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Estimating water quality effects of conservation practices and grazing land use scenarios

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Abstract: Conservation management practices such as reduced tillage, fertilizer management, and buffer strips are well-established means by which to control erosion and nutrient losses from fields planted in annual row crops. However, agricultural systems which include perennial plant cover, such as the perennial forages found in grazing systems, may represent an alternative way to reduce these losses. In this study, management intensive rotational grazing (MIRG) was tested as a means by which to improve water quality on highly vulnerable row crop land, compared to more traditional conservation management schemes in the south branch of the Root River Watershed (a karst-influenced watershed in Southeastern Minnesota). The effects of both sets of alternative scenarios were evaluated with a watershed-based modeling approach using the Soil and Water Assessment Tool. Alternative conservation management practices included conservation tillage, cover crops, and filter strips. Conversion of row crop production to management-intensive rotational grazing of beef cattle was selected to occur on 2.6% of the total watershed area. Both the conservation management practices and land use changes were targeted to reduce contributions of sediment and phosphorus (P) loads from cropped upland areas. Watershed-wide implementation of all conservation management practices resulted in the greatest reductions in sediment (52%) and total P (28%) loads from upland crop areas, but had the largest land area requirements to achieve these results. Cover crops or filter strips on areas of high slope also showed large cumulative reductions across the watershed and also had the greatest reductions per-unit treated area of all conservation management practices. However, changing land use from row crop production to pasture for grazing was most effective at reducing total sediment and P loads on those acres changed, reducing sediment and P by greater than 85% on targeted areas. Simulation results indicate that utilizing alternative conservation management practices or MIRG, when targeted to areas of steeper slope (greater than 4%), could appreciably reduce sediment and P loads in this watershed, with limited reductions in row crop agriculture acreage.

Key words: conservation tillage—cover crops—filter strips—grazing—Soil and Water Assessment Tool—water quality

Nutrients and sediment originating from agricultural fields in the United States Upper Midwest have been implicated in the impairment of both fresh and marine water systems, contaminating drinking water sources and coastal areas (Schulte et al. 2006). Topsoil losses from annually cropped fields can be significant, decreasing the long-term productivity of the land and threatening water resources (Kort et al. 1998; USEPA 2003). Additionally, nutrient export from extensively cropped agriculture areas has resulted in hypoxic environments in coastal marine systems and eutrophication of fresh water lakes (Committee on Environment and Natural Resources 2010; Sharpley et al. 2001). Agricultural systems that incorporate perennial vegetation have been shown to reduce nutrient losses and soil erosion leading to an improvement in water quality (Burkart et al. 2005; Dalzell et al. 2004; Randall et al. 1997; Russelle et al. 2007). However, lack of economic incentives and markets has limited their adoption (Randall and Mulla 2001).

For the upper midwestern United States, cattle production systems that use perennial forages as the primary component of the diet could be an economically viable way to add perennial species to the landscape. However, overuse and continuous grazing of pasture can result in compacted soil, high rates of erosion, and increased nutrient discharge; in the worst cases, the nutrient losses can be greater than for annual cropland (Hubbard et al. 2004). Management intensive rotational grazing systems (MIRG)—where cattle are grazed at high densities for short durations, and time in pasture depends on the vigor of the plant stand—have been found to result in more consistent foliage removal and decrease the amount of bare ground compared to continuous grazing systems in subhumid climates (Oates et al. 2011), potentially reducing some of the harmful impacts of grazing. The Minnesota Natural Resource Conservation Service (NRCS) has identified MIRG as a best management practice and a means to manage pastures for improved water quality and decreased soil erosion (MN NRCS 2012). Using rotational grazing systems, where care is taken to avoid over grazing on pastures, can reduce the losses of sediment and phosphorus (P) compared to less intensively managed grazing systems (Sovell et al. 2000; Chaubey et al. 2010; Haan et al. 2006).

While grazing may represent a viable way to introduce perennial vegetation onto the landscape, agricultural acreages in the Upper Midwest region are valued for their ability to produce grains and other plant food crops, and converting large areas of land from row crop agriculture into pasture for grazing may not be the most economically feasible option for managing agricultural contributions to water quality problems. Conservation prac-

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tices such as reduced tillage, edge-of-field filter strips, and winter cover crops are often viewed as likely candidates of initial conservation efforts because they have been shown to be effective at reducing sediment and nutrient losses (Mulla et al. 2008), and represent less dramatic management changes for conventional row crop systems (as compared to switching to perennial vegetation).

Not all portions of agricultural landscapes contribute sediment and nutrients uniformly to receiving surface waters (Jones et al. 2001). In this regard, there may be environmental benefits in strategically placing conservation management practices on the landscape (Galzki et al. 2011; Vache et al. 2002) or in transitioning key landscape elements from annual row crops to perennial pasture and forage production. In this study, we examined the potential influence that conservation management practices (alone or in combination) and changes in land use from corn (*Zea mays* L.) and soybean (*Glycine max* L.) crop production to pasture for grazing beef cattle, could have on water quality. The analysis presented here is for a karst influenced agricultural watershed located in southeastern Minnesota, the south branch of the Root River. The objectives were to (1) evaluate the effects of conservation practices and conversion of cropland to management intensive grazing of perennial pasture on water quality and (2) to compare the effectiveness of the conservation practices and conversion of cropland to grazed pasture on altering loads of total sediment and P in the watershed.

Materials and Methods

South Branch of the Root River Watershed. The 301.77 km^2 (74,569 ac) south branch of the Root River (SBRR) Watershed is a tributary of the Root River, and is located in Fillmore and Mower counties in southeastern Minnesota (figure 1). The western half of the watershed is mostly flat (<4% slope), while, in contrast, the eastern half of the watershed is characterized by steeper slopes (>4% slope) with karst geology. Approximately 52% of the watershed area has <2% slope, while 10% of the land has a slope >10% (figure 1). In the eastern portion of the watershed, karst processes in the thinly mantled carbonate bedrock strongly influence near-surface hydrologic and geomorphic processes, including flow along dissolutionally-enlarged fractures and through conduits (Runkel et al. 2003). As is typical with karst processes, nutrients, sediments, and other contaminants can be quickly cycled between the surface and groundwater realms, often via overland runoff into sinkholes (Tipping et al. 2006). The predominant land use within the watershed is annual row crop agriculture, composing 67% of the watershed area. The remainder is mixed land use, composed of hay, forest, range, urban, water, and wetlands (figure 1). The western portion of the watershed is almost entirely devoted to corn and soybean production. The eastern portion of the watershed has more acreage in forest, hay, and range, though row crops are the dominant land cover. Average annual precipitation in the watershed is approximately 84 cm (33 in) (Minnesota State Climatology Office 2011). The average annual temperature is 6°C (43°F), with a normal average temperature during the growing season (April through September) of 18°C (64°F; normal temperatures are the 30-year mean from 1971 to 2000) (Minnesota State Climatology Office 2011). Soils in the area are mostly well-drained, class B soil types (56%), with some of those areas being B/D soil types having high water tables (24%). The outlet of the watershed is located within Forestville State Park, where stream flow was measured daily, and water quality was periodically monitored during the study period. Flow (based on a stage-discharge relationship) and water quality data were collected and maintained by the Minnesota Pollution Control Agency and provided to us for this study.

Hydrology and Water Quality Datasets. Measured daily stream flows used for model calibration and validation were available in the SBRR for a five-year period (2004 to 2008). Monthly sediment and P loads were estimated by coupling the daily flow values with periodically collected water quality measurements. Water quality samples were collected at a minimum of biweekly intervals during baseflow conditions. During stormflow events, grab samples were collected more frequently to attempt to capture the rising and falling of the hydrograph. Sediment loads were measured as total suspended solids and P was measured as total P (TP). During the study period from 2004 to 2008, a total of 50 and 113 sediment and P samples were collected. Monthly sediment and TP loads were estimated using FLUX (Walker 1996). In FLUX, a regression approach applied to individual daily flows (method 6) was used to predict series of monthly sediment and TP loading data. Prior to FLUX regression analysis, flow data were divided into three strata based on flow. Strata cutoff values for daily mean flow were set at 2.38, 5.71, and 84.8 m^3 s^{-1} (84.0, 201.7, and 2,994.7 ft^3 sec^{-1}) and were selected to divide available data into low-, mid-, and high-flow conditions. Comparison of observed with regression-predicted values yielded r^2 values of 0.89 and 0.83 for TP and total suspended solids, respectively.

