Heterogeneous changes to North America prairie pothole wetlands under future climate

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Key Points:

- A wetland model in the Prairie Pothole Region is constructed based on surface water balance and ecoregion and shows reliable wetland extents
- Future projected wetland distribution exhibits strong spatial heterogeneity and seasonal variability in the Prairie Pothole Region
- The eastern PPR faces complex challenges to wetland loss where as wetlands become more abundant in the western PPR in future climate

Abstract

Numerous wetlands in North America's Prairie Pothole Region (PPR) provide important ecosystem services to surrounding areas, yet are threatened by climate and land-use changes. Understanding the impacts of climate change on prairie wetlands is critical to effective conservation planning. In this paper, we construct a wetland model with surface water balance (soil water content) and ecoregions and apply it to predict future wetland distribution under a climate change scenario. The future climate forcing is from a dynamical downscaling approach of a high-resolution convection-permitting regional climate model. The results show that the impacts of climate change on wetland extent are spatially heterogenous and seasonally varied. Future wetter climate in the western PPR will favor increased wetland abundance in both spring and summer. In the eastern PPR, particularly in the moist mixed grassland and aspen parkland, wetland area will increase in spring but experience enhanced declines in the summer due to strong evapotranspiration. When combined with historical patterns of anthropogenic drainage, results suggest that diverse conservation and restoration strategies will be needed. The outcomes of this study will be useful to conservation agencies to ensure that current investments will continue to provide good conservation returns in the future.

1 Introduction

The Prairie Pothole Region (PPR) contains millions of small wetlands within topographic depressions (also known as prairie potholes) across five states in the U.S. (Iowa, Minnesota, North Dakota, South Dakota, Montana) and three provinces in Canada (Alberta, Saskatchewan, Manitoba). The Canadian portion of the PPR is also referred as the Canadian Prairies. These prairie pothole wetlands provide important ecosystem services, including improving water quality, water regulation, and supporting biodiversity, especially as crucial habitat for a large proportion of North America's waterfowl (Gleason et al., 2008; Johnson et al., 2010; Niemuth et al., 2014; Hayashi et al., 2016). As a result, the PPR is the focus of conservation programs in both Canada and the U.S. However, wetlands in the PPR face threats from land-use conversion to cropland and possible threats from climate change-related drying.

In the PPR, prairie wetlands exist because of key interactions among topographic, geological, and climatic conditions in this region (van der Kamp and Hayashi, 2009; Hayashi and van der Kamp, 2016). These local depressions, with large areas of hummocky landscapes, were formed by clay-rich glacial till deposition from the continental ice sheet during Pleistocene glaciation. The local topographic variation (hollow and hummock) favors the convergence of surface and shallow groundwater runoff in local depressions. On the other hand, cold winters allow snow accumulation on the ground and sub-surface soil freezing, strongly affecting the water storage in the next year's spring (Ireson et al., 2013). The PPR also has a semi-arid climate and wetlands are most abundant in May, with basins drying out through the summer. Some wetlands remain inundated longer if they are connected with shallow groundwater and/or receive water from summer precipitation. Consequently, the water balance of prairie wetlands is highly sensitive to the variability of shallow groundwater and precipitation (Hayashi et al., 2016). However, the exchanges between shallow groundwater and sub-surface soil have often been neglected in previous observation and modeling studies.

Given the importance of prairie wetlands to wildlife habitats and biodiversity, it is necessary to understand the impacts of future climate change on prairie wetlands, especially for designing conservation policies and prioritizing management (Moilanen et al., 2009; Ando and Mallory, 2012). For this purpose, a common research method is to link spatial wetland distribution, from wetland surveys, with long-term climatic conditions, such as temperature, precipitation, and soil moisture, etc. (Herfindal et al., 2012; Niemuth et al., 2014; Garries et al., 2015; Sofaer et al., 2016). Statistical relationships are often constructed to explore the environmental factors' influence on wetland distributions on a yearly basis. The major variation in wetland distribution can be explained by these climatic records and is sensitive to surface water balance, the wetness conditions on surface. However, many of these statistical methods used precipitation and temperature, but not directly the surface water balance, to imply surface wetness condition. A more physical-based approach is needed to consider the complex hydrometeorological interactions within prairie wetlands.

Studying the impacts of climate change on wetland distribution depends heavily on reliable climate projections from general circulation models (or global climate models, GCMs). However, the coarse resolution of GCM outputs (50~100 km) is not suitable for modelling prairie wetlands owing to their fine scale (10~1000 m). Additionally, GCM-projected future precipitation forecasts are highly uncertain depending on the choice of convection parameterizations, a mathematical description of the convection processes within each model grid cell (Prein et al., 2015; Kendon et al., 2017). This is problematic as precipitation is the key water input for prairie wetlands. Furthermore, shallow groundwater dynamics are strongly connected to wetlands in the PPR, but this process has been simplified or even neglected in many coarse-resolution GCMs, and could result in overprediction of dry surface conditions in the wetland-abundant landscape of the PPR.

Detailed studies of the impact of climate change on prairie wetlands require downscaling of GCM outputs. A convection-permitting regional climate model (CPRCM, resolution < 5-km) has the advantages of improved precipitation forecast as well as detailed representation of surface properties. In such high resolution, convection parameterization can be switched off and the CPRCM can improve precipitation simulation, in terms of diurnal cycle, frequency and intensity (Prein et al., 2015; Kendon et al., 2017). Furthermore, the high spatial resolution also benefits the representation of surface properties, such as topography, land-use and soil properties, which are beneficial to representing fine-scale prairie wetlands.

The purpose of this study is to investigate the impacts of climate change on the future abundance and distribution of wetlands in the PPR. For this purpose, we used the meteorological forcing from a long-term high-resolution CPRCM in the Contiguous U.S. (CONUS, Liu et al., 2017) to drive a physically-based land surface model, Noah-MP (Niu et al., 2011; Yang et al., 2011), with detailed groundwater dynamics (GW, Miguez-Macho et al, 2007; Zhang et al., 2020). The study has two parallel simulations for both current and future climate scenarios. The hydrological outputs from Noah-MP are used to construct a wetland model that reflects the spatial and temporal variation of prairie wetlands, validated using wetland datasets and remote sensing products. Then, we are able to investigate the impacts of hydrological shifts on future prairie wetland abundance and spatial distribution, and the contributions from different water balance components. Finally, we compare the spatial concordance of future wetland distribution and historical wetland drainage in the PPR, demonstrating the potential hazards arising from the combination of climate change and anthropogenic drainage. Results of this study have important implication for wetland conservation, especially for decision-making on prioritizing conservation investments across the PPR.

2 Data and Models

In this study, we model the relationship between variation in water balance and wetland area. First, we constructed a statistical wetland model using Ducks Unlimited Canada's (DUC) Canadian Wetland Inventory (CWI). We modelled wetland area as a function of a physically based variable, soil water content (SWC), which is an indicator for surface water balance. SWC was simulated by the coupled land-groundwater model (Noah-MP-GW), forced by dynamical downscaling of a CPRCM. We use the hydrological simulation from current climate, from October 2000 to September 2013, in the PPR as the baseline of our study, hereafter CTRL simulation. CTRL is contrasted with a Pseudo Global Warming (PGW) scenario to predict changes to wetland abundance and distribution under climate change. The wetland fraction from CTRL was evaluated against another spatial wetland dataset, a model-based wetland product - the Adjusted CanVec (Adj_CanVec). For temporal validation of the wetland model, we use a wetland area time-series derived from the Landsat satellites using Multiple Endmember Spectral Mixture Analysis (MESMA).

2.1 Available wetland datasets

The CWI classifies wetlands according to the Canadian Wetland Classification System (National Wetlands Working Group, 1997) and, in the prairies, delineates wetland basins from stereo pairs, with a minimum mapping unit of 0.02 ha. In the protocol used, the wetland extent spans the wet meadow vegetation zone to the deepest point of the basin and represents the depressional area capable of holding water. Shapefiles from the CWI were compiled into a high-resolution single geodatabase for the PPR to represent wetland fractional area in 4-km grid cells (F_{wet},Fig. 1(a)). Given the challenges in mapping small wetland features, the CWI represents the best available map of prairie wetlands, though it has incomplete coverage of the Canadian prairies.

For a product with prairie-wide coverage, we used a modelled spatial layer, Adj_CanVec (Fig. 1(b)). CanVec is a vector dataset developed by Natural Resources Canada (Natural Resources Canada, 2008). It has good spatial coverage but does not capture all small wetlands and has variable scale (1:10000~1:50000) and accuracy. DUC used CanVec hydrography and water saturated soils features, Soil Landscape of Canada data (Soil Landscapes of Canada Working Group, 2007), and CWI to generate predictive equations to scale CanVec 3.0 data to the high-resolution CWI data in the prairies. Because it is difficult to separate out wetlands and lakes in the CanVec data, the Adj_CanVec includes some non-wetland waterbodies such as shallow prairie lakes. A layer of MODIS-derived water mask was applied to remove large water bodies at 4-km grid scale (n = 174 grid cells).

Fig. 1(a&b) shows the distribution of F_{wet} from CWI and Adj_CanVec in the Canadian Prairies. The Adj_CanVec shows a high wetland fraction close to the northern boundary of PPR in the aspen parkland. Fig. 1(c) is a scatter plot of F_{wet} from these two datasets with their histogram on the top. The majority of the data points are below 0.3, while Adj_CanVec has a longer tail of high F_{wet}. And Fig. 1(d) takes a closer look at the two datasets of F_{wet} from 0 to 0.4. It is evident that most data points are smaller than 0.3 and Adj_CanVec has a tendency for higher F_{wet} than the CWI.

