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Quantifying the Environmental Benefits of Conserving Grassland

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Abstract

The Missouri River Basin (MRB) functions as the “life zone” for the larger Mississippi River Basin, providing grassland habitat that infiltrates precipitation and recharges groundwater, reduces sediment erosion, filters nutrients, stores carbon, and provides critical habitat for wildlife. The role of this region as a producer of food and fuel, both nationally and internationally, creates unique challenges for conservation. To support conservation efforts and sustainable management of this invaluable resource, a large-scale, screening-level evaluation of the water quantity and quality benefits of land conservation efforts in the MRB was performed. This paper describes the development and application of a Soil and Water Assessment Tool (SWAT) model to the MRB study area to provide estimates of water quantity and quality (sediment, total phosphorus, total nitrogen) benefits from the avoided conversion of intact grassland to cultivated cropland. The results of this study indicate that the avoided conversion of grassland to cropland could potentially prevent more than 1.7 trillion gallons of surface runoff as well as prevent the export of approximately 46 million tons of sediment, 87 million pounds of total phosphorus, and 427 million pounds of total nitrogen from the MRB study area landscape every year.

Keywords: agriculture, cropland expansion, grassland conversion, land cover change, Missouri River Basin, Northern Great Plains, sustainability, SWAT, water stewardship

1. Introduction

Temperate grasslands are among the most modified ecosystems on the planet, with the highest ratio of habitat conversion to area protected of all ecosystems. Despite their recognition as an ecosystem of great risk due to extensive habitat loss (Hoekstra et al., 2005), grasslands continue to be converted due to their relatively productive soils, moderate topography and, in some cases, their position atop productive oil and gas plays. Modifying grasslands by converting them to cropland impairs their ability to filter water, store carbon, reduce erosion and provide habitat for wildlife (Sustainable Rangelands Roundtable, 2008). Conversion of grasslands can also adversely impact downstream communities due to flooding caused by increased runoff during wet weather events. In addition, runoff from cropland carries nutrient loads, contributing to eutrophication and zones of hypoxia, which have been routinely observed in receiving waterbodies such as the Gulf of Mexico (Costello et al., 2009).

The rates of conversion of grassland to cropland vary over time and across space. Most of the tallgrass prairie was converted to cropland in the early 19th century, and some estimates suggest that approximately half of the central shortgrass prairie remains (Landscope America, 2017; Smith, 1992). Recent research in various geographies in the U.S. indicates that conversion rates of remaining grassland habitats ranges from 1% to 5% per year (Claassen et al., 2011; Faber et al., 2012; Gage et al., 2016; Goldewijk, 2001; Lark et al., 2015; Rashford et al., 2011; Sylvester et al., 2013; Wright & Wimberley, 2013). While the majority of the most productive soils have already been plowed, new technologies and the profitability of crop production incentivizes landowners to convert intact grassland (hereafter “grassland”) to cultivated cropland (hereafter “cropland”) even on marginal soils (Nelson, personal communication, February 6, 2017). This suggests that many remaining grasslands are still at risk of conversion, which could exacerbate eutrophication and other downstream impacts.

The MRB, which is the focal area for this study, is the largest watershed within the Mississippi River Basin, covering approximately 1.3 million km^2 (more than 320 million acres). The basin includes all or portions of ten states in the U.S. and two Canadian provinces. The Missouri River is the longest river in the U.S. The headwaters begin in the Rocky Mountains of western Montana, and the river flows east towards North Dakota and then south to its confluence with the Mississippi River near St. Louis, Missouri. The dominant land cover in the basin is rangeland, primarily comprised of grassland, at 50% of the total area (United States Department of Agriculture Natural Resources Conservation Service [USDA NRCS], 2012). The remaining land cover consists of cultivated cropland (29%), forest (9%), pasture/hay (6%), urban (3%), wetlands (2%), water (1%) and barren land (<1%) (USDA NRCS, 2012). The western portion of the basin, on average, receives less precipitation (18 inches per year) than the eastern portion (29 inches per year) (USDA NRCS, 2012). There is a wide range in temperature across the basin, with an average low winter temperature of 12 °F in the northern portion (e.g., Montana) and an average high summer temperature of 89 °F in the southern portion (e.g., Kansas) (National Centers for Environmental Prediction Climate Forecast System Reanalysis [NCEP CFSR], 2016). The topography varies across the basin, with slopes that range from <1% to >100% (USDA NRCS Geospatial Data Gateway [GDG] 2016). The soils in the basin include regions of mostly well drained, moderately well drained, and poorly drained soil types. The geographic extent of the study area includes the areas of Montana, North Dakota, Wyoming, South Dakota, Minnesota, Colorado, Nebraska, Iowa, and Kansas that fall within the boundary of the MRB (Figure 1). The study area does not include the state of Missouri or the small northern portion of the basin located in Canada.

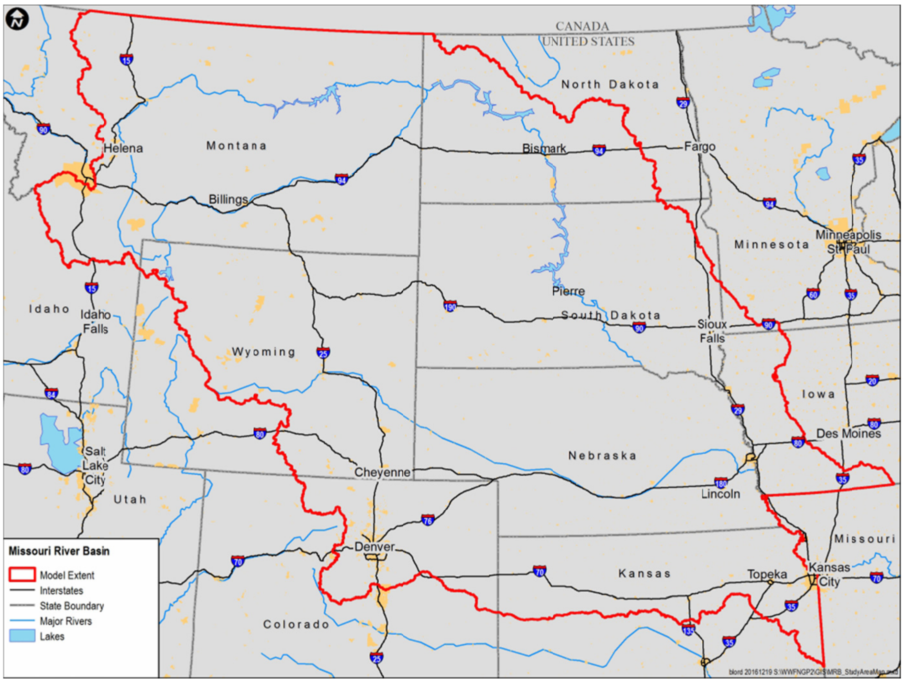

Figure 1. Map of the Missouri River Basin study area (outlined in red)

