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Climate and topography: the two essential ingredients in predicting wetland permanence.

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Abstract. Wetlands in the Prairie Pothole Region (PPR) are forecast to retract in their ranges due to climate change and potholes that typically contain ponded water year-round, which support a larger proportion of biological communities, are most sensitive to climate change. In addition to climate, land use activities and terrain also influence ponded water amounts in PPR wetlands. However, terrain is not typically included in models forecasting the impacts of climate change on PPR wetlands. Using a combination of variables representing climate, land cover and land use, and terrain, we predicted wetland permanence class in the southern Boreal, Parkland and Grassland of the Alberta PPR. We show that while climate is the strongest predictor of wetland permanence class in each Natural Region, topography was nearly as important in the Parkland and Southern Boreal.

1. Introduction

Wetlands provide habitat for diverse communities of flora and fauna (Gibbs, 1993; Loesch et al., 2012; Sundberg et al., 2016) and deliver ecosystem services of disproportionate importance relative to the area they occupy (Mitsch and Gosselink, 2015). The diversity and abundance of flora and fauna in wetland ecosystems is a function of the availability of ponded water (Daniel et al., 2019; Gleason and Rooney, 2018), which is forecast to decline in amount and duration of presence (i.e., hydroperiod) across the prairie pothole region of North America due to climate change (Euliss et al., 2004; Fay et al., 2016; Steen et al., 2014, 2016). In this region, the majority of wetlands are ponded non-permanently and they support resident biological communities (Daniel et al., 2019; Stewart and Kantrud, 1971) that are sensitive to climate change (Fay et al., 2016; Johnson et al., 2010b). Therefore, understanding the relative influence of climate on wetland water levels is critical to improving our understanding of how biological communities in the Prairie Pothole Region (PPR) will respond to climate change.

Given the PPR's semi-arid climate, a decline in wetland hydroperiod is expected because of increases in wetland water deficits (Schneider, 2013; Werner et al., 2013). Simulations for the PPR suggest that the magnitude of change in climatic conditions between 1946 and 2005 were vast enough to drive declines in pond permanence (Werner et al., 2013). Wetlands that contain ponded water year-round are the most sensitive to climate change and they are also rare (Ridge et al., 2021). We expect that these wetlands will experience a 20% decline in their hydroperiod due to climate change (Fay et al., 2016). Furthermore, forecasts suggest that many of the wetlands in the southern and western PPR may be lost completely, driven by drier climate conditions in these areas (Johnson et al., 2005, 2010b; Reese and Skagen, 2017). Alberta lies at the western edge of the Prairie Pothole Region, which encompasses the province's Grassland and Parkland Natural Regions, as well as the southern edge of the Boreal (Schneider, 2013).

In addition to climate, terrain can also affect hydroperiods in PPR wetlands (Johnson et al., 2010b; McCauley et al., 2015; Tsai et al., 2012). The potholes, in which these wetlands are located, form a relic of the land's glaciated history and larger catchments contribute more water resulting in larger water budgets and longer hydroperiods for some pothole wetlands than others (Hayashi et al., 2016; Shaw et al., 2013). Contemporary land-use practices (e.g., filling and ditching) also alter topography, affecting flows of surface and groundwater and subsequently wetland hydroperiod. This phenomenon, referred to as consolidation drainage, fully or partially drains upper-watershed wetlands and directs their water to areas lower in the watershed (McCauley et al., 2015). Consolidation drainage is typically done to lower the probability that neighbouring croplands will flood (Schindler and Donahue, 2006; Verhoeven and Setter, 2010), which increases farming efficiency (Wiltermuth and Anteau, 2016).

Changes in land use can influence wetland hydroperiods by more than associated terrain modification. For example, landscapes with a higher proportion of agricultural activities can have longer hydroperiods due to the combination of increased surface run-off and decreased soil infiltration (van der Kamp et al., 2003; Voldseth et al., 2007). Many studies assessing the impacts of climate change on PPR wetlands incorporate land use (Anteau et al., 2016; Vodseth et al., 2009) and there is resounding evidence that wetlands exposed to the same climate regime, but situated among different land-use activities, differ in their sensitivity to climate change (McCauley et al., 2015; Wiltermuth and Anteau, 2016).

While terrain is an important predictor of pond permanence (Hayashi et al., 2016; Neff and Rosenberry, 2017; Shaw et al., 2013; Wiltermuth and Anteau, 2016), it is rarely included in studies assessing the impacts of climate change on PPR wetlands and/or biota (Wolfe et al., 2019) Even well-established models (e.g., WETSIM (Poiani and Johnson, 1993), WETLANDSCAPE (Johnson et al., 2010b)), applied to the PPR, predict pond permanence in response to climate, but omit terrain. For example, differences in terrain may cause wetlands belonging to the same permanence class to differ in their sensitivity to climate change. Consequently, our failure to incorporate terrain when predicting pond permanence leaves us with an incomplete understanding on how wetland biota are affected by climate change.

Quantifying the individual and combined contribution of climate, land use, and terrain on wetland permanence has not been done, but is necessary to improve wetland and waterfowl population management across the PPR (Fay et al., 2016). To overcome this gap, we analyze data collected across multiple field projects and use spatial data, comprising thousands of wetlands across the PPR in Alberta, Canada. Using these data, we quantify the relative contribution of climate, land cover/land use and terrain for different wetland permanence classes. We also determine the ability of these drivers to predict wetland permanence class.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

2. Methods

2.1. Study Area

The wetlands in our study are in the Albertan extent of the Prairie Pothole Region (PPR) (Figure 1). Wetlands in this region are called potholes because they are depressions filled with ponded water, each formed in the last glacial period (Wright, 1972). Spring snow melt is the largest contributor to ponded water amounts, either from direct precipitation into the wetland or as runoff over frozen ground from upland areas (Hayashi et al., 1998). Potholes can differ in the length of time they contain ponded water, which can range from a few weeks after snowmelt to the entire year (Stewart and Kantrud, 1971). We acquired data on two wetland inventories (Government of Alberta, 2014) that delineated the location, boundary and permanence class based on Stewart and Kantrud's classification of PPR wetlands (Stewart and Kantrud, 1971) (Appendix A). The two wetland inventories differ in their accuracy (Evans et al., 2017) and include wetlands from the Grassland, Parkland and the southern edge of the Boreal Natural Regions of Alberta. The Grassland comprises mixed-grass prairie, and the Parkland comprises deciduous trees and grasses. Both are semi-arid regions with potential evapotranspiration rates that are greater than annual precipitation (Downing and Pettapiece, 2006). The Parkland, however, experiences more precipitation than the Grassland (Downing and Pettapiece, 2006). While the larger Boreal Natural Region is dominated by coniferous trees and annual precipitation amounts typically exceed evapotranspiration rates (Downing and Pettapiece, 2006), the southern margin of the Boreal in Alberta contains pothole wetlands and more semi-arid to subhumid climate conditions (Brown et al., 2010; Devito et al., 2005).

2.2. Wetland Locations and Extents

For our analysis, we selected a subset of wetlands from the Merged Albertan Wetland Inventories within each Natural Region (Figure 1). To ensure wetland conditions were indicative of the natural regions within which they resided, we excluded those within 500 m of a Natural Region boundary. Then, we randomly selected 12,000 wetlands in the Southern Boreal and Parkland Natural Regions (3,000 per permanence class) and 16,000 in the Grassland (4,000 per permanence class). No wetlands were within 1000m of each other.

2.3. Selecting Variables

To select variables representative of climate, land cover/land use and terrain that would be useful in testing the relative contribution of these three factors in predicting prairie pothole wetland permanence class, we conducted a literature review using the Web of Science. We limited the search to papers published between 1950 to 2018 with the following key words: 1) Prairie Pothole Region: PPR, Northern Great Plains, Alberta, Saskatchewan, Manitoba and Dakota; 2) weather: climate, temperature and precipitation; 3) disturbance: land use, agriculture, disturbance, oil and gas, grazing and roads and 4) pond permanence: watershed, hydroperiod, permanence class, catchment and wetland. We used "OR" operators between key words under the same class and "AND" operators between each key word class. To characterize terrain , we selected variables that

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

are commonly used to describe topographic variations, based on a previous review (Branton and Robinson, 2019). Details and results from this review are reported in Appendix B.

2.3.1. Climate

We acquired 2013-2014 daily weather data from the AgroClimatic Information Service of Alberta to calculate climate variables. These data include precipitation and temperature measurements from 7,914 weather stations across the province, observed from October 2013 to August 2014. We calculated seasonal precipitation totals and temperature averages from a compilation of proxy variables (Appendix B) at each station. Then, using a simple inverse distance weighting (Tarroso et al., 2019), we interpolated climate variables at the center of each wetland in R (R Core Team, 2019).

2.3.2. Land Cover and Land Use

Prior research in the PPR identified a strong concordance between landcover within 500 m of wetlands and wetland psychochemical conditions (Kraft et al., 2019). Using land cover data from Agriculture and Agri-Food Canada's (AAFC) Annual Crop Inventory for 2014 (Agriculture and Agri-Food Canada, 2014), we calculated the proportion of each land cover class within a 500 m buffer of each wetland (Appendix B). In addition to land cover characteristics, we also measured the distance of each wetland centroid to the nearest road using the National Road Network from the Government of Canada (Statistics Canada, 2010). We estimated these land cover and land use variables in ArcMap 10.4.1 (ESRI, 2012).

2.3.3. Terrain

We quantified topographic characteristics using a 25-m digital elevation model (DEM) for southern and central Alberta (Yang et al., 2014) (Figure 1). We estimated eight terrain variables (Appendix B) using ArcMap 10.4.1 (ESRI, 2012) and SAGA 2.3.2 (Conrad et al., 2015). These variables may be grouped as those with local (e.g., standard deviation of slope) versus global (e.g., terrain surface convexity) application. For local variables, we applied the formula to areas only within 500 m of the wetland boundary. With global variables, we applied a 100 × 100-m moving window and computed the mean value within the 500 m buffers.