Soil and Water Assessment Tool Model/Inputs. The Soil and Water Assessment Tool (SWAT) 2005 and ArcSWAT interface were used for simulating water quality effects of the alternative land management scenarios in the SBRR watershed. Daily precipitation and temperature data from October of 2004 through December of 2008 were obtained from the Spring Valley weather station, located near the center of the watershed but approximately 1.6 km (1 mi) outside the watershed boundary (there were no rain gauges located within the boundaries of the study watershed). In cases where daily precipitation and temperature data were missing, they were substituted with values from the Grand Meadow weather station, located approximately 3.2 km (2 mi) outside the watershed boundary (this occurred for less than 0.6% and 0.05% of precipitation and temperature data, respectively). For watershed-scale hydrologic modeling, model outputs can be especially sensitive to precipitation data and care has been taken to ensure that the closest available data were used in this study. Remaining climate data play a less sensitive role in determining daily water flux and were collected from the closest available weather stations. Wind speed and relative humidity data were obtained from stations in La Crosse, Wisconsin (90 km [56 mi] from the study watershed), and Minneapolis, Minnesota (160 km [99 mi] from study watershed), respectively. Measured solar radiation data were provided by the Minnesota Climatology Working Group, located in St. Paul, Minnesota (approximately 160 km [99 mi] from the study watershed).

A digital elevation model (DEM) with 10 m (32.8 ft) grid size was used to delineate stream networks, subbasins, and slopes (USGS 2009). County-level soils data were obtained from the Digital Soil Survey Geographic (SSURGO) database (USDA NRCS 2009). User-defined soils data tables were provided by the SWAT development group at Texas

A&M University. Four of the soil map units present in the SSURGO data were not available in the user-defined soil data tables, and were renamed to match adjacent soils map units that had similar texture and hydrologic groups. Land use and land cover data with 30 m (98 ft) grid size were determined from the 2001 National Land Cover Database (NLCD) (MRLC 2001). Some of the smallest land cover classes (those that covered >1% of the watershed area) were aggregated to reduce the number of functional units handled by SWAT.

Stream channel dimensions and hydraulics were measured in 17 representative stream reaches throughout the SBRR watershed. The stream reach surveys were total station-based and followed standard methods (Rosgen 1996; Harrelson et al. 1994) to measure stream cross-sections and longitudinal profiles. Reach selection was based on field reconnaissance and GIS-based analyses of topography, aerial imagery, hydrography, and karst features. Through these analyses stream reaches were selected based on their representativeness of the range of characteristics common throughout the watershed with respect to channel morphology, stream gradient, valley morphology, vegetation, and bed forms. The chosen reaches represented the range of channel types and channel conditions found in the SBRR watershed. Based on the surveyed stream geometry, the following variables were determined for the channels and used to parameterize the SWAT model: (1) average width at the top of the bank, (2) depth from the top of the bank, (3) width-to-depth ratio, (4) longitudinal slope, and (5) the Manning's *n* value. Additionally, the average bankfull longitudinal slope and the length of the main channel were measured from topographic maps. Baseflow velocity measurements were collected using an acoustic Doppler velocimeter and the wading method of discharge determination (Harrelson et al. 1994). The baseflow Manning's values were calculated by solving the Manning Equation for *n* based on the values for velocity, slope, area, and wetted perimeter measured during the field surveys. Typically, Manning's *n* values decrease (i.e., less roughness) as stream stage rises. This is a function of area increasing faster than the wetted perimeter (i.e., increasing hydraulic radius). Nonetheless, factors such as bank vegetation can strongly influence the bankfull roughness and cause it to increase with stage. Our bankfull Manning's *n* values were constrained based on the baseflow roughness value, professional judgment, and published guidance (Arcement and Schneider 1989).

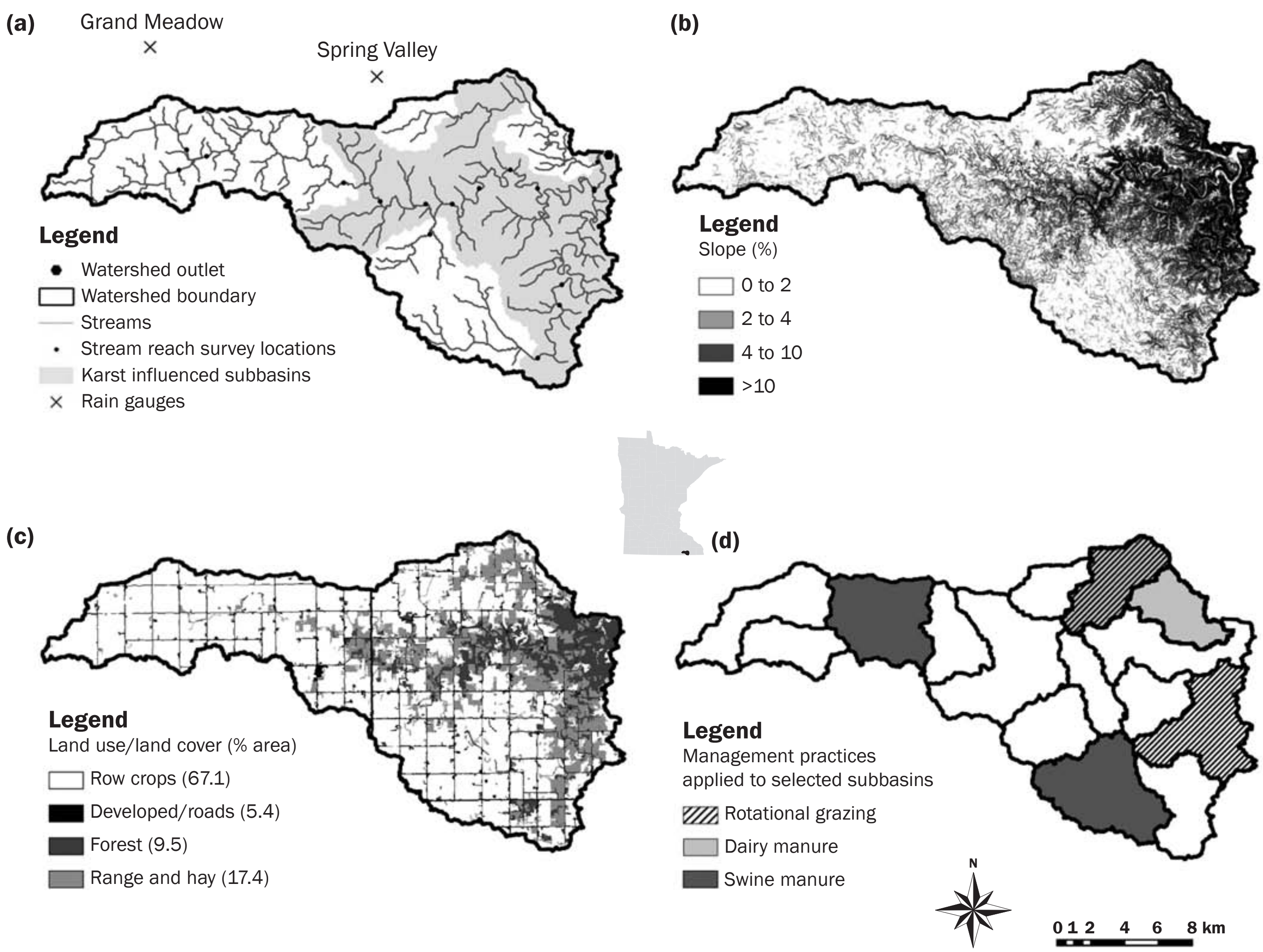
The hydraulic conductivity of the stream bed values input to SWAT were based on measurements in two of the surveyed stream reaches of the SBRR: near Mystery Cave, which is dominated by karst hydrology, and in Etna Creek, which is influenced predominantly by nonkarst conditions. Determinations of the hydraulic conductivities followed the heat pulse method (Silliman and Booth 1993; Ronan et al. 1998; Dogwiler et al. 2007), and were taken during varying flow conditions. Baseflow discharge measurements used in determining the hydraulic conductivity of the stream bed occurred at Etna Creek and near Mystery Cave, and were 0.21 and 1.95 $m^3 s^{-1}$ (7.42 and 68.86 $ft^3 sec^{-1}$), respectively. In each of the two streams, Onset TidbiTTM temperature loggers programmed to record measurements at 5-minute intervals were buried at three depths in the stream substrate. The manufacturer-reported accuracy of the temperature data loggers is ±0.21°C (±0.378°F) in the temperature range of 0°C to 50°C (0°F to 122°F) with a stability (drift) of 0.1°C (0.18°F) per year. At the nonkarst location, they were placed at depths of 2, 9, and 16 cm (0.8, 3.5, and 6.3 in). At the karst location, the temperature loggers were buried at depths of 2, 12, and 22 cm (0.8, 4.7, and 8.6 in). The differences in logger depths between the two reaches reflect the difficulty of excavating and precisely burying the data loggers in a fast flowing stream. However, the differences in the depths between the sites were not critical so long as the absolute depth differences between the temperature loggers were known. Surface water and air temperatures were also measured at each stream reach, and a stage record was collected at the nonkarst location using a pressure transducer. The hydraulic conductivity was determined based on tracking diurnal water temperature maximums through the stream substrate. The amount of time for a thermal maximum to infiltrate from one temperature logger to another deeper temperature logger was used to determine the hydraulic conductivity (cm h^{-1}). A mathematical formula described in Dogwiler et al. (2007) provides compensation to the raw thermal pulse velocity for factors such as the densities and thermal capacities of the substrate sediment and water. The result of this computation is the vertical hydraulic conductivity of the stream sediment. In low-order, gravel-bedded streams, thermal variations tend to be greatest on sunny days at baseflow conditions (Dogwiler and Wicks 2006; Dogwiler et al. 2007). Thus, the data set was filtered to look exclusively at days comprised of baseflow conditions (i.e., with no significant precipitation). Both data sets cover the period from late May through August of 2008 with 49 days of baseflow analyzed at Etna Creek and 55 days at the reach near Mystery Cave. Diurnal temperature ranges at base flow ranged from 1°C to 7.2° C (33.8°F to 45°F) and 1.2°C to 5.9°C (34°F to 43°F), respectively, at the Etna Creek and Mystery Cave sites. The results for each stream were averaged to yield a hydraulic conductivity that integrates variations in diurnal temperature range, solar radiation, stream flow, and other governing factors. Measured stream physical characteristics and hydrologic conductivity values were applied to the spatially corresponding stream reaches in the SWAT model.