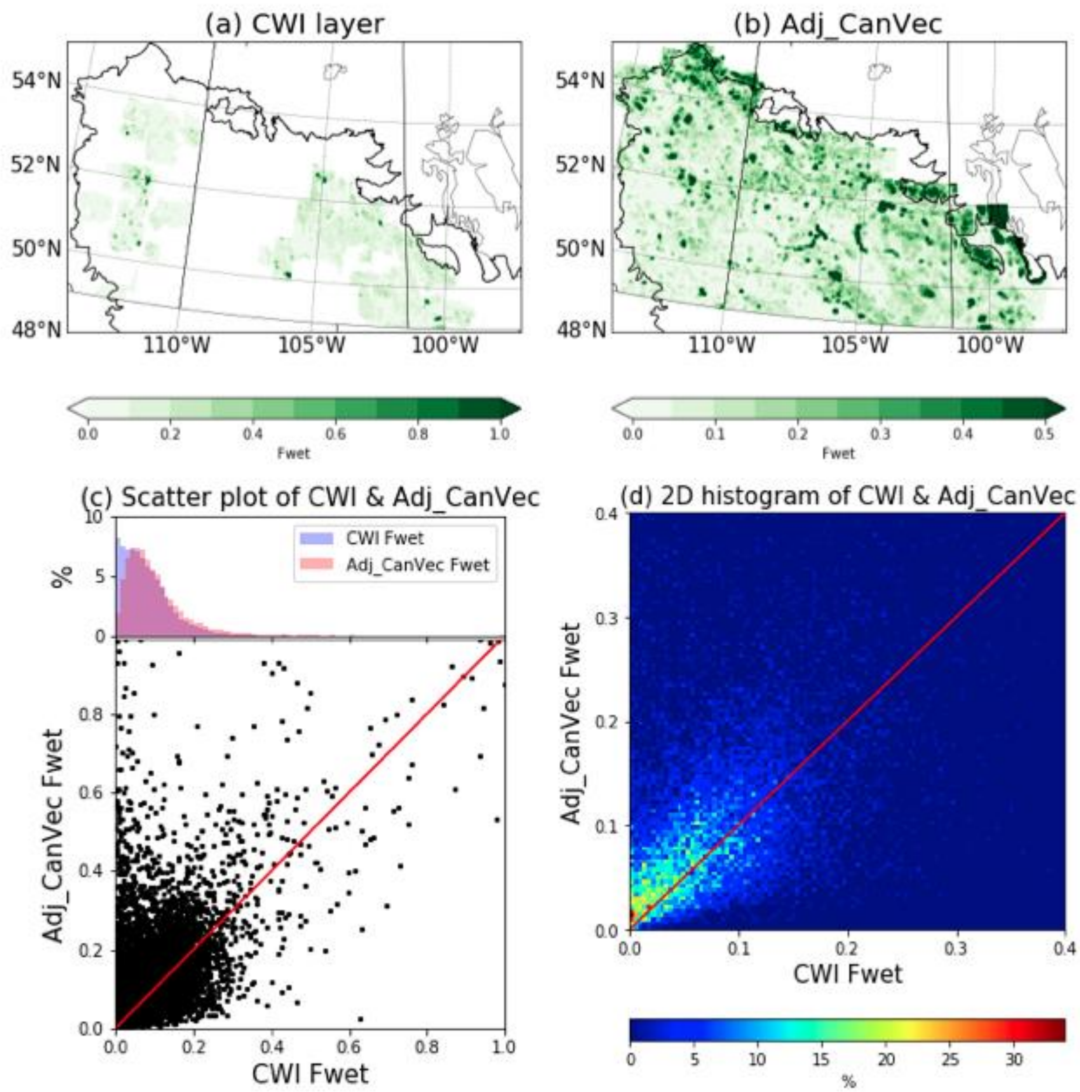

Figure1 (a) F_{wet} spatial distribution from the Canadian Wetland Inventory (CWI); (b) F_{wet} spatial distribution from Adj_CanVec, a modelled wetland dataset; (c) scatter plot (bottom) and histogram (top) of F_{wet} of the CWI (blue) and Adj_CanVec (red) and (d) a 2D histogram of F_{wet} from 0 to 0.4.

Due to the strong wet-dry cycles in the prairies, wetland extent varies both through space and time. However, the CWI and Adj_CanVec are both static products meant to represent long-term conditions and are thus not suitable for evaluating the temporal performance of the statistical model. We investigated temporal changes in wetland fraction in the Smith Creek watershed (50°50'N 101°34'W) in the PPR. This 414 km^2 watershed is a long-term established research site for wetland hydrology in the PPR (Dumanski et al., 2015; Pattison-Williams et al., 2018). To study the temporal dynamics of F_{wet} in the Smith Creek watershed, we used Multiple Endmember Spectral Mixture Analysis (MESMA) to estimate annual changes in wetland extent (see Appendix 1 for a detailed description of the MESMA method). A time series from 1984-2019 is presented in this study and used to evaluate the wetland model F_{wet} dynamics for CTRL simulation from 2001 to 2013 (see section 3.3).

2.2 Climatic and hydrological data

The climatic conditions in this study are derived from two parallel regional climate simulations for current and future climate conditions (Liu et al., 2017). Both simulations were dynamically downscaled using the Weather Research and Forecast model (WRF, Skamarock et al., 2008) in convection-permitting resolution (4-km) in the Contiguous U.S. and southern Canada. The CTRL simulation spins from 2000 October to 2013 September, and uses the 6-hr ERA-Interim reanalysis data as the boundary condition. In the PGW simulation, the boundary forcing was created by adding a delta climate change signal, derived from an ensemble of GCM output by the end of 21st century in RCP8.5 emission scenario, upon the ERA-Interim reanalysis. Therefore, the scientific assumption in PGW is that the atmospheric circulation pattern is similar to the current climate, while the climate background is warmer and moister. The two parallel CPRCM outputs are important for our study, as they provide not only high-resolution output but consistency in attributing the differences in climate forcing, hydrological factors, and wetland distributions to climate change.

To characterize variation in weather, we derived hydrological covariates from gridded output from the Noah-MP-GW model (ver 4.0.1). Noah-MP was originally developed to improve the representation of land surface in climate models and can be used in the stand-alone mode to simulate energy and water for hydrological impact studies (Niu et al., 2011; Yang et al., 2011). The Noah-MP-GW model was forced with hourly data, including temperature, precipitation, humidity, wind, pressure, short and long-wave radiation. It simulated major storage and flux terms of energy and water, including snow water equivalent, sublimation, evaporation, soil moisture, and groundwater recharge (Barlage et al., 2015; Zhang et al., 2020).

In this study, we applied the soil water content (SWC) from a previous groundwater study in the PPR (Zhang et al. 2020). The model-simulated SWC is a good indicator of surface water balance:

$$\Delta SM = P - ET - SR - G \qquad (1)$$

$$SWC = \frac{SM}{SM_{max}} \qquad (2)$$

The net change of soil moisture (*SM*) is the combination of precipitation (*P*), evapotranspiration (*ET*), surface runoff (*SR*) and groundwater recharge (*G*). And SWC takes a standardized form divided by the maximum soil water holding capacity, which is a parameter dependent on the soil type. Note that in the eastern and northern PPR, groundwater is close to the surface and the two-way exchange between soil water and groundwater should be considered. This two-way exchange is characterized by G: positive G means underground drainage and negative G means groundwater supplies soil moisture.

2.3 Ecoregions in the Canadian Prairies

Wetland density varies across the PPR, influenced by both geographic and climatic factors. Figure 2 shows 8 major ecological regions in the Canadian Prairies, as defined by the Ecological Land Classification (Statistics Canada, 2017). Ecoregions categorize broad landscapes based on distinctive regional ecological factors including climate, physiography, vegetation, and soil, and thus have the potential to explain spatial variation in wetland area not covered by hydrological or climatological variables. Ecoregion was therefore used as a categorical factor in the wetland fraction statistical model. The ecoregions only include those where there was overlapping coverage with the CWI. Ecoregions not represented in the CWI were either excluded from analysis (Lake Manitoba Plain) or recoded to an adjacent ecoregion (Cypress Upland reclassified as Mixed Grassland, Wabasca Lowlands and Interlake Plain recoded as Mid-Boreal Uplands). Reclassified grid cells represent less than 1% of all grid cells.

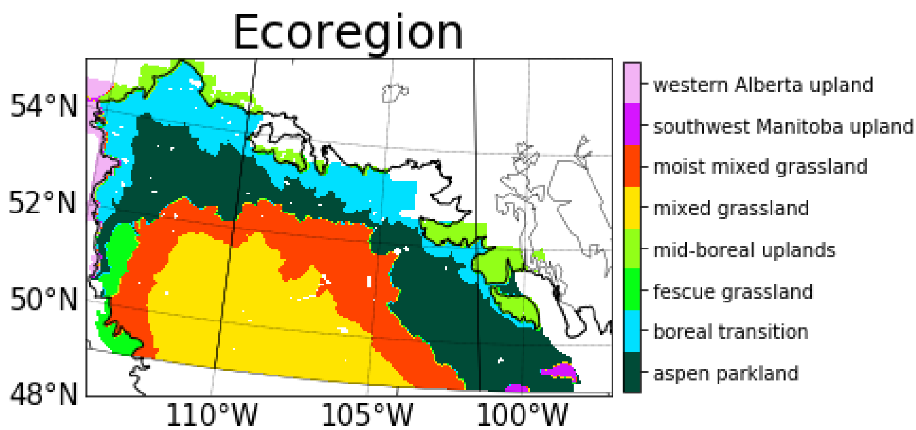

Figure 2. Ecoregions in the Canadian Prairies. Black contour outlines the Prairie Pothole Region and the filled colors represent the 8 ecoregions as used in the wetland model. The area where Adj_CanVec data are unavailable are blank.