2.4. Data Analysis

We aimed to quantify the relative contribution of climate, land cover/land use and terrain for different wetland permanence classes and determine the ability of these drivers for predicting wetland permanence class. Achieving these two outcomes involved four steps: reducing the number of variables to an orthogonal and parsimonious set for application; visualizing if wetlands could be partitioned based on their permanence class (Appendix C); parametrizing and calibrating a predictive model; and then predicting permanence class and assessing model fit. These analyses were performed in R (R Core Team, 2019).

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

2.4.1. Predicting Wetland Permanence Class

We used an extreme gradient boosting model to predict wetland permanence class. Extreme gradient boosting is considered a more robust predictive tool than random forest (Sheridan et al., 2016). Like random forest, extreme gradient boosting creates an ensemble of decision trees that partition data based on a specified grouping (Hastie et al., 2009; McCune et al., 2002), which in our case is wetland permanence class. In the first decision tree, all observations are equally weighted (Cutler et al., 2007). The second decision tree attempts to correct for misclassifications derived from the first tree, assigning a higher weight to observations that were difficult to classify. Each subsequent tree attempts to minimize model error by classifying these error-prone observations (Cutler et al., 2007). The use of the minimum error to build a model ensemble makes extreme gradient boosting models prone to overfitting (Cutler et al., 2007). To correct for overfitting, extreme gradient boosting models include a regularized object that penalizes more complex trees (Chen and Guestrin, 2016).

After parametrizing the model for each Natural region, we predicted wetland permanence class in the 1) Southern Boreal, 2) Parkland and 3) Grassland Natural Regions using a combination of climate, land cover/land use and terrain variables (Appendix D) for information on these parameters). For each model, we also assessed its performance using test data (70:30 training to test ratio) to determine the misclassification error rate, comparing results between training and test data. We also evaluated the relative importance of each variable in predicting permeance class by comparing gain values and assessed under which ranges of each variable a permanence class was more likely to occur with waterfall plots.

3. Results

3.1. Model Performance

We built an extreme gradient boosting model for each Natural Region (southern Boreal, Parkland and Grassland) in our study area. We selected 19 variables that reflected climate (7), land cover/use (4) and terrain (8) (Appendix B).

Our models had moderate to high error rates (Appendix E), which suggests that climate, land use/cover and terrain alone are not sufficient variables in predicting permanence class.

3.2. Relative Importance of Variables in Predicting Wetland Permanence Class Among Natural Regions

In each Natural Region, climate explained the greatest amount of variance in wetland permanence class, based on relative gain values (Figure 2A-C). As anticipated, our results suggest that climate conditions vary systematically among the Natural Regions (Figure 3A-D). Among the climate variables included in our analyses, spring temperature explained the highest magnitude of variance in predicting permanence class in the Southern Boreal and Grassland (Figure 2A;2C) but was less important in the Parkland where values are less extreme (Figure 3A).

Land cover/land use was the second most important category of drivers of wetland permanence class, following climate in the Grassland Natural Region (Figure 2F), but not in the Southern Boreal or Parkland (Figure 2). Yet, unlike climate, land cover/

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Biogeosciences Discussions

land use did not vary systematically among the three Natural Regions (Figure 4E-H). Wetlands surrounded by natural vegetation may have shorter hydroperiods (Figure 3F).

In the southern Boreal and Parkland, terrain was the second most important category of drivers of wetland permeance class, and the order of importance for the terrain metrics were nearly the same (Figure 2G-I). Though terrain metrics were the least important category in the Grassland (Figure 2I), apart from deviation from mean elevation (Figure 3I), variables associated with terrain did not systematically vary among Natural regions (Figure 3J-L).

3.3. Wetland Permeance Class in the Boreal, Parkland and Grassland

Our findings suggest that wetland permanence class in the Prairie Pothole Region of Alberta is sensitive to climate, terrain and to a lesser extent to surrounding land cover/land use. Generally, across the three Natural Regions, wetlands with shorter hydroperiods (e.g., temporary and seasonal) were typically situated in landscapes with higher snowpack amounts and spring temperatures (Figure 5-6) as well as near topographic highs (Figure 8-9). Longer hydroperiod wetlands were typically situated in landscapes with more summer precipitation and lower spring temperatures (Figure 5-6), occupying relatively low topographic positions (Appendix H-I), and were surrounded by less natural cover (Figure 7). Interestingly, the relative importance of variables in predicting the occurrence of both shorter and longer-hydroperiod wetlands were shared, and this agreement was strongest between the Southern Boreal and Grassland (Appendix F-I).

4. Discussion

Our findings support the assertion that climate change will affect wetland hydroperiods in the Prairie Pothole Region (PPR) (Fay et al., 2016; Johnson et al., 2010a, 2005; Johnson and Poiani, 2016; Reese and Skagen, 2017; Werner et al., 2013). We anticipate that reduced winter snowpack will dry out temporarily and seasonally ponded wetlands, while warmer spring temperatures will reduce the hydroperiod of more permanently ponded wetlands. Yet, climate is not the only element driving wetland permanence class in Alberta's PPR - our analysis used a relatively coarse DEM (25 m), and we nonetheless found that terrain was important in predicting permanence class. Consequently, failure to consider terrain limits our understanding about the extent to which hydroperiod, and therefore wetland permanence class, may change in response to climate change. We speculate that the use of finer-scale elevation models derived from high resolution LiDAR (e.g., 1 m) or remotely piloted aircraft (e.g., 2-5 cm) will reveal the importance of terrain in surface runoff and wetland hydroperiod.

4.1. Importance of Climate

The sensitivity of wetland hydroperiods to climate is corroborated in existing literature, which emphasizes that the semi-arid climate drives the region's sensitivity to climate change (Fay et al., 2016; Johnson et al., 2004; Schneider, 2013) In the Southern Boreal and Grassland, regions with warmer spring temperatures are likely to experience an earlier onset of spring snowmelt, higher water deficits (Schneider, 2013; Zhang et al., 2011) and lower pond permanence classes for wetlands, whereas cooler

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

peak spring temperatures favour greater pond permanence in these Natural Regions. In the Parkland, winter snowpack depth was the most important climate variable; and this, we attribute to temporarily and seasonally ponded wetlands requiring a minimum threshold of winter snowpack amount to persist, whereas permanently ponded wetlands also benefit from precipitation in other seasons and so can exist at lower wither snowpack amounts (Figure 3B). Because climate forecasts suggest that warmer springs and changes in precipitation timing are likely (Zhang et al., 2011), our findings support previous studies that suggest PPR wetlands are sensitive climate change (Johnson et al., 2010b; Paimazumder et al., 2013; Schneider, 2013; Viglizzo et al., 2015; Zhang et al., 2011).

4.2. Importance of Terrain

Despite recognition that topography is a useful proxy in wetland mapping (Branton and Robinson, 2019; Los Huertos and Smith, 2013) and that terrain must influence surface runoff generating processes that are essential to wetland function (Hayashi et al., 2016; Mushet et al., 2018), the relative importance of topography in hydrological processes is somewhat debated (Devito et al., 2005). Simulations predicting the influence of climate change on the size and isolation of prairie pothole wetlands have focused on climate and land cover/land use (Anteau et al., 2016; Chasmer et al., 2012; Conly et al., 2001; Johnson and Poiani, 2016; McCauley et al., 2015; Steen et al., 2016; Voldseth et al., 2007). Consequently, 1) there is a lack of research quantifying topographic characteristics of wetlands and the landscapes within which they occur, 2) links between topography, vegetation and wetland condition have not been rigorously studied and 3) policy and guidelines on wetland mitigation and compensation prescribe width-to-length ratios and slopes that are characteristic of permanently-ponded wetlands, which are rarer in the Grassland(Environmental Partnerships and Education Branch Alberta, 2007). Thus, the natural frequency distribution of wetland permanence classes across Alberta's Prairie Pothole Region has skewed toward permanently ponded wetlands (Serran et al., 2017). If we had a better understanding of how terrain structure determines wetland hydrology/function, we could revise policy and regulations governing wetland management to ensure we better match natural landscapes in their frequency and distribution of wetland permanence classes.

4.3. Importance of Land Cover/Land Use

Existing literature identified land cover/land use as the second greatest driver of wetland conditions following climate (Anteau et al. 2016). In the Grassland, the terrain is relatively flat compared to the southern Boreal and Parkland (Alberta Tourism Parks and Recreation, 2015). Consequently, after the important role of climate in the more arid Grassland Natural Region (Government et al., 2014), land cover/land use would be a stronger driver of permanence class than terrain. Importantly, the percent cover of natural vegetation is typically low in the Grassland, where most land has been converted to cropland or pastureland (Alberta Tourism Parks and Recreation, 2015). Combined with the process of consolidation drainage, which shunts water from scattered low hydroperiod wetlands, concentrating it in larger more permanently ponded wetlands downstream (McCauley et al., 2015), this leads to Grassland landscapes with more natural cover being more likely to contain temporary and seasonal wetlands. Thus, wetlands surrounded by natural vegetation may have shorter hydroperiods because

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

cropland resists infiltration and natural vegetation intercepts snow-sourced surface runoff (Anteau, 2012; van der Kamp et al., 2003; Voldseth et al., 2007), which can account for up 27% of ponded water amounts(van der Kamp et al., 2003).

Because some landscapes in the PPR are flatter than others (Schneider, 2013), and land use activities can modify the terrain (Anteau 2012; Wiltermuth and Anteau 2016; Anteau et al. 2016), our findings do highlight the importance of considering land use in forecasting the impacts of climate change on PPR wetlands. Boreal and Parkland wetlands have stronger overlaps in terrain metrics and climate; and, as a result, differences in land use within these regions may be integral in determining future shifts in the frequency distribution of permanence classes. Forecasts for the province of Alberta suggest there will be expansions in the agricultural industry within the next decade (Government of Alberta, 2015), and this suggests that climate impacts on Albertan PPR wetlands will be compounded by land use activities.