Baseline Crop Management Practices. Cropping management practices were developed to represent typical crop operations in this watershed. Crop planting and harvesting dates were average values determined from 10 years of weekly crop reports. Typical tillage and fertilizer practices were determined from surveys of local farmers conducted and published by the Minnesota Department of Agriculture (Rasmussen 2003 and 2007). All cropland was in a two-year rotation of corn and soybean common for the region. Soil management included spring cultivation and fall plowing. Chisel plow was used on soybean residue while disc plow was used on corn residue. Fertilizer application was split to represent the most common practices occurring throughout the watershed. Phosphorus was applied in the fall and at planting for a total application of 60 kg P ha^{-1} (53 lb P ac^{-1}). Nitrogen (N) was applied in the fall during field preparation and at planting for a total application of 144 kg N ha^{-1} (128 lb N ac^{-1}).

Based on the local producer surveys (Rasmussen 2003 and 2007), it was estimated that animal manure was applied to approximately 8% of cropland in the SBRR during any given year. The major sources of manure applied to crop fields were from swine and dairy operations within the watershed, and were the two sources of manure applied for the baseline scenario. Swine manure was applied to two subbasins in the western por-

Figure 1

Location and important features of the south branch of the Root River Watershed. These maps show (a) hydrologic features, locations of weather, and streamflow measurements; (b) watershed slope; (c) predominant land use/land cover; and (d) location of select management practices (manure application and alternative grazing land use scenarios). The watershed boundary and stream network were developed from a 30 m digital elevation model. Water and wetlands compose 0.6% of the land cover in the watershed, but were excluded from the figure for visualization purposes.



tion of the watershed, while dairy manure was applied to two subbasins in the northeastern portion of the watershed (figure 1). Since it was not feasible to know the exact location of all manure application in the study area, this was a simplification of actual manure management practices within the SBRR watershed; in actuality, fields receiving manure are more distributed throughout the watershed. The approach used here was based on the general distribution of animals in the watershed and results provided insight into how manure application influenced nutrient losses from row cropped fields in varying portions of the SBRR watershed.

A crop management schedule was established such that, in those subbasins receiving swine or dairy manure, manure was applied to every corn acre once in four years on rotation. Manure application was divided between fall (67%) and spring (33%) according to the Farm Nutrient Management Assessment Program surveys (Rasmussen 2003 and 2007). For the baseline scenario, commercial N and P fertilizer rates were not changed in response to manure application (personal communication with Minnesota Department of Agriculture staff). This resulted in these fields receiving excess N and P once every four years. Manure was applied to achieve a rate of 98.8 kg P ha^{-1} (88.2 lb P ac^{-1}) based on P application rates reported in the Farm Nutrient Management Assessment Program survey. Manure N:P ratios were taken from a Minnesota Department of Agriculture fact sheet (MDA 1999) and were preserved within the model nutrient database; as a result, manure N application rates were dependent on the amount of manure required to achieve the estimated manure P rate and were different for swine and dairy manure.

Calibration and Validation. All model runs occurred for the years 2002 to 2008; the first two years were included as a warm-up period from which results were not used in order to eliminate model sensitivity to initialization values and allow environmental parameters such as simulated soil moisture to equilibrate to simulated conditions. Following the warm-up period, a five-year simulation period (years 2004 to 2008) was

Table 1
Parameters used for calibration and validation of the Soil and Water Assessment Tool model in the south branch of the Root River Watershed. Most parameters were applied to all hydrologic response units (HRUs); those that varied on an HRU basis are indicated by "varies."

