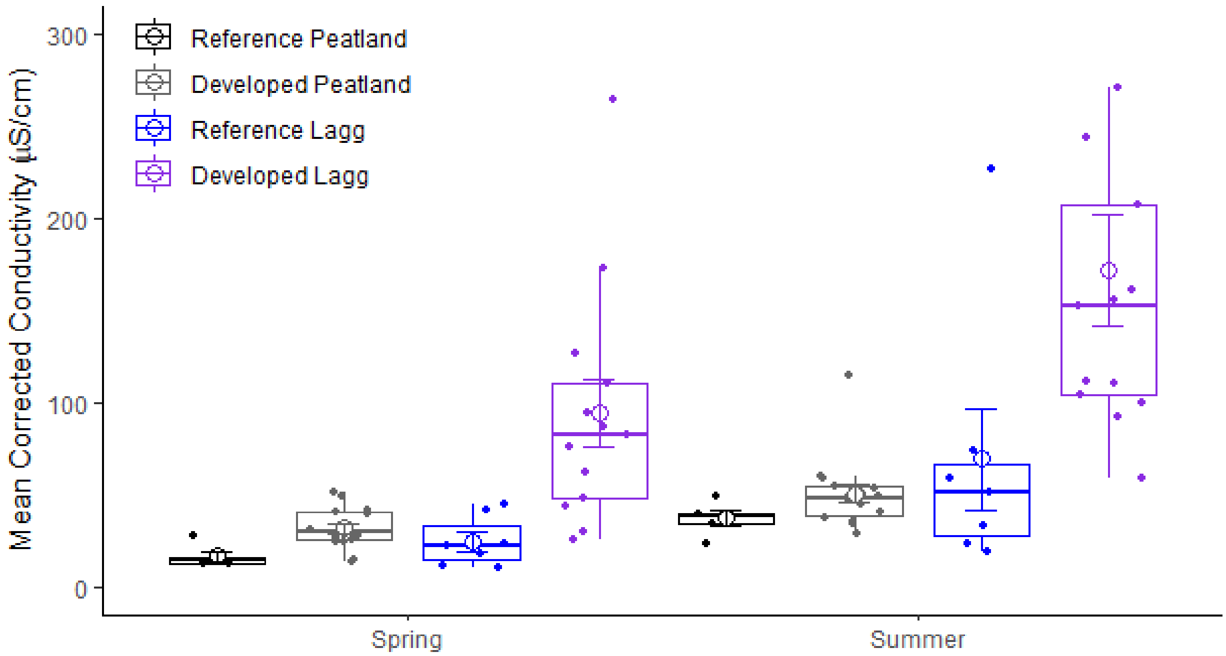


Figure 14. Mean seasonal corrected specific conductivity of porewater in peatland centers and laggs.

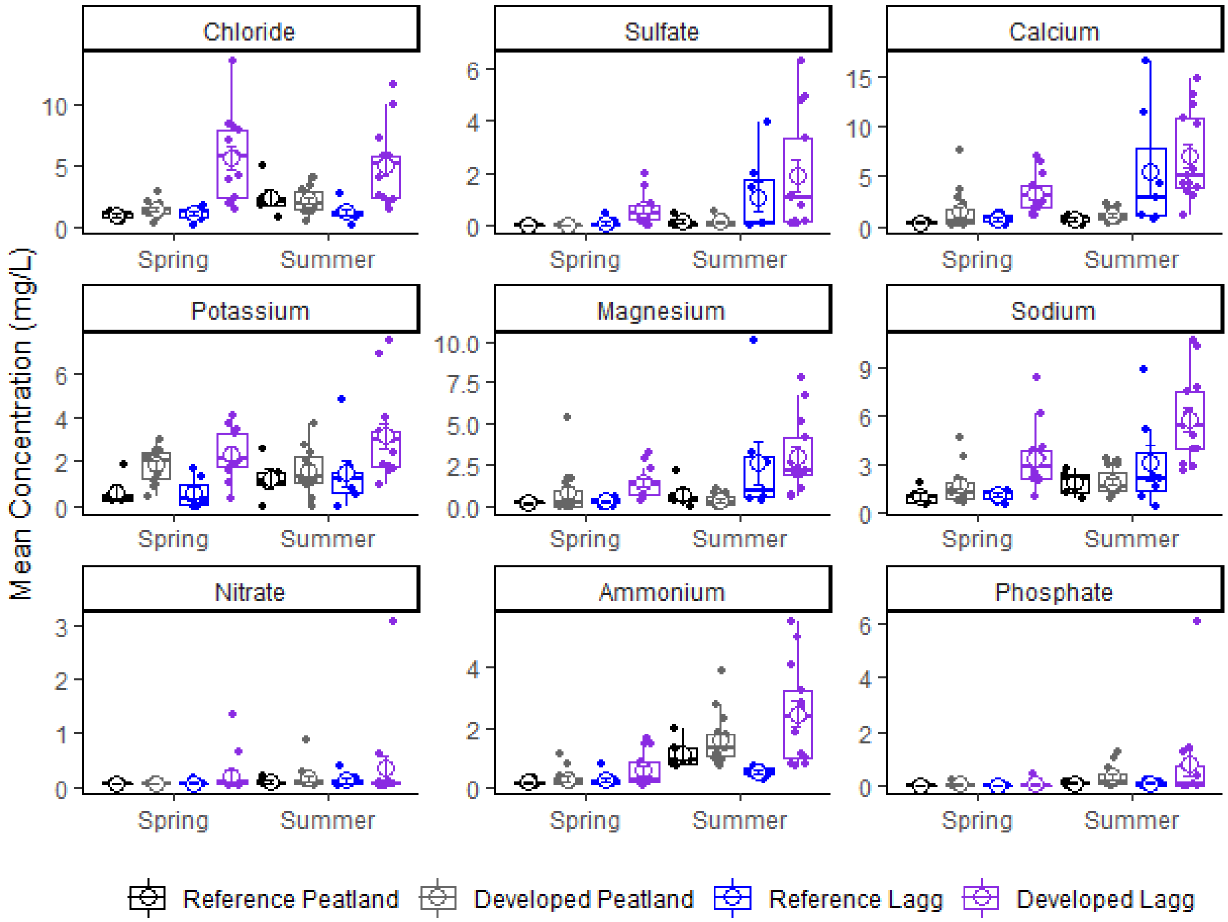


Figure 15. Mean seasonal ion concentrations in porewater of peatland centers and laggs. See Figure 2 for plot descriptions.

seasonally in either wetland position ($p > 0.11$) but were higher in laggs than in peatland centers during late summer (1.51 ± 0.22 versus 2.58 ± 0.44 mg/L; $p = 0.04$). Porewater K^+ was lower in reference peatland centers (0.64 ± 0.30 versus 1.82 ± 0.19 mg/L; $p = 0.01$) and laggs (0.58 ± 0.25 versus 2.32 ± 0.30 mg/L; $p = 0.001$) than in developed sites during spring.

Major nutrient concentrations were generally low and did not differ between peatland centers and laggs in either season ($p > 0.14$; Figure 15). Porewater NO_3^- concentrations averaged less than 0.35 mg/L and did not differ between reference and developed sites ($p > 0.34$). Mean NH_4^+ concentrations increased over the growing season in both wetland positions ($p < 0.001$) from 0.29 ± 0.06 to 1.49 ± 0.18 mg/L in peatland centers, and from 0.48 ± 0.11 mg/L to 1.80 ± 0.36 mg/L in laggs. Porewater NH_4^+ did not vary between reference and developed sites ($p > 0.20$), except in laggs during late summer ($p = 0.01$). Mean PO_4^{3-} was also lower during spring than late summer in both peatland centers (0.04 ± 0.01 versus 0.29 ± 0.08 mg/L; $p = 0.003$) and laggs (0.04 ± 0.02 versus 0.58 ± 0.31 mg/L; $p = 0.09$). Mean PO_4^{3-} was slightly lower in reference peatland centers than in developed sites (0.01 ± 0.01 versus 0.11 ± 0.03 mg/L; $p = 0.09$).

Molar Ca:Mg for porewater samples containing quantifiable Mg^{2+} concentrations ($n = 63$) were generally greater than 1.0 in peatland centers and laggs (Figure 16). Peatland Ca:Mg was lower in spring than summer ($p = 0.03$), increasing from 1.19 ± 0.09 to 2.03 ± 0.29. While Ca:Mg did not vary with nearby land use during spring in peatland centers ($p = 0.67$), it was lower in reference sites during summer (1.05 ± 0.35 versus 2.33 ± 0.32; $p = 0.06$). Mean Ca:Mg was less than 1.0 in four peatland centers during spring (Arrowhead, Kings Lake, Patterson, and Shadow Lake), and in three during late summer (Arrowhead, Cranberry Marsh 4, and Evans Creek). Lagg porewater Ca:Mg did not vary seasonally ($p = 0.69$) or with nearby land use ($p > 0.74$), averaging 1.59 ± 0.11.

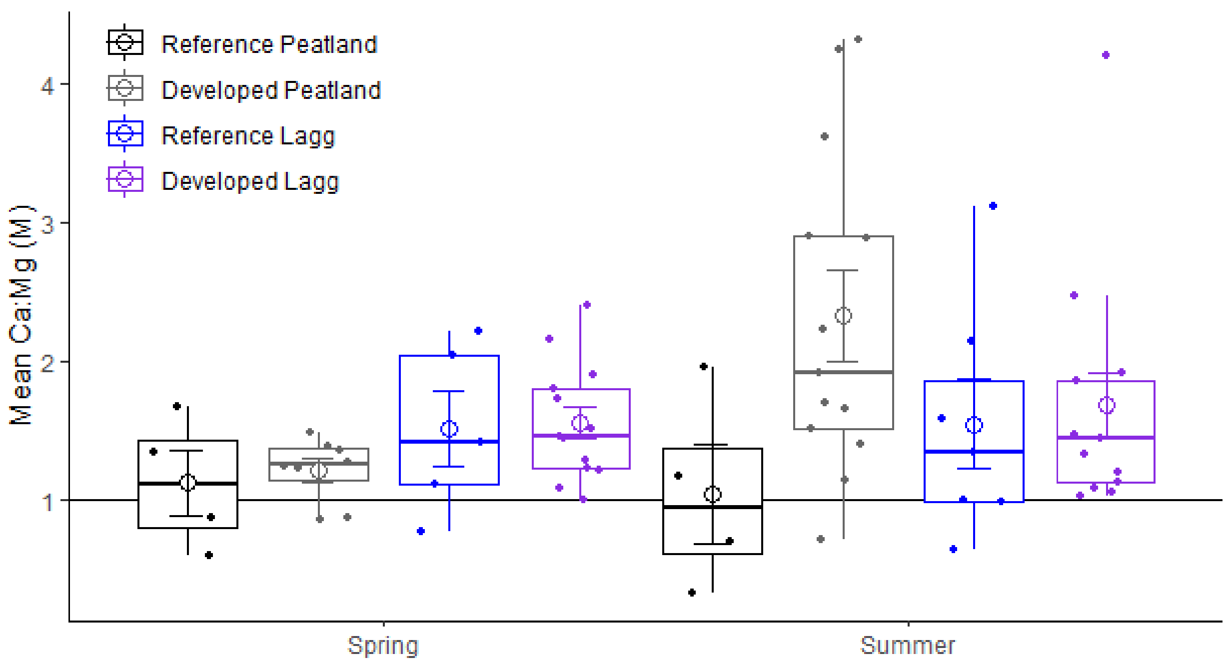


Figure 16. Mean seasonal molar ratios of calcium and magnesium in porewater of peatland centers and laggs.

4.1.3 Vegetation of Puget Lowland Peatlands

4.1.3.1 Vegetation Composition

Synoptic tables summarizing vegetation composition across the study sites are found in Appendix I. It is important to caveat that even our "reference" sites have experienced at least some historical impacts from logging in the surrounding landscape. Stand tables for individual study sites are in Appendix P.

Species richness across all sites and all wetland positions totaled 116 taxonomic entities, five of which were taxa groups (*Sphagnum* mosses, feathermosses, "brown" mosses, "other" mosses, and lichens). Across all sites, species richness in laggs (103) was much higher than richness in peatland centers (34; t-statistic= -1.7; p = 0.06; Table 10), however this pattern wasn't consistent at the site scale (Table 11; Appendix P). Seventy-eight species were limited to laggs while nine were restricted to peatland centers (Table 10). Species richness across lagg plots was much higher in developed sites, but did not show a significant difference between mean plot richness in developed (16) vs reference (23) peatland centers (t-statistic = -0.8; p=0.2) (Table 10). There was a significant difference (t-statistic = -2.1; p=0.05) between mean plot richness in developed (12) vs reference (17) peatland centers. Total site richness tended to decrease with increasing impervious surface area (Figure 17). Further statistical analyses of vegetation compositional changes due to watershed and land use characteristics are presented in Section 4.3.8 Vegetation.

Species growth forms showed variation between peatland centers and laggs (Table 12; Table 13). Forbs and graminoids were proportionally higher in laggs while moss, dwarf shrubs, and trees were proportionally higher in peatland centers. Within peatland centers, dwarf shrubs were proportionally higher in reference sites, forbs more representative of reference sites, and shrubs and trees were proportionally higher in developed sites. Within laggs, dwarf shrubs were proportionally higher in reference sites, forbs and graminoids were higher in developed sites, and shrubs were higher in reference sites. Feather mosses, *Sphagnum* species, and evergreen shrubs showed much higher abundance (i.e., cover) in peatland centers compared to laggs while graminoids, deciduous shrubs, and trees were more abundant in laggs (Table 13). Within peatland centers, feathermoss and deciduous shrub cover increased with a concurrent decrease in cover of *Sphagnum* and lichen cover in developed peatland centers. Graminoid cover in developed laggs was dramatically less than in reference laggs while tree cover was slightly higher in developed laggs.

Table 10. Plant Richness Across Site Types and Wetland Position

Wetland Position	All Study Sites (n=17)		Reference Sites (n=5)		Developed Sites (n=12)	
	Total Richness	Unique To Zone	Total Richness	Unique To Zone	Total Richness	Unique To Zone
Peatland Center	34	9	29	7	27	8
Lagg	103	78	51	29	86	67

Tree Species

Within peatland centers, most tree species cover was documented within the shrub layer (0.5 to 5 m height), with western hemlock being the most common species. Western hemlock was also the predominant regenerating tree species, as it was by far the most common tree species present in the herbaceous layer at 60% of the sites. Western hemlock, western redcedar, and western white pine were represented in the 5 – 10 m layer, but all had very low cover. Trees taller than 10 m were only documented in the developed peatland center study sites and included western hemlock, shore pine and western white pine.

Tree cover in the laggs showed a distinct difference between sites within developed vs 'reference' landscapes. Overall, tree presence in all layers did not have high constancy in developed laggs, tree cover was generally low, and tree composition was more commonly comprised of deciduous trees (i.e., *Alnus rubra* and *Fraxinus latifolia*) than conifers. Western hemlock and western red cedar were the dominant trees (presence and abundance) in reference laggs across all structural layers.

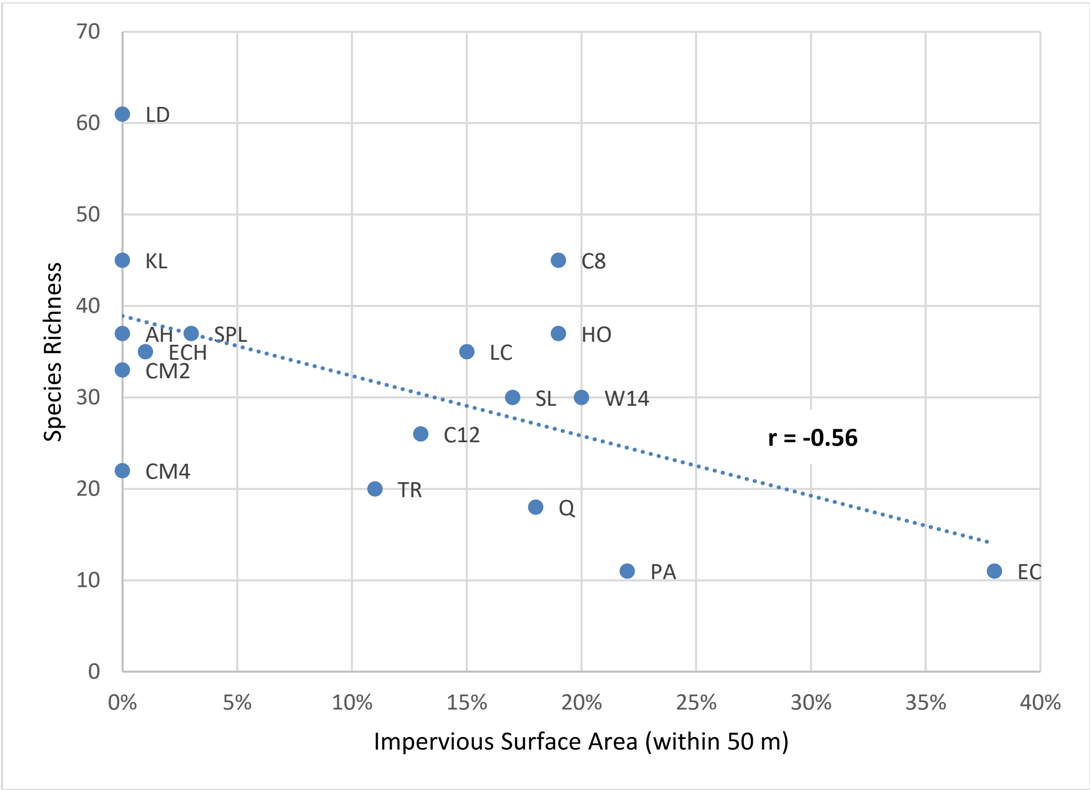


Figure 17. Total Site Plant Richness and Impervious Surface Area

Table 11. Plant Richness at Study Sites

	Study Site	Lagg	Peatland Center	Site Richness
Developed	Covington 12	8	18	26
	Covington 8	32	13	45
	Echo Falls	25	10	35
	Evans Creek	4	7	11
	Hooven	20	17	37
	Lower Cedar	18	17	35
	Patterson	5	6	11
	Queens Bog	8	10	18
	Shadow Lake	17	13	30
	Springer Lake	21	16	37
	Trossachs Bog	8	12	20
	Wetland 14	20	10	30
Reference	Arrowhead	23	14	37
	Cranberry Marsh 2	12	21	33
	Cranberry Marsh 4	8	14	22
	Kings Lake	32	13	45
	Lake Dorothy	38	23	61

Table 12. Growth Form Proportions in Study Sites

Growth Form	Peatland Centers		Laggs	
	Developed	Reference	Developed	Reference
Dwarf shrubs	4%	10%	1%	6%
Ferns	4%	7%	7%	8%
Forbs	15%	20%	38%	33%
Graminoids	11%	10%	20%	10%
Mosses	15%	13%	6%	4%
Shrubs	33%	27%	21%	33%
Trees	19%	13%	6%	6%

Table 13. Growth Form Abundance in Study Sites (average percent ocular cover per site)

Growth Form	Peatland Centers		Laggs	
	Developed	Reference	Developed	Reference
Dwarf shrubs	2%	3%	1%	1%
Ferns	1%	1%	1%	2%
Forbs	<1%	5%	3%	2%
Graminoids	<1%	1%	<1%	37%
Lichen	5%	13%	<1%	8%
Feather mosses	33%	15%	<1%	23%
Sphagnum spp.	27%	48%	4%	2%
Evergreen shrubs	42%	42%	2%	9%
Deciduous shrubs	7%	1%	23%	24%
Trees	3%	2%	11%	6%

Shrub Species

Labrador tea and bog laurel were present in peatland centers of all study sites and had similar cover values in both developed and referenced study sites (Appendix P). Pacific crabapple and bog bilberry (*Vaccinium uliginosum*) were only documented in reference peatland centers. Salal was present in the herbaceous layer in both developed and reference peatland centers, and most abundant in the latter. Salal only occurred in the shrub layer in developed peatland centers.

Shrub richness was higher in laggs than peatland centers. Western hardhack (*Spiraea douglasii*), Pacific crabapple, and Scouler's willow (*Salix scouleriana*) were present and abundant in both developed and reference laggs. Labrador tea was present in 80% of reference laggs, but had low average cover (2%). Average Labrador tea cover was similar in developed laggs, but with lower constancy (33%).

Herbaceous Species
The herbaceous layers of peatland centers and laggs were typically sparse and included tree seedlings, shrub seedlings and diminutive shrubs, and scattered herbaceous species. Overall, herbaceous species had higher constancy in reference peatland centers. This may be an artifact of 3 of the 5 reference sites occurring in western Mason County. That area receives the highest rainfall within our study, with vegetation that compositionally and structurally resembles the more herbaceous-rich coastal *Sphagnum*-dominated peatlands. Beaked sedge (*Carex utriculata*), bracken fern (*Pteridium aquilinum*), skunk-cabbage (*Lysichiton americanum*), arctic starflower (*Lysimachia europaea*), roundleaf sundew (*Drosera rotundifolia*), cottongrass (*Eriophorum chamissonis*), western bunchberry (*Cornus unalaschkensis*), and deer fern (*Struthiopteris spicant*) all had higher constancy in reference peatland centers. Slough sedge (*Carex obnupta*) was only documented in reference laggs, where it occurred in 60% of sites, with an average of 72% cover.

Lady fern (*Athyrium filix-femina* ssp. *cyclosorum*), yellow pond lily (*Nuphar polysepala*), climbing nightshade (*Solanum dulcamara*), and grey sedge (*Carex canescens*) all had higher constancy in developed laggs. Forty-six herbaceous species were documented in developed laggs, but absent in reference laggs.

Nonvascular Species
Sphagnum spp. were present in all peatland centers, but had nearly twice as much cover in reference peatland centers compared to developed peatland centers (48% to 26%, respectively). Feather mosses (e.g., *Pleurozium schreberi*, *Hylocomium splendens*) had high constancy in both developed (92%) and reference (80%) peatland centers but had much higher cover in developed peatlands (42% vs. 19%). Lichens were present in all the reference peatland centers but only in 42% of the developed peatland centers. Lichen cover was similar across sites (13%) they were found within. Although *Sphagnum* spp. were generally not identified to species, observations suggest *Sphagnum capillifolium*, *S. rubellum*, and *S. fuscum* are the predominant *Sphagnum* species in the reference peatland centers.

Feather mosses had higher constancy and cover in reference laggs compared to developed laggs. Peat mosses had much lower constancy and cover in all lagg types compared to peatland centers. Ground cover lichens were not present in any of the laggs.

Ground cover
Bare ground had similar constancy in developed and reference peatland centers, but higher cover in developed sites (11% vs 0.1%). No bare ground was documented in reference laggs, but was present in 25% of the developed laggs. Relatedly, open water was only documented in developed laggs and occurred in 42% of the developed sites. Litter had higher constancy in developed laggs (33% vs 20%), but higher cover (38% to 9%) in reference laggs.

Nonparametric Multivariate Analysis of Variance (PERMANOVA; Anderson, 2001, 2017) was used to explore correlations between ecological variables and vascular and nonvascular composition between sites in reference and developed landscapes (Table 14). Natural factors independent of adjacent land use had relatively weak correlation to vegetation composition (full results in Appendix J). Positive PERMANOVA coefficients indicate a positive relationship with the factor, and vice versa. Note that species level responses were primarily analyzed with Indicator Species Analysis and NMS ordination axis correlations (see below).

Mean annual precipitation and/or summer precipitation are the primary variables affecting compositional differences across strata in peatland centers and laggs (Table 14). Mean annual precipitation ranged from 113 cm (Hooven Bog) to 229 cm (Arrowhead Bog), while summer precipitation ranged from 19 cm (Springer Lake) to 40 cm (Kings Lake). Notably, the five bogs that received the most precipitation also served as reference sites in our study.

4.1.3.2 U.S. National Vegetation Classification Types

U.S. National Vegetation Classification (USNVC) plant association (https://www.usnvc.org; Rocchio et al. 2022) and subgroup (Rocchio and Ramm-Granberg *In progress*) units were classified for each reference study site (Table 15). The peatland centers represented six different USNVC plant associations within three subgroups and two USNVC groups. These subgroups span the full range of bog communities currently classified within the Puget Lowlands: North Pacific Transitional Bog, North Pacific Open Flat Bog, and North Pacific Bog Woodland. Study sites do not include other acidic peatlands such as poor fens or transitional poor fens which are also found in the Puget Lowlands. Of the six plant associations, two are considered State Endangered, three are State Threatened, and one is State Sensitive (Table 15, DNR 2022).

Lagg vegetation varied between eight different USNVC associations within five subgroups and five groups. A common lagg type was the *Malus fusca* Shrub Swamp association (Table 15). Of the eight associations documented in the laggs, one is considered State Endangered, two are State Threatened, two are on State Review lists, and three are of No Concern (Table 15, DNR 2022).

Table 14. Vegetation Composition and Abiotic and Land Use Variables. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Factor	r^2	*p*-value	
Peatland center composition varies by...			
Mean annual precipitation	0.13	0.08	*
Lagg composition varies by…			
Mean annual precipitation	0.11	0.06	*
May-Sept precipitation	0.14	0.01	**
Whether or not the bog borders a lake	0.11	0.07	*
Proportion of nonvascular physiognomic groups in the peatland center varies by...			
Mean annual precipitation	0.23	0.01	**
Peatland center herb composition varies by…			
Mean annual precipitation	0.11	0.03	**
Whether or not the bog borders a lake	0.12	0.05	**
Lagg herb composition varies by…			
Mean annual precipitation	0.18	0.01	***
Watershed area	0.10	0.08	*
Peatland center shrub composition varies by…			
No significant natural factors	--	--	
Lagg shrub composition varies by…			
May-Sept precipitation	0.13	0.02	**

Table 15. U.S. National Vegetation Classification Types of Study Sites. USNVC subgroups are a custom unit developed by WNHP (https://www.dnr.wa.gov/NHPwetlands). State Conservation Status are listed in the 2022 State of Washington Natural Heritage Plan (https://www.dnr.wa.gov/NHPconservation).

Study Site	Wetland Position	USNVC Group	USNVC Subgroup*	USNVC Association	State Conservation Status (Association)
Arrowhead Bog	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Pinus monticola / Ledum groenlandicum / Sphagnum* spp. Treed Bog	Endangered
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
Covington 12	Peatland	North Pacific Maritime Wooded Bog and Poor Fen and North Pacific Open Bog and Acidic Fen	North Pacific Bog Woodland and North Pacific Open Flat Bog	*Pinus contorta* var. *contorta / Ledum groenlandicum / Sphagnum* spp. Treed Bog and *Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog	Threatened and Sensitive
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Spiraea douglasii* Wet Shrubland	No Concern
	Peatland "Edge"	North Pacific Open Bog and Acidic Fen transitioning to → Vancouverian Wet Shrubland	North Pacific Open Flat Bog transitioning to → Vancouverian Lagg Shrub Swamp	*Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog transitioning to → *Spiraea douglasii* Wet Shrubland	Sensitive → No Concern
Covington 8	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum / Sphagnum* spp. Treed Bog	Threatened
	Lagg	North-Central Pacific Maritime Swamp Forest	North Pacific Conifer Basin Swamp	*Tsuga heterophylla - Thuja plicata / Vaccinium ovalifolium - Gaultheria shallon / Lysichiton americanus* Swamp Forest	Threatened
Cranberry Marsh #2	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Transitional Bog	*Ledum groenlandicum / Carex utriculata / Sphagnum* spp. Shrub Bog	Threatened
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
Cranberry Marsh #4	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog	Sensitive

Study Site	Wetland Position	USNVC Group	USNVC Subgroup*	USNVC Association	State Conservation Status (Association)
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
Evans Creek	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive
	Stormwater Inflow	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Spiraea douglasii* Wet Shrubland	No Concern
Echo Falls	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
	Stormwater Inflow	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive
Hooven	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Threatened
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Spiraea douglasii* Wet Shrubland	No Concern
Kings Lake Bog NAP	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Threatened
	Lagg	North-Central Pacific Maritime Swamp Forest	North Pacific Conifer Basin Swamp	*Tsuga heterophylla - Thuja plicata* / *Vaccinium ovalifolium - Gaultheria shallon* / *Lysichiton americanus* Swamp Forest	Threatened
Lake Dorothy	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog	Threatened
	Lagg	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Sphagnum* spp. Treed Bog	Endangered
Lower Cedar	Peatland 2	North Pacific Open Bog and Acidic Fen	North Pacific Transitional Bog	*Ledum groenlandicum* / *Carex utriculata* / *Sphagnum* spp. Shrub Bog	Threatened
	Peatland 1 (high point)	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive
	Lagg	Vancouverian Freshwater Wet Meadow and Marsh	Vancouverian Lagg Marsh	*Typha latifolia* Pacific Coast Marsh and	No Concern

Study Site	Wetland Position	USNVC Group	USNVC Subgroup*	USNVC Association	State Conservation Status (Association)
		and Western North American Temperate Freshwater Aquatic Vegetation	and North Pacific Freshwater Aquatic Vegetation	*Nuphar polysepala* Aquatic Vegetation	
Patterson	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog and North Pacific Transitional Bog	*Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog and *Ledum groenlandicum / Carex utriculata / Sphagnum* spp. Shrub Bog	Sensitive and Threatened
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Spiraea douglasii* Wet Shrubland	No Concern
Queens	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog	Sensitive
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Spiraea douglasii* Wet Shrubland	No Concern
	Stormwater Inflow	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
Shadow Lake	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum / Sphagnum* spp. Treed Bog and *Tsuga heterophylla* - (*Thuja plicata*) / *Sphagnum* spp. Treed Bog	Threatened and Endangered
	Lagg	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Cornus sericea* Pacific Shrub Swamp	Review 1
Springer Lake	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla / Sphagnum* spp. Shrub Bog	Sensitive
	Lagg	Western North American Temperate Freshwater Aquatic Vegetation	North Pacific Freshwater Aquatic Vegetation	*Sparganium angustifolium* Aquatic Vegetation	Review 2

Study Site	Wetland Position	USNVC Group	USNVC Subgroup*	USNVC Association	State Conservation Status (Association)
Trossachs	Peatland	North Pacific Open Bog and Acidic Fen	North Pacific Open Flat Bog	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog	Sensitive
	Lagg (stormwater inflow)	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened
	Peatland "Edge"	North Pacific Open Bog and Acidic Fen transitioning to → Vancouverian Wet Shrubland	North Pacific Open Flat Bog transitioning to → Vancouverian Lagg Shrub Swamp	*Ledum groenlandicum - Kalmia microphylla* / *Sphagnum* spp. Shrub Bog transitioning to → *Spiraea douglasii* Wet Shrubland	Sensitive → No Concern
Wetland 14	Peatland	North Pacific Maritime Wooded Bog and Poor Fen	North Pacific Bog Woodland	*Tsuga heterophylla* - (*Thuja plicata*) / *Ledum groenlandicum* / *Sphagnum* spp. Treed Bog and *Tsuga heterophylla* - (*Thuja plicata*) / *Sphagnum* spp. Treed Bog	Threatened and Endangered
	Stormwater Inflow	Vancouverian Wet Shrubland	Vancouverian Lagg Shrub Swamp	*Malus fusca* Shrub Swamp	Threatened

4.2 Indicators of Ombrotrophic Conditions

4.2.1 Topography

The study peatland centers were 6 to 77 cm above adjacent laggs (as determined by lidar), except Evans Creek, where there was no elevation difference. The majority of peatland centers (47%) were less than 20 cm above their laggs (Arrowhead, Cranberry Marsh 2, Cranberry Marsh 4, Evans Creek, Queens Bog, Springer Lake, Trossachs, and Wetland 14). Another 35% of study sites were 20-50 cm above their laggs (Covington 12, Covington 8, Echo Falls, Lower Cedar, Lake Dorothy, and Patterson). Three (18%) of the study sites had peatland centers > 50 cm above their laggs (Hooven Bog, Kings Lake Bog NAP, and Shadow Lake).

4.2.2 Vegetation Indicators of Ombrotrophic Conditions

Vegetation of peatland centers was indicative of nutrient poor and acidic conditions in all of the study sites. Ericaceous shrubs such as Labrador tea, bog laurel, small cranberry occurred over nearly continuous lawns or hummocks of *Sphagnum* sp. in many sites, especially reference peatland centers (Appendix I). For all other sites, vegetation was an inconclusive indicator and the determination of ombrotrophic conditions was left to the hydrological and chemical indicators discussed in the next section.

4.2.3 Hydrological and Chemical Indicators of Ombrotrophic Conditions

Measures of vertical hydrological gradients (VHGs) were variable. Four sites exhibited upward groundwater flow in shallow peat during at least one season (Covington 12, Echo Falls, Springer Lake, and Wetland 14), which does not appear to be congruent with meteoric water sources.

All the study sites had pH values (Table 16) below those reported for local precipitation (Table 17), and well below those reported for local groundwater (Table 18). The majority of study sites had spring (88%) and summer (71%) pH values below the ombrotrophic pH threshold of < 4.5 used by Malmer et al. (1992) for coastal bogs near Prince Rupert, British Columbia and continental bogs in Alberta. Using the Fennoscandian and British bog pH threshold of < 4.2 (Gorham 1957, Sjörs and Gunnarsson 2002, Tahvanainen 2004, Proctor et al. 2009, Joosten et al. 2017b), 64% of the study sites were below the bar in spring and only 24% were below in summer. Two sites (Lower Cedar and Shadow Lake) had pH > 4.5 for both seasons and four sites exceeded 4.2 in both seasons (Kings Lake, Lower Cedar, Lake Dorothy, and Shadow Lake). Electric conductivity measures for study sites (Table 16) were above local precipitation measures (Table 17), but all were below those in groundwater (Table 18). Five sites (Arrowhead, Cranberry Marsh 2, Kings Lake, Queens Bog, and Springer Lake) also had Mean EC_{corr} values that met the Vitt et al. (1995) threshold of < 39 μS/cm for bogs.

Porewater Ca^{2+} concentrations were < 2.0 mg/L in 76% of the study sites (Table 16). Three sites exceeded this value during the spring (Covington 8, Patterson Creek, and Wetland 14) and Shadow Lake exceeded 2.0 mg/L in both seasons. Molar Ca:Mg exceeded 1.0 at 35% of the study sites in spring months and 76% of study sites in summer months. Proctor et al. (2009) suggested that molar Ca:Mg in ombrotrophic peatlands is generally less than 1.0, although this can vary by geographic region, especially in sites with oceanic influence (Sjörs and Gunnarsson 2002).

Table 16. Summary of physical and chemical evidence for ombrotrophic conditions in study sites. All reported measures are from peatland centers. VHG = vertical hydraulic gradient between 50 and 100 cm depth. Shaded cells for VHG correspond to results that are not consistent with ombrotrophic conditions. ***VHG with $p < 0.10$ (P-value is from t-tests that means differ from zero); **VHG with $p < 0.05$. Shaded cells for pH > 4.5. Shaded cells for EC >50 µS/cm. Shaded cells for Ca^{2+} >2.0 mg/L. Shaded cells for Ca:Mg > 1.0. Relief = difference between ground surface elevation at peatland well and lagg well from bare earth lidar. [1]Reference site. [2]Not calculated due to dry well. [3]Not calculated due to Mg2+ concentrations below detection limits.

Site	VHG (cm/cm)		pH		EC_{corr} (µS/cm)		Ca^{2+} (mg/L)		Ca:Mg (mol/mol)		Relief (cm)
	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	
AH[1]	-0.37±0.06*	NC[2]	4.09±0.01	4.80±0.18	14.6±4.4	38.2±1.2	0.34±0.09	1.18±0.01	0.88	0.34	6
C12	+0.06±0.05	+0.12±0.02*	3.91±0.02	4.30±0.09	42.0±28.6	48.5±15.9	0.54±0.17	0.98±0.17	NC[3]	4.24	30
C8	+0.04±0.00	+0.01±0.00	4.15±0.02	4.42±0.03	13.7±2.5	49.1±15.7	2.89±2.89	1.08±0.09	1.24	1.92	22
CM2[1]	+0.07±0.02	+0.02±0.00	4.19±0.07	4.26±0.03	27.3±11.8	34.2±4.4	0.10±0.10	0.90±0.36	NC[3]	1.18	6
CM4[1]	-0.12±0.01*	NC[2]	4.22±0.09	4.06±0.03	15.8±2.3	49.5±21.1	0.51±0.23	0.60±0.02	1.35	0.71	11
EC	-0.01±0.04	-0.25±0.17	4.22±0.02	4.13±0.02	29.6±2.3	44.8±4.9	0.48±0.09	0.83±0.08	1.39	0.71	0
ECH	+0.22±0.16	-0.10±0.08	4.17±0.11	4.24±0.02	51.6±34.0	37.0±4.9	0.09±0.09	0.93±0.13	NC[3]	4.31	30
HO	-0.07±0.05	-0.02±0.00**	4.05±0.05	4.12±0.04	24.5±10.2	48.4±13.3	0.30±0.08	0.44±0.08	NC[3]	1.66	53
KL[1]	-0.05±0.01	+0.01±0.03	4.29±0.01	4.52±0.06	13.1±0.6	23.8±1.2	0.30±0.30	0.19±0.10	0.61	NC[3]	71
LC	-0.01±0.00	+0.04±0.07	4.62±0.40	5.02±0.06	30.8±11.9	58.7±5.8	0.11±0.11	1.91±0.78	NC[3]	1.15	35
LD[1]	+0.01±0.00	+0.01±0.01	4.36±0.01	4.54±0.15	12.1±2.5	39.6±17.4	0.58±0.35	0.92±0.51	1.68	1.96	22
PA	-0.33±0.15	-0.65±0.13**	4.10±0.02	4.30±0.11	40.4±19.5	50.5±3.2	7.57±7.57	0.75±0.10	0.86	NC	21
Q	-0.12±0.01**	-0.14±0.01**	4.06±0.06	4.27±0.03	24.3±0.5	29.1±1.2	0.41±0.21	0.40±0.06	NC[3]	NC[3]	9
SL	+0.00±0.00	-0.14±0.01**	4.57±0.05	4.93±0.05	25.4±0.4	59.4±10.3	2.38±1.70	2.06±0.44	0.88	1.52	77
SPL	-0.10±0.03	+0.11±0.04	4.04±0.18	4.11±0.08	14.8±4.8	35.6±6.6	1.00±0.73	0.63±0.04	1.49	2.88	15
TR	+0.05±0.05	-0.04±0.04	4.13±0.02	4.49±0.07	49.3±30.1	54.7±5.7	0.32±0.07	1.18±0.31	NC[3]	2.23	18
W14	-0.01±0.02	+0.18±0.03**	4.09±0.11	4.39±0.07	39.6±29.1	115±40.5	3.62±3.62	0.74±0.08	1.36	3.61	15

Table 17. Precipitation Chemistry in the Puget Lowland Ecoregion*

Site	County	Elevation	pH	Electric Conductivity (µS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	NH_4^+ (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)
La Grande	Pierce	617 m (2,024 ft.)	5.15	5.28	0.03	0.02	0.18	0.02	0.05	0.26	0.30	0.31
Marblemount	Skagit	124 m (406 ft.)	5.16	4.56	0.02	0.02	0.12	0.01	0.03	0.26	0.22	0.22

*Annual averages between 1984 to 2021 (National Atmospheric Deposition Program; accessed October 21, 2022; https://nadp.slh.wisc.edu/maps-data/ntn-interactive-map/)

Table 18. Groundwater Chemistry in the Puget Lowland Ecoregion

Data Source	pH	Electric conductivity (µS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)
Vaccaro et al. 1998*	7.3	180	13.0	5.9	6.5	1.8	0.1	5.0	4.7
Turney 1986**									
Island County (n=23)	7.7	950	48.0	31.0	49.0	7.7	0.13	35.0	86.0
King County (n=20 / 21)	7.6	165	16.0	6.2	6.2	1.8	0.1	5.0	2.3
Kitsap County (n=9)	7.5	165	15.0	6.3	5.9	1.5	0.11	1.0	3.3
Mason County (n=5)	7.7	113	11.0	5.8	5.1	0.6	0.04	2.6	1.8
Pierce County (n=35)	7.4	148	13.0	6.2	6.6	1.7	0.18	3.2	3.4
San Juan County (n=57)	7.6	650	50.0	16.0	71.0	2.5	0.05	32.0	46.0
Skagit County (n=7)	6.8	347	23.0	19.0	18.0	3.2	0.51	11.0	26.0
Snohomish County (n=7)	7.7	215	21.0	8.6	6.1	2.0	0.12	1.0	2.3
Thurston County (n=5)	7.2	125	9.6	5.7	5.4	1.7	0.37	2.2	3.2
Whatcom County (n=7)	6.8	295	21.0	7.2	9.1	2.3	1.4	14.0	10.0

*Table 8 in Vaccaro et al. 1998; median values reported; number of samples per measure ranged from 1,117 to 1,905
**Table 1 in Turney 1986; median values reported;

4.3 Effects of Watershed and Land Use Characteristics on Ecological Characteristics of Puget Lowland Peatlands

4.3.1 Water Levels

Measured watershed and land use characteristics were not strongly related to variation in mean annual peatland center water levels (Table 19). The best model for mean water levels explained 7.8% of variability based on watershed area, Land Use Index, and the presence of stormwater inflow (Model 1 in Table B1 in Appendix B). All three covariates were positively related to mean annual water levels, but standardized coefficients indicated that the effects of watershed area were about 2.8 times that of Land Use Index (Table 19). The additional covariates in other candidate models did not improve model fit ($p = 0.44$). The top-ranked models for mean annual water levels in laggs all contained non-significant variables, and conditional r^2 values indicated that much of the variability in laggs was explained by site-specific random effects (Model 1 in Table B2 in Appendix B).

Mean monthly water levels in peatland centers and laggs were related to interactions between month and watershed characteristics. The best model for monthly water levels in peatland centers explained 61.1 % of the variation based on month interactions with watershed area, mean annual precipitation, and Land Use Index (Model 1 in Table B3 in Appendix B). Mean monthly water levels increased with watershed area during April-December, with the largest increases occurring in August and September (Table 20). Monthly water levels decreased with greater annual precipitation during January-March and August-September, but water levels increased with annual precipitation during May-July. During most months, the effects of mean annual precipitation were stronger than those of watershed area. The effects of increasing Land Use Index varied by month, but these were generally much smaller than those of the other covariates.

Mean monthly water levels in laggs were best explained by month interactions with watershed area, mean annual precipitation, and impervious surface area within 50 m of the wetland perimeter (Model 1 in Table B4 in Appendix B). Similar to peatland centers, mean monthly water levels in laggs increased with watershed area during April-December, with the largest increases during August (Table 21). Lagg water levels decreased with higher annual rainfall during January-April, but they increased with rainfall during June-December. However, precipitation effects were much smaller than those of watershed area during the summer dry season (May-September). Water levels increased with buffer impervious surface area, but these effects were much smaller than those of watershed area and annual precipitation. These fixed effects explained 35.8% of variability in mean monthly water levels, while random site effects explained 41.2 % of variability.

The fraction of impervious surface area within 50 to 500 m of study wetland perimeters was not related to mean annual water levels in peatland centers or laggs (Table B5 in Appendix B), but this factor did explain variability in mean monthly water levels (Table B6 in Appendix B). Interactions between month and impervious surface area were significant ($p < 0.001$) for all buffer distances between 50 and 500 m in both peatland centers and laggs, explaining between 50.7 and 54.8 % of variability in peatland centers and between 26.4 and 31.7 % in laggs. In peatland centers, mean water levels increased with impervious surface area during April-August within distances up to 300 m from the wetland perimeter, while impervious surface area within larger buffer distances was associated with decreasing water levels during September-December. In laggs, mean water levels increased with higher impervious surface area for buffer distances between 50 and 500 m. Typical relationships between buffer impervious area and mean monthly water levels are illustrated for August and December (Figure 18).

Table 19. Effects of watershed area, Land Use Index, and the presence of stormwater management facilities on annual mean water levels in peatland centers.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	-42.59	8.29	<0.001
Presence of Stormwater Facility	14.99	4.98	0.010
Land Use Index	7.83	2.72	0.013
Watershed Area	21.59	8.57	0.026

4.3.2 pH

Porewater pH in peatland centers and laggs was most strongly affected by the presence of stormwater management facilities, which altered the effects of other watershed characteristics. Mean pH in peatland centers was best explained by interactions between watershed area and the presence of stormwater management facilities during both spring (Model 4 in Table C1 in Appendix C) and late summer (Model 6 in Table C3 in Appendix C). Porewater pH was lower in larger watersheds at sites with stormwater inflows ($p = 0.03$), but increased in larger watersheds at sites lacking these inflows ($p = 0.04$) during spring ($R^2 = 0.16$) and late summer ($R^2 = 0.30$; Figure 19). The larger absolute values of slope coefficients during late summer indicated that these effects were strongest during the dry season. During both seasons, other models with lower AIC scores contained non-significant covariates that did not improve model fit ($p > 0.71$).

Table 20. Effects of watershed area (AREA), mean annual precipitation (MAP), and Land Use Index (LUI) on mean monthly water levels in peatland centers.

			Month:AREA		Month:MAP		Month:LUI	
Fixed Effects	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**
January	-7.0 ± 6.8	0.32	4.6 ± 11.1	0.69	-26.0 ± 14.5	0.095	7.1 ± 3.0	0.031
February	-0.8 ± 1.5	0.59	4.1 ± 2.4	0.10	-14.8 ± 3.1	<0.001	1.6 ± 0.6	0.008
March	-3.4 ± 1.5	0.022	4.1 ± 2.4	0.095	-8.7 ± 3.1	0.004	-0.1 ± 0.6	0.86
April	-4.1 ± 1.5	0.005	7.7 ± 2.4	0.002	3.7 ± 3.1	0.23	-3.3 ± 0.6	<0.001
May	-7.6 ± 1.4	<0.001	11.0 ± 2.3	<0.001	19.2 ± 3.2	<0.001	-6.2 ± 0.6	<0.001
June	-13.0 ± 1.4	<0.001	16.4 ± 2.3	<0.001	26.0 ± 3.2	<0.001	-7.1 ± 0.6	<0.001
July	-24.9 ± 1.4	<0.001	23.0 ± 2.3	<0.001	23.6 ± 3.2	<0.001	-6.6 ± 0.6	<0.001
August	-45.2 ± 1.4	<0.001	47.0 ± 2.3	<0.001	-38.7 ± 3.0	<0.001	0.3 ± 0.6	0.67
September	-47.0 ± 1.5	<0.001	45.9 ± 2.4	<0.001	-48.1 ± 3.1	<0.001	3.2 ± 0.6	<0.001
October	-25.2 ± 1.6	<0.001	23.4 ± 11.1	<0.001	38.0 ± 3.1	<0.001	-5.9 ± 0.6	<0.001
November	-12.7 ± 1.5	<0.001	16.8 ± 2.4	<0.001	60.5 ± 3.1	<0.001	-8.9 ± 0.6	<0.001
December	-5.0 ± 1.5	<0.001	12.6 ± 2.4	<0.001	43.6 ± 3.1	<0.001	-7.5 ± 0.6	<0.001

Table 21. Effects of watershed area (AREA), mean annual precipitation (MAP), and impervious surface area within a 50 m buffer of the wetland perimeter (BUFF) on mean monthly water levels in laggs.

			Month:AREA		Month:MAP		Month:BUFF	
Fixed Effects	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**	**Estimate ± SE**	**p-value**
January	50.4 ± 22.0	0.04	-29.6 ± 33.4	0.39	-66.6 ± 37.2	0.10	0.3 ± 7.3	0.97
February	2.7 ± 2.4	0.25	-0.2 ± 3.4	0.95	-9.7 ± 4.0	0.02	-0.3 ± 0.8	0.69
March	1.1 ± 2.3	0.65	2.0 ± 3.4	0.56	-12.6 ± 3.9	0.001	-1.7 ± 0.7	0.02
April	-2.2 ± 2.4	0.36	7.2 ± 3.4	0.04	-10.8 ± 4.0	0.01	-2.3 ± 0.8	0.003
May	-10.2 ± 2.3	<0.001	15.4 ± 3.3	<0.001	0.2 ± 4.0	0.97	-2.7 ± 0.7	<0.001
June	-19.2 ± 2.3	<0.001	29.6 ± 3.2	<0.001	7.4 ± 4.0	0.06	-3.7 ± 0.7	<0.001
July	-36.8 ± 2.4	<0.001	56.1 ± 3.2	<0.001	21.2 ± 4.0	<0.001	-6.3 ± 0.7	<0.001
August	-63.9 ± 2.3	<0.001	100.0 ± 3.3	<0.001	29.0 ± 3.9	<0.001	-10.5 ± 0.7	<0.001
September	-61.2 ± 2.4	<0.001	80.8 ± 3.4	<0.001	31.6 ± 3.9	<0.001	-8.9 ± 0.8	<0.001
October	-48.5 ± 2.3	<0.001	40.6 ± 3.4	<0.001	54.3 ± 3.9	<0.001	-1.5 ± 0.7	0.04
November	-31.1 ± 2.3	<0.001	29.0 ± 3.4	<0.001	46.3 ± 3.9	<0.001	-1.5 ± 0.8	0.05
December	-16.9 ± 2.3	<0.001	17.5 ± 3.4	<0.001	24.2 ± 3.9	<0.001	-03 ± 0.7	0.71

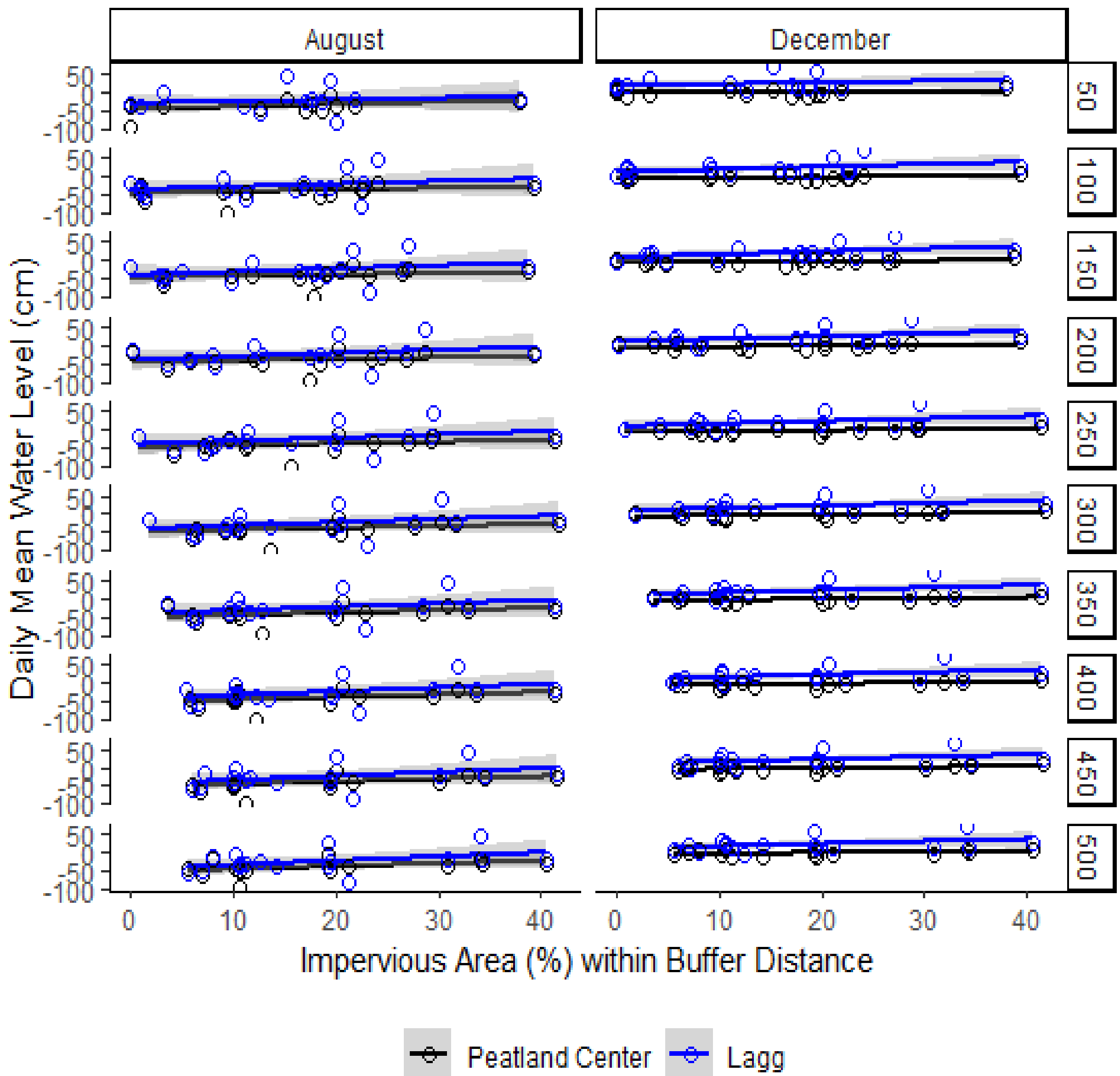


Figure 18. Effects of impervious area within buffer distances of the wetland perimeter on daily mean water levels in peatland centers and laggs during August and December. Buffer distances are shown in the row labels.

