



The Potential of Prairie Pothole Wetlands as an Agricultural Conservation Practice: A Synthesis of Empirical Data

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Abstract

Nutrient pollution causing harmful algal blooms and eutrophication is a major threat to aquatic systems. Throughout North America, agricultural activities are the largest source of excess nutrients entering these systems. Agricultural intensification has also been a driver in the historical removal of depressional wetlands, contributing to increased hydrological connectivity across watersheds, and moving more nutrient runoff into terminal waterbodies such as the Laurentian Great Lakes and Gulf of Mexico. The Prairie Pothole Region of North America (PPR) supports grassland, cropland, wetland, and riverine systems that connect to the Missouri, Mississippi, and Red River Basins. There is a need to synthesize scientific understanding to guide more targeted conservation efforts and better understand knowledge gaps. We reviewed 200 empirical studies and synthesized results from across a minimum of 9 and maximum of 43 wetland basins (depending on the variable data available). We found an average wetland removal rate of nitrate and phosphate of 53% and 68%, respectively. Literature also showed sedimentation rates to be twice as high in wetland basins situated within croplands compared to grasslands. Our synthesis enhances understanding of nutrient processing in wetlands of the PPR and highlights the need for more empirical field-based studies throughout the region.

Keywords Agricultural wetlands · Nutrient management · Nitrogen · Phosphorous · Sediment · Prairie pothole wetlands

Introduction

Prairie Pothole Region of North America and Wetland Benefits

As the last ice age came to an end, glaciers receded, and the melting of the Laurentide Ice Sheet in North America left behind a hummocky landscape containing depressional basins (Dahl 2014; Doherty et al. 2018). Millions of these depressional basins stored accumulated surface water and eventually developed into the largest wetland complex in North America (Keddy 2010). This expansive wetland region, now known as the Prairie Pothole Region (PPR), spans three Canadian provinces (Alberta, Saskatchewan, Manitoba) and five U.S. states (Montana, North Dakota, South Dakota, Minnesota, Iowa), to encompass more than 770,000 km² of the Northern Great Plains (Smith et al. 1964;

Doherty et al. 2018). Teeming with biodiversity and hydrologic complexity, the landscape of the PPR is one of the most unique wetland-grassland ecosystems in the world and supports a significant amount of the continent's rangeland and cultivated cropland agriculture (Kantrud et al. 1989, Leibowitz 2003, Baldassarre and Bolden 2006). Despite the PPR's significance, much is still unknown about how wetland nutrient storage and processing may vary spatially and temporally over the region, illustrating the current need for field-scale empirical data related to this topic.

Prairie pothole wetlands have been the focus of many scientific studies because of the wide array of ecosystem services that they provide. Services provided by these wetlands include biodiversity support (Euliss and Mushet 1999; Babbitt 2005), flood control (Gleason et al. 2008), carbon sequestration (Euliss et al. 2006), groundwater recharge (Winter and Rosenberry 1998), and excess nutrient control (Jordan et al. 2011). Many studies have focused on the wetlands of the PPR because they are a critical breeding region for migratory birds, especially waterfowl, and the surrounding grasslands provide cover and nesting habitat for successful reproduction (Klett et al. 1988; Stephens et al. 2005;

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Winter et al. 2005). Nutrient storage and processing are also important services that wetlands can provide (Jordan et al. 2011) and understanding their value in this region of intense agriculture is crucial.

Loss of Wetlands and Changes in Nutrient Dynamics

Even with the multi-faceted ecological benefits of wetlands, often the perception of depressional wetlands in the PPR has been one of hindrance for the country's agricultural advancement. Over 90% of the PPR is privately owned and has undergone major alterations to become productive cropland for North America (Fig. 1). Wetlands may have made up more than 20% of the PPR landscape prior to settlement, however, 50–90% (depending on the State) have subsequently been lost to drainage and filling for cropland conversion (Dahl 1990; Euliss et al. 2006; Crumpton et al. 2012). These dramatic alterations have resulted in decreased surface water storage that can lead to increases in flood frequencies and nutrient runoff (Brun et al. 1981; Miller and Nudds 1996; Gleason et al. 2011).

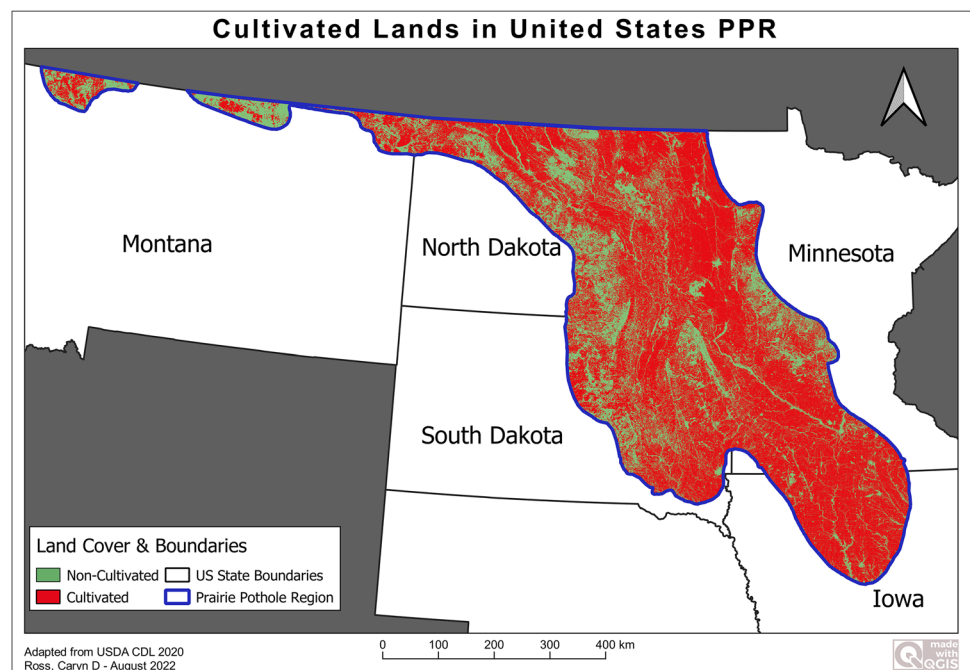
The intense shift in land cover type within the PPR has given way to the extensive use of surface and subsurface drainage systems to remove wetlands and excess soil moisture from terrestrial systems and are rerouted into downstream aquatic systems. This change in hydrological dynamics causes a loss in the wetland's capacity to cycle and remove nutrients, such as nitrogen through denitrification and phosphorous through soil adsorption (Sharpley and Withers 1994; Hey et al. 2005). In addition to drainage practices, fertilizers containing nitrogen and phosphorous are often applied in

large amounts to agricultural fields for increased crop yield (Randall et al. 1997; Sawyer et al. 2006).

Nutrients can be transported from agricultural land to water by air, surface runoff and subsurface flow. These nutrients can be dissolved in water or bound to sediments. Nitrogen is a highly mobile element moving throughout the atmospheric, biologic, geologic, and hydrologic pools (Seelig and DeKeyser 2006). Excessive amounts of nitrogen and phosphorous are correlated with eutrophication of rivers, lakes, and coastal waters (Howarth and Marino 2006, Pinckney et al. 2001, Dodds et al. 2009). Contamination of surface and groundwaters with nitrate and other nitrogen forms are also shown to cause harm to aquatic biota and humans (Townsend and Howarth 2010).