Parameter	Description	Default	Calibrated value
TIMP.bsn	Snow temperature lag factor	1	0
PET method.bsn	Methods for estimating potential evapotranspiration (Wang et al. 2006)	Penman Monteith	Hargreaves
ESCO.bsn	Soil evaporation compensation factor	0.95	0.60
EPCO.bsn	Plant uptake compensation factor	1	0.95
CN_FROZ.bsn	Allows application of curve number approach to frozen soils	Inactive	Active
Crack Flow.bsn	Simulates crack development in soils	Inactive	Active
SURLAG.bsn	Surface runoff lag coefficient	4	3
PRF.bsn	Peak rate adjustment factor for sediment routing	1	0.8
SPCON.bsn	Sediment entrainment factor-linear	0.0001	0.001
EPEXP.bsn	Sediment entrainment factor-exponent	1	1.5
CMN.bsn	Rate factor for humus mineralization	0.0003	0.002
CDN.bsn	Denitrification exponential rate coefficient	0	0.05
SDNCO.bsn	Denitrification threshold water coefficient	0	0.95
OV_N.hru	Manning's roughness coefficient for overland flow		
	Annual crop fields	0.14	0.4
	All other land use	0.14	0.25
DEP_IMP.hru	Depth to impervious layer in soil profile (mm)		
	A and B soils	Inactive	3,750
	A/D, B/D, C, and D soils	Inactive	1,500
CANMX.hru	Maximum canopy storage (mm)	0	4
GW_DELAY.gw	Groundwater delay time (days)	31	1*
Alpha_BF.gw	Base flow recession constant, groundwater response to changes in recharge		
	Nonkarst subbasins	0.048	0.08
	Karst subbasins	0.048	0.64
Rchrg_dp.gw	Deep aquifer percolation fraction	0.05	0.1
GWQMIN.gw	Threshold depth of water in shallow aquifer required for return flow to occur	0	150
FRSD.mgt	Initial age of trees	0	50
Cn2.mgt	Soil Conservation Service curve number	Varies	Decreased by 20% (from default values)
Ch_K2.rte	Hydraulic conductivity of channel bed material (mm h^{-1})		
	Nonkarst subbasins	0	37
	Karst subbasins	0	66
CH_W.rte	Channel width at bankful conditions (m)	Varies	Measured value, varies
CH_D.rte	Channel depth at bankful conditions (m)	Varies	Measured value, varies
W/D.rte	Width/depth ratio	Varies	Measured value, varies
CH_N2.rte	Manning's roughness coefficient for channel flow	0.014	Measured value, varies

*For karst subbasins only.

used to evaluate the model performance and assess baseline and alterative scenarios. The model was manually calibrated with daily and monthly streamflow data and monthly water quality data for the years 2004 to 2005, and validated for the period from 2006 to 2008. The SWAT parameters calibrated from defaults are shown in table 1. Karst influenced subbasins were calibrated based on the assumption of stronger contributions from shallow groundwater and shorter delay in groundwater response time compared with nonkarst subbasins (table 1) (Luhmann 2011). Karst features—including sinkholes, stream sinks, and springs—were obtained from a spatial dataset from the Minnesota Department of Natural Resources (MN DNR 2013). Subbasins were considered karst-influenced based on the occurrence of identified karst features within the subbasin. In general, subbasins with greater than 15 identified karst features were treated as karst-influenced for the purposes of model simulation (figure 1).

Performance of the SWAT model was assessed by comparing monthly values of predicted versus observed flow (mean monthly discharge) and water quality parameters. In addition to comparing mean values for the calibration and validation periods, model performance was evaluated with the Nash-Sutcliffe Efficiency (NSE) metric (Nash and Sutcliffe 1970):

$$E = 1 - \frac{\sum(Y_o - Y_m)^2}{\sum(Y_o - \overline{Y}_o)^2}, \tag{1}$$

Table 2
Description of each alternative scenario simulated in the Soil and Water Assessment Tool. Alternative conservation management scenarios include management practices applied to existing cropland with the goal of reducing sediment and phosphorus losses from fields. The land use change scenarios simulated cropland areas converted into pasture for management intensive rotational grazing of beef cattle.

Alternative scenario	Description	Watershed area in treatment (%)
Conservation management scenarios		
ConsTill 25	Conservation tillage applied to 25% of cropland in a nontargeted approach	17
ConsTill 4	Conservation tillage applied to all cropland with slope greater than 4%	8.4
Filter4	10 m filter strip on all cropland with a slope greater than 4%	8.4
CovCrop4	Cover crops on all cropland with a slope greater than 4%; no manure on croplands with slope greater than 4%	8.4
CovCrop4-ConsTill100	Cover crops on all cropland with a slope greater than 4% and conservation tillage on all remaining cropland; no manure on croplands with slope greater than 4%	67
CovCropFilter4-ConsTill 100	Cover crops and filter strips on all cropland with a slope greater than 4%; conservation tillage on all remaining cropland; no manure on croplands with slope greater than 4%	67
Land use change scenarios		
GLU-steep	Cropland on slopes greater than 4% converted into pasture for grazing in select subbasins	2.6
GLU-CPI	Cropland with low crop productivity indices converted into pasture for grazing in select subbasins	2.6
GLU- random	Cropland, chosen at random, converted into pasture for grazing in select subbasins	2.6

where Y_o is the observed monthly value (discharge or load), Y_m is the modeled value of the same parameter, and $\overline{Y_o}$ is the mean value of the observed data. Nash Sutcliffe Efficiency values can range from $-\infty$ to 1. Perfect agreement between predicted and observed data results in NSE = 1; an NSE value of 0 indicates that the mean of the model prediction is as accurate as the observed. A value greater than 0.75 for monthly NSE can be considered very good; between 0.65 and 0.75 can be considered good model performance, while a value between 0.5 and 0.65 is considered satisfactory (Moriasi et al. 2007).

Alternative Scenarios. Two sets of alternative scenarios were evaluated for the SBRR watershed. The first set of management practices considered no change in land use, and that conservation practices typical for the region would be employed on select cropland. Under the second set of alternative scenarios, a portion of the cropland was converted to pasture for MIRG of beef cattle. Each alternative scenario simulated is summarized in table 2. The evaluation for each suite of practices was compared to the result from the baseline crop management and land use practices (which describe current row crop farming practices) to obtain the relative changes in performance of the alternative scenarios.

Alternative Management Row Crops. Chisel and disk tillage practices were replaced with a generic conservation tillage practice, maintaining the use of field cultivators for planting. The conservation tillage practices were not as deep or well-mixed as conventional practices, allowing for more crop residue to remain on the soil surface, reducing soil erosion. Two conservation tillage scenarios were developed: (1) conservation tillage uniformly distributed across 25% of the cropland in the watershed (i.e., geography, landscape position, or geology were not considered), and (2) conservation tillage applied to cropland with greater than 4% slope. The 4% threshold represents a user-defined break point used in HRU generation. In the study watershed, 8.4% of row crops are situated on lands with slopes greater than 4%.

A second alternative crop management practice utilized a rye (*Secale cereal* L.) cover crop, simulated on croplands with slope greater than 4%. This practice also had no dairy manure applied on croplands with slope greater than 4%; manure that would have gone on these areas was redistributed to cropland with slopes less than 4% so that the total application rate in the watershed was the same as in the baseline scenario. Rye was planted immediately following fall harvest of corn or soybean and allowed to grow in the fall and following spring (as allowed by temperature). Immediately prior to spring field preparation (for corn or soybean), the rye crop was killed and field preparations resumed with primary tillage, field cultivation, and planting.

The effectiveness of filter strips in reducing field losses of sediment and TP was also modeled. A 10 m (33 ft) wide filter strip was applied to croplands with a slope greater than 4% based on a summary of general filter strip guidelines by Lee et al. (2004). Additional scenarios were also developed that were combinations of one or more of the above scenarios, including the following: croplands with slope greater than 4% were planted in cover crops, and conservation tillage was used on the remaining cropland; and cover crops and 10 m (33 ft) filter strips were used on croplands with slope greater than 4%, with conservation tillage used on the remaining cropland areas. Both of these combination scenarios also had no dairy manure applied on croplands with slope greater than 4%; manure that would have gone on these areas was redistributed to cropland with slopes less than 4% so that the total application rate in the watershed was the same as in the baseline scenario.

Alternative Land Use Grazing. For the grazing land use (GLU) scenario, a small percentage of cropland under the baseline scenario was converted into pasture for grazing beef cattle. The percent change in land area to be converted from cropland into pasture was based on the results of a deterministic model (Wilson 2012) developed to calculate the area of land needed to produce enough "grass-finished" (perennial forage-fed) beef to satiate the beef demand by a defined population (in this case, the demands of the watershed) (Wilson 2012). The land area was calculated based on (1) the energy needs of the cattle (NRC 1984) and average performance observations for grass-finished cattle; and (2) the energy available from perennial forage crops per unit land area (based on assumptions on cattle diet composition and average yield of perennial forage plants in southeastern Minnesota) (Wilson 2012). Based on the results on the deterministic model, the calculated land area was determined to equal 2.6% of the total watershed area, or approximately 8.10 km^2 (2,001 ac).

