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ORIGINAL RESEARCH

Prerequisites for Understanding Climate-Change Impacts on Northern Prairie Wetlands

Michael J. Anteau[1] · **Mark T. Wiltermuth**[1] · **Max Post van der Burg**[1] · **Aaron T. Pearse**[1]

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Abstract The Prairie Pothole Region (PPR) contains ecosystems that are typified by an extensive matrix of grasslands and depressional wetlands, which provide numerous ecosystem services. Over the past 150 years the PPR has experienced numerous landscape modifications resulting in agricultural conversion of 75–99 % of native prairie uplands and drainage of 50–90 % of wetlands. There is concern over how and where conservation dollars should be spent within the PPR to protect and restore wetland basins to support waterbird populations that will be robust to a changing climate. However, while hydrological impacts of landscape modifications appear substantial, they are still poorly understood. Previous modeling efforts addressing impacts of climate change on PPR wetlands have yet to fully incorporate interacting or potentially overshadowing impacts of landscape modification. We outlined several information needs for building more informative models to predict climate change effects on PPR wetlands. We reviewed how landscape modification influences wetland hydrology and present a conceptual model to describe how modified wetlands might respond to climate variability. We note that current climate projections do not incorporate cyclical variability in climate between wet and dry periods even though such dynamics have shaped the hydrology and ecology of PPR wetlands. We conclude that there are at least three prerequisite steps to making meaningful predictions about effects of climate change on PPR wetlands. Those evident to us are: 1) an understanding of how physical and watershed characteristics of wetland basins of similar hydroperiods vary across temperature and moisture gradients; 2) a mechanistic understanding of how wetlands respond to climate across a gradient of anthropogenic modifications; and 3) improved climate projections for the PPR that can meaningfully represent potential changes in climate variability including intensity and duration of wet and dry periods. Once these issues are addressed, we contend that modeling efforts will better inform and quantify ecosystem services provided by wetlands to meet needs of waterbird conservation and broader societal interests such as flood control and water quality.

Keywords Agriculture · Climate change · Conservation · Consolidation drainage · Hydrology · Wetland drainage · Wetland dynamics · Waterbird · Waterfowl

✉ Michael J. Anteau
manteau@usgs.gov

[1] U. S. Geological Survey, Northern Prairie Wildlife Research Center, 8711 37th St. SE, Jamestown, ND, USA

Background

The Prairie Pothole Region (PPR) contains key North American ecosystems that are typified by a matrix of grasslands and depressional wetlands, which support diverse aquatic and terrestrial communities. Wetlands of this region also provide numerous important ecosystem services (e.g., flood protection, groundwater recharge, carbon sequestration, biodiversity, etc.; Zedler and Kercher 2005; Gleason et al. 2008). This region's ecological importance has been primarily attributed to its role in supporting waterbird populations by providing critical migratory and breeding habitat (Krapu 1981; Batt et al. 1989; Arzel et al. 2006; Anteau and Afton 2009a). Accordingly, abundance and quality of wetlands in the PPR affect persistence and trajectory of migratory waterbird populations (Kaminski and Gluesing 1987; Raveling and Heitmeyer 1989; Anteau and Afton 2011).

Wetlands of the PPR also shape ecosystems, recreation, and economics outside the PPR. Migratory waterbirds dependent upon PPR wetlands for stopover or breeding habitat function as predators of invertebrates (Anteau and Afton 2009b), provide prey for avian and mammalian predators (Todd et al. 1982; Rockwell and Gormezano 2009), and facilitate dispersal of aquatic organisms (Swanson 1984; Charalambidou and Santamaria 2005). Furthermore, migratory waterfowl that come to this region are of great interest to the public for wildlife viewing and hunting, as well as subsistence harvest in some more northern areas.