Nitrogen and phosphorous yield from fields can vary depending on type of crop, tillage, amount of fertilizer, timing, adsorption, and weather. The amount of nitrogen transported is highly dependent on sediment losses and is estimated to be between 1–50 kg/ha/yr from agricultural lands (Baker and Lafen, 1983; Johnson and Baker 1984; Smith et al. 1993; Downing et al. 1999). The potential for nitrogen transport is heightened when incorporating a subsurface drainage system, with estimates increasing to 2–130 kg/ha/yr of nitrogen being transported in agricultural runoff (Gast et al. 1978, Baker 1980, Baker and Johnson 1981, Kladivko et al. 1991, Weed and Kanwar 1996, Randall et al. 1997, Blann et al. 2009). Subsurface drainage is shown to decrease phosphorous losses via surface runoff; however, it also reduces the amount of time phosphorous comes in contact with soil minerals (Sharpley et al. 1994). Decreasing contact time leads to an inability for adsorption to soil

Fig. 1 Map of United States Prairie Pothole Region depicting cultivated and non-cultivated lands adapted from USDA Cropland Data Layer (2020)



and organic matter, ultimately accelerating the transport of phosphorous in runoff (Ruark et al. 2012). Agricultural land is the primary source of excessive phosphorous accumulation in soils, due to long-term phosphorous losses from fields (Sharpley et al. 2001). Excess phosphorous in soil is then able to transport via surface and subsurface runoff or erosion. Without proper edge of field conservation practices, such as wetlands, agricultural runoff from fields has a direct path to rivers and streams, ultimately ending up in coastal waters and translocating accumulated nutrients along the way (Crumpton and Baker 1993, Howarth et al. 2002).

A Need for Solutions

The main source of hypoxia, or “dead zone”, in the Gulf of Mexico is directly related to the loss of nitrogen and phosphorous from the agricultural areas of the Midwestern U.S., within the Mississippi River Basin (Goolsby et al. 1999, USEPA 2008, Robertson and Saad, 2013). To reverse these multi-decadal effects of eutrophication, an estimated 60% reduction in watershed nitrogen loading may be necessary to adequately reduce eutrophication in the Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2017 Report to Congress). Like the Gulf of Mexico, Lake Winnipeg (10th largest freshwater lake in the world) is the terminal waterbody that the Red River of the North drains into and has been subject to increased nutrient loading that has been linked with agricultural runoff (Koehler et al. 2021). This has caused algal blooms on Lake Winnipeg that have reached as high as 96% of the lake’s surface area (Binding et al. 2018). Understanding and bridging the knowledge gap in nutrient dynamics of the wetlands in the PPR may lead to more effective nutrient reduction strategies in these areas.

With an estimated 10 million acres of restorable wetlands in the US PPR alone, there is an extreme potential for wetland restoration projects given the historic wetland presence, importance to wildlife, and the need for water and nutrient runoff mitigation (Dahl 2014). For example, within the Mississippi River Basin, watershed-scale statistical modeling estimates that a 22% increase in wetland area could decrease nitrogen loading to the Gulf of Mexico up to 54% (Cheng et al. 2020). Advancements in technology such as remote sensing, access to large climate and other observational datasets, and the ability to process big data more easily has greatly improved wetland modeling efforts in recent years. These sophisticated approaches allow for more dynamic modeling necessary at the landscape scale. However, in terms of model accuracy in complex regions, such as the PPR, there is still room for improvement (Evenson et al. 2021).

Synthesizing the current in situ wetland nutrient storage and transformation rates from field-based studies is critical for understanding the return on investment of wetland restoration and creation in agricultural systems. The aim of our synthesis is to enhance understanding of factors contributing to variability of wetland nutrient processing rates in wetlands of the PPR and to identify knowledge gaps that may be addressed with more empirical field-based studies within the region. These findings may also improve process-based modeling by providing “soft data” of the agricultural conservation potential of depressional wetlands within the PPR.

Methods

The purpose of this review is to evaluate our current knowledge on the nutrient processing potential of depressional wetlands within agricultural systems of the United States PPR. Our analysis focuses on the ability of wetlands in an agricultural landscape to capture nutrient and sediment runoff from croplands prior to transport to aquatic systems. This review is an effort to synthesize a range of field study removal rates by wetlands in the PPR. We focus on empirical studies providing data on edge of field losses of nitrogen, phosphorous and sediment into wetlands and the removal efficiency of the wetland.

Using the search engines Google Scholar and Web of Science, we reviewed approximately 200 journal articles. Search terms were initially limited to “agricultural runoff of nitrogen, phosphorous, and sediment” and “nitrogen, phosphorous, and sediment removal by wetlands”. These articles were further narrowed down to only include studies of non-floodplain wetlands that are within agricultural systems of the PPR. This left seven studies with data on nitrogen transport, three studies with data on phosphorous transport, and three studies with data on sediment accumulation in wetlands. Nitrogen and phosphorous studies were limited to only two states, Iowa and Minnesota, and sediment study sites were located in North Dakota, South Dakota, and Minnesota.

From the studies, when possible, we extracted the following data values: wetland location, year of study, wetland area, watershed area, annual precipitation, nitrogen/phosphorous inflow, nitrogen/phosphorous outflow, nitrogen/phosphorous retained, sediment vertical and mass accumulation, and catchment type.

The analyses were performed using R Statistical Software (v4.1.2; R Core Team 2021). Looking at wetland nutrient removal efficiencies, histograms were created to visualize the spread of nitrate removal ($n=36$) and phosphate removal ($n=9$). A linear regression was performed to assess the relationship between nitrate inflow to wetlands and nitrate retention by wetlands ($n=30$). Similarly, a linear regression was

performed regarding the relationship between phosphate inflow and retention by the wetland ($n=9$). Looking further into wetland nutrient trends, linear regressions were performed to assess a relationship between wetland area and percent mass of nitrate removed ($n=40$), as well as wetland to watershed area ratio and percent mass of nitrate removed ($n=43$).

Results

Nitrogen and Phosphorous

Edge-of-field nutrient loss to prairie pothole wetlands ranged from 15–100% nitrogen retention rates (Fig. 2) and 12–100% phosphorus retention rates (Fig. 3). Wetlands captured an average of 52% nitrogen and 67% phosphorous from agricultural runoff before water was transported downstream.

Looking at the relationship between the amount of nutrient inflow versus amount of nutrient removed by prairie pothole wetlands can be used to better characterize how removal efficiencies may change depending on loading rates. The wetlands from these various studies show a nearly linear relationship, with a strong upward trend, of nitrate inflow (3.7–3,807 kg/ha/yr) and the wetland’s ability to remove the nutrient from the system (Fig. 4). Phosphate inflow (0.05–3.2 kg/ha/yr) and the wetland’s ability to remove the nutrient from the system did not show a strong linear relationship (Fig. 5).