Because a small area of land was to be converted into pasture, GLU was only applied to two subbasins in the watershed (figure 1), chosen based on their contribution of sediment and TP loads. The pollutant loads from cropland under the baseline simulation were aggregated by subbasins, which were then ranked based on their contribution to the total loads of pollutants calculated under the baseline scenario simulation. Grazing land use was applied to hydrologic response units (HRUs) in the two subbasins that showed both a high contribution of pollutants, and had a total combined area equal to the target area. Three approaches were then used to target where the land use change was applied within those subbasins: in areas of high slope (steep approach), in areas with low crop productivity index (CPI) values (CPI approach), and randomly distributed (random approach).

In the steep approach, HRUs on cropland with greater than 4% slopes were targeted for grazing land use. In the CPI approach, locations were targeted based on the potential yields of corn production in the SBRR watershed based on soil characteristics. The CPI index ranges from 0 to 100, with 0 indicating very low expected corn yield and 100 indicating very high yields. Within the two targeted subbasins, areas with the lowest expected corn yield had GLU implemented. Crop productivity index data obtained in raster format from the Minnesota Geospatial Information Office (Minnesota Geospatial Information Office 2011) was joined to the HRU data using ESRI ArcMap to identify HRUs with the lowest CPI values. The CPI values for GLU HRUs ranged from 15 to 78. The random approach was to locate pasture randomly on cropland within the targeted subbasins. The HRUs which corresponded to cropland under baseline conditions were selected with a random number generator (Microsoft Excel). In all three approaches, HRUs were chosen so that the total area undergoing land use change was approximately equal to the target area (8.10 km^2 [5 mi^2]). While the target area of land transformed was the same for all three approaches (8.10 km^2 [5 mi^2]), the actual geographical area was not exactly the same due to the fact that not all HRUs were the same size. In order to compare the outcomes of the three approaches, final sediment and TP outputs were normalized by area.

Winter pasture was used as the modeled vegetation type for the grazing land use scenarios. All plant growth parameters in SWAT were left at defaults, except the heat units to reach maturity, which were decreased to 1,000 in order for the modeled plant growth to more closely match expected values. The SWAT-modeled evapotranspiration (ET) for winter pasture was compared against recorded ET rates in grasslands in the Upper Midwest to ensure that simulated plant growth and water use was realistic for the region. Average ET for grasslands were obtained from water vapor flux data from the AmeriFlux network (AmeriFlux 2012) and synthesized for sites in the Upper Midwest by taking available data collected in 30-minute intervals and computing daily average values. Daily values from multiple years were averaged to compute annual averages. The calculated average annual ET for grassland in Illinois and South Dakota were 636 and 703 mm (25 to 28 in), respectively. Average modeled ET for the GLU HRUs was 687 mm y^{-1} (27 in yr^{-1}), within the range of ET reported for grassland cover in the Upper Mississippi River Basin.

The GLU scenarios assumed MIRG where cattle would be rotated through pastures based on plant vigor and height in order to avoid overgrazing and allowing for recovery periods for the plants. In order to simplify the GLU scenarios in the SWAT, key inputs for the SWAT grazing setup—biomass removed and manure applied during grazing—were averaged over the course of the grazing season. Setting up a true MIRG system in the SWAT would have been difficult, since the length of time the cattle spend on pasture depends on examination of plant vigor in the field. Rotational grazing was scheduled to begin on May 1 every year and continue for 184 days, ending on October 31. The herbage removal rate per unit area on grazing land was equal to 18 kg ha^{-1} d^{-1} (16 lb ac^{-1} day^{-1}). The initial assumptions on cattle feed intake assumed high quality forage (high in protein and energy content), so this rate of consumption was assumed to represent in a stocking rate of 1,064 kg (2,346 lb) cattle live-weight per hectare per day (Wilson 2012). Trampling of vegetation during grazing was considered to equal 20% of the herbage removed during grazing (Gerrish 2002). No minimum threshold for plant height was set for grazing to occur, however based on the yield for winter pasture simulated in the SWAT there was enough biomass grown to meet cattle feed intake. Manure (dung and urine) from the grazing cattle was deposited at a rate of 6.6 kg dry matter (DM) ha^{-1} d^{-1} (5.9 lb DM ac^{-1} day^{-1}), based on cattle growth and population assumptions described in Wilson (2012) and using the American Society of Agricultural Engineers Manure Production and Characteristics Standard (ASAE 2005). No additional fertilizer or manure was applied to pasture.

Since the rotational grazing system assumed a vigorous plant stand in the pasture (Oates et al. 2011), the Soil Conservation Service curve numbers for HRUs converted to GLU were chosen to reflect good hydrologic conditions; the definition of good hydrologic soil conditions was greater than 75% ground cover and lightly or only occasional grazed (Neitsch 2005). Grazing at high cattle stocking rates (as frequently seen with management intensive rotational grazing) has been shown to alter soil physical properties, resulting in soil compaction (Warren et al. 1986), reduced infiltration (Kumar et al. 2012), and changes in soil bulk density (Daniel et al. 2002). To account for these changes, the Soil Conservation Service curve number for HRUs converted to GLU was adjusted to reflect a soil type with greater runoff potential. Curve numbers were chosen to be intermediate to the soil type and one step down, i.e., a B soil group was set to have its curve number equal to the intermediate value of B and C hydrologic soil groups for pasture in good hydrologic condition.

Grazing cattle were assumed to be housed under shelter during the winter, with their manure collected and applied to corn acreages the following spring, as is common practice for pasture-based beef producers in the region. The study assumed an application rate of 135 kg N ha^{-1} (121 lb N ac^{-1}), typical to that applied in the watershed. Winter manure produced by cattle in the SBRR watershed contained 56,234 kg N (123,975 lb N) (Wilson 2012). Based on N losses during manure storage in the region, it was assumed that 50% of the total N in the manure was available for application in the spring (Rasmussen 2007), resulting in 28,117 kg N (61,987 lb N) for corn. To achieve an application rate of 135 kg N ha^{-1} (120.5 lb N ac^{-1}), 209 ha (516 ac) needed to have manure applied. This acreage was split between corn acreage in the two targeted subbasins. Cattle manure was applied every spring at a rate of 13,500 kg DM ha^{-1} (12,049 lb DM ac^{-1}).

Results and Discussion

Calibration and Validation. Observed and simulated monthly streamflow, sediment yield, and TP stream loads during the calibration (2004 to 2005) and validation (2006 to 2008) periods are shown in figure 2. Observed data were not available for all months and are indicated by gaps in the observed data (usually winter months when average temperatures were below 0°C [32°F]). Months lacking observed data do not factor into calculations of model performance. Mean monthly calibration and validation results are shown in table 3, along with monthly estimates of model performance. For predicting sediment and TP loads, the model performed better during the validation period than during the calibration period, though overall the model-predicted values matched the observed data in general magnitude and timing (figure 2). Given that the goal of this study was to compare the relative differences in pollutant reduction rates, the results of the calibration and validation were considered acceptable. Notable months of disagreement between observed and predicted data occur during the validation period in August of 2007 and June of 2008. Both of these months were characterized by large precipitation events and multiple events over the course of several days. Compared against the 10-year mean from 1999 to 2009, county precipitation for August of 2007 and June of 2008 were 304% and 148% greater than average values, respectively. More importantly, summer precipitation events in the Upper Midwest are often associated with convective thunderstorms that can be very intense, but isolated and difficult to characterize with rain gauge data. The available precipitation data likely did not capture the spatial availability that occurred during these precipitation events, leading to disagreement between observed and predicted values during these months. Factors that account for stream bank erosion were not considered for this study so the model does not treat this as a sediment source. Previous work on a watershed sediment budget in the same region showed that erosion from stream banks is relatively minor compared to net upland erosion (Trimble 1999).