2.4 Statistical model

In this study, we used a generalized additive model (GAM) to analyze the relationship between wetland fraction and hydrological and ecological covariates. GAMs accommodate a variety of response distributions/link functions and allow for flexible, additive effects of predictor variables (Hastie and Tibshirani, 1990). In this study, we fit the following statistical model:

$$g\big(E(Fwet)\big) = s(SWC) + ER \qquad (3)$$

We used a binomial distribution and logistic link of wetland fraction (i.e., $g(p) = \ln(p/(1-p))$, a smooth function of soil water content ($s(SWC)$) , and intercept-adjustments for each of eight ecoregions (ER). The fitted model was used to predict current wetland fraction (*Fwet*_CTRL), which was evaluated against Adj_CanVec data in the Canadian Prairies. Finally, to study the impacts of future climate change, we substituted SWC from the future climate model scenario (PGW) to predict future wetland fraction (*Fwet*_PGW). The difference between *Fwet*_PGW and *Fwet*_CTRL can be attributed to the impacts of climate change.

2.5 Model evaluation and sensitivity

Fig. 3 shows the evaluation results from *Fwet*_CTRL, predicted by the GAM model, and the mean Adj_CanVec, at the grid scale histogram (Fig. 3(a)) and ecoregion scale scatter plot (Fig. 3(b)), respectively. We see that the average ecoregion *Fwet*_CTRL tends to be lower than average Adj_CanVec, but they covary positively, with both indices similarly ranking the ecoregions with respect to wetland fraction. The root-mean-square-error of the model prediction in current climate is 0.1020 and for 89% of the grids, abs (*Fwet*_CTRL - Adj_CanVec)| < 0.1.

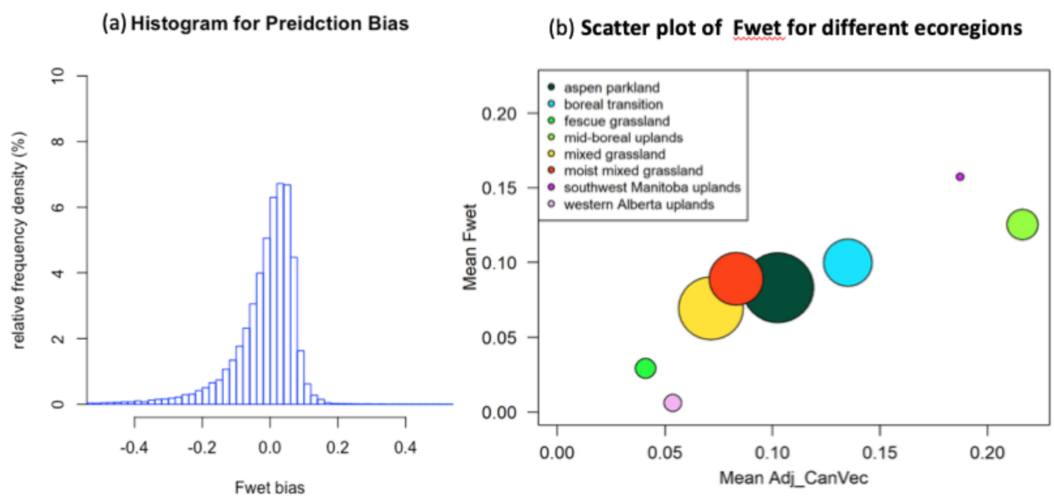

Figure 3. (a) Histogram of the model bias (*Fwet*_CTRL-Adj_CanVec), y axis label is the relative frequency density of the whole grid cells in the Canadian Prairies; (b) scatter plot of mean *Fwet*_CTRL compared with mean Adj_CanVec by ecoregion. Point sizes are proportional to the square root of sample sizes.

As the soil water content and ecoregions are the two predictors in our statistical model, wetlands in different ecoregions may respond differently to perturbed climate conditions. Figure 4 shows the aggregated change in *Fwet* in eight ecoregions in the Canadian Prairies with perturbed SWC, to illustrate the sensitivity of *Fwet* to changes in SWC. Given that the statistical model fitted is additive in the effects of ecoregion and *s(SWC)*, perturbed change of 1% in SWC may translate into non-linear responses to *Fwet*, depending on the ecoregion. For the whole domain, the model-predicted *Fwet* increased at twice the rate of the perturbed change in SWC in the Canadian Prairies. There is a clear gradient in the response of wetland fraction to SWC, with a weaker response in the moist southwest Manitoba uplands and aspen parkland compared with strong responses in drier regions including the western Alberta uplands, mid-boreal uplands, and fescue grassland.

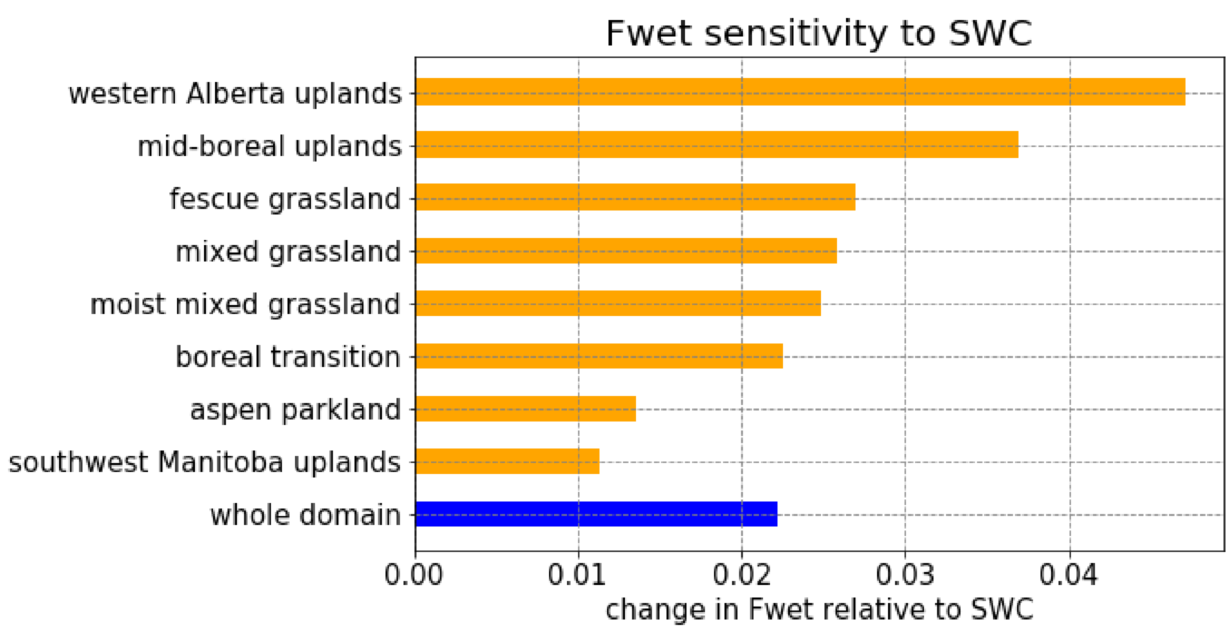

Figure 4. Bar plot of change in *Fwet* relative to a 1% increase in SWC for the entire domain and eight ecoregions.

3 Results – Wetland changes in future climate

In this section, we describe wetland change in the future climate scenario (PGW), including both spatial distribution and temporal variation. The spatial distribution of annual mean wetland fraction is shown for CTRL and PGW. Then, to illustrate the strong intra-seasonal variation, we contrast wetland fraction in spring and summer. Finally, to demonstrate the model's performance to capture inter-annual variation, a timeseries analysis of Smith Creek watershed in Saskatchewan is compared with the timeseries of open water fraction derived from the MESMA method.

3.1 Spatially heterogeneous wetland changes

The model results from CTRL and PGW show a similar spatial pattern. There exists a spatial gradient of wetland fraction from the wetland-dense areas in the aspen parkland to relatively lower wetland fraction in the mixed grassland in the southwest PPR. This gradient generally agrees with the soil moisture gradient, as it reflects the surface wetness. However, the climate change impacts on wetland fraction show strong spatial heterogeneity. Here we present the impacts on *Fwet* between current and future climate as the relative change between *Fwet* _CTRL and *Fwet* _PGW, calculated as ((*Fwet* _PGW- *Fwet* _CTRL)/*Fwet* _CTRL). For the area in southwest mixed grassland in Alberta and Saskatchewan, projected F_{wet} increases by more than 30% (Fig. 5(c&d)). In contrast, for the moist mixed grassland and mid-boreal uplands regions in Manitoba, which is a wetland-dense area under current climate, a decline in wetland fraction of about 20% is evident (Fig. 5(e)).

Fig. 5(d&e) shows the water balance components in the areas circled in blue and red in Fig. 5(c), where significant wetland losses appear due to climate change. They are corresponding to mixed grassland and mid-boreal upland, respectively. In the mixed grassland (d), the total available water (*P-ET*) is projected to decrease for a minimal amount (-1 mm), compared to significant amount reduced (-11 mm) in mid-boreal uplands. The net loss of available water is common to all ecoregions (see Fig. S1). It is noteworthy that the sign of groundwater contribution is different in these two regions: in negative sign (-7 mm) in mixed grassland shows soil water drains downwards to recharge groundwater, while the positive sign (2 mm) in mid-boreal uplands shows groundwater supplies upper soil water through capillary rise. This means groundwater aquifer is acting as a buffer that absorbs excessive water when upper soil is wet and sustain upper soil moisture and the wetlands when it's dry. The change in surface runoff is not significant in these regions. A complete water balance analysis for all eight ecoregions is provided in the supplemental information.