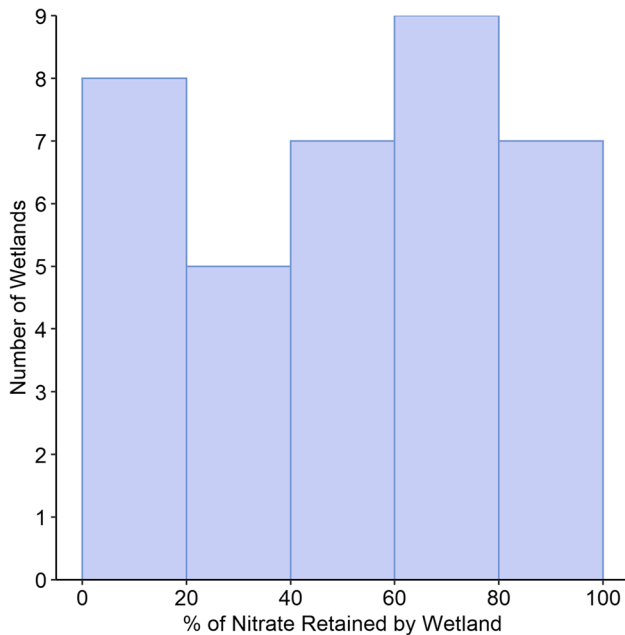


Fig. 2 Percent of nitrate retained by wetland. Each bin represents 20 percent increments

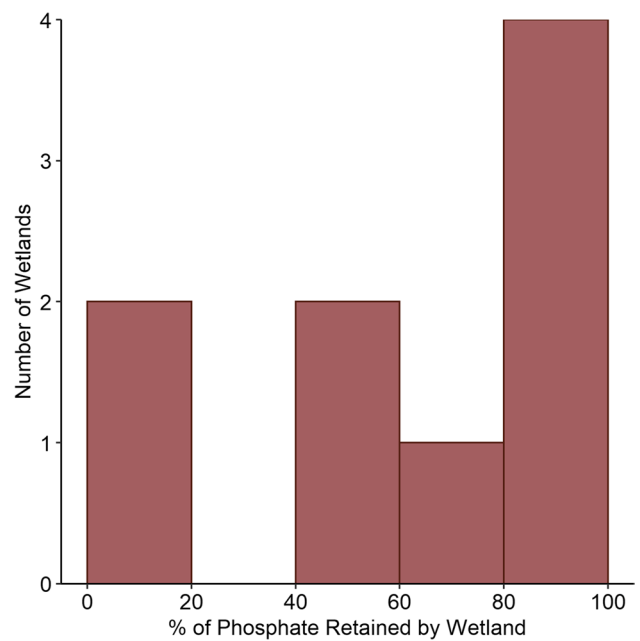


Fig. 3 Percent of phosphate retained by wetland. Each bin represents 20 percent increments

The relationship between wetland area and percent of nitrate mass removal was also weak, not revealing any obvious trends (Fig. 6). However, when incorporating the watershed area by using a wetland to watershed ratio, the

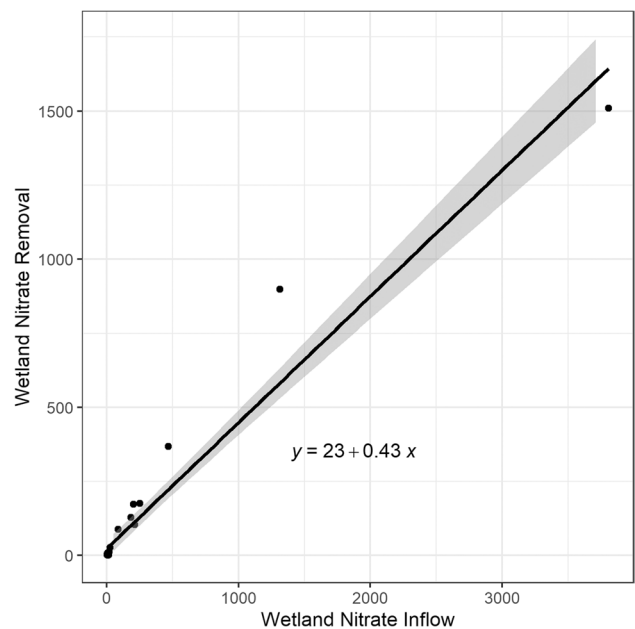


Fig. 4 Linear regression model showing the relationship between the amount of nitrate inflow and amount of nutrient removed by wetland. Gray shaded area represents 95% confidence interval. ($R^2=0.94$; $p < 0.001$)

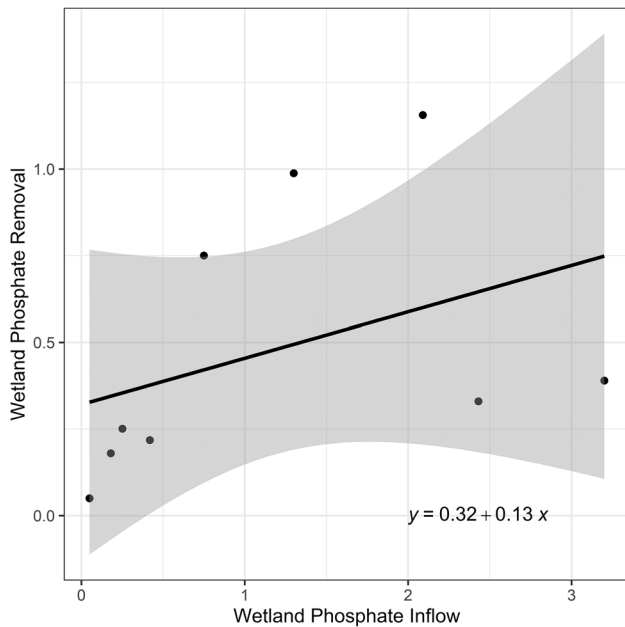


Fig. 5 Linear regression model showing the relationship between the amount of phosphate inflow and amount of nutrient removed by wetland. Gray shaded area represents 95% confidence interval. ($R^2=0.03$); ($p=0.30$)

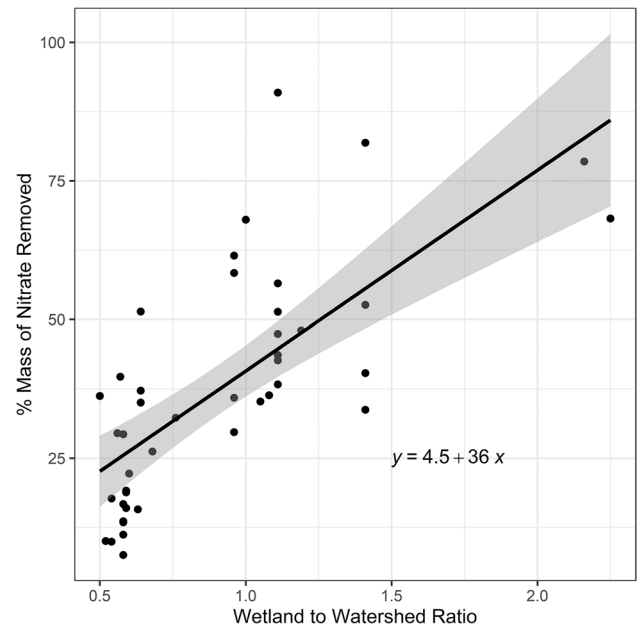


Fig. 7 Linear regression model showing the relationship between the wetland to watershed ratio and percent mass of nitrate removal. Gray shaded area represents 95% confidence interval. ($R^2=0.50$); ($p<0.001$)

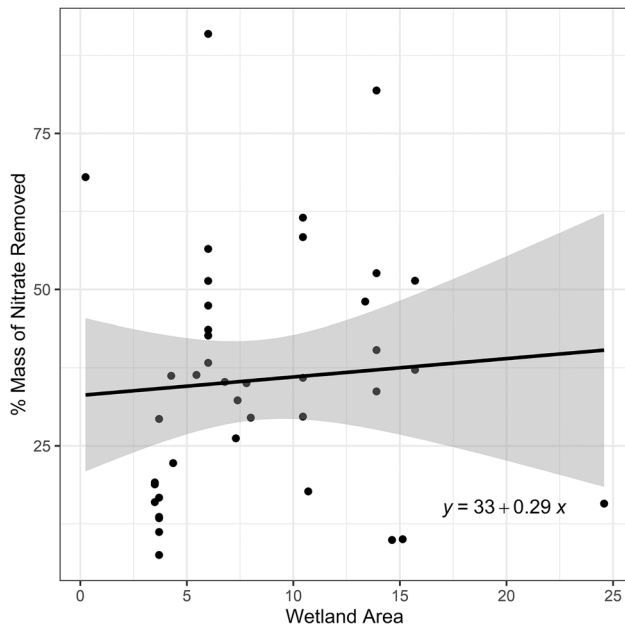


Fig. 6 Linear regression model showing the relationship between wetland area and percent mass of nitrate removal. Gray shaded area represents 95% confidence interval. ($R^2=-0.0205$); ($p=0.65$)

relationship of wetland to watershed ratio and nitrate mass removal rates reveals a significant linear relationship with an upward trend (Fig. 7).