Despite many important wetland-derived ecological services, the motivation for most wetland conservation policies and practices in the PPR has been to provide habitat for migratory birds. Many hundreds of millions of dollars are spent annually on protection and restoration of wetlands and surrounding uplands for the benefit of waterfowl and waterbird populations (U.S. Fish and Wildlife Service 2011; Walker et al. 2013; U.S. Department of Agriculture, 2016). Those investments are administered by the U.S. Fish and Wildlife Service (e.g., Small Wetlands Acquisition Program or "Duck Stamp Program", Partners for fish and Wildlife Program), US Department of Agriculture (e.g., Conservation Reserve Program [CRP], Wetland Reserve Program [WRP]), non-governmental organizations (e.g., Ducks Unlimited, The Nature Conservancy), and State and Provincial governments. However, long-term changes in temperature and precipitation in the PPR threaten many of the other services that these wetlands provide. Accordingly, there is a critical need for understanding how wetlands in the PPR will respond to projected climate change because that knowledge can help inform how and where conservation dollars could be spent either in response to climate change or to abate stressors caused by climate change (Johnson et al. 2005, 2010; Loesch et al. 2012).

While there have been previous scenario-based modeling efforts to predict impacts of climate change on PPR wetlands (e.g., Johnson et al. 2005, 2010), those approaches did not fully incorporate interacting or potentially overshadowing impacts of land use on wetland hydrology and ecology (Anteau 2012; Niemuth et al. 2014; McCauley et al. 2015). Much of the data used to develop mechanistic models of wetland hydrology has come from wetlands situated in landscapes that are more intact than the majority of wetlands in the PPR (i.e., Cottonwood Study Area, in North Dakota, Orchid Meadows in South Dakota; Johnson et al. 2005, 2010). Another pressing concern is that climate model outputs (i.e., climate projections) do not incorporate or explore potential changes in the cyclical variability in climate between wet and dry periods, which have shaped the hydrology and ecology of PPR wetlands. In this manuscript we outline some prerequisite needs for building more informative models to predict how climate change may influence wetlands within the PPR.

Variation in Physical and Watershed Characteristics

Often scientists generalize the function of wetlands based on a classification system that uses a spectrum of observed states to organize wetlands based on ponded water permanence, while accounting for inter-annual variability in moisture conditions (e.g., Stewart and Kantrud 1971). Such classifications provide broad-level descriptions of observed hydroperiods, as opposed to reasons why a certain hydroperiod has been observed. In an area as expansive as the PPR, temperature and precipitation gradients are evident (see Johnson et al. 2005). Therefore, for wetlands to have the same observed hydrologic state (e.g., semipermanently-ponded wetland) across geographic gradients, they must have differing physical characteristics such as contributing watershed area, soil attributes, and connections to ground water. Given these fundamental differences, when spatially modeling wetland dynamics, one must recognize that a wetland of a given class in the southeastern PPR, for instance, likely has different physical and watershed characteristics compared to another wetland of the same class in the northwestern PPR. Moreover, such differences should be incorporated into models used to predict hydrologic outcomes (e.g., hydroperiod and outflow). Unfortunately, these apparent regional differences pose a significant challenge for mechanistically modeling wetland dynamics because these models generally require detailed information about physical and watershed characteristics which are largely not available across the entire PPR landscape. Of course, one could assume that all wetlands are similar to those few intensely studied wetlands in the PPR. But considering our points above, this is likely not a tenable assumption because predictions of those models likely would be biased geographically and understanding geographic differences has been a major objective of such modeling efforts. Alternatively, wetland classifications of observed hydrological states can be useful in statistical models, particularly when considering spatially-standardized climate data (e.g., PRISM; Daly et al. 2000; Di Luzio et al. 2008) because statistical models can be developed to describe observed hydrological states while accounting for unknown spatial variability in watershed characteristics (van der Post et al. 2016). We contend that capturing and describing this variation is a needed first step toward informing more mechanistic hydrologic models.