Previous studies in the MRB indicate that avoided conversion of grassland to cropland, as well as implementation of on-farm conservation practices, can prevent substantial increases in surface runoff and sediment and nutrient loading in the region’s waterways (LimnoTech, 2014; USDA NRCS, 2012). The goal of this study was to build on previous work to quantify the benefits of avoided grassland conversion on surface runoff and sediment and nutrient loading across the U.S. portion of the basin. A SWAT model was developed and applied to quantify the benefits based on two cases: a “business as usual” case of continued conversion of grassland to cropland over time; and a case that avoids future predicted conversion, thus maintaining existing grassland. For the purposes of this study, the term “grassland” refers to all grasslands (shortgrass, mixed-grass, tallgrass), vegetated wetlands and shrubland-steppe habitats. The results of this study provide guidance on the potential benefits of conserving grasslands in the region as well as spatially explicit information that can help guide future investments in conservation.

2. Methods

2.1 Benefit Quantification

Water quantity and quality benefits can be estimated using a suite of standard empirical and process-based watershed management methods and tools. Watershed based methods for calculating benefits have been previously applied to evaluate watershed enhancement activities funded as part of corporate water stewardship programs (Rozza et al., 2013). The type of water quantity and quality benefits calculated and the quantification methodology applied varies by project type. For example, the water quantity benefit of a reforestation project in an upland area can be estimated as the decreased volume of annual surface runoff due to the change in vegetative cover, calculated using the Curve Number Runoff method as implemented in the SWAT model (Neitsch et al., 2011). For this study, a more advanced and complex application of the SWAT model was developed to determine the water quantity and quality benefits associated with the avoided conversion of grassland to cropland.

The water quantity and quality benefits are calculated as the difference in the SWAT model results between two scenarios: a "baseline" scenario that represents the baseline (or existing) conditions in the MRB, and a "grassland conversion" scenario that represents the conversion of grassland to cropland, described in more detail below. The water quantity benefit is calculated as the avoided increase in surface runoff (or the water "saved") as a result of the avoided conversion of grassland to cropland. The water quantity benefit calculations were performed on a long-term, average annual basis to estimate benefits in units of inches per year (in/yr).

Water Quantity Benefit = Avoided Increase in Surface Runoff =

[Surface Runoff with Grassland Conversion] – [Surface Runoff with Baseline] (1)

The water quality benefit is calculated as the avoided increase in the landscape sediment, total phosphorus (TP), and total nitrogen (TN) load as a result of the avoided conversion of grassland to cropland. The water quality benefit calculations were performed on a long-term, average annual basis to estimate benefits in units of tons per acre per year (tons/ac/yr) for sediment and pounds per acre per year (lbs/ac/yr) for TP and TN.

Water Quality Benefit = Avoided Increase in Landscape Load =

[Landscape Load with Grassland Conversion] – [Landscape Load with Baseline] (2)

It is recognized that the estimated benefits have some uncertainty, as they are based on best-available data and information using models and estimation techniques. To address this uncertainty, scientifically defensible methodologies and conservative assumptions were employed in the benefit quantification process.

2.2 Model Development and Application

A more detailed description of the model development and application methodology is provided in LimnoTech (2016). The following sections provide a condensed summary of the steps involved in the model development and application process.

2.2.1 Soil and Water Assessment Tool (SWAT)

SWAT is a semi-empirical, semi-spatially explicit, semi-distributed parameter, continuous simulation model that operates on a daily time step and is designed to predict the impact of land management on water, sediment, nutrients, and pesticide yields. SWAT can simulate environmental processes on the landscape and in receiving waters; however, for this study, only the landscape portion of the SWAT model was required and utilized. Model features include plant growth, crop rotations, tillage operations, fertilizer applications, irrigation, and tile drains. SWAT can be applied to watersheds that range in size from field plots, to very small watersheds of a few acres, to large complex watersheds with millions of acres (Gassman et al., 2007).

The conceptual framework of SWAT is based on hydrologic response units (HRUs), which represent the unique combination and grouping of land that has similar environmental conditions and, therefore, similar hydrologic and pollutant loading processes and responses to climate forcings and activities on the land. A HRU represents individual land areas with the same type of climate, slope, soil, land use/land cover (LULC), and suite of land management practices. Land areas that are scattered throughout a defined region can be lumped together and combined to form a single HRU (Arnold et al., 2013; Neitsch et al., 2011). One important assumption of the HRU concept is that there is no interaction between HRUs. Surface runoff flow, sediment and nutrient loads are calculated separately for each individual HRU and can then be summed together to determine the total contribution from a watershed or subbasin (Arnold et al., 2013; Neitsch et al., 2011).

2.2.2 Model Inputs

The datasets required for the model application included state political boundaries, climate, digital elevation models (DEMs), soils, LULC, and agricultural practices. A binning and categorization (or grouping) approach was designed for each dataset to represent climate (e.g., precipitation), slope, soils, and LULC conditions in the model in a scientifically defensible manner. This approach was necessary to avoid simulating an excessive number of individual HRUs, which would have increased model complexity without significant gains in the accuracy of the model predictions and estimates of water quantity and quality benefits. Table A1 in Appendix A provides a summary of the model inputs, data sources, and categorization approach. A brief description of each dataset is provided below.