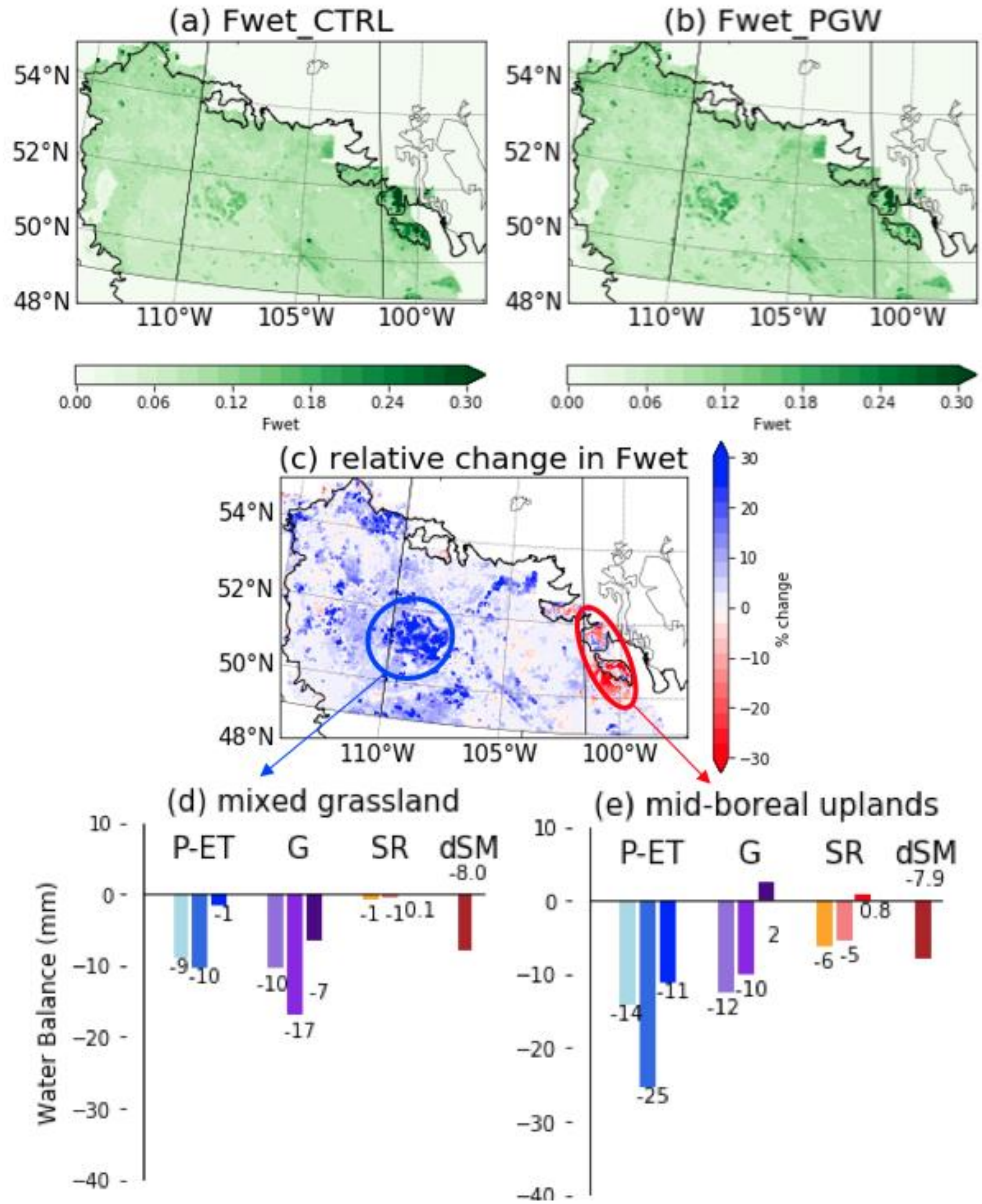

Figure 5. Mean *Fwet* from (a) current climate (*Fwet*_CTRL), (b) future climate (*Fwet*_PGW), and (c) their relative change (*Fwet*_PGW- *Fwet*_CTRL)/ *Fwet*_CTRL. The blue and red circle in (c) highlights the wetland gain in mixed grassland and loss in mid-boreal uplands. Their water balance (mm) figure from spring through summer (March-August) are shown in (d&e). Three bars of each water balance component (precipitation-evapotranspiration [*P-ET*], groundwater [*G*], surface runoff [*SR*]) are shown, the first one is for CTRL, the second one is for PGW, and the third one is for the change of PGW-CTRL, and *dSM* represents the net change in soil moisture.

3.2 Temporally fluctuating wetland changes

In addition to spatially heterogenous changes in the future wetland distribution, climate change will also alter the hydrological cycle, which leads to temporally fluctuating wetland abundance at both intra- and inter-annual scales. Figure 6 separates the climate change impacts on wetland fraction in two seasons, spring (March-April-May, MAM) and summer (June-July-August, JJA) and the changes in water balance components in these two seasons between CTRL and PGW (PGW-CTRL). The yellow and green symbols in Fig. 6(c&d) corresponds to the mixed grassland and mix-boreal uplands in Fig.5 (c-e). The mixed grassland always has the highest available water value in spring and summer (PGW-CTRL) in all ecoregions, while in mid-boreal uplands the available water is much less than other ecoregions.

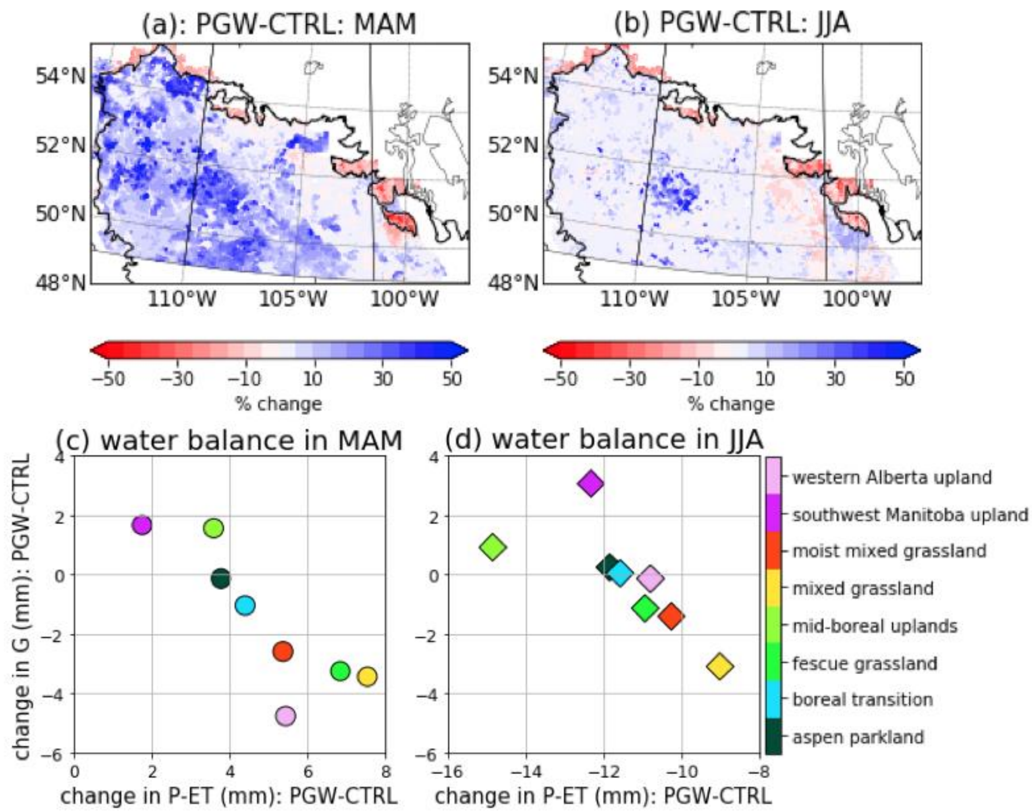

Figure 6. (a) Seasonal *Fwet* changes in spring (MAM), and (b) summer (JJA) between future and current climate (PGW-CTRL), relative to the CTRL values; (c) scatter plot of water balance change (PGW-CTRL) in MAM and (d) JJA for eight ecoregions. The x-axis is the available water (*P-ET*) and the y-axis is the contribution of groundwater.

In the western PPR, wetland fraction under PGW is greater in both spring and summer when compared with CTRL, though the trend is more pronounced in the spring. On the other hand, in the eastern PPR, wetland fraction changes little in spring and declines ~20% in summer. The areas which are most vulnerable and impacted by climate change lie along the mid-boreal uplands ecoregion at the northern edge of the PPR, showing consistent drying in both spring and summer. In a semi-arid region like the PPR, there is a drying signal from spring to summer, due to strong evapotranspiration. This drying signal is stronger and extends over larger regions in the projected future climate. Intensified drying, and associated loss of wetland area, is projected to be especially strong in areas that are currently more humid, such as southeast Saskatchewan and southwest Manitoba.

Fig. 6(c) and (d) represent the change in water balance (PGW-CTRL), in eight ecoregions in MAM and JJA. A significant shift in available water (*P-ET*) is evident, from positive (surplus) in spring to negative (deficit) in summer. On the other hand, the change in *G* (PGW-CTRL) represents net contribution from groundwater to soil moisture, with positive values indicating less underground drainage and negative values more underground drainage. There is an almost linear relationship between the change in available water and groundwater contributions in these eight ecoregions from PGW-CTRL indicating that the more water is available for partitioning, the more that will be lost due to underground runoff. Two ecoregions, southwest Manitoba uplands and mid-boreal uplands, stand out in the water balance analysis, as the net groundwater contribution is always positive through spring and summer. This again highlights the important buffer effect of groundwater in maintaining surface water balance in regions where the water table is shallow, further reinforcing why this process should not be neglected in land surface hydrological models.