Sediment

Empirically derived sedimentation rates in the reviewed studies in prairie pothole wetlands range from 0.21–0.6 cm/yr of vertical accumulation and an average mass accumulation of 0.268 g/cm²/yr adjacent to agricultural land. Adjacent to grassland, vertical accumulation ranges from 0.06–5 cm/yr with an average mass accumulation of 0.068 g/cm²/yr (Table 1). Note in Table 1 that Martin and Hartman (1987) did not find a significant difference in vertical sediment accretion rates between the two land types. They did however find a significant difference in the dry densities of the sediments, with cultivated sediment being significantly higher due to high silt and clay contents. Additionally, total nitrogen concentrations were significantly higher in soils and sediments of the grassland watersheds and phosphorous was transported at almost twice the rate to wetlands surrounded by cultivated land. Readers should also note that this review only contains data on sediment from three studies located in the states of Montana, South Dakota, and North Dakota. More studies are needed to confirm the comparison between cropland and grassland catchment effects on sediment accumulation in wetlands.

Table 1 Studies of sedimentation rates of wetlands in the PPR

Sedimentation Rate				Study Wetlands	Source
Grassland		Cropland			
vertical accumulation	mass accumulation	vertical accumulation	mass accumulation		
0.08 cm/yr	0.068 g/cm ² /yr	0.26 cm/yr	0.268 g/cm ² /yr	7 grassland, 12 cropland	Gleason 2001
0.4 – 0.5 cm/yr	NA	0.4 – 0.6 cm/yr	NA	5 grassland, 7 cropland	Martin & Hartman 1987
0.06 cm/yr	NA	0.21 cm/yr	NA	4 grassland, 4 cropland	Preston et al. 2013

Discussion

Studies with a larger pool for compiling wetland data than this review, such as Land et al. (2016) study on wetlands of North America and Europe, found significantly linear relationships between nitrogen and phosphorous loading rates and a wetland's removal efficiency. Crumpton and Baker (1993) also found that constructed wetland mesocosms were able to reduce nitrate levels by more than 80% when testing a range of nitrogen concentrations (3–15 mg/L) and given a residence time of one week. The results implied the possibility for constructed wetlands to remove nutrient exports at the field scale in the Midwest, leading to further investigations of agricultural treatment wetlands. Kovacic et al. (2000) constructed three treatment wetlands in Illinois to intercept tile drainage from corn and soybean fields in the Midwest. Over a three-year period, the wetlands were able to remove 37% of nitrate before draining into an adjacent river. While these studies are not located in the PPR, they reveal similar results to this review, with a significant correlation between nitrate loads and removal efficiencies (Fig. 4), which may also explain the wide range in wetland retention rates (15–100%) (Fig. 2). However, many of the available studies on wetlands in agricultural settings of North America take place in Illinois, Minnesota, and Iowa. Given that all of the nutrient studies in this review were only available in the portion of the PPR that is located in Iowa and Minnesota, we are unable to say whether our results are a reliable representation of the region as a whole. More studies in Montana, North Dakota, and South Dakota need to be conducted in order to have a spatially relevant representation of the PPR.

Utilizing data on wetland and watershed area where available, we were able to look further into the relationship of wetland nitrate removal efficiency and the wetland area alone (Fig. 6), and the wetland to watershed area ratio (Fig. 7). The wetland area alone did not show a significant relationship with nitrate mass removal efficiency, while the wetland percent of nitrate removal mass was at least partially explained by the wetland to watershed ratio. Given a larger sample size with a wider range of wetland to watershed ratios, more distinct trends in the relationship with nitrogen retention could be explored.

Wetland presence within agricultural areas of the PPR can provide sufficient time and space for nitrogen management through denitrification within the wetland basins (Hey et al. 2012). A recent study by Gordon et al. (2021) found that even a small edge-of-field wetland (0.11 ha), located in Minnesota, was able to remove 67% of nitrate inputs from a 10.1 ha row-crop field. Within this same study, they found that harvesting vegetation from the wetland was a successful practice to remove phosphorous. This is consistent with other studies on vegetation harvesting for phosphorous removal from aquatic systems (Grosshans et al. 2014; Skłodowski et al. 2014; Bartodziej et al. 2017).

A relationship of phosphate inflow and phosphate retention was not significant when analyzing the wetlands included in this review (Fig. 5). These results could simply be because the sample size was too small ($n=9$) to reveal any significant trends. Investigating relationships between phosphorous inflow and retention rates to include more information on vegetation type, structure, and harvesting could be valuable in understanding this relationship further. Prairie pothole wetlands are known to support dynamic vegetation communities that are capable of removing excess nutrients (Dierberg et al. 2002). A portion of our review data on phosphate was from Gordon et al. (2021) and they state that plant harvesting was the main mechanism for phosphate removal, but we were not able to glean vegetation information from the other studies used to look into this further.

Dependent on influences of phosphorous surplus inputs in soil, such as fertilizer application and tillage practices, there can be large variations in spatiotemporal losses of phosphorous from agricultural fields of the PPR (Detenbeck et al. 2002). Variations in precipitation have also been shown to play a large role in phosphorous losses between different fields and even within the same field (Johnson and Baker 1984, Mendes, 2020). We found that studies within the PPR have found annual surface runoff phosphorous concentration ranges between 0.23–1 mg/L (0.017 – 1.34 kg/ha) (Davis et al. 1981, Baker and Johnson 1981, Johnson and Baker 1984, Badiou et al. 2018). Natural, restored, and constructed wetlands in the PPR can store excess runoff in wet years and capture phosphorous-rich sediments, while drained wetlands pose a risk of increased

runoff due to their lack of storage capacity (Zedler 2003; Badiou et al. 2018; Green et al. 2019).

There are a variety of variables we were not able to explore that could have had an effect on wetland phosphate retention rates, such as vegetation structure or wetland saturation level, that may explain the wide range of wetland phosphate retention rates (12–100%) (Fig. 3). Within the Canadian portion of the PPR, Badiou et al. (2018) compared phosphorous retention rates between intact and drained prairie wetlands. They found major differences in the chemical characteristics of sediment and soils that effected phosphorous sorption capacity between the two types of wetlands. These characteristics appeared to be driven by saturation and submergence level of the particular wetland location in question. Intact wetlands were shown to have higher phosphorous sorption and phosphorous buffering capacity. Their results indicate that prairie pothole wetlands can play a critical role in nonpoint source pollution mitigation, especially in an area where excess nutrients from agriculture is abundant.

Studies in the PPR estimate soil loss from agricultural areas ranging from 867–5,387 kg/ha/yr, while loss from natural grasslands are observed at only 50 kg/ha/yr (Baker and Johnson 1981, Johnson and Baker 1984; Chaplot et al. 2004). Erosion and sedimentation are natural geologic processes; however, they are exacerbated and accelerated by the conversion of natural landscapes (Alewell et al. 2019). When cultivating land, the topsoil (where nutrients and organic matter are concentrated) is disturbed, causing increases in runoff, nutrient leaching, and erosion leading to sedimentation of waterways and depressional basins where lakes and prairie pothole wetlands exist (Gleason 2001, Chaplot et al. 2004, Burris and Skagen 2013, Preston et al. 2013).