State political boundaries were used as a proxy to capture the variability in the MRB in terms of climate, vegetation and cropping systems. Climate input data are required by the model to drive the simulation of hydrology. Daily precipitation, minimum and maximum air temperature, wind speed, solar radiation, and relative humidity are required inputs. A total of 59 unique climate stations were represented in the model and used to define climate regions. A DEM is required to represent watershed boundaries and land slope to support the simulation of hydrologic processes and sediment and nutrient load generation from the landscape. Mean slopes for individual HRUs ranged from 0.40% to 55%. Soils and LULC are important factors in controlling how water, sediment, and nutrients move through a landscape environment. The soil inputs for the model were determined based on the most representative soil for each unique state, climate region, slope category, and soil category combination, with a total of 148 unique soil types used to represent soils in the basin. The LULC was limited to land areas that were either grassland or cropland. The 2014 Cropland Data Layer (CDL) was used to define the grassland areas, and the WWF Plowprint data layer was used to define the cropland areas (Gage et al., 2016). The SWAT model is designed to estimate crop (and other vegetation) yields and biomass. Plant growth has a direct impact on hydrology, sediment erosion, and nutrient cycling processes. The model requires the development of agricultural management schedules, which are used to specify the crop types, rotations and planting and harvest dates; tillage operation type and date; fertilizer application type, rate, method and date; irrigation; and tile drain operation.

The tillage risk model dataset (Smith et al., 2016) was used to define the grassland conversion scenario. The tillage risk model was developed based on climate, topography and soils data (Smith et al., 2016). It was assumed that a cutoff value of ≥0.7 indicates land could potentially be cultivated and tilled for cropland. This cutoff value is based on a "constrained" scenario of cropland expansion based on soil type across the study area (Lipsey et al., 2015; Smith et al., 2016). This scenario is the more conservative of the scenarios of cropland expansion outlined in Smith et al. (2016). Figure 2 shows the range of estimated grassland acres converted to cropland. The mapped values are based on the sum of grassland acres converted to cropland for each 8-digit hydrologic unit code (HUC8) in the MRB study area.

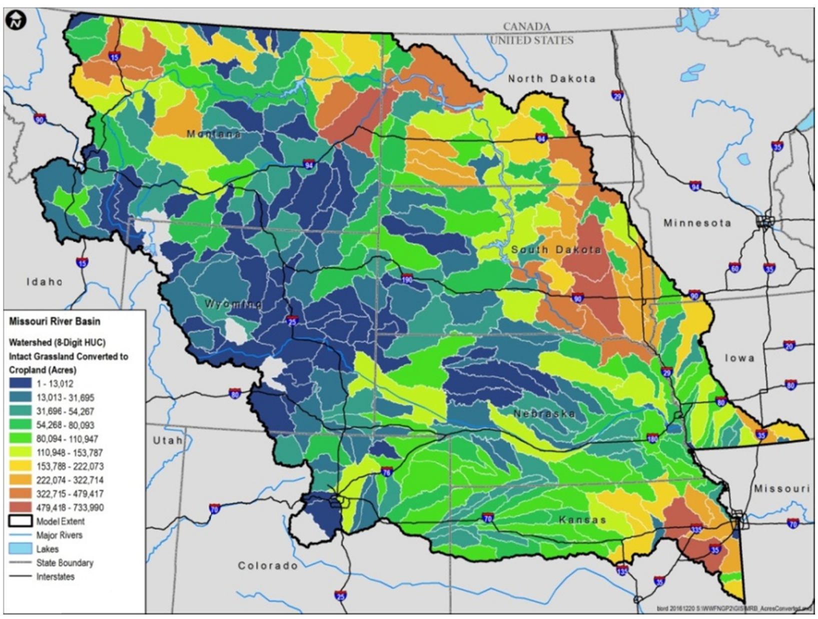

Figure 2. Map of the acres of intact grassland converted to cropland summed at a HUC8 watershed scale

Note. Watersheds in "gray" indicate that zero acres of grassland is assumed to be at risk for conversion to cropland.

2.2.3 Model Construction

The SWAT model was constructed to simulate water and sediment, TP, and TN yields from the landscape for the 1995-2013 time period (LimnoTech, 2016). The model uses the SWAT 2012 version of the model source code (Arnold et al., 2013) with custom revisions and corrections made to the model source code by LimnoTech (2016). The first three model simulation years (1995-1997) serve as a "warm-up period" to allow the model to initialize and not be strongly influenced by the initial soil and nutrient conditions. Therefore, the processed model results and the water quantity and quality benefit estimates are based on the 1998-2013 time period. Model construction involved the definition of HRUs to divide the MRB study area into individual land segments that are assumed to produce similar hydrologic and water quality responses due to similar environmental conditions. Spatial datasets were processed using ESRI ArcGIS version 10.3 tools. A study area mask was created to limit the land area in the model application to the land areas of interest (i.e., grassland and cropland) and within the defined geographic area. All of the spatial datasets were scaled, as needed, to a 30 meter spatial resolution and clipped to the study area mask. The spatial datasets were processed and then "stacked" to define a unique HRU code that denotes the state + climate region + slope + soil + LULC for each raster pixel at a 30 meter spatial resolution. This resulted in a total of 1,491 unique HRUs.

The cropland HRUs were then expanded to represent the three different types of tillage (conservation, reduced, and intensive). Tillage was the only dataset with a non-spatial component and was incorporated into the HRU definition after the spatial processing was completed. The tillage inputs for the cropland HRUs were developed based on the cropping system and the percentage of each tillage type for a given area based on a compilation of several datasets. Specifically, each cropland HRU was expanded to represent each tillage type as "state + climate region+ slope + soil + LULC + tillage", where tillage is conservation tillage (CT, >30% residue), reduced tillage (RT, 15-30% residue) and intensive tillage (IT, <15% residue). The area of each cropland HRU was then assigned to each tillage type based on the estimated percentages of tillage type by state and crop type. This resulted in an expanded total of 3,351 HRUs.

Finally, additional placeholder cropland HRUs were created for the potential conversion of grassland to cropland to ensure that every grassland HRU had corresponding cropland HRUs with the same environmental conditions (i.e., state, climate region, soil, slope, etc.). These placeholder HRUs were assigned a "zero" area in the baseline scenario. If grassland was converted in the grassland conversion scenario, then area was moved from the grassland HRU to the corresponding cropland HRUs. With this iteration, a total of 6,597 HRUs were defined for the large-scale, screening-level SWAT model evaluation of the MRB study area.