4.4. Topographic Position of Wetlands by Permanence Class

Semi-permanent and permanently-ponded wetlands typically occur in topographic lows, likely because they 1) can hold larger volumes of ponded water (i.e., larger pond size/volume (Novikmec et al., 2016)) and 2) receive higher volumes of water inputs from the surrounding landscape (e.g., surface run-off, groundwater Euliss et al., 2004, 2014; LaBaugh et al., 1998; Toth, 1963)). We are unable to partition the natural hydrogeological effects of topographic position on wetland permanence class from the effects of human alteration of the surrounding landscape, yet the importance of topographic position to wetland permanence class is likely reinforced by consolation drainage. Because of consolidation drainage, when wetlands situated higher in the landscape are drained and the water is redirected to wetlands positioned lower in the landscape (McCauley et al., 2015; Wiltermuth and Anteau, 2016), we may observe increases in hydroperiod of wetlands in topographic lows. In the arid but heavily farmed Grassland Natural Region, consolidation drainage can eliminate temporary and seasonally ponded wetlands from areas with limited remaining natural cover (Serran et al., 2017), which aligns with our model results. Thus, we recommend that future work investigate the role of topographic position on permanence class, in the absence of human disturbance to control for the influence of consolidation drainage.

4.5. Model Error

We hypothesize that our inability to account for soil characteristics (Schneider, 2013) could explain these high error rates. Schneider (2013) stated that within Natural Regions, both elevation (which we did account for), and soil characteristics can vary across the landscape. As such, wetlands situated similarly in the landscape may not have the same soil characteristics, and soil characteristics are understood to influence wetland hydrology by dictating the proportion of incident precipitation that is converted to surface run of (Hayashi et al., 2016). Though Schneider (2013) also mentioned an influence of disturbance history on ecosystems, prior work in our study region reported no temporal lag in wetland environmental conditions and surrounding land cover (Kraft et al., 2019)

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

5. Conclusion

Because some landscapes in the PPR are flatter than others(Schneider, 2013), and land use activities can modify topography(Anteau, 2012; Anteau et al., 2016; Wiltermuth and Anteau, 2016), our findings also highlight the importance of considering land use in forecasting the impacts of climate change on PPR wetlands. Southern Boreal and Parkland wetlands are most congruent in the relative importance of climate and terrain variables; and, as a result, differences in land use within these regions may be integral in determining future shifts in the frequency distribution of permanence classes. Forecasts for the province of Alberta suggest expansion in the agricultural industry over the next decade (Government of Alberta, 2015), which suggests that climate impacts on Alberta's PPR wetlands will be compounded by changes in land use activities.

6. Code/Data availability

On acceptance of the manuscript, the code and data will be uploaded to FigShare for archiving and a DOI provided.

7. Author Contributions

RCR conceptualized the study, acquired funding and resources, supervised and curates the data; DR and JD gathered the data; JD analysed and visualized the data and wrote the original draft; all authors contributed to investigation and review and editing.

8. Competing Interests

The authors declare that there are no competing interests or conflicts of interest.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

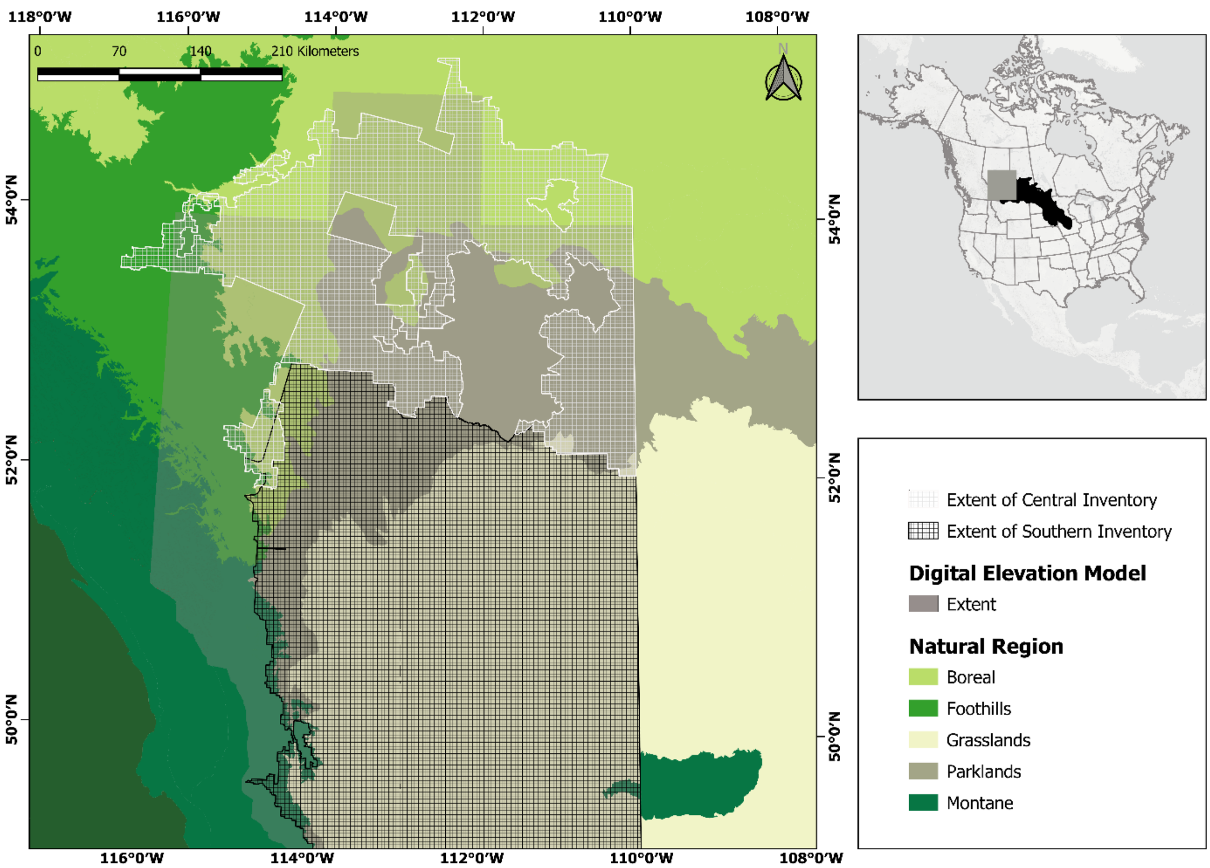

Figure 1: Extents of the Central and Southern Wetland Inventories used to delineate wetlands in our study. We selected wetlands from three Natural Regions – Boreal (12,0000), Parkland (12,0000) and Grassland (16,0000). These wetlands are within the southern-Albertan Prairie Pothole Region. There are 356,246 wetlands delineated in the Southern Inventory and 253,873 in the Central Inventory.

https://doi.org/10.5194/bg-2021-200
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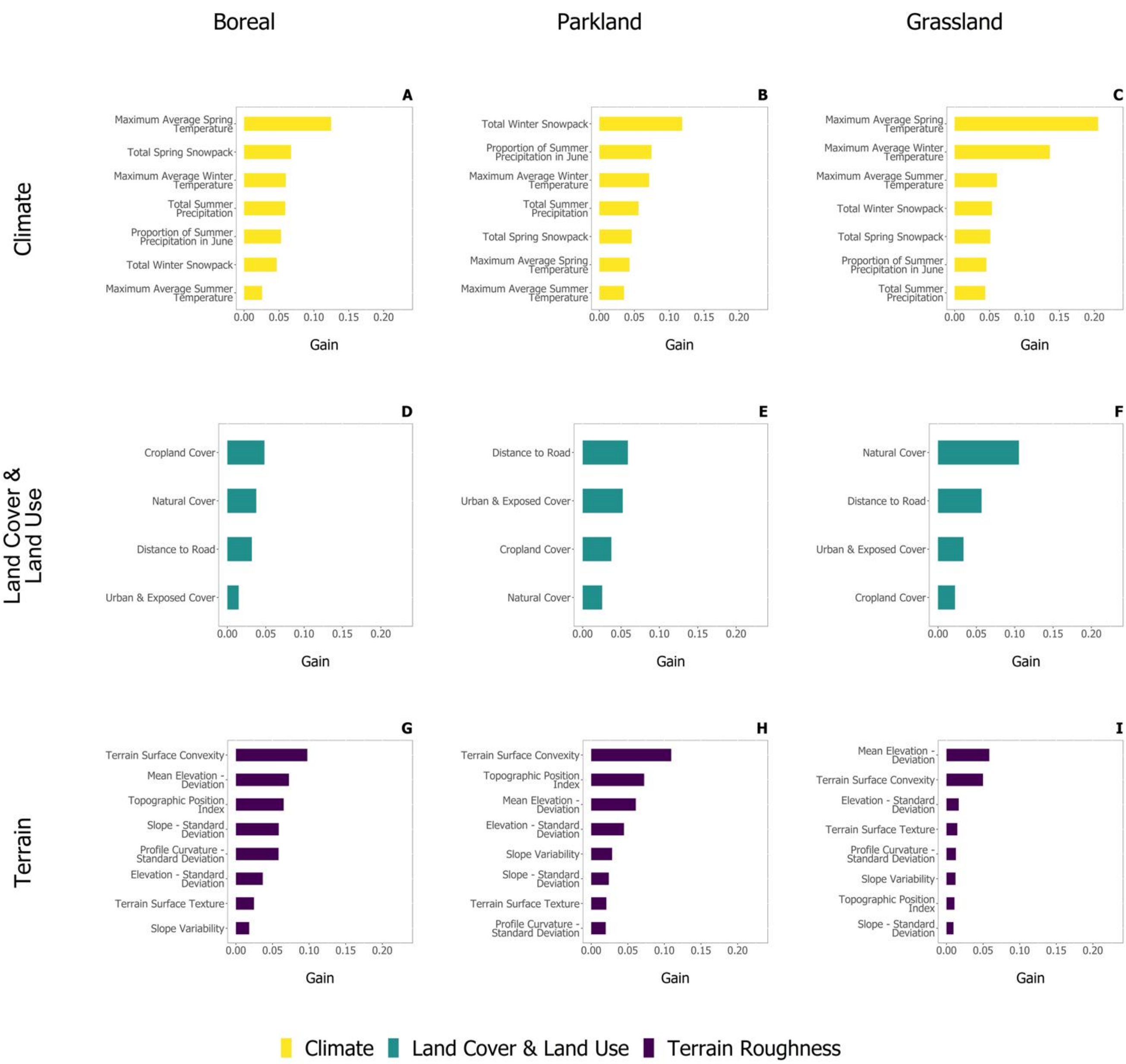