In addition to geographically-driven variation in watershed characteristics there is potential for substantial variation within landscapes that experience similar climate. We suspect there are several combinations of physical and watershed characteristics that lead to a similar observed hydroperiod state. Furthermore, it is reasonable to assume that climate change may not affect each of those variables uniformly (e.g., watershed area vs. connection to groundwater inputs). Therefore, a more robust mechanistic modeling approach would be informed by a larger sample or census of physical wetland parameters.

Statistical models can be used for inferring relationships over broad areas and through time while allowing for uncertainties from multiple sources, but they tend to be somewhat restricted to a region and time period of inference (Cressie et al. 2009; Cressie and Wilke 2011). In contrast, mechanistic models tend to be less uncertain because they rely on fairly well known processes to make predictions (Clark and Gelfand 2006; Clark 2007). However, many mechanistic models rely on input parameters derived from site-specific studies, which may limit their applicability in making broader spatial and temporal predictions of system dynamics (e.g., Johnson et al. 2005, 2010). Recent advances in computing have opened up the option of merging statistical estimation with mechanistic process models that should lead to better understanding of how systems work and also allow for broader spatial and temporal predictive capacity (Clark and Gelfand 2006; Cressie and Wilke 2011). We suggest that a major step forward in modeling wetland hydrologic dynamics on a landscape scale will require integrating statistical spatiotemporal relationships into mechanistic wetland hydrologic models in order to improve broad-scale predictions.

Land Use Changes in the Prairie Pothole Region

During the past 150 years the PPR has been subject to increasingly intensive and extensive landscape modifications for agricultural production. Demand for increased agricultural production has resulted in conversion of 75–99 % of native prairie uplands (Samson and Knopf 1994) and drainage of 50 to 90 % of the original wetlands (e.g., North Dakota and Iowa, respectively; Dahl 1990). Similar landscape conversion has also occurred in the Canadian portion of the PPR. Cortus et al. (2009) reported that over 40 % of wetlands in Saskatchewan have been drained. Given the intensity and extent of various landscape modifications in this region, we argue that not accounting for such changes likely limits inference about wetland function because only a small proportion of wetlands occur in relatively unaltered prairie landscapes. Discounting land use change also could result in suboptimal allocation of conservation actions taken to abate impacts of climate change.

Effects of Cropping Practices on Wetland Hydrology A number of studies have suggested that wetlands situated in watersheds dominated by cropland receive more surface-water runoff than those occurring in grassland-dominated landscapes (Euliss and Mushet 1996; van der Kamp et al. 2003; Voldseth et al. 2007). Although a critical consideration for making hydrological predictions of wetlands under particular climate scenarios, situational differences in surface runoff has yet to receive adequate study in the context of informing landscape-scale hydrological models across the range of cropping practices and soil types throughout the PPR. Moreover, effects of land use on ponded-water area of wetlands may interact with climate. For instance, McCauley et al. (2015) found that semipermanently- and permanently-ponded wetlands in landscapes dominated by cropping had smaller pond area during dry periods than those situated in grassland-dominated landscapes. However, during wet periods they found no difference in ponded-water area between those same wetlands. These findings point to a need for a better understanding of how land use influences runoff into wetlands during both dry and wet periods, as well as evaluations of how various crop types and grassland communities affect groundwater and pond area of wetlands (McCauley et al. 2015).

Effects of Consolidation Drainage on Wetland Hydrology Various types of wetland and upland drainage are landscape modifications often associated with agriculture, which have led to changes in responses of wetlands to climate throughout the PPR. Many wetlands in the PPR have been mechanically leveled or ditched, which effectively eliminates wetland basins and increases velocity of water flow from uplands to stream networks. Other forms of drainage have impacts on wetlands remaining on the landscape. The southeast portion of the PPR region (IA, MN) has a long history of using tile drainage in upland and wetland areas, but this landscape modification is relatively recent in the eastern portions of North and South Dakota (Oslund et al. 2010; Finocchiaro 2014). Upland tile drainage changes surface and near-surface runoff rates and alters the groundwater table, which could potentially shorten hydroperiods in some wetlands while simultaneously increasing inflow into other wetlands or streams depending on where the tile discharges. Although debate over agricultural benefits and ecological impacts of upland-tile drainage continues (see Blann et al. 2009), effects of upland-tile drainage on wetland hydrology are only beginning to be quantified.