Baseline Conditions. For the five-year (2004 to 2008) evaluation period simulated, average annual precipitation was 1,020.7 mm (40.2 in). Under baseline conditions during the evaluation period, ET removed 70% of the annual precipitation from the watershed, with 25% of the average precipitation contributing to water yield at the outlet. Of the total water that reached the outlet of the watershed, the majority (59%) was from groundwater flow, 17.3% from tile flow, 14.3% from surface runoff, and 9.2% from lateral soil flow. The strong groundwater component is a reflection of the karst influence in this basin. By way of comparison, the water budget for an agricultural watershed located in the Minnesota River Basin (without karst influence) showed that groundwater flow contributed just 0.4% of the water yield while tile flow, surface runoff, and lateral soil flow contributed 63.1%, 23%, and 13.6%, respectively (Dalzell et al. 2012).

Sediment and TP loads under baseline conditions were calculated based on cumulative loads delivered to HRU outlets. Over the five-year evaluation period, average annual loads of sediment and TP from all HRU outlets in the watershed were 0.89 t ha^{-1} (0.4 tn ac^{-1}) and 0.73 kg ha^{-1} (0.65 lb ac^{-1}), respectively. A small number of HRUs were responsible for a large proportion of the annual load of sediment and TP; 25% of the total watershed area was responsible for 75% of the total sediment load, and 64% of TP loads (figure 3). Hydrologic response units considered steep cropland—those with annual crops on slopes greater than 4%—contributed loads of sediment and TP disproportionate to their area. Annually, these HRUs contributed 51% of the total sediment loads and 38% of TP loads, even though they accounted for only 8.4% of the total land area.

Sediment Reduction—Alternative Scenarios. Figure 4 shows the change in sediment loads with the alternative scenarios relative to the baseline scenario. These rates were calculated as the average annual sediment loads delivered to the HRU outlets (during the five-year simulation period), and reported as both a function of the total watershed area (cumulative sediment loads from all HRU outlets in the watershed) and as a function of treated area (sediment loads from treated HRUs only). Alternative conservation management practices scenarios that targeted landscape elements contributing the greatest sources of sediment were, not surprisingly, the most effective at reducing it. Cover crops and filter strips on croplands with slopes steeper than 4% reduced cumulative HRU loads of sediment in the watershed by 28% and 37%, respectively. Targeted conservation tillage was less effective, reducing the cumulative sediment loads to HRU outlets in the watershed by only 7%. The greatest reduction in sediment was seen when a combined approach was simulated, which employed both cover crops and filter strips on croplands steeper than 4%, along with conservation tillage on all remaining cropland. Under this management practice, the cumulative sediment load in the watershed was reduced by 53%. However, this practice also involved the greatest fraction of the watershed area (67% of watershed area).

Of the conservation management practices, reductions in sediment loads as a function of only treated areas were greatest with cover crops or filter strips on slopes greater than 4%; on just the 8.4% of cropland that had cover crops or filter strips applied, sediment was reduced by 55% (cover crops) and 75% (filter strips) compared to the loads from those HRUs under baseline management practices (figure 4). These simulated reductions of sediment per-unit treated area are consistent with reported reductions in field losses of sediment. Rye and oat (*Avena sativa* L.) cover crops following no-till soybean in Iowa reduced rill erosion by 79% and 49%, respectively (Kaspar et al. 2001). Also in Iowa, Lee et al. (2000) found that a 7.1 m (23.3 ft) grass buffer on cropland with average slope of 5% resulted in 70% reduction of sediment lost from the field; while Robinson et al. (1996) reported 85% sediment trapping efficiency for 9.1 m (29.9 ft) buffers boarding cropland with 12% slope. The alternative management scenarios evaluated here focus on practices that occur in (or adjacent to) crop fields—scenarios for which SWAT is well suited. There are additional measures that can be employed to reduce sediment loads in SBRR streams that focus on structural practices such as terracing and construction of earthen dams. These structural practices were not evaluated in the present study.

Implementation of the GLU scenarios using all three targeted approaches also resulted in cumulative reductions in HRU

Figure 2

Observed and simulated monthly (a) streamflow, (b) sediment, and (c) total phosphorus at the outlet of the south branch of the Root River Watershed (SBRR). Data gaps in the observed measurements occur when monitoring equipment was not deployed (usually a result of winter ice cover).

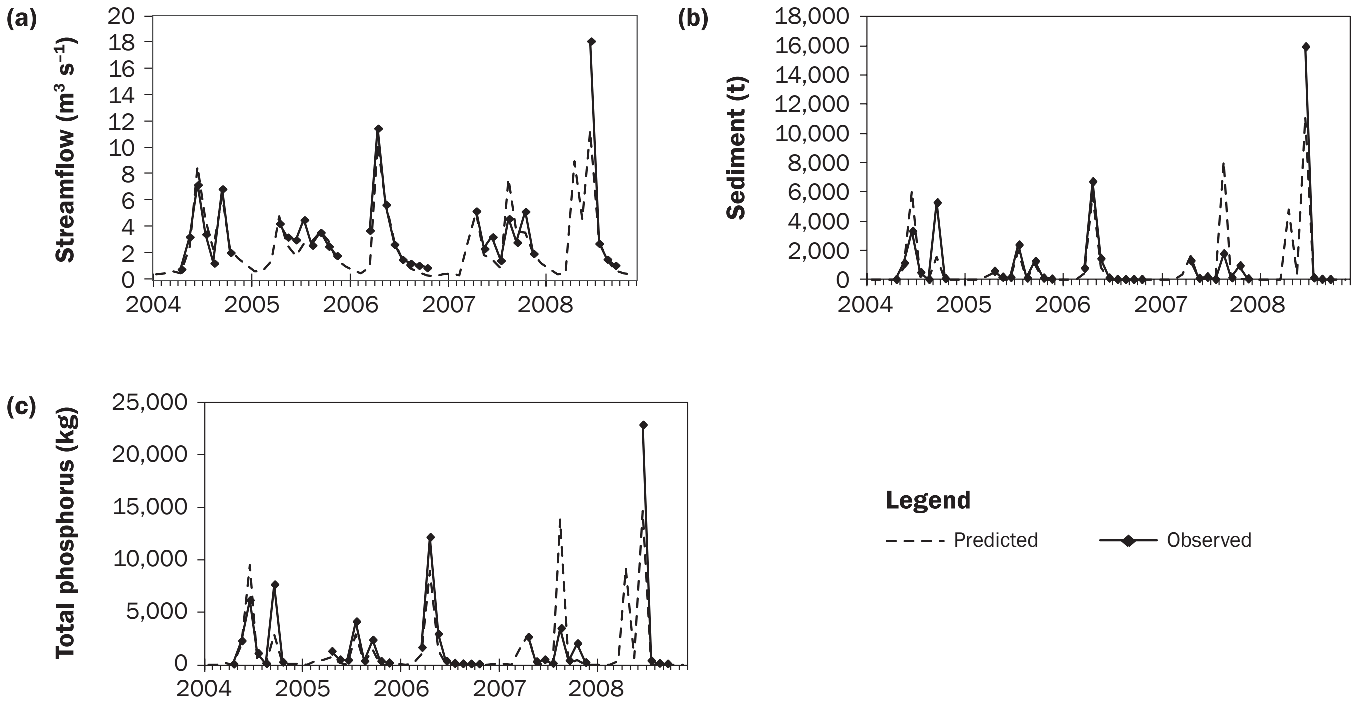


Table 3

Calibration (cal) and validation (val) results for the south branch of the Root River Watershed. Observed and simulated streamflow, sediment, and total phosphorus are average monthly values.