Figure 2. Variables ranked by their importance in the extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions. These variables were proxies for climate (A-C), land cover and land use (D-F) and terrain (G-I).

https://doi.org/10.5194/bg-2021-200
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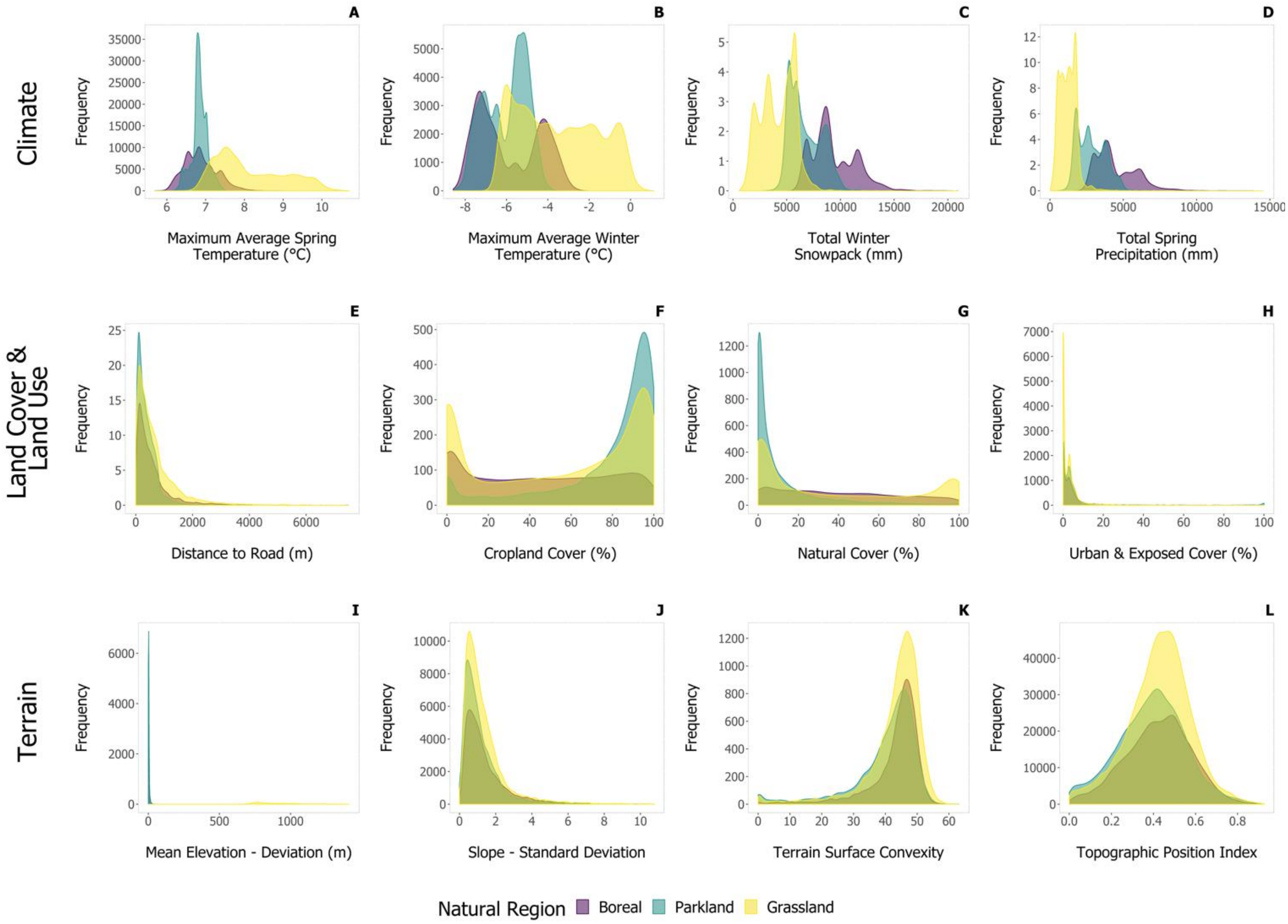
Biogeosciences
Discussions



275 **Figure 3.** Frequency distribution of the top four climate, land cover and land use and terrain variables by Natural Region.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

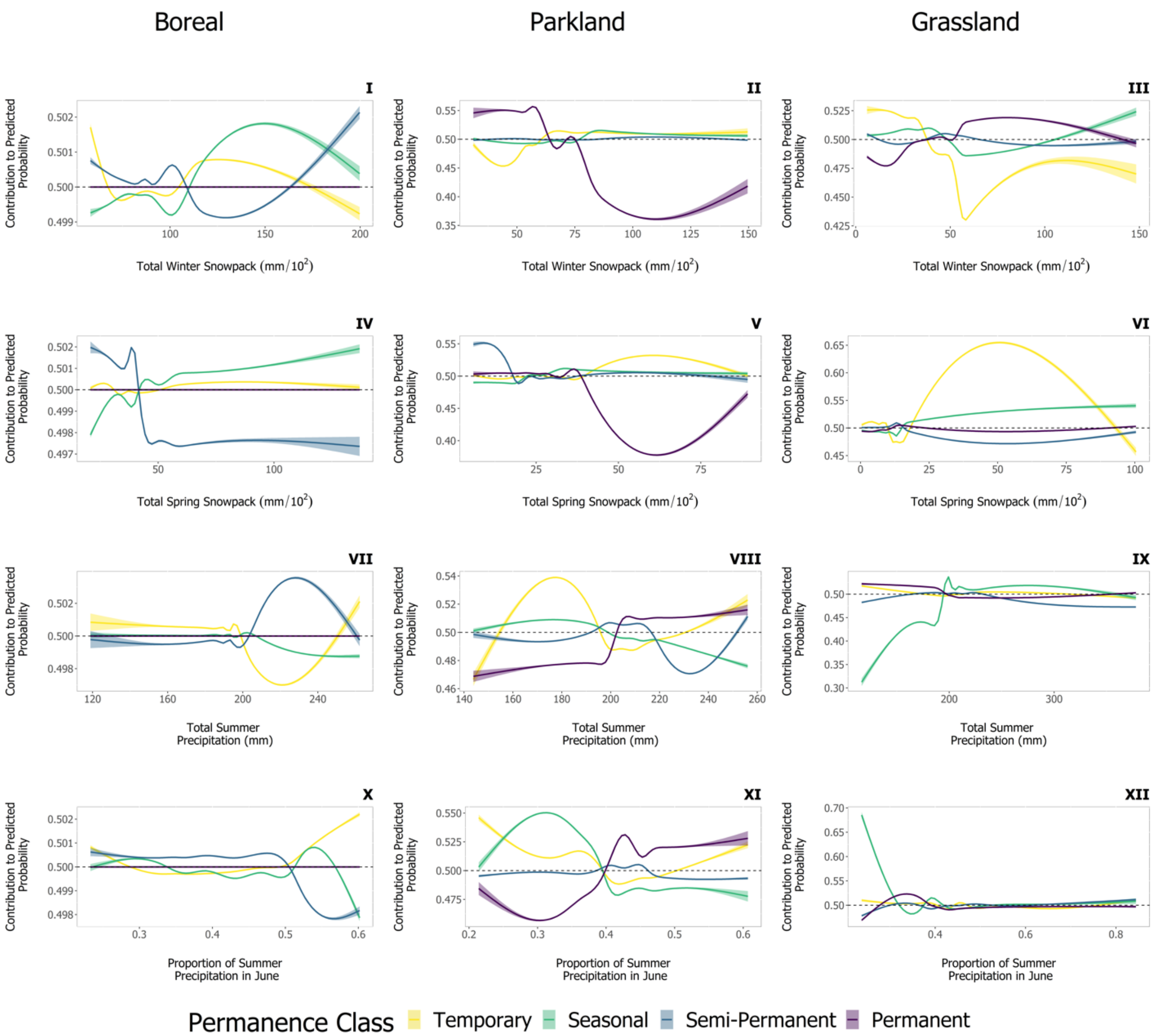


Figure 4. Partial dependence plots for the four wetland classes – temporary, seasonal, semi-permanent and permanent based on precipitation metrics. Predicted probabilities below 0.5 suggest that at this measured value of the metric, observing that permeance class is unlikely. We show 95 % confidence intervals and used a generalized additive model-based trend line. Probabilities were derived from extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions.

