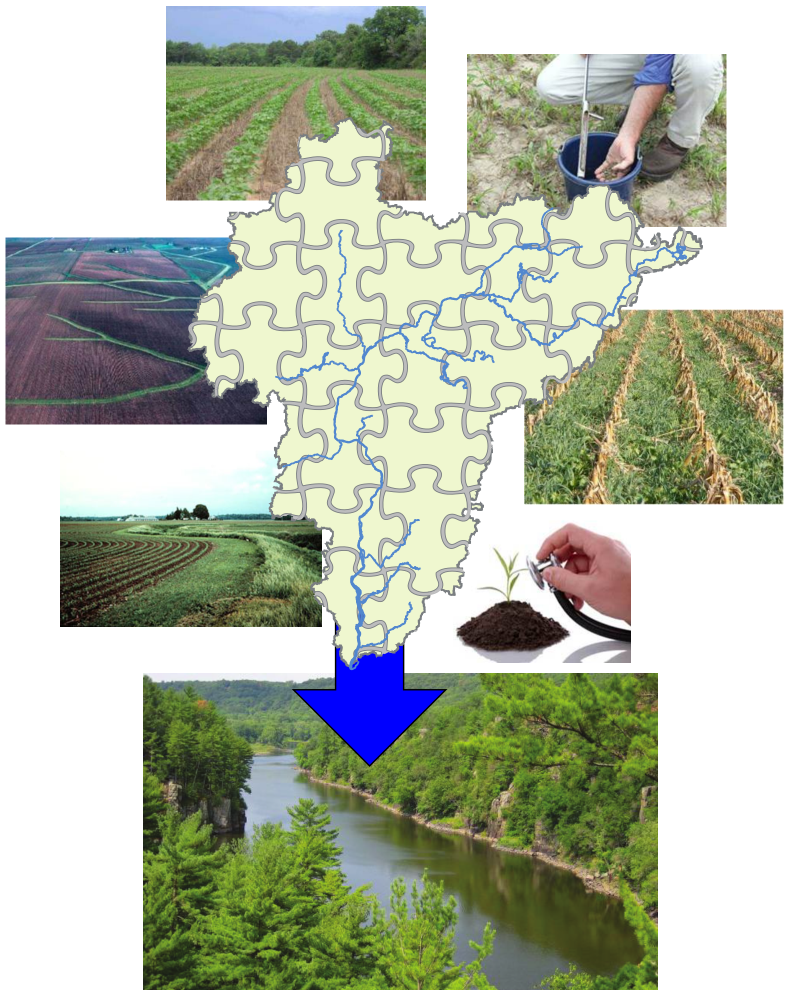
Applying a SWAT Model of the St. Croix River Basin to Estimate Reductions in Sediment and Phosphorus Loads due to Agricultural Best Management Practices



Prepared by the St. Croix Watershed Research Station, Science Museum of Minnesota

For the St. Croix Basin Water Resources Planning Team

Science Museum of Minnesota

St. Croix Watershed Research Station

Protecting the St. Croix

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Extended Abstract

The St. Croix River, along with its tributary the Namekagon River, is a federally designated scenic and recreational riverway administered as a unit of the National Park Service (NPS). Lake St. Croix, the lowermost 40 km of the river, is listed as impaired by eutrophication from excessive phosphorus loads. These loads come largely from nonpoint sources scattered across the 20,000 km^2 basin, which straddles the Minnesota-Wisconsin border. To address this impairment, the states authored a total maximum daily load (TMDL) study that set a goal to reduce phosphorus loads to Lake St. Croix by 27%. To better characterize the nonpoint sources of phosphorus and its transport to receiving waters, the NPS funded construction of a computer model of the St. Croix basin that was built using the Soils and Water Assessment Tool (SWAT). The present study used this calibrated SWAT model to estimate possible reductions of phosphorus and sediment loads that might accrue from implementation of agricultural best management practices (BMPs), thus testing the feasibility of achieving the goal set forth in the TMDL study. SWAT allows output to be extracted at different spatial scales, notably at the upland (edge-of-field) scale where the impact of BMPs is most evident, and far downstream at the watershed scale that includes the effects of transport factors between the sources and receiving waters, Lake St. Croix in this case.