Springtime lagg pH was best explained by the interaction between Land Use Index and the presence of stormwater management facilities (Model 3 in Table C2 in Appendix C). In sites with stormwater inflows, lagg pH was higher in sites with higher Land Use Index ($p = 0.09$) but decreased with higher Land Use Index (i.e. more natural) in all other sites ($p = 0.10$), and these factors explained 22.1 % of variability (Figure 20). Other candidate models consisted of non-significant variables or contained additional covariates that did not increase explanatory power ($p = 0.16$). Late summer pH in laggs was not strongly related to the measured predictors. The best model included interactions between the presence of natural surface inflows and stormwater inflow

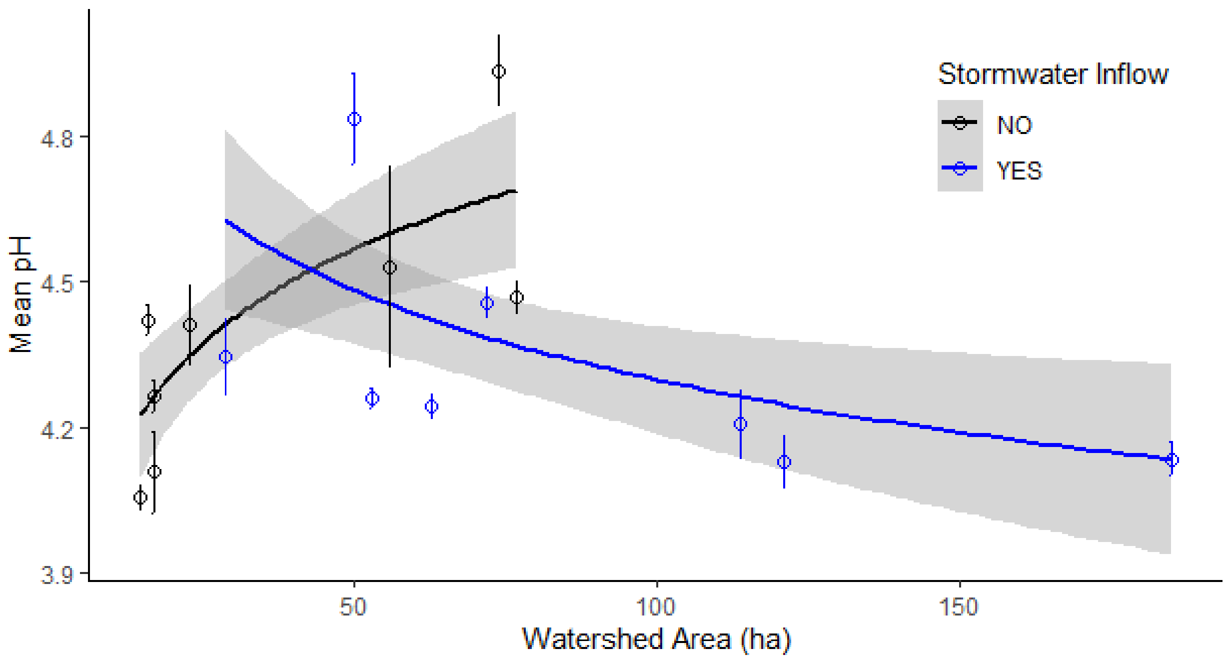


Figure 19. Effects of watershed area and the presence of stormwater inflows on mean porewater pH in peatland centers during late summer.

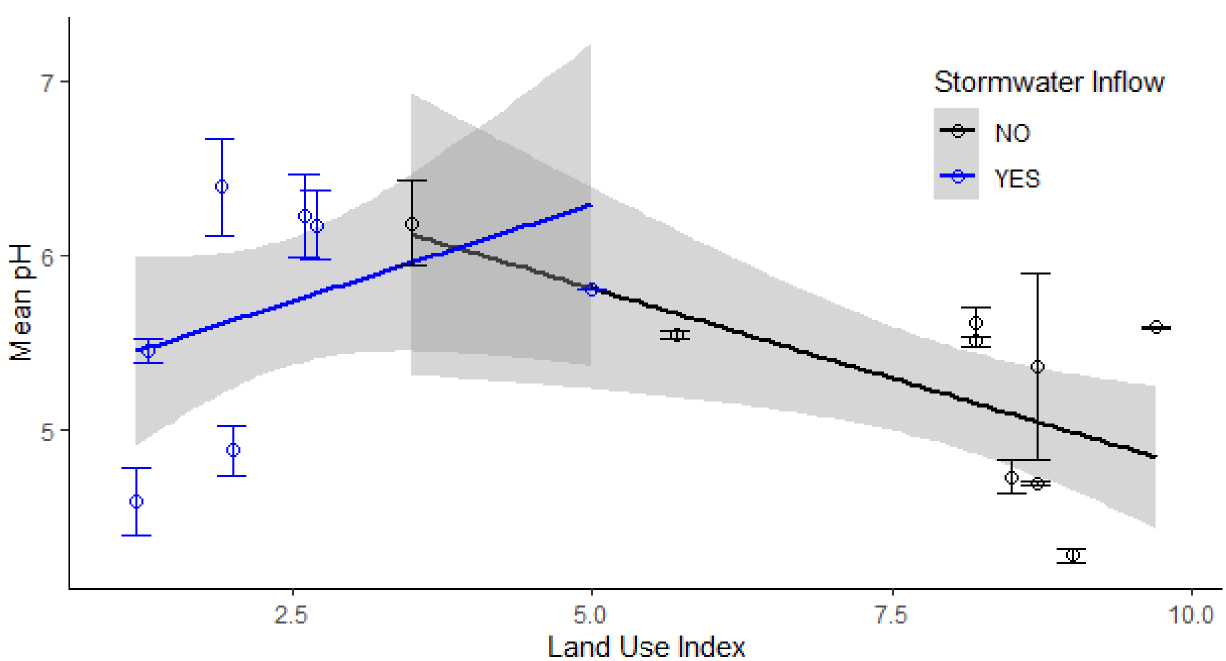


Figure 20. Effects of Land Use Index and the presence of stormwater inflows on mean porewater pH in laggs during spring. High Land Use Index scores = fewer human-induced stressors.

(Model 2 in Table C4 in Appendix C). This interaction had weak effects ($p = 0.64$) and comparison of least-squares means suggested that stormwater inflows decreased summertime lagg pH by 0.94 ± 0.53 when natural surface water inflows were present ($p = 0.10$), but stormwater inflows had no effect in isolated wetlands ($p = 0.34$). Additional covariates did not enhance the explanatory power of this relationship ($p \geq 0.11$). Porewater pH in both peatland centers and laggs was not strongly related to impervious surface area within distances of 500 m of the wetland perimeter during spring (in Table C5 in Appendix C) or late summer (Table C6 in Appendix C).

4.3.3 Corrected Conductivity

Inflows from stormwater management facilities affected EC_{corr} in both peatland centers and laggs during spring. The presence of stormwater inflow provided the best explanation of peatland center porewater EC_{corr} (Model 1 in Table D1 in Appendix D), and additional covariates did not yield better models ($p \geq 0.29$). Mean EC_{corr} in peatland centers receiving stormwater inputs was 34.5 ± 4.3 μS/cm, while the other sites averaged 21.2 ± 4.3 μS/cm ($p = 0.04$). Lagg EC_{corr} was best explained by interactions between Land Use Index and stormwater management facilities (Model 2 in Table D2 in Appendix D), while additional covariates in other top-ranked models did not improve explanatory power ($p = 0.11$). Mean EC_{corr} decreased with higher Land Use Index (i.e., fewer human-induced stressors) in laggs without stormwater inflows ($p = 0.002$), but it increased with Land Use Index where stormwater inputs occurred ($p = 0.03$), although with considerable variability (Figure 21; $R^2 = 0.345$).

During late summer, Land Use Index and other watershed factors influenced EC_{corr} in peatland centers and laggs. The best model for peatland centers included the effects of Land Use Index and impervious surface area within the watershed and within a 50 m buffer (Model 3 in Table D3 in Appendix D); additional covariates in other top-ranked models did not improve goodness of fit ($p = 0.11$). Corrected conductivity decreased with increasing Land Use Index and impervious surface area within the watershed, although it was negatively related to impervious surface area within a 50 m buffer (Table 22; $R^2 = 0.20$). In laggs, Land Use Index was the best predictor of EC_{corr} (Model 1 in Table D4 in Appendix D) and additional covariates did not improve model fit ($p = 0.18$). Corrected conductivity decreased with higher Land Use Index ($p = 0.031$), and this explained 15.9 % of the variability (Figure 22).

Table 22. Effects of impervious surface area within the watershed and a 50 m buffer of the wetland perimeter, and Land Use Index on porewater EC_{corr} in peatland centers during late summer.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	69.73	19.37	0.01
Impervious surface area within Watershed	-11.53	5.68	0.08
Impervious surface area within 50 m Buffer	9.19	4.84	0.09
Land Use Index	-10.98	5.09	0.06

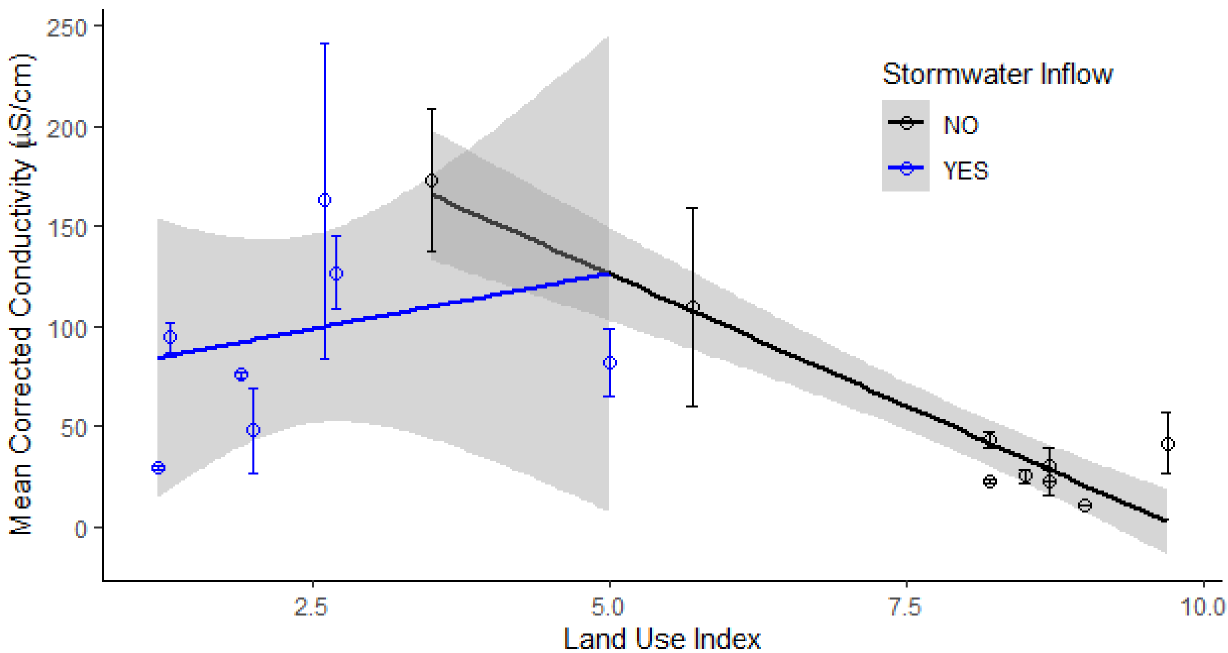


Figure 21. Effects of Land Use Index and the presence of stormwater inflows on mean porewater EC_{corr} in laggs during spring. High Land Use Index scores = fewer human-induced stressors.

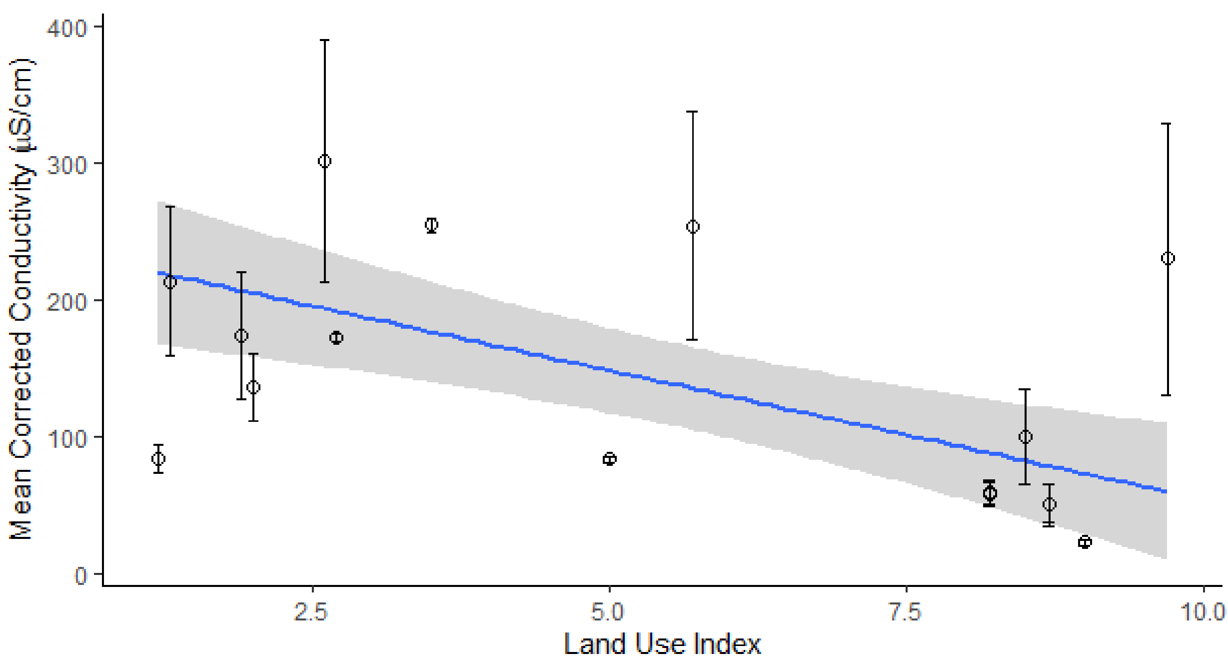


Figure 22. Effects of Land Use Index on mean porewater EC_{corr} in laggs during late summer. High Land Use Index scores = fewer human-induced stressors.

The proportion of impervious surface area surrounding each study site had varying effects on porewater EC_{corr} in peatland centers and laggs. During spring, EC_{corr} in peatland centers was not related to impervious surface area within buffer distances up to 500 m, but significant relationships occurred for laggs (Figure 23, Table D5 in Appendix D). Lagg EC_{corr} increased with higher impervious surface area, although the relationship was weaker at buffer distances of 500 m (p = 0.09). During late summer, impervious surface area was positively correlated to EC_{corr} in peatland centers for buffer distances up to 250 m, and in laggs for buffers up to 500 m from the wetland perimeter (Figure 23, Table D6 in Appendix D).

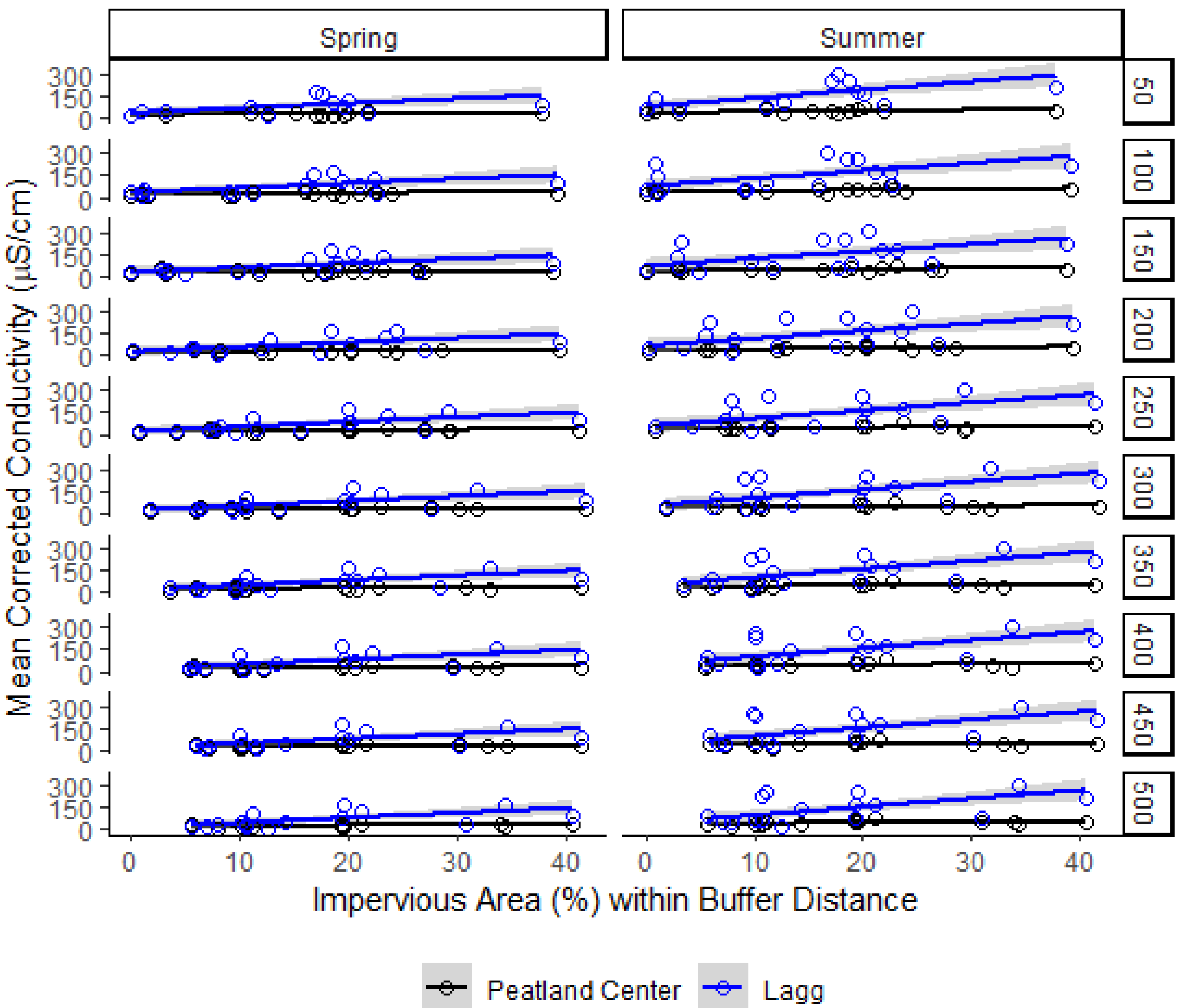


Figure 23. Effects of impervious area within buffer distances of the wetland perimeter on seasonal mean corrected conductivity in peatland centers and laggs. Buffer distances are shown in the row labels.

4.3.4 Chloride

The effects of watershed and land use characteristics on porewater Cl^- concentrations varied with wetland position and season. Chloride concentrations in peatland centers during spring were related to interactions between watershed area and Land Use Index (Model 5 in Table E1 in Appendix E) and interactions between watershed area and mean annual precipitation (Model 3 in Table E1 in Appendix E). Other top-ranked models contained non-significant covariates that did not improve fit. Mean Cl^- increased with watershed area but the rate of increase declined with higher Land Use Index, and these fixed effects explained 27.4 % of variability (Table 23). Similar patterns were evident for Model 3, where increasing mean annual rainfall offset increases in Cl^- associated with larger watersheds ($R^2 = 0.28$).

In laggs, springtime Cl^- concentration was best explained by the effects of watershed area, mean annual precipitation, and impervious surface area within 50 m of the wetland (Model 2 in Table E2 in Appendix E). The model with a lower AIC score contained a non-significant interaction that yielded only marginal increases in explanatory power ($p = 0.06$). In contrast to peatland centers, lagg Cl^- concentration decreased with larger watershed area, and buffer impervious surface area had a similar effect (Table 24; $R^2 = 0.44$). In this model, lagg Cl^- increased with annual rainfall ($p = 0.03$) but this effect was much smaller than that of the other variables.

During late summer, watershed area was the best predictor of Cl^- concentrations in peatland centers (Model 4 in Table 31 in Appendix E). More complex candidate models contained non-significant interactions or covariates that did not improve goodness of fit ($p > 0.07$). Summertime mean Cl^- increased with watershed area ($p = 0.01$) and this explained 10.4 % of variability (Figure 24). Lagg Cl^- concentrations during late summer were best explained by mean annual precipitation and the presence of stormwater inflow (Model 1 in Table E4 in Appendix E). Mean Cl^- decreased with higher annual precipitation ($p = 0.08$), but this decline was much sharper in sites receiving inflows from stormwater management facilities ($p = 0.002$) and this relationship explained 50.4 % of the variation (Figure 25).

Table 23. Effects of watershed area and Land Use Index on porewater Cl- in peatland centers during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.43	0.60	0.47
Watershed Area (AREA)	4.03	1.46	0.01
Land Use Index (LUI)	0.23	0.22	0.32
AREA:LUI	-1.54	0.70	0.03

Table 24. Effects of watershed area, mean annual precipitation, and impervious surface area within 50 m of the wetland perimeter on porewater Cl- in laggs during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	4.88	2.75	0.10
Watershed Area	-8.73	3.87	0.05
Mean Annual Precipitation	2.18	0.87	0.03
Impervious surface area within 50 m	-9.54	4.58	0.06

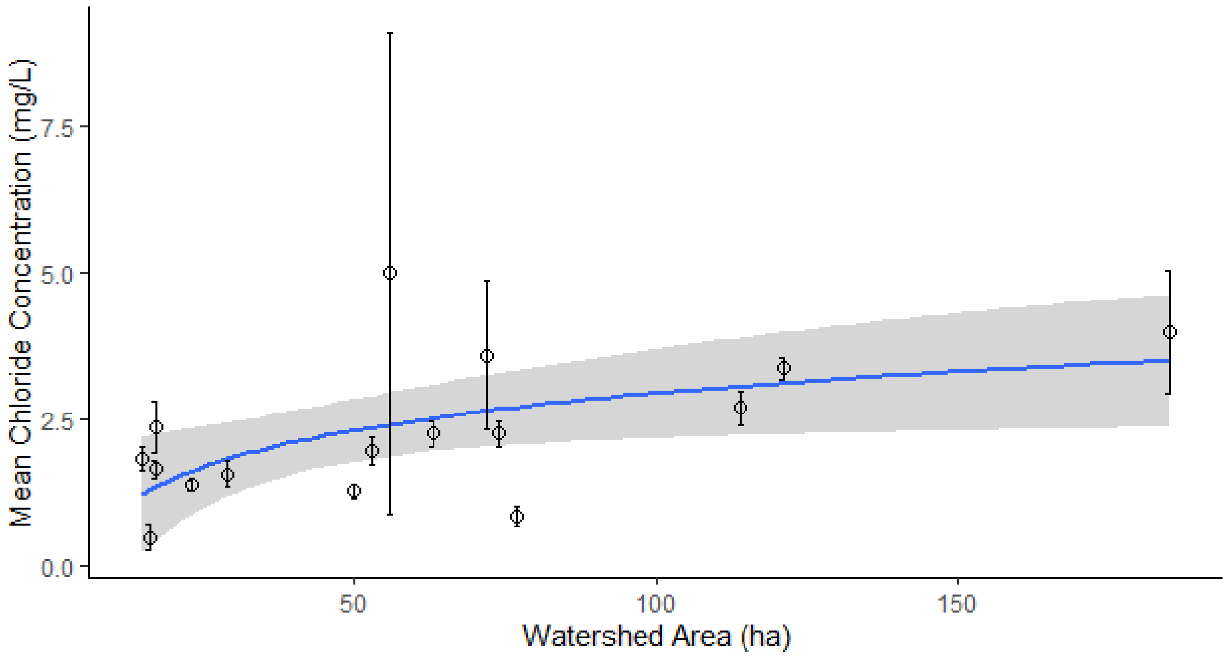


Figure 24. Effects of watershed area on mean porewater chloride concentration in peatland centers during late summer.

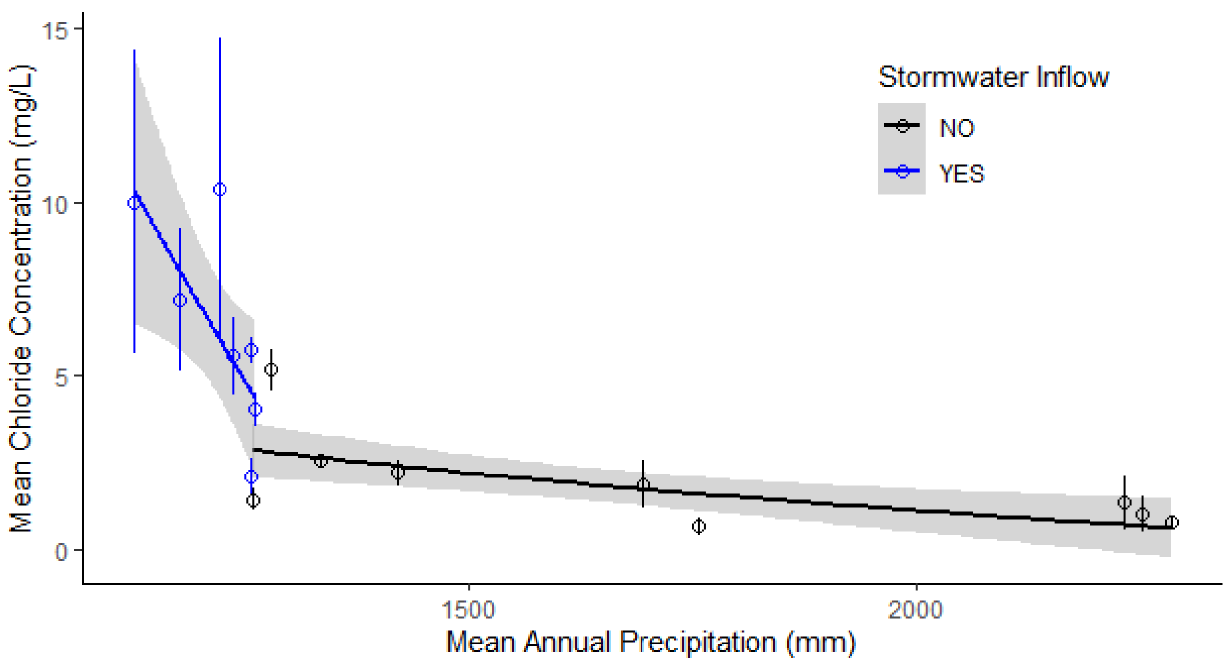


Figure 25. Effects of mean annual precipitation and the presence of stormwater inflows on mean porewater chloride concentration in laggs during late summer.

Springtime porewater Cl^- concentrations in peatland centers and laggs increased with the fraction of impervious surface area surrounding wetlands (Figure 26, Table E5 in Appendix E). These effects were strong for buffer distances up to 300 m in both settings ($p < 0.03$), although weaker effects were apparent for distances to 400 m in peatland centers ($p < 0.09$) and up to 500 m in laggs ($p < 0.08$). During summer, peatland centers Cl^- was not related to impervious surface area, but positive relationships were apparent in laggs for distances up to 500 m (Table E6 in Appendix E).

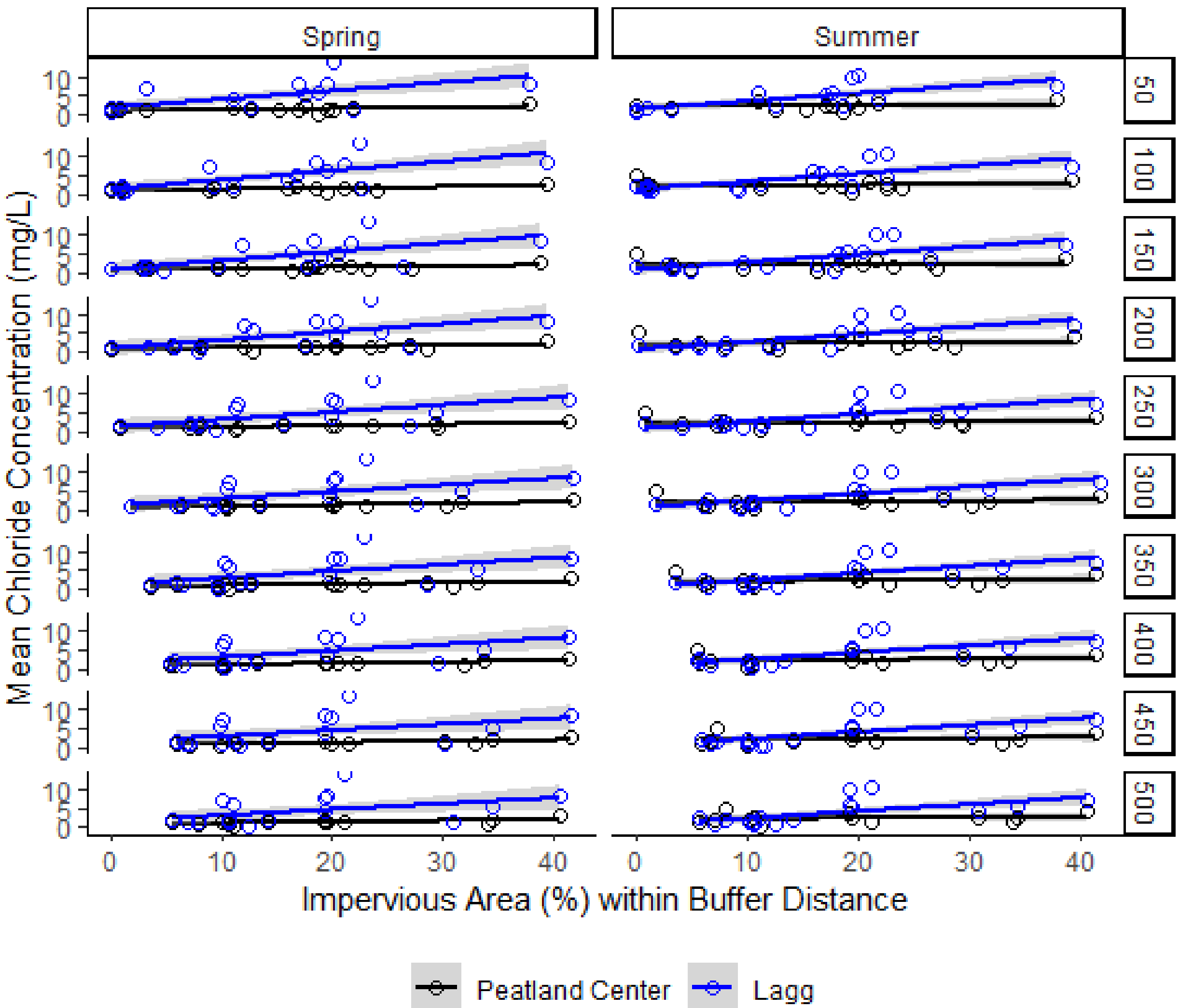


Figure 26. Effects of impervious area within buffer distances of the wetland perimeter on seasonal mean chloride concentrations in peatland centers and laggs. Buffer distances are shown in the row labels.

4.3.5 Calcium

Peatland center Ca^{2+} concentrations during spring were best explained by the interaction between mean annual rainfall and impervious surface area within 50 m of the wetland (Model 1 in Table

F1 in Appendix F). Calcium concentrations decreased with higher annual rainfall, but increased with rainfall as impervious surface area increased (Table 25; $R^2 = 0.18$).

Lagg Ca^{2+} concentrations during spring were best explained by watershed impervious surface area and interactions between stormwater inflows and watershed area (Model 1 in Table F2 in Appendix F), and this model explained more variability than simpler candidate models ($p = 0.04$). Mean Ca^{2+} concentration increased with the fraction of impervious surface area within the watershed, but Ca^{2+} decreased with watershed area when stormwater inflows were present (Table 26; $R^2 = 0.50$).

Table 25. Effects of mean annual precipitation and impervious surface area within 50 m of the wetland perimeter on porewater Ca2+ in peatland centers during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.09	1.81	0.96
Watershed Area	-14.65	7.54	0.06
Mean Annual Precipitation	-0.58	0.88	0.51
Impervious surface area within 50 m	14.98	6.58	0.03

Table 26. Effects of mean annual precipitation and impervious surface area within 50 m of the wetland perimeter on porewater Ca^{2+} in laggs during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.89	0.88	0.32
Watershed Area (AREA)	-0.00	2.78	0.99
Impervious surface area within Watershed	1.45	0.50	0.01
Presence of Stormwater Inflow (STORM)	4.52	1.45	0.004
AREA:STORM	-8.18	4.15	0.06

Peatland center Ca^{2+} concentrations during summer were most strongly related to Land Use Index and the presence of stormwater inflows (Model 1 in Table F3 in Appendix F). Mean Ca^{2+} declined with higher Land Use Index ($p = 0.01$), but increased with Land Use Index when stormwater management facilities were present ($p = 0.003$), and this model explained 24.0 % of variability (Figure 27). Late summer lagg Ca^{2+} concentrations were not strongly related to the measured variables, but the best model included watershed area and impervious surface area within a 50 m buffer (Model 1 in Table F4 in Appendix F). Standardized coefficients indicated that mean Ca^{2+} concentration was primarily driven by watershed area (Table 27; $R^2 = 0.24$).

During spring, porewater Ca^{2+} concentrations increased in laggs along with the fraction of impervious surface area surrounding wetlands to distances of 500 m ($p < 0.02$). Weak increases were evident in peatland centers with impervious surface area to distances of 150 m (Figure 28, Table F5 in Appendix F). Impervious surface area did not have detectable effects on mean Ca^{2+} in either wetland position during late summer (Table F6 in Appendix F).

Table 27. Effects of watershed area, the presence of natural surface water inflows, and impervious surface area within 50 m of the wetland perimeter on porewater Ca^{2+} in laggs during late summer.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	474	2.59	0.11
Watershed Area	-17.71	8.22	0.06
Impervious surface area within 50 m Buffer	2.92	1.49	0.09
Presence of Natural Surface Water Inflow	3.96	2.87	0.21
AREA:STORM	-8.18	4.15	0.06

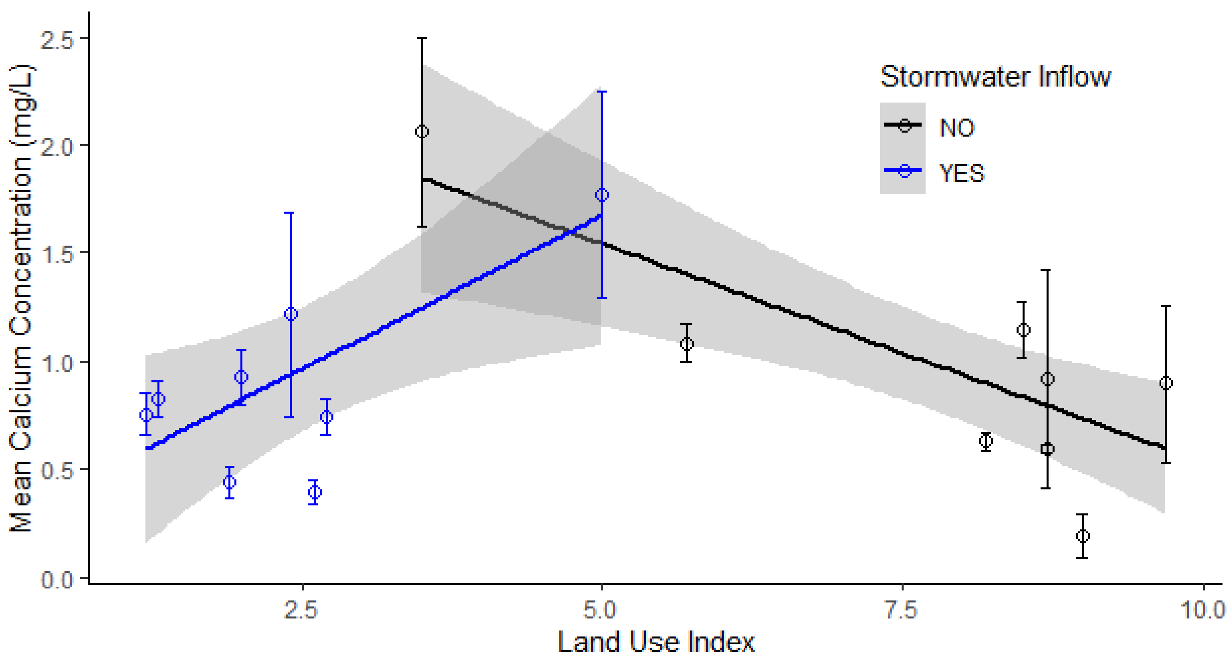


Figure 27. Effects of Land Use Index and the presence of stormwater inflows on mean porewater calcium concentration in peatlands during late summer. High Land Use Index scores = fewer human-induced stressors.

4.3.6 Ammonium

Porewater NH_4^+ concentrations in peatland centers and laggs were affected by the fraction of impervious surface area within their watersheds during spring. Peatland NH_4^+ concentrations were best explained by watershed area and watershed impervious surface area (Model 4 in Table G1 in Appendix G), and additional covariates in more complex models did not improve explanatory power ($p > 0.08$). Mean NH_4^+ decreased with greater watershed area and increased with impervious surface area within the watershed (Table 28; $R^2 = 0.18$). Lagg porewater NH_4^+ concentrations were best explained by the presence of natural surface water inflows, and impervious surface area within the watershed and within 50 m of the wetland (Model 1 in Table G2 in Appendix G). Mean NH_4^+ increased with watershed impervious surface area; this increase was greater when natural surface

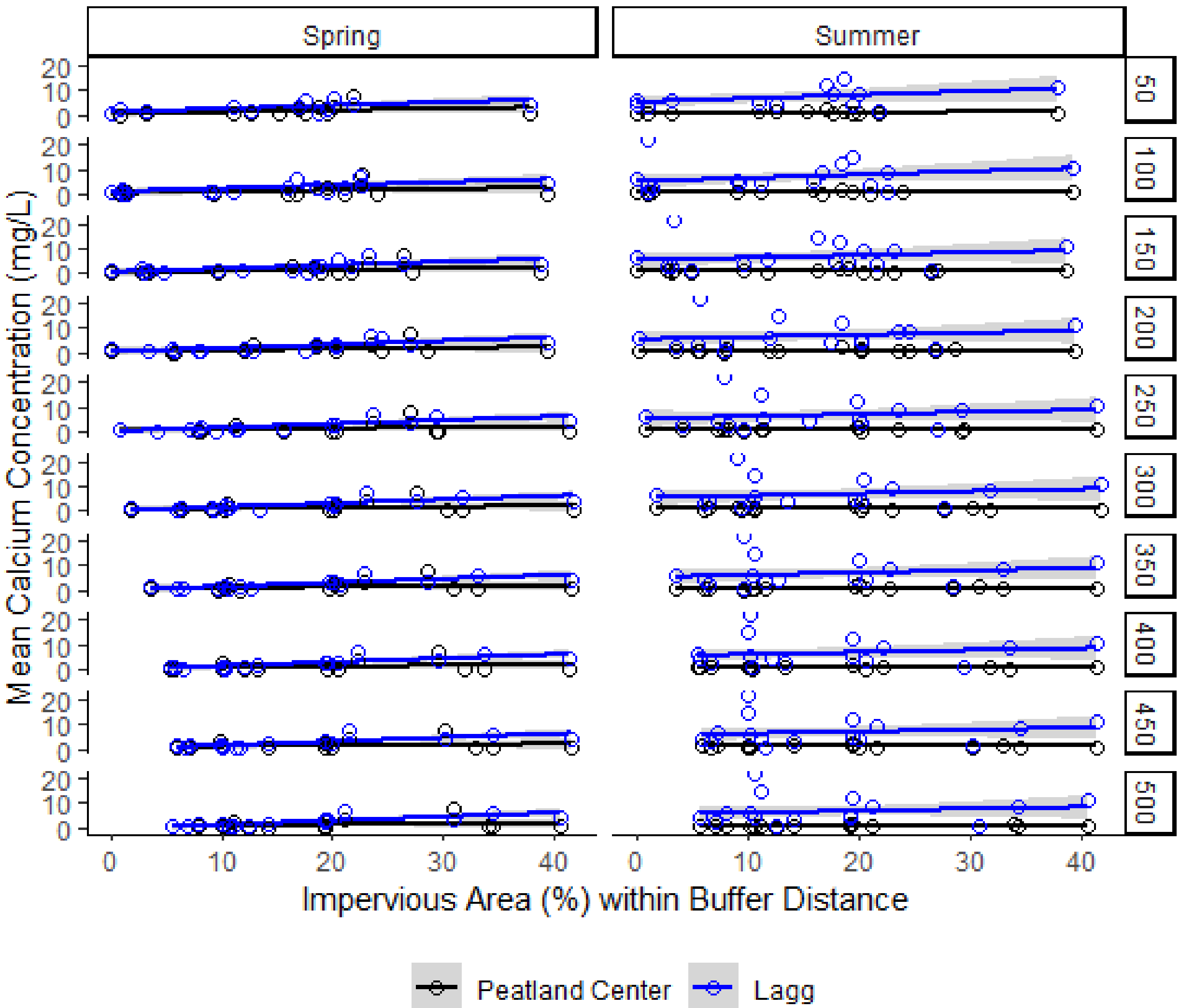


Figure 28. Effects of impervious area within buffer distances of the wetland perimeter on seasonal mean calcium concentration in peatland centers and laggs. Buffer distances are shown in the row labels.

water inflows were present (Table 29; $R^2 = 0.36$). Impervious surface area within 50 m of the wetland had a small negative effect on porewater NH_4^+ concentrations.

During late summer, peatland NH_4^+ concentrations were best explained by interactions of watershed area and the presence of stormwater inflows (Model 2 Table G3 in Appendix G). The model with a lower AIC score contained a non-significant covariate that only slightly improved model fit ($p = 0.09$). Mean NH_4^+ decreased with watershed area when stormwater inflows were present ($p = 0.07$), but area had no effect on NH_4^+ otherwise ($p = 0.56$) and this explained 11.3 % of variation (Figure 29). Lagg NH_4^+ concentrations were best explained by mean annual precipitation (Model 1 Table G4 in Appendix G). Mean NH_4^+ declined with increasing annual rainfall (Figure 30; $R^2 = 0.13$).

Ammonium concentrations in peatland centers were not related solely to the fraction of impervious surface area within 500 m of the wetland perimeter in either season, but they were in laggs (Figure 31, Table G5 and G6 in Appendix G). During spring, lagg NH_4^+ concentrations increased with impervious surface area within distances of 100 to 500 m of the wetland perimeter ($p < 0.10$), but these relationships were strongest for impervious surface area within buffer distances of 250-450 m ($p < 0.05$). During late summer, the effects of impervious surface area on lagg NH_4^+ concentrations were strongest within buffers 300 to 500 m from the wetland perimeter.

Table 28. Effects of watershed area and impervious surface area within the watershed on porewater NH_4^+ in peatland centers during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.09	0.12	0.49
Watershed Area	-0.69	0.36	0.06
Impervious surface area within Watershed	0.19	0.07	0.01

Table 29. Effects of watershed area and impervious surface area within the watershed on porewater NH_4^+ in laggs during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.36	0.20	0.09
Presence of Natural Surface Water (INFLOW)	-0.89	0.40	0.05
Impervious surface area within Watershed (SHED)	0.35	0.15	0.04
Impervious surface area within 50 m Buffer	-0.34	0.16	0.06
INFLOW:SHED	0.53	0.18	0.02

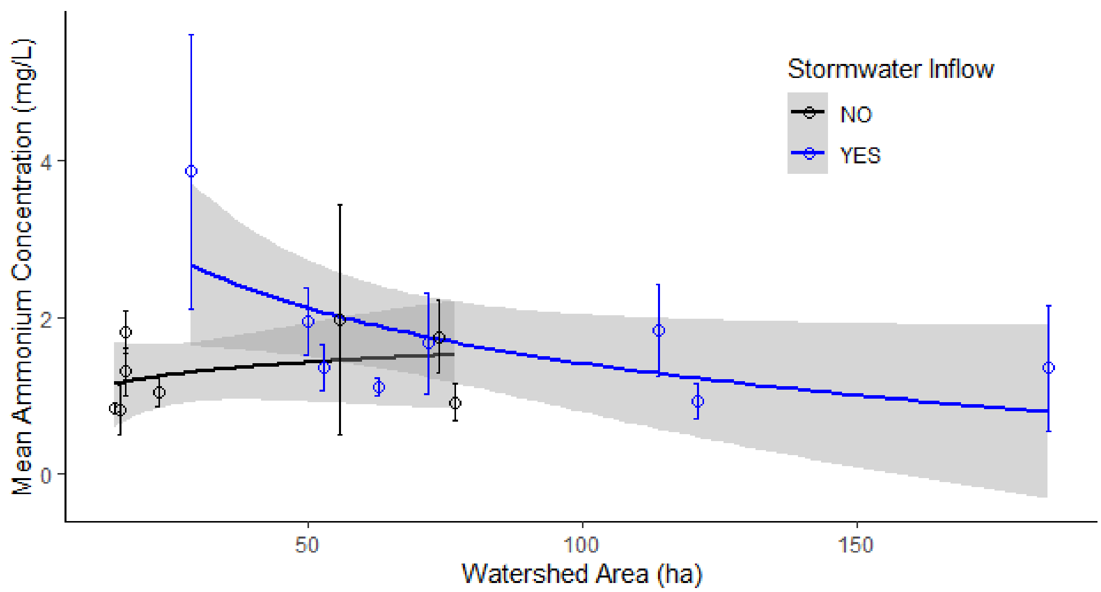


Figure 29. Effects of watershed area and the presence of stormwater inflows on mean porewater ammonium concentration in peatland centers during late summer.

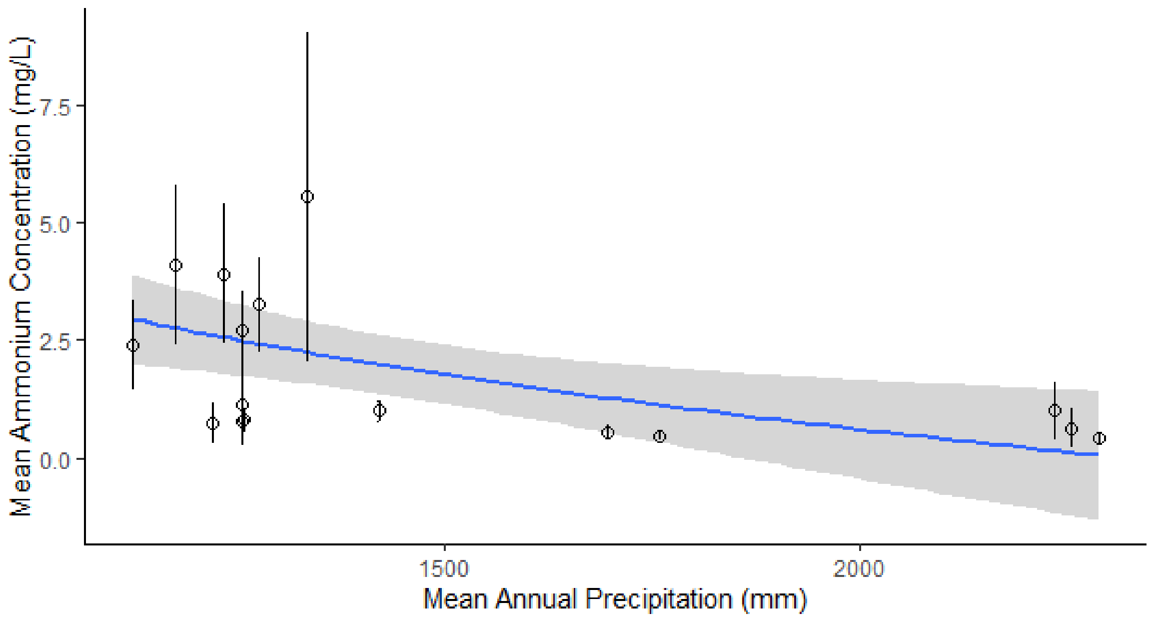


Figure 30. Effects of mean annual precipitation on mean porewater ammonium concentration in laggs during late summer.

4.3.7 Phosphate

Porewater phosphate concentrations in both peatland centers and laggs during spring were most strongly related to surface water inflows. Mean PO_4^{3-} concentrations in peatland centers were best explained by the presence of stormwater management facilities (Model 3 in Table H1 in Appendix H), or Land Use Index and the presence of natural surface water inflows (Model 7). Springtime PO_4^{3-} concentration in peatland centers receiving stormwater inflow averaged 0.07 ± 0.02 mg/L, compared to 0.02 ± 0.02 mg/L in sites without stormwater inflows ($p = 0.04$; $R^2 = 0.11$). Two other models that included stormwater inflow had slightly lower AIC scores, but both contained covariates that were not statistically significant (Table H1 in Appendix H) and did not improve the goodness of fit ($p \geq 0.10$). Peatland center PO_4^{3-} concentrations also decreased with higher Land Use Index values ($p = 0.04$; fewer human-induced stressors) when the effects of natural surface water inflows were included ($p = 0.09$), and this model explained 13.9 % of the variability (Table 30). In laggs, the best models explaining springtime PO_4^{3-} concentrations included interactions between natural surface water inflows and watershed characteristics such as drainage area (Model 1 in Table H2 in Appendix H) and impervious surface area within 50 m of the wetland perimeter (Model 6). When natural surface water inflows were present, mean PO_4^{3-} concentration increased with watershed area ($p < 0.001$), but the effects of watershed area were very small in sites without surface water connections ($p < 0.001$; Table 31), and this model explained 85.2 % of the variability. Similar effects were apparent for impervious surface area within a 50 m buffer (Figure 32; $R^2 = 0.85$). Mean PO_4^{3-} concentration increased with impervious surface area when natural inflows were present ($p < 0.001$), but the effect of impervious surface area was small in isolated wetlands ($p < 0.001$). All other top-ranked models for springtime lagg PO_4^{3-} concentrations contained non-significant covariates that did not improve goodness of fit ($p \geq 0.38$).

During the late summer, PO_4^{3-} concentrations in peatland centers were best explained by mean annual precipitation and watershed area (Model 1 in Table H3 in Appendix H). Mean PO_4^{3-}

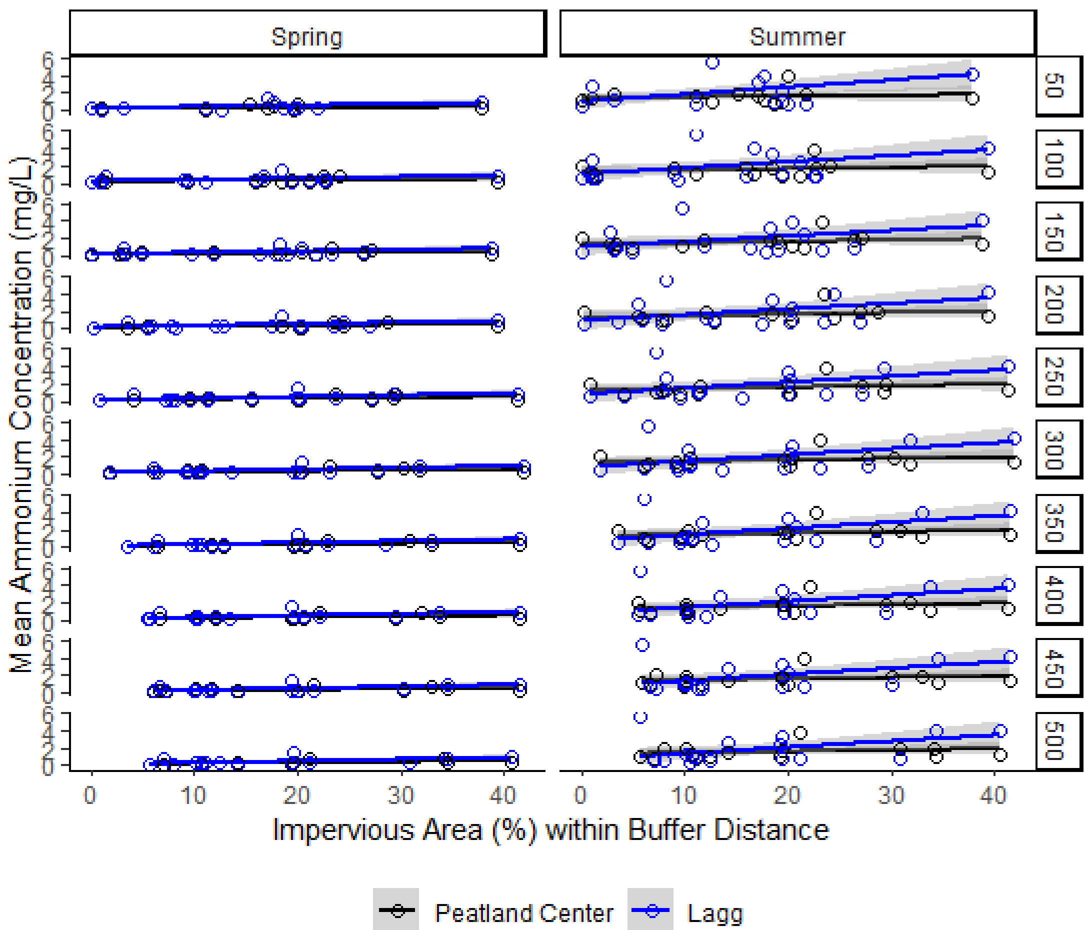


Figure 31. Effects of impervious area within buffer distances of the wetland perimeter on seasonal mean ammonium concentration in peatland centers and laggs. Buffer distances are shown in the row labels.