Fig. 7 shows the timeseries of F_{wet} in the Smith Creek watershed, in southeast Saskatchewan. The average values for F_{wet} from April to September are shown for MESMA and model-simulated F_{wet} under CTRL and PGW climate (annual average plus seasonal range for spring and summer). The MESMA timeseries from 1984 to 2019 reflects the fluctuations in F_{wet} through wet-dry cycles, showing that wetland fraction in the watershed has fluctuated by more than 5% over the last couple decades (equivalent to wetland area varying by 21.7 km^2 between the wettest and driest years). The modeled F_{wet} from CTRL often underestimates the absolute value, but generally matches an increasing trend of the F_{wet} from the MESMA method, for the 13-year period The underestimate of CTRL is less than 0.01 (F_{wet}_CTRL- F_{wet}_MESMA) of the 4-km grid cell and could be due to differences in resolutions and methods. MESMA detects open water portion within 30-m pixels, whereas the GAM-derived F_{wet} from CTRL climate is a function of soil water content at the 4-km grid scale, reflecting the original CWI depressions. The tendency for modelledF_{wet} to under-predict wetland extent is also evident compared to the Adj_CanVec data in Fig. 3. The trend of increasing wetland extent observed in both datasets (MESMA and CTRL) from 2001 to 2013 is confirmed by field observations of increasing pond (wetland) counts by the Waterfowl Breeding Population and Habitat Survey(Ballard et al., 2014).

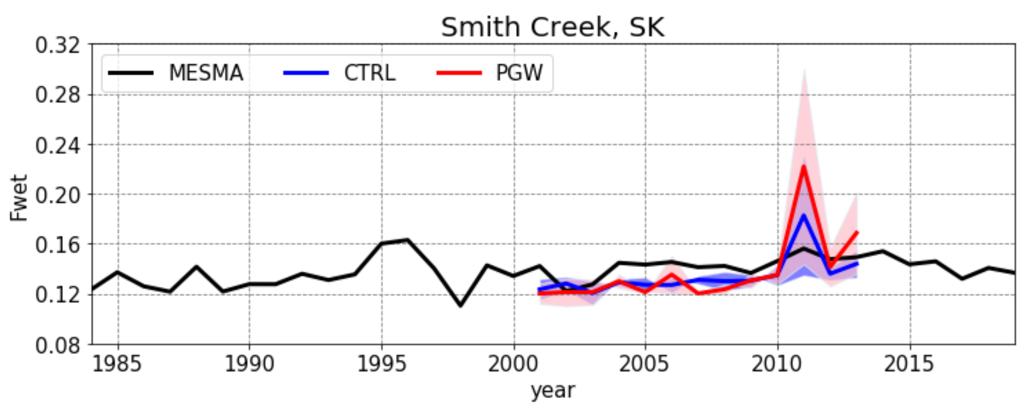

Figure 7. F_{wet} timeseries in current (CTRL) and future (PGW) climate in the Smith Creek watershed, Saskatchewan. The MESMA method represents annual wetland fraction from April to September. The red and blue shading represent the seasonal range of F_{wet} within the spring [MAM] and summer [JJA] for CTRL and PGW climate.

The seasonal variation in F_{wet} is represented by the blue and red shading for CTRL and PGW climate, respectively. The range of F_{wet} is driven by the filling in spring due to snowmelt (surface runoff) and drying in summer due to evapotranspiration, indicating strong intra-annual variation. Therefore, it is important to investigate F_{wet} at the seasonal scale. This is especially evident in the spring of 2011, when a record-breaking intensive precipitation event occurred and induced flooding (Dumanski et al., 2015; Pattison-Williams et al., 2018). This results in the highest F_{wet} value since 1996 and is well captured by CTRL. The F_{wet} peak in spring and summer in 2011 in PGW is even larger than in current climate, indicating the potential intensification of the hydrological cycle in these wetlands. Higher predicted spring F_{wet} is driven by greater precipitation and stronger surface runoff from snowmelt. In contrast, drying trends in the summer are owed to higher temperatures and more variable summer precipitation.

4 Discussion

4.1 Climate change studies in the PPR

Several studies have projected climate change impacts on wetland densities in the PPR, ranging from local-scale (Johnson et al., 2005; Liu et al., 2012) to regional-scale (Niemuth et al., 2014; Garris et al., 2015; Sofaer et al., 2016) investigations. Variable study scales and data sources have made linking wetland spatial distribution and climatic conditions a challenge. The most common approach has been to statistically relate different climatic variables, landscape management types, and human footprints with wetland abundance (Herfindal et al., 2015, Niemuth et al. 2014, Sofaer et al., 2015, Garris et al., 2015). Typically, the key variable in these studies has been water balance (P-PET, Herfindal et al., 2015). On the other hand, physical process-based hydrology or land surface models have been also applied in wetland studies (Johnson et al., 2005; Capehart et al., 2011; Fan et al., 2012). These studies attempted to simulate the hydroperiod, soil wetness, and shallow water table, to represent the dynamics of wetlands in PPR. Importantly, these variables are analogous to the surface water balance, as represented by the soil water content (*SWC*) in this study.

Conclusions about climate change's impacts on wetlands in the PPR vary. Wetland distribution under climate change reflects the change in climate forcing and thus may be sensitive to methodological differences, including the choice of GCMs and whether and how the GCMs are downscaled. For example, Johnson et al. (2005) applied three climate change scenarios uniformly across the entire PPR (18 study sites) and concluded that the region with greatest productivity in the central PPR will shift east- and southwards. However, climate change signals from GCM models are far from uniform. In contrast, Sofaer et al. (2016) and Garris et al. (2015) applied statistically downscaled climate forcings from an ensemble of GCMs and found the wetlands in the American portion of the PPR are projected to decline but with little shift in the regions with highest wetland densities.

In our study, dynamical downscaled results from an ensemble of GCMs show that wetlands in the western Canadian PPR may benefit from wetter conditions under future climate. On the other hand, the eastern Canadian PPR will experience higher risk of wetland loss, especially due to intensified ET demand in summer. In this approach, critical hydrological processes at local and watershed scales, such as blowing snow and fill-and-spill, are underrepresented in our model. However, these processes, which occur at sub-grid resolution (4-km), may be not as important as changes in precipitation, ET, and recharge at large (regional) scales (Shaw et al., 2012).

4.2 The impacts of land use change on wetland fraction

In addition to impacting wetlands via change in the surface water balance, climate change may have indirect effects on wetlands via land use change. Wetland conservation strategies should take into account these direct and indirect climate effects. For example, Beaman (2016) found that climate change may alter agricultural economics such that annual-seeded crops increase at the expense of natural and semi-natural landcovers. Given that drainage for agriculture has been the historical driver of wetland loss on the prairies, with ongoing losses of ~ 3% of wetland area per decade, land use change could augment or offset direct climate effects on wetlands (PHJV 2014).

Because our modelled F_{wet} was constrained by the CWI data, it necessarily reflects the results of historical drainage (i.e., the CWI does not map drained wetland basins). Drainage is not otherwise incorporated into our model. Figure 8 shows a qualitative wetland drainage score, based on the density of agricultural surface ditches as detected through aerial photography and high-resolution satellite imagery, in the PPR (for detailed methods and score descriptions see Appendix 11 in PHJV, 2014). Low drain score areas show minimal evidence of anthropogenic drainage whereas high drain scores exhibit extensive ditching and related drainage (Fig. 8). Three examples of drain score photos are included in Fig. 8: in a low drain score, most wetlands remain intact; in a medium drain score, many small wetlands have been drained; in a high drain score, most prairie potholes are drained and converted to cropland.

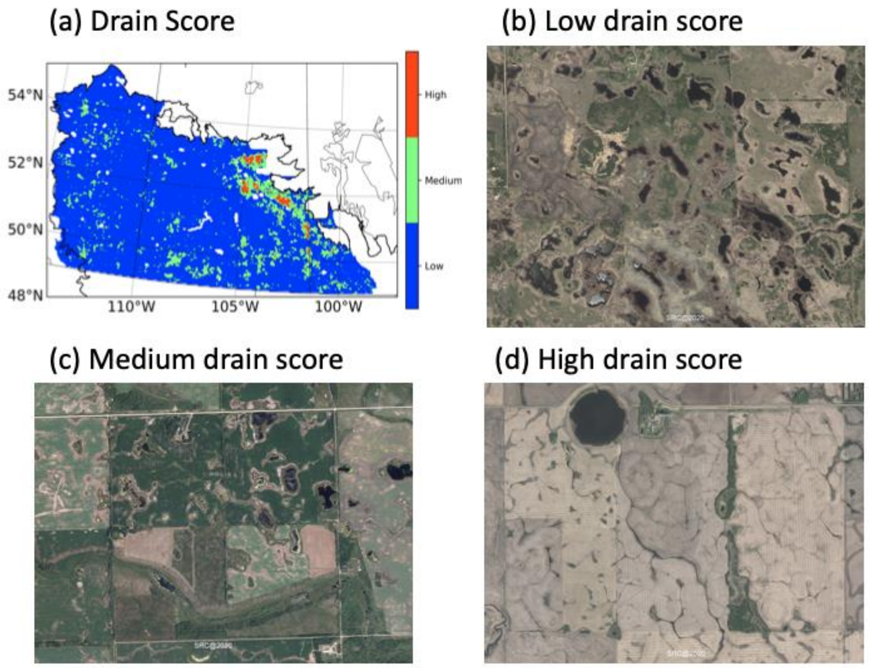

Figure 8. (a) A qualitative drain score map from the Prairie Habitat Joint Venture (PHJV 2014), (b-d) are examples of the three drain scores (photos are from the Saskatchewan Geospatial Imagery Collaborative).