2.2.4 Reasonableness Check

This study was intended to be a large-scale, screening-level evaluation; therefore, it did not involve model calibration and validation with empirical data. A detailed description of watershed model calibration and validation theory and methods is discussed in Moriasi et al. (2007), Parajuli et al. (2009), and United States Environemental Protection Agency [USEPA] (2009). The model provides a long-term, 16-year simulation over a range of environmental conditions (i.e., wet, dry and average precipitation). While the model was not calibrated and validated, reasonableness checks were performed to ensure that the model was producing realistic results. Water, sediment, TP and TN yields generated by the model were compared against results from other studies conducted on the MRB (USDA NRCS, 2012; Zhang & May, 2013). Adjustments were made to parameters related to plant growth, hydrology, and pollutant loading to ensure that the model results generally fell within the range of reported water, sediment, TP and TN yields (Table 1) (USDA NRCS, 2012; Zhang & May, 2013). It is important to note that the comparisons made with the other MRB studies represented a relative comparison and not a direct or one-to-one comparison due to differences in the model frameworks, simulation time periods, varying levels of calibration and validation, and objectives for each study. The USDA NRCS (2012) study of the MRB is focused on the portion of the basin that is cultivated cropland (29% of the total basin area) to estimate the effects of on-farm conservation practices. The Zhang & May (2013) study of the MRB is focused on the entire MRB to understand the transport and fate of sediment, phosphorus and nitrogen loading in the basin.

For a few HRUs, the model predicted water, sediment and nutrient yields that fell outside the range of typically reported values in the literature. These HRUs tended to be small in land area, located in areas of high precipitation, and/or have high slopes; and they only represented approximately 4% of the grassland area that is assumed to be at risk for conversion to cropland. It was determined that a cap should be placed on the HRU results that fell outside the range of reported values. Therefore, the benefit quantification results that were over the 95th percentile of all results generated by the model for surface runoff, sediment, and nutrient yields are reported as greater than the associated 95th percentile value, where surface runoff = 10.4 inches; sediment = 13.9 tons/ac/yr; TP = 15.6 lbs/ac/yr; and TN = 52.5 lbs/ac/yr.

Table 1. Relative comparison of model results with other MRB modeling studies where values represent area-weighted averages

Parameter	*This Study*	*Other MRB Modeling Studies*[1,2]
Water Yield (in/yr) *(surface runoff + subsurface flow)*	4.6	4.4 *(same result for both studies)*
Sediment (tons/ac/yr)	0.44	0.26-1.6
Total Phosphorus (lbs/ac/yr)	0.93	0.68-1.5
Total Nitrogen (lbs/ac/yr)	5.9	5.7-9.5

Note. [1] Information obtained from USDA NRCS (2012). APEX-SWAT model results for the relative comparison are based on the "baseline conservation condition" scenario for cultivated cropland, which represents cropping patterns, farming activities, and conservation practices as reported in the National Resources Inventory (NRI)-Conservation Effects Assessment Project (CEAP) Cropland Survey sample time period 2003-2006 and other sources (e.g., USDA NASS 2007 Census of Agriculture). The cultivated cropland inputs were based on practices for the 2003-2006 time period. The model was simulated for 47 years using historical weather data for the 1960-2006 time period. Cultivated cropland was defined for this study as row crops or close-grown crops (such as wheat and other small grain crops), hay and pasture in rotation with row crops and close-grown crops, and land in long-term conserving cover. Cultivated cropland did not include agricultural land that had been in hay, pasture, or horticulture for four or more consecutive years.

[2] Information obtained from Zhang & May (2013). SWAT model results for the relative comparison are based on a baseline run that represents the calibrated and validated model at the subbasin scale (HUC8 watersheds). The LULC was based on the 2007, 2008, 2009, and 2010 CDLs. The cultivated cropland inputs were based on practices over varying time periods where crop rotations are based on the 2007-2010 time period and the tillage operations are based on the 1989-2004 time period. The model was simulated for 20 years using historical weather data for the 1990-2009 time period.

2.2.5 Model Scenarios

Following the completion of model development and the reasonableness checks, the next step was to apply the model to estimate the water quantity and quality benefits of avoiding the conversion of grassland to cropland. The quantification of water, sediment and nutrient benefits was accomplished by comparing the "baseline" scenario with the "grassland conversion" scenario and assessing the relative change between the simulations.

The "baseline" scenario represents the baseline (or existing) conditions in the MRB. The climate was based on the 1998-2013 time period. The LULC was based on the 2012, 2013, and 2014 CDLs and the WWF Plowprint layer (Gage et al., 2016). This scenario accounts for the best available representation of present-day land management practices (e.g., grasslands and pastureland, cropping systems, tillage patterns, fertilizer applications, irrigation, tile drainage, etc.) in the MRB.

The "grassland conversion" scenario represents the conversion of grassland to cropland in the MRB. All of the inputs were the same as the baseline scenario with the exception of grassland areas that were determined to be at risk for conversion to cropland based on the Smith et al. (2016) dataset. The total area of grassland represented as being suitable for conversion to cropland in this scenario was 25,239,248 acres, which is equivalent to 16% of the total grassland area represented in the baseline scenario.

3. Results

3.1 Water Quantity & Quality Benefits

Water quantity and quality benefit results were produced for each grassland HRU assumed to be at risk for conversion to cropland based on the tillage risk model (cutoff value of ≥0.7) (Lipsey et al., 2015; Smith et al., 2016), which consisted of 16% of the total grassland in the MRB study area and 228 HRUs. Table 2 provides a summary of the range of estimated water quantity and quality benefits on a per acre basis, across all HRUs, as the avoided increase in surface runoff in inches per year and as sediment and nutrient loads in tons or pounds per acre year, respectively. The overall estimated water quantity benefit for the avoided conversion of grassland to cropland in the MRB is approximately 1,697,300 million gallons per year. The overall estimated water quality benefit for the avoided conversion of grassland to cropland in the MRB is as follows: sediment = 46,260,600 tons/yr; TP = 87,503,800 lbs/yr; and TN = 427,043,200 lbs/yr. To be conservative, the benefits reported have been rounded down to nearest hundred.