Table 30. Effects of Land Use Index and the presence of natural surface water inflows on porewater phosphate concentrations in peatland centers during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.109	0.030	<0.001
Land Use Index	-0.028	0.013	0.04
Natural Inflow Present	-0.054	0.031	0.09

concentration declined with annual precipitation ($p = 0.04$), when the smaller negative effect of watershed area was accounted for ($p = 0.07$), and this model explained 16.8 % of the variability (Table 32). Other candidate models contained covariates that did not enhance explanatory power ($p \geq 0.23$) or lacked significant estimates for fixed effects (Table H3 in Appendix H).

Table 31. Effects of Land Use Index and the presence of natural surface water inflows on porewater phosphate concentrations in laggs during spring.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.013	0.013	0.34
Log_{10}(Area)	0.005	0.046	<0.001
Natural Inflow Present	-0.349	0.040	<0.001
Log_{10}(Area): Natural Inflow Present	1.202	0.103	<0.001

Table 32. Effects of mean annual precipitation and watershed area on porewater phosphate concentrations in laggs during late summer.

Fixed Effects	Estimate	Std. Error	p-value
Intercept	0.860	0.239	0.003
Log_{10}(MAP)	-1.268	0.564	0.04
Log_{10}(Area)	-0.932	0.480	0.07

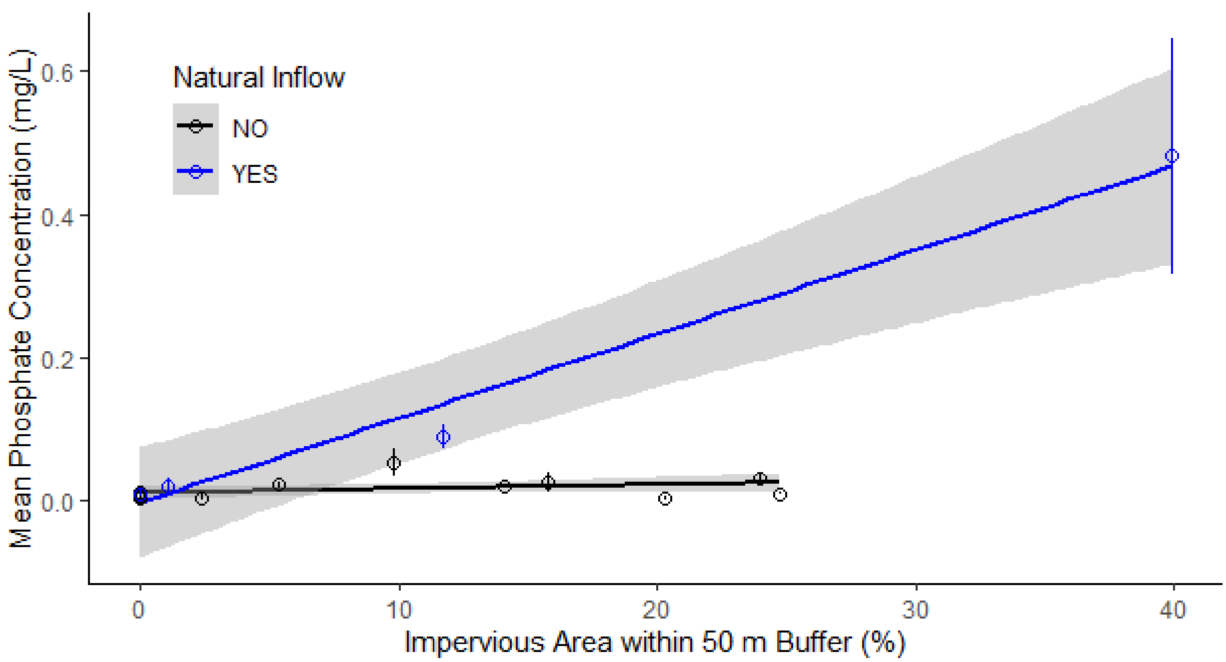


Figure 32. Effects of buffer impervious surface area and natural surface water inflows on porewater phosphate concentrations in laggs during spring.

Late summer PO_4^{3-} concentrations in laggs were best explained by inflows from natural surface water and stormwater management facilities (Model 1 in Table H4 in Appendix H), or impervious surface area within 50 m of the wetland perimeter (Model 4). Mean PO_4^{3-} concentration in laggs receiving stormwater inflow was 0.65 ± 0.14 mg/L, compared to 0.12 ± 0.12 mg/L in other sites ($p = 0.01$). Laggs with both natural inflows and stormwater inflows averaged 0.76 ± 0.26 mg/L higher than laggs without surface water connections ($p = 0.05$), and 0.92 ± 0.31 mg/L higher than laggs with only natural inflows ($p = 0.05$; $R^2 = 0.18$). Lagg PO_4^{3-} concentrations also increased (p

= 0.03) with greater impervious surface area within 50 m of the wetland perimeter (Figure 33; R^2 = 0.10).

Impervious surface area near the wetland perimeter was associated with higher phosphate concentrations in laggs during spring and late summer, but no difference was evident in peatland centers (Figure 34, Table H5 and H6 in Appendix H). During spring, lagg PO_4^{3-} increased with impervious surface area within distances up to 500 m, but this relationship was strongest within distances of 400 m ($p < 0.05$). During late summer, lagg PO_4^{3-} increased with impervious surface area for all buffer distances except for 150 and 200 m.

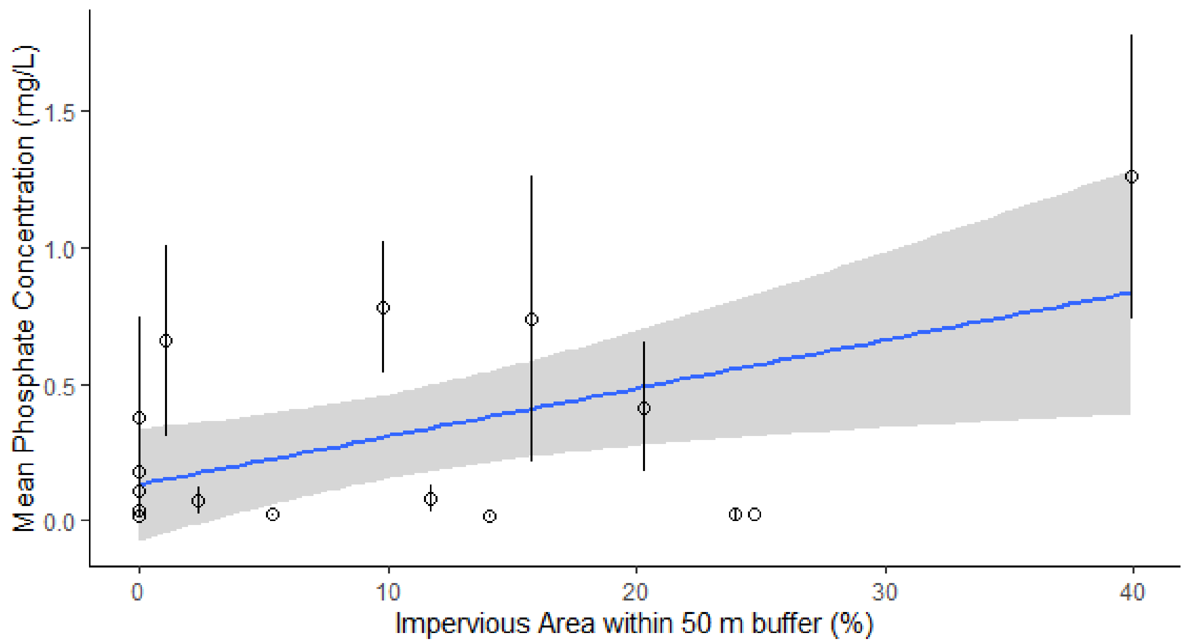


Figure 33. Effects of buffer impervious surface area on porewater phosphate concentrations in laggs during late summer.

4.3.8 Vegetation

Variation of peatland center vegetation was most strongly related to porewater chemistry gradients ($p = 0.01$), while lagg vegetation varied with hydrologic regime and land use factors (Table 33; Appendix J). While overall peatland center composition varied with Ca:Mg during the summer sampling period, lagg composition varied across many more factors (Table 33), including the presence of stormwater inflows, Land Use Index, min/mean/max water levels in all seasons, spring EC_{corr}, and % impervious surface within 500 m (within the watershed). Species level responses were analyzed in more detail via Indicator Species Analysis and NMS ordination axis correlations (see below).

Nonvascular physiognomic group proportions varied with minimum, mean, and maximum water levels during the summer sampling period (Table 34). Perhaps counterintuitively, lichens, feathermosses, and other non-*Sphagnum* nonvascular species increased in abundance with increasing summer water tables (Appendix K). Variation in nonvascular physiognomic group abundance within peatland centers also varied based on the density of herbaceous cover (Table 34; $p = 0.10$).

Herbaceous composition in both peatland centers and laggs varied with most abiotic and land use factors, though all effects were weak (Table 35). As with overall floristic composition, herbaceous composition was more closely related to water levels in the lagg than at the peatland centers. Peatland center herbs varied with increasing impervious surface area, mean summer EC_{corr}, mean spring calcium and mean spring magnesium. Laggs varied with many of these same factors, along with August minimum water levels and January mean and maximum levels.

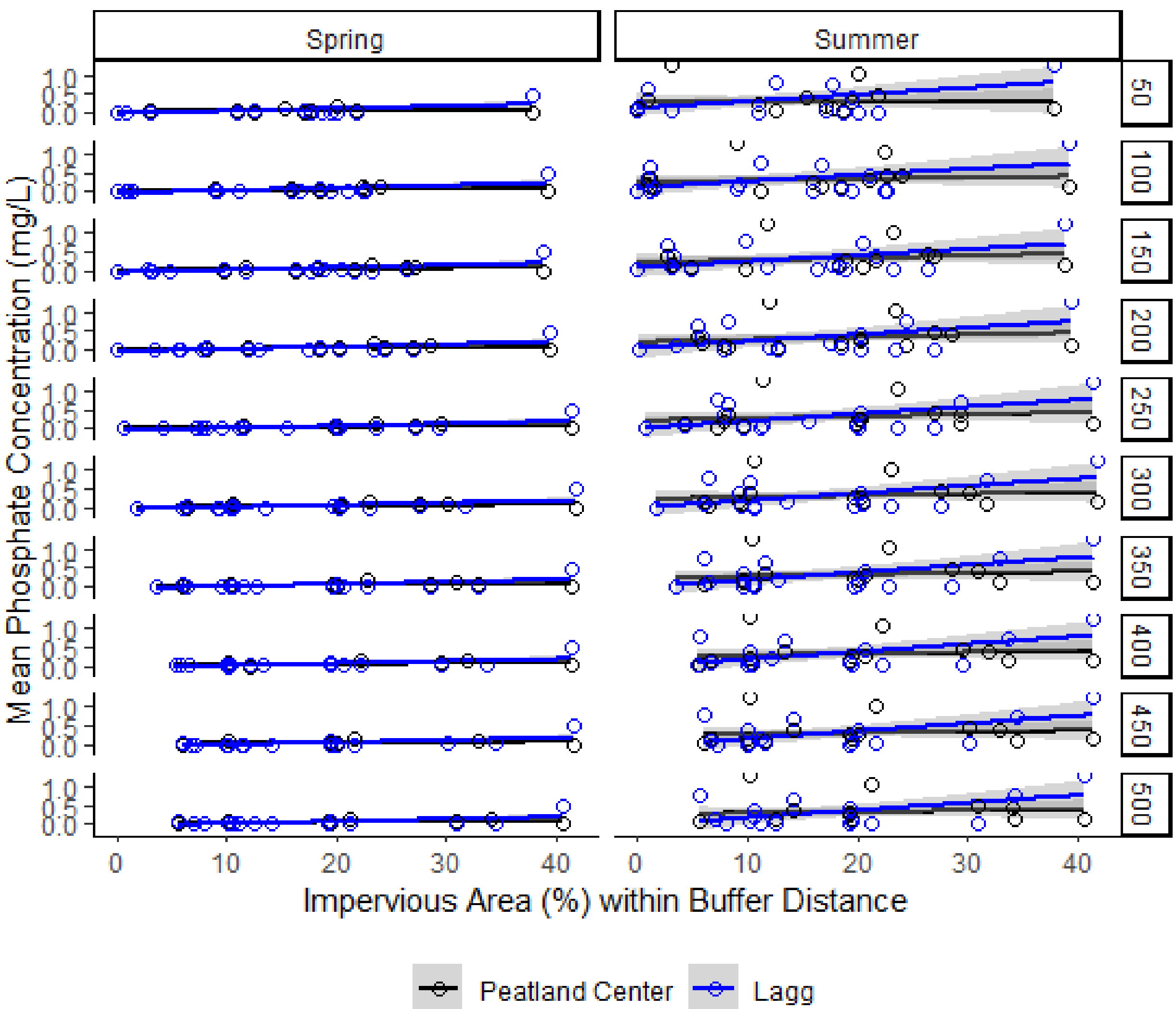


Figure 34. Effects of impervious area within buffer distances of the wetland perimeter on seasonal mean phosphate concentration in peatland centers and laggs. Buffer distances are shown in the row labels.

Summer Ca:Mg was a significant predictor of shrub composition of the peatland centers ($r^2 = 0.31$; p = <0.1; Table 36; Appendix J). Lagg shrub composition varied with both summer and winter water levels, particularly minimum August water level (Table 36).

As noted in Appendix Q , summer precipitation explained a significant amount of variation in total tree stem height class ($r^2 = 0.44$; $p < 0.01$), seedlings (<0.5 m, $r^2 = 0.40$; p = 0.01), saplings (0.5-5 m, $r^2 = 0.43$; p = 0.004), and by small diameter trees (< 5 cm DBH; $r^2 = 0.49$; p = 0.002). Somewhat surprisingly, tree stem counts were greater in bogs with more summer precipitation (Figure 35). Further dendrochronological analysis would be necessary to determine climatological patterns in tree establishment.

Table 33. Hydrological and land use variables correlated with peatland center and lagg vegetation composition.

Variable	R^2	P-value
Peatland center composition varies by...		
Summer Ca:Mg	0.20	0.01
Lagg composition varies by…		
Presence of stormwater inflows	0.12	0.04
Land Use Index of watershed	0.10	0.09
Mean August water level	0.13	0.02
Minimum August water level	0.17	< 0.01
Maximum August water level	0.10	0.08
Mean January water level	0.13	0.02
Minimum January water level	0.12	0.04
Maximum January water level	0.14	0.01
Spring mean EC_{corr}	0.11	0.07
% impervious surface area within 500 m buffer within watershed	0.12	0.04

Table 34. Hydrological and land use variables correlated with nonvascular physiognomic group abundance.

Factor	R^2	P-value
Abundance of nonvascular physiognomic groups in the peatland center varies by...		
Total herb cover	0.14	0.10
Mean August water level	0.21	0.02
Minimum August water level	0.21	0.01
Maximum August water level	0.19	0.02

All NMS ordinations used two dimensions. Vascular plant composition of peatland centers was clearly distinct from lagg composition and showed less variability (Figure 36). Reference sites did not group separately from developed sites when looking at the full suite of vascular species. Looking at abiotic and nonvascular axis correlations, laggs consistently had higher pH, $EC_{corr,}$ summer Ca^{2+}, summer Mg^{2+}, winter water levels, and maximum summer water levels, but lower feathermoss and *Sphagnum* cover (Figure 36, Table 37). The variability in lagg floristic composition also tracks the greater variability in hydrologic regime in the laggs. Since land use estimates were identical for peatland centers and laggs from the same peatland site, these factors were not useful for distinguishing peatland centers from laggs.

Table 35. Hydrological and land use variables correlated with peatland center and lagg herbaceous composition.

Factor	R^2	P-value
Peatland center herb composition varies by…		
Land Use Index of watershed	0.10	0.07
% impervious surface w/i the watershed	0.10	0.08
Summer mean EC_{corr}	0.12	0.01
% impervious surface w/i 50 m buffer of wetland	0.13	0.01
% impervious surface w/i 100 m buffer of wetland	0.14	0.01
% impervious surface w/i 150 m buffer of wetland	0.13	0.01
% impervious surface w/i 200 m buffer of wetland	0.12	0.02
% impervious surface w/i 250 m buffer of wetland	0.11	0.05
% impervious surface w/I 300 m buffer of wetland	0.10	0.07
% impervious surface w/i 350 m buffer of wetland	0.10	0.08
% impervious surface w/i 50 m buffer of wetland within watershed	0.10	0.07
% impervious surface w/i 100 m buffer of wetland within watershed	0.13	0.01
% impervious surface w/i 150 m buffer of wetland within watershed	0.14	0.01
% impervious surface w/i 200 m buffer of wetland within watershed	0.14	0.01
% impervious surface w/i 250 m buffer of wetland within watershed	0.13	0.01
Spring mean Ca	0.10	0.07
Spring mean Mg	0.10	0.07
Lagg herb composition varies by…		
Land Use Index of watershed	0.11	0.08
% impervious surface w/i the watershed	0.10	0.09
Minimum August water level	0.10	0.07
Mean January water level	0.10	0.08
Maximum January water level	0.10	0.07
Spring mean EC_{corr}	0.13	0.01
% impervious surface w/i 50 m buffer of wetland	0.12	0.01
% impervious surface w/i 100 m buffer of wetland	0.11	0.05
% impervious surface w/i 50 m buffer of wetland within watershed	0.11	0.02
% impervious surface w/i 100 m buffer of wetland within watershed	0.11	0.03
% impervious surface w/i 450 m buffer of wetland within watershed	0.11	0.06
Spring mean Ca	0.10	0.06
Spring mean Mg	0.10	0.09

Table 36. Hydrological and land use variables correlated with peatland center and lagg shrub composition.

Factor	R^2	P-value
Peatland center shrub composition varies by…		
Summer mean Ca	0.16	0.08
Summer Ca:Mg	0.31	< 0.01
Lagg shrub composition varies by…		
Mean August water level	0.12	0.03
Minimum August water level	0.16	0.01
Mean January water level	0.11	0.07
Maximum January water level	0.11	0.06

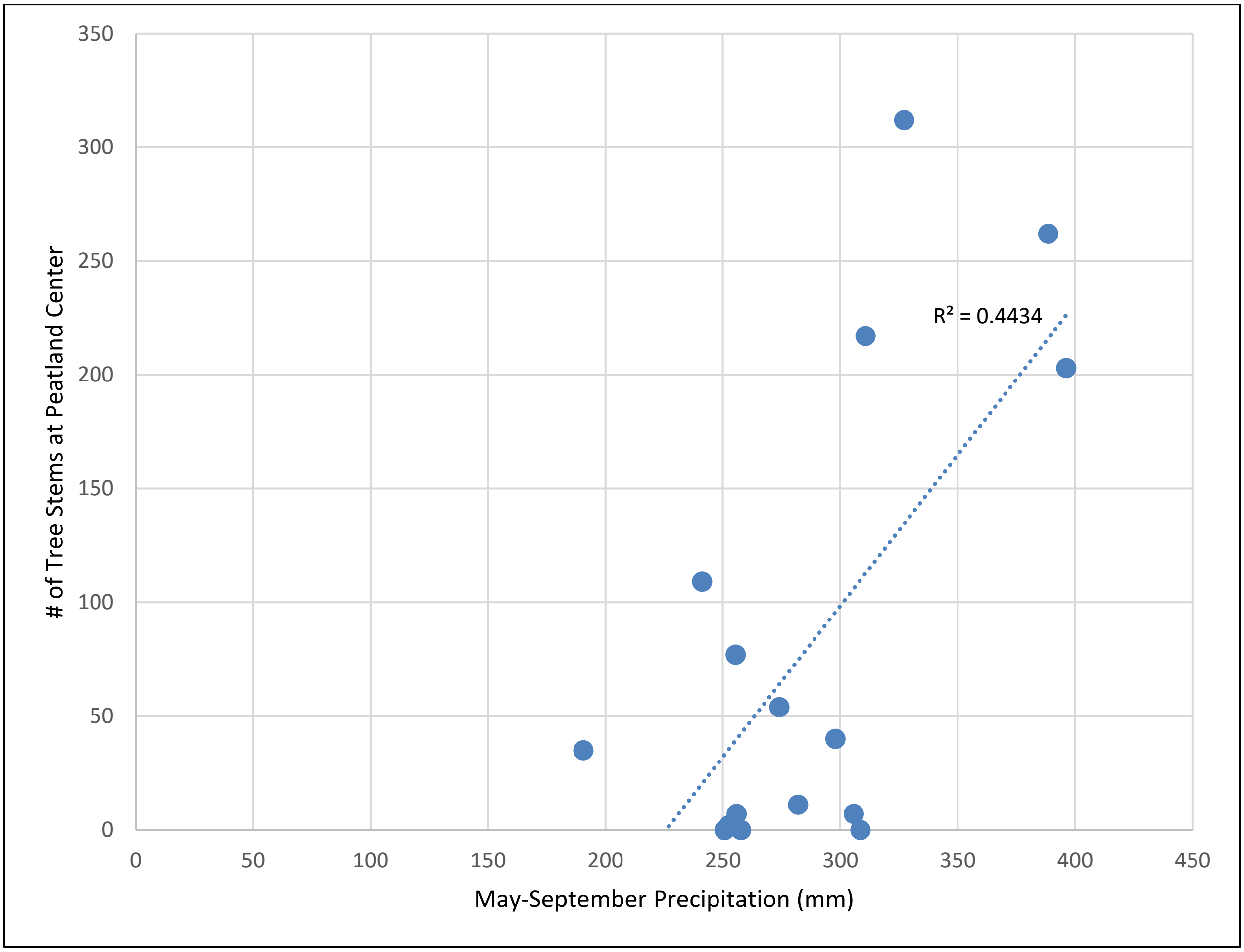


Figure 35. Total number of tree stems at peatland center as a function of summer precipitation.

When analyzing all sites together, Axis 1 in the NMS ordinations primarily represents a shift from *Kalmia microphylla* + *Rhododendron groenlandicum* dominance (peatland centers) and *Spiraea douglasii* + *Malus fusca* dominance (laggs) (Figure 36; Table 38). The few lagg relevés that group toward the left side of axis 1 represent forested laggs that had little or no *Spiraea douglasii* or *Malus fusca* present. Developed and reference sites intermingle in the ordination, but all of the wettest sites are in developed settings.

While a separate NMS analysis of peatland centers alone did not produce meaningful results, ordinations restricted to laggs showed that floristic variation correlated with a gradient of increasing elevation and decreasing winter water levels (axis 1), as well as decreasing summer calcium/magnesium and increasing summer water levels (axis 2; Figure 37; Table 39). Floristically, axis 1 of the lagg-only NMS (Figure 37) represents a gradient of decreasing *Spiraea douglasii* and increasing mesic species (*Gaultheria shallon*, *Rhododendron menziesii*, *Struthiopteris spicant*, etc.) characteristic of forested laggs (Table 40). This follows the gradients of decreasing winter water levels, increasing feathermoss cover, and increasing Land Use Index (i.e. fewer human-induced stressors). Axis 2 represents decreasing *Malus fusca* and *Oenanthe sarmentosa*, along with increasing cover of species characteristic of permanently flooded or permanently saturated conditions (e.g., *Carex cusickii*, *Carex aquatilis* var. *dives*, *Nuphar polysepala*, *Typha latifolia*, and others). This follows the gradients of increasing summer water levels and decreasing calcium and magnesium exhibited in the laggs (Table 39). Variation in floristic composition along axis 2 appears to be unrelated to land use.

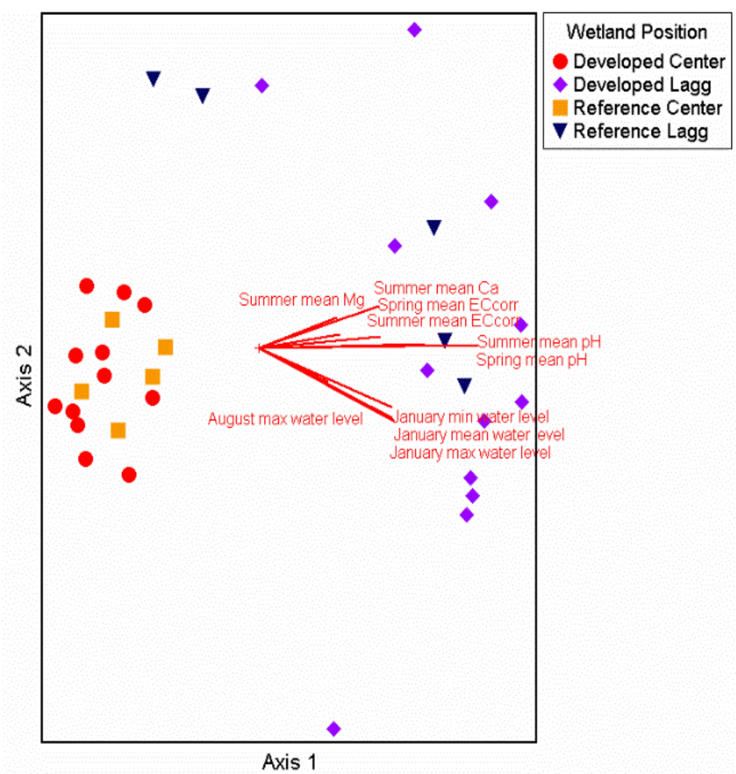


Figure 36. NMS ordination of vascular composition in peatland centers and laggs. Biplots represent hydrological and hydrochemistry factors.

Table 37. Abiotic and nonvascular correlations with all relevé plots NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Spring mean pH	0.82	0.67	Mean January water level	-0.46	0.21
Summer mean pH	0.71	0.51	Maximum January water level	-0.45	0.20
Mean January water level	0.64	0.41	Land Use Index of 100-500 m buffer	0.46	0.21
Minimum January water level	0.64	0.41			
Maximum January water level	0.64	0.41			
Summer mean EC_{corr}	0.61	0.37			
Summer mean Ca	0.61	0.37			
Spring mean EC_{corr}	0.50	0.25			
Summer mean Mg	0.49	0.24			
Maximum August water level	0.46	0.21			
Proportion of *Sphagnum* in Ground Layer	-0.69	0.47			
Proportion of Feather Moss in Ground Layer	-0.71	0.50			

Table 38. Floristic correlations with all relevé plots NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Spiraea douglasii	0.66	0.44	*Gaultheria shallon*	0.61	0.37
Malus fusca	0.60	0.36	*Oenanthe sarmentosa*	0.56	0.32
Kalmia microphylla	-0.73	0.53	*Rhododendron menziesii*	0.54	0.29
Rhododendron groenlandicum	-0.74	0.55	*Tsuga heterophylla*	0.54	0.29
			Rubus ursinus	0.53	0.28
			Mycelis muralis	0.53	0.28
			Athyrium filix-femina ssp. *cyclosorum*	0.51	0.26
			Vaccinium parvifolium	0.49	0.24
			Polystichum munitum	0.49	0.24
			Rubus spectabilis	0.45	0.20
			Carex cusickii	-0.46	0.21
			Carex echinata ssp. *echinata*	-0.48	0.23
			Carex aquatilis var. dives	-0.48	0.23
			Comarum palustre	-0.48	0.23
			Eleocharis spp.	-0.48	0.23
			Juncus acuminatus	-0.48	0.23
			Lycopus uniflorus	-0.48	0.23
			Nuphar polysepala	-0.48	0.23
			Scirpus cyperinus	-0.48	0.23
			Typha latifolia	-0.48	0.23
			Juncus hesperius	-0.50	0.25
			Lemna spp.	-0.50	0.25

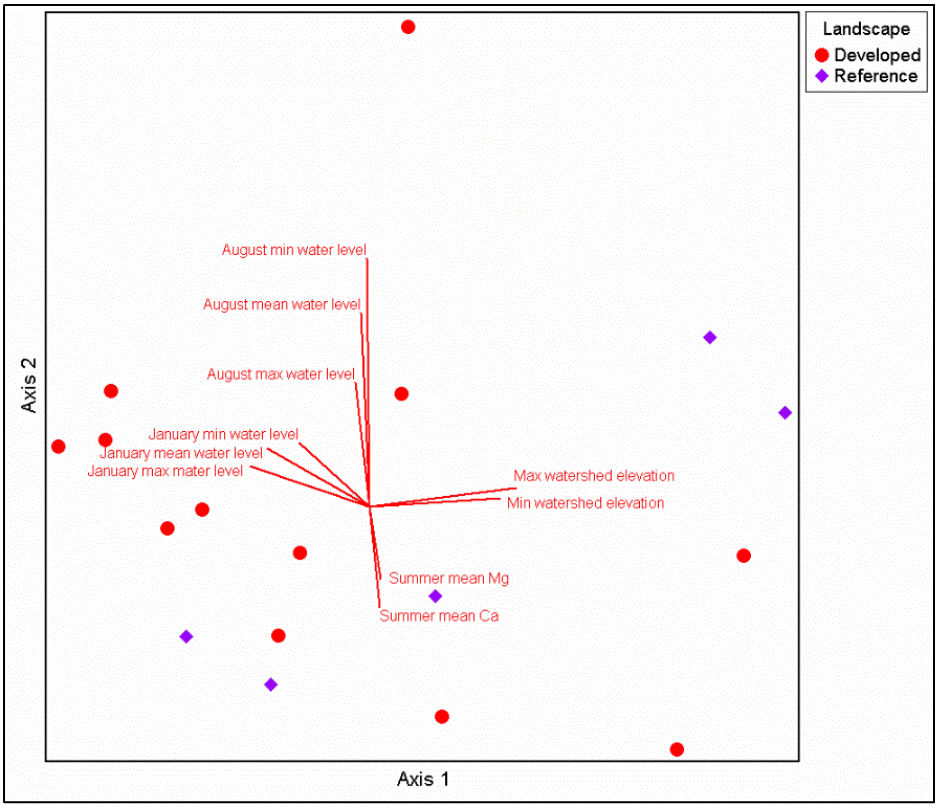


Figure 37. NMS ordination of vascular composition in laggs. Biplots represent abiotic axis correlations.

The results of Indicator Species Analysis showed no significant indicators ($p < 0.10$) of developed peatland centers or laggs (Table 41). However, a few species were shown to have moderate value as indicators of reference peatland centers and reference laggs.

An NMS ordination of nonvascular physiognomic groups (*Sphagnum*, feathermosses, and other mosses) in peatland centers is shown in Figure 38 (data presented are only from peatland centers, where systematic nonvascular transects occurred). Axis 1 represents an abiotic gradient of decreasing summer Ca:Mg and increasing summer water levels (Table 42). Mean spring magnesium and mean annual precipitation also vary somewhat with axis 1, but these factors are more directly correlated to axis 2. Feather moss cover increased and *Sphagnum* and other mosses decrease with greater summer water levels and lower summer Ca:Mg (Table 43). Lichen cover increased with greater annual precipitation and lower spring magnesium levels (axis 2), while "other mosses" showed the opposite relationship. Broadly speaking and with a few exceptions, peatland centers in developed landscapes appear to have higher proportions of feather and "other" mosses (Figure 38, Figure 39). "Other moss" was also shown to be an indicator of developed site (Table 44). Abiotic correlation of the abundance of *Sphagnum* was inconclusive (Figure 40). Indicator species analysis identified lichen cover as a significant indicator of reference conditions but the NMS ordination suggest it may be more related to annual precipitation (Figure 41).

Table 39. Abiotic and nonvascular correlations with lagg relevé plots NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Maximum elevation of watershed	0.64	0.40	Minimum August water level	0.83	0.68
Proportion of Feather Moss in Ground Layer	0.62	0.38	Mean August water level	0.73	0.53
Minimum elevation of watershed	0.60	0.36	Maximum August water level	0.59	0.34
Land Use Index of 100-500 m buffer (WNHP Level 2 EIA)	0.56	0.31	Summer mean Mg	-0.45	0.20
Land Use Index of 500 m buffer (WNHP Level 2 EIA)	0.45	0.20	Summer mean Ca	-0.53	0.28
Mean January water level	-0.53	0.28			
Maximum January water level	-0.57	0.33			

Table 40. Floristic correlations with lagg relevé plots NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Gaultheria shallon	0.73	0.54	*Carex cusickii*	0.74	0.54
Rhododendron menziesii	0.69	0.47	*Carex aquatilis* var. *dives*	0.71	0.51
Tsuga heterophylla	0.65	0.42	*Carex echinata* ssp. *echinata*	0.71	0.51
Struthiopteris spicant	0.58	0.33	*Comarum palustre*	0.71	0.51
Mycelis muralis	0.54	0.30	*Eleocharis* spp.	0.71	0.51
Vaccinium parvifolium	0.52	0.27	*Juncus acuminatus*	0.71	0.51
Cornus unalaschkensis	0.51	0.26	*Lycopus uniflorus*	0.71	0.51
Rubus ursinus	0.50	0.25	*Nuphar polysepala*	0.71	0.51
Thuja plicata	0.50	0.25	*Scirpus cyperinus*	0.71	0.51
Oenanthe sarmentosa	0.50	0.25	*Typha latifolia*	0.71	0.51
Rubus spectabilis	0.49	0.24	*Juncus hesperius*	0.65	0.42
Lysichiton americanus	0.48	0.23	*Lemna spp.*	0.65	0.42
Alnus rubra	0.48	0.23	*Carex canescens*	0.50	0.25
Spiraea douglasii	-0.82	0.68	*Oenanthe sarmentosa*	-0.47	0.22
			Malus fusca	-0.59	0.34

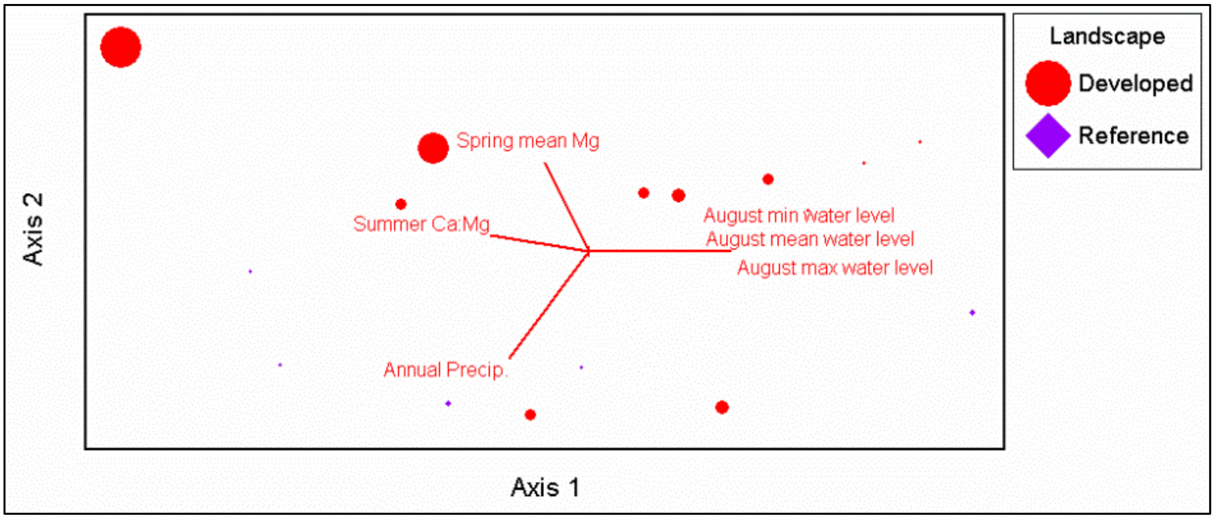


Figure 38. NMS ordination of nonvascular physiognomic group proportions in peatland centers. Biplots represent abiotic axis correlations. Larger relevé markers represent a higher proportion of "other moss".

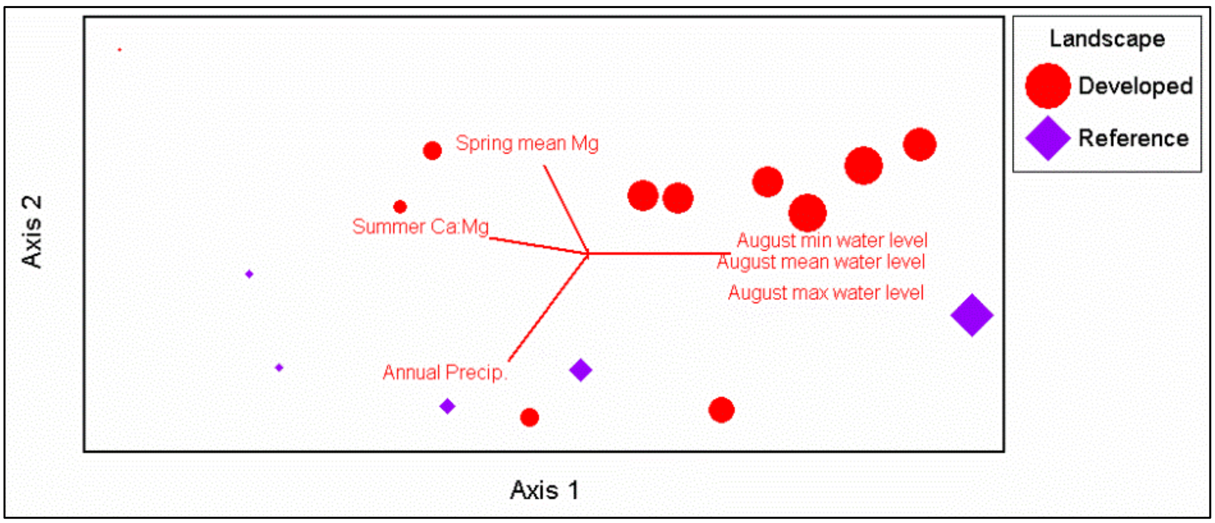


Figure 39. NMS ordination of nonvascular physiognomic group proportions in peatland centers. Biplots represent abiotic axis correlations. Larger relevé markers represent a higher proportion of feathermosses.

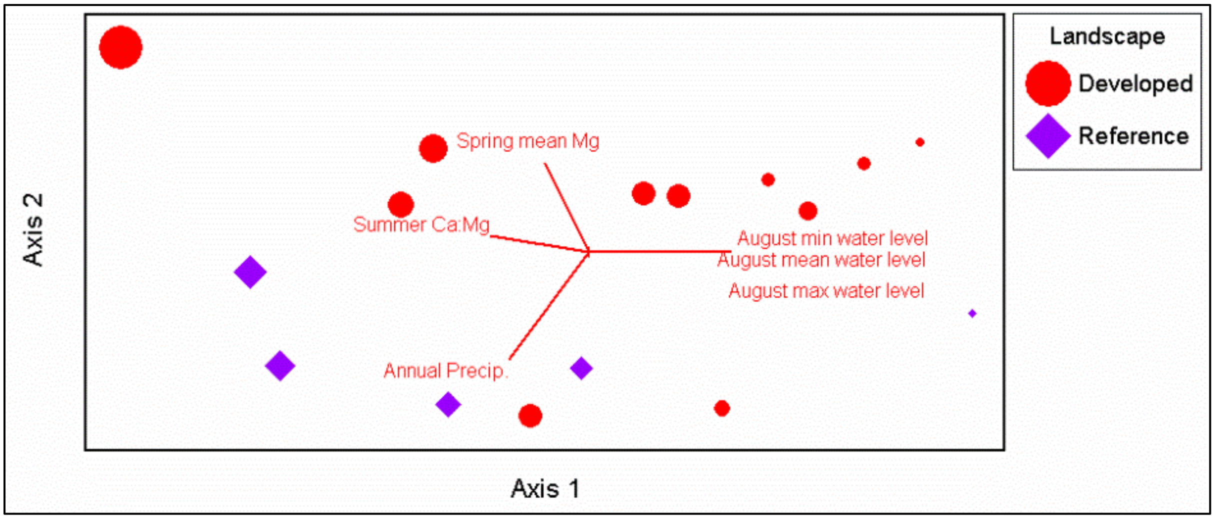


Figure 40. NMS ordination of nonvascular physiognomic group proportions in peatland centers. Biplots represent abiotic axis correlations. Larger relevé markers represent a higher proportion of *Sphagnum*.

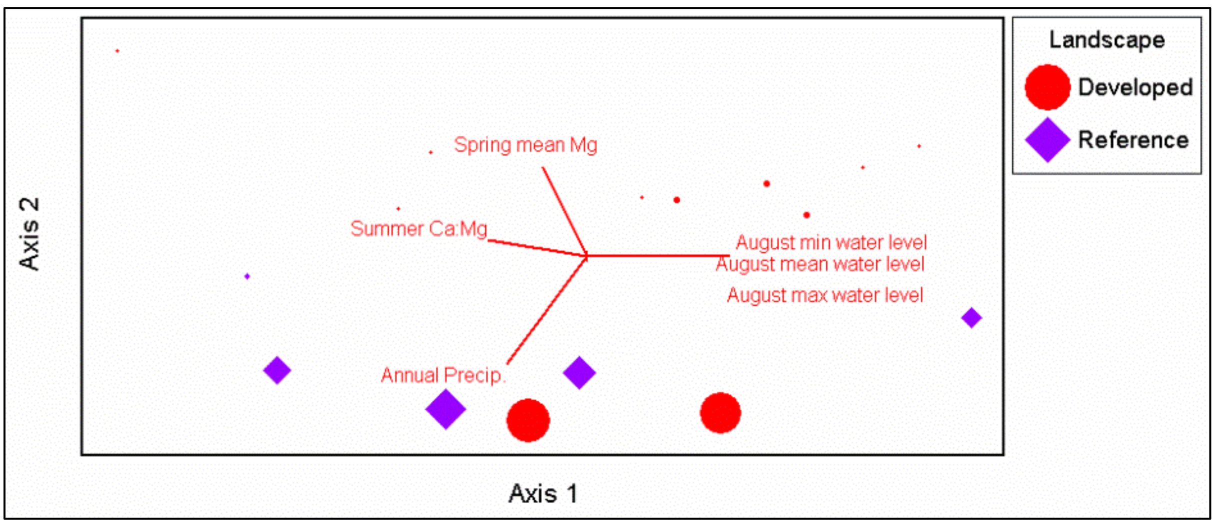


Figure 41. NMS ordination of nonvascular physiognomic group proportions in peatland centers. Biplots represent abiotic axis correlations. Larger relevé markers represent a higher proportion of lichen.

Table 41. Vascular plant species indicators of reference vs. developed study sites. Indicator values range from 0 to 100 (100 = perfect indicator). Only statistically significant results ($p < 0.10$) 5 are shown.

Wetland Position	Species	Reference	Developed	P-value
Peatland center	*Vaccinium uliginosum*	60	0	0.01
Peatland center	*Thuja plicata*	50	3	0.06
Peatland center	*Lysimachia europaea*	40	0	0.07
Peatland center	*Struthiopteris spicant*	40	0	0.08
Peatland center	*Cornus unalaschkensis*	40	0	0.08
Peatland center	*Malus fusca*	40	0	0.08
Peatland center	*Picea sitchensis*	40	0	0.08
Peatland center	*Carex utriculata*	48	3	0.08
Lagg	*Thuja plicata*	80	0	0.00
Lagg	*Carex obnupta*	60	0	0.02
Lagg	*Gaultheria shallon*	71	14	0.05
Lagg	*Pteridium aquilinum* ssp. *pubescens*	46	4	0.07
Lagg	*Lonicera involucrata* var. *involucrata*	40	0	0.08
Lagg	*Rosa pisocarpa*	40	0	0.08
Lagg	*Cornus unalaschkensis*	40	0	0.08
Lagg	*Rhododendron groenlandicum*	61	10	0.09

Table 42. Abiotic correlations with peatland center nonvascular NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Maximum August water level	0.58	0.33	Spring mean Mg	0.46	0.21
Minimum August water level	0.55	0.30	Mean annual precipitation	-0.50	0.25
Mean August water level	0.53	0.28			
Summer Ca:Mg	-0.48	0.23			

Table 43. Nonvascular physiognomic group correlations with peatland center nonvascular NMS axes. Only $r^2 > 0.20$ included.

Axis 1	r	r^2	Axis 2	r	R^2
Feather mosses	0.97	0.95	Other Moss	0.49	0.24
Other mosses	-0.47	0.22	Lichen	-0.93	0.86
Peat mosses (*Sphagnum* spp.)	-0.97	0.95			

Table 44. Nonvascular physiognomic group indicators of peatland centers in reference v. developed landscapes. Only statistically significant results ($p < 0.10$) are shown.

Nonvascular Physiognomic Group	Indicator Value (0-100)		P-value
	Reference	Developed	
Lichen	74	12	0.03
Other Moss	5	64	0.099

4.4 Testing Rapid Assessments in Puget Lowland Peatlands

4.4.1 Ecological Integrity Assessment

Correlations between measured variables and Condition scores (a component of Ecological Integrity Assessment scores) are presented in Table 45. Condition scores were used in these analyses because many land use variables are auto-correlated or explicitly assessed in the Landscape Context metrics that are included in a full EIA score. [See Appendix L and Appendix N] Conditions scores ranged from 2.84 (B-) to 4.00 (A+) across our study sites. The positive correlation between precipitation and Condition score is presumably a result of the moister climates of our reference sites. Negative correlations between Condition scores and impervious surface area, spring chlorine concentrations, and the presence of stormwater inflows were strong (Table 45, Figure 42, Figure 43). Condition scores were also negatively correlated with watershed area and the summer ratio of calcium to magnesium.

EIA assessment areas were delineated based on the extent of the peatland center plant communities (laggs were excluded from EIAs because they support distinct vegetation communities—see Rocchio et al. 2020a). However, some hydrological and porewater chemical variables in the laggs were correlated with Condition scores for the peatland centers. Spring mean calcium and magnesium in the laggs were both significantly negatively correlated with Condition scores in associated centers (Table 46; Figure 44).

4.4.2 Floristic Quality Assessment

Numerous Floristic Quality Assessment (FQA) indices were calculated for peatland centers and laggs and correlated with environmental variables. All FQA indices had significant correlations with abiotic variables, but only two are discussed here: Mean Coefficient of Conservatism (Mean C (all)) and Floristic Quality Assessment Index (FQAI). Due to the infrequent occurrence of nonnative species in these systems, there was no need to exclude nonnative species (e.g., Mean C (nat) and FQAI (nat))—doing so had no meaningful impact on the results. Adjusted Floristic Quality Assessment Index is strongly correlated with Mean C (all) and nonnative species richness, so it was also unnecessary for analyzing an almost entirely native species list. Full results—including regressions for these additional FQA indices—are in Appendix M and Appendix O.

4.4.2.1 Mean Coefficients of Conservatism (Mean C)

Peatland center Mean C (all) ranged from 3.89 to 6.50 (Appendix M and Appendix O), increasing along with stormwater inflows, impervious surface area, maximum January water level (e.g. winter flooding), and spring mean chlorine (Table 47; Figure 45). Mean C (all) values in lagg relevé plots ranged from 2.26 to 4.67. These values were negatively correlated with both spring mean pH and EC_{corr} (Table 48; Figure 46).

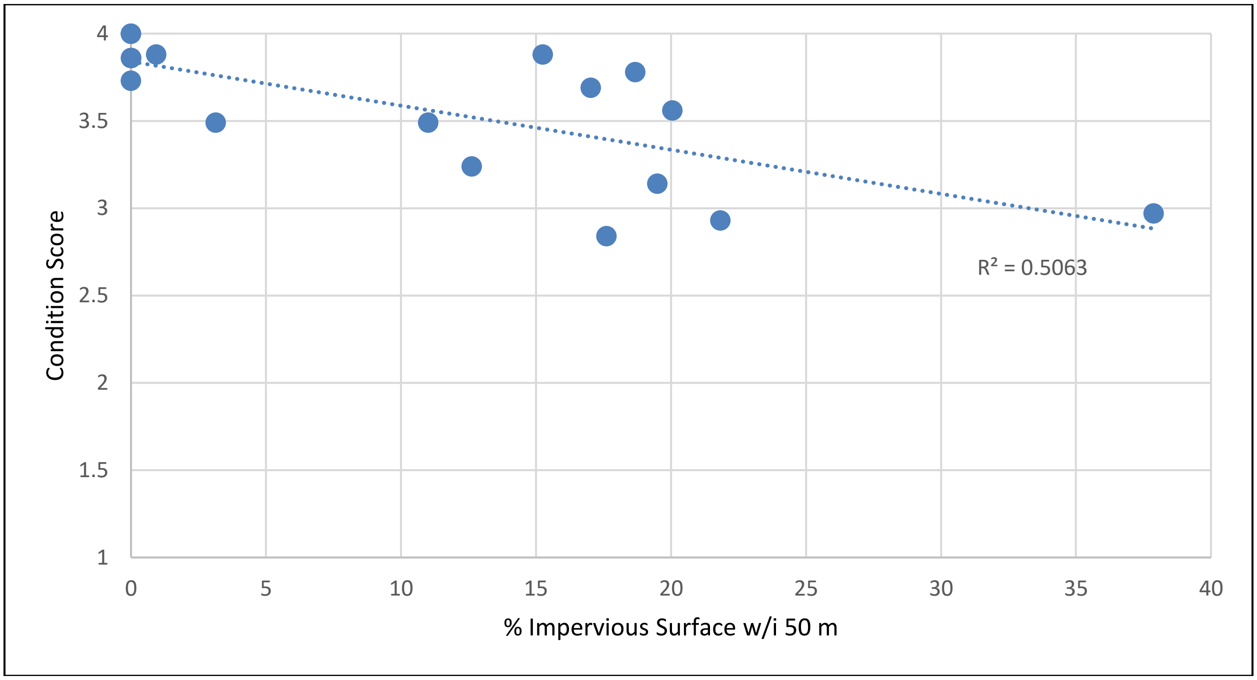


Figure 42. Relationship between Condition Score and the percentage of impervious surfaces within 50 m of the peatland ($p < 0.001$).

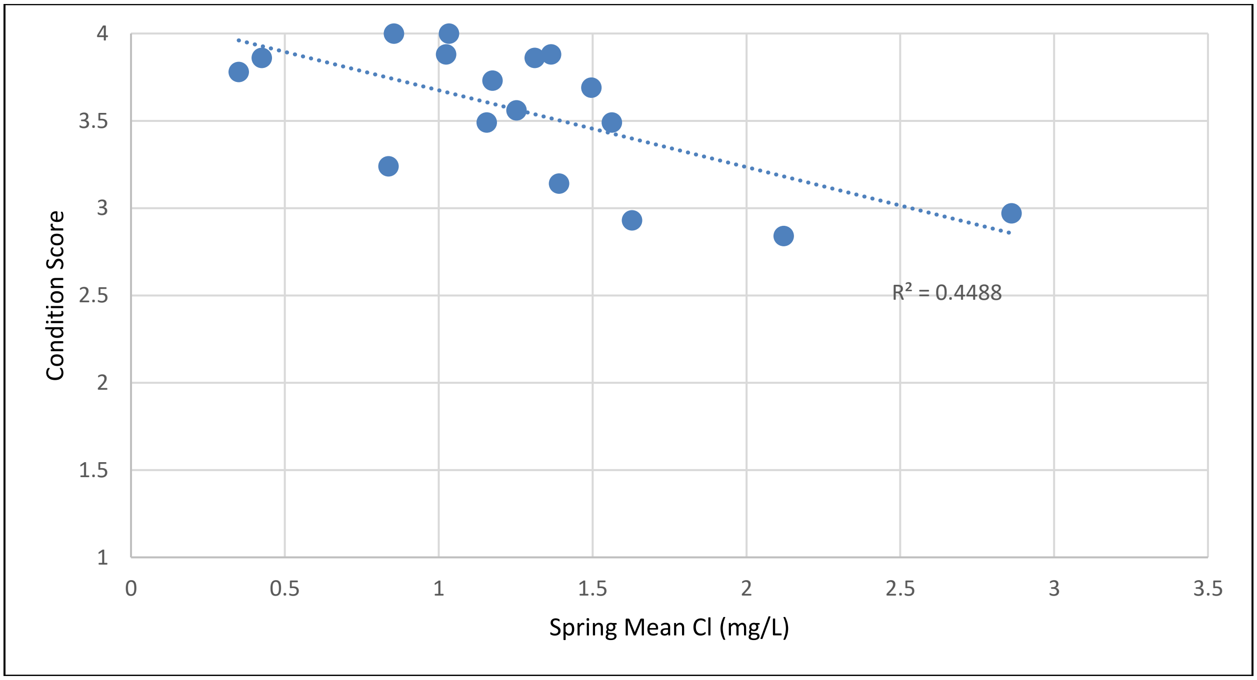


Figure 43. Relationship between Condition Score and spring Cl ($p < 0.001$).

Table 45. Hydrological and land use variables correlated with Condition Scores of Peatland Centers. Note: Hydrological and hydrochemical variables presented in this table are from the peatland center. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown. *b* = the regression slope, i.e. the estimated change in the peatland center Condition score for a given value of that variable. A positive *b* indicates a positive relationship, and vice versa.