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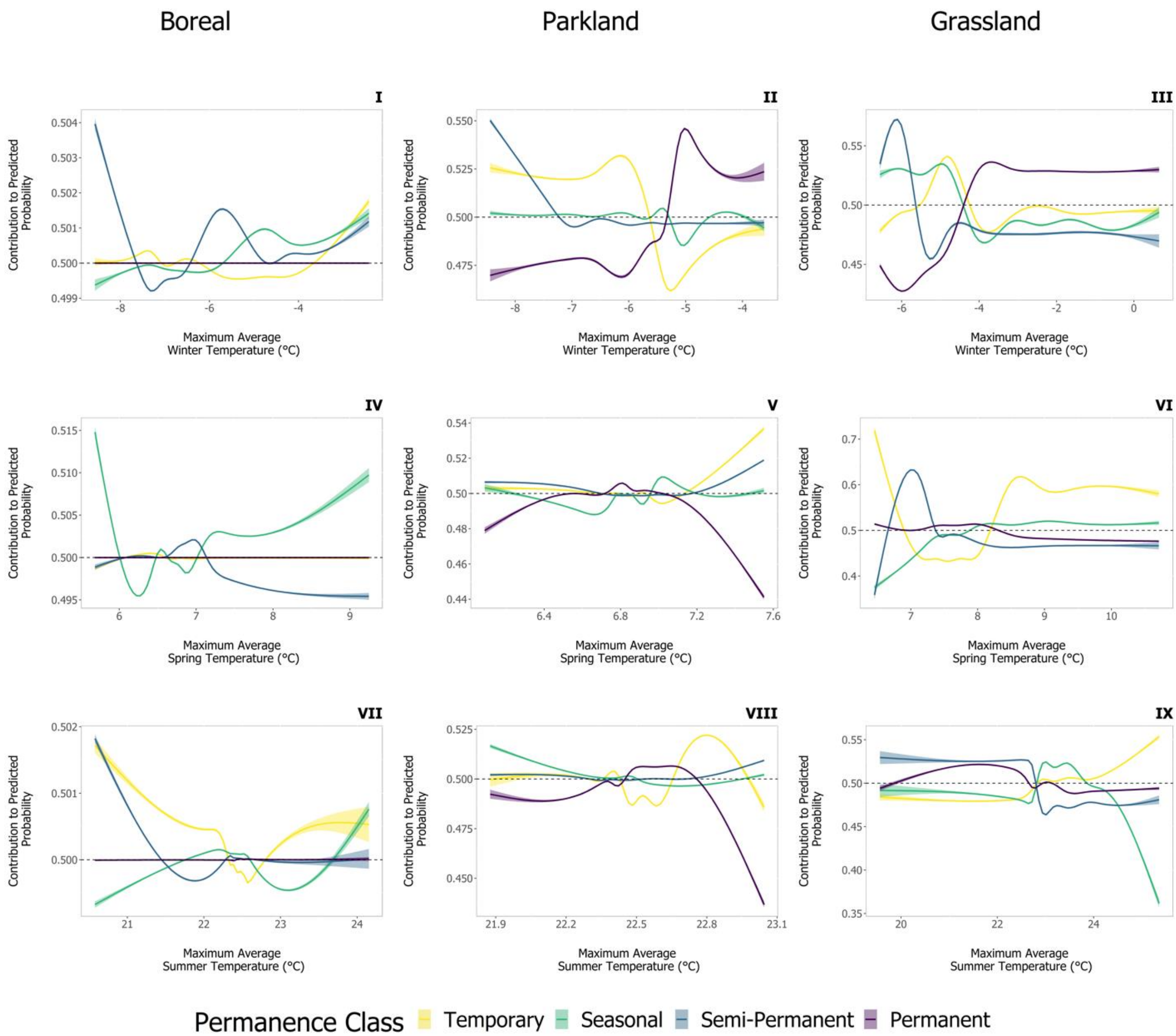

Figure 5. Partial dependence plots for the four wetland classes – temporary, seasonal, semi-permanent and permanent based on temperature metrics. Predicted probabilities below 0.5 suggest that at this measured value of the metric, observing that permeance class is unlikely. We show 95 % confidence intervals and used a generalized additive model-based trend line. Probabilities were derived from extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions.

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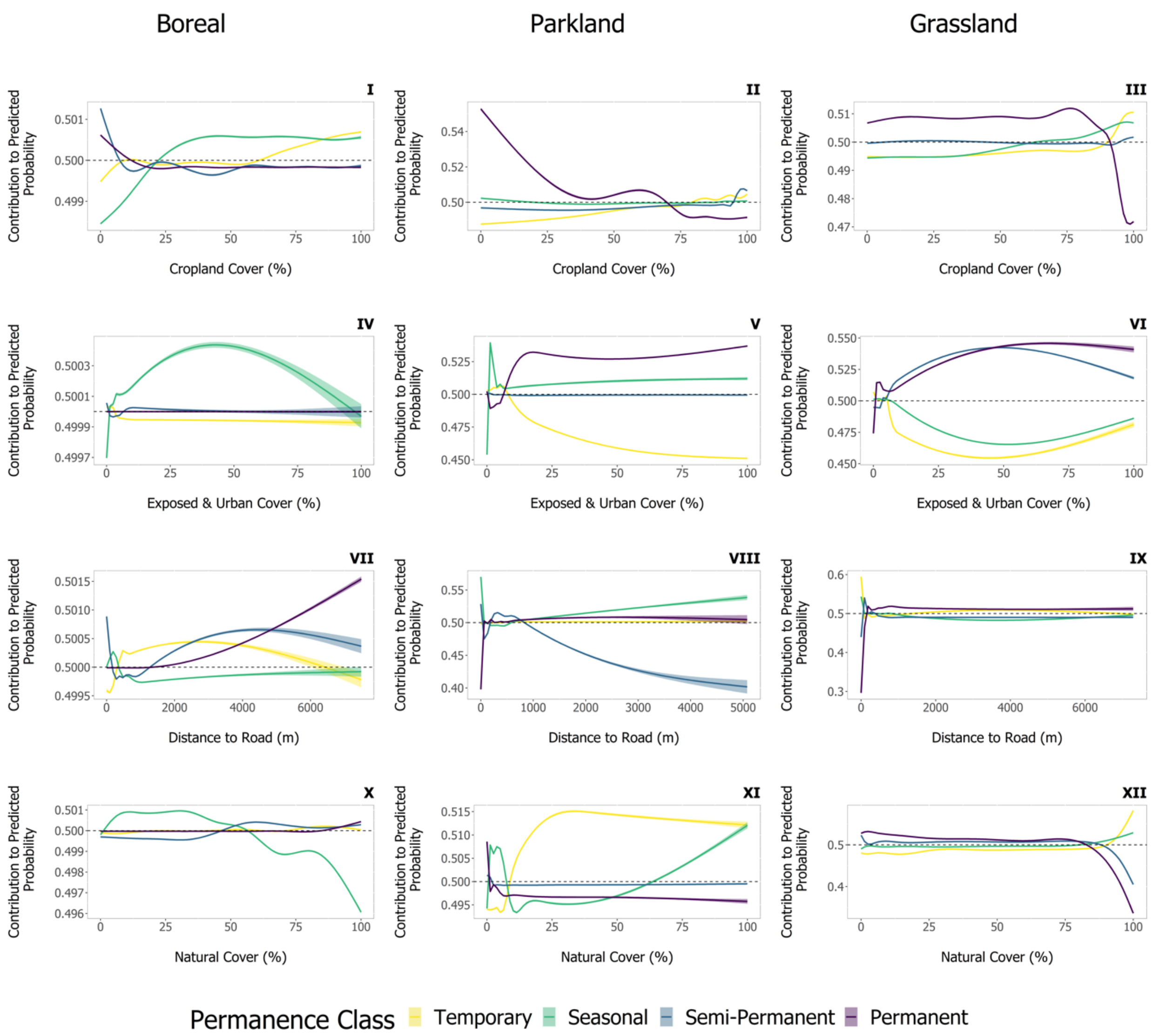

Figure 6. Partial dependence plots for the four wetland classes – temporary, seasonal, semi-permanent and permanent based on land use and land cover metrics. Predicted probabilities below 0.5 suggest that at this measured value of the metric, observing that permeance class is unlikely. We show 95 % confidence intervals and used a generalized additive model-based trend line. Probabilities were derived from extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions.

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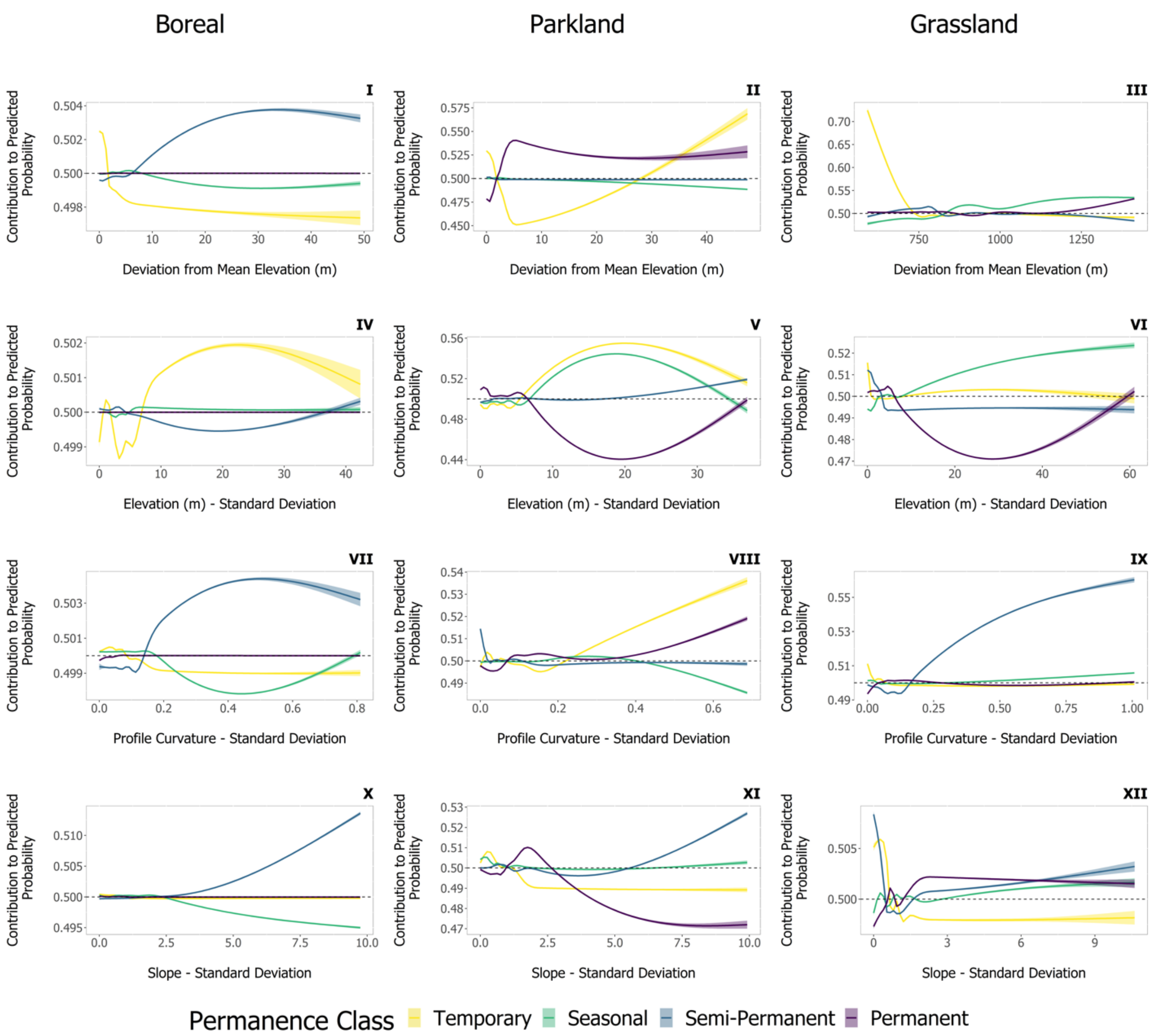

300 **Figure 7.** Partial dependence plots for the four wetland classes – temporary, seasonal, semi-permanent and permanent based on four of eight terrain metrics. Predicted probabilities below 0.5 suggest that at this measured value of the metric, observing that permeance class is unlikely. We show 95 % confidence intervals and used a generalized additive model-based trend line. Probabilities were derived from extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions.