4.3 Prioritizing wetland conservation in an uncertain future

The spatial heterogeneity of climate change impacts on wetland fraction in the PPR is a challenge to conservation decision-makers, especially under extreme climate conditions and uncertainties associated with anthropogenic drainage. Considering extreme climate conditions (droughts and floods) can constrain the magnitude of possible wetland area change; including anthropogenic drainage can help spatially prioritize conservation efforts by revealing both areas that may remain robust to climate change and areas where wetland ecosystem services may be imperilled by climate change and drainage.

Fig. 9 shows the concordance of future climate change impacts and the drainage score in extreme drought and flood conditions. The change of extreme dry and wet conditions (PGW-CTRL) are characterized by the *Fwet* values at 5th and 95th percentile, i.e. (*Fwet*_PGW_95th-*Fwet*_CTRL_95th and *Fwet*_PGW_5th-*Fwet*_CTRL_5th). A threshold value of $\Delta Fwet$=0.1 is selected and overlaid with the qualitative drain score shown in Fig.8. The wetland loss and gain under extreme conditions complements the average climate projections (Fig. 5) and suggests the need for a diversified approach to distributing conservation efforts. For example, the consistent wetland gain in the western PPR, under both wet and dry extremes, suggests conservation and restoration are viable under climate change. The wetland basins in the western PPR will have available water to fill wetlands to maintain wildlife habitats even in relatively dry summers. Current conservation efforts in this area should continue to provide a valuable return on investment under extreme climate conditions.

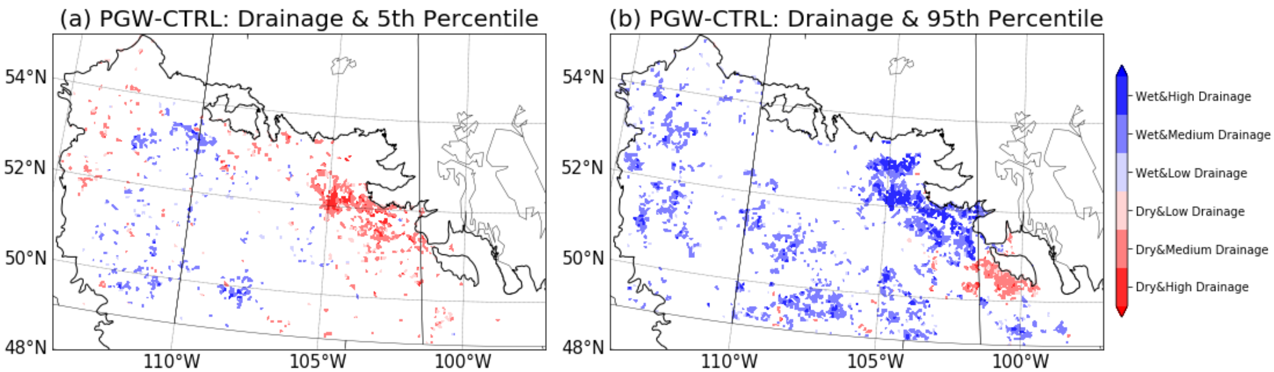

Figure 9. Combined effect of climate change and drainage in extreme (a) dry and (b) wet conditions. Drainage intensity is from the PHJV drainage score (PHJV, 2014). The drought and flooding conditions are selected from the 5th and 95th percentile of the monthly wetland fraction results from CTRL and PGW climate.

On the other hand, highly drained areas in eastern Saskatchewan will be challenged under fluctuating hydrological conditions. The combination of high wetland loss and intensified drought conditions under climate change will mean a shortage of wildlife habitat in dry years. In contrast, extreme wet conditions may lead to flooding in spring snowmelt season, exacerbated by wetland loss. Therefore, conserving wetlands in the Aspen Parkland and Boreal transition regions in eastern Saskatchewan may buffer against flooding during intensified future wet periods. Other areas of the Canadian prairies, like western Manitoba, could become challenged by moisture deficits (even in the wettest years) that will not favour the inundation and persistence of wetlands. Historically, the cost of restoring drained wetlands has been several times that of conserving existing wetlands (Loesch et al., 2012; Pomeroy et al., 2015). However, the combination of the drainage score and predicted wetland changes from this study can be used to identify areas with both numerous restoration opportunities and suitable future climate to maximize the benefits of investments in restoration.

5 Conclusions

Conservation of prairie wetlands is crucial to protect the many values they provide including regulating water, improving water quality, and supporting biodiversity. Knowing that climate change poses a threat to wetland habitats through alteration of the hydrological cycle, it is necessary to consider the impacts of climate change in conservation planning. Previous studies, especially those covering the Canadian portion of the PPR, used GCM-scale climate and hydrological covariates, which are less informative and more uncertain. Therefore, in this study, we used a dynamical downscale from a CPRCM, which has better representation of land surface properties and less uncertainty in precipitation forecast, as our climate projection. We linked the physically modeled soil water content (SWC) with a statistical model to predict the wetland fraction in a 4-km resolution grid and showed the impacts on wetlands under climate change.

Overall, the climatic change is projected to be wetter, but with strong spatial heterogeneity and seasonal variation. For the western PPR, wetland fraction is shown to increase in future climate in both the spring and summer seasons. However, in the eastern PPR, wetlands are expected to increase in spring while decrease in summer, due to intensified ET demand. Groundwater has an important buffer effect to sustain wetland ecosystems, especially in mid-boreal uplands and southern Manitoba uplands in the eastern PPR. The heterogeneous change in projected climatic and hydrological conditions may alter the current wetland distribution, where natural wetlands are more abundant in the eastern PPR.

Loss of future wetland ecosystem services may be especially pronounced in the eastern PPR owing to challenges from both climatic drying and anthropogenic land-use change. The areas expected to experience extended summer drying coincide with areas with high density of drainage ditches (and thus, presumably, already high wetland loss). The western PPR, with moisture conditions conducive to wetland persistence through the spring and summer, will remain a safe choice for wetland conservation efforts. Assessments of the effects of climate change on wetland conservation must fully consider ecological, economic, and social realities along with the potential for climate-induced changes to determine the most effective spatial targeting of wetland conservation and restoration.

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Data Availability Statement

The WRF simulation over the contiguous US (CONUS, Liu et al., 2017) can be accessed at https://rda.ucar.edu/datasets/ds612.0/ TS1 (last access: August 2020). The Noah-MP GW model is driven by the NCAR high-resolution land data assimilation system (HRLDAS, Chen et al., 2007) and can be downloaded from https://github.com/NCAR/hrldas-release/ (last access: August 2020). The Noah-MP GW simulation data from the Prairie Pothole Region are available upon request from the corresponding author (yanping.li@usask.ca). The Canadian Wetland Inventory, Adjusted CanVec data are kindly provided by Ducks Unlimited Canada. The drain score in the Canadian Prairies are provided by Prairie Habitat Joint Venture (2014) Prairie Habitat Joint Venture Implementation Plan 2013-2020: The Prairie Parklands. Report of the Prairie Habitat Joint Venture. Environment Canada, Edmonton, AB.

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Figures

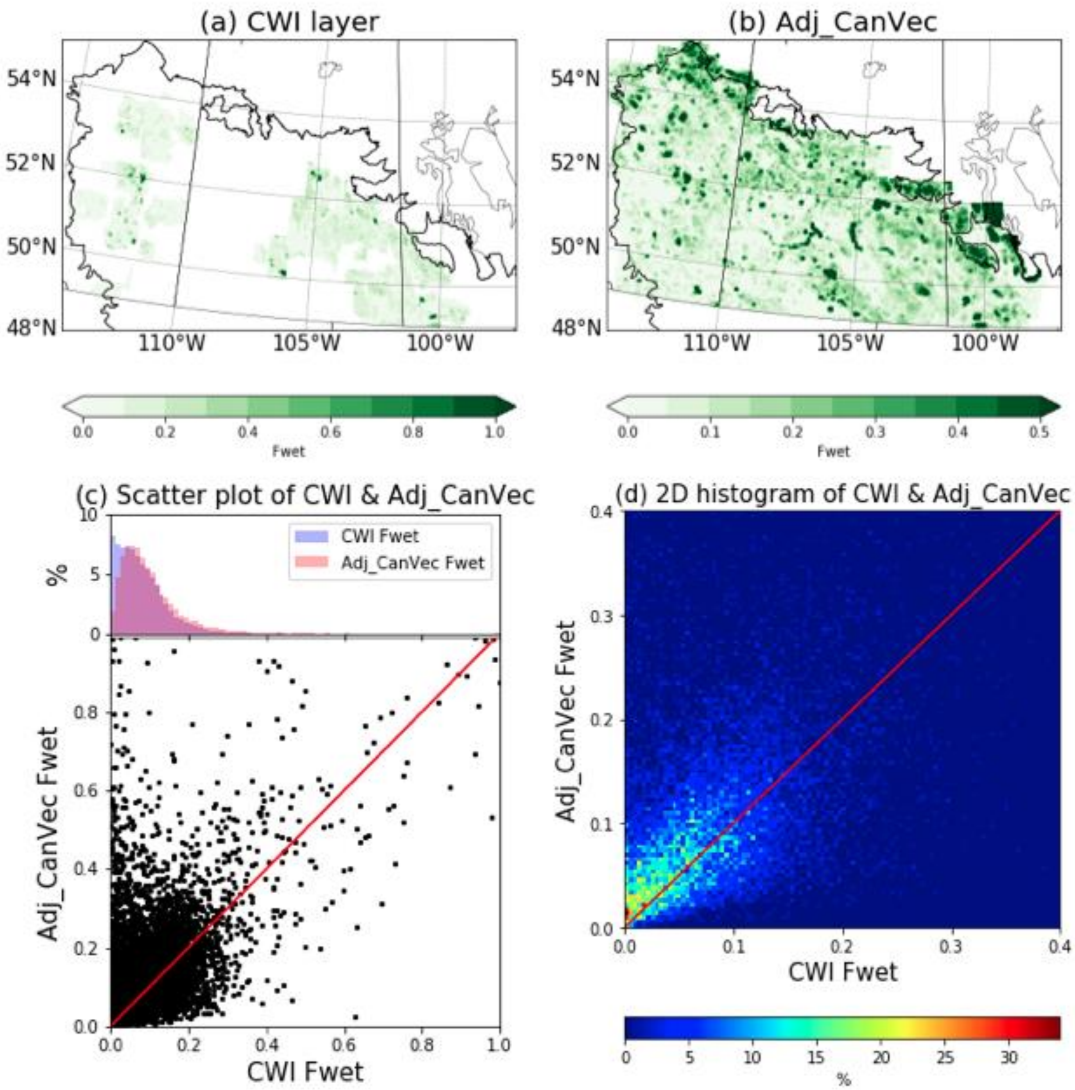


Figure1 (a) F_{wet} spatial distribution from the Canadian Wetland Inventory (CWI); (b) F_{wet} spatial distribution from Adj_CanVec, a modelled wetland dataset; (c) scatter plot (bottom) and histogram (top) of F_{wet} of the CWI (blue) and Adj_CanVec (red) and (d) a 2D histogram of F_{wet} from 0 to 0.4.