Variables	R^2	P-value	*b*
Mean annual precipitation	0.32	< 0.01	> 0.00
May-Sept precipitation	0.30	< 0.01	> 0.00
Presence of stormwater inflows	0.28	< 0.01	-0.40
Watershed Area	0.35	< 0.01	< 0.00
% impervious surface w/i the local watershed	0.36	< 0.01	-1.90
% impervious surface w/i 50 m buffer of wetland	0.51	< 0.01	-2.53
% impervious surface w/i 100 m buffer of wetland	0.39	< 0.01	-2.23
% impervious surface w/i 150 m buffer of wetland	0.39	< 0.01	-2.29
% impervious surface w/i 200 m buffer of wetland	0.40	< 0.01	-2.33
% impervious surface w/i 250 m buffer of wetland	0.41	< 0.01	-2.31
% impervious surface w/i 300 m buffer of wetland	0.42	< 0.01	-2.30
% impervious surface w/i 350 m buffer of wetland	0.42	< 0.01	-2.31
% impervious surface w/i 400 m buffer of wetland	0.40	< 0.01	-2.27
% impervious surface w/i 450 m buffer of wetland	0.39	< 0.01	-2.22
% impervious surface w/i 500 m buffer of wetland	0.36	< 0.01	-2.16
% impervious surface w/i 50 m buffer of wetland within watershed	0.52	< 0.01	-2.42
% impervious surface w/i 100 m buffer of wetland within watershed	0.42	< 0.01	-2.12
% impervious surface w/i 150 m buffer of wetland within watershed	0.43	< 0.01	-2.18
% impervious surface w/i 200 m buffer of wetland within watershed	0.42	< 0.01	-2.21
% impervious surface w/i 250 m buffer of wetland within watershed	0.41	< 0.01	-2.12
% impervious surface w/i 350 m buffer of wetland within watershed	0.25	< 0.01	-1.13
Summer Ca:Mg	0.30	< 0.01	0.00
Spring Mean Cl	0.49	< 0.01	-0.78

Table 46. Lagg abiotic variables correlated with Condition Scores of Peatland Centers. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown. *b* = the regression slope, i.e. the estimated change in the peatland center Condition score for a given value of that variable. A positive *b* indicates a positive relationship, and vice versa.

Factor	R^2	P-value	*b*
Spring mean Ca	0.37	< 0.01	-0.12
Spring mean Mg	0.30	< 0.01	-0.23

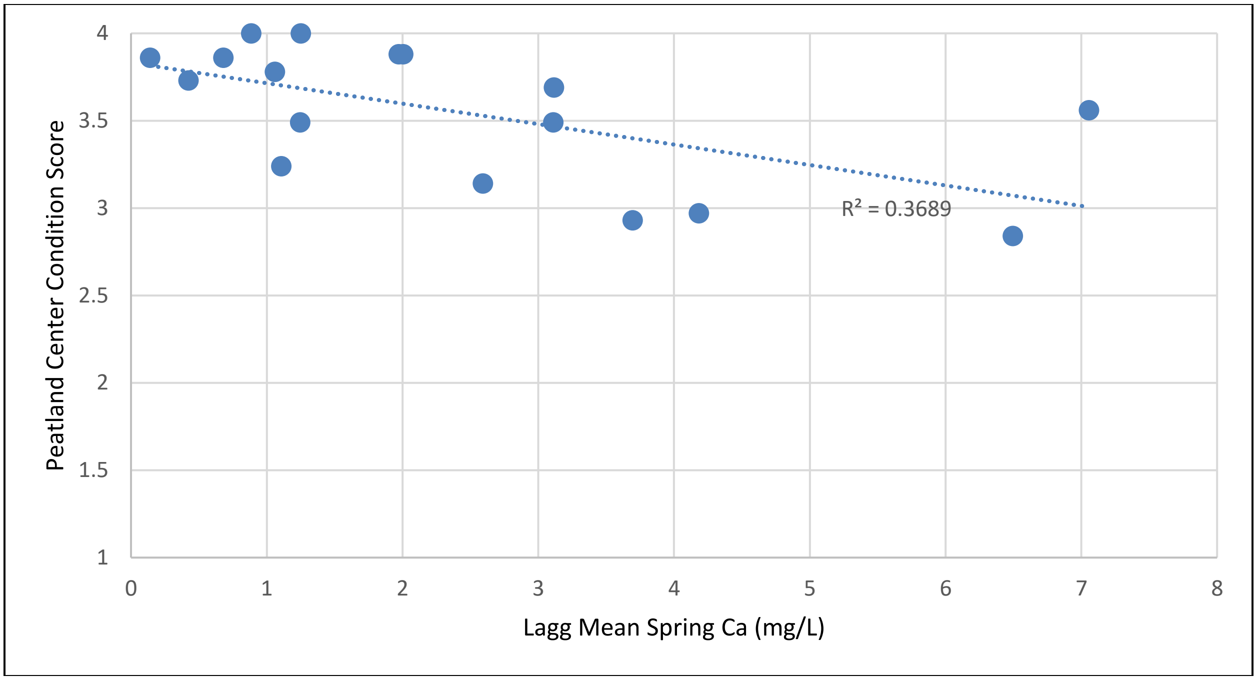


Figure 44. Relationship between peatland center Condition score and lagg mean spring Ca ($p < 0.001$).

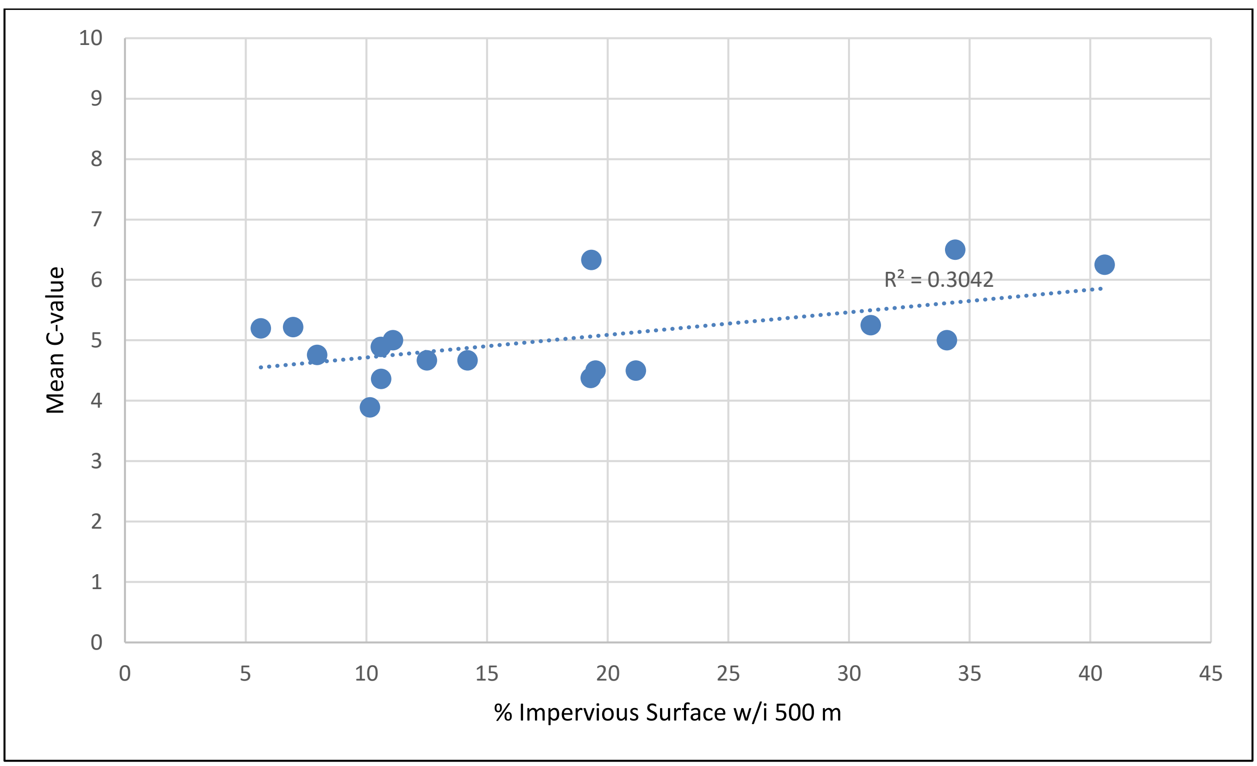


Figure 45. Relationship between peatland center Mean C (all) and the percentage of impervious surfaces within 500 m of the peatland ($p < 0.001$).

Table 47. Hydrological and land use variables correlated with Mean C (all) in peatland centers. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown. *b* = the regression slope, i.e. the estimated change in the peatland center Mean C (all) score for a given value of that variable. A positive *b* indicates a positive relationship, and vice versa.

Factor	R^2	P-value	*b*
Presence of stormwater inflows	0.25	< 0.01	0.68
Maximum January water level	0.37	< 0.01	0.03
% impervious surface w/i 250 m buffer of wetland	0.26	< 0.01	3.33
% impervious surface w/I 300 m buffer of wetland	0.29	< 0.01	3.46
% impervious surface w/i 350 m buffer of wetland	0.30	< 0.01	3.56
% impervious surface w/i 400 m buffer of wetland	0.31	< 0.01	3.60
% impervious surface w/i 450 m buffer of wetland	0.31	< 0.01	3.63
% impervious surface w/i 500 m buffer of wetland	0.30	< 0.01	3.61
Spring mean Cl	0.35	< 0.01	0.73

Table 48. Hydrological and land use variables correlated with Mean C (all) in laggs. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown.

Factor	r^2	P-value	*b*
Spring mean pH	0.40	0.00	-0.64
Spring mean EC_{corr}	0.65	0.00	-0.01

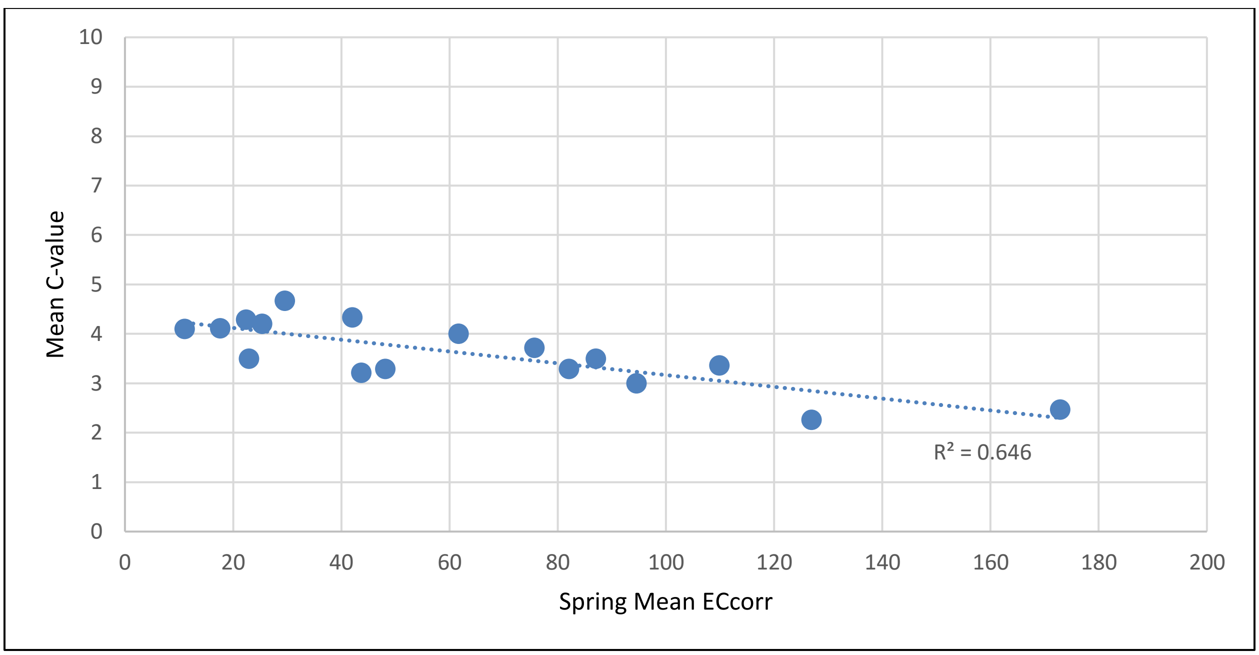


Figure 46. Relationship between lagg mean c-value and spring mean EC_{corr} (µS/cm) ($p < 0.001$).

4.4.2.2 Floristic Quality Assessment Index (FQAI)

Floristic Quality Assessment Index (FQAI) values are calculated by multiplying the mean c-value by the square root of species richness (Taft et al., 1997). FQAI in peatland centers decreased with higher impervious surface area, as well as spring and summer porewater EC_{corr}, and summer phosphate levels (Table 49; Figure 47). Similarly, FQAI in laggs dropped with higher impervious surface area, spring calcium, and spring magnesium (Table 50; Figure 48).

Table 49. Hydrological and land use variables correlated with Floristic Quality Assessment Index in peatland centers. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown. *b* = the regression slope, i.e. the estimated change in the peatland center Mean C (all) score for a given value of that variable. A positive *b* indicates a positive relationship, and vice versa.

Factor	R^2	P-value	*b*
Mean annual precipitation	0.36	< 0.01	0.00
Land Use Index of watershed	0.28	< 0.01	0.45
Spring mean EC_{corr}	0.39	< 0.01	-0.13
Summer mean EC_{corr}	0.30	< 0.01	-0.08
% impervious surface w/i 100 m buffer of wetland	0.26	< 0.01	-12.79
% impervious surface w/i 150 m buffer of wetland	0.26	< 0.01	-12.99
% impervious surface w/i 100 m buffer of wetland within watershed	0.27	< 0.01	-11.81
% impervious surface w/i 150 m buffer of wetland within watershed	0.30	< 0.01	-12.86
% impervious surface w/i 200 m buffer of wetland within watershed	0.30	< 0.01	-13.14
% impervious surface w/i 250 m buffer of wetland within watershed	0.26	< 0.01	-11.73
Summer PO4	0.31	< 0.01	-4.08

Table 50. Hydrological and land use variables correlated with Floristic Quality Assessment Index in laggs. Only statistically significant results ($p < 0.05$) with $r^2 > 0.25$ are shown.

Factor	R^2	P-value	*b*
% impervious surface w/I 300 m buffer of wetland	0.26	< 0.01	-16.73
% impervious surface w/i 350 m buffer of wetland	0.27	< 0.01	-17.15
% impervious surface w/i 400 m buffer of wetland	0.29	< 0.01	-17.56
% impervious surface w/i 450 m buffer of wetland	0.30	< 0.01	-17.92
% impervious surface w/i 500 m buffer of wetland	0.28	< 0.01	-17.58
% impervious surface w/i 450 m buffer of wetland within watershed	0.28	< 0.01	-9.66
Spring mean Ca	0.41	< 0.01	-1.13
Spring mean Mg	0.26	< 0.01	-1.96

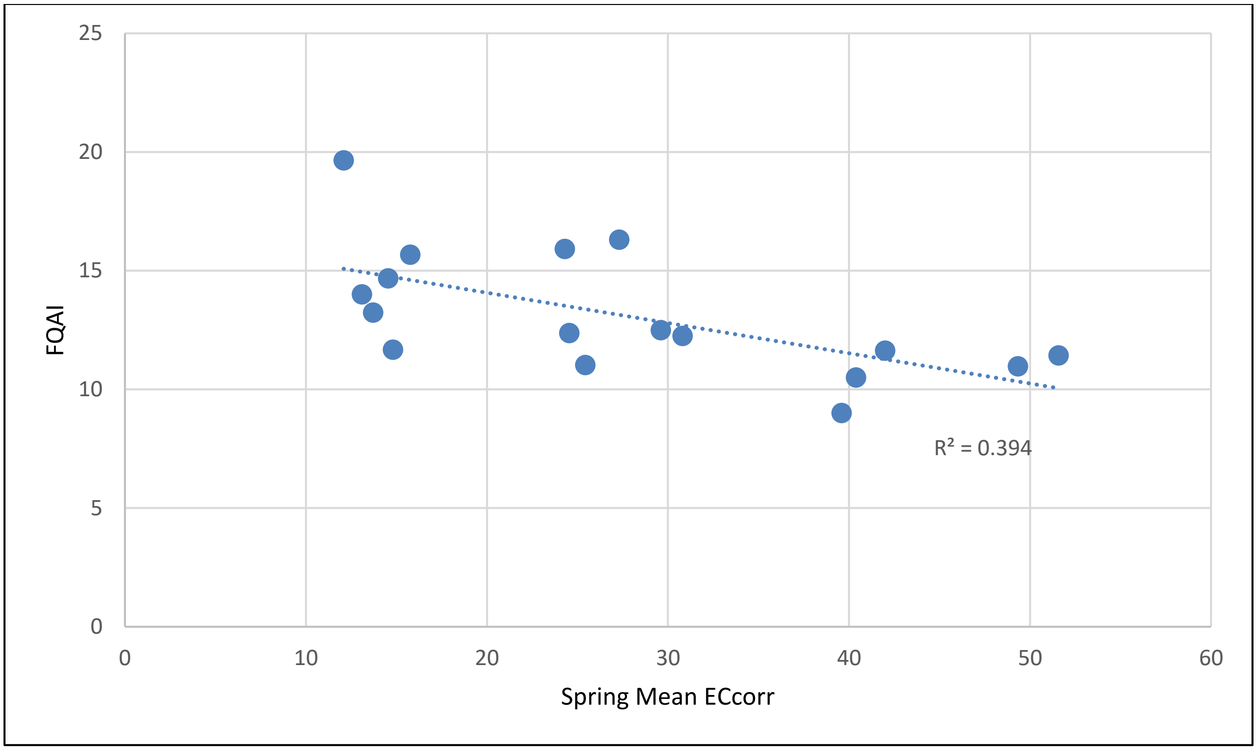


Figure 47. Relationship between peatland center FQAI and spring mean EC_{corr} (µS/cm) ($p < 0.001$).

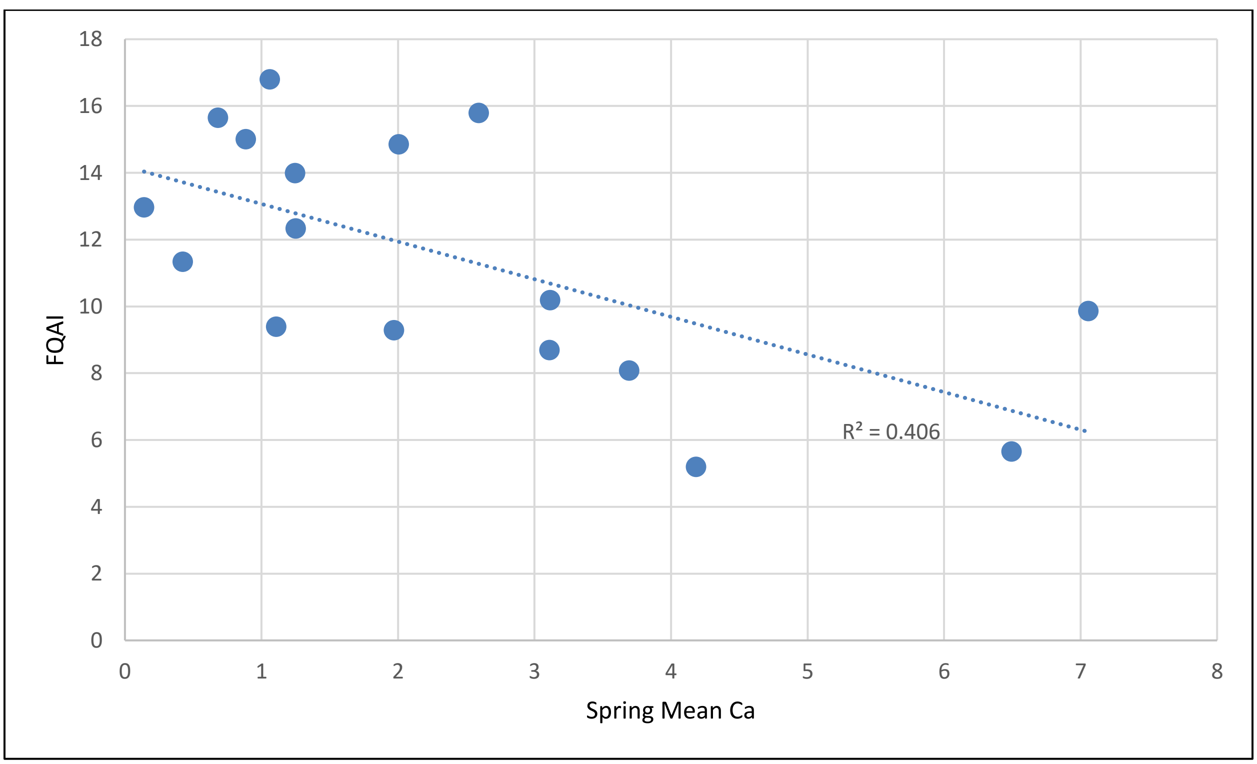


Figure 48. Relationship between lagg FQAI and spring mean Ca ($p < 0.001$).

4.4.3 Comparison of Ecological Integrity Assessment & Floristic Quality Assessment

4.4.3.1 Peatland Center Comparisons

Peatland center Mean C (all) exhibited a negative relationship with Condition scores (Figure 49). Binning the Condition scores into ranks also demonstrated a potentially negative relationship (ANOVA p = 0.06, Figure 50), but the dataset lacked severely degraded study sites (i.e., Condition Ranks of C or D). While sites were stratified by watershed size, inflows, and the proportion of surrounding development, the study design did not explicitly aim to sample across the full potential gradient of on-site condition. Mean C (all) also had a negative relationship with the Vegetation Major Ecological Factor score (Figure 51). This may be due to fen/marsh species with high C-values establishing in peatland centers with slight alterations to hydrology and/or porewater chemistry.

Comparison of Condition scores with Floristic Quality Assessment Index (FQAI) scores did not show a significant correlation ($r^2 = 0.10$, $p = 0.22$).

The strongest correlation between FQA and EIA would be expected between the EIA Native Plant Species Composition metric (VEG3) and FQA indices. All of our study sites received ‘A’ or ‘B’ ranks for this metric. While there was a significant difference in Mean C (all) values between these two EIA ranks (ANOVA p = 0.04), sites that received ‘B’ ranks had higher Mean C (all) values (Figure 52) than those that received ‘A’ ranks.

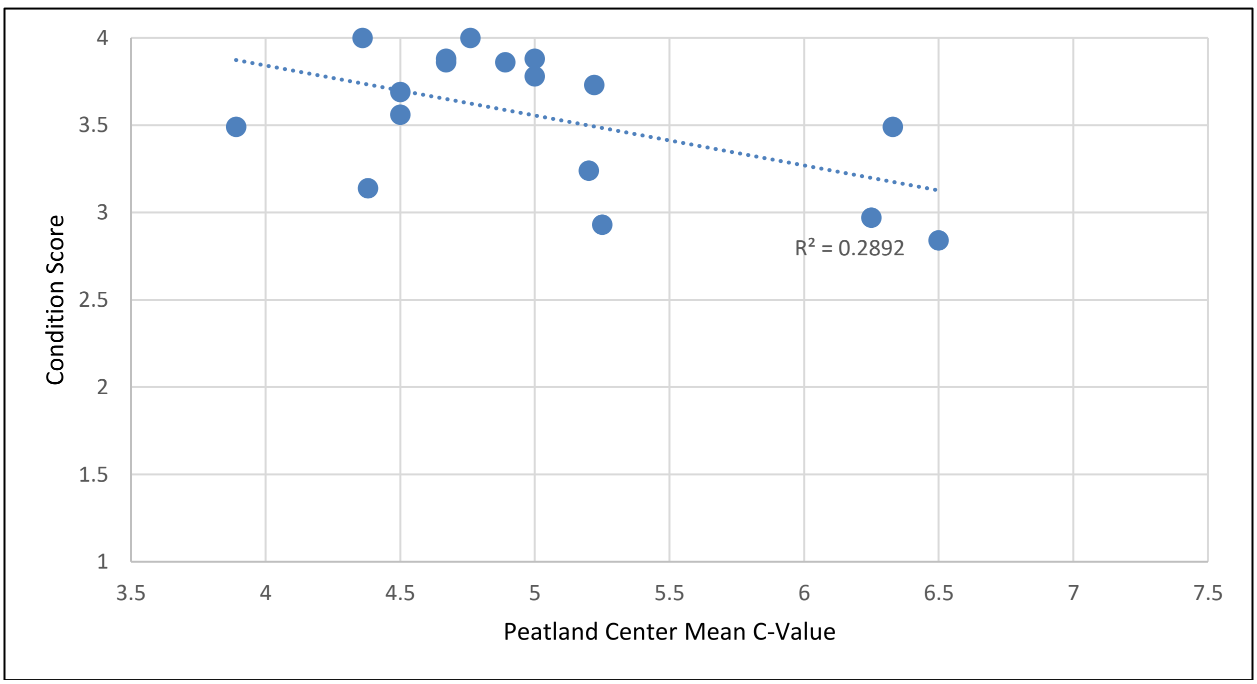


Figure 49. Relationship between peatland center Mean C (all) and Condition score ($p < 0.05$).

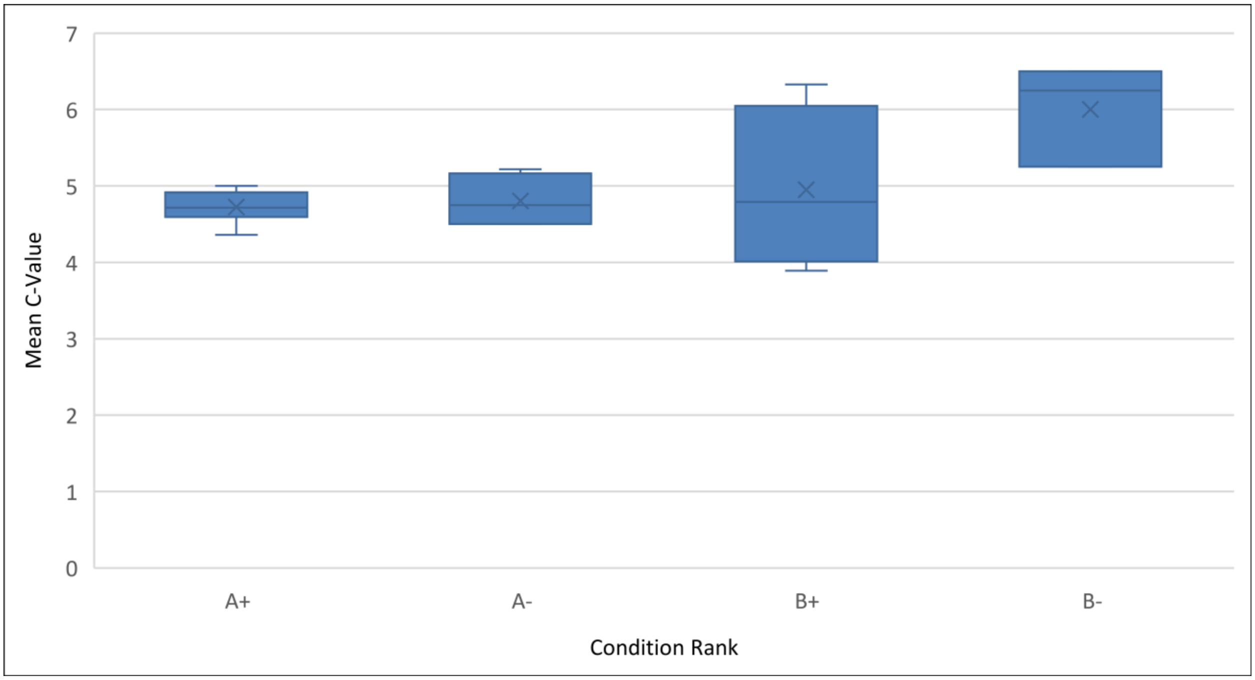


Figure 50. Range of mean C-values by Condition rank (≥3.8 = A+, 3.5-3.79 = A-, 3.0-3.49 = B+, 2.5-2.99 = B-) (ANOVA p = 0.06). Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers

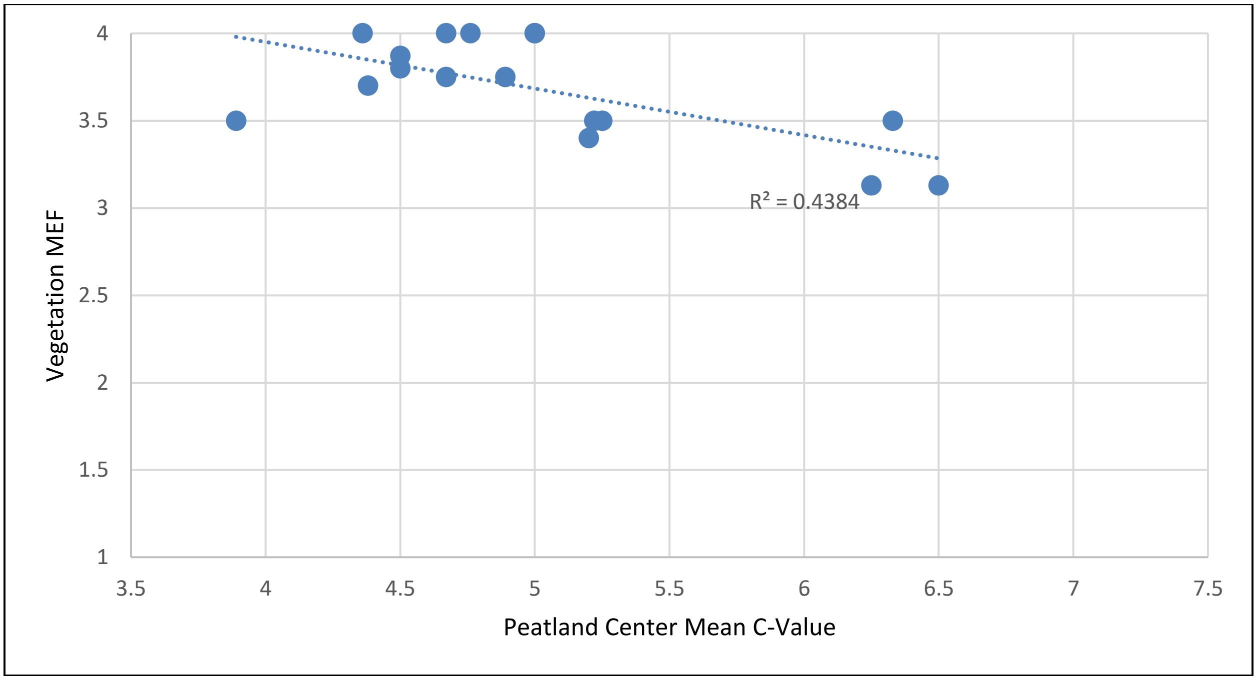


Figure 51. Relationship between peatland center Mean C (all) values and peatland center Vegetation Major Ecological Factor score (p < 0.01).

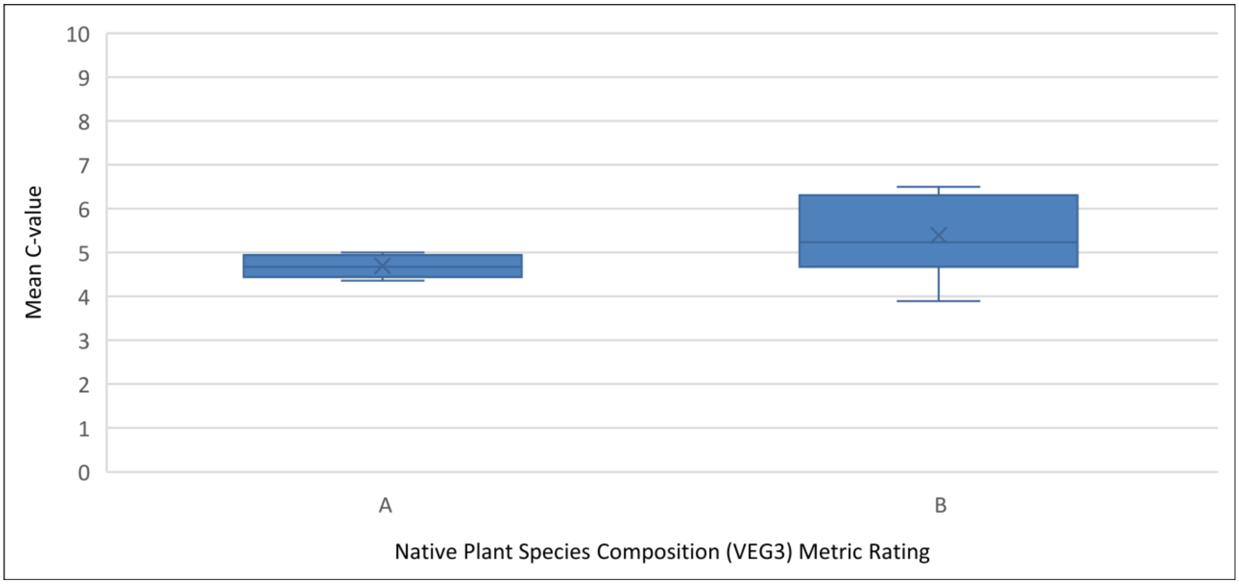


Figure 52. Range of Mean C (all) values by Native Plant Species Composition (VEG3) metric rating (within peatland centers). Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers.

4.4.3.2 Lagg Comparisons

The relationship between Mean C (all) values in the lagg and Condition score (for the peatland center) was not significant (Figure 53). There was no significant difference in lagg mean c-values between bog EIA ranks (Figure 54, ANOVA p = 0.32).

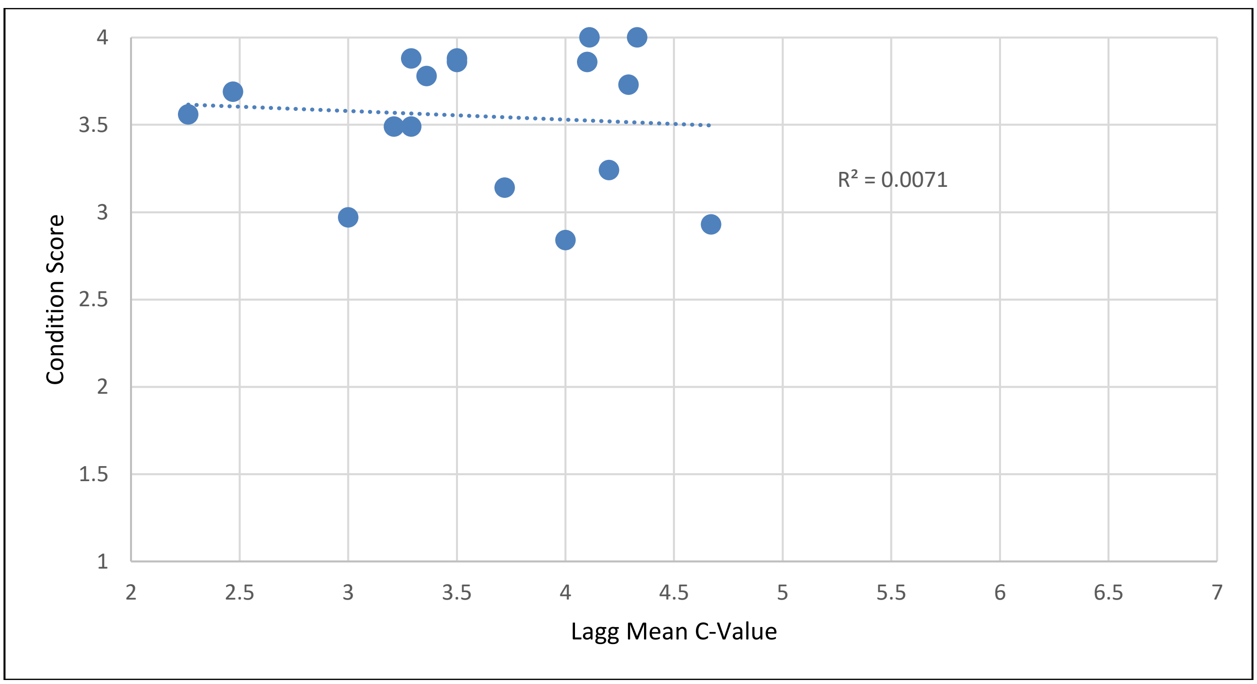


Figure 53. Relationship between lagg Mean C (all) values and peatland center Condition score (p = 0.75).

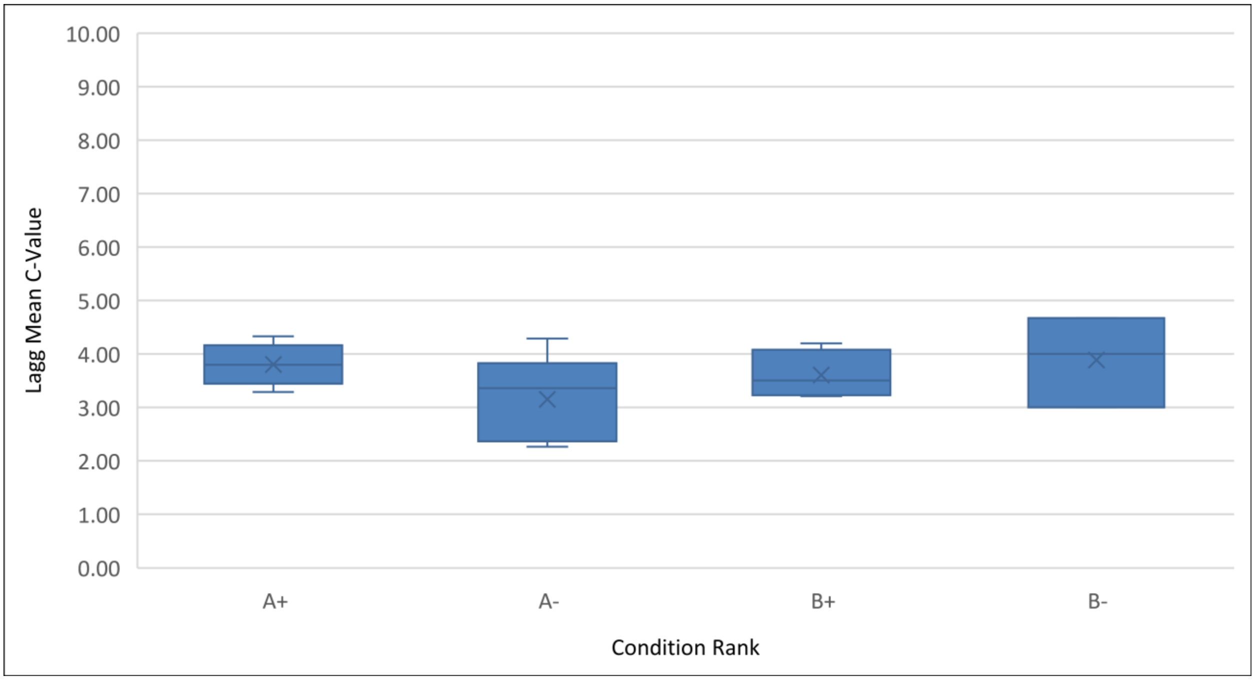


Figure 54. Range of lagg Mean C (all) values by Condition rank (≥3.8 = A+, 3.5-3.79 = A-, 3.0-3.49 = B+, 2.5-2.99 = B-) (ANOVA p = 0.32). Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers

4.4.4 Rapid Water Table Measures Using PVC Tape

A total of 160 total bamboo garden stakes were installed and collected between 2018 and 2020 (Table 51). A total of 74 stakes were installed to represent the rainy season, 40 stakes to represent the dry season, and 46 stakes to represent a full year. Stakes with black PVC tape showed no visible color change and were excluded from analyses (n=18). Additional stakes were excluded because of human or bear vandalism (n=4), logger error (n=3), they became cemented in the ground and were not extractable (n=1), they broke during extraction (n=1), or because stickup values were unreliable due to extremely soft/mucky substrate (n=2). 131 stakes were ultimately used in analysis, with 65 left to represent the rainy season, 33 to represent the dry season, and 33 to represent the full year.

4.4.4.1 Field vs. Laboratory Measures

Measurements of color change were made both in the field, immediately following removal of the stake form the ground, and in the laboratory by an independent observer where muck and other obscuring material could be removed more thoroughly and measurements could be made under a consistent light source. ANCOVA showed that the differences between field and lab measurements were not statistically significant (p = 0.66). Field and laboratory measurements of minimum water level differed by 2.9 cm on average (maximum difference = 16 cm) and maximum water level by an average of 4.5 cm (maximum = 57 cm) (Table 52, Figure 55, Figure 56).

All stake measurements (including minimum and maximum) had their greatest correlation with the mean water level recorded by the data loggers (Table 52). Maximum water levels explained the greatest amount of variation in the logger-recorded means (r^2 = 0.59, Table 52, Figure 56). The midpoint of field measurements (r^2 = 0.59) and the maximum lab measurement (r^2 = 0.57) performed nearly as well.

Since there was no significant difference between the field and lab measurements, only field measurements were used for subsequent analyses described in sections below. Dependent variables were reduced to the mean, 5th percentile, and 95th percentile daily mean water levels from the loggers. Correlations between these dependent variables and the minimum, maximum, and midpoint of the PVC color changes did not vary with PVC tape color, peatland position (i.e. lagg vs. peatland center), or seasonality.

Table 51. Number of PVC-taped garden stakes by season.

Season	# of Stakes Installed	# of Stakes Used in Analysis	Average # of Days (Min-Max)*
Winter (Rainy season, Fall-Spring)	74	65	191 (183-204)
Summer (Dry season, Spring-Fall)	40	33	168 (162-176)
Full Year (Spring-Spring)	46	33	356 (304-366)
Totals	**160**	**131**	n/a

*First/last seven days have been trimmed.

Table 52. Linear regression results for stake measurements made in the field, lab, and an average of the two as functions of the minimum, 5th percentile, mean, 95th percentile, and maximum daily mean water level as recorded by data logger. Bold numbers = highest correlation for that stake measurement. Shaded cells = highest correlation for that logger measurement. p-values all <0.01.

Data Logger		**PVC-taped Stakes**					
		Field			**Lab**		
		Min	**Max**	**Midpt.**	**Min**	**Max**	**Midpt.**
Min	r^2	0.19	0.09	0.17	0.17	0.18	0.20
5th Perc	r^2	0.25	0.17	0.24	0.21	0.26	0.27
Mean	r^2	**0.51**	**0.59**	**0.59**	**0.37**	**0.57**	**0.51**
95th Perc	r^2	0.29	0.46	0.37	0.23	0.40	0.33
Max	r^2	0.26	0.36	0.32	0.20	0.33	0.28

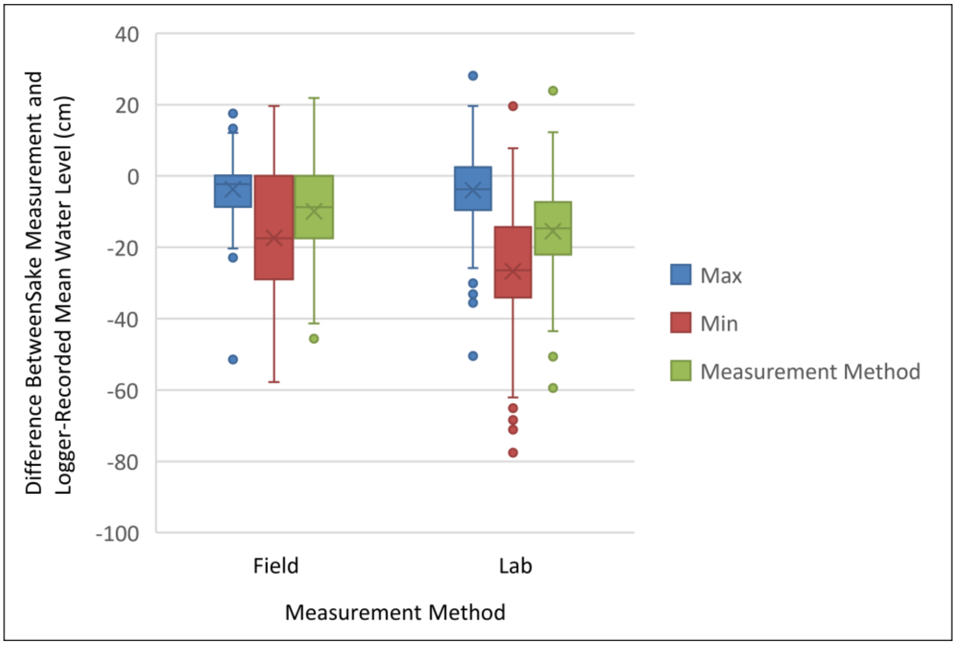


Figure 55. Difference between maximum, minimum, and midpoint measurements and logger-recorded mean water levels. Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers.

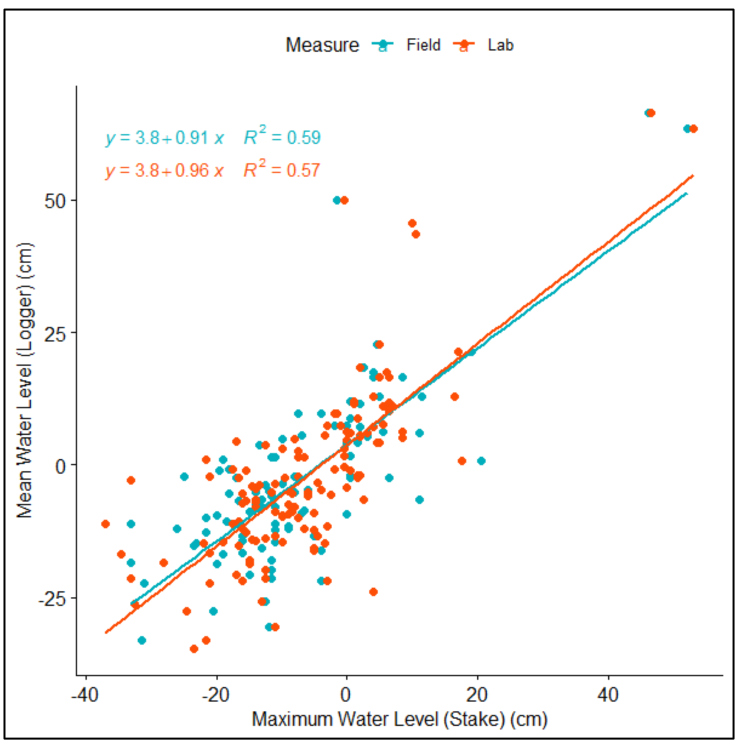


Figure 56. Mean water level recorded by data logger as a function of maximum water level derived from field stake measurements. ANCOVA showed lab measures were not significantly different ($p = 0.66$).

4.4.4.2 PVC Tape Color

All 131 stakes were divided into groups based on their tape color—(1) light (yellow, white) and (2) dark (blue, red, green) bundles and were compared using ANCOVA. Reducing conditions resulted in a gray discoloration on the PVC tape (Figure 57). On black tape, this was never visible to the naked eye. Both field and lab staff found it easier to detect color changes on light-colored PVC tape than on dark tape. The dark-colored subset had been in wetland sites that had water table levels (as determined by data loggers) ranging from -33 to 50 cm, while the light-colored subset came from wetland sites where water table levels ranged from -30 to 66 cm. Measurements derived from light-colored PVC tape had far stronger correlations with logger-recorded water levels (Table 53; Figure 58), with the maximum and midpoint of stake measurements being most highly correlated with logger-recorded mean water level ($r^2 = 0.73$ and 0.75, respectively). ANCOVA indicated that measurements taken from light-colored tape were superior estimates of water level, increasing the slope by 0.31 (i.e., closer to perfect agreement) when comparing maximum stake-derived water level to mean logger water level ($p = 0.03$). However, a t-test of the differences between logger measurements and stake measurements of light and dark tape was not significant ($p = 0.16$) (Figure 59), indicating that the mean difference between water levels derived from stakes and loggers did not vary by color. In other words, since the average error was not significantly different, it is possible that the significantly better slope from the light-colored tape may be influenced by the larger range of logger water level values in the light-colored data set.

Figure 57. Gray discoloration on red PVC electrical tape (bottom) caused by reducing conditions.

Table 53. Linear regression results for stake measurements made in the field as functions of the 5th percentile, mean, and 95th percentile daily mean water level as recorded by data logger. Results subdivided by dark and light colored PVC tape. Bold numbers = highest correlation for that stake measurement. Shaded cells = highest correlation for that logger measurement. p-values all <0.01.

Data Logger		**PVC-taped Stakes**					
		Light Color (White, Yellow)			**Dark Color** (Red, Green, Blue)		
		Min	Max	Midpt.	Min	Max	Midpt.
5th Perc	r^2	0.35	0.28	0.37	0.17	0.06	0.13
Mean	r^2	**0.66**	**0.73**	**0.75**	**0.32**	**0.40**	**0.36**
95th Perc	r^2	0.44	0.66	0.54	0.12	0.26	0.18

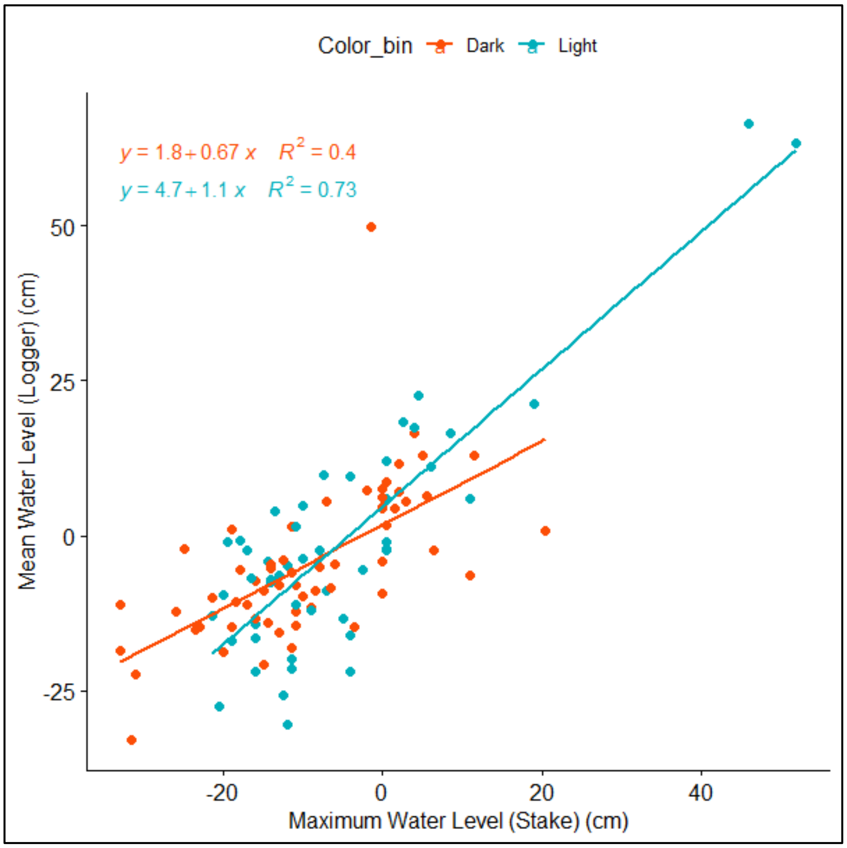


Figure 58. Comparison of linear regressions of water level recorded by data logger as a function of maximum water level derived from light- and dark-colored PVC tape. ANCOVA showed light tape significantly improved the relationship (slope +0.31, p=0.03).

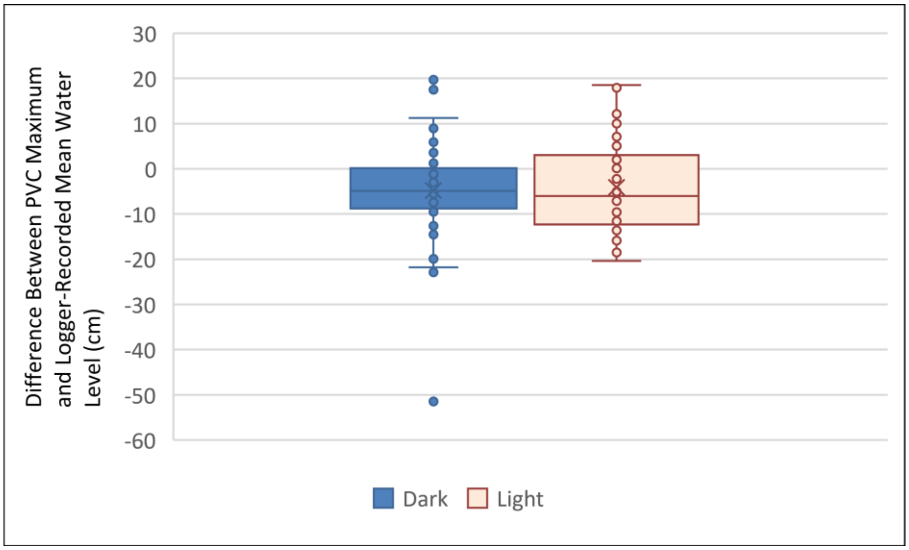


Figure 59. Difference between measured maximum and logger-recorded mean water levels for both light- and dark-colored PVC tape. T-test was not significant (p=0.16), although light and dark tape had significantly different slopes in the regression (ANCOVA p=0.03).

4.4.4.3 Peatland Position

To maintain a robust sample size, all colors of PVC tape (besides black) were included in this analysis. PVC maximum water level (= first detected color change) was more highly correlated with the logger-recorded mean water level in laggs ($r^2 = 0.65$) than in peatland centers ($r^2 = 0.02$) (Table 54; Figure 60). Restricting the analysis to only light-colored PVC tape dropped the sample size to 30 and did not improve correlations (max $r^2 = 0.09$). ANCOVA confirmed that stake-derived water measurements from laggs were better estimates of true water level than those at peatland center, increasing the slope by 0.87 ($p < 0.01$). However, the spread of differences between lagg and peatland center measurements and their respective data loggers was similar, despite the much larger range of potential water levels found in laggs (Figure 61). A t-test showed that the mean difference between PVC maximum water level and logger mean water level in the two peatland positions was not statistically significant ($p = 0.18$).