In many parts of the PPR, complex anthropogenic drainage systems are not extensively used, likely due to a combination factors such as crop types, crop prices, growing season length, soil fertility, rainfall, and undulating topography. In areas without complex drainage systems, agricultural producers commonly use surface modifications such as drainage ditches in attempts to increase farmable area or efficiency. This practice involves the drainage of wetlands that reside higher in the watershed into those positioned lower in the watershed (i.e., consolidation drainage; Fig. 1). Consolidation drainage can alter how remaining wetlands respond to climate variation (Anteau 2012; Wiltermuth 2014; McCauley et al. 2015).

We present a conceptual model that summarizes the effects of consolidation drainage upon wetland hydrology, and propose this model as a hypothesis that is supported by recent and

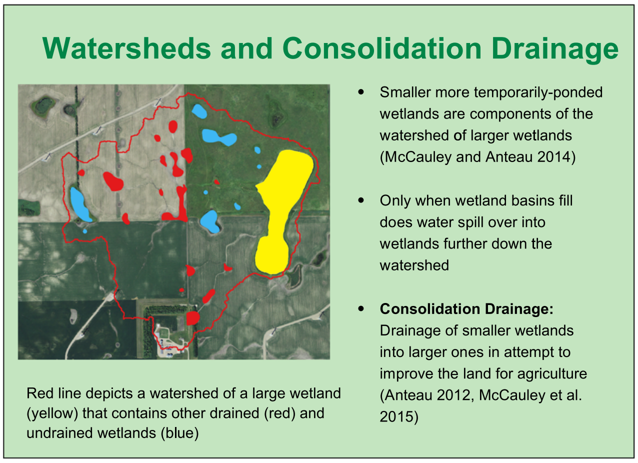

Fig. 1 Callout box describing the concepts of wetland watersheds and consolidation drainage

historical literature (Fig. 2). Over the past century many semipermanently- and permanently-ponded wetlands have become larger and have drawn down less extensively during dry periods; these observed changes have been primarily attributed to increased consolidation drainage within their watersheds (Anteau 2012; McCauley et al. 2015). Historically, semipermanently-ponded wetlands responded slowly to climate variation. However, current observations indicate faster hydrologic response to wetting periods, and attenuated response to drying periods (McCauley et al. 2015; van der Post et al. 2016).

It appears that mechanisms at play behind the progression of increased wetland size is the functional increase in contributing watershed area that increases the amount of surface-water runoff these wetlands receive, particularly during wet periods (Fig. 2; McCauley and Anteau 2014; McCauley et al. 2015). We suspect that even during dry periods wetlands within drained watersheds receive more surface runoff than those in undrained watersheds. As ponded area of a wetland increases, it captures precipitation which would have normally infiltrated into the ground, been taken up by plants, or evaporated (Winter 2003). For wetlands positioned in deeper basins (≳ 2 m depth to spill point), those entering into the dry period with more water will likely experience lower rates of evapotranspiration caused by a reduction in surface area to volume ratio and presumably fewer respiring emergent plants. Accordingly, wetlands in drained watersheds receive more runoff causing increased ponded area that attenuates their response to dry periods. Wiltermuth (2014), borrowing from epidemiology terminology, referred to this phenomenon as a progressively-chronic effect of consolidation drainage. Much like a long-term chronic disease, the effects of prior causal factors (watershed drainage, in this case) are not as serious at first, but progressively become worse with time. We expect that the nominal effects, those observable at the local watershed level, of consolidation drainage will not be fully realized until a wetland basin is full and excess water moves into higher-order watersheds (Fig. 2). When these basins contribute water to higher-order watersheds, there is potential for progressively-chronic effects over a much broader spatial extent. For example, as of 2010, approximately 40 % of the watersheds of semipermanently-ponded wetlands in North Dakota had sufficient drainage to create a pattern of increasing growth over time (Wiltermuth 2014; M. J. Anteau, unpublished data; see Fig. 2). Twenty-four percent of modified watersheds had terminal wetlands that were >90 % of their total basin area, suggesting that those wetlands were likely stabilized and spilling runoff water into higher order watersheds.