Table 2. The range of estimated water quantity and water quality benefits for the avoided conversion of grassland to cropland in the MRB on a per acre basis

Statistic	*Avoided Increase in Surface Runoff (in/yr)*	*Avoided Increase in Sediment Yield (tons/ac/yr)*	*Avoided Increase in TP Yield (lbs/ac/yr)*	*Avoided Increase in TN Yield (lbs/ac/yr)*
Area-Weighted Average	2.5	1.8	3.5	16.9
Minimum	0.1	0.002	0.01	0.31
Maximum	10.4	13.9	15.6	52.6

Maps of the water quantity and quality benefits, at the HUC8 watershed scale, are provided in Appendix B.

3.2 Comparison of Benefits

The water quantity and quality benefits were compared to a separate study that modeled the entire MRB (Zhang & May, 2013) to put the estimated benefits of avoided grassland conversion into greater context in terms of how the benefits compare to the overall flow and loads predicted to be generated from the basin. Because this study did not include simulation of the delivery of water yield and sediment and nutrient loads to reservoirs or the stream network, both comparisons are relative to the estimated landscape flow and load predictions, rather than flow and loads delivered to the MRB outlet.

The Zhang & May (2013) study provides estimates of the total flow volume from the landscape (i.e., surface runoff + lateral flow + groundwater flow) and the total landscape sediment and nutrient loads from the entire MRB, including all LULC types. It is important to note that this study and the Zhang & May (2013) study have differences in terms of spatial coverage, LULC types represented, input datasets, and simulation periods. The comparison between the estimated benefits from this study and the Zhang & May (2013) study indicates that the avoided increase in surface runoff represents 4% of the total flow volume, the avoided increase in sediment represents 9% of the total load, the avoided increase in TP represents 17% of the total load, and the avoided increase in TN represents 22% of the total load (Table 3). The comparison between this study and the Zhang & May (2013) study indicates that avoided grassland conversion will likely result in substantial water quantity and quality benefits.

Table 3. Comparison of the avoided increase in surface runoff and sediment, TP and TN loads relative to a study that modeled the entire MRB (Zhang & May, 2013)

	Flow Volume (MG)	*Sediment (tons/yr)*	*TP (lbs/yr)*	*TN (lbs/yr)*
Avoided Increase	1,697,300*	46,260,600	87,503,800	427,043,200
Entire MRB (per Zhang & May, 2013)	39,408,400**	523,408,100	513,384,100	1,906,093,800
Percent of Entire MRB (per Zhang & May, 2013)	4%	9%	17%	22%

Note. MG is million gallons;* Represents only the surface runoff fraction of total flow; ** Represents total flow, which is equivalent to surface runoff + lateral flow+ groundwater flow

4. Discussion & Conclusions

Prioritizing areas for conservation action is a time consuming endeavor, and rarely are the impacts of conservation actions on the aquatic resources of the region integrated into prioritization schemes for terrestrial systems. This work provides a baseline assessment that can be used for establishing more robust and comprehensive conservation priorities that address water resources and the impacts of grassland conversion on those resources. The results of this study echoes previous work by the authors and others, indicating that conservation of grasslands can have substantial benefits to water quantity and quality (LimnoTech, 2014; USDA NRCS, 2012). While improving the sustainability of on-farm practices is a key factor in increasing sustainability, focusing only on this piece of the puzzle ignores the significant impact of the initial conversion of grassland to cropland on ecosystem services and grassland function. This study suggests that avoiding conversion of grassland to cropland may prevent substantial quantities of surface runoff and pollutant loads from reaching waterbodies. For instance, the result of approximately 1.7 trillion gallons (or 6.4 million ML) of water conserved due to avoided surface runoff is the equivalent to the annual water usage by 11.6 million four-person U.S. households (USEPA, 2017). The amount of TN loading prevented due to avoided conversion is 16.9 lbs/ac/yr, which is approximately 13% of the TN needed per acre (including nitrogen already present in the soil) to grow corn in North Dakota (Franzen, 2016). These represent significant savings of runoff and pollutants into waterways of the MRB.

The impacts of excess nitrogen and phosphorus on aquatic systems are well known. Eutrophication and acidification of aquatic systems due to increased nutrient inputs leads to increased algal blooms, decreased quality of habitat for aquatic species and decreased oxygen availability for fish and other species, among other issues (Camargo & Alonso, 2006; Carpenter et al., 1998). In addition, nutrient pollution is directly linked to the hypoxia zone in the Gulf of Mexico (NOAA, 2003), into which the Missouri River ultimately flows. Numerous downstream communities rely on grasslands to buffer against flooding from high rainfall events (USFS, 2017). The results of this study suggest that continued conversion of grassland to cropland in the MRB could contribute to exacerbation of these downstream issues.

While the work summarized here provides a unique approach for quantifying the benefits of avoided loss of habitat, every model has some underlying assumptions and limitations that should be acknowledged. First, as noted above, the objective of the study was to estimate the landscape benefits of avoiding the conversion of grassland to cropland. Therefore, only landscape water, sediment and nutrient yields are simulated, which means there is no simulation of the landscape delivery of water yield and sediment and nutrient loads to reservoirs or the stream network. Likewise, there is no simulation of reach routing and delivery to the MRB study area outlet. Second, the SWAT model is not calibrated or validated, and the benefit estimates of sediment, TP, and TN are less certain than the surface runoff estimates due to an inherently higher level of uncertainty for landside water quality processes. The water quality estimates are dependent on the accuracy of the hydrology simulation, and many input parameters must be estimated and additional assumptions made (e.g., agricultural practices) to represent the pollutant loading.

In addition, the model that was used to determine the predicted number of acres of conversion over time includes inherent assumptions, the most significant of which is the cutoff value of 0.7, meaning that relatively high-quality soils were used as a proxy for conversion risk. It is known from field observation that landowners convert land of low and marginal quality throughout the study region (Evans, personal communication, April 15, 2014), meaning that the cutoff value is providing a relatively conservative estimate of future conversion risk. Finally, the models are based on the most recently available public datasets, each of which has its own set of assumptions and errors that must be accounted for when determining the limitations of the models.

This study is unique in attempting to quantify the water-related benefits of avoiding conversion, thus allowing conservation practitioners to better predict the outcomes of their work in the region. Also important are the many other benefits of maintaining intact grasslands, including: the protection of wildlife and aquatic habitat; the protection of water availability for downstream communities and wildlife and aquatic species; increased carbon storage; and the reduced risk of flood frequency and hazard to communities along the Missouri River. While many communities rely on built infrastructure to manage water availability, protecting intact natural systems is a simple way to ensure high-quality water supplies for future generations (Abell et al., 2017). Taken together, these benefits suggest that avoiding grassland conversion to cropland is an important strategy for protecting future water supplies and water quality in the MRB and beyond.