The various studies we analyzed within the PPR show higher rates of sediment input to wetlands of the PPR with cropland catchments compared to wetlands within grasslands attributed to the higher contents of clay in sediment from cultivated areas (Table 1) (Adomaitis et al. 1967; Martin and Hartman 1987; Gleason 1996, 2001; Gleason and Euliss 1998). Skagen et al. (2016) used a common modeling approach (Revised Universal Soil Loss Equation), validated their model using two of the studies utilized in this review (Gleason 2001, Preston et al. 2013), and found that accumulation of sediment was greater in wetlands with larger catchments and steeper slopes. In agreement with empirical studies within the PPR, results from Skagen et al. (2016) showed accumulation was determined not only by the topographic features but rainfall and agricultural practices as well—sediment increased with the increase of tilled land within the catchment (Gleason 2001, Burris and Skagen 2013, Preston et al. 2013).

Best Management Practices

When considering a prairie pothole wetland as an agricultural conservation practice, it is important to note their vulnerability to geological processes such as sedimentation when adjacent to cultivated lands. When used as a best management practice, runoff water from agricultural lands enters a wetland, transporting excess nutrients and sediment that will then settle out of the water to the bottom of the wetland. The maximum storage potential of a wetland will be reduced as sediment accumulates at the base of the wetland, therefore reducing the water storage capacity over time (Steglich et al. 2016). Gleason et al. (2003) suggests that wetland sedimentation from agricultural practices also leads to a reduction in the ability of aquatic plants and invertebrates to reestablish. With as little as 0.5 cm of sedimentation, there can be a significant reduction in the emergence of wetland seedlings and invertebrates – essential resources for wetland dependent vertebrates (Jurik et al. 1994; Gleason et al. 2003). A wetland's overall effectiveness and longevity as a sustainable conservation practice will be dependent on upland management practices within their catchments (De Steven and Mushet 2018).

To get the most out of wetlands as a conservation practice and improve sustainability, a combination of in-field and edge-of-field practices could be considered. Limiting the amounts of fertilizers applied to only the amount necessary for crop production can reduce nutrient inputs in runoff by more than 30% (Jaynes et al. 2004). Not only the amount, but the seasonal timing of fertilizer application in uplands can greatly affect the amount of fertilizer that is able to nitrify and leach into downstream waters (Randall and Mulla 2001). Upland conservation tillage practices are also successful methods of soil and sediment erosion reduction (Johnson et al. 1979; Ginting et al. 1998; Zhao et al. 2001). According to the latest Conservation Effects Assessment Project report, many farmers in the US have recently adopted advanced technology and in-field conservation practices to control erosion and trap sediment. As a result, between the time periods compared (2003–2006 and 2013–2016), edge-of-field sediment losses declined by 74 million tons and nitrogen and phosphorous losses via surface pathways decreased by 3 and 6% (USDA NRCS 2022). Reduction of excess nutrients in the wetland system may also contribute to the reduction of invasive species present, particularly those with a strong response to nutrient enrichment, such as *Typha* species (Bansal et al. 2019).

The presence of a wetland in an agricultural field as a management practice has the potential to benefit farmers by reducing field flooding, improving the water quality in the area, and supporting biodiversity (Neely and Baker 1989, Crumpton and Baker 1993, Richardson and Craft 2020, Bedford 1999, Keddy 2010). Wetlands can also benefit farmers

financially by reducing flood frequency, therefore reducing crop failure, and improving livestock health through cleaner water (Walker 1966, Jager et al. 2020). The increased water quality of downstream waters is a benefit for human water consumption and recreational activities such as fishing. Having an edge of field wetland can also lead to enjoyment of increased biodiversity through activities like bird watching.

Modeling Wetlands and Nutrient Dynamics

Evenson et al. (2021) assessed wetland restoration impacts on nitrate dynamics, resulting in a 12% reduction of nitrate from the Upper Mississippi River with 8,000 km² of restored wetlands. While their estimates are lower than previous landscape scale estimates in the region, their findings still suggest wetlands to be an effective strategy for mitigating nitrate but spatially the effectiveness can vary based on different processes and landscape dynamics. Based on our literature review which shows a lack of spatial range in the available empirical studies assessing wetland nutrient dynamics in the PPR, this highlights our need for more empirical studies to reveal trends in underlying mechanisms of the entire PPR landscape and improve model estimates.

Mckenna et al. (2020) has demonstrated a new method for simulating depression wetlands within the Conservation Effects Assessment Project (CEAP) cropland modeling framework using Agricultural Policy/Environmental eXtender (APEX). Their results show reduced runoff from a field by 8% with incorporation of an edge-of-field wetland, a 9% reduction when adding a buffer strip between the field and wetland, and an 18% reduction when converting the entire upland to grassland. Additionally, reductions in sediment, nitrogen, and phosphorous entering the wetland occurred with the addition of a buffer strip and more so with the complete upland conversion to grassland (Mckenna et al. 2020).

While these models are already advanced, studies utilizing them often refer to parameter refinement and calibration as a way to improve their simulation results (Saleh and Du 2004, Arabi et al. 2008, Perez-Valdivia et al. 2017). If models are provided with region-specific empirically derived values for calibration, this will provide more accurate watershed-scale estimates of the conservation potential of prairie pothole wetlands in agriculture.

It is important to note the lack of spatial diversity of current studies on wetland nutrient and sediment processing in agricultural settings of the PPR. The majority of studies have been conducted in the states of Iowa and Minnesota, leaving a large knowledge gap for the northwestern portion of the PPR. The region is vast, and the wetlands within it vary in physical size of basins, shape, and connectivity, to stream networks. They exist along a climate gradient; the northwest PPR is colder and drier, while the southeast PPR is warmer and wetter (Kantrud et al. 1989, Leibowitz 2003, Millett

et al. 2009). The high variability of wetland characteristics and climate between wetlands in the PPR has the potential to be a major source of uncertainty in current modeling efforts without more empirical evidence of wetland nutrient dynamics to represent the entire region.

Conclusions

When compared to pristine areas, it is clear that agricultural lands increase nutrient and sediment mobility. Including a prairie pothole wetland as an agricultural conservation practice can greatly reduce the downstream effects of edge-of-field nutrient loads. Rate of reduction in agricultural prairie pothole wetlands are variable and can change based on many different factors, including nutrient loading rates. The nutrient and sediment export dynamics from agricultural lands in the PPR is a complex issue that will likely persist along with agricultural intensification.

There are many strategies to reduce downstream nutrient pollution and combining approaches could ultimately give the best results. Based on the available studies investigated for this review, having a wetland as a conservation practice within an agricultural system is certainly beneficial compared to no wetland present. Consideration of other conservation practices such as buffer strips, nutrient control at the source (field), and utilizing vegetation as a nutrient uptake mechanism, especially for phosphorous, can be used in tandem with a wetland to enhance impact reduction.

In order to implement management strategies or predict wetland removal efficiencies and return on investment, more field-based studies on nutrient dynamics of PPR wetlands within agricultural settings are needed to fully understand the mechanisms associated with all parts of this expansive region.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author.

Declarations

Competing Interests The Authors have no relevant financial or non-financial interests to disclose.