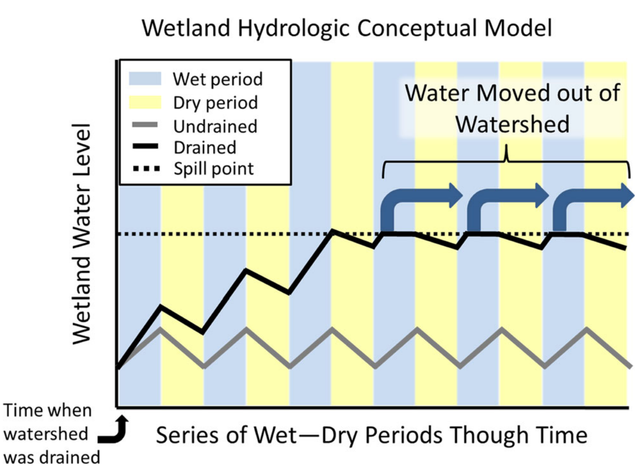

Fig. 2 Conceptual model that incorporates observed and theoretical relationships describing the response of wetland water levels to climate variability in undrained landscapes and those that have had extensive consolidation drainage

Although wet and dry periods clearly influence the amount of ponded water in wetlands (Fig. 3; Euliss et al. 2004; van der Post et al. 2016), the addition of increased consolidation drainage alters hydrologic responses to climate events (Anteau 2012; McCauley et al. 2015). While the models we described here were developed to explain observed changes in land use and their effects on wetland hydrology (Fig. 2), it is also likely that potential future increases in intensity of precipitation events due to climate change, such that they increase runoff events (Winter 2003), could cause similar escalations in wetland size.

Historical Climate of the Prairie Pothole Region

Climatic shifts between wet and dry periods have driven water-level fluctuations in wetlands of this region for over 2000 years (Fig. 3; Laird et al. 2003). Such fluctuations have driven the hydrology of PPR wetlands and shaped the evolution of species and communities dependent on those wetlands. Dynamics in ponded water levels are thought to be a driver of wetland productivity because drying of benthos facilitates

Fig. 3 Photo series depicting a semipermanently-ponded wetland situated in an undrained landscape responding to a series of climatic conditions from 2003 to 2012

nutrient cycling (i.e., oxidation) and leads to a pulse of primary productivity when wet conditions subsequently return (Murkin 1989; Euliss et al. 1999; Euliss et al. 2004). Evaluations of recent historical and long-term proxy climate data in the PPR suggest substantial spatial and temporal heterogeneity in wet and dry periods (for example, even within 100 km; Laird et al. 2003; van der Post et al. 2016). Such a patchwork of climatic conditions likely provided prime migratory and breeding habitat for waterbirds during most years (Anteau 2012).

Increases in temperature and changes in precipitation are typically considered when evaluating potential effects of climate change. However, an alternating pattern of wet–dry periods shaped the evolution of species and ecosystems in the PPR. Moreover, our conceptual model predicts that these wet–dry periods are also important for understanding changes in wetland hydrology caused by climate and land use. An important question about effects of climate change not yet considered is: *Have there been or will there be changes in the magnitude, frequency, and spatial relationships of these wet–dry periods*? Given the strong link between ecology, hydrology, and land use and the variability of wet and dry periods in the PPR, we suggest that more work needs to be done to develop climatological models that can make meaningful projections about wet and dry periods that current regional downscaled models cannot.