Performance measures	Streamflow ($m^3 s^{-1}$) Cal	Streamflow ($m^3 s^{-1}$) Val	Sediment (t) Cal	Sediment (t) Val	Phosphorus (kg) Cal	Phosphorus (kg) Val
Observed	3.18	3.39	998	1,477	1,820	2,544
Simulated	3.27	3.24	811	1,403	1,371	2,191
Monthly NSE	0.76	0.78	0.32	0.75	0.53	0.67

loads in the watershed, reducing annual HRU loads of sediment by 12% under the steep approach, 8% with the CPI approach, and 6% with the random approach (figure 4). Compared to the alternative conservation management practices, the GLU scenarios resulted in relatively small reductions in HRU loads of sediment at the watershed level; however the GLU scenarios did result in the largest reductions in sediment loads on a per-unit treated area basis (figure 4). For only those HRUs which were converted from cropland to grazing, sediment loads were reduced by 86% with the steep approach, 85% with the CPI approach, and 87% with the random approach. These large reductions per-unit treated area are primarily a result of the land cover factor in the Modified Universal Soil Loss Equation (MUSLE). The MUSLE is used in SWAT to calculate sediment yield in each HRU as a function of surface runoff, soil type, slope, and land cover (Neitsch et al. 2005). For those HRUs which were converted from row crops to pasture for grazing, two of these factors—surface runoff and land cover cover—changed between the baseline and GLU scenarios. Surface runoff accounted for a greater percentage of the total precipitation for GLU HRUs compared to the baseline. Higher runoff volumes would be expected to increase the sediment yield from the GLU HRUs. However, the overall reduction in sediment yield seen in model simulations is due to the lower value of the land cover factor used in the MUSLE, a result of having greater plant residue and cover throughout the entire year with the GLU scenarios.

Phosphorus Reduction—Alternative Scenarios. In the alternative conservation management scenarios where dairy manure was not applied to slopes steeper than 4% (CovCrop4 [cover crops on all cropland with a slope greater than 4%; no manure on croplands with slope greater than 4%], CovCrop4-ConsTill100 [cover crops on all cropland with a slope greater than 4% and conservation tillage on all remaining cropland; no manure on croplands with slope greater than 4%], and CovCropFilter4-ConsTill100 [cover crops and filter strips on all cropland with a slope greater than 4%; conservation tillage on all remaining cropland; no manure on croplands with slope greater than 4%]), there was approximately a 49% increase in rates of dairy manure application (during the year it was applied) on fields with slopes less than 4% (because the total amount of manure applied in the watershed was held constant compared to the baseline scenario). Simulated manure application rates were already in excess of plant requirements and this redistribution of manure could result in increased nutrient loss from those fields receiving additional

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Figure 3
Cumulative upland (a) sediment and (b) total phosphorus (TP) yield, plotted as a function of cumulative watershed area for the south branch of the Root River Watershed. One fourth of the total watershed area accounted for 75% of sediment loads and 64% of TP loads. Sediment and TP loads from developed/roads and hay/rangeland land uses make up the rest of the cumulative upland yields. (Developed roads are indicated by the light colored line on the sediment figure; the description was not included in the figure due to space restrictions).

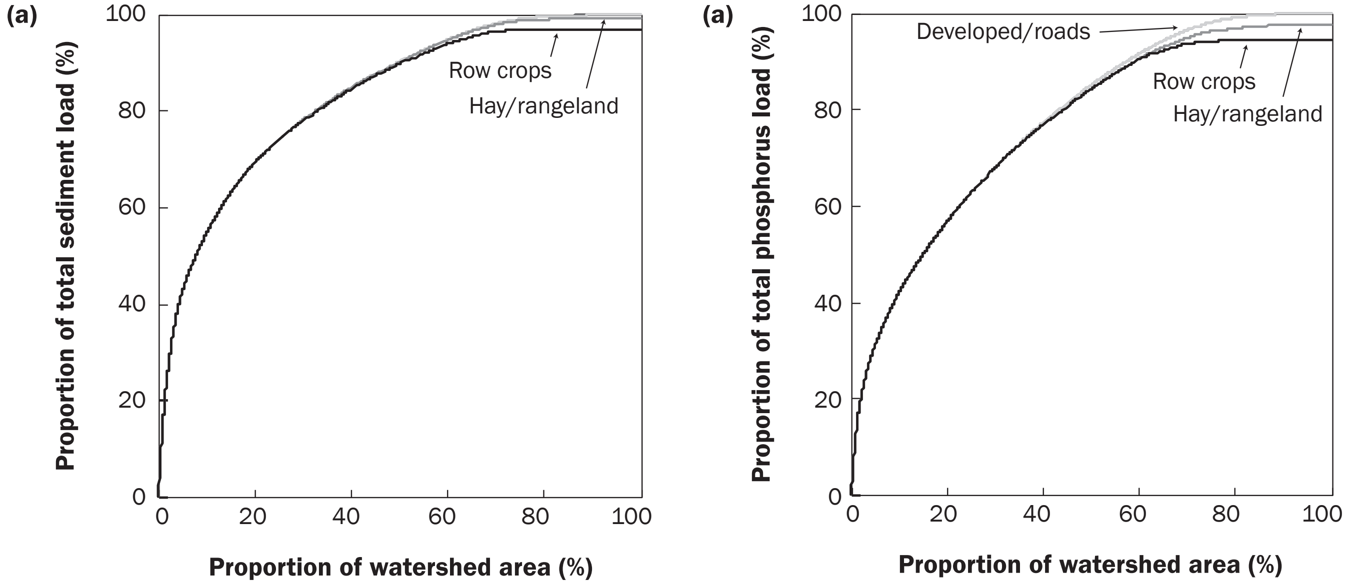
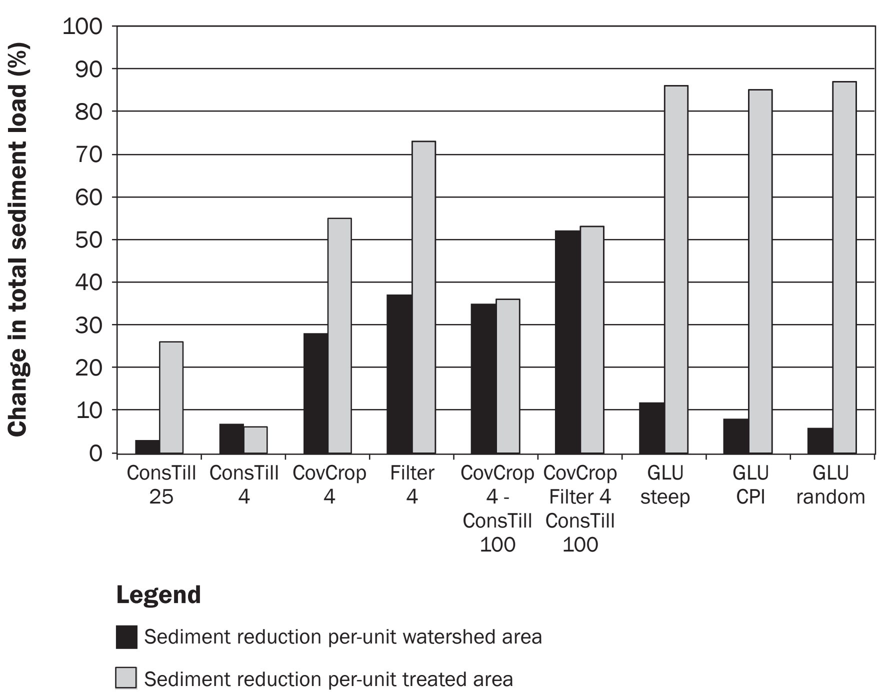


Figure 4
Percent change in simulated annual sediment load (averaged over the five-year simulation period) from the hydrologic response units during alternative scenarios relative to baseline scenario. (X-axis terms are described in table 2).



manure. (Manure was applied in this way based on the assumption that it was not likely to be transported longer distances to additional fields due to the logistics and cost of manure transportation.)