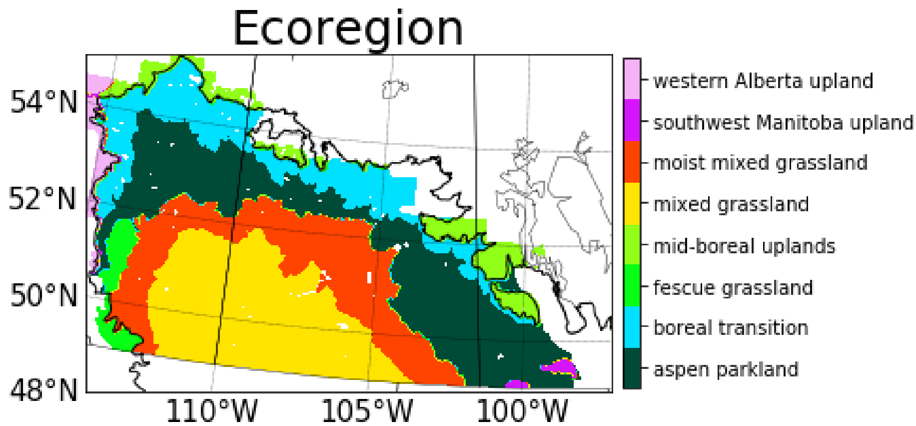


Figure 2. Ecoregions in the Canadian Prairies. Black contour outlines the Prairie Pothole Region and the filled colors represent the 8 ecoregions as used in the wetland model. The area where Adj_CanVec data are unavailable are blank.

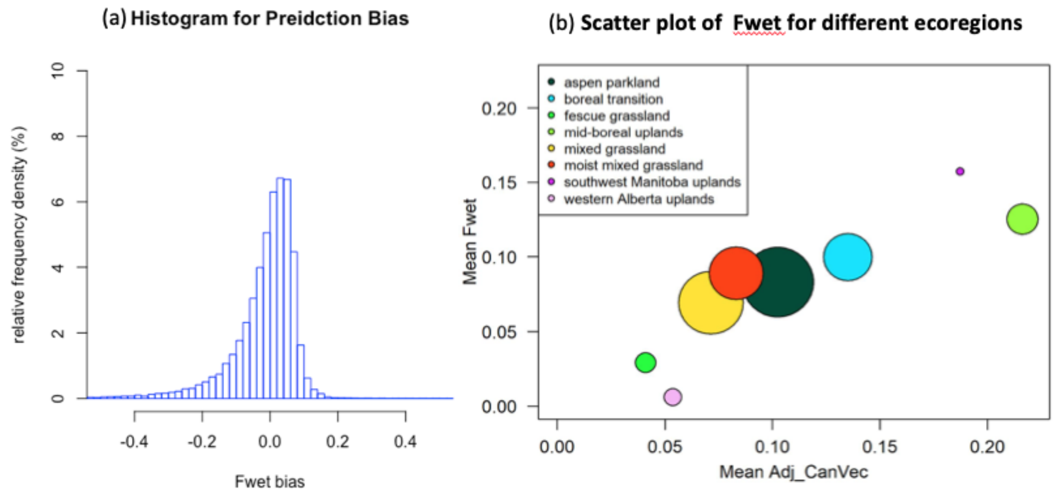


Figure 3. (a) Histogram of the model bias (*Fwet*_CTRL-Adj_CanVec), y axis label is the relative frequency density of the whole grid cells in the Canadian Prairies; (b) scatter plot of mean *Fwet*_CTRL compared with mean Adj_CanVec by ecoregion. Point sizes are proportional to the square root of sample sizes.

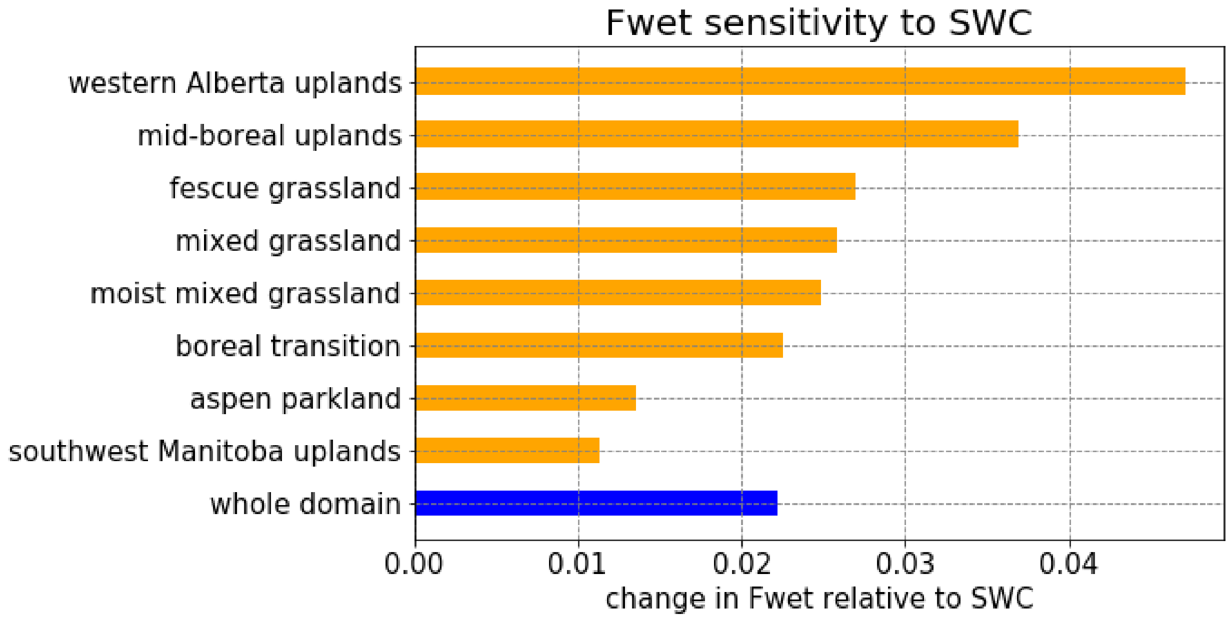


Figure 4. Bar plot of change in *Fwet* relative to a 1% increase in SWC for the entire domain and eight ecoregions.