BMPs were applied to tilled cropland in the basin, namely corn-alfalfa (CA) or corn-soybean (CS) rotations, each of which occupied about 6% of the basin. Results from BMP scenarios were compared against a baseline run based on relatively current land cover (2000-07) and point-source inputs (2006-09). Loads of phosphorus entering Lake St. Croix were reduced in the model by up to 4% for no-till (NT) scenarios, 3% for vegetated filter strip (VFS) scenarios, 6% for grassed waterway (GWAT) scenarios, and 5% for reduced initial soil-test phosphorus (STP) scenarios. Implementation of fall cover crops (FCCs), which provides cover of large parts of the landscape formerly protected only by crop residue, resulted in larger reductions of

phosphorus loads, up to a 23% reduction if FCCs were fully implemented following all corn and soybean crops in all rotations. Improved soil health (ISH) was modeled as an incremental variant of the FCC scenarios, which reduced phosphorus loads reaching Lake St. Croix by a few additional percent, up to 25% reduction. Reduction of STP within the ISH scenario added another percent improvement, to a 26% reduction in phosphorus load reaching Lake St. Croix. Percentage reductions of phosphorus loads at the upland (edge of field) scale were generally about twice those at the watershed scale, because transport factors that trapped phosphorus between source and receiving waters muted the response by the time these constituents reached Lake St. Croix. Sediment load reductions followed a very similar pattern to those of phosphorus, including the muting of response at Lake St. Croix relative to the uplands.

These results indicate that achieving the TMDL goal of a 27% reduction in phosphorus loads entering Lake St. Croix may be difficult with agricultural BMPs alone, requiring essentially full implementation of FCCs on all cropland. Establishment of more living cover, whether as FCCs or perennials, will almost certainly be part of the solution. Furthermore, in the face of commodity prices and government policies that encourage expansion of row crops, and probable urban development resulting from the new bridge at Stillwater, Lake St. Croix will likely degrade further unless we act to curb phosphorus loads from all sources, however partial or incremental. Protection and improvement of Lake St. Croix will require continued effort, and lags in response by Lake St. Croix may delay evidence of improvement.

Introduction

The St. Croix River (Figure 1) along the Minnesota/Wisconsin border is a federally designated scenic and recreational riverway, harboring at least 60 state and federally listed endangered or threatened species (Waters 1977, Holmberg et al. 1997). Because of its proximity to the Minneapolis-St. Paul metropolitan area, the St. Croix is heavily used with more than one million visitors annually (NPS 1995). The lowermost 40 km of the riverway comprises the naturally impounded Lake St. Croix, which has been listed by both states as impaired by eutrophication due to excessive phosphorus loads. Lake-sediment stratigraphic studies have demonstrated that the lake now receives about four times the natural loads of sediment and phosphorus from its tributaries. The increase in loads accelerated after 1940 with the mechanization of agriculture and the widespread application of inorganic fertilizers (Triplett et al. 2009).