Potential Interactions of Climate and Land Use Changes

Ecological Impacts The ecological fate of wetlands that fill to their spill point due to aforementioned progressively-chronic effects likely trend in one of two directions depending upon on the depth of the basin (Wiltermuth 2014; Wiltermuth and Anteau 2016). In deeper basins (≳ 2 m depth to spill point), wetlands would function more like stabilized lacustrine systems. In shallower basins (≲ 2 m depth to spill point), stabilization and the concurrent deposition of upland sediments create conditions for expansion of cattail (*Typha* spp.) and these wetlands may become cattail choked (Kantrud 1992; Swanson 1992; Gleason and Euliss 1998; Wiltermuth and Anteau 2016). Both of these outcomes would represent dramatic shifts in the ecology of semipermanently-ponded wetlands in the PPR, and neither is favorable for wildlife species that are major drivers of conservation policy in the region (e.g., waterfowl).

Terrestrial and aquatic ecological communities in the PPR evolved in an environment shaped by dynamic hydrological responses of wetlands to climate variability. Moreover, wetland communities of the PPR also evolved under generally isolated conditions with only periodic-surface-hydrologic connections among wetlands (Leibowitz and Vining 2003; Mushet et al. 2015). Stabilized and interconnected wetland basins are likely to favor invasive species such as fish and cattail that generally have negative impacts on the native communities of the Northern Prairie Region (Bouffard and Hanson 1997; Anteau et al. 2011; Wiltermuth 2014). There have been observed increases in the abundance and occurrence of invasive and native fish species in wetlands of the PPR (Peterka 1989; Anteau and Afton 2008; Wiltermuth 2014). Interconnected and stable lakes, while providing habitat for various species of fish, provide much less food and foraging habitat for waterbirds because fish reshape invertebrate communities (Duffy 1998; Zimmer et al. 2000; Anteau and Afton 2011; Anteau et al. 2011). Without periodic interannual drawdowns, birds requiring shallow water, exposed shoreline, or mud banks are also less likely to find suitable habitat during spring and early summer (Niemuth et al. 2006; Anteau 2012; McCauley et al. 2016).

Flooding Impacts Inspection of temporal dynamics of the water volume of Devils Lake in North Dakota provides an instructive case study illustrating how land use changes may affect the way higher order watersheds respond to climate. Measured water volume of Devils Lake (calculated from available stage data and stage-to-volume tables; U. S. Geological Survey 2016) has experienced substantial variation since the 1930s, typified by a marked increase in volume beginning in the early 1970s (Fig. 4). We used procedures outlined by McCauley et al. (2015) to make a climate-based prediction of water volume of Devils Lake using a moving average of 16 previous years of a standardized precipitation and evapotranspiration index ($SPEI_{16}$) derived from readily available spatially explicit climate data (see Post van der et al. 2016). Similar to McCauley et al. (2015), we estimated parameters of a predictive model using data restricted to an era before the recent major land use changes in the watershed (1930–1960). This simple linear regression model with a single climate-based variable explained 92 % of the variation in measured water