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References

Abell, R., Asquith, N., Boccaletti, G., Bremer, L., Chapin, E., Erickson-Quiroz, A., …& Wood, S. (2017). *Beyond the source: The environmental, economic and community benefits of source water protection*. Arlington, VA: The Nature Conservancy. Retrieved from https://thought-leadership-production.s3.amazonaws.com/2017/01/26/17/25/54/87c054aa-e945-4413-9163-ca11053110d7/Beyond_The_Source_Full_Report_Final.pdf

Arnold, J. G., Kiniry, J. R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2013). Soil and Water Assessment, Input/Output Documentation, Version 2012. Retrieved from http://swat.tamu.edu/documentation/2012-io/

Camargo, J. A., & Alonso, A. (2006). Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International, 32*, 831-849. https://doi.org/10.1016/j.envint.2006.05.002

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications, 8*, 559-568. https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Cash, D., Sims, J., Bowman, H., & Smith, B. (1995). Growing peas in Montana. MONTGUIDE Agriculture, Report No. MT 9520. Montana State University (MSU) Extension Service.

Claassen, R., Carriazo, F., Cooper, J. C., Hellerstein, D., & Ueda, K. (2011). Grassland to cropland conversion in the Northern Plains: The role of crop insurance, commodity, and disaster programs. Retrieved from https://www.ers.usda.gov/webdocs/publications/err120/7477_err120.pdf

Costello, C., Griffin, W. M., Landis, A. E., & Matthews, H. S. (2009). Impact of biofuel crop production on the formation of hypoxia in the Gulf of Mexico. *Environmental Science and Technology, 43*, 7985-7991. https://doi.org/10.1021/es9011433

CTIC (Conservation Technology Information Center). (2008). 2008 Amendment to the national crop residue management survey. Retrieved from http://www.ctic.purdue.edu/media/pdf/National%20Summary%202008%20(Amendment).pdf

Davis, J. G., & Brick, M. A. (2009). Fertilizing dry beans, fact sheet No. 0539, Colorado State University (CSU) Extension. Reviewed April 2009. Retrieved from https://erams.com/static/wqtool/PDFs/manure_nutrient/00539.pdf

Faber, S., Rundquist, S., & Male, T. (2012). Plowed under: How crop subsidies contribute to massive habitat losses. Retrieved from http://static.ewg.org/pdf/plowed_under.pdf

Franzen, D. W. (2016). North Dakota fertilizer recommendation tables and equations. Retrieved from https://www.ndsu.edu/fileadmin/soils/pdfs/sf882.pdf

Fuka, D., Walter, M. T., MacAlister, C., Degaetano, A. T., Steenhuis, T. S., & Easton, Z. M. (2014). Using the Climate Forecast System Reanalysis as weather input data for watershed models. *Hydrological Processes, 28*, 5613-5623. https://doi.org/10.1002/hyp.10073

Gage, A. M., Olimb, S. K., & Nelson, J. (2016). Plowprint: Tracking cumulative expansion to target grassland conservation. *Great Plains Research, 26*, 107-116. https://doi.org/10.1353/gpr.2016.0019

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold J. G. (2007). The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Transactions of the American Society of Agricultural and Biological Engineers (ASABE), 50*(4), 1211-1250. https://doi.org/10.13031/2013.23637

Goldewijk, K. K. (2001). Estimating global land use change over the past 300 years: The HYDE Database. *Global Biogeochemical Cycles, 15*, 417-433. https://doi.org/10.1029/1999GB001232

Hergert, G. W., & Schild, J. A. (2013). Fertilizer management for dry edible beans., NebGuide, G1713, University of Nebraska-Lincoln (UNL) Extension, Institute of Agriculture and Natural Resources. Retrieved from http://extensionpublications.unl.edu/assets/pdf/g1713.pdf

Hoekstra, J. M., Boucher, T. M., Ricketts, T. H., & Roberts, C. (2005). Confronting a biome crisis: Global Disparities of Habitat Loss and Protection. *Ecology Letters, 8*, 23-29. https://doi.org/10.1111/j.1461-0248.2004.00686.x

Horowitz, J., Ebel, R., & Ueda, K. (2010). No-Till farming is a growing practice. ERS Report Summary, EIB-70, United States Department of Agriculture, Economic Research Service. Retrieved from https://www.ers.usda.gov/webdocs/publications/eib70/8084_eib70_reportsummary.pdf

Landscope America. (2017). Central shortgrass prairie ecoregion. Retrieved from http://www.landscope.org/explore/natural_geographies/ecoregions/central_shortgrass_prairie_ecoregion/

Lark, T. J., Salmon, J. M., & Gibbs, H. K. (2015). Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environmental Research Letters*, 10, 044003. https://doi.org/10.1088/1748-9326/10/4/04400

LimnoTech. (2014). *Estimated water quantity and quality benefits of conserving grasslands in two Northern Great Plains watersheds* (Unpublished technical report). Prepared for World Wildlife Fund, Northern Great Plains Program, Bozeman, MT.

LimnoTech. (2016). *Assessing the water quantity and quality benefits of avoided grassland conversion in the Missouri River Basin* (Unpublished technical report). Prepared for World Wildlife Fund, Northern Great Plains Program, Bozeman, MT.

Lipsey, M. K., Doherty, K. E., Naugle, D. E., Fields, C., Evans, J. S., Davis, S. K., & Koper, N. (2015). One step ahead of the plow: Using cropland conversion risk to guide Sprague's Pipit conservation in the Northern Great Plains. *Biological Conservation, 91*, 739-749. https://doi.org/10.1016/j.biocon.2015.08.030

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers (ASABE), 50*(3), 885-900.