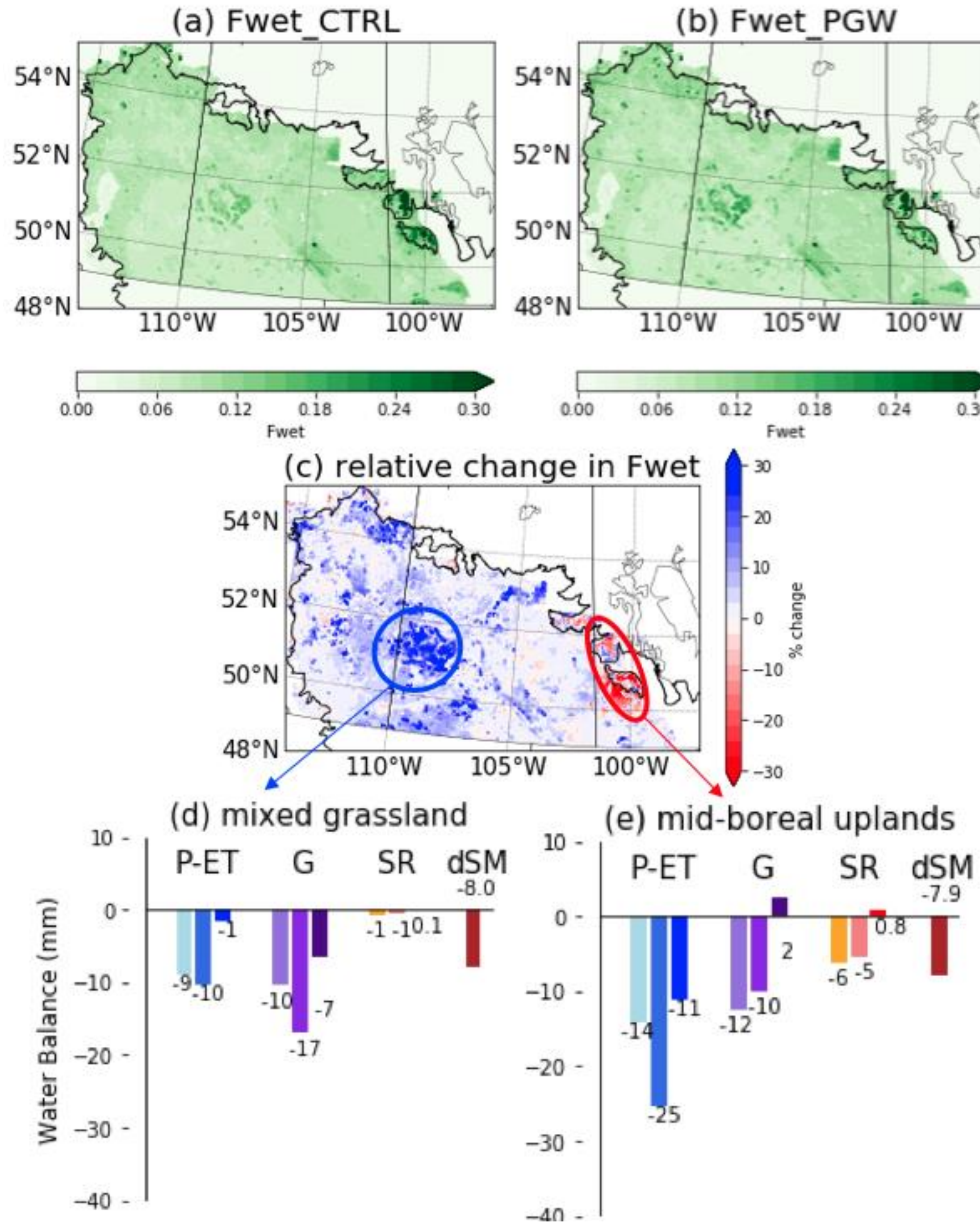


Figure 5. Mean *Fwet* from (a) current climate (*Fwet*_CTRL), (b) future climate (*Fwet*_PGW), and (c) their relative change (*Fwet*_PGW- *Fwet*_CTRL)/ *Fwet*_CTRL. The blue and red circle in (c) highlights the wetland gain in mixed grassland and loss in mid-boreal uplands. Their water balance (mm) figure from spring through summer (March-August) are shown in (d&e). Three bars of each water balance component (precipitation-evapotranspiration [*P-ET*], groundwater [*G*], surface runoff [*SR*]) are shown, the first one is for CTRL, the second one is for PGW, and the third one is for the change of PGW-CTRL, and *dSM* represents the net change in soil moisture.

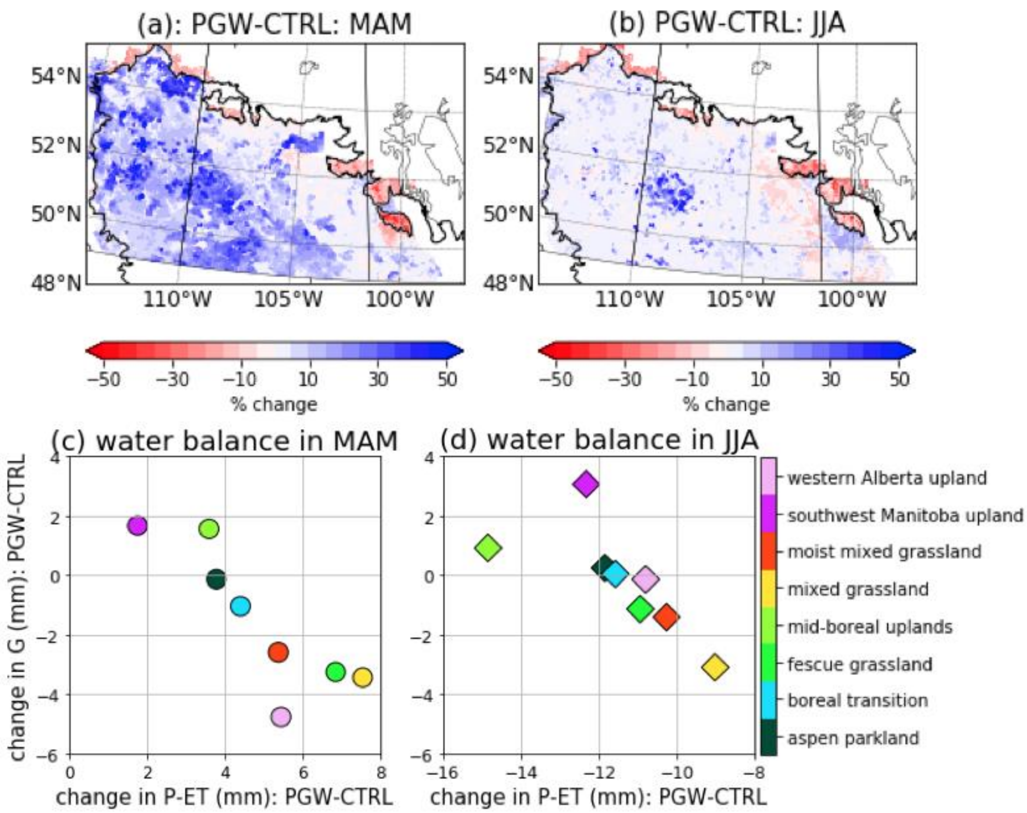


Figure 6. (a) Seasonal *Fwet* changes in spring (MAM), and (b) summer (JJA) between future and current climate (PGW-CTRL), relative to the CTRL values; (c) scatter plot of water balance change (PGW-CTRL) in MAM and (d) JJA for eight ecoregions. The x-axis is the available water (*P-ET*) and the y-axis is the contribution of groundwater.

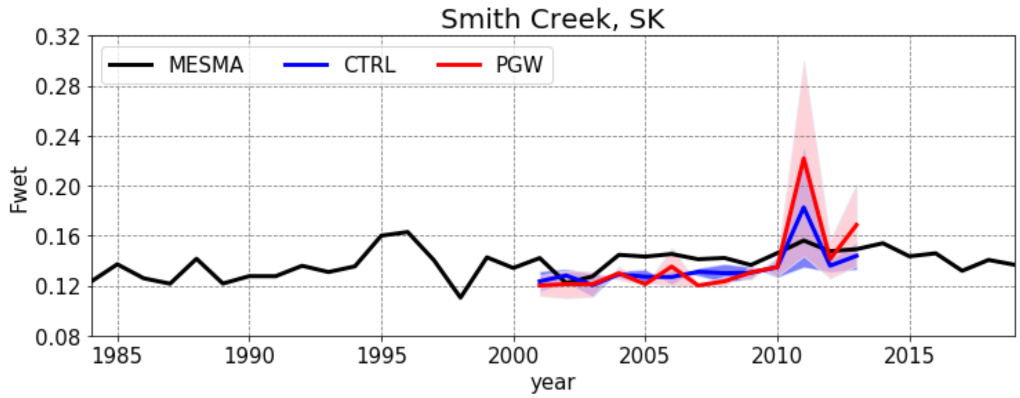
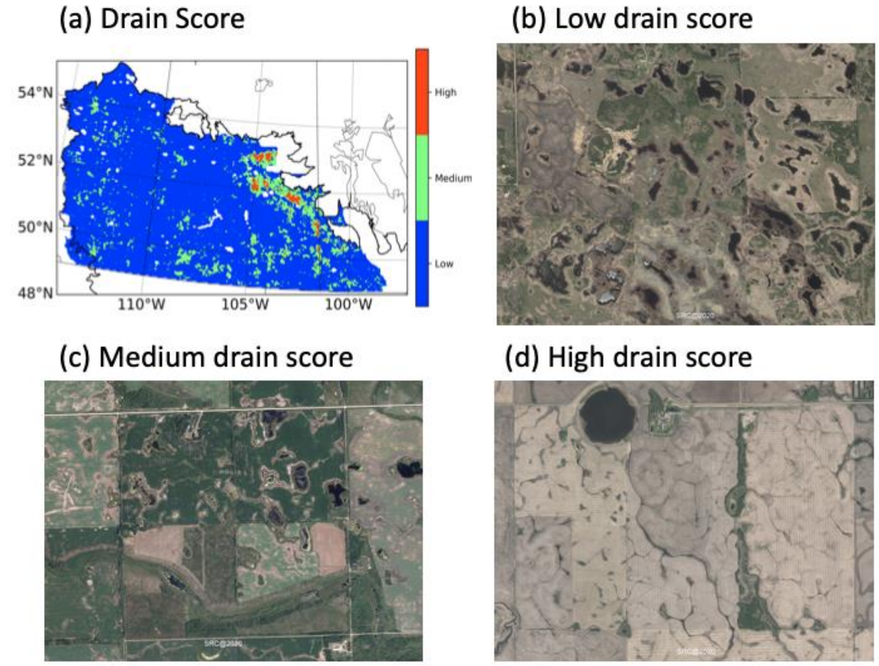


Figure 7. F_{wet} timeseries in current (CTRL) and future (PGW) climate in the Smith Creek watershed, Saskatchewan. The MESMA method represents annual wetland fraction from April to September. The red and blue shading represent the seasonal range of F_{wet} within the spring [MAM] and summer [JJA] for CTRL and PGW climate.



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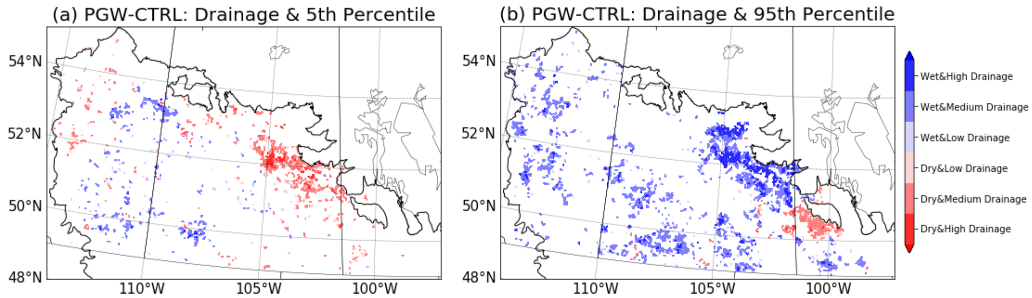

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