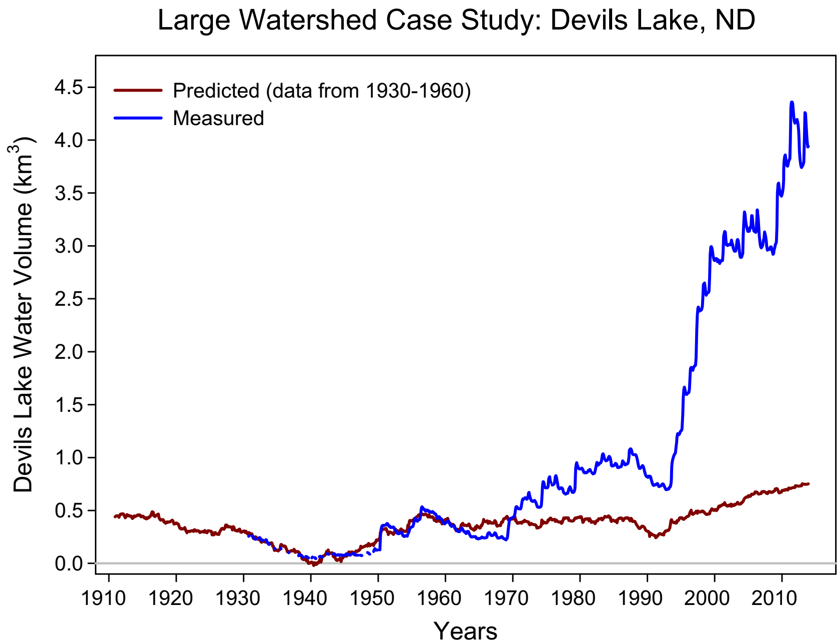

Fig. 4 Plot of the measured (*blue*) and predicted (*red*) water volume (km^3) of Devils Lake, North Dakota, by years of climate record. The predicted values represent expected water volumes based on the relationship of climate data and lake volume from 1930 to 1960, a period prior to large-scale landscape modifications and wetland drainage

volume during 1930–1960. We used parameter estimates from this model (Devils Lake volume [km^3] = 0.369 + 0.160 * SPEI$_{16}$) to predict water volume for the period 1910–2014 (Fig. 4). Lake volume predicted solely based on climate diverged from measured volume after 1960, suggesting a fundamental change in the way the Devils Lake watershed responded to variation in climate, potentially due to changes in land use occurring after 1960. Furthermore, measured lake volume between 1970 and 1990 experienced a cumulative set of increases with each wetting phase during that time despite numerous dry phases. This sharply contrasts with climate-predicted values, which show the lake would have experienced a relatively stable volume (Fig. 4). This pattern of increasing water volume, during similar intensity wetting and drying periods of 1970–1990, seems to be consistent with our conceptual model (Fig. 2) presented earlier.

Flooding of rivers and lakes is becoming a major issue in the midcontinent portion of North America and costs of flooding have been particularly high for population centers located in and around river floodplains within and downstream of the PPR. Due to hummocky topography, the PPR was historically composed of numerous areas that did not contribute to major watersheds (e.g., Missouri River, Devils Lake, Lake Winnipeg, etc.). However, once a basin fills to its spill point it would essentially add that wetland's entire watershed to the contributing area of the next higher-ordered watershed. Similar to the process of consolidation drainage increasing the contributing area and concomitant runoff, the spilling of water outside a watershed could unbalance higher-order watersheds and cause a cascading effect into rivers and large lake systems. Escalations in the amount of ponded water in wetlands could also be driven by future changes in the intensity of precipitation events. Our conceptual model suggests that there may be time-lags between the perturbation or change and the observed effect on higher-order watersheds because it may take some time to fill basins to the point of spilling into higher-order watersheds. Addressing interacting effects of land use and climate change on flooding in and downstream of the PPR will require detailed understanding of the nested hydrologic processes among low- to high-ordered watersheds.