4.4.4.5 Seasonality

Stakes were subdivided by the seasonal range in which they were in the ground: summer (spring-fall), winter (fall-spring), or a full year (spring-spring). Linear regressions were calculated using the full sample of stakes, as well as the subset of stakes with light-colored PVC tape (Table 55).

The magnitude of water level changes was much smaller during the seasonal drought. For stakes left in the ground through the winter, data logger water levels at a given well nest varied by 65 cm, while summer data logger water levels varied by only 40 cm (annual variation averaged 74 cm). Summer PVC measurements had stronger correlations with 5th percentile water levels than in the winter (Table 55). Theoretically, this could occur because the water spends more time at or near

Table 54. Linear regression results for stake measurements in laggs and peatland centers as functions of the minimum, 5th percentile, mean, 95th percentile, and maximum of data logger daily mean water levels. Bold numbers = highest correlation for that stake measurement. Shaded cells = highest correlation for that logger measurement. p-values all <0.01.

Data Logger		Lagg			Peatland center		
		Min	Max	Midpt.	Min	Max	Midpt.
5th Perc	r^2	0.32	0.38	0.34	0.07	< 0.01	0.03
Mean	r^2	**0.50**	**0.65**	**0.62**	**0.14**	0.02	**0.08**
95th Perc	r^2	0.29	0.50	0.37	< 0.01	**0.10**	0.02

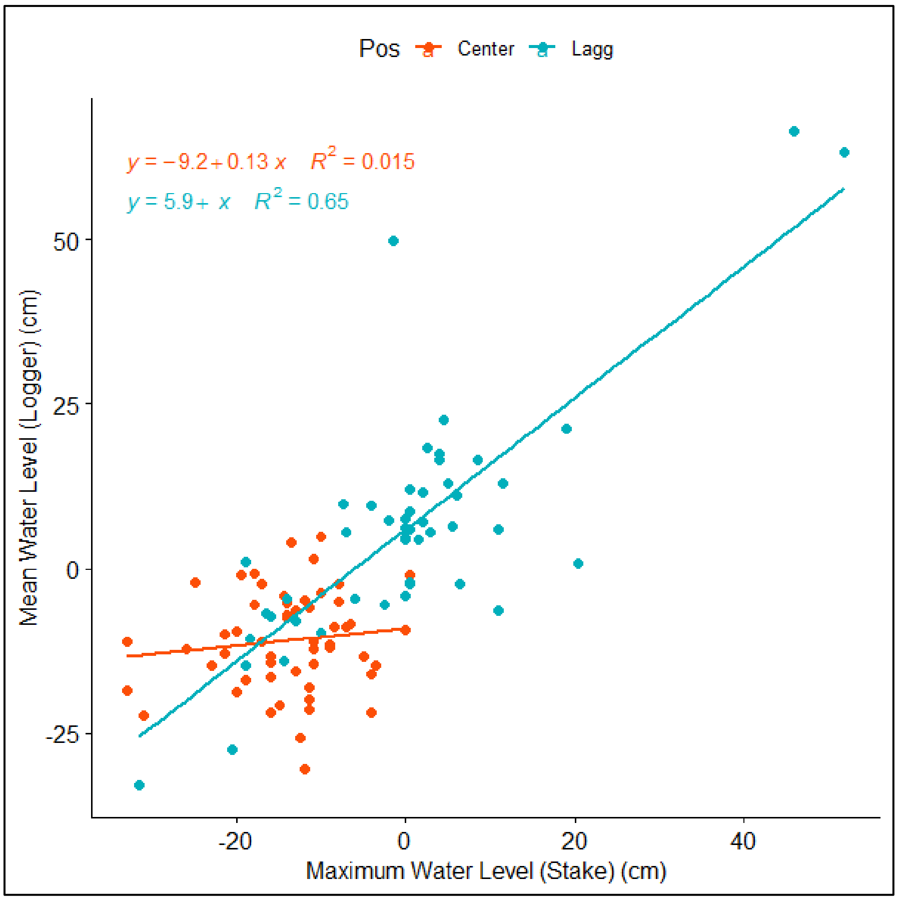


Figure 60. Comparison of linear regressions of water level recorded by data logger as a function of maximum water level derived from PVC tape in laggs and peatland centers. ANCOVA showed laggs had significantly stronger relationship (slope +0.87, p < 0.01).

this minimum level during the seasonal summer drought or because the chemical reactions involved in discoloration occur faster at higher temperatures. Summer was also the only period in which the strongest correlations were between PVC measurements and 95th percentile water levels. However, ANCOVA did not show a significant difference in seasonal relationships between stake-derived water level and data logger water level (Summer::Winter p-value = 0.26, Summer::Full

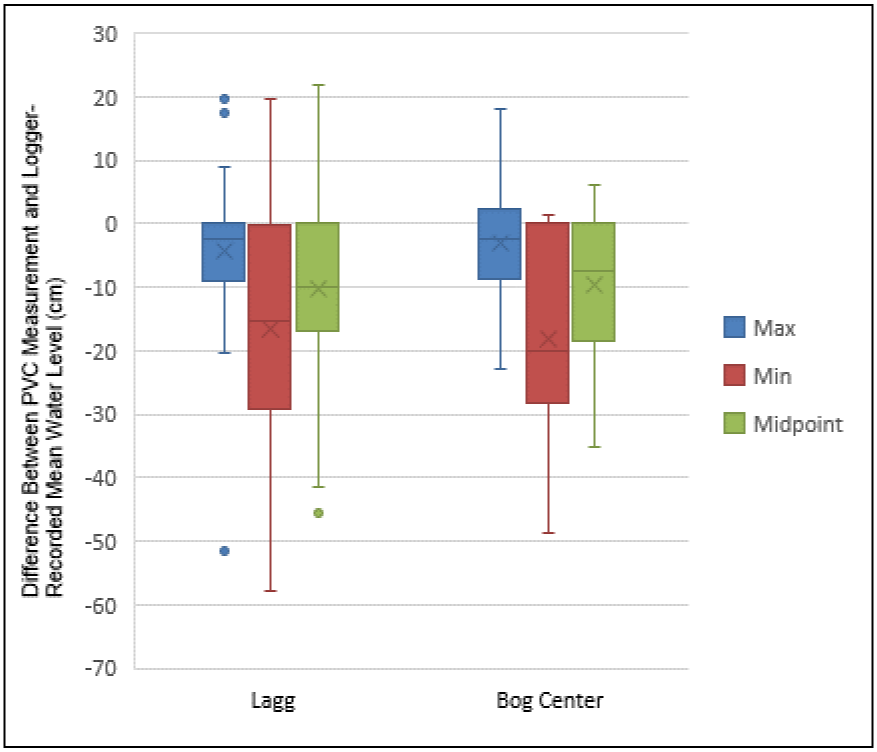


Figure 61. Difference between maximum, minimum, and midpoint measurements and logger-recorded mean water levels in laggs and peatland centers. T-test was not significant ($p=0.18$), although laggs and bog centers had significantly different slopes in the regression (ANCOVA $p < 0.01$). Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers.

Year p-value = 0.10) (Figure 62; Figure 63). Restricting the sample to measurements taken from light-colored PVC tape did not strengthen differences (Summer::Winter p-value = 0.42, Summer::Full Year p-value = 0.35) (Figure 64). Note that summer measurements had the lowest sample size (n = 40, Table 51).

4.4.4.6 Influence of pH

There was no significant correlation between pH and the amount of error in the PVC measures ($r^2 = 0.03$, $p = 0.09$, Figure 65).

4.5 Pollen Analysis

Results of the pollen analysis to detect recent vegetation changes (~100-200 years) of three of the study sites are discussed below.

4.5.1 Evans Creek (EC) Pollen Analysis

Results are discussed relative to different depth zones, starting with the deepest (Figure 66). Age, pollen type, pollen concentration, and charcoal concentration are shown in Figure 66.

Table 55. Linear regression results for seasonal stake measurements as functions of the minimum, 5th percentile, mean, 95th percentile, and maximum of data logger daily mean water levels. Results also shown for light-colored PVC only. Bold numbers = highest correlation for that stake measurement + season. Shaded cells = highest correlation for that logger measurement + season. p-values all <0.01.

Data Logger		All Colors of PVC								
		Summer			Winter			Full Year		
		Min	Max	Midpt.	Min	Max	Midpt.	Min	Max	Midpt.
5th Perc	r^2	**0.59**	0.04	0.36	0.12	0.13	0.13	0.55	0.45	0.51
Mean	r_2	0.55	0.42	**0.54**	**0.43**	**0.64**	**0.56**	**0.66**	**0.75**	**0.69**
95th Perc	r^2	0.40	**0.43**	0.42	0.22	0.59	0.39	0.31	0.41	0.32
Data Logger		**Light-Colored PVC Only**								
		Summer			**Winter**			**Full Year**		
		Min	Max	Midpt.	Min	Max	Midpt.	Min	Max	Midpt.
5th Perc	r^2	0.38	0.07	0.29	0.25	0.19	0.27	0.64	0.71	0.71
Mean	r_2	**0.52**	0.32	0.61	**0.65**	**0.76**	**0.78**	**0.78**	**0.85**	**0.86**
95th Perc	r^2	**0.52**	**0.45**	**0.65**	0.35	0.71	0.53	0.67	0.74	0.74

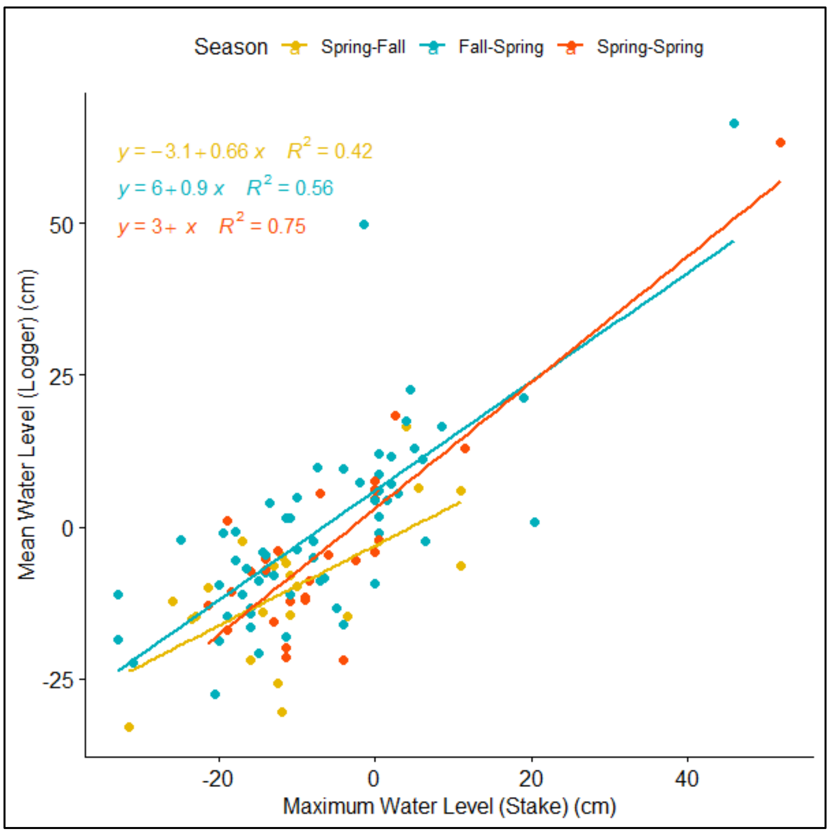


Figure 62. Comparison of linear regressions of seasonal maximum water levels derived from PVC tape (all colors), as a function of mean water level recorded by data logger. Differences in slope were not statistically significant according to ANCOVA.

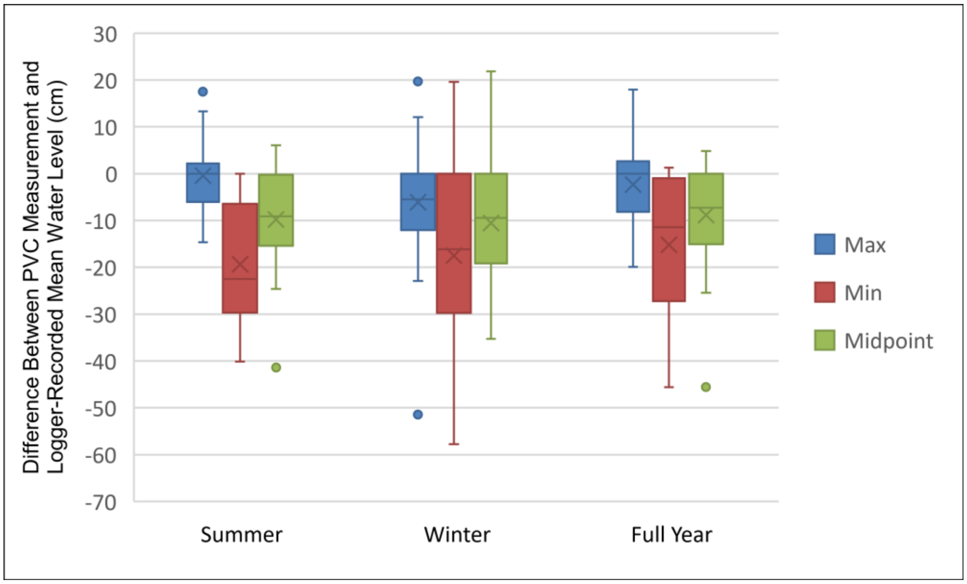


Figure 63. Difference between seasonal maximum, minimum, and midpoint measurements and logger-recorded mean water levels. Boxes represent the interquartile, lines within the box represent the mean, whiskers extend to the minimum and maximum, and points beyond the whiskers represent outliers.

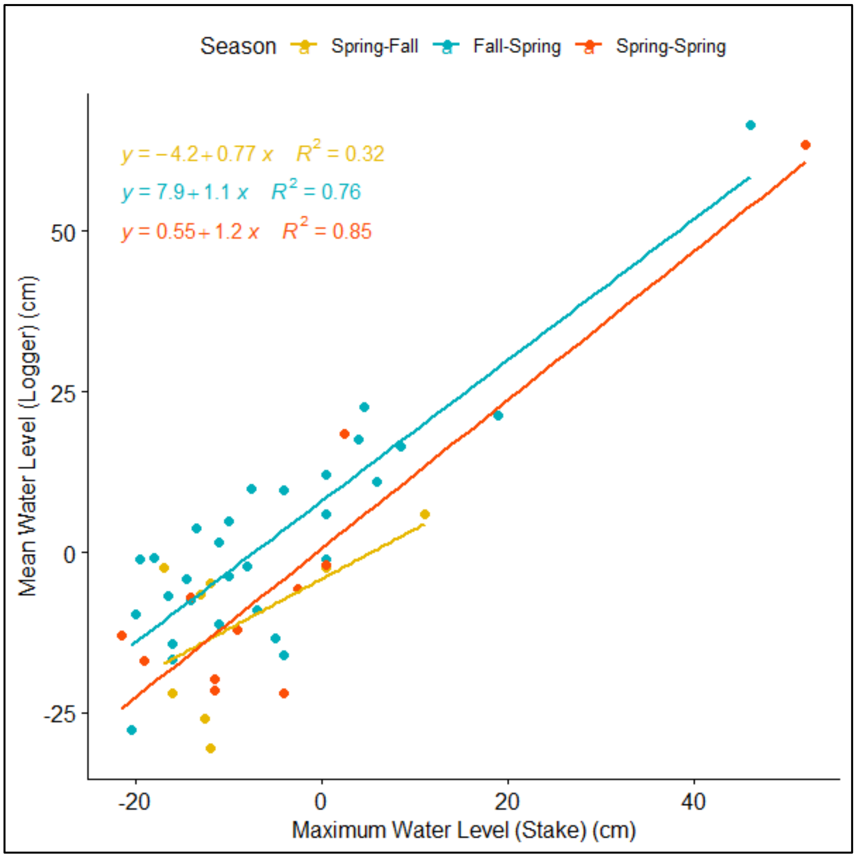


Figure 64. Comparison of linear regressions of seasonal maximum water levels derived from PVC tape (light colors only), as a function of mean water level recorded by data logger. Differences in slope were not statistically significant according to ANCOVA.

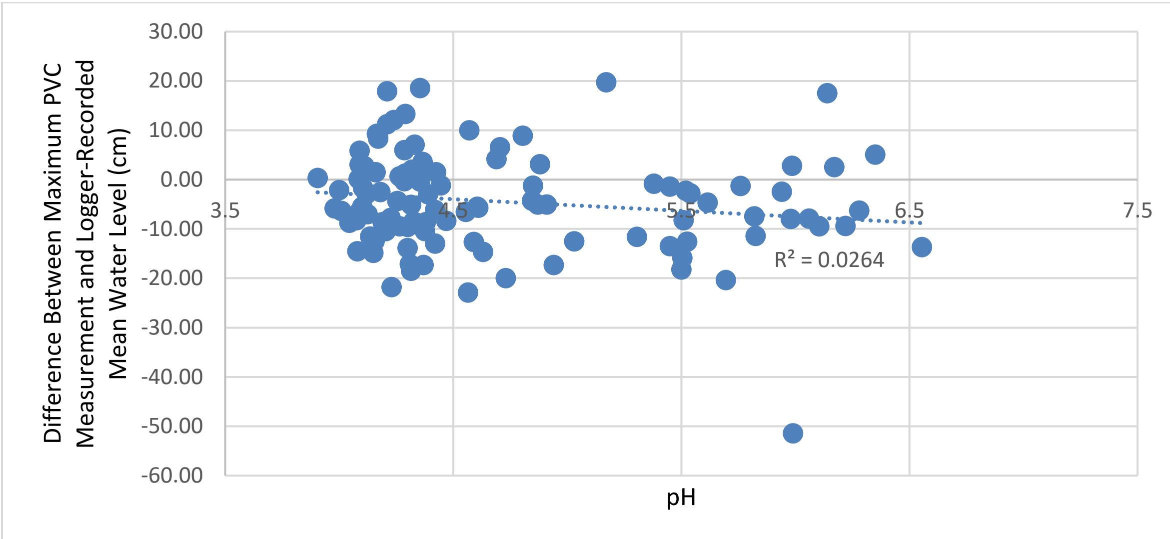


Figure 65. Relationship between pH and the difference between PVC maximum and logger mean water level measurements (p = 0.09).

4.5.1.1 Zone EC-I (50-53 cm; -28 to -26 cal yr BP; 1980-1977 AD)

Only two pollen samples were contained within this zone. The zone is distinguished by having the highest percentages of *Pinus* (8-9%) and Cupressaceae (20-22%). The remainder of the arboreal taxa consisted of minor amounts of *Tsuga heterophylla* (4-5%), *Abies* sp. (~2%), *Pseudotsuga* (6-8%), *Alnus rubra* (17-18%), and Ericaceae species (5-8%). Other minor components included *Picea* (1-3%), *Acer* (~1%), *Betula* (~1%), *Salix* (<1%), *Populus* (~2%), and *Quercus* (<1%). Herbaceous taxa consisted of Poaceae (14-15%), Cyperaceae (~2%), *Ambrosia*-type (2-4%), and *Chenopodium*/*Amaranthus*-type (2-3%) species. There were very minor amounts of members of the Asteraceae family (*Artemisia* 1-2%, Liguliflorae-type 0-1 %, and Tubuliflorae-type 0-1%). *Isoetes* was the only aquatic pollen type present in this zone and was only present in the lowermost sample. Both *Sphagnum* (4-6%) and *Pleurozium* (13-18%) spores were present within this zone. Pollen concentration varied between 26,700 and 39,500 grains/cc of peat.

A total of four charcoal samples were analyzed from this zone. CHAR varied between 3 and 16 pieces/cm^2/year for the 250 µm size fraction, and 10 to 26 pieces/cm^2/year for the 125 µm size fraction.

4.5.1.2 Zone EC-II (23-50 cm; -47 to -28 cal yr BP; 2001-1980 AD)

This is the largest zone within the core and was comprised of nine pollen samples. This zone stands out from the other pollen zones by having the highest percentages of *Alnus rubra* (22-36%), *Pseudotsuga* (8-18%), *Tsuga heterophylla* (1-6%), *Sphagnum* (0-13%), *Pleurozium* (1-60%; which varied greatly throughout this zone), and *Pteridium* (0-4%). This was the only zone within the core that shows the presence of *Corylus* at this site. The remainder of the arboreal component of the ecosystem consisted of *Pinus* (1-6%), *Picea* (2-4%), *Abies* (0-3%), Cupressaceae (10-21%), *Acer* (1-2%), *Betula* (0-2%), *Quercus* (0-1%), *Salix* (0-1%), *Populus* (0-3%), and Ericaceae (5-12%). Poaceae (8-17%) dominated the herbaceous taxa and increased towards the top of the core.

Cyperaceae (1-4%), members of the Asteraceae family (*Ambrosia*-type 1-2 %, *Artemisia* 0-1%, Liguliflorae-type 0-2%, and Tubuliflorae-type 0-1%), and *Chenopodium*/*Amaranthus*-type (0-5%) comprised the remainder of the herbaceous taxa present within this zone. Potamogetonaceae (<1%), *Typha* (<1%), Isoetes (<1%), *Polystichum* (<1%), and *Dryopteris* (<1%) were present within this zone, but only in minor abundances. *Botryococcus* (5-6%) is another aquatic taxa present in this zone and increased in abundance near the top of this core section. Pollen concentration was the lowest in this section of the core, varying between 28,700 and 47,200 grains/cc.

Twenty-seven charcoal samples were analyzed from this zone. In the 250 µm size fraction, CHAR ranged from 0 to 11 pieces/cm^2/year, and 0 to 33 pieces/cm^2/year for the 125 µm size fraction.

4.5.1.3 Zone EC-III (5-23 cm; -60 to -47 cal yr BP; 2015-2001 AD)

This zone consists of six pollen samples and had the highest percentage of Poaceae (12-21%). This zone can be distinguished from other zones by a decrease in *Alnus rubra* (19-30%) and an increase in both Cyperaceae (3-7%) and *Chenopodium*/*Amaranthus*-type (2-7%) taxa. The remainder of the arboreal taxa consisted of *Pinus* (3-6%), *Tsuga heterophylla* (1-3%), *Picea* (1-6%), *Abies* (1-3%), *Pseudotsuga* (5-11%), Cupressaceae (13-20%), *Acer* (0-1%), *Betula* (1-2%), *Quercus* (~1%), *Salix* (1-3%), *Populus* (1-3%), and Ericaceae (4-10%). Members of the Asteraceae family (*Ambrosia*-type 1-3%, Liguliflorae-type <1%, and Tubuliflorae-type 1-2%) comprised the remainder of the understory taxa. Aquatic taxa including Potamogetonaceae (1-3%), *Typha* (0-1%), *Botryococcus* (4-11%), and *Isoetes* (0-3%) increased in abundance in this section. *Sphagnum* (0-1%), *Pleurozium* (0-3%), and *Pteridium* (<1%) all decreased in abundance in this zone. Pollen concentration increased throughout this portion of the core, varying between 42,900 and 62,700 grains/cc.

Eighteen charcoal samples were analyzed within this zone. CHAR ranged from 0 to 19 pieces/cm^2/year in the 250 µm size fraction. For the 125 µm size fraction, CHAR varied from 1 to 67 pieces/cm^2/year with the highest accumulation rate occurring at 19 cm.

4.5.1.4 Zone EC-IV (0-5 cm; -63 to -60 cal yr BP; 2019-2015 AD)

The uppermost zone in this core consisted of three pollen samples. High percentages of *Tsuga heterophylla* (4-7%), *Abies* (2-5%), *Pseudotsuga* (11-17%), Poaceae (14-20%), and Cyperaceae (9-10%) distinguished this zone. *Pinus* (5-7%), Cupressaceae (8-19%), *Alnus rubra* (13-21%), and Ericaceae (2-9%) comprised the majority of arboreal taxa within this zone, along with minor percentages of *Picea* (1-2%), *Acer* (1-2%), *Betula* (<1%), *Quercus* (<1%), *Salix* (1-2%), and *Populus* (0-2%). The herbaceous taxa present included members of the Asteraceae family (*Ambrosia*-type ~1% and Tubuliflorae-type 1-2%) and *Chenopodium*/*Amaranthus*-type (1-3%). Aquatic taxa present during this time include Potamogetonaceae (<1%), *Typha* (0-1%), *Botryococcus* (1-5%), and *Isoetes* (0-2%). Within this zone, both *Sphagnum* (2-3%) and *Pleurozium* (2-4%) were present. Pollen concentrations were highest (68,200 grains/cc) in this portion of the core, with a drop in concentration in the uppermost sample (40,500 grains/cc).

A total of six charcoal samples comprise the uppermost zone in the core. CHAR varied between 0 and 6 pieces/cm^2/year for the 250 µm size fraction and 4 to 14 pieces/cm^2/year for the 125 µm size fraction.

4.5.2 Kings Lake (KL) Pollen Analysis

Results are discussed relative to different depth zones, starting with the deepest (Figure 67). Age, pollen type, pollen concentration, and charcoal concentration are shown in Figure 67.

4.5.2.1 Zone KL-I (45-63 cm; -24 to -8 cal yr BP; 1975-1959 AD)

The lowest zone in this core consists of six pollen samples. *Tsuga heterophylla* (7-27%) occurred in the highest abundance at the base of the peat core and decreased towards the top of this zone. *Alnus rubra* (20-51%) increased dramatically from the base to the top of this zone. The remainder of the arboreal taxa present in this ecosystem included *Pinus* (4-11%), *Picea* (2-6%), *Abies* (1-4%), *Pseudotsuga* (3-8%), Cupressaceae (6-11%), *Betula* (0-1%), *Corylus* (0-1%), *Populus* (0-1%), and Ericaceae (6-13%). Poaceae (4-9%) and Cyperaceae (2-5%) are the major components of the understory taxa within this zone. Minor herbaceous components within this zone included members of the Asteraceae family (*Ambrosia*-type 0-1%, *Artemisia* 0-2%, and Tubuliflorae-type 0-1%) and *Chenopodium*/*Amaranthus*-type (0-3%). *Typha* (the only aquatic pollen or spore within this core) was present near the middle of this zone (52 cm). *Sphagnum* (0-6%) occurred at its highest abundance at the base of this zone, while *Pleurozium* (2%) was only present at 55 cm. *Pteridium* (0-7%) occurred at its highest abundance at the top of this section while *Dryopteris* (<1%) was very low in abundance, only occurring near the base and top of this section. Pollen concentration was the highest within this zone and increased dramatically from the base to the top, varying between 20,300 and 135,000 grains/cc of peat.

A total of 17 charcoal samples were analyzed from this zone, which has the highest charcoal abundance compared to the rest of the Kings Lake core. The highest CHAR values (for both size fractions) were located near the middle of this zone (50-56 cm). CHAR varied between 0 and 105 pieces/cm^2/year for the 250 µm size fraction and 3 to 926 pieces/cm^2/year for the 125 µm size fraction.

4.5.2.2 Zone KL-II (23-45 cm; -43 to -24 cal yr BP; 1997-1975 AD)

This is the largest zone within the core and consisted of eight pollen samples. This zone stands out from the other pollen zones due to high amounts of *Alnus rubra* (31-47%), Cupressaceae (7-15%), and Poaceae (3-12%), and low abundance of Ericaceae (1-9%). *Pinus* (7-14%), *Picea* (1-5%), *Abies* (1-4%), *Pseudotsuga* (6-11%), *Betula* (<1%), *Salix* (<1%), and *Populus* (0-1%) constituted the remainder of the arboreal taxa present within this zone. The herbaceous taxa within this zone included members of the Asteraceae family (*Ambrosia*-type 0-2%, *Artemisia* 0-1%, Liguliflorae-type 0-1%, and Tubuliflorae-type 0-1%) and *Chenopodium*/A*maranthus*-type (0-4%). This is the only Kings Lake core zone with Saxifragaceae present. *Sphagnum* (0-1%) is the only moss present and occurred only in the upper half of this section. Both *Pteridium* (0-4%) and *Dryopteris* (0-3%) were present throughout this zone. Pollen concentration has an overall decreasing trend throughout this zone, varying from between 28,900 grains/cc and 84,500 grains/cc.

Twenty-two charcoal samples were analyzed from this zone. Samples show a low CHAR in this section of the core. CHAR ranged between 0 and 8 pieces/cm^2/year for the 250 µm size fraction and 0 to 20 pieces/cm^2/year for the 125 µm size fraction.

4.5.2.3 Zone KL-III (10-23 cm; -54 to -43 cal yr BP; 2009-1997 AD)

This zone is comprised of four pollen samples with the highest percentages of *Pinus* (11-15%), *Tsuga heterophylla* (14-16%), and *Pseudotsuga* (9-17%), and the lowest percentages of *Alnus* *rubra* (19-28%). The remainder of the arboreal taxa consisted of *Picea* (3-4%), *Abies* (2-4%), Cupressaceae (7-11%), and Ericaceae (9-12%) with minor amounts of *Betula* (1-2%), *Quercus* (0-2%), *Corylus* (0-1%), *Salix* (~1%), and *Populus* (~1%). The herbaceous component of this zone contained minor amounts of Cyperaceae (3-5%), members of the Asteraceae family (*Ambrosia*-type <1%, *Artemisia* <1%, Liguliflorae-type 0-1%, and Tubuliflorae-type <1%), and *Chenopodium*/*Amaranthus*-type (0-1%). Both *Sphagnum* (0-2%) and *Pleurozium* (0-1%) were found throughout this section in relatively low percentages. *Dryopteris* (1-2%) was also present throughout this zone while *Pteridium* (0-4%) was only present in the lower half of this zone. Overall, the pollen concentration of this zone was low, varying from 19,300 grains/cc to 30,700 grains/cc.

A total of twelve charcoal samples were analyzed within this zone. CHAR continued to remain low in this zone of the core, with the 250 µm size fraction ranging from 0 to 8 pieces/cm^2/year, and 1 to 13 pieces/cm^2/year for the 125 µm size fraction.

<u>4.5.2.4 Zone KL-IV (0-10 cm; -63 to -54 cal yr BP; 2019-2009 AD)</u>

The uppermost zone in this core consisted of five pollen samples. This zone is distinguished from other Kings Lake zones by high percentages of Ericaceae (5-50%) and relatively low percentages of *Pinus* (4-8%). Both *Picea* (2-7%) and *Abies* (2-7%) occurred in higher percentages within this zone relative to the rest of the core. The remainder of the arboreal taxa included *Tsuga heterophylla* (7-11%), *Pseudotsuga* (5-12%), Cupressaceae (5-13%), *Alnus rubra* (16-36%), *Betula* (0-1%), *Corylus* (0-1%), *Salix* (0-1%), and *Populus* (0-1%). The majority of the herbaceous taxa consisted of Poaceae (5-11%) and Cyperaceae (2-11%). The remainder of the understory was comprised of members of the Asteraceae family (*Ambrosia*-type 0-1%, *Artemisia* 0-1%, and Tubuliflorae-type 0-1%) and *Chenopodium*/*Amaranthus*-type (0-1%). Both *Sphagnum* (0-2%) and *Pleurozium* (1-2%) were present in this section of the core, but *Sphagnum* was absent in the two uppermost samples. *Pteridium* (0-2%), *Polystichum* (0-1%), and *Dryopteris* (0-1%) were present with low abundances. Pollen concentrations within this zone were slightly higher than in the previous zone (Zone KL-III), varying between 23,100 grains/cc and 42,700 grains/cc.

Eleven charcoal samples were taken from the uppermost zone in the core and both size fractions had low CHAR. CHAR varied between 0 and 2 pieces/cm^2/year for the 250 µm size fraction and 0 to 5 pieces/cm^2/year for the 125 µm size fraction.

4.5.3 Shadow Lake (SL) Pollen Analysis

Results are discussed relative to different depth zones, starting with the deepest (Figure 68). Age, pollen type, pollen concentration, and charcoal concentration are shown in Figure 68.

<u>4.5.3.1 Zone SL-I (66-96 cm; -18 to 110 cal yr BP; 1924-1833 AD)</u>

The lowest zone of this core is composed of eleven pollen samples. This zone is distinguished by having the highest percentages of Cupressaceae (10-33%), Poaceae (5-19%), *Sphagnum* (0-26%), and *Pteridium* (1-64%), and the lowest percentages of both *Pinus* (1-6%) and *Alnus rubra* (7-44%). Both *Sphagnum* and *Pteridium* peaked near the middle of this zone (85 cm and 88 cm). The percentage of *Alnus rubra* increased from the bottom to the top of this zone. The remainder of the arboreal taxa mainly consisted of *Tsuga heterophylla* (5-21%), *Picea* (1-8%), *Abies* (1-4%), and *Pseudotsuga* (7-17%) with minor amounts of *Betula* (0-1%), *Salix* (0-1%), *Populus* (0-2%), and Ericaceae (0-2%). *Acer*, *Corylus*, Rosaceae, and Berberidaceae were all present within this section.

Herbaceous taxa within this zone were comprised of Cyperaceae (3-10%), members of the Asteraceae family (*Ambrosia*-type 0-1%, *Artemisia* 0-2%, Liguliflorae-type <1%, and Tubuliflorae-type <1%), and *Chenopodium*/*Amaranthus*-type (0-1%). Both Polygonaceae and Saxifragaceae were present in this zone. The aquatic taxa present in this zone consisted of *Isoetes*, *Pediastrum*, and *Botryococcus* (0-4%). *Polystichum* was present near the top of this zone, while *Dryopteris* (0-2%) was present in the lower two-thirds of this zone. Pollen concentration varied from 23,300 grains/cc to 98,800 grains/cc.

A total of 31 charcoal samples were analyzed from this zone and both size fractions had their lowest CHAR of the core. CHAR varied between 32 and 7880 pieces/cm^2/year for the 250 µm size fraction and 2 to 85 pieces/cm^2/year for the 125 µm size fraction.

4.5.3.2 Zone SL-II (30-66 cm; -46 to -18 cal yr BP; 1977-1924 AD)

This zone consists of twelve pollen samples and had the highest percentages of *Alnus rubra* (55-71%). *Tsuga heterophylla* (2-15%) increased from the bottom to the top of this zone, while Cupressaceae (4-12%) decreases. *Pinus* (2-8%), *Picea* (0-3%), *Abies* (0-2%), *Pseudotsuga* (2-8%), *Betula* (0-1%), *Salix* (0-1%), *Populus* (0-1%), and Ericaceae (1-4%) comprised the remainder of the arboreal taxa. *Acer*, *Corylus*, and Rosaceae pollen grains were present in this zone, but in very low amounts (1-2 pollen grains). The herbaceous taxa were comprised of Poaceae (1-5%), Cyperaceae (1-4%), members of the Asteraceae family (*Ambrosia*-type 0-1%, *Artemisia* 0-1%, Liguliflorae-type 0-1%, and Tubuliflorae-type 0-1%), and *Chenopodium*/*Amaranthus*-type (0-1%). *Typha* and *Isoetes* were the only two aquatic taxa present within this zone. *Pleurozium* (0-2%) was present in the top two-thirds of this section and *Dryopteris* (0-1%) was present in the uppermost sample in this zone. Pollen concentration varied greatly throughout the zone (35,300 grains/cc to 167,900 grains/cc), with the peak occurring near the middle of the section (46 cm).

Thirty-six pollen samples were analyzed in this section. The highest CHAR for both size fractions occurred near the base, between 56 and 65 cm (250 µm size fraction: 6960 and 965,000 pieces/cm^2/year; 125 µm size fraction: 48 to 1290 pieces/cm^2/year). For both size fractions, CHAR decreased above 55 cm ranging between 570 and 19,800 pieces/cm^2/year for the 250 µm size fraction and 13 to 182 pieces/cm^2/year for the 125 µm size fraction.

4.5.3.3 Zone SL-III (0-30 cm; -63 to -46 cal yr BP; 2019-1977 AD)

The uppermost zone of the Shadow Lake core consisted of 12 pollen samples. This zone had the highest percentages of *Tsuga heterophylla* (9-24%) within the Shadow Lake peat core. Both *Pinus* (4-14%) and *Pseudotsuga* (8-18%) showed increasing trends in pollen percentages from the base of the zone towards the top, while *Alnus rubra* (24-60%) percentages decrease towards the top of this zone. The remainder of the arboreal taxa in this section included *Picea* (1-4%), *Abies* (1-4%), *Betula* (0-2%), *Quercus* (0-1%), *Salix* (0-1%), *Populus* (0-2%), and Ericaceae (0-2%). *Acer*, *Corylus*, and Rosaceae were minor components of the arboreal taxa. Herbaceous taxa were comprised of Poaceae (1-4%), Cyperaceae (1-4%), members of the Asteraceae family (*Ambrosia*-type <1%, *Artemisia* 0-2%, Liguliflorae-type 0-1%, and Tubuliflorae-type <1%), and *Chenopodium*/*Amaranthus*-type (0-2%). Onagraceae and Saxifragaceae were also present in this section of the core. The only aquatic taxon present was *Pediastrum,* which occurs near the base of this zone (27 cm). *Pleurozium* (0-3%) was the only moss spore present within this zone. Both *Polystichum* and *Dryopteris* (0-1%) were present throughout most of this section. Pollen concentrations are low overall when compared to the rest of the core, only varying from 12,300 grains/cc to 42,700 grains/cc.

A total of 30 charcoal samples were analyzed from this zone. CHAR continues to decrease in both size fractions. The 250 µm size fraction, CHAR ranges between 25 and 10,880 pieces/cm^2/year, and 5 to 75 pieces/cm^2/year for the 125 µm size fraction.

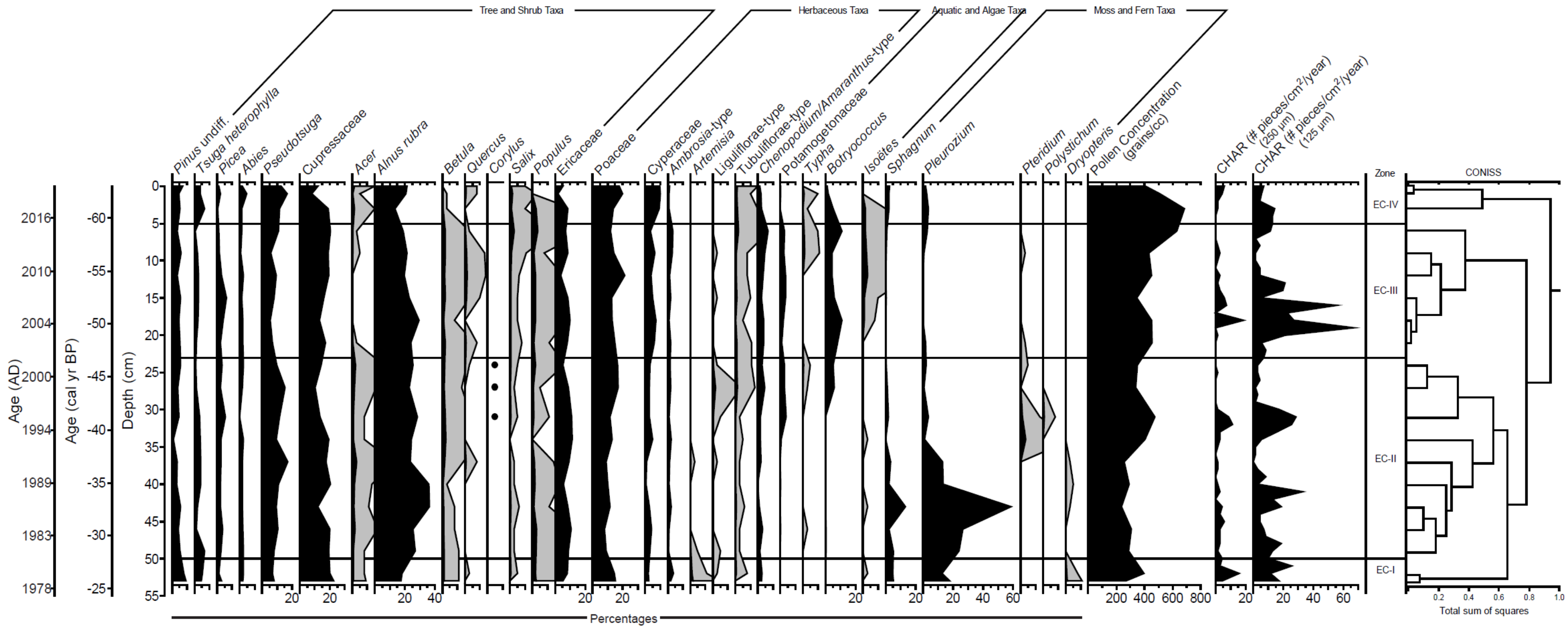


Figure 66. Pollen record from Evans Creek showing the relative abundance (% of total pollen), pollen concentration (grains/cc), CHAR (pieces/cm2/year for the 250 µm and 125 µm size fractions), and CONISS (constrained incremental sum of squares cluster diagram). Presence of *Corylus* is shown by circle symbols. Black lines (with a gray shadow) for *Acer*, *Betula*, *Quercus*, *Salix*, *Populus*, *Artemisia*, Liguliflorae-type, and Tubuliflorae-type, *Typha*, *Isoetes*, *Pteridium*, *Polystichum*, and *Dryopteris* indicate 10x exaggeration.

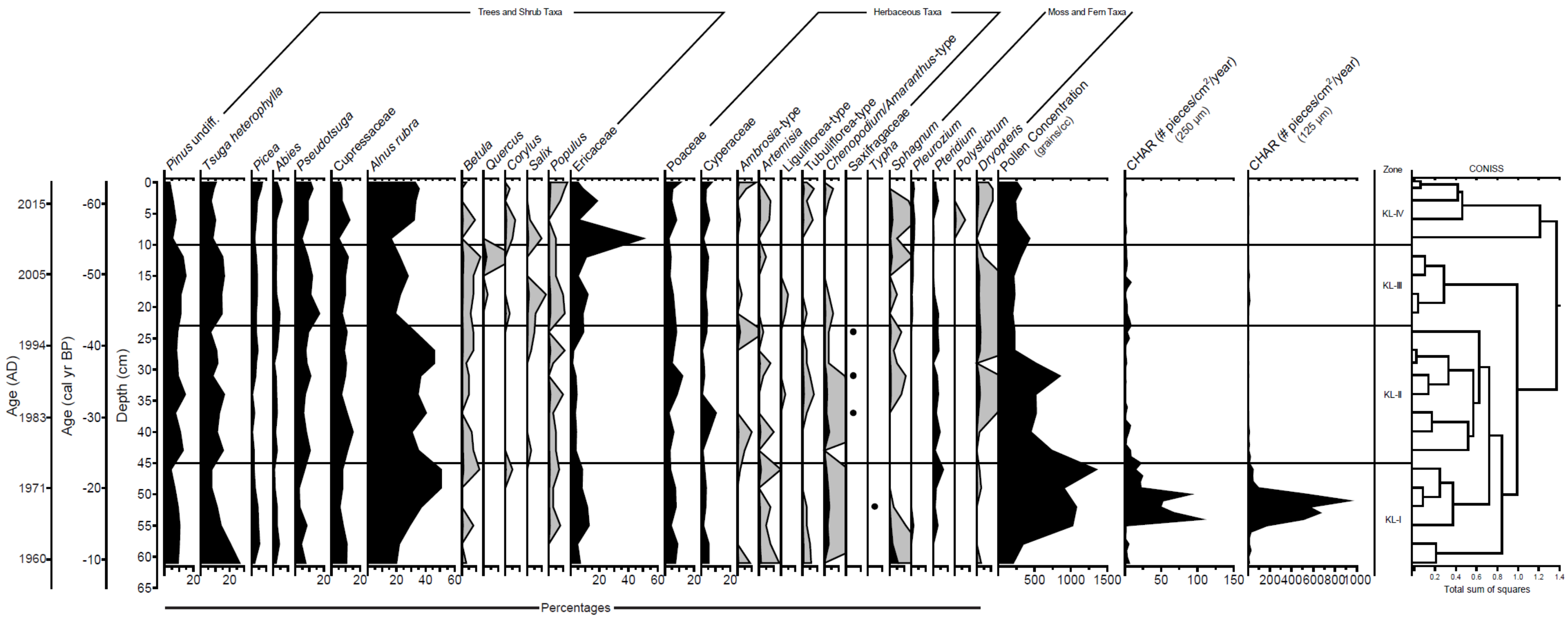


Figure 67. Pollen record from Kings Lake showing the relative abundance (% of total pollen), pollen concentration (grains/cc), CHAR (pieces/cm2/year for the 250 µm and 125 µm size fractions), and CONISS (constrained incremental sum of squares cluster diagram). Presence of Saxifragaceae and *Typha* are shown by circle symbols. Black lines (with a gray shadow) for *Betula*, *Quercus*, *Corylus*, *Salix*, *Populus*, *Ambrosia*-type, *Artemisia*, Liguliflorae-type, and Tubuliflorae-type, Saxifragaceae, *Chenopodium*/*Amaranthus*-type, *Sphagnum*, *Pleurozium*, *Polystichum*, and *Dryopteris* indicate 10x exaggeration.

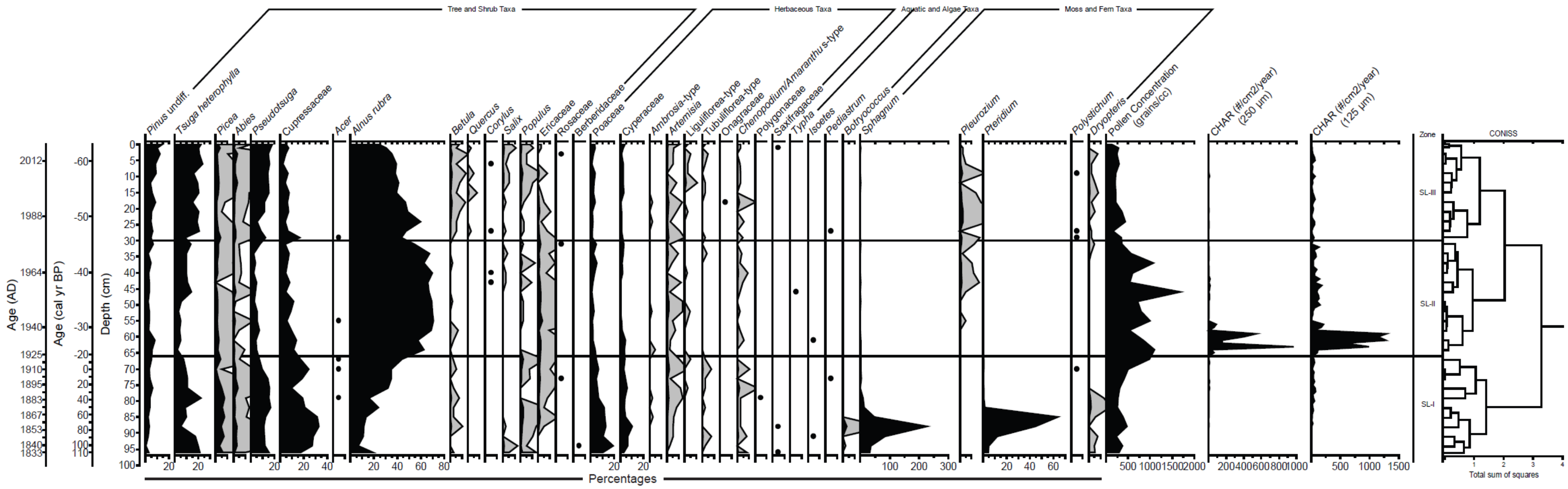


Figure 68. Pollen record from Shadow Lake showing the relative abundance (% of total pollen), pollen concentration (grains/cc), CHAR (pieces/cm2/year for the 250 µm and 125 µm size fractions), and CONISS (constrained incremental sum of squares cluster diagram). Presence of *Acer*, *Corylus*, Rosaceae, Berberidaceae, Onagraceae, Polygonaceae, Saxifragaceae, *Typha*, *Isoetes*, *Pediastrum*, and *Polystichum* are shown by circle symbols. Black lines (with a gray shadow) for *Picea*, *Abies*, *Betula*, *Quercus*, *Salix*, *Populus*, Ericaceae, *Ambrosia*-type, *Artemisia*, Liguliflorae-type, and Tubuliflorae-type, *Chenopodium*/*Amaranthus*-type, *Botryococcus*, *Pleurozium* and *Dryopteris* indicate 10x exaggeration.

5.0 DISCUSSION

5.1 BIOTIC AND ABIOTIC PATTERNS OF PUGET LOWLAND *SPHAGNUM*-DOMINATED PEATLANDS

5.1.1 Hydrology and Water Chemistry Patterns

The hydrologic and chemical regimes of *Sphagnum*-dominated peatlands and adjacent laggs vary with topography, climate, and land use within watersheds of the Puget Lowlands. Seasonal hydrological patterns were similar between peatland centers and laggs with the highest water tables during the winter rainy season and dropping to the lowest levels in mid- to late-summer. This suggests that our study sites are primarily supported by precipitation and/or local, shallow groundwater or surface water tied to seasonal precipitation.

The positive relationships between water levels and watershed area in both peatland centers and laggs indicate that shallow water tables are not maintained solely by direct precipitation. At the monthly timescale, watershed area was the strongest predictor of water levels in laggs and was a secondary driver in peatland centers, and these effects were strongest during the summer dry season, particularly in August. Watershed area was also positively related to porewater chloride concentrations in peatland centers during spring and late summer, suggesting that slower drainage processes such as shallow groundwater flow are important water sources that limit seasonal water level declines during the summer dry months. Because the Puget Lowlands is a landscape of rolling hills and low plateaus composed of predominantly coarse unconsolidated glacial deposits, groundwater flow directions in both surficial local and deeper regional aquifers follow major topographic features (Vaccaro et al. 1998, Jones 1999). These topographic controls on surficial aquifer boundaries and flow directions explain the connection between water levels and watershed area, particularly during the summer dry season, when runoff is minimal.

We found an unexpected negative relationship between mean annual precipitation and monthly water levels in peatland centers and laggs, particularly during the winter rainy season. The mechanisms underlying this relationship are unclear since water level variations in both settings closely correspond to the strong seasonality of precipitation in this region. One explanation could be that the study sites located in Mason County have the highest mean annual precipitation totals but also very small watersheds. These sites also have little impervious surface area around them. The counterintuitive results could also reflect unmeasured variables that are correlated to mean annual precipitation. For example, greater soil and vegetation development associated with increasing mean annual precipitation could result in higher precipitation losses to infiltration, canopy interception, and evapotranspiration in upland areas.

Porewater chemistry was distinct between peatland centers and laggs, highlighting the hydrological and ecological zonation in the peatlands (Howie and van Meerveld 2011, 2012, 2013; Howie et al. 2016). Laggs had higher pH and ionic concentrations than peatland centers, which is expected given that laggs typically receive water from peatland centers and adjacent upland or wetlands (Gorham 1953, Damman and French 1987, Golinski 2004, Howie and van Meerveld 2011, Langlois et al. 2015). Similar patterns were observed with Mean EC_{corr}, which was significantly lower in peatland centers than laggs in spring (27.8 μS/cm vs 69.6 μS/cm) and summer (47.2 μS/cm vs 136 μS/cm). Almost all seasonal porewater concentrations of major anions and cations were significantly lower in peatland centers than laggs. Lower ion concentrations in peatland centers compared to laggs is characteristic of ombrotrophic bogs, especially those with laggs that are confined by adjacent topography, which was the case for all of the study sites (Crum 1992; Golinski 2004, Howie and van Meerveld 2011, Howie and van Meerveld 2013, Langlois et al. 2015). The observed increases in ionic concentrations and EC_{corr} throughout the dry summer periods in both peatland centers and laggs could be due to evaporative enrichment, highlighting the importance of considering seasonality when characterizing hydrochemistry in these ecosystems.

5.1.2 Vegetation Patterns

Total vascular plant species richness across all study sites and wetland positions was 111 which is similar to what Golinski (2004) found (105 species) in a study of 14 disturbed and intact *Sphagnum*-dominated peatlands on the eastern side of Vancouver Island. Unsurprisingly, species richness was nearly three times higher in laggs, across all sites, compared to peatland centers. Due to higher pH, increased nutrient availability, and more dynamic water levels within and across sites, laggs typically support a wider range of species (Howie and Meerveld, 2012, 2013; Howie et al. 2016). However, when comparing mean plot richness, relationships were more variable and the inverse was often true (the peatland center had higher richness than the lagg). Laggs supported 78 species not found in peatland centers while 9 species were limited to peatland centers, highlighting the ecological distinction of laggs from peatland centers (Howie et al. 2016).

Peatland centers and laggs also exhibited characteristic differences in the abundance of various growth forms, with *Sphagnum*, ericaceous shrubs, and stunted trees dominating peatland centers and forbs, graminoids, and deciduous shrubs dominating the more minerotrophic laggs. Similar species distributions have been documented in Crowberry Bog on the Olympic peninsula (Rocchio et al. 2021) and *Sphagnum*-dominated peatlands in southwest British Columbia (Hebda and Biggs 1981; Golinski 2004; and Howie et al. 2016).

Tree distribution across structural classes in peatland centers suggests the distribution of tree height is conspicuously skewed toward short (presumably young) trees in Puget Lowland *Sphagnum*-dominated peatlands. This is consistent with the documented 20th century increase in tree occurrences in *Sphagnum*-dominated peatlands throughout the region (Zong and Shaw 2019), and could be a result of recent tree encroachment due to land use stressors, climate change, and/or successional dynamics. For example, increased tree cover has been shown to occur in regional *Sphagnum*-dominated peatlands following disturbance, especially drainage (Golinski, 2004, Hebda and Biggs 1981). However, 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; Bisbing et al., 2015). Another explanation is that there persistent high mortality of tree seedings and saplings over the long-term.