305

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

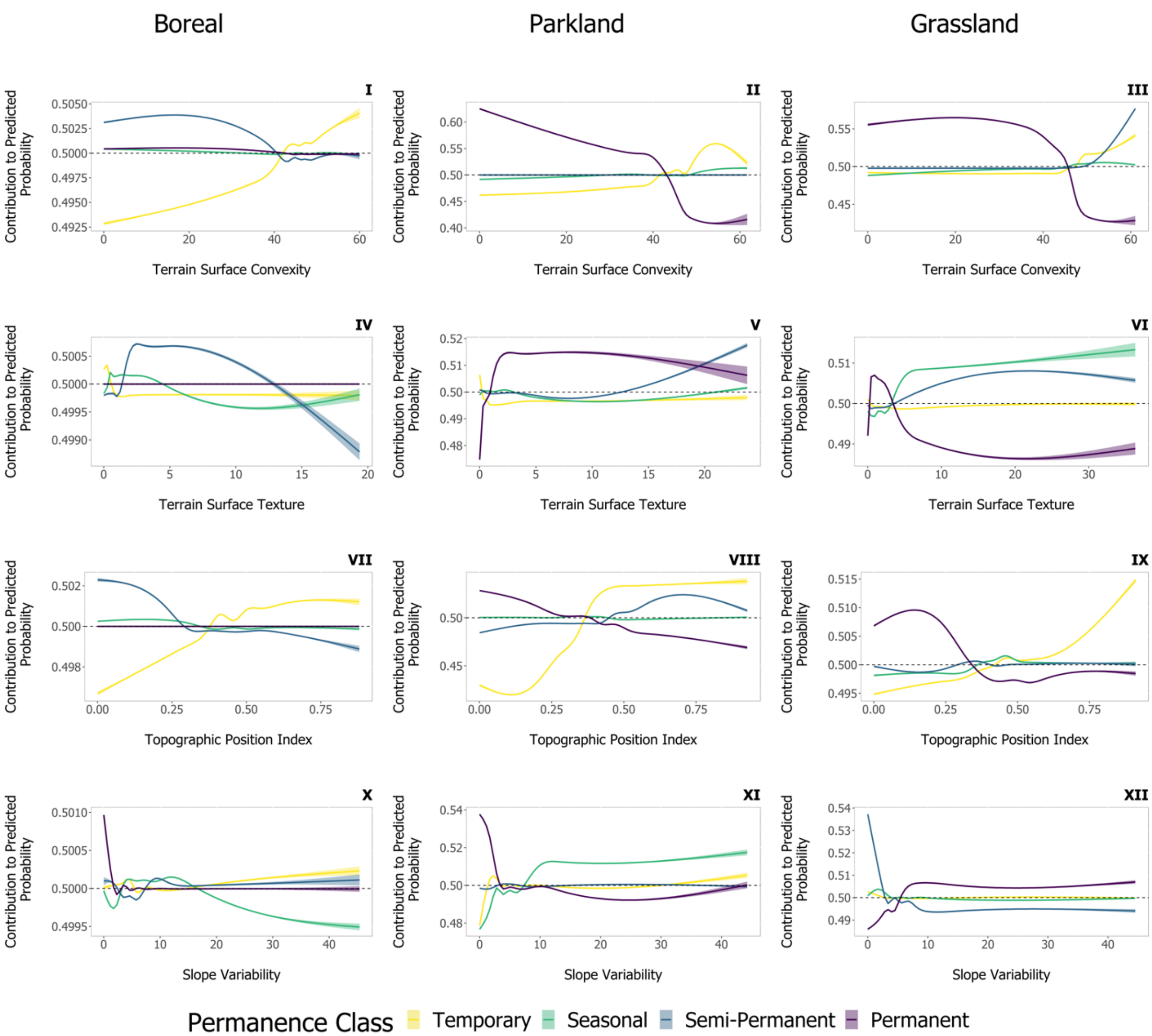

Figure 8. Partial dependence plots for the four wetland classes – temporary, seasonal, semi-permanent and permanent based on four of eight terrain metrics. Predicted probabilities below 0.5 suggest that at this measured value of the metric, observing that permeance class is unlikely. We show 95 % confidence intervals and used a generalized additive model-based trend line. Probabilities were derived from extreme gradient boosting models for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Region.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Appendix A. Descriptions of the four permanence classes included in our study. We describe the typical length of time that these prairie pothole wetlands will contain ponded water, their associated vegetation zones, as described by Stewart and Kantrud (Stewart and Kantrud, 1971), and the number of wetlands belonging to each class in the Alberta Merged Wetland Inventory (Government of Alberta, 2014) that were within the extent of our 25-m Digital Eleveation Model.

Permanence class	**Typical hydroperiod**	**Vegetation zones**	**Natural Region**		
			Boreal	**Parkland**	**Grassland**
Temporary	Until mid-spring, typically for four weeks	Wet-meadow (includes wet-meadow emergent), low-prairie, high seepage	40461	51062	153872
Seasonal	Late spring to early summer for approximately two months	Shallow-marsh (vegetation zones from shallow to deep: emergent plants, submerged aquatic plants), wet-meadow, low prairie	30890	43836	108924
Semi-permanent	Dries fully in drought years only	Deep-marsh (vegetation zones from shallow to deep: emergent vegetation, open-water with bare-soil), shallow-marsh, wet-meadow, low-prairie	39375	47075	12240
Permanent	Open water year-round	Open water, deep marsh, shallow-marsh, wet-meadow, low-prairie	5704	10785	4952

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Appendix B. List of climate, land cover and land use and terrain metrics used to predict wetland permanence class. In this table, we include a description of the significance of each metric for wetland hydroperiod and the proxy metrics we selected. For our analysis, winter months range from November to February, spring April to May and summer June to August. We used Web of Science to conduct this review, limiting the search to papers published between 1950 to 2018, and key words for: 1) the PPR: Prairie Pothole Region, Northern Great Plains, Alberta, Saskatchewan, Manitoba and Dakota; 2) weather: climate, temperature and precipitation; 3) disturbance: land use, agriculture, disturbance, oil and gas, grazing and roads and 4) pond permanence: watershed, hydroperiod, permanence class, catchment and wetland. We used "OR" operators between key words under the same class and "AND" operators between each key word class. For the terrain metrics, we used selected metrics that are commonly used to describe topographic variations, based on a previous review (Branton and Robinson, 2019).

Category	**Variable**	**Significance for Wetland Hydroperiod/Formula**	**Proxy/Class[1]**
Climate	Snowpack/Winter precipitation	Snowpack accounts for 30-60% of ponded water amounts(Hayashi et al., 1998; Tangen and Finocchiaro, 2017) Longer hydroperiods with higher winter precipitation (Collins et al., 2014)	Total Spring Precipitation Total Winter Precipitation Total Precipitation in Winter & Spring Total Spring Snowpack Total Winter Snowpack Total Snowpack in Winter & Spring
	Sumer Precipitation	Longer hydroperiods from increased summer precipitation(Clare and Creed, 2014; Eisenlohr, 1972; Euliss et al., 2014; Leibowitz and Vining, 2003)	Total Summer Precipitation
	Summer Temperature	Evapotranspiration rates/water losses higher in summer (from June)(Heagle et al., 2007)	Average Maximum Temperature in June Average Maximum Temperature in July Average Maximum Temperature in Summer
	Winter/Spring/Summer Temperature	Snowpack may melt too fast with warmer conditions(Crosbie et al., 2013),13]	Average Maximum Temperature in Spring Average Maximum Temperature in Winter Average Maximum Temperature in Spring & Winter
	Precipitation Timing	Fewer wetlands dry up when summer precipitation is earlier in the summer(Meyers, 2018; Vinet and Zhedanov, 2011)	Proportion of Summer Precipitation in June

[1] This differentiates terrain metrics by global (estimated using a 100 × 100-m moving window and mean value within 500-m buffer recorded) and local (estimated within a 500-m buffer of the wetland.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Biogeosciences Discussions
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Category	Variable	Significance for Wetland Hydroperiod/Formula	Proxy/Class[1]
Land Use & Land Cover	Natural Vegetation	Loss of natural cover increases surface runoff (Clare and Creed, 2014)	% Natural Cover
	Cropland Cover	Because soil is less porous (more compacted), much of the accumulated water, either from the snowpack or spring/summer precipitation, flows into the wetland – this increases water levels (van der Kamp et al., 2003; Voldseth et al., 2007)	% Cropland Cover
	Urban Cover	Longer hydroperiods in urban landscapes, mostly because of higher runoff (when compared to those in croplands)(Fossey and Rousseau, 2016)	% Urban Cover & Bare Ground
	Grazing	Grazing lowers snow accumulation (Willms and Chanasyk, 2013), which can increase runoff and hydroperiod(Collins et al., 2014; Niemuth et al., 2010)	% Pastureland
	Culverts/Roads	Lowers hydroperiods by blocking surface runoff(Shaw et al., 2012)	Distance to Road
	Tilling	Can lower pond area/depth, and by extent hydroperiod, as increases in sedimentation can in fill ponds(Skagen et al., 2016)	% Cropland Cover
Terrain Metrics	Mean Elevation (DEM) - Deviation	$\lvert Elevation - Elevation_{mean} \rvert^2$	Local
	Elevation (DEM) - Standard Deviation	$\sqrt{\frac{\sum(Elevation - Elevation_{mean})}{n}}$	Local
	Profile Curvature (PC) - Standard Deviation	$\sqrt{\frac{\sum(Profile\ Curvature - Profile\ Curvature_{mean})}{n}}$	Local
	Slope - Standard Deviation	$\sqrt{\frac{\sum(Slope - Slope_{mean})}{n}}$	Local
	Terrain Surface Convexity	Percentage of upwardly-convex cells within the moving window(Iwahashi and Pike, 2007).	Global
	Terrain Surface Texture	Relative frequency of pits and peaks in a 100 × 100-m moving window(Iwahashi and Pike, 2007)	Global
	Topographic Position Index	$\frac{Elevation_{mean} - Elevation_{min}}{Elevation_{max} - Elevation_{min}}$	Local
	Slope Variability	$Slope_{max} - Slope_{min}$	Local