Anthropogenic Feedbacks The future climate may allow agricultural producers to intensify cropping practices to increase production in the PPR because of longer growing seasons and increased precipitation. Global demand for crop production is also expected to increase (Tilman et al. 2001; Tilman et al. 2011), and so the economic, technological, climatological, and geographical parameters will likely dictate changes in favor of increased extent and intensity of anthropogenic modifications for agriculture in the PPR (Rashford et al. 2011a, b). But if climate change also leads to increased wetness in the PPR, we expect that wetlands will hold water longer, which could necessitate more consolidation drainage or connections to stream networks using surface modifications and subsurface tile drainage. On a local scale, this may benefit producers by increasing tillable area. However, over a larger scale, drainage of these basins into higher order watersheds means that some producers will experience increased flooding and decreased farmable area. Producers that may have historically not needed to use drainage systems will need to adopt these measures to decrease agricultural-land flooding impacts. Broader-scale adoption of practices to mitigate local flooding may, thus, have larger scale implications for urban centers and other communities located near lakes or rivers, who must then also adopt flood mitigation strategies. We suggest that the potential for positive feedbacks between wetland drainage and climate change will likely cause rapid and non-linear changes in characteristics of the landscape of the PPR. This means that in order to evaluate the potential influences of climate change on wetland hydrology and ecosystems of the PPR, we first need to fully account for these potential feedbacks.

Conclusions

Conservation dollars are spent to protect wetlands in the PPR by many organizations, but changes in hydrology due to climate and land-use changes may render those investments ineffective in meeting conservation goals. In addition, past and future land use will continue to affect wetland hydrology, and it is uncertain how climate and land-use changes may interact to influence wetland hydrology. It is unknown if resulting combinations of land use and climate change will produce positive, neutral, or negative outcomes for wetland functionality, and it is likely that the response will not be consistent across the PPR. Accordingly, there is a clear need for modelling efforts that can provide spatially appropriate state-dependent predictions of wetland hydrology given changes in climate and land use. Predicted hydrologic responses will facilitate additional efforts to examine resulting influence on a number of key species important for conservation. These efforts would also better inform and quantify wetland ecosystem services that have broader societal interests than waterbird conservation, for example flood control and water quality.

Some climate models project increased precipitation in the Northern Plains (IPCC 2013, 2014; Shafer et al. 2014). Flooding exacerbated by land-use practices coupled with potential climate change has direct economic implications on agriculture, transportation infrastructure, and residential and commercial property (Adger et al. 2005; Carrera et al. 2015). When wetlands increase in size to their spilling point, they contribute to flows into downstream water bodies (Wiltermuth 2014). Given existing flooding concerns on the Missouri River, Red River, and Devils Lake, increased flow into these systems due to climate and land use changes must be understood to better predict and manage these problems. Hydrologic models incorporating climate and land use changes in the PPR are a prerequisite step to understanding surface outflows from wetlands, and thus provide information necessary for a subsequent economic assessment of conservation strategies to restore upper-watershed water storage (i.e., functional wetlands complexes) vs. infrastructure to abate flooding issues (e.g., raising roads, buying out landowners, diversions, dams, etc.).

When we reviewed what is known about how wetlands respond hydrologically to anthropogenic changes on the landscape we found that we do not have a very clear understanding of the actual mechanisms driving observed relationships. Most studies involving land use change have been observational in nature and it is left up to researchers to offer hypotheses about the mechanisms, our conceptual model included. We believe this is symptomatic of too few detailed studies focused on mechanistic functions of wetland hydrology in this landscape and none that have been adequately replicated across a land use gradient. Therefore, we contend a number of prerequisites remain before meaningful predictions can be made about the effects of climate change on PPR wetlands. Those evident to us are:

1) An understanding of variation in physical and watershed characteristics of wetlands with similar hydroperiods across the PPR
2) A mechanistic understanding of how wetlands respond to climate across a gradient of anthropogenic modifications in the PPR
3) Improved climate predictions for the PPR that can predict potential changes in climate variability including intensity and duration of wet and dry periods

Climate and land use driven changes in hydrology across this region have potential to increase risk of flooding, including that in metropolitan areas, and cause cascading large-scale ecological issues (e.g., community shifts and Gulf of Mexico hypoxia). We contend that there is much at stake to making informed wetland conservation decisions in the PPR, thus it is important to inform the public, conservation decision makers, and policy makers with information about the many ecosystem services provided by wetlands in addition to that of the existing conservation model (i.e., waterbird habitat).

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