National Centers for Environmental Prediction Climate Forecast System Reanalysis [NCEP CFSR]. (2016). Global weather data for SWAT. Retrieved from http://globalweather.tamu.edu/

National Oceanic and Atmospheric Administration [NOAA] Council Committee on Environment and Natural Resources. (2003). An assessment of coastal hypoxia and eutrophication in U.S. waters. National Science and Technology Council Committee on Environment and Natural Resources, Washington, D.C.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil and Water Assessment Tool, Theoretical Documentation, Version 2009. Retrieved from http://swat.tamu.edu/media/99192/swat2009-theory.pdf

Parajuli, P. B., Nelson, N. O., Frees, L. D., & Mankin, K. R. (2009). Comparison of AnnAGNPS and SWAT model simulation results in USDA-CEAP agricultural watersheds in south-central Kansas. *Hydrological Processes, 23*, 748-763. https://doi.org/10.1002/hyp.7174

Rashford, B. S., Walker, J. A., & Bastian, C. T. (2011). Economics of grassland conversion to cropland in the Prairie Pothole Region. *Conservation Biology, 25*, 276-284.

Rozza, J. P., Richter, B. D., Larson, W. M., Redder, T., Vigerstol, K., & Bowen, P. (2013). Corporate water stewardship: Achieving a sustainable balance. *Journal of Management and Sustainability, 3*(4), 41-52. https://doi.org/10.5539/jms.v3n4p41

Schatz, B., & Endres, G. (2009). Field pea production. Report No. A-1166, North Dakota State University (NDSU) Extension Service. Retrieved from http://www.pulseusa.com/docs/a1166.pdf

Smith, D. D. (1992). Tallgrass prairie settlement: prelude to the demise of the tallgrass ecosystem. *Proceedings of the Twelfth North American Prairie Conference 1990*, 195-200. Cedar Falls, IA. Retrieved from http://images.library.wisc.edu/EcoNatRes/EFacs/NAPC/NAPC12/reference/econatres.napc12.dsmith.pdf

Smith, J. T., Evans, J. S., Martin, B. H., Baruch-Mordo, S., Kiesecker, J. M., & Naugle, D. E. (2016). Reducing cultivation risk for at-risk species: predicting outcomes of conservation easements for sage-grouse. *Biological Conservation, 201*, 10-16. https://doi.org/10.1016/j.biocon.2016.06.006

Sugg, Z. (2007). Assessing US farm drainage: Can GIS lead to better estimates of subsurface drainage extent. World Resources Institute (WRI), Washington, DC. Retrieved from http://pdf.wri.org/assessing_farm_drainage.pdf

Sustainable Rangelands Roundtable. (2008). Sustainable rangelands ecosystem good and services. Fort Collins, CO: SRR Monograph No.3.

Sylvester, K. M., Brown, D. G., Deane, G. D., & Kornak, R. N. (2013). Land transitions in the American Plains: Multilevel Modeling of Drivers of Grassland Conversion (1956-2006). *Agriculture, Ecosystems and Environment, 168*, 7-15. https://doi.org/10.1016/j.agee.2013.01.014

United States Department of Agriculture, National Agricultural Statistics Service [USDA NASS]. (2010). Field crops: usual planting and harvesting dates, agricultural handbook, number 628. Retrieved from http://usda.mannlib.cornell.edu/usda/current/planting/planting-10-29-2010.pdf

United States Environmental Protection Agency [USEPA]. (2009). Guidance on the development, evaluation, and application of environmental models. Council for Regulatory Environmental Modeling. Retrieved from https://www.epa.gov/sites/production/files/2015-04/documents/cred_guidance_0309.pdf

United States Forest Service [USFS]. (2017). Ecosystem services from national grasslands. Retrieved from https://www.fs.fed.us/grasslands/ecoservices/index.shtml

USDA NASS. (2014). Census of agriculture: Volume 1, Part 51: geographic area series. Retrieved from https://www.agcensus.usda .gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

USDA NASS. (2016). County maps by crop type. Retrieved from https://www.nass.usda.gov/Charts_and_Maps/Crops_County/

USDA NASS. (2016). Quick Stats 2.0. Retrieved from https://quickstats.nass.usda.gov/

USDA NRCS, Geospatial Data Gateway [GDG]. (2016). Geospatial Data Gateway. Retrieved from https://datagateway.nrcs.usda.gov/

USDA NRCS. (2016). Description of STATSGO2 Database. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629

USDA, Natural Resources Conservation Service [NRCS]. (2012). Assessment of the effects of conservation practices on cultivated cropland in the Missouri River Basin. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1048710.pdf

USEPA. (2017). Indoor water use in the United States. Retrieved from https://www3.epa.gov/watersense/pubs/indoor.html

Wade, T., Classen, R., & Wallander, S. (2015). Conservation practice adoption rates vary widely by crop and region. Report No. EIB-147, United States Department of Agriculture, Economic Research Service. Retrieved from https://www.ers.usda.gov/webdocs/publications/eib147/56332_eib147.pdf

Wright, C. K., & Wimberly, M. C. (2013). Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proceedings of the National Academy of Sciences, 110*, 4134-4139. https://doi.org/10.1073/pnas.1215404110

Zhang, Z., & May, W. (2013). Analysis of riverine sediment and nutrient exports in Missouri River Basin by application of SWAT model. Report No. ANL/ESD-13/12, United States Department of Energy, Energy Systems Division, Argonne National Laboratory. Retrieved from https://greet.es.anl.gov/files/morb-swat

Appendix A

Table A1. A summary of MRB SWAT model inputs, data sources, and categorization approach