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References

- Adomaitis VA, Kantrud HA, Shoemith JA (1967) Some chemical characteristics of aeolian deposits of snow-soil on prairie wetlands. *Proceedings of the North Dakota Academy of Science* 21:65–69
- Alewell C, Borrelli P, Meusburger K, Panagos P (2019) Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research* 7(3):203–225. <https://doi.org/10.1016/j.iswcr.2019.05.004>
- Arabi M, Frankenberger JR, Engel BA, Arnold JG (2008) Representation of agricultural conservation practices with SWAT. *Hydrological Processes: An International Journal* 22(16):3042–3055
- Babbitt KJ (2005) The relative importance of wetland size and hydroperiod for amphibians in southern New Hampshire, USA. *Wetlands Ecology and Management* 13(3):269–279. <https://doi.org/10.1007/s11273-004-7521-x>
- Badiou P, Page B, Akinremi W (2018) Phosphorus Retention in Intact and Drained Prairie Wetland Basins: Implications for Nutrient Export. *Journal of Environmental Quality* 47(4):902–913. <https://doi.org/10.2134/jeq2017.08.0336>
- Baker JL (1980) Agricultural areas as nonpoint sources of pollution. In Overcash MR, Davidson JM (eds) *Environmental impact of nonpoint source pollution*. pp 275–311
- Baker JL, Johnson HP (1981) Nitrate-Nitrogen in Tile Drainage as Affected by Fertilization. *Journal of Environmental Quality* 10(4):519–522. <https://doi.org/10.2134/jeq1981.00472425001000040020x>
- Baker JL, Laffen JM (1983) Water quality consequences of conservation tillage: New technology is needed to improve the water quality advantages of conservation tillage. *J Soil Water Conserv* 38(3):186–193
- Baldassarre GA, Bolden EG (2006) *Waterfowl Ecology and Management*. Krieger Publishing company, Malabar, Florida, p 580
- Bansal S, Lishawa SC, Newman S (2019) Typha (Cattail) invasion in North American wetlands: biology, regional problems, impacts, ecosystem services, and management. *Wetlands* 39:645–684. <https://doi.org/10.1007/s13157-019-01174-7>
- Bartodziej WM, Blood SL, Pilgrim K (2017) Aquatic Plant Harvesting: an Economical Phosphorus Removal Tool in an Urban Shallow Lake. *J Aquat Plant Manage* 55:26–34
- Bedford BL (1999) Cumulative effects on wetland landscapes: Links to wetland restoration in the United States and Southern Canada. *Wetlands* 19(4):775–788. <https://doi.org/10.1007/BF03161784>
- Binding CE, Greenberg TA, McCullough G, Watson SB, Page E (2018) An analysis of satellite-derived chlorophyll and algal bloom indices on Lake Winnipeg. *J Great Lakes Res* 44(3):436–446. <https://doi.org/10.1016/j.jglr.2018.04.001>
- Blann KL, Anderson JL, Sands GR, Vondracek B (2009) Effects of agricultural drainage on aquatic ecosystems: A review. *Critical Reviews in Environmental Science and Technology* 39(11):909–1001. <https://doi.org/10.1080/10643380801977966>
- Brun LJ, Richardson JL, Enz JW, Larsen JK (1981) Stream flow changes in the Southern Red River Valley of North Dakota [Water resources, flooding]. *North Dakota Farm Research*
- Burris L, Skagen SK (2013) Modeling sediment accumulation in North American playa wetlands in response to climate change, 1940–2100. *Climatic Change* 117(1–2):69–83. <https://doi.org/10.1007/s10584-012-0557-7>
- Chaplot V, Saleh A, Jaynes DB, Arnold J (2004) Predicting water, sediment and NO₃-N loads under scenarios of land-use and management practices in a flat watershed. *Water Air Soil Pollut* 154(1–4):271–293. <https://doi.org/10.1023/B:WATE.0000022973.60928.30>
- Cheng FY, Van Meter KJ, Byrnes DK, Basu NB (2020) Maximizing US nitrate removal through wetland protection and restoration. *Nature* 588(7839):625–630. <https://doi.org/10.1038/s41586-020-03042-5>
- Crumpton WG, Baker JL (1993) Integrating wetlands into agricultural drainage systems: Predictions of nitrate loading and loss in wetlands receiving agricultural subsurface drainage. *Integrated Resource Management and Landscape Modification for Environmental Protection*. ASAE, St. Joseph, MI, 118–126
- Crumpton W, Van Der Valk A, Hoyer W, Osterberg D (2012) Wetland restoration in Iowa challenges and opportunities. *The Iowa Policy Project* 1–24
- Dahl TE (2014) *Status and trends of prairie wetlands in the United States 1997 to 2009*. Washington, DC: US Fish and Wildlife Service
- Dahl TE (1990) *Wetlands losses in the United States, 1780's to 1980's*. US Department of the Interior, Fish and Wildlife Service
- Davis C, Baker J, van der Valk A, Beer C (1981) Prairie pothole marshes as traps for nitrogen and phosphorus in agricultural runoff. *Selected Proceedings of the Midwest Conference on Wetland Values and Management*, 153–163
- De Steven D, Mushet D (2018) Estimating the effects of wetland conservation practices in croplands: approaches for modeling in CEAP-cropland assessment. In *CEAP-Wetlands Science Note*
- Detenbeck NE, Elonen CM, Taylor DL, Cotter AM, Puglisi FA, Sanville WD (2002) Effects of agricultural activities and best management practices on water quality of seasonal prairie pothole wetlands. *Wetlands Ecology and Management* 10(4):335–354. <https://doi.org/10.1023/A:1020397103165>
- Dierberg FE, DeBusk TA, Jackson SD, Chimney MJ, Pietro K (2002) Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: Response to hydraulic and nutrient loading. *Water Research* 36(6):1409–1422. [https://doi.org/10.1016/S0043-1354\(01\)00354-2](https://doi.org/10.1016/S0043-1354(01)00354-2)
- Dodds Walter K, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, Schloesser JT, Thornbrugh DJ (2009) Eutrophication of U. S. freshwaters: Analysis of potential economic damages. *Environmental Science and Technology* 43(1):12–19. <https://doi.org/10.1021/es801217q>
- Doherty K, Howerter D, Devries J, Walker J (2018) *Prairie Pothole Region of North America. The Wetland Book II: Distribution, Description, and Conservation*, August, 679–688. <https://doi.org/10.1007/978-94-007-4001-3>
- Downing JA, Baker JL, Diaz RJ, Prato T, Rabalais NN, Zimmerman RJ (1999) *Gulf of Mexico Hypoxia: Land and Sea Interactions*. In Series: Task force report (Council for Agricultural Science and Technology) ; no. 134