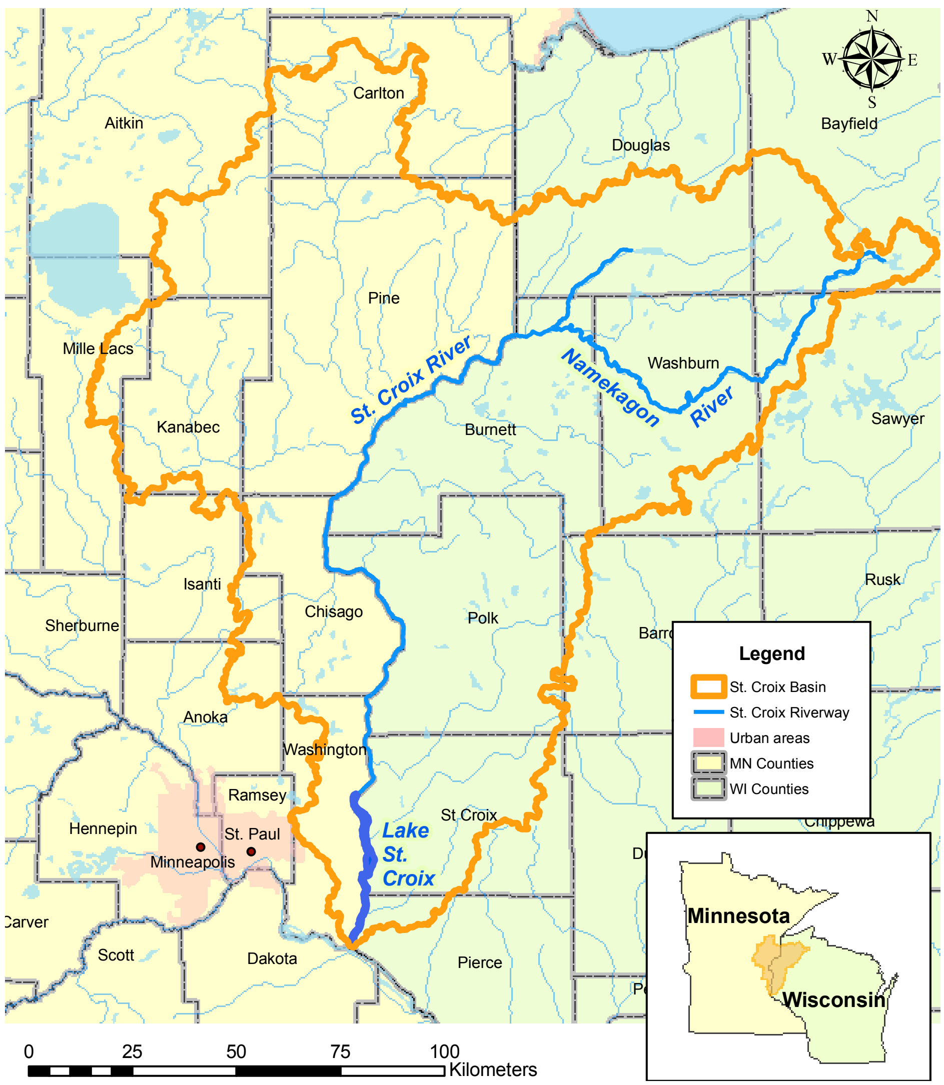


Figure 1. The St. Croix River Basin, eastern Minnesota and western Wisconsin

To address the eutrophication impairment of Lake St. Croix, the states generated a total maximum daily load (TMDL) study that aims to reduce phosphorus loads by 27%, relative to 1990s loads as a baseline (MPCA and WDNR 2012). Upgrades to waste-water treatment plants have reduced point-source phosphorus loads during the last decade or two, but population increases and urbanization may overwhelm this relative success (Edlund et al. 2009). In particular, recent legislation has permitted construction of a new bridge crossing Lake St. Croix at Stillwater, MN. The bridge will almost certainly spur urban development, which will likely generate increased loads of nutrients from both point sources and nonpoint sources. Further, increased demand and prices for corn and soybeans in the last decade has created financial incentives for farmers to plant more acres of row crops at the expense of retired lands (CRP and CREP), thereby increasing nonpoint loads of sediment and nutrients.

Consequently, achieving the TMDL goal will be challenging, because the phosphorus load reductions will have to go beyond the 27% stated in the TMDL to compensate for these potential additional loads above the current baseline. Even before the water-water treatment plant upgrades, nonpoint sources dominated the phosphorus loads to Lake St. Croix (Robertson and Lenz 2002, Edlund et al. 2009). Hence, most of the phosphorus load reductions needed to meet the TMDL goal will have to come from nonpoint sources. To reduce nonpoint loads, resource managers need to know at least two critical pieces of information: the source (location and land use) of the largest contributors of the nutrient loads, and what best management practices (BMPs) are most effective in reducing these loads.

To identify source areas for nonpoint phosphorus loads, the TMDL study used land cover alone as the determinant of which subbasins were the largest yielders of phosphorus in order to target implementation (MPCA and WDNR 2012). For this analysis, total phosphorus export coefficients (TPECs) were carefully calibrated to estimated loads at the basin-wide scale. Because of this calibration, the TPECs so calculated actually embed the basin-scale effect of transport between sources and receiving waters, spatially averaged over the entire basin. Hence, for use in the St. Croix basin, these St. Croix-specific TPECs are a significant improvement over generic TPECs developed elsewhere at a variety of scales. Nonetheless, these TPECs cannot accommodate spatial variation across the basin due to subbasin-specific transport differences. Neither can they account for changes in phosphorus export due to BMP implementation or to interannual weather variability, let alone directional climate change.