5.2 Are Puget Lowland *Sphagnum*-Dominated Peatlands Ombrotrophic?

Multiple lines of evidence were investigated to determine whether the study sites exhibited ombrotrophic conditions: topography, vegetation, hydrology, and porewater chemistry (Malmer et al. 1992, Sjörs and Gunnarsson 2002, Tahvanainen 2004, McHaffie et al. 2009, Proctor et al. 2009, Joosten et al. 2017b). No study site had clear ombrotrophic indicators for all measures, in all seasons. Given the variability of hydrological measures and lack of agreement with some of the chemical indicators of ombrotrophic conditions, we considered the preponderance of available evidence to identify the ombrotrophic status of each peatland. Hydrological and water chemistry indicators of each peatland were summarized as (1) predominantly ombrotrophic, (2) not ombrotrophic, or (3) inconclusive (Table 56).

5.2.1 Topography, Ecological Zonation and Vegetation

Peatland surfaces raised above the lagg provide topographic evidence of ombrotrophic conditions, since near-surface groundwater would likely be derived from meteoric sources in those elevated areas. Only three sites were raised more than 50 cm and about 30% of the sites were raised less than 10 cm above their laggs. Ombrotrophic conditions are not limited to raised bogs and can be found in flat sites where the ombrotrophic peat in the center extends below the mineral soil water limit in the laggs (Damman 1978, Damman 1986). For example, despite only being raised 50 cm above its lagg, a plateau bog in Sweden had ombrotrophic conditions (as determined by very low Ca^{2+} concentrations (< 1.6 mg/L)) to a depth of at least 3 m, where minerotrophic water was first detected (Damman 1978). Over time, the vertical change in surface position during bog development can result in ombrotrophic peat occurring below the mineral soil water limit in contemporary laggs (Damman 1978). Our dataset did not allow us to examine this potential scenario in our study sites. As such, topography alone was not a strong indicator of ombrotrophic conditions at the study sites.

A common characteristic of ombrotrophic bogs is the presence of a lagg around its perimeter (Howie and van Meerveld 2011). Laggs were present at all study sites and have more generally been recognized as characteristically occurring around Puget Lowland *Sphagnum*-dominated peatlands (Rigg 1925, Osvald 1933; Rigg 1958, Kulzer et al. 2001). Study site laggs had hydrological, chemical, and floristic differences from peatland centers. The presence of a lagg suggests there is enough convexity, or at least lateral drainage from the peatland center toward the edge, as well as drainage from adjacent areas, to produce a characteristic mixing zone. Vegetation differences between the peatland centers and laggs of the study sites were strongly reflective of distinct hydrological and chemical differences between the two zones. Species tolerant of acidic, nutrient poor conditions such as ericaceous shrubs and *Sphagnum* spp. dominated the peatland centers, while species more commonly found in regional fens, swamps, and marshes dominated the laggs (Golinski 2004, Hebda et al. 2000, Howie and van Meerveld 2011, 2012, 2013, and Rocchio et al. 2021). Although *Sphagnum* species were not collected as part of this project, herbarium records (CNABH 2022), reports from other researchers (Kulzer et al. 2001; Rocchio et al. 2021), and the primary author's observations suggest *Sphagnum capillifolium*, *S. fuscum,* and *S. rubellum* are the primary and dominant hummock formers in Puget Lowland *Sphagnum*-dominated peatlands. Those species are typically absent in laggs, where species tolerant of more minerotrophic conditions such as *Sphagnum henryense*, *S. palustre*, *S. pacificum*, *S. miyabeanum*, *S. mendocinum*, *S. teres* and others are likely to be more abundant. Study site laggs have more deciduous shrubs, fewer evergreen shrubs, and much less *Sphagnum* cover compared to peatland centers. While these differences are not necessarily an indicator of ombrotrophic conditions, they clearly speak to a distinct ecological difference and indicate that the peatland centers are much more acidic and ion-poor than the laggs, which are more affected by local groundwater, surface water, and overland flow. Minimally, vegetation zonation suggests that peatland centers are less affected by these water sources and that precipitation is a primary water source.

5.2.2 Water Sources and Water Flow

Elevations of well nests in peatland centers and laggs were surveyed at 8 of the 17 study sites. Water level data showed that five of these sites (Cranberry Marsh 2, Echo Falls, Evans Creek, Kings Lake, and Queens Bog) had water tables in peatland centers that were slightly elevated above those in their laggs. This suggests that lateral groundwater flowed from peatland centers toward laggs—a characteristic of ombrotrophic bogs (Damman 1986, Damman and French 1987, Howie and van Meerveld 2011; Rocchio et al. 2021). Two sites, Arrowhead and Cranberry Marsh 4, had equal or higher water tables in the laggs relative to peatland centers, suggesting lateral flow from the laggs into the peatland centers. Other explanations could be (1) that underlying substrate in the peatland center is more permeable than found in the lagg, thus the peatland center is functioning as a drain; (2) conductivity of the peat in the lagg is lower than the peatland center, thus water flow between the two zones is slow and water remains in the lagg for longer periods; or (3) clogging of well slots in the fine-grained mineral substrate of the laggs resulted in residual water ponding on the bottom of some wells. Howie and van Meerveld (2013) found that water levels in bogs of southwest British Columbia decreased from the bog center toward the lagg, but a few sites showed an inverse relationship. They described these sites as either not being ombrotrophic or as potentially experiencing flow reversals, in which precipitation results in downward and lateral flow during the rainy season, but mineral-rich water is able to flow into the peatland center during the dry season. Additional measures along the transect from peatland center to lagg are needed at Arrowhead and Cranberry Marsh 4 to understand water flow patterns at those sites. Lateral flow dynamics could not be determined at the nine sites that were not surveyed for elevation.

Piezometer data indicated that vertical flow directions were highly variable in peatland centers. Shallow water tables maintained solely by the infiltration of meteoric waters would likely produce a negative (downward) VHG while a strong positive (upward) VHG would indicate upwelling groundwater, as occurs in portions of fens. Arrowhead, Cranberry Marsh 4, Evans Creek, Queens Bog, and Patterson had a negative VHG during spring and summer, indicating downward flow throughout the year. Arrowhead and Cranberry Marsh 4 wells were dry in summer, indicating a lack of groundwater inputs during the dry season. Shadow Lake had a negative VHG during summer months, indicating that groundwater discharge did not occur in the top 1 m of the peat profile during summer months. Echo Falls also had downward flow during the dry summer season but stormwater discharge from an outfall on the peatland margin appeared to cause upwelling during the rainy season. This site may be an example of the impacts of contemporary stormwater inputs on the hydrological regime of the site. Groundwater appears to be a predominant water source at Covington 12, which had upwelling water during summer months, although precipitation during winter months moderated groundwater inputs. Springer Lake showed downward flow during the rainy season and upward flow during summer. VHGs for the remaining study sites did not show strong indicators of upward or downward movement. Near-zero seasonal VHGs may reflect the dominance of lateral water redistribution within the wetland between rainfall events, lateral flow through the wetland complex, or ponded conditions. Vertical and lateral flow dynamics in such sites could be clarified in the future with transects of piezometer nests spanning from peatland center to the lagg, rather than one nest in each position. Peat deposits are highly anisotropic, with hydraulic conductivity and groundwater flow velocity decreasing with depth due to the greater density and lower porosity in deeper peat (Beckwith et al. 2003, Rydin and Jeglum 2013, Siegel and Glaser 2006). This is consistent with the very small VHG values observed in deeper (100-200 cm) peat horizons at our sites. Extremely low hydraulic conductivity in deeper peat can impede downward flow and force the redistribution of water horizontally within the upper fibric peat horizons (Beckwith et al. 2003). The seasonal occurrence of upward VHGs at shallow depths in four of our study peatlands may have resulted from localized upwelling of lateral groundwater movement within the fibric peat, or lateral groundwater inputs from adjacent surficial aquifers. Seasonal groundwater discharge has been documented in ombrotrophic peatlands and may be critical for stabilizing ground water in regions with strong, seasonal precipitation (Siegel and Glaser 1987, Glaser et al. 1997; Rocchio et al. 2021). Our analyses demonstrated that porewater chemistry is not strongly related to VHGs, highlighting the challenges of determining wetland water sources based on hydraulic gradients alone. Additional data, such as stable isotope analysis (Keimowitz et al. 2013), could help to clarify water sources.

5.2.3 Water Chemistry

Porewater pH, EC_{corr}, and ion concentrations in the study peatland centers were similar to values reported for ombrotrophic peatlands in other parts of the Northern Hemisphere (Damman 1986; Wheeler and Proctor 2000, Golinski 2004; Bourbonniere 2009, Howie and van Meerveld 2012). Similarities between precipitation and porewater chemistry of peatlands has been shown to be a strong indicator of ombrotrophic conditions (Damman, 1986; Glaser et al., 1997; Ingram, 1983; Proctor et al., 2009; Siegel and Glaser, 1987). All study sites had pH, Ca^{2+}, and EC_{corr} values much closer to local precipitation values than groundwater values, suggesting that even if the sites are not solely ombrotrophic, all are predominantly supported by precipitation.

The majority of study sites (64%) were below pH of < 4.2 in spring, which is a commonly used threshold for bogs, but only 24% met the threshold in summer (Sjörs 1950; Gorham 1957, Glaser et al. 1981, Glaser et al. 1990, Sjörs and Gunnarsson 2002, Tahvanainen 2004, Proctor et al. 2009, Joosten et al. 2017b). Mean pH at four sites (Arrowhead, Kings Lake, Lake Dorothy, and Trossachs) exceeded 4.2, but were less than 4.5 in summer, the ombrotrophic threshold used by Malmer et al. (1992) for coastal bogs in British Columbia and continental bogs in Alberta. The pH in Lower Cedar and Shadow Lake was > 4.5 for both seasons, suggesting those sites are supported by minerotrophic groundwater and/or that stormwater inputs contribute mineral-rich water and alter the acidity of these sites. Ombrotrophic bogs in the Fraser River lowlands of southwest British Columbia were reported to have pH < 4.2, while bogs on the western coast of Vancouver Island have been reported as generally being < 4.5 (Howie and van Meerveld 2012, 2013) and southeastern Alaska (Bisbing et al. 2015). Crowberry Bog, the only known raised, ombrotrophic bog in the western conterminous United States, has pH values in the peatland center between ~ 4.2 and 4.5, with the relatively high values attributed to proximity to the open ocean, which may contribute salt to local precipitation (Rocchio et al. 2021). Maritime-influenced ombrotrophic bogs in Sweden have pH up to 4.8, attributed to higher Mg^{2+} concentrations (Sjörs and Gunnarsson, 2002). Raised oceanic bogs in Newfoundland have pH ranging from 4.1 to 4.5, with relatively high Mg^{2+} concentrations (Glaser, 1992).

The majority of electric conductivity measures for study sites exceeded conductivity of local precipitation, but were < 50 µS/cm and well below the EC_{corr} of local groundwater. Arrowhead, Cranberry Marsh 2, Kings Lake Bog, Queens Bog, and Springer Lake had mean EC_{corr} values that met the Vitt et al. (1995) threshold of < 39 µS/cm for bogs. At Burns Bog, near Vancouver, British Columbia, EC_{corr} values have been reported from 35 to 70 µS/cm (Howie and van Meerveld 2012). Other bogs in the Fraser River lowlands and southeastern Vancouver Island have ranges from 24 to 30 µS/cm in undisturbed sites and 23 to 108 µS/cm in disturbed bogs (Golinski 2004).

Because Ca^{2+} concentrations are extremely low in precipitation, Ca^{2+} concentrations <2.5 mg/L or Ca:Mg $\leq$1.0 have been used to indicate ombrotrophic conditions (Malmer et al. 1992, Sjörs and

Gunnarsson 2002, Tahvanainen 2004; McHaffie et al. 2009, Proctor et al. 2009, Joosten et al. 2017b). Heinselman (1970) considered Ca^{2+} concentration to be the best indicator of ombrotrophic conditions and found concentrations of 0.8 – 2.8 mg/L in Minnesota ombrotrophic bogs. Most sites in this study (71%) had porewater Ca^{2+} concentrations < 2.0 mg/L in both seasons, suggesting they are ombrotrophic. Three sites exceeded this value during the spring (Covington 8, Patterson Creek, and Wetland 14), suggesting that groundwater flow reaches the upper peat layers at this time and/or that stormwater flows are affecting porewater chemistry. Shadow Lake exceeded 2.0 mg/L in both seasons. Very low Ca^{2+} concentrations (i.e., 0.1 to 0.8 mg/L) were observed at Crowberry Bog, a raised plateau bog on the western Olympic peninsula (Rocchio et al. 2021). Calcium concentrations in ombrotrophic bogs in southwest British Columbia have been reported between 0.4 to 2.8 mg/L (Golinski 2004; Howie and van Meerveld). Malmer et al. (1992) found that calcium concentrations range from < 1 mg/L to 2.5 mg/L in bogs in western Canada while Vitt et al. (1994) found even lower concentrations (< 1 mg/L) in the same region. In a review of 65 raised bogs in eastern North America, Glaser (1992) demonstrated that 97% of those sites had Ca^{2+} concentrations < 2.0 mg/L.

Proctor et al. (2009) suggested that molar Ca:Mg in ombrotrophic peatlands is generally ≤ 1.0 (with Ca^{2+} concentrations around 2 mg/L) and similar to the ratio in local precipitation which can regionally vary. A more useful threshold may be whether a site's Ca:Mg is equal to or lower than Ca:Mg in local precipitation (Vitt et al. 1994; Proctor et al. 2009). Despite our study sites occurring in a coastal landscape, Ca:Mg of local precipitation is near 1.0 and thus should be a sensitive indicator of ombrotrophic conditions in our study sites. The molar Ca:Mg at 35% of the study sites (6 sites) exceeded 1.0 in spring months and 76% (11) of the study sites exceeded 1.0 in summer months. However, during spring months, four of the six sites that exceeded Ca:Mg of 1.0 had Ca^{2+} concentrations < 2 mg/L. Conversely, two of the 11 sites that were below Ca:Mg of 1.0, had Ca^{2+} concentrations > 2 mg/L. One of those sites (Patterson) had high Ca^{2+} concentration (7.57 mg/L) and high Mg^{2+} concentration (5.35. mg/L). During summer months, 7 of the 11 sites that exceeded Ca:Mg of 1.0 also had Ca^{2+} concentrations < 2 mg/L. Proctor et al. (2009) acknowledged that a Ca:Mg of 1 was "no more than an initial informed guess" and that an alternative approach would be to assess the distribution of Ca:Mg from various local sites where ombrotrophic conditions can be assumed. In other words, molar Ca:Mg in peatland waters needs to be regionally calibrated with concentrations in local precipitation and ombrotrophic peatlands (Sjörs and Gunnarsson 2002, Howie and van Meerveld 2011). Unfortunately, there is only one known raised bog in Washington State, and ombrotrophic conditions can't be assumed in *Sphagnum*-dominated peatlands in the region. Similar to the findings of Howie and van Meerveld (2012), Ca:Mg was concluded to not be a useful indicator of ombrotrophic conditions for the study sites and was not used to discern ombrotrophic status (Table 56).

5.2.4 Summary of Ombrotrophic Conditions
Lateral and vertical hydraulic gradients reflected variation in potential water sources among sites. Seasonal water level declines at sites in former kettle ponds are probably limited by either immobile water within the depressions or lateral groundwater fluxes through the depressions, while those on the margins of larger lakes are clearly influenced by surface and subsurface watershed contributions. Porewater chemistry in the Puget Sound peatlands was generally consistent with that of ombrotrophic peatlands in other regions. Based on the preponderance of evidence outlined above, 35% (six) of the study sites were concluded to be ombrotrophic, 53% of the study sites (nine) were deemed inconclusive, and 12% (two) were concluded to not be

ombrotrophic (Table 56). Arrowhead Bog, Cranberry Marsh #4, Evans Creek, Hooven Bog, Patterson Creek, and Queens Bog predominantly showed ombrotrophic indicators. Evans Creek and Queens Bog were the only two study sites that met all ombrotrophic indicators in all seasons. Interestingly, both of these sites have experienced direct impacts to the peatland center—peat mining at Evans Creek in the 1930's (Rigg 1958) and pipeline installation across Queens Bog—and both are also surrounded by housing developments.

The ombrotrophic status of Covington 8, Covington 12, Cranberry Marsh #2, Echo Falls, Kings Lake, Lake Dorothy, Springer Lake, Trossachs, and Wetland 14 had conflicting indicators and were deemed inconclusive. Despite Echo Falls having chemical signatures of ombrotrophic conditions, there was evidence of groundwater upwelling during the rainy season that appears to be associated with known stormwater inputs into the basin. The site had downward flow during the dry, summer season, suggesting that persistent groundwater discharge is not occurring. This site may be an example where the baseline condition is ombrotrophic, but where contemporary stormwater inputs have altered the natural hydrological regime. Kings Lake also had ombrotrophic chemical signatures, but hydrology measures were inconclusive, with slight downward flow in spring and slight upward flow in summer when pH was also slightly above the 4.5 threshold. This might be explained by winter precipitation counteracting slight upward groundwater flow during the rainy season, but the slightly more minerotrophic water is able to reach into the top 1 m of peat during dry, summer months. However, Stroh (2001) suggests that the relatively small catchment basin and the beaver dams at the outlet of the bog keep water level fluctuations in the bog and pond relatively small. Springer Lake showed the same hydrological pattern, but also had increased magnesium concentrations in summer, perhaps reflective of the lake water that is likely driving the seasonal upward movement of the water table.

The preponderance of evidence for Lower Cedar and Shadow Lake suggests that they are not ombrotrophic. The *Sphagnum*-dominated peatland at Shadow Lake likely developed from a process of terrestrialization of a shallow arm of the lake. The peatland's water table may still be connected to and influenced by adjacent lake water chemistry. Shadow Lake is classified as a mesotrophic lake in which water quality has been declining over time, presumably due to land development in its basin (King County 2021). Such chemical changes may be influencing the dramatic increase in tree cover in the peatland. Another explanation for the abundance of tree cover at the site may be fire: Old, burned fence posts, charred, old western hemlock trees, and the pollen/charcoal data collected for this project indicate that the Shadow Lake peatland burned circa 1930. Contemporary vegetation patterns may be a result of this burn.

Sjörs (1983) noted that ombrotrophic bogs and poor fens in southern Alaska and Fennoscandia could not be easily differentiated using vegetation indicators; even a clear hydrological boundary between the two was difficult to determine. This supports the argument that chemical indicators are the most objective evidence for ombrotrophic conditions (Proctor et al. 2009). If the ombrotrophic status of each site were limited to an assessment of chemical indicators, 88% (15 sites) of our sites would be considered ombrotrophic, with only Lower Cedar and Shadow Lake not meeting ombrotrophic indicators as described in Table 56.

Integration of the chemical and hydrologic data suggest that many peatlands in the Puget Lowlands are either (1) predominantly ombrotrophic and/or (2) support a thin ombrotrophic layer of near-surface peat, with deeper groundwater maintained by surface and subsurface watershed

Table 56. Ombrotrophic Status of Study Sites. **Omb =** result was indicative of ombrotrophic conditions; NotOmb = result was not indicative of ombrotrophic conditions; Cells marked with "—" were inconclusive or had insufficient data (insufficient data were treated as inconclusive). Ombrotrophic Status: Yes = site had ombrotrophic indicator in at least one season for all indicators; Inconclusive = site lacked ombrotrophic indicator in both seasons in at least one indicator; No = site was missing two or more ombrotrophic indicators in both seasons;

Site	VHG* (cm/cm)		pH Omb = < 4.5		EC_{corr} (µS/cm) Omb = < 50 µS/cm		Ca^{2+} (mg/L) Omb = 2.0 mg/L		Ombrotrophic Status
	Spring	**Summer**	**Spring**	**Summer**	**Spring**	**Summer**	**Spring**	**Summer**	
AH[1]	**Omb**	dry	**Omb**	NotOmb	**Omb**	**Omb**	**Omb**	**Omb**	Yes
C12	—	NotOmb	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Inconclusive
C8	—	—	**Omb**	**Omb**	**Omb**	**Omb**	NotOmb	**Omb**	Inconclusive
CM2[1]	—	—	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Inconclusive
CM4[1]	**Omb**	dry	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Yes
EC	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Yes
ECH	NotOmb	—	**Omb**	**Omb**	NotOmb	**Omb**	**Omb**	**Omb**	Inconclusive
HO	—	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Yes
KL[1]	—	—	**Omb**	NotOmb	**Omb**	**Omb**	**Omb**	**Omb**	Inconclusive
LC	—	—	NotOmb	NotOmb	**Omb**	NotOmb	**Omb**	**Omb**	No
LD[1]	—	—	**Omb**	NotOmb	**Omb**	**Omb**	**Omb**	**Omb**	Inconclusive
PA	—	**Omb**	**Omb**	**Omb**	**Omb**	NotOmb	NotOmb	**Omb**	Yes
Q	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Yes
SL	—	**Omb**	NotOmb	NotOmb	**Omb**	NotOmb	NotOmb	NotOmb	No
SPL	—	NotOmb	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	**Omb**	Inconclusive
TR	—	—	**Omb**	**Omb**	**Omb**	NotOmb	**Omb**	**Omb**	Inconclusive
W14	—	NotOmb	**Omb**	**Omb**	**Omb**	NotOmb	NotOmb	**Omb**	Inconclusive

*Only statistically significant results were used contributions. Glaser et al. (1990) described a scenario in the Lost River peatlands of Minnesota where seasonal minerotrophic groundwater was detected at a 50 cm depth in an ombrotrophic bog, but ion concentrations were diluted from precipitation inputs, resulting in a chemical signature indistinguishable from ombrotrophic waters (Glaser et al. 1990). They postulated that the vegetation was too shallow-rooted to be affected by the minerotrophic groundwater. Heinselman (1970) recognized a "semi-ombrotrophic" bog in Minnesota where slight inputs of minerotrophic water were flushed during precipitation events, leaving chemical composition very similar to ombrotrophic bogs, but with slightly higher Ca^{2+} concentrations. Some of this project's study sites had similar mixed indicators of ombrotrophic conditions where hydrological indicators suggest some level of groundwater inputs, but porewater chemistry is reflective of ombrotrophic conditions. Relatively thin ombrotrophic peat layers (< 1 m) may be present in these sites and influence the vegetation's rhizosphere. Under that scenario, the dominant *Sphagnum* spp.—the primary functional species of the sites—would be functioning within ombrotrophic conditions, while more deep rooted species (e.g., beaked sedge, shore pine, potentially western hemlock), are able to access deeper minerotrophic groundwater, as described by Proctor et al. (2009). Future work documenting the abundance of individual *Sphagnum* species would be invaluable for such as an interpretation as dominance of oligotrophic species such as *S. capillifolium*, *S. fuscum*, and *S. rubellum* would be indicative of a surficial ombrotrophic layer.

In summary, the majority of study sites exhibited chemical characteristics of ombrotrophic bogs and most lacked evidence of strong upward (groundwater) or downward (precipitation) flow. This suggests that even if groundwater is affecting upper peat profiles, precipitation is still a predominant water source and likely the strongest factor in the ecology of these sites. As emphasized by Proctor et al. (2009), discerning a distinct line between ombrotrophic and minerotrophic conditions is never completely sharp. As an example, even Crowberry Bog—the only known raised bog in the western conterminous United States—did not have clear evidence for each indicator despite being raised nearly 3 m above the surrounding landscape (Rocchio et al. 2021). From a management perspective, a more nuanced view of ombrotrophic conditions is prudent, where recognition of proportional input of precipitation versus groundwater inputs should be the primary consideration, rather than management being dictated by a stark line between ombrotrophic and minerotrophic conditions.

5.3 Effects of Land Use on Puget Lowland Peatlands

5.3.1 Hydrochemical Impacts

Suburban development appears to have larger effects on the hydrologic regime in laggs than peatland centers, highlighting the important function of laggs as buffering zones (Howie and van Meerveld 2016). Mean water levels in laggs within developed landscapes were higher than in reference sites, and these developed laggs sometimes remained inundated throughout the year but these effects did not vary by season or month. In contrast, mean water levels in peatland centers did not differ between reference and developed landscapes. However, measures of development such as Land Use Index and impervious area within 50 m of the wetland perimeter did affect water levels in peatland centers and laggs once natural landscape variables were accounted for. Azous and Horner (1997) demonstrated a correlation between impervious surface area and increased water levels and degree of fluctuation in Puget Sound wetlands, but peatlands were not specifically addressed in that research. Our data showed that water level fluctuations in peatland centers were larger in reference sites during September and October relative to those in developed landscapes, but otherwise strong connections between landscape development factors and water level fluctuations were not apparent. Water table fluctuations in disturbed *Sphagnum*-dominated peatlands of southeast Vancouver Island were significantly greater than in undisturbed sites (Golinski 2004). Comparisons of recent aerial photography with historical imagery suggests that water levels have increased in laggs surrounding many Puget Lowland peatlands, likely a result of urban runoff into these basins. A particularly extreme example is the peatland that formerly existed at Thomas Lake, a site near Mill Creek, which has experienced dramatic change over nearly 75 years resulting from both direct losses to development and increased water levels from surrounding urban development (Figure 69). Very little of the original peatland remains and the site is much wetter than it was in 1941.

In contrast, we did not detect monthly water level differences between peatland centers in reference and developed sites were not detected. Instead, mean monthly water levels in both peatland centers and laggs in our study sites were most strongly related to watershed area and mean annual precipitation, while the hydrologic effects of suburban development were comparatively small. Tree harvest in managed timber landscapes can increase water levels, by reducing evapotranspiration rates and increasing runoff into the peatland (Asada et al. 2003, 2004; Ireland and Booth 2012). None of our study sites were embedded in landscapes free of past or recent logging, and this could potentially limit detection of hydrological effects of land use in our dataset.

Figure 69. Example of Stormwater-induced Conversion of a *Sphagnum*-dominated Peatland

Patterns in porewater chemistry indicated that solute loads from developed areas impact both peatland centers and laggs. Variation in seasonal porewater chemistry was best explained by land use and impervious surface area metrics. Inflows from stormwater management facilities commonly mediated the effects of watershed and land use characteristics on porewater pH, EC_{corr}, and ion concentrations, particularly during the rainy season. Our analyses indicate that hydrologic inputs other than direct precipitation affect porewater chemistry in some of the study sites, but the seasonal effects of watershed and land use characteristics vary between peatland centers and laggs.

At the end of the rainy season, EC_{corr} in both wetland positions were higher in developed landscapes, and elevated EC_{corr} was associated with the presence of stormwater inflow from roads and residential areas. Although late summer EC_{corr} was similar in reference and developed sites, the lowest values occurred for peatland centers and laggs in watersheds with high Land Use Index values, which reflect more intact natural vegetation. Porewater EC_{corr} in laggs was higher with the fraction of impervious surface area up to 500 m away during both seasons, while in peatland centers this relationship was only apparent during late summer for buffer distances up to 250 m. Disturbed *Sphagnum*-dominated peatlands on southeastern Vancouver Island had significantly higher EC than undisturbed peatlands (Golinski 2004). Similarly, Taylor et al. (1995) found elevated conductivity in Puget Lowland wetlands with more than 3.5% impervious surface area, with another significant increase above 20% impervious surface area. Even in developed sites, mean EC_{corr} in peatland centers was still lower than in adjacent laggs, highlighting the important buffering function of laggs (Howie and van Meerveld 2012).

The lack of significant pH differences between developed and reference peatland centers could be a result of the buffering effect of laggs, which had higher pH in developed sites (5.66) versus reference (5.02) sites, similar to what has been observed in laggs of *Sphagnum*-dominated peatlands of southwest British Columbia (Howie and van Meerveld 2011; 2012). Summer pH did not differ, which further suggests the pH was driven by seasonal water inputs. However, pH was higher in peatland centers that had stormwater inputs into their basin and this effect increased with watershed area. The effects of land use would likely manifest first in laggs since they are at the interface of watershed inputs into the peatland basin. It is not unusual to find laggs impacted by adjacent land use stressors, while the interior peatland center remains unaffected (Howie and van Meerveld 2011). If the stressors are persistent and increase, over time the lagg may lose its buffering capacity and the peatland center will eventually be exposed to incoming hydrological and chemical stressors (Howie and van Meerveld 2011). This appears to be occurring at Queen's Bog where a dense stand of western hardhack has been encroaching into bog vegetation occupying the peatland's center.

Peatland center Ca^{2+}, $Mg,^{2+}$ and Na^{+} concentrations did not differ between reference or developed sites, but lagg concentrations were significantly higher in developed sites during spring. These patterns reflect the ecological distinction between peatland centers and laggs and also suggest that increased adjacent development contributes excess ions into peatland basins. This has been well documented in other regions (Golinski 2004; Howie and van Meerveld 2011; Ireland and Booth 2012). The fact that most ion concentrations in developed peatland centers were lower than developed laggs suggest these laggs are still providing a buffer between peatland centers and adjacent land use. Banner et al. (2005) note that because ombrotrophic bogs are isolated from groundwater and surface water inputs, they may not be affected by logging activities that surround the bog. However, this function may begin to decline over time if stressors continue or intensify. An important research question remains: How long can the lagg continue to provide a buffering function for the peatland center if it is continuously affected by adjacent land use stressors?

Porewater Ca^{2+} concentrations at peatland centers were related to impervious surface area within 50 m of the wetland and concentrations in laggs were related to the impervious surface area within the watershed (when variability due to other watershed characteristics were accounted for) and model coefficients indicated that wetlands in small watersheds were most affected by impervious surface areas. This is significant because, as noted previously, Ca^{2+} concentrations are naturally very low in peatland centers and increasing concentrations would result in an ecosystem shift away from a *Sphagnum*-dominated peatland toward a more minerotrophic wetland type. Increasing impervious surface area also resulted in higher ammonium concentrations in both wetland settings. Porewater PO_4^{3-} concentrations in peatland centers and laggs were largely influenced by surface water inputs, suggesting that PO_4^{3-} adsorbed to suspended sediment was the primary input. After the rainy season, PO_4^{3-} concentrations were higher in peatland centers affected by stormwater management facilities and laggs with natural surface water connections. The effects of surface water inputs in laggs were similar during the summer dry period, but peatland PO_4^{3-} concentrations at this time were more strongly related to climate. These relationships between ionic concentrations and impervious surface area demonstrate that suburban development within the watershed can produce measurable changes in peatland geochemistry, even if vegetated wetland buffers within 50 m of the wetland perimeter are retained.

5.3.2 Vegetation Changes

The hydrological and chemical stressors resulting from increased land use in peatland watersheds can increase species richness in laggs but decrease richness in peatland centers. Golinski (2004) observed a similar pattern on Vancouver Island but noted that sites embedded within a disturbed landscape often retain higher species richness if they have intact laggs. All of this project's study sites retain their laggs, suggesting that species richness in peatland centers could have been even lower without them. Although species richness was higher in laggs in the population of developed sites, the difference was not significant at the plot scale. Laggs in the Fraser River lowland and eastern Vancouver Island showed a similar pattern, with lagg species richness higher across all study sites, but frequently reversed when examined at the site (or plot) scale (Howie et al. 2016). Lagg plant composition, hydrological regime, and water chemistry can vary greatly across sites, producing increased plant diversity at the landscape scale, but lower site-scale diversity is still possible— especially in impacted wetlands (Howie and van Meerveld, 2012, 2013; Howie et al. 2016).

Variation in abundance of certain growth forms between developed and reference peatland center sites is consistent with previously reported changes resulting from increased human stressors. These changes include a decrease in *Sphagnum* and lichen cover and an increase in feathermosses (e.g., *Pleurozium schreberi*, *Hylocomium splendens*) and deciduous shrub cover. Changes may be the result of drier conditions, increased nutrients, fire, or shading (Hebda and Biggs 1981, Gignac et al. 1991, Golinski 2004, Benscoter and Vitt 2008, Ireland and Booth 2012, Pasquet et al. 2015). Numerous researchers have found that runoff from roads and specific ions such as Cl^- decrease *Sphagnum* cover in peatlands (Bubeck et al. 1971; Wilcox 1986; Ehrenfeld and Schneider 1991). Most *Sphagnum* species are not very tolerant of shade (Clymo and Hayward 1982), so as woody vegetation cover increases, subsequent shading can induce a loss of moss cover or a shift in dominance from *Sphagnum* to feathermosses, which are generally more shade-tolerant (Lachance and Lavoie 2004; Benscoter and Vitt 2008). However, decreasing *Sphagnum* cover was not correlated with increasing woody vegetation cover in our study but was correlated with increasing feathermoss cover (r=-0.60; Figure 70). Feather mosses, especially *Pleurozium schreberi*, are more drought and shade tolerant than the dominant *Sphagnum* species found in Puget Lowland *Sphagnum*-dominated peatlands (Foster 1985, Gignac et al. 1991, Lachance and Lavoie 2004, Benscoter and Vitt 2008, Pellerin et al. 2016, Laine et al. 2018). In western Canadian continental peatlands, *Pleurozium schreberi* is often a dominant species, especially on the driest hummocks, where it codominates with *Cladonia* species (Gignac and Vitt 1991). *Racomitrium lanuginosum* and *Sphagnum* (e.g., *S. austinii*) tend to replace *Pleurozium* in these relatively dry habitats in hyperoceanic areas (Gignac and Vitt 1991). Lack of fire may also explain this pattern. After 80 years without fire in western Canadian boreal bogs, feathermosses (e.g., *Hylocomium splendens*, *Pleurozium schreberi*, etc.) increased in abundance and outcompeted *Sphagnum* spp. (Foster 1985; Benscoter and Vitt 2008). The cessation of known tribal burning in local *Sphagnum*-dominated peatlands may be resulting in conditions similar to these boreal peatlands (Anderson 2009).

Tree distribution across structural classes in peatland centers suggests a reverse J-shaped distribution of tree height in Puget Lowland *Sphagnum*-dominated peatlands. This could be a result of recent tree encroachment due to stressors, climate change, and/or successional dynamics. For example, increased tree cover has been show to occur in regional *Sphagnum*-dominated peatlands following disturbance, especially drainage (Golinski, 2004, Hebda and Biggs 1981). Fitzgerald (1966) found that warm winters increase survival of western hemlock seedlings at King Lake Bog Natural Area Preserve (one of our study sites), suggesting that climate change could be a driver of increased tree establishment in local *Sphagnum*-dominated peatlands. Alternatively, this could reflect cohort dynamics where either (1) frequent mortality of the abundant seedlings observed in the herbaceous layer result in few tall trees, or (2) harsh growing conditions of the peatland centers prevent old trees from becoming tall. However, tree height may not be well correlated with age in stressful environments such as bogs. Hebda and Biggs (1981) found that tall vigorous, straight shore pine at Burns Bog germinated on recently burned surfaces while the more typical, short, bonsai-like statured shore pine germinated on *Sphagnum*-hummocks. The areas supporting these different shore pine growth forms also appeared to respond to fire in different ways: (1) Following fire, there was a sharp decrease of shore pine in the areas supporting tall shore pine pre-fire, but (2) where shore pine was previously absent or stunted, it increased sharply following fire (Hebda 1977). The co-occurrence of both growth forms of shore pine has been observed in many western Washington *Sphagnum*-dominated peatlands, where they are growing in close proximity and thus experiencing the same hydrological and chemical conditions. Rigg (1958) noted indicators of recent and past fire at many of the *Sphagnum*-dominated peatlands he surveyed. Thus, the distribution of trees across structural layers could also be a result of past fire. Lack of fire could also be the cause of tree encroachment, as demonstrated in boreal peatlands in Alberta (Benscoter and Vitt 2008). Local tribes are known to have periodically burned *Sphagnum*-dominated peatlands on the western Olympic peninsula to keep woody vegetation cover low (for increased cranberry production) and to increase leaf production on desired shrubs (Anderson 2009). Additional research is needed to understand cohort dynamics in these peatlands.

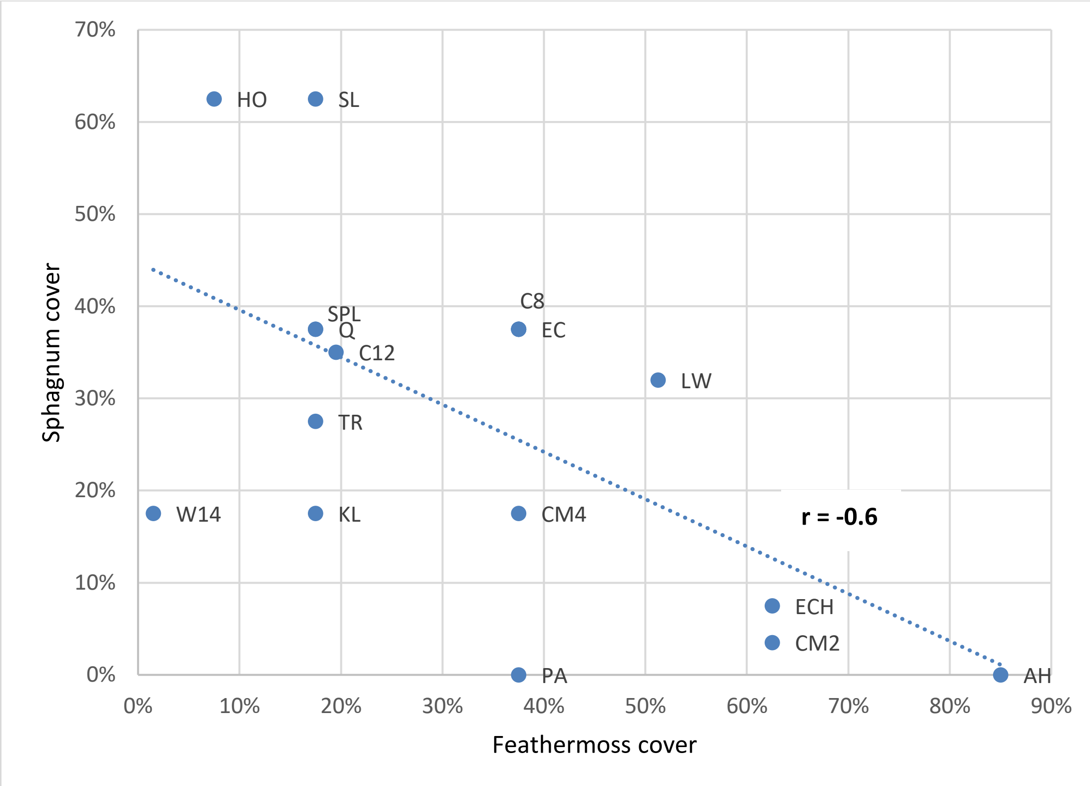


Figure 70. Correlation Between *Sphagnum* and Feathermoss Cover in Peatland Centers.

5.4 Effectiveness of Rapid Assessment Methods

5.4.1 Ecological Integrity Assessment & Floristic Quality Assessment

The EIA and FQA rapid assessment tools are both intended to estimate the ecological integrity of an ecosystem occurrence. However, there were conflicting results between the two methods, with EIA generally performing better.

Because the EIA includes multiple metrics of landscape context and on-site condition, only the latter were assessed for correlation in our data (to avoid auto-correlation with land use data). Nearly all statistically significant relationships between measured variables and EIA were either autocorrelated (e.g. our highest-quality reference sites were all in climatically wetter portions of the Puget Trough) or involved factors that were explicitly considered in the EIA (stormwater inflows and impervious surfaces in the surrounding buffer). One exception was watershed area, which had a weakly negative relationship with EIA score. Bogs with larger watersheds had somewhat lower EIA scores, as they are more likely to overlap with significant areas of development. Additionally, spring mean calcium and magnesium in the laggs were both significantly correlated with lower EIA scores in associated bogs. Several EIA metrics (Water Source, Land Use Index, and others) are designed in part to serve as proxy measures of nutrient input. In other words, the EIA appears to be performing as expected for detecting changes induced by these stressors.

FQA indices such as Mean C for peatland centers did not perform as expected, with indices generally increasing (suggesting higher ecological integrity) along with stressors such as impervious surface areas and stormwater inflows. This may be due to floristic changes in peatland centers resulting from increased minerotrophic conditions, with presumably conservative fen and/or marsh species establishing in the peatland centers. FQA indices calculated from lagg relevés had more logical results, with lagg Mean C significantly negatively correlated with spring pH and EC_{corr}. Some laggs are more similar to their associated peatland centers than others, in terms of both plant composition and hydrochemistry. Thus, the relationship between Mean C and pH and EC_{corr} may be influenced by the potential habitat bias discussed above. In other words, laggs with more characteristic "bog" plant species may get a Mean C boost only because the c-values for those species are potentially inflated by their habitat restriction and not by any sensitivity to disturbance. Also notable is that reference sites in this study tended to have narrower laggs than peatlands in developed settings. The relatively wide mixing zones in the developed peatlands is likely a result of greater minerotrophic input on the peatland margins. This relates to FQA in that the steeper gradient from lagg to bog in the reference sites may result in a larger proportion of bog-associated species in the lagg relevés. It is important to note that FQA does not factor in nonvascular species composition, as there are no coefficients of conservatism assigned to bryophytes or lichens in Washington State. It is possible that nonvascular composition tracks stressors with greater fidelity than vascular species.

Coefficients of conservatism values for the Washington flora were originally assigned by aggregating values chosen by botanical experts around the state (Rocchio and Crawford, 2013). Because peatland center vegetation in our study sites are made up of relatively few vascular plant species, it is possible that incorrectly assigned c-values for just a few species may have a large impact on the resulting averages. C-values for some peatland obligates may be inflated due to misapplication of the FQA rating criteria, with high values potentially assigned simply due to their association with relatively rare habitats, rather than a consideration of their ability to persist in degraded occurrences of such habitats. However, as noted previously, it is also possible that these non-intuitive results may be indicating floristic changes in peatland centers resulting from increased minerotrophic conditions, with presumably conservative fen and/or marsh species establishing in the peatland centers. If reference standard Mean C ranges were established for different ecosystem types (e.g., fens, bogs, marshes, etc.), this positive relationship might be more informative (i.e., demonstrating a move to different ecosystem type).

In summary, the EIA appears to be a more effective and reliable rapid assessment tool for assessing ecological integrity of peatlands as a whole, but FQA may be effective for assessing changes in the lagg.

5.4.2 Rapid Water Table Measurements

Stake measurements—especially 'maximum' water level recorded on the stakes—proved to be reliable, rapid proxies for mean water level, but only in laggs. This was the case even though laggs were more likely to be flooded (above-ground water is likely to have more dissolved oxygen and thus not exhibit reducing conditions (Belyea, 1999)). Booth et al. (2005) also found a strong correspondence between maximum PVC-derived water level (high point of discoloration) and the mean annual water table, hypothesizing that the microbes important in mediating redox conditions may be more frequent in that stratum.

The actual differences between PVC and logger mean measurement errors were not statistically significant (according to t-tests), but the laggs experienced greater overall water level fluctuations.

In the peatland centers, where there was less variation between minimum and maximum water levels, it may have been more difficult to discern where color changes began and ended. Reduced water level variance also made the margin of error in the stake measurements more important (measurement error of +/- 10 cm obfuscates trends much more when water levels vary by 40 cm than if they vary by 65 cm).

Minimum stake measurements (i.e., minimum water level) were not useful, likely due to the difficulty in delineating the exact point of initial discoloration on the stake (Booth et al. 2005).

It is possible that the effect of pH on redox potential (Ross, 1995; Charman, 2002) could influence the reliability of stake surrogates. However, similar to this project's results, Booth et al. (2005) found no significant correlation between pH (and other chemical measures) and the amount of error in the PVC measures. Belyea (1999) thought the consistent underestimation found in PVC proxy methods were due to a time lagg or imperfect correspondence with water level. It is notable that the stakes left in place for a full year did have the highest correlations among our sample.

Measurements made in the lab did not provide significantly different results, even though they benefited from overhead lighting, clean stakes, and side-by-side comparisons with other stakes. It may have been easier to catch erroneous measurements made in the field, thanks to the additional context. For example, field staff may have looked more closely at a maximum water level measurement of 20 cm that was made while standing in 60 cm of water. While the measurement errors from light- and dark-colored PVC tape were not statistically different, light tape is still recommended for ease of reading.

A few confounding variables may have influenced this project's results. Maximum water level was difficult to capture with these stakes, particularly in flooded laggs where water levels sometimes fluctuated by greater than 1.5 m in the period of time the stake was in the ground. Even when a stake was high enough to capture above-ground water level, sun bleaching and algal accumulation complicated interpretation. For 28 stakes, maximum water levels recorded by the loggers exceeded the stickup of the stake, including 6 stakes from 5 different peatland centers. These stakes were exceeded by 1-43 cm (mean = 12 cm). For stakes that went entirely underwater, we may have occasionally measured the "maximum water level" (first visible color change) at the level that actually represented the *minimum* water level.

At other sites, too *much* stickup was left. For 12 stakes, the water levels dropped below the minimum water level that could be captured by the stakes. Longer and/or paired stakes (one deeper, one with greater stickup) may be advisable at locations where the general degree of water level fluctuation is not known. However, stakes made of a more durable material than bamboo may be required for deeper insertion. Another option would be to leave stakes in for a shorter time period, in which the water level is unlikely to vary to such a degree, but this solution has its own drawbacks (measurement error is more likely to obfuscate trends)

One other potentially confounding variable is that, on some occasions, a new stake may have been placed in the same hole as a previously collected stake. This could potentially allow greater penetration of oxygen and confuse the true water level. A follow-up study would also benefit from reducing the number of variables in play (e.g. using the same color tape in the same bog and same bog position, but left in for different time periods).

In summary, PVC-taped stakes appear to be a cost effective method for measuring mean water levels in laggs, but not peatland centers. The stakes were not effective for detecting minimum or maximum water levels, regardless of wetland position.

5.5 Pollen Records of Select Puget Lowland Peatlands

The pollen records recovered from all three sites show that the overall vegetation composition surrounding the peatlands remained the same throughout the record, with changes observed only in the abundance of different species. All interpretations are presented by site and discussed by pollen zone based on the constrained cluster analysis (based on terrestrial pollen percentages).

5.5.1 Evans Creek

The Evans Creek *Sphagnum*-dominated peatland has a long history of human disturbance. Most of the living *Sphagnum* was removed (harvested for sale) in the 1930s (Rigg, 1958). A walkway to a gazebo at the center of the peatland was constructed on fill material after 1968. The gazebo was removed prior to 2002, but the walkway still exists at the site today. The site is currently surrounded by a suburban neighborhood that was built in the 1980s.

The pollen and charcoal recovered from the Evans Creek peat core represents a record of the last 42 years (2019 to 1977 AD). The three peaks in CHAR occurring at 52 cm (1979 AD), 32 cm (1994 AD), and 18 cm (2005 AD) are not representative of local fire events. The charcoal that accumulated throughout this record are likely the result of brush clearing burn piles from the surrounding areas, or were transported by wind from areas further away. The pollen taxa present remained stable throughout the entirety of the record, with only minor changes to the abundances of taxa present. The slight changes observed in the pollen record (the different pollen zones) are indicative of small changes to the areas adjacent to the peatland due to human influence on the landscape (i.e. changes to the landscaping surrounding the homes of the neighborhood) and changes to the forested areas surrounding the site. The base of the core, Zone EC-I (50-53 cm; 1980-1977 AD), coincides with clearing of adjacent lands in preparation for home construction. Cupressaceae (likely *Thuja plicata*), *Pinus*, *Tsuga heterophylla*, and Poaceae pollen all decrease in abundance, while *Alnus rubra* (a disturbance adapted taxa) increases in abundance in the area surrounding the site during this time. Construction of the homes surrounding the site began at the base of Zone EC-II (23-50 cm; 2001-1980 AD) in 1980 (50 cm), with the majority completed by 1991 (37 cm). The decrease in *Alnus rubra* pollen in the bottom half of this zone (37 cm) coincides with the end of home construction in the area. The increase in Poaceae and *Pteridium* along with a slight increase in pollen from members of the Asteraceae family (Liguliflorae-type and Tubuliflorae-type) in the upper half of this zone suggests a transition to a more open, less treed landscape, which likely occurred due to homeowners' preferences for lawns and open spaces.

The transition into Zone EC-III (5-23 cm; 2015-2001 AD) is denoted by an increase in Potamogetonaceae, *Typha*, and *Botryococcus* (algae), suggesting that the water level of the peatland began to increase. Within the zone, *Isoetes* (quillwort) abundance increases, adding further support for the presence of standing water for at least part of the year within the peatland (standing water is known to occur in the region where past peat mining has occurred). Poaceae, Cyperaceae, *Chenopodium/Amaranthus*-type, and taxa of the Asteraceae family increase in abundance, while the abundance of tree species such as *Alnus rubra* decrease, indicating that open spaces continued to be maintained around the peatland. The uppermost zone (representing the modern pollen assemblage), Zone EC-IV (0-5 cm; 2019-2015 AD), has an increase in pollen abundance of several tree species (*Tsuga heterophylla*, *Abies*, and *Pseudotsuga*), and a significant decrease in Cupressaceae. The difference in tree pollen is likely the result of changes in the surrounding upland forests, as well as planted trees (in homeowners' yards) reaching reproductive maturity.

5.5.2 Kings Lake

The lands adjacent to Kings Lake bog have experienced less human disturbance than both the Evans Creek and Shadow Lake sites. The forests were logged and burned in the 1930s (Fitzgerald, 1966; Lebednik and del Moral, 1976), then logged again in the late 1970s/early 1980s (Kunze, 1986). In the mid-1980s, the site and some of the adjacent uplands were purchased by the Nature Conservancy with the goal of preserving the peatland and the surrounding landscape. In 1987, ownership was transferred to the Washington Department of Natural Resources and incorporated into the Natural Area Preserve system.

The pollen and charcoal record from the peat core extracted at Kings Lake represents the last 61 years (2019 to 1959 AD). The major drivers of changes in taxa abundance surrounding Kings Lake were likely human disturbance (logging), fire (natural or post-logging burning), and natural succession. The vegetation surrounding the peatland in the lowest pollen zone, Zone KL-I (45-63 cm; 1975-1959 AD), was initially dominated by *Tsuga heterophylla*, with minor amounts of Cupressaceae. The only peaks in CHAR in the Kings Lake core occur near the middle of this section (50-55 cm; 1970-1966 AD). These higher CHAR values likely indicate one major fire event, or a series of fire events occurring in a short amount of time, such as post-logging burning of slash piles (logging debris). During and after these peaks in CHAR, taxa abundances within and surrounding the peatland shift. *Tsuga heterophylla* (a non-disturbance-adapted species) pollen decreases significantly (dropping from 27% to 7%), while *Alnus rubra* increases from 20% to 51%. Ericaceae and *Pteridium* abundance increases slightly during this time, while *Pseudotsuga* and Cupressaceae decrease in abundance. This shift in vegetation suggests both logging and a post-logging fire had an impact on the vegetation surrounding the Kings Lake peatland, allowing disturbance adapted taxa to become more dominant (abundant) near the top of this zone.

The remaining pollen zones show a forest/woodland environment undergoing succession during a period of recovery following a disturbance event (likely from logging and post logging burning). Very little to no charcoal accumulated within the top three pollen zones of the core, suggesting that fire was not a major component of the landscape during this time. In Zone KL-II (23-45 cm; 1997-1975 AD), *Alnus rubra* remains a major component of the surrounding vegetation with an understory consisting of Poaceae, Cyperaceae, members of the Asteraceae family (*Ambrosia*-type, *Artemisia*, Liguliflorae-type, and Tubuliflorae-type), *Chenopodium/Amaranthus*-type, Saxifragaceae, and *Pteridium.* The increase in *Alnus rubra* and many herbaceous taxa indicates a period of recovery on the landscape, with many secondary colonizers dominating the landscape. The transition to Zone KL-III (10-23 cm; 2009-1997 AD), is marked by a shift to higher abundances of *Tsuga heterophylla*, *Pseudotsuga*, and Ericaceae, while the abundance of *Alnus rubra* decreases. Herbaceous taxa also decrease in abundance, indicating that the landscape transitioned to a more developed/closed forest landscape. The uppermost zone in the core KL-IV (0-10 cm; 2019-2009 AD) shows a significant initial increase in Ericaceae pollen (with a decrease in all other taxa). After this peak in Ericaceae pollen, all taxa present in this zone increase to modern levels.

5.5.3 Shadow Lake

The peat core recovered from the Shadow Lake peatland is the longest record analyzed from the three sites, representing the last 189 years (2019-1833). A total of three pollen zones were identified in this core. Each change in pollen abundance appears to have been driven by the occurrence of fire on the landscape. Initially the forest within pollen Zone SL-I (66-96 cm; 1924-1833 AD) was dominated by *Tsuga heterophylla* and Cupressaceae, with a low abundance of *Alnus rubra*. CHAR remains relatively low within this section, with a slight increase occurring in the upper third, starting at 83 cm (1860 AD), but only in the smaller size fraction (indicating extra local or regional fires). The timing of this slight increase in CHAR occurs around the same time as the earliest settlements around Lake Washington (Davis, 1973). As the smaller fraction of CHAR increases, the abundance of *Alnus rubra* increases and both *Tsuga heterophylla* and Cupressaceae decrease. The increase in *Alnus rubra* may have been driven by clearing of the surrounding land via logging and/or burning for settlements (building material and preparing the land for farming). The newly cleared areas that were not used for farming were likely recolonized by disturbance adapted taxa.