- Euliss NH, Gleason RA, Olness A, McDougal RL, Murkin HR, Roberts RD, Bourbonniere RA, Warner BG (2006) North American prairie wetlands are important nonforested land-based carbon storage sites. *Science of the Total Environment* 361(1–3):179–188. <https://doi.org/10.1016/j.scitotenv.2005.06.007>
- Euliss NH, Mushet DM (1999) Influence of Agriculture on Aquatic Invertebrate Communities of Temporary Wetlands in the Prairie Pothole Region of North Dakota, USA. *Wetlands* 19(3):578–583
- Evenson GR, Golden HE, Christensen JR, Lane CR, Rajib A, D'Amico E, Mahoney DT, White E, Wu Q (2021) Wetland restoration yields dynamic nitrate responses across the Upper Mississippi river basin. *Environ Res Commun* 3:1–10. <https://doi.org/10.1088/2515-7620/ac2125>
- Gast RG, Nelson WW, Randall GW (1978) Nitrate accumulation in soils and loss in tile drainage following nitrogen applications to continuous corn. American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America 7(2):18–21
- Ginting D, Moncrief JF, Gupta SC, Evans SD (1998) Interaction between Manure and Tillage System on Phosphorus Uptake and Runoff Losses. *Journal of Environmental Quality* 27(6):1403–1410. <https://doi.org/10.2134/jeq1998.00472425002700060017x>
- Gleason RA, Euliss NH (1998) Sedimentation of prairie wetlands. *Great Plains Res* 8(1):97–112
- Gleason RA, Euliss NH, Tangen BA, Laubhan MK, Browne BA (2011) USDA conservation program and practice effects on wetland ecosystem services in the Prairie Pothole Region. *Ecological Applications*, 21(3 SUPPL.). <https://doi.org/10.1890/09-0216.1>
- Gleason RA (1996) Influence of agricultural practices on sedimentation rates, aquatic invertebrates, and bird-use in prairie wetlands: Arcata, Calif., Humboldt State University. master's thesis
- Gleason RA, Euliss NH, Hubbard DE, Duffy WG (2003) Effects of sediment load on emergence of aquatic invertebrates and plants from wetland soil egg and seed banks. *Wetlands* 23(1):26–34. [https://doi.org/10.1672/0277-5212\(2003\)023\[0026:EOSLOE\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2003)023[0026:EOSLOE]2.0.CO;2)
- Gleason RA (2001) Invertebrate egg and plant seed banks in of restored, natural and drained wetlands in the prairie pothole region (USA) and potential effects of sedimentation on recolonization of hydrophytes and aquatic invertebrates. *Wildlife and Fisheries*, Ph.D., 154
- Goolsby DA, Battaglin WA, Lawrence GB, Artz RS, Aulenbach BT, Hooper RP, Keeney DR, Stensland GJ (1999) Flux and sources of nutrients in the mississippi-atlafalaya river basin: topic 3 report for the integrated assessment on hypoxia in the gulf of Mexico. NOAA coastal ocean program decision analysis series No. 17. NOAA coastal ocean program. NOAA Coastal Ocean Program Decision Analysis Ser 17(17):130
- Gordon BA, Lenhart C, Peterson H, Gamble J, Nieber J, Current D, Brenke A (2021) Reduction of nutrient loads from agricultural subsurface drainage water in a small, edge-of-field constructed treatment wetland. *Ecological Engineering*, 160(January). <https://doi.org/10.1016/j.ecoleng.2020.106128>
- Green DIS, McDeid SM, Crumpton WG (2019) Runoff Storage Potential of Drained Upland Depressions on the Des Moines Lobe of Iowa. *Journal of the American Water Resources Association* 55(3):543–558. <https://doi.org/10.1111/1752-1688.12738>
- Grosshans R, Grieger L, Ackerman J, Gauthier S, Swystun K, Gass P, Roy D (2014) Cattail Biomass in a Watershed-Based Bioeconomy: Commercial-scale harvesting and processing for nutrient capture, biocarbon and high-value bioproducts. *Policy Commons*
- Hey DL, Kostel JA, Crumpton WG, Mitsch WJ, Scott B (2012) The roles and benefits of wetlands in managing reactive nitrogen. *Journal of Soil and Water Conservation* 67(2):47–53. <https://doi.org/10.2489/jswc.67.2.47A>
- Hey DL, Urban LS, Kostel JA (2005) Nutrient farming: The business of environmental management. *Ecological Engineering* 24(4 SPEC. ISS.):279–287. <https://doi.org/10.1016/j.ecoleng.2004.11.014>
- Howarth RW, Marino R (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography* 51(1 II):364–376. https://doi.org/10.4319/lo.2006.51.1_part_2.0364
- Howarth RW, Sharpley A, Walker D (2002) Sources of nutrient pollution to coastal waters in the United States: Implications for achieving coastal water quality goals. *Estuaries* 25(4):656–676
- Jager HI, Parish ES, Langholtz MH, King AW (2020) Perennials in Flood-prone areas of agricultural landscapes: A climate adaptation strategy. *Bioscience* 70(4):278–280
- Jaynes DB, Dinnes DL, Meek DW, Karlen DL, Cambardella CA, Colvin TS (2004) Using the Late Spring Nitrate Test to Reduce Nitrate Loss within a Watershed. *Journal of Environmental Quality* 33(2):669–677. <https://doi.org/10.2134/jeq2004.6690>
- Johnson HP, Baker JL (1984) Field-to-Stream Transport of Agricultural Chemicals and Sediment in an Iowa Watershed: Part II. Data Base for Model Testing. *Ecological Research Series (USA)* (1979–1980)
- Johnson HP, Baker JL, Shrader WD, Laflen JM (1979) Tillage system effects on sediment and nutrients in runoff from small watersheds. *Transactions of the ASAE* 22(5):1110–1114
- Jordan SJ, Stoffer J, Nestlerode JA (2011) Wetlands as Sinks for Reactive Nitrogen at Continental and Global Scales: A Meta-Analysis. *Ecosystems* 14(1):144–155. <https://doi.org/10.1007/s10021-010-9400-z>
- Jurik TW, Wang S-C, van der Valk AG (1994) Effects of sediment load on seedling emergence from wetland seed banks. *Wetlands* 14(3):159–165
- Keddy PA (2010) *Wetland ecology: principles and conservation*. Cambridge University Press
- Kladivko EJ, Van Scoyoc GE, Monke EJ, Oates KM, Pask W (1991) Pesticide and Nutrient Movement into Subsurface Tile Drains on a Silt Loam Soil in Indiana. *Journal of Environmental Quality* 20(1):264–270. <https://doi.org/10.2134/jeq1991.00472425002000010043x>
- Klett AT, Shaffer TL, Johnson DH (1988) Duck nest success in the prairie pothole region. *The Journal of Wildlife Management*. 431–440
- Koehler G, Brua RB, Enders EC (2021) Foreword to the second Lake Winnipeg special issue. *J Great Lakes Res* 47(3):553–555. <https://doi.org/10.1016/j.jglr.2021.03.024>
- Kovacic DA, David MB, Gentry LE, Starks KM, Cooke RA (2000) Effectiveness of Constructed Wetlands in Reducing Nitrogen and Phosphorus Export from Agricultural Tile Drainage. *Journal of Environmental Quality* 29(4):1262–1274. <https://doi.org/10.2134/jeq2000.00472425002900040033x>
- Land M, Granéli W, Grimvall A, Hoffmann CC, Mitsch WJ, Tonderski KS, Verhoeven JTA (2016) How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A Systematic Review. *Environmental Evidence* 5(1):1–26. <https://doi.org/10.1186/s13750-016-0060-0>
- Leibowitz SG (2003) Isolated wetlands and their functions: An ecological perspective. *Wetlands* 23(3):517–531. [https://doi.org/10.1672/0277-5212\(2003\)023\[0517:IWATFA\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2003)023[0517:IWATFA]2.0.CO;2)
- Martin DB, Hartman WA (1987) The effect of cultivation on sediment composition and deposition in prairie pothole wetlands. *Water, Air, and Soil Pollution* 34(1):45–53. <https://doi.org/10.1007/BF00176866>
- McKenna OP, Osorio JM, Behrman KD, Doro L, Mushet DM (2020) Development of a novel framework for modeling field-scale conservation effects of depressional wetlands in agricultural landscapes. *Journal of Soil and Water Conservation* 75(6):695–703. <https://doi.org/10.2489/JSWC.2020.00096>