Model Inputs	*Data Source(s)*	*Description*	*Categorization Approach*
State Boundaries	USDA NRCS GDG, 2016	Political State Boundaries of the United States	Not applicable
Climate	Fuka, et al., 2014; NCEP CFSR, 2016	Global Weather Dataset for SWAT, 38 km grid	Long-term, annual average precipitation across the basin for the 1995-2013 time period was mapped and grouped into 10 bins that represent the following intervals (in/yr): <10.3, >10.3–15, >15–18.6, >18.6–21.5, >21.5–24.1, >24.1–30, >30–33.6, >33.6–37.7, >37.7–44, and >44.
Digital Elevation Model (DEM)	USDA NRCS GDG, 2016	United States Geological Survey (USGS), 30 meter	Two slope categories were defined; a low slope at 0-6% (or ≤6%) and a high slope at >6%.
Soils	USDA NRCS GDG, 2016	USDA STATSGO2, 1:250,000	Two soil categories were defined; Hydrologic Soil Groups (HSGs) A and B for low runoff and HSGs C and D for high runoff.
Land Use/Land Cover (LULC)	Gage et al., 2016; USDA NRCS GDG, 2016; USDA NRCS, 2012;	Cropland Data Layers (CDLs), 30 meter, years 2012, 2013 and 2014; WWF Plowprint, 56 meter, years 2008-2013	Non-grassland or non-cropland reclassified as static and masked out (e.g., forest, urban, wetland, etc.). Grassland defined as alfalfa, other hay/non-alfalfa, clover/wildflowers, sod/grass seed, switchgrass, and grassland/pasture. Cropland reclassified into one of five cropping systems: corn-soybean, corn-soybean-small grain crops, wheat, small grain crops, and vegetables/other.
Cropping Systems	USDA NASS, 2016; USDA NRCS GDG, 2016	Cropland Data Layers (CDLs), 30 meter, years 2012, 2013 and 2014; USDA NASS county maps of planted acres	Five crop types are represented in a four-year rotation.
Planting and Harvesting	All crops except field peas USDA NASS, 2010 Field peas Cash et al., 1995; Schatz & Endres, 2009	USDA NASS reports; land grant university extension publications	Median of the earliest and latest planting and harvesting dates used to assign the month/day to plant and harvest the crop in the SWAT model by state.
Tillage	CTIC, 2008; Horowitz et al., 2010; USDA NASS, 2014; USDA NASS, 2016; Wade et al., 2015	Center (CTIC) tillage surveys; USDA Economic Research Service (ERS) bulletins; USDA NASS 2012 Census of Agriculture; USDA NASS Quick Stats Database	Representative tillage operation practices were assigned by state and crop type. Three tillage types were represented: conservation tillage (>30% residue), reduced tillage (15-30% residue) and intensive or conventional tillage (<15% residue).

Fertilizer	Cash et al., 1995; Davis & Brick, 2009; Hergert & Schild, 2013; Schatz & Endres, 2009; USDA NASS, 2016	USDA NASS Quick Stats Database; land grant university extension publications	Typical fertilizer application types, rates, timing, and placement for each crop by state was assumed.
Irrigation	USDA NASS, 2014; USDA NASS, 2016	USDA NASS 2012 Census of Agriculture; USDA NASS Quick Stats Database	State- and crop-specific targets for the irrigated fraction of all planted acres was determined. Irrigation assignments were based on the state where the HRU was located; the crop that was being grown; and the climate region of the HRU.
Tile Drains	Sugg, 2007	World Resources Institute (WRI) tile drainage map of the United States	Tile drains were only applied to HRUs that met the following criteria: LULC is cropland; HSG is either a C or D (i.e., "high runoff" soils category); slope is 6%; and HRU is located in either Iowa or Minnesota.
Grassland at Risk for Conversion to Cropland	Jeffery Evans of The Nature Conservancy (TNC) (Lipsey et al., 2015)	Tillage Risk Model	A cutoff value of ≥0.7 indicates that land could potentially be cultivated and tilled for cropland.

Appendix B

Water Quantity and Quality Benefit Maps

The water quantity and quality benefits represent the overall, long-term, annual average avoided increase in surface runoff and sediment, TP, and TN yields for the avoided conversion of grassland to cropland for each HUC8 watershed. The results shown are only the grassland areas that were converted to cropland and represent the area-weighted average benefit from all grassland HRUs that were converted to cropland HRUs. Mapped watershed areas shown in "gray" indicate that zero acres of grassland were assumed to be at risk for conversion to cropland per the tillage risk model (Lipsey et al., 2015) and water quantity and quality benefits do not exist.

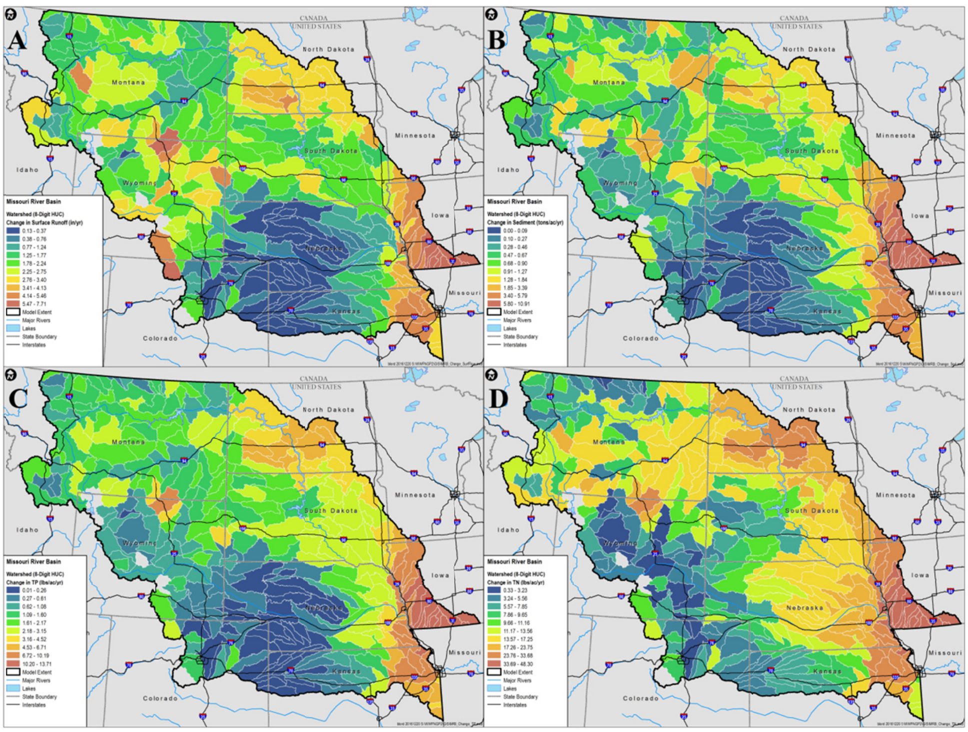

Figure B-1. Maps of water quantity and quality benefits for the avoided conversion of grassland to cropland summed at a HUC8 watershed scale. A. Surface runoff in inches/yr. B. Sediment in tons/ac/yr. C. TP in lbs/ac/yr D. TN in lbs/ac/yr