The middle pollen Zone SL-II (30-66 cm; 1977-1924 AD) shows a significant transition occurring on the landscape. This section has a large increase in CHAR (in both size fractions) at its base, suggesting a single major fire event, or a series of fire events occurring in a short amount of time. Based on historical logging records from the area, the peak CHAR occurring at 63 cm may be the result of post-logging burning in the 1930s. As charcoal increases, so does the pollen from *Alnus rubra*, which is the dominant species on the landscape in this period. Poaceae and Cyperaceae decrease in this section while other herbaceous taxa remain present in low abundance (*Chenopodium/Amaranthus*-type and Asteraceae like *Ambrosia*-type, *Artemisia*, Liguliflorae-type, and Tubuliflorae-type). *Tsuga heterophylla* increases in the upper half of this section as this species was recolonizing. The decrease in *Alnus rubra*, low CHAR, and subsequent increase in other arboreal taxa (mainly *Tsuga heterophylla* and *Pseudotsuga*) distinguish the transition to the top pollen Zone SL-III (0-30 cm; 2019-1977). The vegetation in this zone is transitioning to a mature forest after a disturbance event (fire) and reflects the landscape around the site today.

5.5.4 Summary

The pollen records recovered from Evans Creek, Kings Lake, and Shadow Lake peatlands all demonstrate that the composition of the vegetation adjacent to the peatlands remained stable throughout the entirety of the record, with only individual taxa abundances changing. These changes appear to have been driven by anthropogenic disturbance, particularly land use changes (logging, burning, and land clearing for home building). This baseline information provides some confidence that the vegetation patterns observed in the project are not explicitly from past land use, although historical conditions are always a factor in determining current ecological patterns of a given site.

One of the initial goals of this study was to use pollen and charcoal records to see how the vegetation has changed since Euroamerican contact. The high sedimentation rates observed across all three sites (Evans Creek 1.42 cm/yr, Kings Lake 1.14 cm/yr, and Shadow Lake 0.24 cm/yr to 1.67 cm/yr) was a surprise and all three peat cores were younger than we expected to observe. Due to these high sedimentation rates, we were able to see a detailed record of relatively modern changes, but no accounting of longer term dynamics.

The core taken from Shadow Lake Bog is the only site that covers the time period of Euroamerican settlement in the area. From this single record, we do see changes in the pollen record post European settlement, with a slight increase in CHAR (smaller size fraction, indicating a regional increase in charcoal) and disturbance-adapted taxa (i.e. *Alnus rubra* and *Pteridium*) and a decrease in arboreal taxa such as Cupressaceae (likely *Thuja plicata*) and *Tsuga heterophylla*. For a more comprehensive understanding of how the landscape changed after Euroamerican settlement, longer records are needed at all three sites. Longer records would document the landscape pre-and post-Euroamerican arrival, helping distinguish between local (occurring at a particular site) and regional pollen changes (occurring across all three sites). Additionally, accurate dating of the top of these cores, such as with radioisotopes ^{210}Pb and ^{137}Cs, would refine the estimated timing of changes in the pollen record.

5.6 Climate Change

Understanding how climate change may be affecting Puget Lowland *Sphagnum*-dominated peatlands is critical for understanding their long-term viability, as well as for attributing contemporary changes to the correct causal agent(s)—climate change, land use impacts, fire, natural succession, or a combination of these variables can all result in similar changes in a peatland. In this section, potential climate-induced changes are described. However, in order to prescribe appropriate conservation and management actions, a full understanding of how peatlands react to these various drivers of change is needed. Rarely will ecological change be a result of just one of these factors; more commonly, multiple disturbance processes are in play, especially with climate change now a ubiquitous factor.

5.6.1 Expected Changes to Primary Ecological Processes

Average temperatures in the Pacific Northwest increased 1.3°F between 1895 and 2011, with warming occurring in every season except spring (Mote 2003, Dalton et al. 2013, Kunkel et al. 2013). The frequency of warmer extremes, including nighttime heat events, has increased (Bumbaco et al. 2013). However, precipitation patterns have not significantly changed over the same period (Dalton et al. 2013). Change in annual precipitation is projected to be small (Mote et al. 2013), but seasonal changes are predicted, including drier summers. Models estimate that summer precipitation could decrease 6 to 8% by the 2050s—some models predict up to a 30% decrease (Mote et al. 2013). Conversely, most models predict precipitation increases of 2 to 7% in winter, spring, and fall, with an increase in the proportion falling as rain instead of snow (Mote et al. 2013).

These existing and projected changes are concerning for the long-term viability of regional *Sphagnum*-dominated peatlands. Low elevation *Sphagnum*-dominated peatlands reach their southern extent in western North American in Washington State and coastal Oregon (Gignac et al. 2000; Halsey et al. 2000, Gajewski et al. 2001). The subset of these peatlands that are predominantly supported by precipitation (e.g., those included in this study) appear to reach their southern extent at the same point as the extent of continental glaciation (and associated periglacial landscapes) in western Washington. This area extends as far south as Tenino in the South Sound region. Coastal, *Sphagnum*-dominated peatlands in southwest Washington and Oregon have vegetation indicators suggesting some groundwater input, but their hydrology and water chemistry have not been investigated (Kunze 1994; Christy 2001). Montane *Sphagnum*-dominated peatlands, all of which are fens, reach further south along coastal and interior mountain ranges, to at least central California.

Low summer water tables are already a seasonal condition in *Sphagnum*-dominated peatlands in western Washington due to the strong seasonal pattern of precipitation (Rocchio et al. 2021). However, the duration of low water tables may be extended with predicted summer drought and heat going forward. Although precipitation is predicted to increase during the wet season, this extra precipitation is unlikely to compensate for drier summers due to the fact that Puget Lowland *Sphagnum*-dominated peatlands already reach saturation during winter months under current climatic conditions. Any additional moisture will simply drain off the peatland into the lagg, either flowing downstream or remaining in the lagg, potentially resulting in expansion of the lagg zone.

Because Puget Lowland *Sphagnum*-dominated peatlands already occur at their southern climatic extent, they logically seem to be highly susceptible to ongoing and future climate change impacts. Based on our current understanding of these regional peatlands, expected climate-induced changes include tree encroachment, increased shrub growth, a shift from *Sphagnum* to feathermoss (primarily *Pleurozium*), and solarization or scorching of hummocks. Longer duration low summer water tables would not only provide trees and shrubs a competitive advantage (Weltzin et al. 2000; Moore 2002), but could also result in increased peat decomposition and subsequent loss of accumulated peat (Moore 2002). Many of these conditions have already been observed in local *Sphagnum*-dominated peatlands. Although those changes can't be confidently attributed to climate impacts, they are consistent with expected responses to changing climatic conditions. Additionally, climate-induced impacts may also complicate interpretation and attribution of ecological changes resulting from other stressors.

5.6.2 Tree Encroachment

Tree encroachment has been observed in many regional *Sphagnum*-dominated peatlands (Rigg 1958; Rocchio et al. 2021) as well as in many other regions of the world (Gunnarsson and Rydin 1998, Gunnarsson et al. 2002, Lachance et al. 2005). Climate-induced warming and drying have been associated with widespread tree encroachment in bogs during the Holocene (Edvardsson et al. 2015). Heijmans et al. (2013) found that modeled climate-induced drought in European, temperate bogs only resulted in transient tree encroachment, but temperature increases > 1^{o} C resulted in a persistent shift to tree-dominated peatlands. Agren et al. (1983) were unable to confidently attribute tree encroachment in a *Sphagnum*-dominated fen in northern Sweden to climate—other factors such as fire or natural succession may have been causal factors instead. Many non-climatic stressors may result in tree encroachment, including draining and other direct disturbances, increased nutrients, etc. (Hebda and Biggs 1981; Gunnarsson et al. 2000, Golinski 2004).

Causal factors of tree encroachment in Puget Lowland *Sphagnum*-dominated peatlands are uncertain, but may be related to climate-induced changes. In summary, the following are possible explanations for observed tree encroachment in local *Sphagnum*-dominated peatlands:

- <u>Pre-existing climatic tension</u> - Because Puget Lowland *Sphagnum*-dominated peatlands already occur at their southern climatic extent, the tension between open and woody cover may be part of the natural dynamics of local *Sphagnum*-dominated peatlands. In other words, tree encroachment may be inherent in this transition zone and there has always been a tension between open and woody vegetation in these ecosystems. As such, slight changes in climate or local environmental condition could results in conspicuous shift in dominance of woody vegetation. This may explain why tribes are known to have used fire to periodically burn *Sphagnum*-dominated peatlands on the western Olympic peninsula (Anderson 2009). A bioclimatic distribution model of *Sphagnum*-dominated peatlands shows Puget Lowland peatlands at the southern-most boundary in western North America (Gignac et al. 2001). Extant occurrences of *Sphagnum*-dominated peatlands extend a bit further south than the model predicts, suggesting either (1) the model is incorrect or (2) the peatlands south of the predicted occurrences are in disequilibrium. "Disequilibrium" refers to the fact that their development occurred in a former, more favorable climate, whereas current climatic conditions are outside those conditions. If the latter is correct, then this model demonstrates that Puget Lowland *Sphagnum*-dominated peatlands are indeed located within a climatic tension zone, between conditions conducive for development of *Sphagnum*-dominated peatland and those that are not.

- <u>Natural succession</u> – Conifers are a characteristic component of *Sphagnum*-dominated peatlands along the western coast of North America (Osvald 1933; Sjörs, 1983, Bisbing et al. 2015). Rigg (1917) noted that "in general, the forest is advancing upon the bogs of the Puget Sound region", and described trees growing in *Sphagnum* in nearly all the local bogs, including abundant tree seedlings. Rigg's observation could indicate a natural tendency for local peatlands to become treed, which may be related to the first bullet point, concerning a climatic tension zone between forested and open peatlands. The regular summer dry season is unusual for maritime bog formation. Peat profiles from numerous locations across western Washington also demonstrate that successional dynamics in local peatlands are not linear, with many sites experiencing periods dominated by woody vegetation followed by periods of *Sphagnum*-dominated vegetation. It is possible that disturbances such as fire, naturally induced flooding (beaver dams, landslides, etc.), or cycles of tree establishment followed by woodland decay explain the abundance of woody vegetation in local *Sphagnum*-dominated peatlands.

- <u>Climate change</u> – Warmer winter temperatures have been found to result in increased survival of western hemlock seedlings at Kings Lake Bog (Fitzgerald 1966). Increased duration of low water tables resulting from warmer and driers summers may provide a competitive advantage to conifer seedlings. It is also possible that warmer winter temperatures, rather than lower water tables, are a causal factor of observed tree encroachment (Heijmans et al. 2013).

- <u>Fire</u> – Past fires may have created conditions that allowed woody vegetation to gain an initial competitive advantage and what we see today is the successional outcome of those conditions. Fire results in a flux of nutrients that may give trees a competitive advantage. Rigg (1958) described numerous *Sphagnum*-dominated peatlands as having been burned, attributing much of the burning to efforts at clearing sites for eventual cultivation. As previously noted, tribes used fire to periodically burn peatlands. If this was a common practice in the Puget Lowlands, then its possible that current tree encroachment is a result of a *lack* of fire. This pattern is similar to that described for regional upland prairies where tribal use of fire is known to have been a key reason that prairies remained on the landscape when, following the hypsithermal, a cooler and wetter climate favored tree encroachment into the prairies (Norton 1979, Whitlock 1992, Agee 1996, Tveten and Fonda, 1999).

In summary, trees are abundant in most Puget Lowland *Sphagnum*-dominated peatlands and, in some cases, encroachment has converted previous areas of open *Sphagnum* vegetation to closed canopy swamps or peatlands. An extreme example occurs at Shadow Lake, where tree encroachment has resulted in canopy closure and a complete conversion of a once open *Sphagnum*-dominated peatland into a forested stand with an understory of nearly continuous feathermosses (Figure 71). There is an urgent need to understand the mechanisms driving tree establishment and survival. Understand these mechanisms may allow us to better predict the long-term carbon dynamics and viability of regional peatlands and determine whether management intervention (such as tree removal) could be effective in keeping sites open enough for continued *Sphagnum* growth and peat accumulation. The full implications of such aggressive management must be known before implementation.

Figure 71. Outcome of canopy closure in *Sphagnum*-dominated peatland.

5.6.3 Increased Shrub Density

Similar to tree encroachment, the density of shrubs (specifically, bog laurel and especially Labrador tea) observed in some sites may be related to climate change. However, other stressors such as hydrological and chemical alterations may also be causal factors. Rigg (1958) described Labrador tea as one of the last bog species to persist through disturbance, noting that the shrub becomes very dense and increases in height (>1 m) with human disturbances. Shrub density in some Puget Lowland *Sphagnum*-dominated peatlands can be very dense, to the extent that *Sphagnum* cover is dramatically reduced, which could in turn dramatically reduce the rate of peat accumulation. Many of these Puget Lowland peatlands have conspicuous stressors, whether on-site or in adjacent areas (Rigg 1958).

Potential causal factors for increasing shrub density are similar to those described for tree encroachment, thus the following questions need to be addressed to better understand shrub density dynamics:

- Are dense stands of shrubs part of the natural, successional dynamics of Puget Lowland *Sphagnum*-dominated peatlands?

- Is climate change providing a competitive advantage to these shrubs, as predicted for trees?

- Does shrub density respond favorably to fire? Or, conversely, increase when fire is absent?

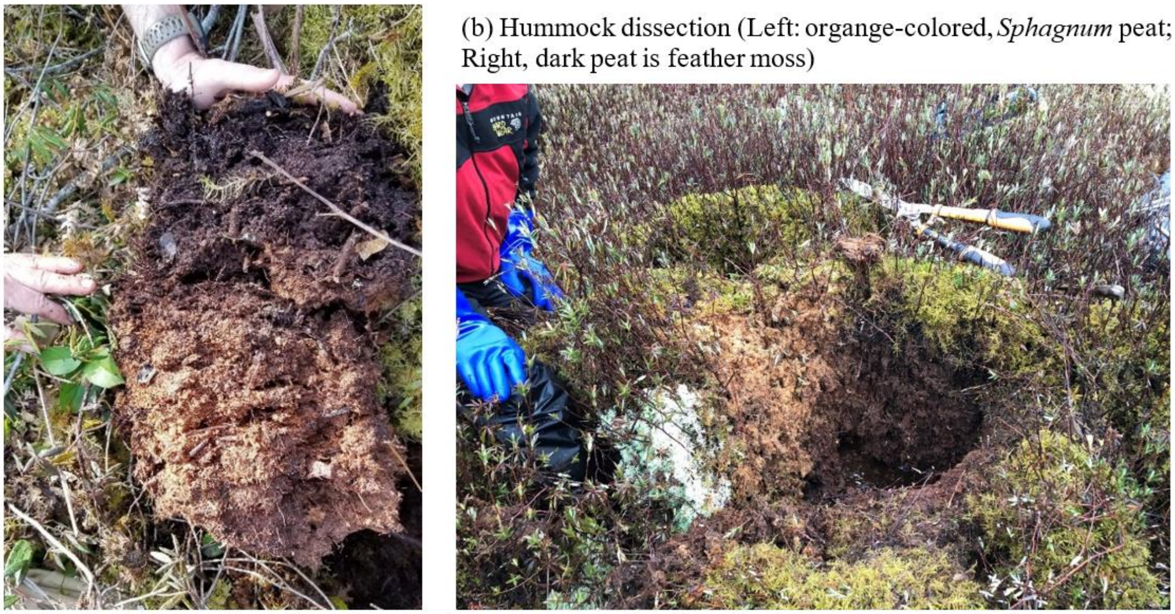
5.6.4 Shifts in Dominant Mosses

Oke and Hager (2017) modeled the distribution of *Sphagnum*-dominated peatlands and found that suitability for *Sphagnum*-dominated peatlands under future climates is highest in coastal areas, including, in western North America, Washington, Oregon, and British Columbia. However, as noted previously, while precipitation is predicted to increase during winter, spring, and fall in future climates, that extra precipitation may not compensate for increased soil moisture deficits that will occur during the warmer and drier summers, since local peatlands already reach saturation during winter months and would not have the capacity to "store" excess water.

Observations from Puget Lowland *Sphagnum*-dominated peatlands include some patterns that are consistent with what might be expected from warmer, drier summers. However, as with woody encroachment, other stressors and/or natural dynamics and succession may also be causal factors.

- Shift in dominant mosses – *Sphagnum* spp. are the dominant ground cover in ombrotrophic bogs and acidic fens in the Puget Lowlands. Feather mosses, especially *Pleurozium schreberi*, dominates the top of tall, dry hummocks, or in shady portions of wooded peatlands. In other words, the presence of feathermosses isn't necessarily an indicator of climate change effects, but the shift in proportional abundance is of concern, especially in places where other causal factors don't seem to be in play. However, one effect from a longer dry season could be a reduced growing season for *Sphagnum*, making it less competitive with other mosses, specifically feathermosses. Tree encroachment can also lead to such changes, as feathermosses have a competitive advantage under low light conditions. In a few of the study sites (Kings Lake and Shadow Lake), abrupt shifts in the upper peat profile from *Sphagnum* to feathermoss were observed, both in terms of vertical accretion and within a given hummock (Figure 72). The relative proportion of these shifts needs to be determined across a larger sample of sites.

- Hummock scorching – Another observation in Puget Lowland *Sphagnum*-dominated peatlands is the degradation of numerous *Sphagnum* hummocks in many sites. A researcher in Italy found that south-facing *Sphagnum*-dominated hummocks were scorched during an extreme heat wave and had not recovered within four years (Bragazza 2008). Anecdotally, degradation of south-facing hummocks in Puget Lowland sites is occurring (Figure 73). It is not clear if extreme heat events and increased solarization are scorching these hummocks. Another potential factor may be trampling (e.g., from wildlife), which could expose hummock interiors and make them more susceptible to increases in heat and solarization, thus leading to desiccation and ultimately degradation of the hummock. This process might occur regardless of climate change effects.



(b) Hummock dissection (Left: organge-colored, *Sphagnum* peat; Right, dark peat is feather moss)

(a) Vertical peat section. Top of section is current ground surface. Dark top peat layer is feathermoss. Orange-colored peat on bottom is *Sphagnum*.

Figure 72. Dominant moss competition.

Figure 73. Hummock-scorching in Puget Lowland Sphagnum-dominated peatlands

6.0 IMPLICATIONS FOR PEATLAND CONSERVATION, MANAGEMENT, & RESTORATION

Historical loss of *Sphagnum*-dominated peatlands in the Puget Lowlands has likely been significant. Bell (2002) documented a 69% decline in such peatlands in King County, with much of that loss occurring prior to the passage and implementation of the State Environmental Policy Act, Forest Practice Rules, Growth Management Act, and other policies that aim to protect further loss of these sensitive and unique wetland types. These legislative actions have slowed the direct loss of many sites, but *Sphagnum*-dominated peatlands continue to experience degradation from adjacent land uses. Similar to the findings of Azous and Horner (1997) for other types of Puget Lowland palustrine wetlands, this study has demonstrated that adjacent land use, as primarily measured by impervious surface areas, inflicts hydrological, chemical, and biological changes on *Sphagnum*-dominated peatlands.

In this section, we provide recommendations for improving conservation, management, and regulatory actions and watershed planning to help regulators, managers, planners, and citizens to better protect peatlands in the lowlands of western Washington. Our recommendations build on (or in some cases reiterate) guidance provided by other resources, especially recommendations offered by Kulzer et al. (2001) and Sheldon et al. (2005).

An initial recommendation is to develop a comprehensive map of *Sphagnum*-dominated peatlands across western Washington. Such a product would be highly beneficial for implementing many of the recommendations below.

6.1 PRESERVATION OF PUGET LOWLAND PEATLANDS

Restoring severely impacted *Sphagnum*-dominated peatlands has proven to be very difficult given the long-time frame over which these peatlands develop. As such, preservation of *Sphagnum*-dominated peatlands should be a primary mechanism of ensuring policies such as "no net loss" or are successfully implemented. Avoidance measures built into mitigation sequencing is an important step toward such goals, but avoidance is not the same as dedicated preservation of *Sphagnum*-dominated peatlands, which is best completed through acquisitions by organizations that have the ability to manage conservation sites over the long term.

Sheldon et al. (2005) describe numerous tools to achieve preservation. Our recommendations emphasize the use of Washington Department of Natural Resources, Natural Heritage ecosystem conservation priorities to guide preservation activities. The Natural Heritage Program has outlined a prioritized list of conservation targets, including *Sphagnum*-dominated peatlands, for the State of Washington (DNR 2022). The 2022 State of Washington Natural Heritage Plan provides two lists of priorities: (1) State Conservation Status (overall conservation priority) and (2) Natural Area Representation Priorities (priority for representation in the statewide system of natural areas, which is a collection of sites focused solely on the conservation of biodiversity features they contain. Such sites include state Natural Area Preserves, federal Research Natural Areas, and some land trust preserves. The statewide system of natural areas is critical to the long-term persistence of Washington's natural heritage; however, the overall conservation need for protecting Washington's biodiversity is much greater than can be provided by designated natural areas. Significant conservation is achieved through both voluntary protection and the implementation of numerous laws, policies, and regulations. The State Conservation Status of each ecosystem type helps public agencies, non-governmental organizations, and private individuals make informed land use decisions. The 2022 State of Washington Natural Heritage Plan identifies the USNVC, North Pacific Acidic Open Bog & Fen Group, which includes all the *Sphagnum*-dominated peatlands occurring in the Puget Lowlands to be a State Threatened ecosystem type. Additionally, the North Pacific Acidic Open Bog & Fen Group is considered a Habitat of Greatest Conservation Need in the Washington State Wildlife Action Plan due to the dependency on this ecosystem type of some Species of Greatest Conservation Need (WDFW 2015). The more fine-scale plant communities (i.e., USNVC Associations) that are included within the North Pacific Acidic Open Bog & Fen Group are considered to be State Endangered, Threatened, or Sensitive. Given the significant conservation values of *Sphagnum*-dominated peatlands, the following preservation actions are recommended:

- Federal, state, and local agencies and non-governmental organizations (such as land trusts) should seek opportunities for proactive preservation of occurrences of the North Pacific Acidic Open Bog & Fen Group.

- Federal, state, and local agencies and non-governmental organizations should target USNVC Associations associated with the North Pacific Acidic Open Bog & Fen Group that have a Natural Area Representation Priority as candidates for inclusion in the Statewide System of Natural Areas. Washington Department of Natural Resources, Natural Heritage Program staff can assist with this process.

- Increased incentives for preservation of high-quality examples of the North Pacific Acidic Open Bog & Fen Group should be considered within a regulatory wetland mitigation context.

    - Current mitigation guidance suggests, “If avoidance is not practicable, the agencies consider preservation of a bog or calcareous fen to be the only viable option to compensate for impacts. Ratios would start at 24:1. This means that 24 acres of bog or calcareous fen would need to be preserved to compensate for one acre of impact to these wetlands.”

    - In addition to this scenario, we recommend consideration of preservation of *Sphagnum*-dominated peatlands as mitigation for impacts to other, more common wetlands. Of course, no-net loss of certain wetland types or functions must also be considered.

    - As Sheldon et al. (2005) note, preservation of rare or high-quality wetlands protects them from unmitigated impacts that can degrade them over time. In addition, preservation avoids the uncertainty of success with compensatory creation, enhancement, and restoration projects.

- Federal, state, local, and non-governmental planners are encouraged to use the list of priorities associated with the North Pacific Acidic Open Bog & Fen Group in Appendices C and E of the 2022 State of Washington Natural Heritage Plan (DNR 2022) to ensure protection of *Sphagnum*-dominated peatlands are considered in any land use decisions.

- One of the stated goals of the statewide system of natural areas is to provide places for biodiversity and ecological research and education. Numerous sites included within the statewide system of natural areas protect *Sphagnum*-dominated peatlands. Researchers and educators are encouraged to contact Washington Department of Natural Resources, Natural Areas Program to apply for research permits or to arrange educational opportunities.

- Local municipalities should consider incorporating protection of *Sphagnum*-dominated peatlands into their Critical Areas Ordinances and/or other codes (such as identified in the Washington Wetland Rating System)

- Preservation should always include the lagg. Although the lagg is described as providing buffering functions to the peatland center, the lagg is itself a critical part of the peatland ecosystem.

- Washington Department of Ecology (2021) recommends that any preservation strategy should include measures to minimize stormwater inputs, including providing adequate upland buffers.

6.2 Management & Restoration Recommendations

6.2.1 Runoff and Stormwater Management

The types and proportion of water sources supporting a wetland have significant effects on its ecology. The majority of the *Sphagnum*-dominated peatlands included in this study appear to be primarily (if not solely) supported by precipitation inputs. For ombrotrophic, or even nearly ombrotrophic peatlands, the addition of surface and/or groundwater inputs can result in dramatic changes to the site's biodiversity and ecological functions. These peatlands should be managed with the goal of preventing any anthropogenically-derived surface or groundwater inputs from entering the peatland basin. As such, we recommend the following actions to protect *Sphagnum*-dominated peatlands:

- Determine the relative proportion of water source(s) using the methods described in this study for determining ombrotrophic conditions.

- *Sphagnum*-dominated peatlands should not be used to treat runoff and/or stormwater drainage.

- Divert stormwater or road runoff downstream of the peatland or into a separate basin. *Any* stormwater inputs can change the site's ecology.

- Divert excess flows resulting from logging impacts in a peatland's watershed away from, or downstream of, the peatland (Kulzer et al. 2001).

- Restrict any land disturbing activities from occurring in the peatland's watershed, including logging, during the rainy season (Kulzer et al. 2001).

- Land disturbing activities in the peatland's watershed during the dry season should be revegetated before the rainy season begins to avoid sediment transport into the peatland (Kulzer et al. 2001).

- Maintaining natural land cover within the peatland's watershed is critical for protecting the ecological integrity of the peatland (Kulzer et al. 2001).
    - Forest cover in the buffer is an important predictor of species richness changes, especially within 300 from the wetland edge (Houlahan et al. (2006).
    - Natural land cover within 100 m of the wetland edge has been found to be associated with ecological integrity of a peatland (Rooney et al. 2012).
- If discharge into a peatland is unavoidable, Kulzer et al. (2001) recommend a flow dispersal system at the edge of a 200-foot wetland buffer instead of piped discharge. However, data from the Echo Falls study site demonstrate that even such a dispersed system may still impact the peatland. The dispersal system did seem to minimize impacts from chemical alterations, but further research into the effectiveness of these dispersal systems should occur before widespread adoption.
- Road construction within the watershed of a *Sphagnum*-dominated peatland should be avoided (Kulzer et al. 2001).
- Use of calcium-containing materials (e.g., Portland cement, whitewash, cement structures, etc.) should be avoided within a *Sphagnum*-dominated peatland's watershed (Kulzer et al. 2001).
- Avoid fertilization of forests and lawns within the watershed of *Sphagnum*-dominated peatlands (Kulzer et al. 2001).

6.2.2 Buffer Recommendations

Buffers are required for many permitted and proposed activities around wetlands, including *Sphagnum*-dominated peatlands. A key question is whether current buffer widths are sufficient to moderate potential negative stressors from land use outside the buffer. Recommended buffer widths vary according to the targeted functions to be protected (Hruby 2013).

- Immediate watershed boundaries around a *Sphagnum*-dominated peatland should be delineated using lidar or other accurate topographic models.
- Ideally, the entire immediate watershed of a *Sphagnum*-dominated peatland should be protected and/or managed as the buffer.
- Our results demonstrate that impervious surfaces within at least 500 m (1640 ft) significantly impact the hydrologic and chemical conditions within *Sphagnum*-dominated peatlands of the Puget Sound Basin. Solute loads to the laggs increase with the amount of impervious area within 500 m. Minimizing development within 500 m of the wetland perimeter will help to ensure the sustainability of these ecosystems.
- Buffers should extend from the outer edge of the lagg (not the peatland center); The lagg is a natural, functional component of the peatland (Hebda et al. 2000, Howie and van Meerveld 2011) and should not be considered a "buffer" in the context used in this section.

- If the entire watershed cannot be protected, buffer widths are most effective for a wide range of ecological functions when they are > 500 ft. (~150 m; Sheldon et al. 2005).

- Buffers focused on protecting the hydrological and chemical integrity of peatlands are likely only effective when they occur within the peatland's watershed. As such, a continuous 500 ft. around a peatland may not be the most effective and instead placement of the buffer should be maximized around areas with the most potential to convey surface water into the peatland basin.

- Buffers around any contributing streams are critical and, in fact, may be more important for protecting the hydrological and chemical integrity of peatland centers than buffers around the basin, which mostly protect against sheetflow inputs.

6.2.3 Restoration Guidance

Restoration of *Sphagnum*-dominated peatlands can be a difficult task, depending on the initial conditions of the site. As such, regulatory guidance discourages impacts to these peatlands, strongly encourages avoidance during mitigation sequencing, and suggests very high mitigation ratios if impacts are unavoidable. Because restoration scenarios can be quite variable and site-specific, specific restoration guidance needs to be developed based on each site's ecological characteristics, past and current stressors, and limitations imposed by adjacent land use. No published accounts of *Sphagnum*-dominated peatland restoration from Washington State could be located. As such, regionally-specific guidance is difficult to develop. However, some general guidance includes:

- Restoration activities of *Sphagnum*-dominated peatlands should not be used in a compensatory mitigation context since most ecological outcomes would not be realized within a reasonable time-frame.

- Conduct multi-year monitoring of the target site to determine stressor sources, especially related to water sources and water chemistry.

- If stormwater water inputs have converted an ombrotrophic (or near ombrotrophic) peatland to one dominated by surface and/or groundwater inputs, restoration should focus on redirecting stormwater inputs outside of the peatland basin.

- If peat has been mined, or otherwise physically disturbed, consider the following:

    - Donor peat, donor living *Sphagnum* moss, or other species from otherwise intact *Sphagnum*-dominated peatlands are not recommended for use, unless the donor site is not viable over the long-term or extraction of the donor material can be shown to not have a negative effect on the donor site. Note that donor peat can be problematic (i.e., hydrophobic) if extracted from depth and dried before application (Rocchio 1998).

    - Peatland experts, including those with *Sphagnum*-expertise, should be engaged to select diaspore from appropriate sites and species.

6.3 Information Needs

6.3.1 Map Location of Sphagnum-dominated Peatlands

A comprehensive inventory and map of *Sphagnum*-dominated peatlands in the lowlands of western Washington is critical for proactive land use planning, conservation prioritization, and watershed assessments. Such a map is in development (Rocchio, *unpublished data*) but further work is needed to complete the effort.

6.3.2 Determine Significance of Fire as Disturbance Process

The ecological role of fire in Puget Lowland *Sphagnum*-dominated peatlands is unknown. Research from other regions has demonstrated that fire periodically occurs in bogs and plays a significant role in peat and vegetation dynamics (Crum 1992, Benscoter and Vitt 2008). Locally, fire is known to have occurred in many *Sphagnum*-dominated peatlands (Rigg 1958, Anderson 2009, Rocchio, personal observations). The following questions related to fire and Puget Lowland *Sphagnum*-dominated peatlands need to be addressed:

- What is the frequency, intensity and origin of fires in regional peatlands?
- What is the biotic and abiotic response of fire over time?
- How have historical fires shaped contemporary ecological conditions?
- Did Puget Lowland tribes utilize fire in a similar manner as coastal tribes (Anderson 2009)?
- Is fire a potentially useful management tool for mitigation of climate change impacts?

6.3.3 Understand Long-term Successional Dynamics

Many of the vegetation changes resulting from on-site or adjacent land use could also be attributed to long-term successional dynamics. It has already been established that the presence and abundance of conifer trees in local *Sphagnum*-dominated peatlands is characteristic of peatlands along the north-central Pacific coast. However, many stressors (land use, climate change, or fire) could also result in increased tree growth. Peat profiles from numerous Puget Lowland *Sphagnum*-dominated peatlands show that the successional dynamics of many sites is not linear and alternating shifts between *Sphagnum* to woody peat, *Sphagnum* to sedge peat, and other combinations is not uncommon (Rigg 1958). In order to confidently attribute certain vegetation conditions to specific stressors, a better understanding of historical, successional dynamics is needed.

During the course of this project, our project team partnered with additional researchers from University of Oregon (Dan Gavin), the U.S. Forest Service Northern Research Station (Kate Heckman), and Colorado State University (John Hribljan; currently at University of Nebraska, Omaha) collected peat cores from eight of the 17 study site. Preliminary analyses of these peat cores were conducted to determine age, composition, and patterns over time, but much remains. Completing analysis of these (and potentially additional peat cores from local sites) would help us understand long-term successional dynamics in Puget Lowland *Sphagnum*-dominated peatlands. This research could help predict vulnerability and/or expected changes in these peatlands under climate change.

To complement the peat core work, a region-wide assessment of tree encroachment needs to occur. This would entail a population estimate of the number of sites experiencing recent (~ past 100 years) tree encroachment, dendrochronological studies, and potential causal factor driving such changes.

6.3.4 Understand tribal use of peatlands in Puget Lowlands

Regional tribes are known to have intensely managed many different ecosystem types, including peatlands, for a variety of uses (Norton 1979, Anderson 2009). Understanding how native peoples managed *Sphagnum*-dominated peatlands is critical for understanding current ecological conditions as well as providing guidance for future management. For example, the past use of fire by local tribes in the dry, upland prairies in the Puget Lowlands provided critical insight into management and restoration goals for maintaining critical biodiversity resources that are restricted to these prairies (Norton 1979, Whitlock 1992, Agee 1996, Tveten and Fonda, 1999).

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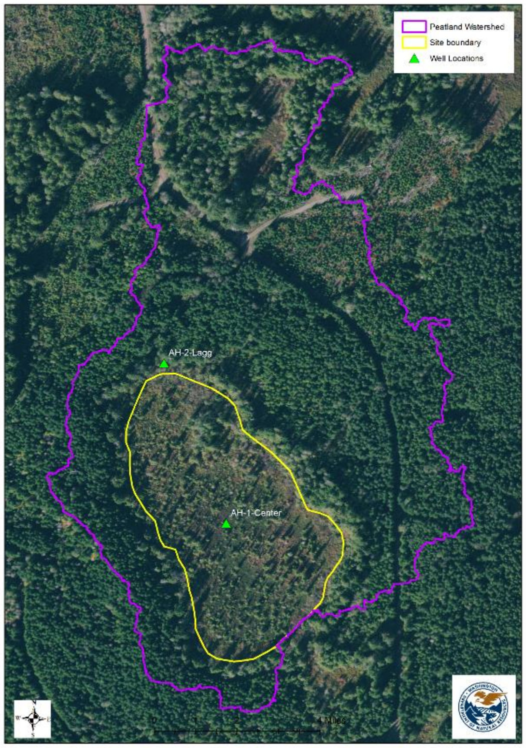
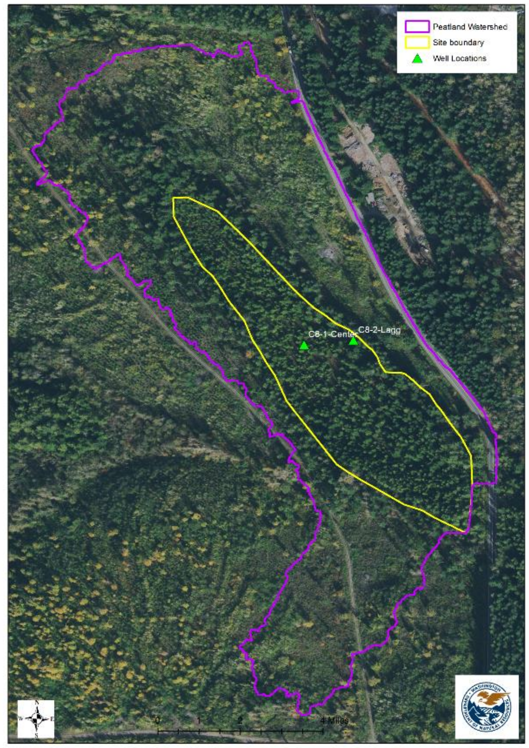
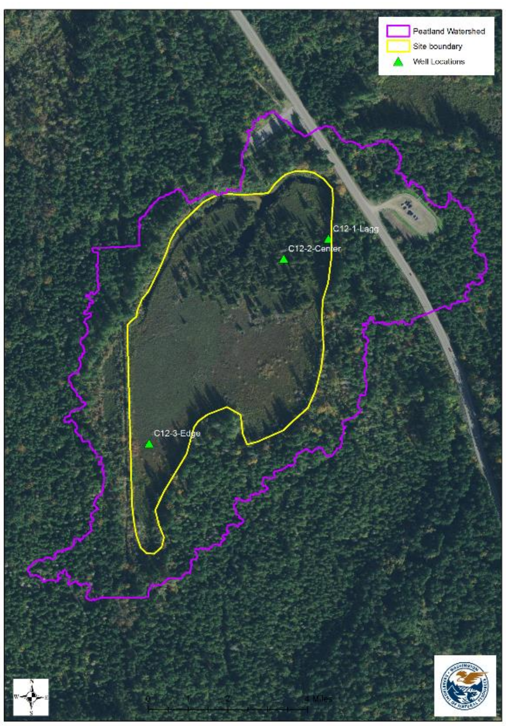
APPENDIX A. STUDY SITE BOUNDARIES AND WATERSHEDS



Arrowhead Bog (AH)



Covington 8 (C8)



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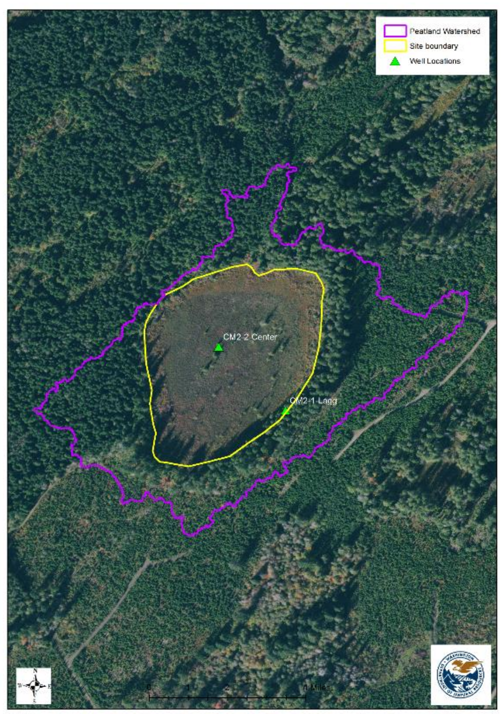
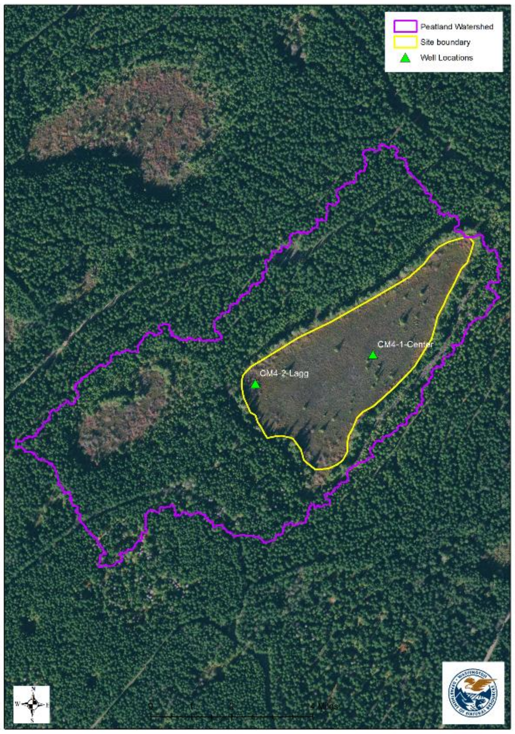
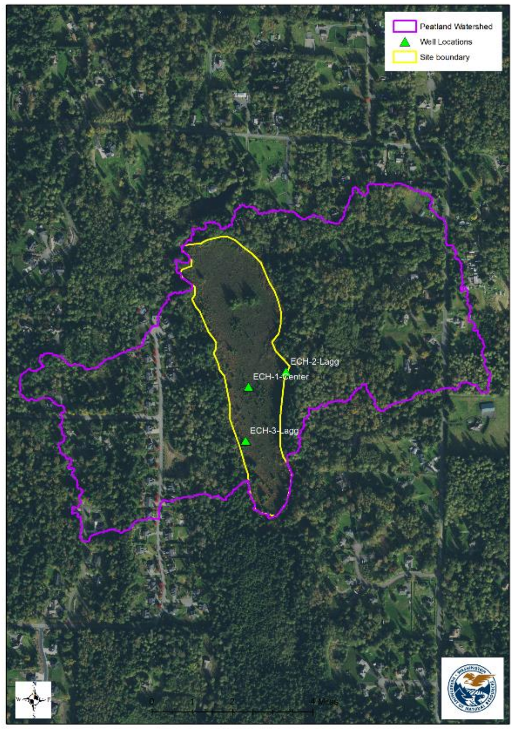


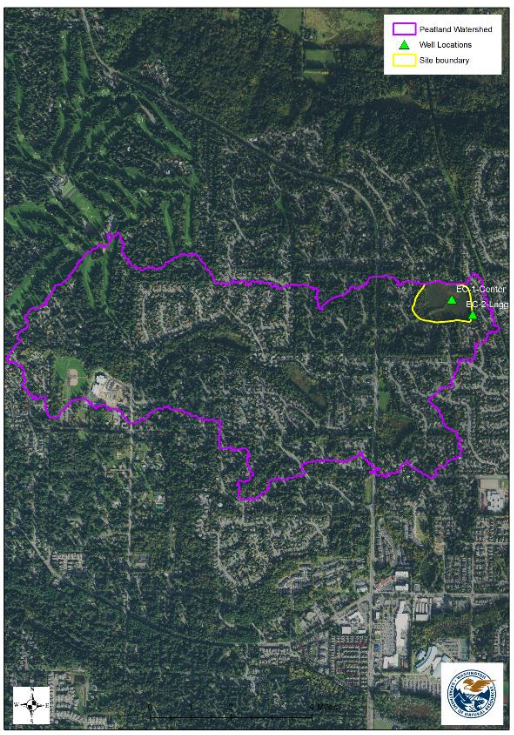
Cranberry Marsh #2 (CM2)



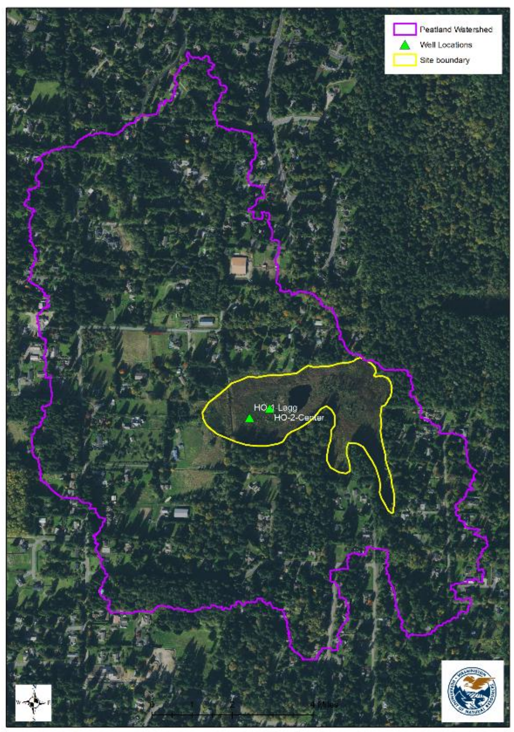
Cranberry Marsh #4 (CM4)



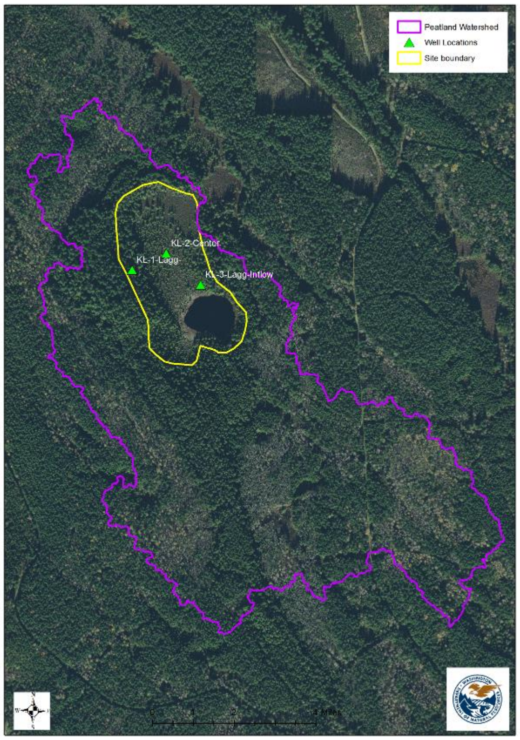
Echo Falls (ECH)



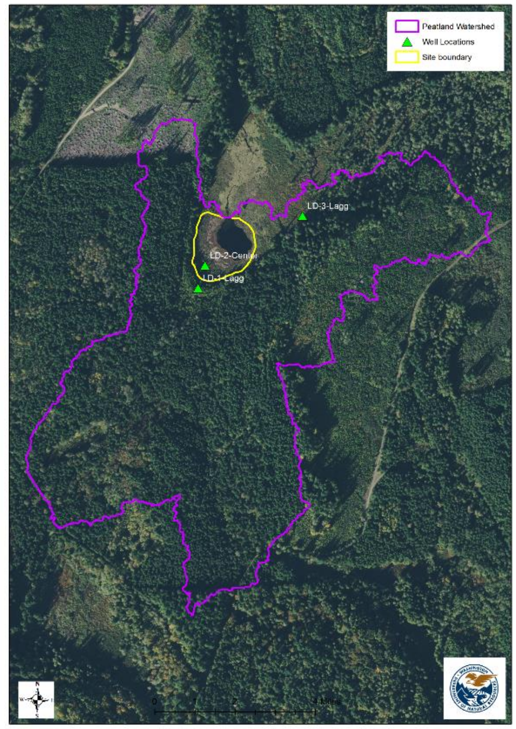
Evans Creek (EC)



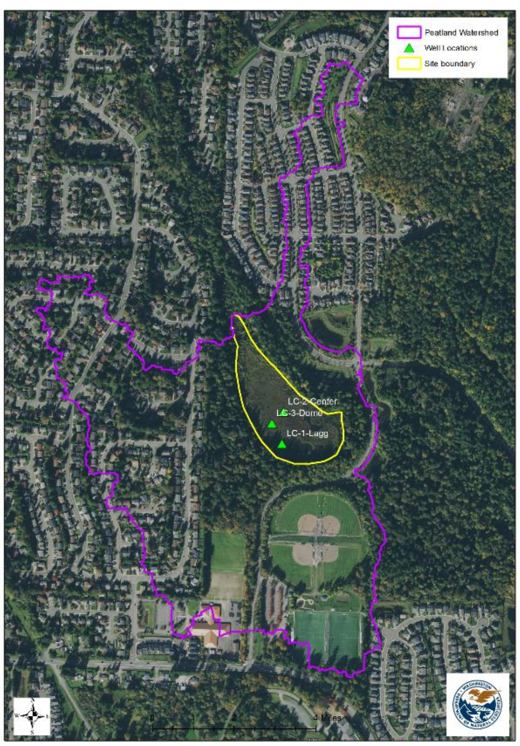
Hooven Bog (HO)



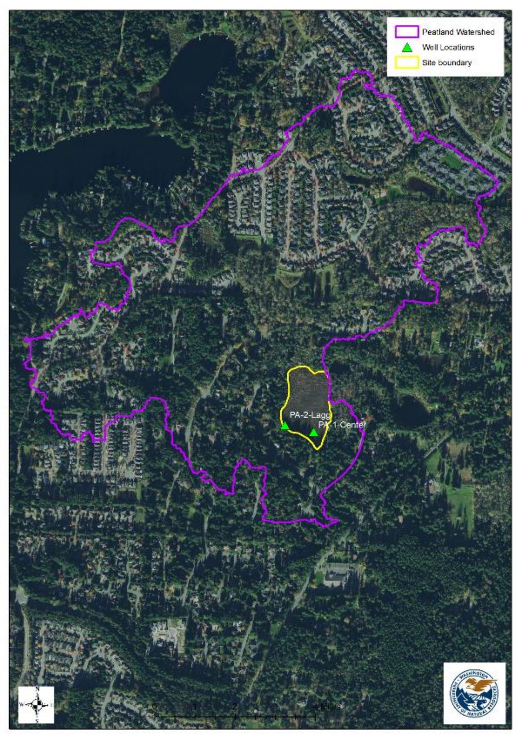
Kings Lake Bog NAP (KL)



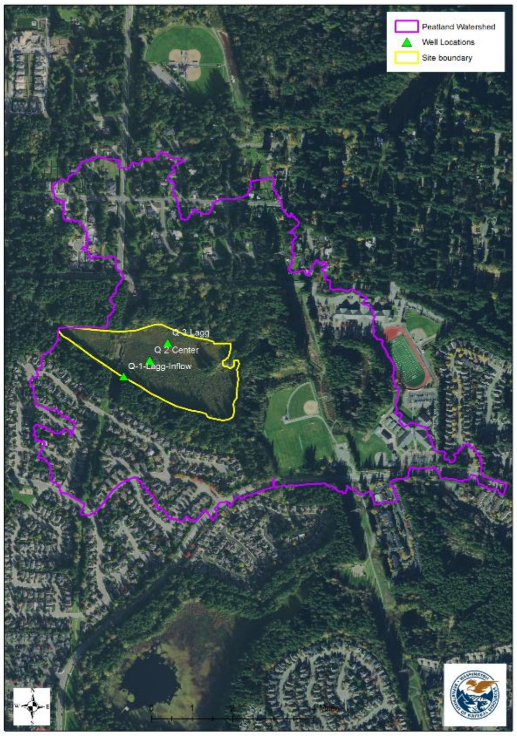
Lake Dorothy (LD)



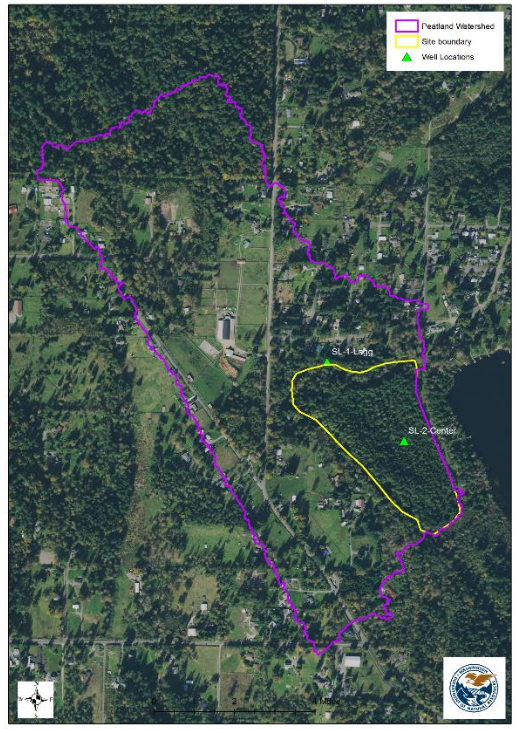
Lower Cedar (LC)



Patterson Creek (PA)

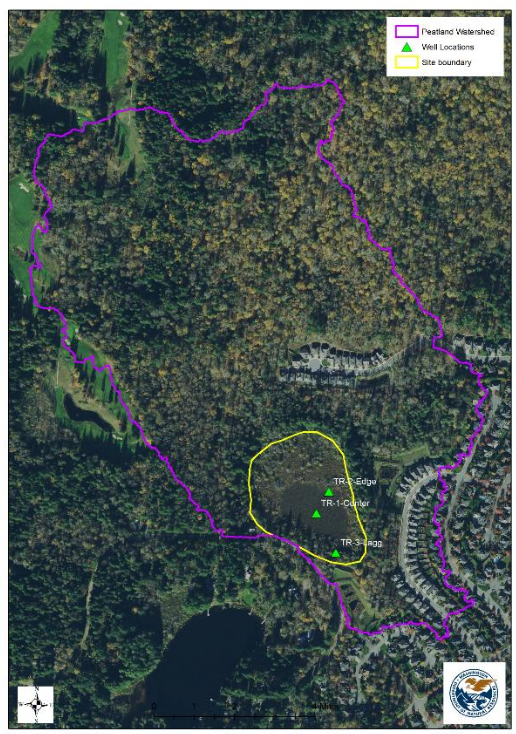


Queens Bog (Q)

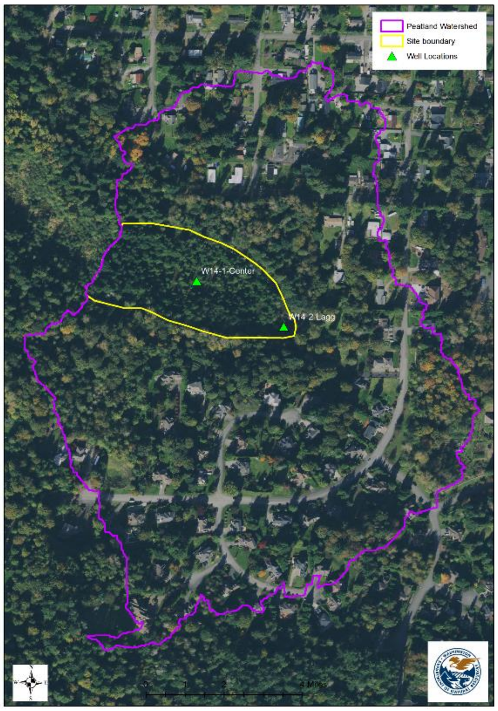


Shadow Lake (SL)

Spring Laker (SPL)