- Mendes LRD (2020) Edge-of-Field technologies for phosphorus retention from agricultural drainage discharge. *Applied Sciences* (Switzerland), 10(2). <https://doi.org/10.3390/app10020634>
- Miller MW, Nudds TD (1996) Prairie landscape change and flooding in the Mississippi River Valley. *Conservation Biology* 10(3):847–853
- Millett B, Johnson WC, Guntenspergen G (2009) Climate trends of the North American prairie pothole region 1906–2000. *Climatic Change* 93(1–2):243–267. <https://doi.org/10.1007/s10584-008-9543-5>
- Neely RK, Baker JL (1989) Nitrogen and phosphorus dynamics and the fate of agricultural runoff. *Northern Prairie Wetlands*. 92–131
- Perez-Valdivia C, Cade-Menun B, McMartin DW (2017) Hydrological modeling of the pipestone creek watershed using the Soil Water Assessment Tool (SWAT): Assessing impacts of wetland drainage on hydrology. *Journal of Hydrology: Regional Studies* 14:109–129
- Pinckney JL, Paerl HW, Tester P, Richardson TL (2001) The role of nutrient loading and eutrophication in estuarine ecology. *Environmental Health Perspectives* 109(SUPPL. 5):699–706. <https://doi.org/10.1289/ehp.01109s5699>
- Preston TM, Sojda RS, Gleason RA (2013) Sediment accretion rates and sediment composition in prairie pothole wetlands under varying land use practices, Montana, United States. *Journal of Soil and Water Conservation* 68(3):199–211. <https://doi.org/10.2489/jswc.68.3.199>
- R Core Team (2021) R: a Language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
- Randall GW, Iragavarapu TK, Bock BR (1997) Nitrogen application methods and timing for corn after soybean in a ridge-tillage system. *Journal of Production Agriculture* 10(2):300–307. <https://doi.org/10.2134/jpa1997.0300>
- Randall GW, Mulla DJ (2001) Nitrate Nitrogen in Surface Waters as Influenced by Climatic Conditions and Agricultural Practices. *Journal of Environmental Quality* 30(2):337–344. <https://doi.org/10.2134/jeq2001.302337x>
- Richardson CJ, Craft CB (2020) Effective phosphorus retention in wetlands: fact or fiction?. *Constructed Wetlands for Water Quality Improvement* 271–282
- Robertson DM, Saad DA (2013) SPARROW Models Used to Understand Nutrient Sources in the Mississippi/Atchafalaya River Basin. *Journal of Environmental Quality* 42(5):1422–1440. <https://doi.org/10.2134/jeq2013.02.0066>
- Ruark M, Madison A, Cooley E, Stuntebeck T, Komiskey M (2012) Phosphorus Loss from Tile Drains: Should We Be Concerned? In *Proceedings of the Wisconsin Crop Management Conference*, University of Wisconsin, Madison, WI, USA, 10–12 January, 9–14
- Saleh A, Du B (2004) Evaluation of SWAT and HSPF within BASINS program for the upper North Bosque River watershed in central Texas. *Transactions of the ASAE* 47(4):1039
- Sawyer J, Nafziger E, Randall G, Bundy L, Rehm G, Joern B (2006) Concepts and rationale for regional nitrogen rate guidelines for corn concepts and rationale for regional nitrogen rate guidelines for corn. Iowa State University, University Extension, April 2006, 1–28
- Seelig B, DeKeyser S (2006) Water quality and wetland function in the Northern Prairie Pothole region. Cooperative States Research, Education and Extension Service, August, 1–25
- Sharpley AN, McDowell RW, Kleinman PJA (2001) Phosphorus loss from land to water: integrating agricultural and environmental management. *Plant and Soil* 237:287–307. <https://doi.org/10.1023/A:1013335814593>
- Sharpley AN, McDowell RW, Weld JL, Kleinman PJ (2001) Assessing site vulnerability to phosphorus loss in an agricultural watershed. *Journal of Environmental Quality* 30(6):2026–2036. <https://doi.org/10.2134/jeq2001.2026>
- Sharpley AN, Withers PJA (1994) The environmentally-sound management of agricultural phosphorus. *Fertilizer Research* 39(2):133–146. <https://doi.org/10.1007/BF00750912>
- Sharpley AN, Chapra SC, Wedepohl R, Sims JT, Daniel TC, Reddy KR (1994) Managing agricultural phosphorus for protection of surface waters: Issues and options. *J Environ Qual* 23(3):437–451
- Skagen SK, Burris LE, Granfors DA (2016) Sediment Accumulation in Prairie Wetlands under a Changing Climate: the Relative Roles of Landscape and Precipitation. *Wetlands* 36:383–395. <https://doi.org/10.1007/s13157-016-0748-5>
- Skłodowski M, Kiedrzyńska E, Kiedrzyński M, Urbaniak M, Zielińska KM, Kurowski JK, Zalewski M (2014) The role of riparian willows in phosphorus accumulation and PCB control for lotic water quality improvement. *Ecological Engineering* 70:1–10
- Smith AG, Stoudt JH, Gollop JB (1964) *Prairie potholes and marshes. Waterfowl Tomorrow*. United States Fish and Wildlife Service. Washington DC 770pp, 39–50
- Smith SJ, Sharpley AN, Ahuja LR (1993) Agricultural Chemical Discharge in Surface Water Runoff. *Journal of Environmental Quality* 22(3):474–480. <https://doi.org/10.2134/jeq1993.00472425002200030011x>
- Steglich EM, Osorio J, Jeong J, Doro L (2016) APEX model parameterization manual for conservation practices and other modeling activities. USDA-NRCS 1–33
- Stephens SE, Rotella JJ, Lindberg MS, Taper ML, Ringelman JK (2005) Duck nest survival in the Missouri Coteau of North Dakota: Landscape effects at multiple spatial scales. *Ecological Applications* 15(6):2137–2149. <https://doi.org/10.1890/04-1162>
- Townsend AR, Howarth RW (2010) Fixing the global nitrogen problem. *Sci Am* 302(2):64–71
- USDA National Agricultural Statistics Service Cropland Data Layer (2020) Published crop-specific data layer [Online] USDA-NASS, Washington, DC. Available at <http://nassgeodata.gmu.edu/CropScape/>. Accessed 05/01/2022
- USEPA (2008) Hypoxia in the Northern Gulf of Mexico. Hypoxia in the Northern Gulf of Mexico, 1–338.
- Walker PH (1966) Postglacial environments in relation to landscape and soils on the Cary Drift, Iowa (No. 549). Agriculture and Home Economics Experiment Station, Iowa State University, Ames, IA
- Weed DAJ, Kanwar RS (1996) Nitrate and Water Present in and Flowing from Root-Zone Soil. *Journal of Environmental Quality* 25(4):709–719. <https://doi.org/10.2134/jeq1996.00472425002500040010x>
- Winter M, Johnson DH, Shaffer JA (2005) Variability in vegetation effects on density and nesting success of grassland birds. *The Journal of Wildlife Management* 69(1):185–197
- Winter TC, Rosenberry DO (1998) Hydrology of prairie pothole wetlands during drought and deluge: a 17-year study of the cottonwood lake wetland complex in north dakota in the perspective of longer term measured and proxy hydrological records. *Climatic Change* 40:189–209. <https://doi.org/10.1023/A:1005448416571>
- Zedler JB (2003) Wetlands at Your Service: Reducing Impacts of Agriculture at the Watershed Scale. *Frontiers in Ecology and the Environment* 1(2):65. <https://doi.org/10.2307/3868032>
- Zhao SL, Gupta SC, Huggins DR, Moncrief JF (2001) Tillage and Nutrient Source Effects on Surface and Subsurface Water Quality at Corn Planting. *Journal of Environmental Quality* 30(3):998–1008. <https://doi.org/10.2134/jeq2001.303998x>

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