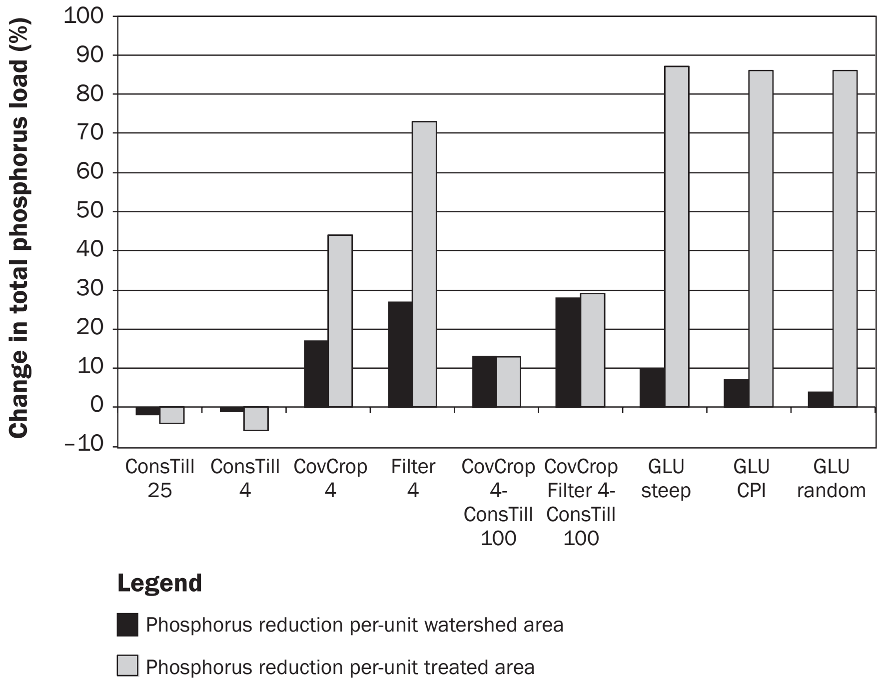
Figure 5 shows the change in TP loads with the alternative conservation management scenarios relative to the baseline scenario. These rates were calculated as the average annual loads delivered to the HRU outlets (during the five-year simulation period), and reported as both a function of the total watershed area (cumulative sediment loads from all HRU outlets in the watershed) and as a function of treated area (sediment loads from treated HRUs only). Similar to the simulation results for sediment loads, large reductions in loads of TP occurred with cover crops or vegetated filter strips on croplands with slopes steeper than 4%. These practices (in addition to manure redistribution for the cover crops scenario) resulted in cumulative reductions of TP loads in the watershed by 17% and 27%, respectively. The combination of cover crops and filter strips with conservation tillage on remaining cropland achieved the greatest reduction in cumulative HRU loads of TP loads in the watershed (28%). In contrast to the sediment results, conservation tillage did little to reduce TP loss and actually increased it in some scenarios (figure 5). This is the result of crop residue decomposition within the SWAT model framework. Within the model, less efficient (and more shallow) tillage results in a greater proportion of crop residue remaining on the soil surface where it is allowed to decompose and transition from organic to mineral P, thus increasing the potential losses of soluble P from farm fields, even though sediment erosion is diminished. The SWAT-predicted losses of soluble P are minor and generally comprised less than 8% of the total predicted P losses for all scenarios.

Implementation of the GLU scenarios also resulted in reductions in annual cumulative HRU loads of TP in the watershed, with a 10% reduction in TP loads under the steep approach, 7% with the CPI approach, and 4% with the random approach (figure 5). The decision to use a seasonal average of manure deposition could result in simulated TP results differing from actual field conditions, where manure would be concentrated in areas which were being actively grazed. However, the majority (>90%) of predicted TP loss for this watershed is caused through organic and mineral attachment of P to sediment in surface runoff. By maintaining adequate plant cover, these losses should be minimal. Similar results have been reported in field studies of grazing in Iowa. Haan et al. (2006) found that surface runoff from pastures which were managed to maintain adequate residual forage cover did not contribute greater sediment or TP to surface waters than ungrazed grassland.

Reductions in TP loads as a function of only treated area followed a similar pattern to sediment loads. On the 2.6% of land that was changed from cropland to grazing, TP loads from those HRU outlets were decreased by 87% under the steep GLU approach and 86% for both the CPI and random approaches—the largest reductions of TP on a per-unit treated area basis in the study. The alternative management practice showing the greatest reduction in TP per-unit treated area were filter strips and cover crops placed on croplands with slope greater than 4%, with a reduction of 73% and 44% on the treated acres, respectively. These simulated reductions in TP with cover crops and filter strips are consistent with reduction in reported field losses of TP. Under simulated rainfall, Lee et al. (2000) found a 7.1 m (23.3 ft) grass buffer on 5% slope removed 72% of TP, while cover crops have been shown to decrease TP losses between 54% to 94% (Kaspar et al. 2008).

Figure 5

Percent change in simulated annual total phosphorus load (averaged over the five-year simulation period) from the hydrologic response units during alternative scenarios relative to baseline scenario. (X-axis terms are described in table 2).



Summary and Conclusions

Simulation results of baseline watershed land use and management conditions indicate that cropland on areas of high slope (greater than 4%) in the SBRR watershed contribute loads of sediments and P disproportional to their area, with 8.4% of the area of the watershed contributing 51% of total sediment loads and 38% of TP loads. Alternative conservation management practices that targeted croplands on areas of high slope were most effective at reducing loads of sediment and TP. The practice most effective at reducing losses across the watershed was the combination of filter strips and cover crops on croplands with slope greater than 4% with conservation tillage on all remaining cropland, resulting in sediment and TP loss reductions of 52% and 28%, respectively. However, in order to achieve these results, a large fraction (67%) of the total watershed land area needed to be utilizing a conservation management practice. In contrast, when either cover crops or filter strips were targeted to the 8.4% of the watershed with cropland areas on a slope greater than 4%, cumulative sediment loads for the watershed were reduced by 37% and 28%, and TP loads were reduced by 27% and 17%, respectively. Additionally, on a per-treated area basis, filter strips or cover crops reduced simulated sediment loads by 73% and 55%, respectively, and TP loads by 73% and 44%, respectively. Given these high reductions in loads per-unit treated area, as well per the entire watershed area, these two practices are the most effective conservation management treatment with regard to achieving the largest reductions of sediment and TP while being needed on relatively few acres.

Changing land use from row crop agriculture to grazed pasture resulted in the greatest reductions in sediment and TP per-unit treated area in the study, reducing both sediment and TP loads by over 85%, regardless of placement strategy. Additionally, when targeted to areas of high slope the small (2.6%) reduction in cropland area in favor of pasture also resulted in comparatively large reductions in sediment (12%) and TP (10%) loads across the watershed. However, while the reductions in sediment and TP in the watershed are four times greater than the area of land converted from cropland to pasture, the overall reduction in the watershed was smaller than for other conservation management strategies (such as cover crops or filter strips on croplands with slopes greater than 4%).

The results of this study indicate that converting land use from row crop production to highly managed grazed pasture may be an effective way to decrease sediment and TP loads from the most vulnerable (i.e., highly sloped) land areas in the SBRR watershed. However, these reductions have a relatively small effect on the cumulative loads of sediment and TP over the entire watershed. Further reductions could be observed if pasture was increased to cover a greater percentage of the watershed area. Large scale conversion of row crop agriculture in this region is unrealistic; however, a small conversion, as used in this study, may be a feasible target. Of the conservation management practices, conservation tillage on its own, even when targeted to vulnerable areas, is not a very efficient way to control loads of sediment and TP in this watershed, especially compared to the reductions seen when these same land areas have management practices such as cover crops or filter strips applied. Combinations of conservation tillage, cover crops, and filter strips are the most effective at reducing loads of sediment and TP, though conservation management practices need to be applied to a large fraction of the total land area. In this regard, the most effective means to reduce loads of sediment and TP is in targeting cover crops and filter strips toward areas with slopes greater than 4%. Data from this study will be useful in helping water quality professionals assess whether changes in agricultural land use or management may be a viable part of moving toward water quality goals while still maintaining a working landscape.

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