Trossachs Bog (TR)



Wetland 14 (W14)

APPENDIX B. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON WATER LEVELS

Table B1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on annual mean daily water levels in peatland centers, based on Akaike Information Criterion (AIC). MAP = $\log_{10}$(mean annual precipitation) (mm); AREA = $\log_{10}$(watershed area) (ha); INFLOW = natural surface water inflow (present/absent); BUFF50 = impervious surface area within 50 m buffer; STORM = presence of stormwater inflow facility; LUI = land use index; SHED = impervious surface area within watershed. **Bold** variables, $p \leq 0.05$; *Italic* variables, $0.05 < p \leq 0.10$; all others, $p > 0.10$. R^2m = Marginal R^2 or variance explained by fixed effects only. R^2c = Conditional R^2 or variance explained by the addition of random effects.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	**AREA** + **LUI** + **STORM**	192505	192493	0.078	0.147
2	**AREA** + **LUI** + *STORM* + LUI:STORM	192506	192492	0.075	0.147
3	*AREA* + *SHED* + STORM + **STORM:SHED**	192506	192492	0.069	0.143
4	**MAP** + **STORM** + LUI + *MAP:LUI*	192506	192492	0.073	0.144
5	AREA + **STORM** + *LUI* + AREA:LUI	192507	192493	0.077	0.152
6	**AREA** + **STORM** + **LUI** + AREA:STORM	192507	192493	0.077	0.151
7	**LUI** + **STORM** + SHED	192508	192496	0.065	0.152
8	MAP + **STORM** + LUI + STORM:LUI	192508	192494	0.065	0.148
9	INFLOW + **LUI** + **STORM** + *INFLOW:LUI*	192508	192494	0.073	0.155
10	*MAP* + **STORM** + **LUI** + MAP:STORM	192508	192494	0.070	0.149

Table B2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on annual mean daily water levels in laggs, based on Akaike Information Criterion (AIC). See Table A1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	MAP + *AREA* + BUFF50 + **MAP:AREA**	207020	207006	0.171	0.482
2	MAP	207020	207012	0.048	0.435
3	SHED	207020	207012	0.052	0.438
4	MAP + BUFF50 + SHED + MAP:BUFF50	207021	207007	0.136	0.462
5	MAP + *BUFF50* + *SHED* + MAP:SHED	207021	207007	0.144	0.467
6	LUI	207021	207013	0.049	0.439
7	STORM	207021	207013	0.048	0.439
8	MAP + *STORM* + BUFF50 + *MAP:STORM*	207021	207007	0.124	0.459
9	INFLOW + LUI	207021	207011	0.086	0.457
10	MAP + INFLOW	207021	207011	0.075	0.451

Table B3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on monthly mean daily water levels in peatland centers, based on Akaike Information Criterion (AIC). See Table A1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	*AREA* + MAP + LUI + **AREA:Month** + **MAP:Month** + **LUI:Month**	167471	167371	0.611	0.724
2	AREA + MAP + SHED + **AREA:Month** + **MAP:Month** + **SHED:Month**	167829	167729	0.596	0.721
3	AREA + MAP + BUFF50 + **AREA:Month** + **MAP:Month** + **BUFF50:Month**	167876	167776	0.596	0.721
4	MAP + LUI + SHED + **MAP:Month** + **LUI:Month** + **SHED:Month**	167941	167841	0.583	0.720
5	MAP + LUI + BUFF50 + **MAP:Month** + **LUI:Month** + **BUFF50:Month**	167985	167885	0.577	0.720
6	MAP + LUI + INFLOW + **MAP:Month** + **LUI:Month** + **INFLOW:Month**	168085	167985	0.572	0.720
7	AREA + MAP + STORM + **AREA:Month** + **MAP:Month** + **STORM:Month**	168100	168000	0.599	0.718
8	MAP + **LUI** + **STORM** + **MAP:Month** + **LUI:Month** + **INFLOW:Month**	168247	168147	0.619	0.716
9	MAP + LUI + **MAP:Month** + **LUI:Month**	168321	168245	0.575	0.713
10	*AREA* + MAP + INFLOW + **AREA:Month** + **MAP:Month** + **INFLOW:Month**	168417	168317	0.595	0.713

Table B4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on monthly mean daily water levels in laggs, based on Akaike Information Criterion (AIC). See Table A1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	AREA + MAP + BUFF50 + **AREA:Month** + **MAP:Month** + **BUFF50:Month**	187728	187628	0.358	0.770
2	AREA + MAP + LUI + **AREA:Month** + **MAP:Month** + **LUI:Month**	187740	187640	0.364	0.772
3	AREA + MAP + STORM + **AREA:Month** + **MAP:Month** + **STORM:Month**	187760	187660	0.366	0.772
4	AREA + SHED + BUFF50 + **AREA:Month** + **SHED:Month** + **BUFF50:Month**	187914	187814	0.378	0.769
5	AREA + STORM + BUFF50 + **AREA:Month** + **STORM:Month** + **BUFF50:Month**	187953	187853	0.350	0.772
6	AREA + MAP + INFLOW + **AREA:Month** + **MAP:Month** + **INFLOW:Month**	188070	187970	0.381	0.767
7	AREA + LUI + BUFF50 + **AREA:Month** + **LUI:Month** + **BUFF50:Month**	188129	188029	0.360	0.770
8	AREA + MAP + SHED + **AREA:Month** + **MAP:Month** + **SHED:Month**	188148	188048	0.374	0.767
9	AREA + MAP + **AREA:Month** + **MAP:Month**	188184	188108	0.360	0.759
10	AREA + SHED + LUI + **AREA:Month** + **SHED:Month** + **LUI:Month**	188233	188133	0.360	0.768

Table B5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean annual water levels in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	1.52	0.24	0.010	0.42	0.53	0.010
100	0.89	0.36	0.006	0.90	0.36	0.021
150	0.48	0.50	0.003	0.88	0.36	0.021
200	0.42	0.52	0.003	1.04	0.32	0.025
250	0.38	0.55	0.003	1.03	0.33	0.025
300	0.70	0.42	0.007	1.09	0.32	0.034
350	0.17	0.69	0.002	0.87	0.37	0.035
400	0.24	0.63	0.003	1.13	0.31	0.044
450	0.02	0.89	0.000	1.63	0.23	0.075
500	0.06	0.82	0.001	2.12	0.18	0.108

Table B6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean monthly water levels in peatland centers and laggs. Values are for buffer:month interactions.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	20.6	<0.001	0.548	27.9	<0.001	0.302
100	21.6	<0.001	0.546	24.9	<0.001	0.314
150	23.2	<0.001	0.545	22.8	<0.001	0.313
200	31.8	<0.001	0.547	16.3	<0.001	0.317
250	36.2	<0.001	0.547	14.6	<0.001	0.317
300	34.2	<0.001	0.517	22.7	<0.001	0.290
350	41.1	<0.001	0.517	29.0	<0.001	0.264
400	36.3	<0.001	0.517	25.5	<0.001	0.273
450	68.9	<0.001	0.507	31.7	<0.001	0.286
500	72.2	<0.001	0.500	40.3	<0.001	0.421

APPENDIX C. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON SEASONAL PH

Table C1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater pH during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	*SHED* + *BUFF50* + INFLOW	-8.9	-20.9	0.205	0.391
2	*SHED* + **BUFF50** + INFLOW + SHED:INFLOW	-8.4	-22.4	0.230	0.404
3	INFLOW	-7.9	-15.9	0.075	0.382
4	**AREA** + STORM + **AREA:STORM**	-7.8	-19.8	0.164	0.404
5	*SHED* + *BUFF50* + INFLOW + SHED:INFLOW	-7.6	-21.6	0.214	0.404
6	*SHED* + *BUFF50*	-7.6	-17.6	0.131	0.357
7	**INFLOW** + STORM + INFLOW:STORM	-7.3	-19.3	0.155	0.412
8	SHED + BUFF50 + INFLOW + SHED:BUFF50	-7.2	-21.2	0.201	0.405
9	*AREA* + STORM + SHED + **AREA:STORM**	-6.7	-20.7	0.182	0.418
10	AREA + SHED + **BUFF50**	-6.5	-18.5	0.147	0.378

Table C2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater pH during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	LUI	77.7	69.8	0.106	0.629
2	MAP	77.8	69.8	0.098	0.628
3	STORM + LUI + *STORM:LUI*	77.8	65.8	0.221	0.652
4	MAP + AREA + MAP:AREA	78.3	66.3	0.251	0.672
5	SHED	78.4	70.4	0.079	0.630
6	AREA + *LUI*	78.6	68.6	0.163	0.649
7	BUFF50	78.6	70.6	0.067	0.630
8	STORM	78.7	70.7	0.068	0.630
9	INFLOW + *STORM* + *INFLOW:STORM*	78.7	66.7	0.198	0.658
10	*STORM* + LUI + SHED + *STORM:LUI*	78.7	64.7	0.244	0.666

Table C3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater pH during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	**AREA + SHED + STORM + AREA:SHED**	-16.1	-30.1	0.372	0.720
2	STORM + **SHED** + *BUFF50* + **STORM:SHED**	-15.8	-29.8	0.367	0.722
3	**AREA +** SHED + STORM **+ AREA:STORM**	-15.3	-29.3	0.360	0.726
4	**STORM** + **SHED** + *LUI* + **STORM:SHED**	-15.0	-29.0	0.338	0.721
5	**AREA +** LUI + STORM **+ AREA:STORM**	-15.0	-29.0	0.344	0.724
6	**AREA +** *STORM* **+ AREA:STORM**	-14.9	-26.9	0.302	0.714
7	STORM + **SHED** + BUFF50 + *STORM:BUFF50*	-14.2	-28.2	0.355	0.733
8	**AREA +** MAP + STORM **+ AREA:STORM**	-14.1	-28.1	0.313	0.720
9	**SHED** + BUFF50 + *INFLOW* + *SHED:BUFF50*	-13.8	-27.8	0.331	0.728
10	**AREA + LUI +** *STORM* **+ AREA:LUI**	-13.5	-27.5	0.305	0.725

Table C4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater pH during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	*INFLOW* + STORM + AREA + **INFLOW:STORM**	97.4	83.4	0.241	0.613
2	INFLOW + STORM + *INFLOW:STORM*	98.0	86.0	0.168	0.601
3	INFLOW + STORM + LUI + *INFLOW:STORM*	98.4	84.4	0.184	0.601
4	MAP	98.5	90.5	0.016	0.568
5	SHED	98.5	90.5	0.015	0.569
6	LUI	98.5	90.5	0.015	0.569
7	BUFF50	98.6	90.6	0.010	0.571
8	AREA	98.7	90.7	0.009	0.573
9	INFLOW	98.8	90.8	0.004	0.573
10	AREA + SHED	98.9	88.9	0.077	0.586

Table C5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean pH spring (March) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.22	0.64	0.01	1.51	0.24	0.07
100	0.00	0.96	0.00	2.41	0.14	0.10
150	0.00	0.97	0.00	2.09	0.17	0.09
200	0.01	0.92	0.00	2.11	0.17	0.09
250	0.06	0.81	0.00	2.68	0.12	0.12
300	0.05	0.82	0.00	2.91	0.11	0.14
350	0.07	0.79	0.00	1.67	0.22	0.10
400	0.13	0.73	0.01	1.45	0.26	0.09
450	0.00	0.99	0.00	1.03	0.34	0.08
500	0.02	0.90	0.00	0.63	0.45	0.05

Table C6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean pH during late summer (August-September) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.33	0.57	0.01	0.25	0.63	0.01
100	0.01	0.93	0.00	0.40	0.54	0.02
150	0.04	0.84	0.00	0.16	0.70	0.01
200	0.10	0.75	0.00	0.11	0.74	0.01
250	0.16	0.69	0.01	0.22	0.64	0.01
300	0.15	0.71	0.01	1.63	0.22	0.07
350	0.00	0.95	0.00	1.01	0.34	0.05
400	0.01	0.91	0.00	0.96	0.35	0.05
450	0.04	0.84	0.00	0.80	0.40	0.05
500	0.02	0.89	0.00	0.64	0.45	0.05

APPENDIX D. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON SEASONAL CORRECTED SPECIFIC CONDUCTIVITY

Table D1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater EC_{corr} during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	**STORM**	356.3	348.3	0.109	0.109
2	**STORM** + SHED	357.2	347.2	0.129	0.129
3	*MAP*	357.5	349.5	0.083	0.083
4	**LUI** + SHED	357.6	347.6	0.122	0.122
5	AREA + **STORM**	358.0	348.0	0.114	0.114
6	MAP + STORM	358.0	348.0	0.114	0.114
7	*LUI*	358.0	350.0	0.071	0.071
8	INFLOW + **STORM**	358.2	348.2	0.108	0.108
9	STORM + LUI	358.3	348.3	0.107	0.107
10	STORM + BUFF50	358.3	348.3	0.107	0.107

Table D2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater EC_{corr} during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	**STORM** + **LUI** + SHED + **STORM:LUI**	425.9	411.9	0.381	0.381
2	**STORM** + **LUI** + **STORM:LUI**	426.5	414.5	0.345	0.354
3	**STORM** + **LUI** + BUFF50 + **STORM:LUI**	427.6	413.6	0.352	0.367
4	**STORM** + **LUI** + AREA + **STORM:LUI**	428.0	414.0	0.346	0.359
5	**STORM** + **LUI** + INFLOW + **STORM:LUI**	428.4	414.4	0.337	0.361
6	**STORM** + **LUI** + MAP + **STORM:LUI**	428.5	414.5	0.336	0.356
7	**LUI**	429.8	421.8	0.212	0.284
8	**SHED** + *BUFF50* + *SHED:BUFF50*	430.1	418.1	0.280	0.302
9	AREA + **LUI**	430.2	420.2	0.245	0.300
10	**LUI** + BUFF50 + LUI:BUFF50	430.4	418.4	0.273	0.313

Table D3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater EC_{corr} during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	SHED + *BUFF50* + *LUI* + SHED:BUFF50	488.2	474.2	0.229	0.275
2	SHED + **BUFF50** + *STORM* + *SHED:BUFF50*	488.3	474.3	0.227	0.272
3	*SHED* + *BUFF50* + *LUI*	488.7	476.7	0.199	0.266
4	SHED + *BUFF50* + *STORM* + SHED:STORM	489.8	475.8	0.207	0.275
5	SHED + BUFF50 + *LUI* + LUI:BUFF50	489.9	475.9	0.203	0.284
6	INFLOW + SHED + **LUI** + INFLOW:SHED	489.9	475.9	0.207	0.263
7	STORM + *BUFF50* + AREA	489.9	477.9	0.185	0.283
8	STORM + LUI + BUFF50 + *STORM:LUI*	490.1	476.1	0.203	0.262
9	**LUI** + SHED + INFLOW	490.2	478.2	0.179	0.258
10	AREA + **LUI**	490.3	480.3	0.156	0.279

Table D4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater EC_{corr} during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	**LUI**	664.9	656.9	0.159	0.400
2	AREA + **LUI**	665.1	655.1	0.213	0.420
3	*STORM* + **BUFF50** + *STORM:BUFF50*	665.1	653.1	0.235	0.430
4	STORM + **LUI**	665.3	655.3	0.187	0.416
5	*LUI* + BUFF50 + LUI:BUFF50	665.5	653.5	0.229	0.421
6	**BUFF50**	665.6	657.6	0.132	0.408
7	STORM + **LUI** + AREA	665.7	653.7	0.228	0.435
8	*LUI* + BUFF50 + MAP + *LUI:BUFF50*	665.8	651.8	0.259	0.441
9	LUI + BUFF50 + AREA	665.9	653.9	0.231	0.436
10	*SHED*	665.9	657.9	0.129	0.402

Table D5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean corrected specific conductivity during spring (March) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.92	0.34	0.023	**4.69**	**0.045**	**0.136**
100	0.93	0.34	0.023	**5.58**	**0.030**	**0.157**
150	0.82	0.37	0.021	**4.76**	**0.044**	**0.140**
200	0.69	0.41	0.017	**5.41**	**0.034**	**0.154**
250	0.56	0.46	0.014	**8.15**	**0.012**	**0.206**
300	0.90	0.35	0.027	**8.11**	**0.015**	**0.219**
350	0.24	0.62	0.008	**7.23**	**0.025**	**0.224**
400	0.25	0.62	0.008	**6.78**	**0.029**	**0.215**
450	0.01	0.92	0.000	5.18	0.058	0.198
500	0.00	0.99	0.000	3.98	0.092	0.174

Table D6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean corrected specific conductivity during late summer (August-September) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	**4.97**	**0.040**	**0.108**	**4.69**	**0.046**	**0.132**
100	**7.26**	**0.016**	**0.141**	4.38	0.053	0.126
150	**7.17**	**0.016**	**0.139**	2.99	0.10	0.093
200	**5.56**	**0.032**	**0.116**	3.08	0.10	0.097
250	4.11	0.061	0.093	**4.60**	**0.050**	**0.136**
300	1.93	0.19	0.059	**8.67**	**0.012**	**0.241**
350	2.14	0.17	0.087	**10.7**	**0.008**	**0.300**
400	1.86	0.20	0.079	**10.9**	**0.008**	**0.301**
450	1.12	0.32	0.057	**8.25**	**0.021**	**0.279**
500	0.84	0.39	0.048	**7.17**	**0.032**	**0.269**

APPENDIX E. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON CHLORIDE CONCENTRATION

Table E1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Cl^- during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	*INFLOW* + SHED + **STORM** + **INFLOW:SHED**	89.8	75.8	0.316	0.316
2	AREA + BUFF50 + STORM + **AREA:STORM**	90.2	76.2	0.309	0.309
3	**AREA +** MAP + **AREA:MAP**	90.2	78.2	0.282	0.282
4	INFLOW + BUFF50 + **STORM + INFLOW:BUFF50**	90.3	76.3	0.307	0.307
5	**AREA +** LUI + **AREA:LUI**	90.7	78.7	0.274	0.274
6	AREA + INFLOW + *STORM* + **AREA:INFLOW**	90.8	76.8	0.299	0.299
7	**AREA +** LUI + STORM **+ AREA:LUI**	99.0	77.0	0.296	0.296
8	AREA + BUFF50 + *AREA:BUFF50*	91.0	79.0	0.268	0.268
9	AREA + STORM + *AREA:STORM*	91.4	79.4	0.261	0.261
10	AREA + STORM + INFLOW + *AREA:STORM*	91.5	77.5	0.288	0.288

Table E2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Cl^- during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	**AREA +** MAP + **BUFF50 +** MAP:BUFF50	204.6	190.6	0.477	0.486
2	*AREA* + **BUFF50 + MAP**	206.2	194.2	0.435	0.494
3	AREA + SHED + **BUFF50 +** *AREA:SHED*	207.3	193.3	0.429	0.507
4	AREA + MAP + BUFF50 + AREA:BUFF50	207.9	193.9	0.428	0.513
5	AREA + *MAP* + *BUFF50* + MAP:BUFF50	208.2	194.2	0.424	0.520
6	AREA + STORM + **BUFF50 +** *AREA:STORM*	208.3	194.3	0.413	0.517
7	AREA **+ BUFF50 +** AREA:BUFF50	208.8	196.8	0.384	0.504
8	*AREA* + LUI + **BUFF50** + AREA:LUI	209.1	195.1	0.403	0.524
9	AREA **+ BUFF50**	209.2	199.2	0.354	0.494
10	AREA + **BUFF50** + INFLOW + AREA:BUFF50	209.4	195.4	0.394	0.519

Table E3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Cl^- during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	**AREA** + *SHED*	239.7	229.7	0.152	0.152
2	**INFLOW + STORM + LUI** + INFLOW:STORM	240.6	226.6	0.191	0.191
3	**AREA +** INFLOW + SHED	240.8	228.8	0.163	0.163
4	**AREA**	241.0	233.0	0.104	0.104
5	INFLOW + **STORM** + LUI + INFLOW:LUI	241.1	227.1	0.184	0.184
6	**AREA** + INFLOW + LUI + INFLOW:LUI	241.2	227.2	0.182	0.182
7	**AREA** + LUI	241.3	231.3	0.129	0.129
8	**AREA +** MAP + INFLOW + *MAP:INFLOW*	241.4	227.4	0.180	0.180
9	**AREA +** STORM + *SHED*	241.5	229.5	0.153	0.153
10	AREA + SHED + AREA:SHED	241.5	229.5	0.153	0.153

Table E4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Cl^- during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	*MAP* + **STORM + MAP:STORM**	263.3	251.3	0.504	0.504
2	MAP + BUFF50 + **STORM + MAP:STORM**	263.8	249.8	0.512	0.512
3	MAP + SHED + **STORM + MAP:STORM**	264.3	250.3	0.508	0.508
4	MAP + LUI + **STORM + MAP:STORM**	264.8	250.8	0.504	0.504
5	*MAP* + AREA + **STORM + MAP:STORM**	264.9	250.9	0.503	0.503
6	MAP + INFLOW + **STORM + MAP:STORM**	265.3	251.3	0.498	0.504
7	INFLOW + **STORM + BUFF50** + *INFLOW:STORM*	265.5	251.5	0.495	0.495
8	**MAP** + **LUI + MAP:LUI**	265.8	253.8	0.481	0.481
9	**MAP** + **LUI +** BUFF50 + **MAP:LUI**	266.2	252.2	0.490	0.490
10	MAP + **BUFF50 +** *MAP:BUFF50*	266.3	254.3	0.473	0.473

Table E5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater chloride concentration during spring (March) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	**7.43**	**0.012**	**0.164**	**11.0**	**0.006**	**0.289**
100	**6.74**	**0.017**	**0.154**	**14.2**	**0.003**	**0.332**
150	**6.51**	**0.019**	**0.149**	**10.2**	**0.007**	**0.280**
200	**6.98**	**0.016**	**0.158**	**9.00**	**0.011**	**0.262**
250	**7.94**	**0.010**	**0.177**	**9.23**	**0.010**	**0.271**
300	**6.14**	**0.024**	**0.173**	**6.36**	**0.029**	**0.232**
350	4.12	0.061	0.138	4.54	0.064	0.207
400	3.38	0.088	0.120	4.13	0.074	0.193
450	2.37	0.15	0.105	4.69	0.069	0.241
500	2.07	0.19	0.103	4.75	0.068	0.319

Table E6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater chloride concentration during late summer (August-September) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.34	0.57	0.007	**21.5**	**<0.001**	**0.380**
100	0.21	0.65	0.004	**23.3**	**<0.001**	**0.395**
150	0.08	0.78	0.002	**16.8**	**0.001**	**0.348**
200	0.03	0.86	0.001	**13.9**	**0.003**	**0.320**
250	0.03	0.86	0.001	**13.7**	**0.003**	**0.322**
300	0.00	0.99	0.000	**10.6**	**0.009**	**0.305**
350	0.24	0.63	0.006	**7.71**	**0.024**	**0.277**
400	0.38	0.55	0.010	**7.45**	**0.026**	**0.270**
450	1.05	0.31	0.027	4.85	0.067	0.220
500	0.92	0.35	0.026	4.09	0.089	0.200

APPENDIX F. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON CALCIUM CONCENTRATION

Table F1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Ca^{+} during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	*MAP* + BUFF50 + **MAP:BUFF50**	195.7	183.7	0.184	0.184
2	*MAP* + LUI + BUFF50 + **MAP:BUFF50**	196.7	182.7	0.198	0.198
3	*MAP* + AREA+ BUFF50 + **MAP:BUFF50**	196.8	182.8	0.196	0.196
4	*BUFF50*	197.2	189.2	0.076	0.076
5	INFLOW + **BUFF50 +** *INFLOW:BUFF50*	197.2	185.2	0.155	0.155
6	*MAP* + STORM+ BUFF50 + **MAP:BUFF50**	197.3	183.3	0.186	0.186
7	*MAP* + SHED+ BUFF50 + **MAP:BUFF50**	197.4	183.4	0.184	0.184
8	MAP + *INFLOW* + **BUFF50 + INFLOW:BUFF50**	197.6	183.6	0.181	0.181
9	*MAP* + INFLOW + BUFF50 **+ MAP:BUFF50**	197.7	183.7	0.180	0.180
10	**BUFF50 +** INFLOW + STORM + **INFLOW:BUFF50**	197.7	183.7	0.179	0.179

Table F2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Ca^{+} during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	AREA + **STORM + SHED** + *AREA:STORM*	166.1	152.1	0.500	0.500
2	AREA + **STORM + BUFF50** + **AREA:STORM**	166.7	152.7	0.492	0.492
3	AREA + **STORM + SHED**	168.3	156.3	0.451	0.451
4	AREA + **STORM + SHED** + AREA:SHED	168.4	154.4	0.469	0.469
5	**STORM + SHED**	168.7	158.7	0.424	0.424
6	STORM + LUI + **SHED** + STORM:LUI	169.4	155.4	0.457	0.457
7	INFLOW + **STORM +** *SHED* + INFLOW:STORM	170.3	156.3	0.444	0.444
8	AREA + SHED + STORM + STORM:SHED	170.3	156.3	0.444	0.444
9	*SHED* + LUI + STORM	170.5	158.5	0.421	0.421
10	AREA + **BUFF50 + STORM** + AREA:SHED50	170.5	156.5	0.441	0.441

Table F3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Ca^+ during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	**STORM + LUI + STORM:LUI**	121.1	109.1	0.240	0.246
2	INFLOW + **STORM + LUI + STORM:LUI**	121.9	107.9	0.252	0.269
3	SHED + **STORM + LUI + STORM:LUI**	123.1	109.1	0.235	0.257
4	MAP + **STORM + LUI + STORM:LUI**	123.1	109.1	0.234	0.258
5	BUFF50 + **STORM + LUI + STORM:LUI**	123.1	109.1	0.235	0.257
6	AREA + **STORM + LUI + STORM:LUI**	123.1	109.1	0.235	0.257
7	**STORM + SHED + STORM:SHED**	126.3	114.3	0.161	0.260
8	*STORM* + *SHED* + LUI + **STORM:SHED**	127.1	113.1	0.172	0.264
9	**STORM + BUFF50 + STORM:BUFF50**	127.2	115.2	0.143	0.248
10	INFLOW + **STORM + BUFF50 + STORM:BUFF50**	127.4	113.4	0.166	0.267

Table F4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater Ca^+ during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	*AREA* + INFLOW + *BUFF50*	366.2	354.2	0.140	0.304
2	AREA + BUFF50	367.0	357.0	0.092	0.299
3	*AREA* + INFLOW + BUFF50 + INFLOW:BUFF50	367.7	353.7	0.143	0.342
4	*AREA* + INFLOW + BUFF50 + AREA:INFLOW	367.8	353.8	0.141	0.341
5	AREA + INFLOW + AREA:INFLOW	367.9	355.9	0.110	0.339
6	AREA	368.1	360.1	0.018	0.306
7	STORM + BUFF50	368.1	358.1	0.063	0.318
8	AREA + STORM + BUFF50	368.1	356.1	0.101	0.326
9	AREA + INFLOW + BUFF50 + AREA:BUFF50	368.2	354.2	0.134	0.340
10	BUFF50	368.2	360.2	0.014	0.294

Table F5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater calcium concentration during spring (March) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	3.23	0.080	0.076	**12.5**	**0.002**	**0.280**
100	3.11	0.086	0.074	**11.4**	**0.003**	**0.268**
150	3.37	0.074	0.080	**10.5**	**0.005**	**0.256**
200	2.75	0.11	0.066	**11.6**	**0.003**	**0.272**
250	2.09	0.16	0.051	**15.1**	**0.001**	**0.313**
300	1.21	0.28	0.035	**13.8**	**0.003**	**0.311**
350	1.19	0.28	0.039	**11.2**	**0.009**	**0.291**
400	1.14	0.30	0.038	**11.4**	**0.009**	**0.292**
450	0.93	0.37	0.037	**9.41**	**0.019**	**0.280**
500	0.85	0.40	0.040	**8.30**	**0.009**	**0.265**

Table F6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater calcium concentration during late summer (August-September) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.07	0.80	0.002	0.49	0.50	0.014
100	0.13	0.73	0.003	0.47	0.51	0.014
150	0.15	0.70	0.004	0.08	0.79	0.003
200	0.14	0.72	0.004	0.04	0.85	0.001
250	0.11	0.74	0.003	0.09	0.76	0.003
300	0.10	0.75	0.003	2.41	0.15	0.078
350	0.01	0.92	0.000	3.40	0.097	0.103
400	0.00	0.97	0.000	3.14	0.11	0.097
450	0.04	0.85	0.002	2.53	0.15	0.098
500	0.03	0.86	0.002	1.94	0.21	0.084

APPENDIX G. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON AMMONIUM CONCENTRATION

Table G1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater NH_4^+ during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	AREA + **STORM + SHED +** *AREA:STORM*	33.6	19.6	0.259	0.259
2	AREA **+ SHED +** AREA:SHED	33.9	21.8	0.223	0.223
3	**AREA** + LUI **+ SHED +** *AREA:LUI*	34.3	20.3	0.246	0.246
4	*AREA* + **SHED**	34.5	24.5	0.177	0.177
5	**AREA** + **SHED +** STORM	35.0	23.0	0.201	0.201
6	AREA + **SHED +** STORM + AREA:SHED	35.4	21.4	0.227	0.227
7	AREA + **SHED +** INFLOW + AREA:SHED	35.7	21.7	0.221	0.221
8	AREA + **STORM** + BUFF50 + **AREA:STORM**	35.7	21.7	0.221	0.221
9	AREA + **SHED +** BUFF50 + AREA:SHED	35.8	21.8	0.220	0.220
10	AREA + MAP + **SHED +** AREA:SHED	35.8	21.8	0.219	0.219

Table G2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater NH_4^+ during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	*INFLOW* + **SHED +***BUFF50* + **INFLOW:SHED**	41.0	27.0	0.362	0.447
2	**STORM +** LUI + *SHED* + STORM:LUI	43.9	29.9	0.306	0.425
3	INFLOW + SHED + *INFLOW:SHED*	44.5	32.5	0.265	0.440
4	STORM + **SHED**	45.2	35.2	0.213	0.411
5	INFLOW + STORM + SHED + INFLOW:SHED	45.2	31.2	0.279	0.457
6	AREA + INFLOW + SHED + *INFLOW:SHED*	45.5	31.5	0.277	0.456
7	STORM + **SHED +** STORM:SHED	45.6	33.6	0.240	0.426
8	**SHED**	45.7	37.7	0.163	0.390
9	*STORM* + **LUI**	45.8	35.8	0.198	0.427
10	LUI + SHED + STORM	45.8	33.8	0.235	0.430

Table G3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater NH_4^+ during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	AREA + **STORM +** BUFF + **AREA:STORM**	187.4	173.4	0.154	0.154
2	AREA + **STORM +** *AREA:STORM*	188.3	176.3	0.113	0.113
3	*AREA* + *INFLOW* + **STORM +** *INFLOW:STORM*	189.3	175.3	0.125	0.125
4	STORM	189.3	181.3	0.035	0.035
5	AREA + **STORM +** SHED + *AREA:STORM*	189.6	175.6	0.121	0.121
6	SHED	189.8	181.8	0.027	0.027
7	LUI	189.9	181.9	0.026	0.026
8	AREA + *STORM*	189.9	179.9	0.059	0.059
9	AREA + INFLOW + **STORM +** AREA:STORM	189.9	175.9	0.117	0.117
10	AREA + MAP + **STORM +** *AREA:STORM*	190.1	176.1	0.114	0.114

Table G4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater NH_4^+ during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	**MAP**	247.9	239.9	0.132	0.208
2	MAP + BUFF50	249.6	239.6	0.133	0.222
3	MAP + SHED	249.7	239.7	0.131	0.221
4	**MAP +** INFLOW	249.7	239.7	0.129	0.237
5	*MAP* **+** INFLOW	249.7	239.7	0.128	0.232
6	LUI + BUFF50 + *LUI:BUFF50*	249.8	237.8	0.162	0.231
7	*MAP* + AREA	249.9	239.9	0.128	0.223
8	MAP + INFLOW + MAP:INFLOW	249.9	237.9	0.160	0.262
9	MAP + LUI	249.9	239.9	0.125	0.226
10	*BUFF50*	250.2	242.2	0.084	0.220

Table G5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater ammonium concentration during spring (March) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.68	0.42	0.018	2.18	0.16	0.079
100	1.28	0.27	0.033	3.25	0.093	0.112
150	1.35	0.26	0.034	3.18	0.097	0.111
200	1.96	0.17	0.048	4.11	0.064	0.138
250	2.26	0.15	0.054	**6.70**	**0.024**	**0.199**
300	1.77	0.19	0.051	**6.41**	**0.033**	**0.209**
350	1.65	0.21	0.054	**11.9**	**0.018**	**0.317**
400	2.03	0.17	0.065	**10.8**	**0.020**	**0.303**
450	2.11	0.16	0.078	**8.07**	**0.043**	**0.292**
500	1.95	0.18	0.078	9.79	0.061	0.326

Table G6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater ammonium concentration during late summer (August-September) in peatland centers and laggs.

	Peatland			**Lagg**		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.84	0.37	0.015	3.60	0.078	0.084
100	1.51	0.22	0.027	3.01	0.10	0.073
150	1.44	0.24	0.026	2.30	0.15	0.058
200	1.47	0.23	0.026	2.39	0.15	0.061
250	1.37	0.25	0.014	3.55	0.083	0.085
300	0.62	0.43	0.013	**9.73**	**0.010**	**0.204**
350	0.14	0.71	0.003	**7.79**	**0.025**	**0.194**
400	0.14	0.71	0.003	**8.18**	**0.022**	**0.198**
450	0.16	0.69	0.004	**7.42**	**0.037**	**0.204**
500	0.02	0.88	0.001	**8.80**	**0.031**	**0.231**

APPENDIX H. EFFECTS OF WATERSHED AND LAND USE CHARACTERISTICS ON PHOSPHATE CONCENTRATION

Table H1. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater PO_4^{3-} during spring (March) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	AREA + **STORM**	-87.4	-97.4	0.159	0.159
2	AREA + **STORM** + AREA:STORM	-87.1	-99.1	0.188	0.188
3	**STORM**	-86.7	-94.7	0.106	0.106
4	*AREA* + *STORM* + SHED	-86.6	-98.6	0.178	0.178
5	INFLOW + **STORM**	-86.5	-96.5	0.142	0.142
6	*AREA* + *STORM* + MAP	-86.4	-98.4	0.176	0.176
7	*INFLOW* + **LUI**	-86.4	-96.4	0.139	0.139
8	AREA + *STORM* + SHED + AREA:STORM	-86.3	-100.3	0.206	0.206
9	**MAP** + INFLOW	-86.2	-96.2	0.134	0.134
10	AREA + **STORM +** BUFF50 + AREA:STORM	-86.1	-100.1	0.203	0.203

Table H2. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater PO_4^{3-} during spring (March) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	Variables	AIC	Deviance	R^2m	R^2c
1	**AREA** + **INFLOW + AREA:INFLOW**	-121.7	-133.7	0.852	0.852
2	**AREA** + **INFLOW +** STORM + **AREA:INFLOW**	-120.5	-134.5	0.852	0.852
3	**AREA** + **INFLOW +** MAP + **AREA:INFLOW**	-120.4	-134.4	0.851	0.851
4	**AREA** + **INFLOW +** LUI + **AREA:INFLOW**	-120.2	-134.2	0.850	0.850
5	**AREA** + **INFLOW +** BUFF50 + **AREA:INFLOW**	-120.2	-134.2	0.850	0.850
6	**INFLOW + BUFF50** + **INFLOW:BUFF50**	-120.1	-132.1	0.846	0.846
7	**AREA** + **INFLOW +** SHED + **AREA:INFLOW**	-119.9	-133.9	0.849	0.849
8	**INFLOW + BUFF50** + LUI + **INFLOW:BUFF50**	-118.5	-132.5	0.844	0.844
9	**INFLOW + BUFF50** + SHED + **INFLOW:BUFF50**	-118.4	-132.4	0.843	0.843
10	**INFLOW + BUFF50** + STORM + **INFLOW:BUFF50**	-118.2	-132.2	0.842	0.842

Table H3. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater PO_4^{3-} during late summer (August-September) in peatland centers, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	*AREA* + **MAP**	57.5	47.5	0.168	0.488
2	**AREA** + MAP **+** BUFF50 + MAP:BUFF50	58.6	44.6	0.215	0.511
3	*AREA* + MAP **+** STORM	59.0	47.0	0.173	0.504
4	AREA + *MAP* **+** INFLOW	59.2	47.2	0.169	0.507
5	*AREA* + MAP **+** SHED	59.4	47.4	0.166	0.509
6	AREA + *MAP* **+** AREA:MAP	59.4	47.4	0.164	0.506
7	AREA + MAP **+** LUI	59.5	47.5	0.162	0.508
8	REA + *MAP* **+** BUFF50	59.5	47.5	0.162	0.507
9	MAP	59.6	51.6	0.058	0.471
10	AREA + STORM	59.7	49.7	0.114	0.490

Table H4. Top ten ranked linear mixed-effects models (subject = site) of the effects of watershed and land use characteristics on mean porewater PO_4^{3-} during late summer (August-September) in laggs, based on Akaike Information Criterion (AIC). See Appendix Table B1 for descriptions.

Rank	**Variables**	**AIC**	**Deviance**	**R^2m**	**R^2c**
1	INFLOW + **STORM** + *INFLOW:STORM*	97.5	85.5	0.175	0.203
2	INFLOW + STORM + SHED + *INFLOW:STORM*	98.0	84.0	0.194	0.211
3	INFLOW + STORM + BUFF50 + *INFLOW:STORM*	98.1	84.1	0.193	0.219
4	**BUFF50**	98.3	90.3	0.103	0.140
5	AREA + *INFLOW* + **STORM + AREA:INFLOW**	98.3	84.3	0.192	0.192
6	MAP + INFLOW + *STORM* + *INFLOW:STORM*	99.0	85.0	0.177	0.215
7	*STORM*	99.1	91.1	0.090	0.120
8	BUFF50 + INFLOW + STORM + *INFLOW:BUFF50*	99.2	85.2	0.177	0.194
9	STORM + BUFF50	99.4	89.4	0.118	0.136
10	AREA + INFLOW + *STORM* + *INFLOW:STORM*	99.5	85.5	0.170	0.224

Table H5. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater phosphate concentration during spring (March) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.90	0.35	0.023	**12.4**	**0.003**	**0.386**
100	1.68	0.20	0.041	**10.9**	**0.005**	**0.360**
150	1.93	0.17	0.047	**7.66**	**0.015**	**0.291**
200	2.22	0.14	0.054	**7.63**	**0.016**	**0.294**
250	1.94	0.17	0.047	**8.22**	**0.013**	**0.316**
300	0.97	0.33	0.029	**7.38**	**0.019**	**0.327**
350	0.55	0.46	0.019	**5.49**	**0.042**	**0.304**
400	0.65	0.43	0.022	**5.34**	**0.044**	**0.298**
450	0.81	0.38	0.032	4.01	0.081	0.280
500	0.60	0.45	0.025	3.80	0.093	0.285

Appendix Table H6. Effects of impervious surface area within various buffer widths from the wetland perimeter on mean porewater phosphate concentration during late summer (August-September) in peatland centers and laggs.

	Peatland			Lagg		
Buffer Width (m)	**F**	**p**	**R^2m**	**F**	**p**	**R^2m**
50	0.10	0.75	0.004	**5.56**	**0.034**	**0.103**
100	0.15	0.70	0.005	3.39	0.087	0.071
150	0.20	0.66	0.007	2.44	0.14	0.054
200	0.26	0.62	0.009	2.74	0.12	0.060
250	0.19	0.67	0.007	4.10	0.070	0.082
300	0.01	0.93	0.000	**7.25**	**0.010**	**0.131**
350	0.05	0.82	0.003	**5.97**	**0.019**	**0.124**
400	0.06	0.82	0.003	**6.25**	**0.017**	**0.130**
450	0.60	0.46	0.034	**5.12**	**0.030**	**0.124**
500	0.98	0.36	0.028	**5.28**	**0.028**	**0.134**

APPENDIX I. VEGETATION SYNOPTIC TABLE

Color codes: 40-59% constancy, 60-79% constancy, ≥ 80% constancy. Dominant species in **bold** (average ≥ 10% cover when present). Stratum definitions: Canopy (> 10 m high), Subcanopy (5 to 10 m), Shrub (0.5 to 5 m), Herbaceous (< 0.5 m), and Ground (nonvascular on substrate surface)

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	12		12		5		5	
Species	Growth Form	Stratum	Const (%)	Cover (%)	Const. (%)	Cover (%)	Const. (%)	Cover (%)	Const. (%)	Cover (%)
Tsuga heterophylla	Tree	C	17	8	**8**	**38**	0	0	**40**	**40**
Pinus contorta var. *contorta*	Tree	C	8	8	0	0	0	0	0	0
Pinus monticola	Tree	C	8	4	0	0	0	0	0	0
Thuja plicata	Tree	C	0	0	0	0	0	0	**40**	**35**
Fraxinus latifolia	Tree	C	0	0	**8**	**18**	0	0	0	0
Tsuga heterophylla	Tree	SC	42	6	0	0	20	0.1	20	2
Pinus contorta var. *contorta*	Tree	SC	**8**	**18**	0	0	0	0	0	0
Pinus monticola	Tree	SC	8	4	0	0	20	0.1	0	0
Pseudotsuga menziesii	Tree	SC	8	4	0	0	0	0	0	0
Thuja plicata	Tree	SC	8	2	0	0	40	0.1	20	8
Alnus rubra	Tree	SC	0	0	**8**	**38**	0	0	0	0
Tsuga heterophylla	Tree	SH	75	6	8	2	**60**	**10**	40	2
Pseudotsuga menziesii	Tree	SH	17	1	0	0	0	0	0	0
Pinus contorta var. *contorta*	Tree	SH	8	2	0	0	0	0	0	0
Pinus monticola	Tree	SH	8	4	0	0	20	2	0	0
Thuja plicata	Tree	SH	8	0.1	0	0	40	1	80	3
Picea sitchensis	Tree	SH	0	0	8	4	20	2	0	0
Alnus rubra	Tree	SH	0	0	17	4	0	0	0	0
Tsuga heterophylla	Tree	H	58	1	8	0.1	60	2	20	2
Pinus contorta var. *contorta*	Tree	H	8	0.1	0	0	0	0	0	0
Pinus monticola	Tree	H	8	0.1	0	0	0	0	0	0
Picea sitchensis	Tree	H	0	0	0	0	20	0.1	0	0

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	**12**		**12**		**5**		**5**	
Species	**Growth Form**	**Stratum**	**Const (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**
Thuja plicata	Tree	H	0	0	8	0.1	40	0.1	0	0
Alnus rubra	Tree	H	0	0	8	0.1	0	0	0	0
Rhododendron groenlandicum	Shrub	SH	**100**	**50**	33	2	**100**	**52**	80	2
Kalmia microphylla	Shrub	SH	**100**	**43**	17	0.1	**100**	**48**	20	0.1
Gaultheria shallon	Shrub	SH	17	4	25	7	0	0	60	6
Spiraea douglasii	Shrub	SH	17	2	**75**	**47**	60	1	**60**	**28**
Frangula purshiana ssp. *purshiana*	Shrub	SH	8	0.1	16	5	40	0.1	20	8
Vaccinium corymbosum	Shrub	SH	8	4	0	0	20	0.1	0	0
Acer circinatum	Shrub	SH	0	0	**17**	**20**	0	0	0	0
Cornus occidentalis	Shrub	SH	0	0	**17**	**20**	0	0	0	0
Lonicera involucrata var. *involucrata*	Shrub	SH	0	0	0	0	0	0	20	2
Malus fusca	Shrub	SH	0	0	**67**	**29**	40	2	**60**	**55**
Rhododendron menziesii	Shrub	SH	0	0	8	4	0	0	20	2
Rosa pisocarpa	Shrub	SH	0	0	0	0	0	0	40	4
Rubus bifrons	Shrub	SH	0	0	8	2	0	0	0	0
Rubus laciniatus	Shrub	SH	0	0	8	2	0	0	0	0
Rubus spectabilis	Shrub	SH	0	0	25	4	0	0	20	0.1
Salix geyeriana	Shrub	SH	0	0	8	8	0	0	0	0
Salix hookeriana	Shrub	SH	0	0	0	0	0	0	20	8
Salix scouleriana	Shrub	SH	0	0	**16**	**13**	0	0	**20**	**68**
Salix sitchensis	Shrub	SH	0	0	8	2	0	0	0	0
Sambucus racemosa	Shrub	SH	0	0	17	2	0	0	0	0
Vaccinium ovalifolium	Shrub	SH	0	0	8	4	40	2	**40**	**32**
Vaccinium parvifolium	Shrub	SH	0	0	17	2	0	0	20	0.1

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	12		12		5		5	
Species	**Growth Form**	**Stratum**	**Const (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**
Vaccinium uliginosum	Shrub	SH	0	0	0	0	20	0.1	20	0.1
Viburnum edule	Shrub	SH	0	0	0	0	0	0	20	0.1
Vaccinium oxycoccos	Shrub	H	83	2	0	0	60	6	0	0
Gaultheria shallon	Shrub	H	25	6	33	3	60	5	60	6
Frangula purshiana ssp. *purshiana*	Shrub	H	8	0.1	0	0	20	0.1	0	0
Vaccinium ovalifolium	Shrub	H	8	0.1	0	0	0	0	0	0
Vaccinium parvifolium	Shrub	H	8	0.1	8	0.1	0	0	0	0
Cornus occidentalis	Shrub	H	0	0	8	4	0	0	0	0
Lonicera involucrata var. *involucrata*	Shrub	H	0	0	0	0	0	0	20	0.1
Malus fusca	Shrub	H	0	0	17	0.1	20	0.1	0	0
Rhododendron groenlandicum	Shrub	H	0	0	8	0.1	0	0	0	0
Rhododendron menziesii	Shrub	H	0	0	0	0	0	0	20	2
Rosa pisocarpa	Shrub	H	0	0	0	0	0	0	20	0.1
Spiraea douglasii	Shrub	H	0	0	17	1	20	0.1	0	0
Vaccinium uliginosum	Shrub	H	0	0	0	0	40	0.1	0	0
Rubus ursinus	Shrub	H	0	0	17	0.1	0	0	20	0.1
Pteridium aquilinum ssp. *pubescens*	Herb	H	17	4	17	4	60	1	60	3
Carex utriculata	Herb	H	17	1	8	0.1	60	1	20	2
Drosera rotundifolia	Herb	H	8	0.1	0	0	20	0.1	0	0
Lysichiton americanus	Herb	H	8	4	42	8	40	0.1	60	2
Eriophorum chamissonis	Herb	H	8	0.1	0	0	20	2	0	0
Juncus bufonius	Herb	H	8	0.1	0	0	0	0	0	0
Athyrium filix-femina ssp. *cyclosorum*	Herb	H	0	0	42	2	0	0	20	0.1

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	**12**		**12**		**5**		**5**	
Species	**Growth Form**	**Stratum**	**Const (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**
Dryopteris expansa	Herb	H	0	0	8	0.1	0	0	0	0
Polystichum munitum	Herb	H	0	0	33	1	0	0	20	0.1
Struthiopteris spicant	Herb	H	0	0	8	0.1	40	0.1	40	0.1
Callitriche stagnalis	Herb	H	0	0	8	4	0	0	0	0
Comarum palustre	Herb	H	0	0	8	0.1	0	0	0	0
Cornus unalaschkensis	Herb	H	0	0	0	0	40	1	40	1
Dicentra formosa ssp. *formosa*	Herb	H	0	0	17	0.1	0	0	0	0
Epilobium spp.	Herb	H	0	0	8	0.1	0	0	0	0
Galium spp.	Herb	H	0	0	8	0.1	0	0	0	0
Gentiana sceptrum	Herb	H	0	0	0	0	0	0	20	0.1
Geranium robertianum	Herb	H	0	0	8	2	0	0	0	0
Hippuris vulgaris	Herb	H	0	0	8	2	0	0	0	0
Iris pseudacorus	Herb	H	0	0	8	0.1	0	0	0	0
Lemna minor	Herb	H	0	0	8	2	0	0	0	0
Lemna spp.	Herb	H	0	0	17	0.1	0	0	0	0
Ludwigia palustris	Herb	H	0	0	17	1	0	0	0	0
Lycopus spp.	Herb	H	0	0	8	0.1	0	0	0	0
Lycopus uniflorus	Herb	H	0	0	8	0.1	0	0	0	0
Lysimachia europaea	Herb	H	0	0	8	0.1	40	0.1	20	0.1
Maianthemum dilatatum	Herb	H	0	0	0	0	20	8	20	2
Mycelis muralis	Herb	H	0	0	17	0.1	0	0	0	0
Myriophyllum spp.	Herb	H	0	0	17	1	0	0	0	0
Nuphar polysepala	Herb	H	0	0	**8**	**18**	0	0	0	0
Oenanthe sarmentosa	Herb	H	0	0	33	8	0	0	20	0.1
Persicaria lapathifolia	Herb	H	0	0	8	4	0	0	0	0

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	12		12		5		5	
Species	**Growth Form**	**Stratum**	**Const (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**
Persicaria spp.	Herb	H	0	0	8	0.1	0	0	0	0
Potamogeton spp.	Herb	H	0	0	8	2	0	0	0	0
Ranunculus repens	Herb	H	0	0	8	0.1	0	0	0	0
Rumex spp.	Herb	H	0	0	8	0.1	0	0	0	0
Solanum dulcamara	Herb	H	0	0	33	1	0	0	0	0
Veronica americana	Herb	H	0	0	8	0.1	0	0	0	0
Veronica scutellata	Herb	H	0	0	17	2	0	0	0	0
Xerophyllum tenax	Herb	H	0	0	0	0	**20**	**38**	0	0
Agrostis scabra	Herb	H	0	0	8	0.1	0	0	0	0
Glyceria elata	Herb	H	0	0	8	4	0	0	0	0
Phalaris arundinacea	Herb	H	0	0	17	4	0	0	0	0
Torreyochloa pallida var. *pauciflora*	Herb	H	0	0	8	0.1	0	0	0	0
Carex aquatilis var. *dives*	Herb	H	0	0	8	0.1	0	0	0	0
Carex arcta	Herb	H	0	0	8	2	0	0	0	0
Carex canescens	Herb	H	0	0	25	0.1	0	0	0	0
Carex cusickii	Herb	H	0	0	17	2	0	0	0	0
Carex echinata ssp. *echinata*	Herb	H	0	0	8	0.1	0	0	0	0
Carex leptopoda	Herb	H	0	0	17	0.1	0	0	0	0
Carex obnupta	Herb	H	0	0	0	0	0	0	**60**	**72**
Eleocharis spp.	Herb	H	0	0	8	0.1	0	0	0	0
Juncus acuminatus	Herb	H	0	0	8	0.1	0	0	0	0
Juncus balticus	Herb	H	0	0	8	8	0	0	0	0
Juncus hesperius	Herb	H	0	0	17	0.1	0	0	0	0
Juncus spp.	Herb	H	0	0	8	0.1	0	0	0	0
Rhynchospora alba	Herb	H	0	0	0	0	20	2	0	0

			Developed Peatland Center		Developed Lagg		Reference Peatland Center		Reference Lagg	
		Plot Count >	**12**		**12**		**5**		**5**	
Species	**Growth Form**	**Stratum**	**Const (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**	**Const. (%)**	**Cover (%)**
Scirpus cyperinus	Herb	H	0	0	8	4	0	0	0	0
Scirpus microcarpus	Herb	H	0	0	8	0.1	0	0	0	0
Sparganium emersum	Herb	H	0	0	17	4	0	0	0	0
Typha latifolia	Herb	H	0	0	**8**	**18**	0	0	0	0
Hedera helix	Herb	H	0	0	8	4	0	0	0	0
Sphagnum spp.	Nonvascular	G	**100**	**26**	33	7	**100**	**48**	40	2
Undifferentiated Feather Moss	Nonvascular	G	**92**	**42**	25	2	**80**	**19**	**60**	**42**
Undifferentiated Brown Moss	Nonvascular	G	58	4	8	2	20	0.1	0	0
Undifferentiated Lichen	Nonvascular	G	**42**	**13**	0	0	**100**	**13**	0	0
Undifferentiated Moss (non-*Sphagnum*, non-Feather)	Nonvascular	G	33	4	25	2	40	2	0	0
Ricciocarpos natans	Nonvascular	G	0	0	8	0.1	0	0	0	0
Polytrichum commune	Nonvascular	G	0	0	8	0.1	0	0	0	0
Bare soil	n/a	G	**25**	**11**	25	2	20	0.1	0	0
Litter	n/a	G	8	8	33	9	0	0	**20**	**38**
Water	n/a	G	0	0	**42**	**25**	0	0	0	0

APPENDIX J. PERMANOVA (RESULTS COMPARING VEGETATION AND ECOLOGICAL VARIABLES)

APPENDIX K. PERMANOVA_COEFF (COEFFICIENTS OF VEGETATION AND ECOLOGICAL VARIABLES)

APPENDIX L. EIA RESULTS

APPENDIX M. FQA RESULTS

APPENDIX N. EIA_COEFF (CENTER & LAGG)

APPENDIX O. FQA_COEFF (CENTER & LAGG)

APPENDIX P. VEG BY WETLAND (VEGETATION DATA BY WETLAND POSITION)

APPENDIX Q. TREE DENSITY

APPENDIX R. TREE DENSITY REG (REGRESSIONS)