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

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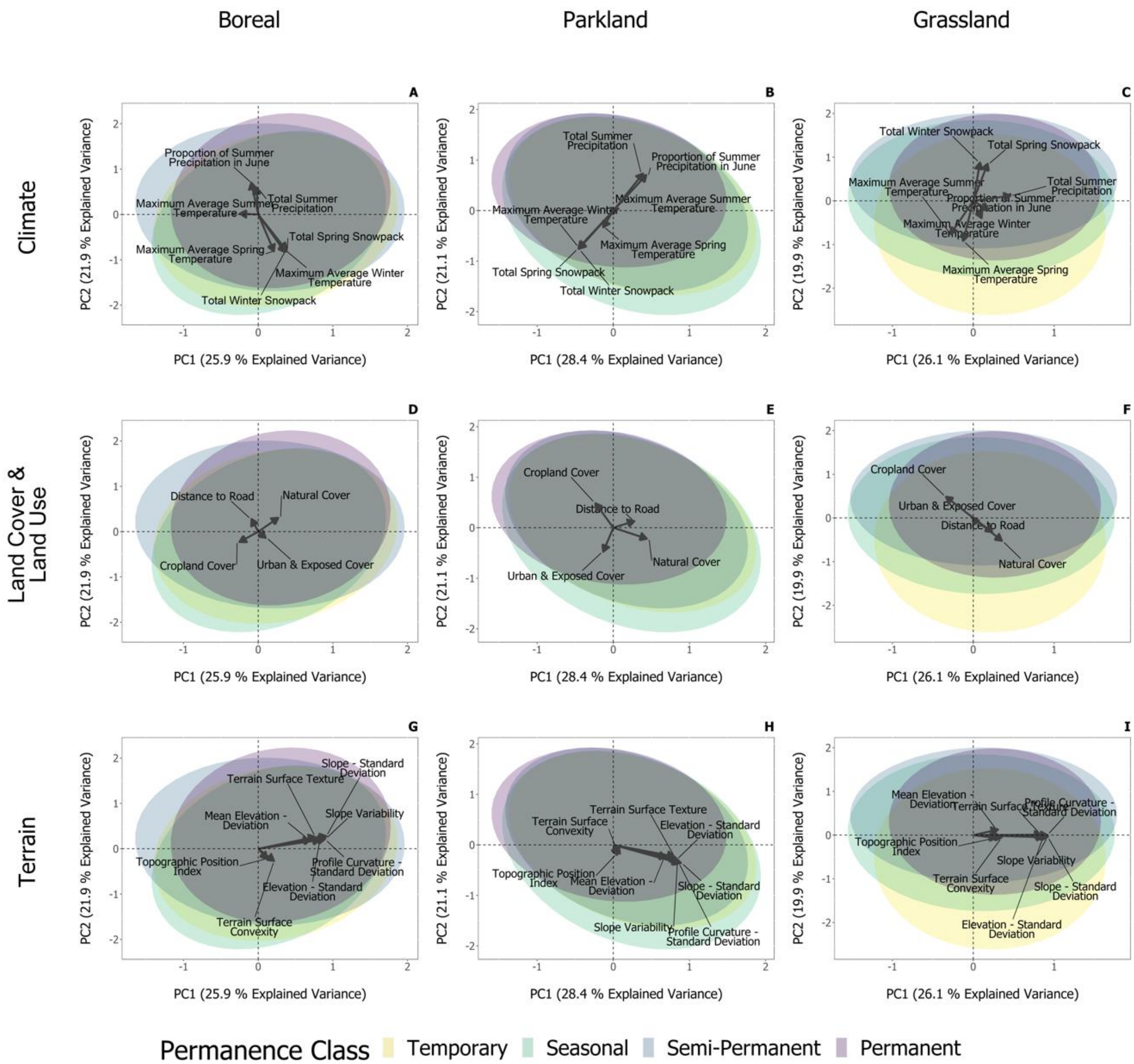

Appendix C. Principal Components Analysis for wetlands delineated in the 1) Boreal (totalling 12,000 wetlands), 2) Parkland (totalling 12,000 wetlands) and 3) Grassland (totalling 16,000 wetlands) Natural Regions. PCAs apply an orthogonal transformation to summarize the data into axes that explain the variance between two correlation matrices. Our data were scaled before implementing the PCA. Vectors on climate (A-C), land use and land cover (D-F) and terrain roughness (G-I) show correlations with both axes. Axis two, for all datasets, represents a hydroperiod gradient and terrain roughness is represented on axis 1.

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Appendix D. List of parameters tuned for the extreme gradient boosting model, a descript of these parameters, their ranges and the ranges evaluated in our cross validation.

Parameter	**Description**	**Range**
Learning rate	Used to control the contribution of each tree to model. Lower values result in the model being more robust to overfitting.	Typical: 0-1 Model: 0-0.3 Boreal (0.01), Parkland (0.1); Grassland (0.05)
Gamma	This controls the complexity of the model. It determines how much loss (difference between prediction and observation) allowable for the formation of a new node.	Typical: 0-20 Model: 0-10 Boreal (8), Parkland (4); Grassland (10)
Maximum depth of a tree	This sets the maximum number of nodes that can exists between the tree root and leaves. The larger the value, the more likely a tree is to overfit.	Typical: 1-7 Model: 1-7 Boreal (5), Parkland (7); Grassland (7)
Minimum sum of instance weight needed in a child	This sets a minimum weight/purity of data (e.g., number belonging to a given group) for spiting to create a new node in a tree. The higher this number is, the more conservative the algorithm will be.	Typical: 1-7 Model: 1-7 Boreal (5), Parkland (3); Grassland (7)
Subsample ratio of the training instance	This sets the number of rows (fractional) that should be included in building a tree.	Typical: 0-1 Model: 0.6-1 Boreal (0.8), Parkland (0.65); Grassland (0.7)
Subsample ratio of columns when constructing each tree	This sets the number of predictors (fractional) that should be considered in each tree.	Typical: 0-1 Model: 0.6-1 Boreal (0.8), Parkland (1); Grassland (0.9)

https://doi.org/10.5194/bg-2021-200
Preprint. Discussion started: 17 August 2021

Appendix E. Value of parameters used in extreme gradient boosting models for our three datasets, the misclassification error rates and number of trees for our models.

Parameter	**Natural Region**		
	Boreal	**Parkland**	**Grassland**
Learning rate	0.01	0.1	0.05
Gamma	4	6	8
Maximum depth of a tree	5	5	7
Minimum sum of instance weight needed in a child	5	5	7
Subsample ratio of the training instance	0.8	0.90	0.70
Subsample ratio of columns when constructing each tree	0.8	1.0	0.90
Misclassification error rate	49.6 (training) 56.3 (test)	52.6 (training) 59.7 (test)	45.3 (training) 50.1 (test)
Number of trees	37	52	46

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Preprint. Discussion started: 17 August 2021

Biogeosciences
Discussions
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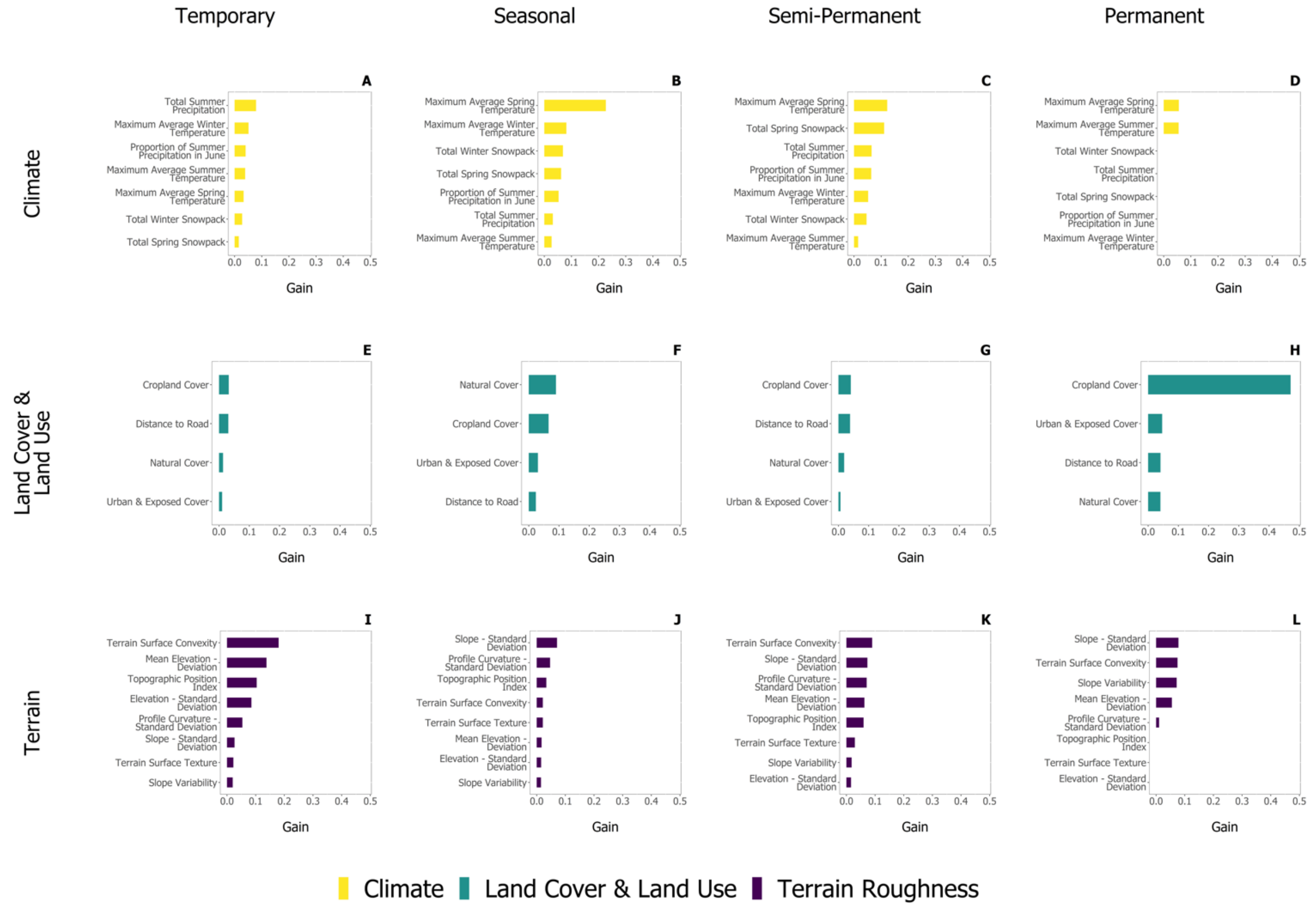
Appendix F. Variables ranked by their importance in the extreme gradient boosting models for wetlands delineated in the Boreal (totalling 12,000 wetlands) by permanence class. These variables were proxies for climate (A-D), land cover and land use (E-H) and terrain roughness (I-L).



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Preprint. Discussion started: 17 August 2021

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Discussions
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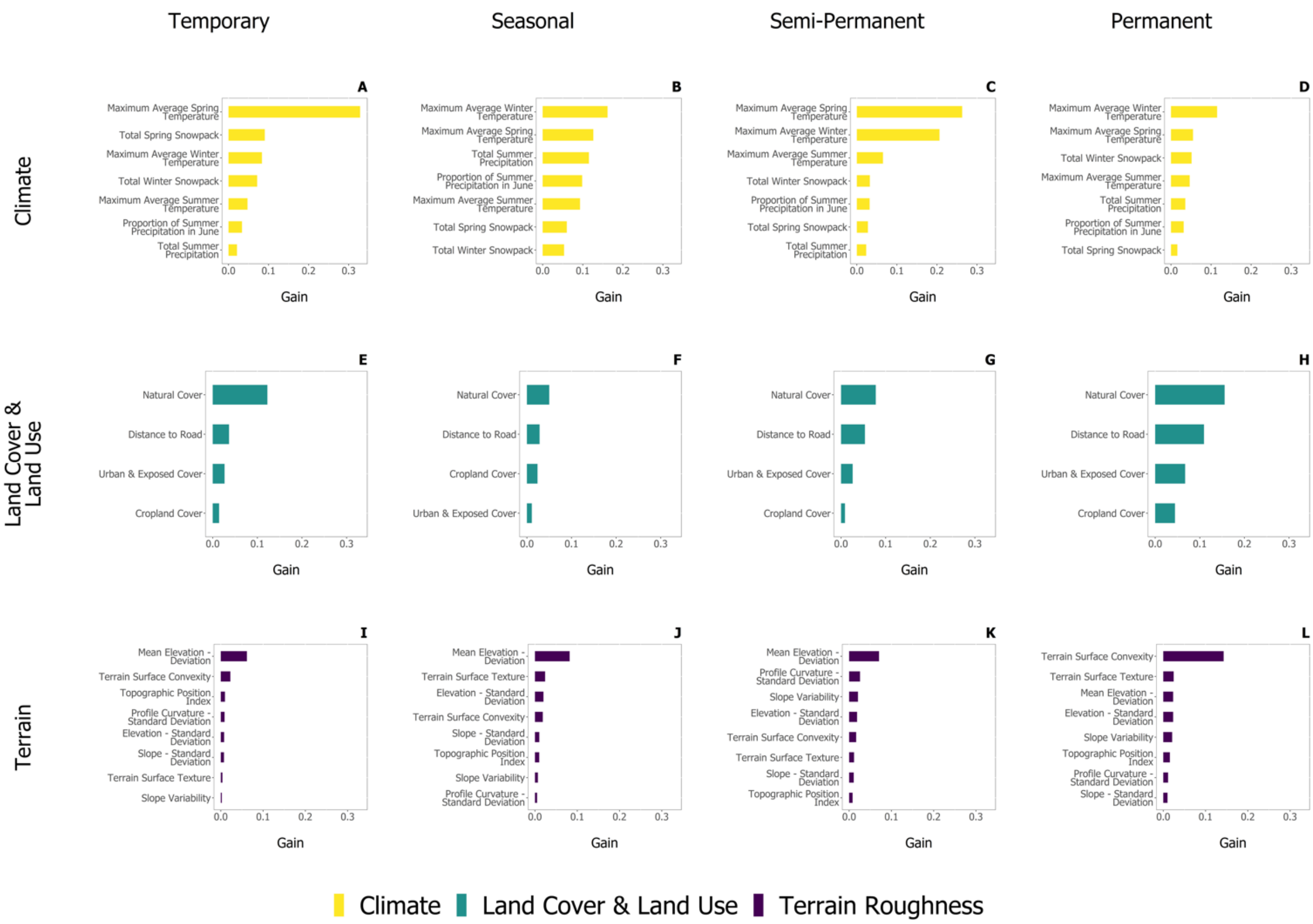
Appendix G. Variables ranked by their importance in the extreme gradient boosting models for wetlands delineated in the Parkland (totalling 12,000 wetlands) by permanence class. These variables were proxies for climate (A-D), land cover and land use (E-H) and terrain roughness (I-L).



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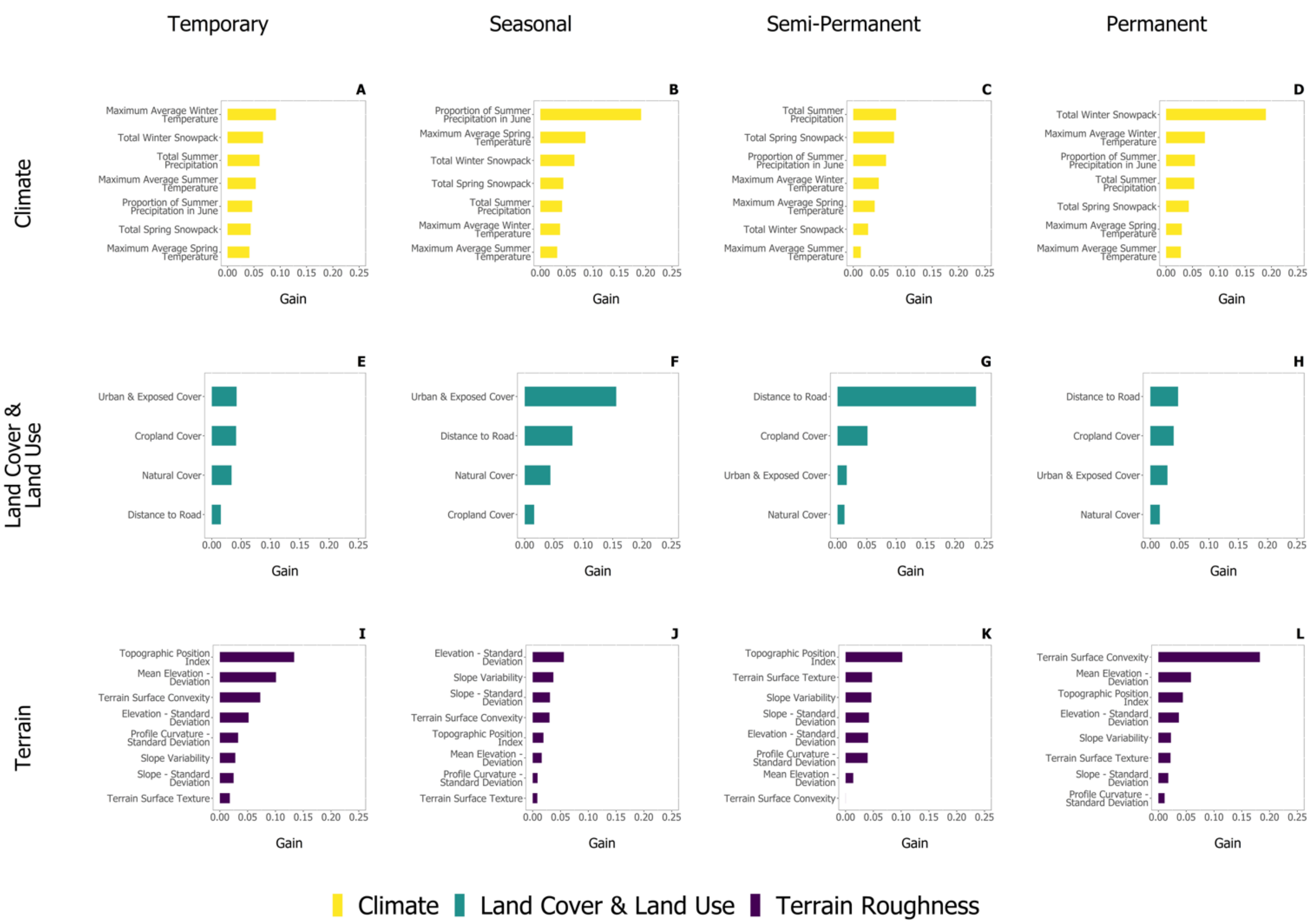
Preprint. Discussion started: 17 August 2021

Appendix H. Variables ranked by their importance in the extreme gradient boosting models for wetlands delineated in the Grassland (totalling 12,000 wetlands) by permanence class. These variables were proxies for climate (A-D), land cover and land use (E-H) and terrain roughness (I-L).



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