A watershed model provides an improved tool to target implementation location, with additional capabilities to test BMPs and consider differences in weather from year to year (Borah and Bera 2004). A watershed model can account for significant spatial differences in transport capacity across a watershed, caused by an uneven distribution of landscape depressions (lakes, ponds, and wetlands) that can trap nonpoint pollutants. Selected BMPs can be implemented in the model to test their local and aggregate effectiveness in reducing loads of sediment and nutrients. Changes in export can be tested under a range of weather variations, to identify loads for dry, wet, or typical years. Changes in land use can be input to the model to estimate changes in phosphorus loads due to increased urbanization resulting from the new Stillwater bridge, or due to conversion of grassland to row crops. To these ends, a watershed computer model for the St. Croix basin was constructed and calibrated with the Soil and Water Assessment Tool (SWAT) with funding from the National Park Service (Almendinger et al. 2014). This model characterized the sources of nonpoint sediment and phosphorus loads in terms of (a) source-area strength (yield, or kg/ha/yr) for each land-use type, and (b) spatial location in the basin and transport factors linking sources to receiving waters.

The present report documents the use of this model to estimate reductions in phosphorus and sediment loads to Lake St. Croix as a result of implementing agricultural BMPs across the basin. These BMPs included implementation of no-till, vegetated filter strips, grassed waterways, reductions in soil phosphorus concentrations, fall cover crops, and improved soil health. Edge of field reductions ranged from nearly zero to 56% for phosphorus and 74% for sediment. The largest reductions came from full implementation of fall cover crops within row crops (corn and soybeans). Because of transport factors, reductions in loads to Lake St. Croix were muted compared to edge-of-field reductions, reaching up to 26% for phosphorus loads and 50% for sediment loads. These results indicate that achieving the full 27% phosphorus load reduction goal for Lake St. Croix stated in the TMDL study may be difficult. Nonetheless, without action, increasing pressures from urban development and agricultural expansion would likely degrade Lake St. Croix even further. Because further degradation is unacceptable, implementation of BMPs is thus warranted even if the result is only the maintenance of Lake St. Croix in its current state.

Study Area

The St. Croix River extends 250 km from its headwaters to its confluence with the Mississippi River (Figure 1). The 158-km-long Namekagon River in Wisconsin, which joins the St. Croix just upstream of the Minnesota/Wisconsin border, is included as part of the federally designated St. Croix National Scenic Riverway. At least 15 other major tributaries contribute to the St. Croix from the basin beyond the narrow Riverway corridor. As noted earlier, the lower 40 km of the Riverway, from Stillwater, MN, to Prescott, WI, is a natural impoundment called Lake St. Croix, dammed at its mouth by sediment from the Mississippi River.

The St. Croix basin drains an area of about 20,000 km^2, most of which (58%) was forested based on average values over 1990-2007 used in the SWAT model (Figure 2; land cover data from NASS 2009, 2010, 2011; see Almendinger et al. 2014 for compilation details). In this data set, open water and wetland made up at least 14% of the landscape, although some of the listed forest cover was likely actually wetland as well. These wetlands are the source of the humic compounds that give the St. Croix waters their distinctive "tea" coloring. Grassland comprised about 15% of the landscape. Based on livestock populations and estimated stocking densities, grassland was partitioned into 6% grazed and 9% ungrazed grassland. Cropland occupied about 12% of the landscape, partitioned into 7% corn-alfalfa rotations and 5% corn-soybean rotations. These averages smooth the change in rotations that took place over that 18-year period. During the 1990s, corn-alfalfa rotations accounted for two-thirds of the cropland, but during the 2000s the rising value of cash crops had induced farmers to increase their corn-soybean acreage to be roughly equivalent to that of corn-alfalfa. The SWAT model accounted for this shift in crop-rotation acreage in an approximate way, as a step-change that occurred at the 1999-2000 transition.

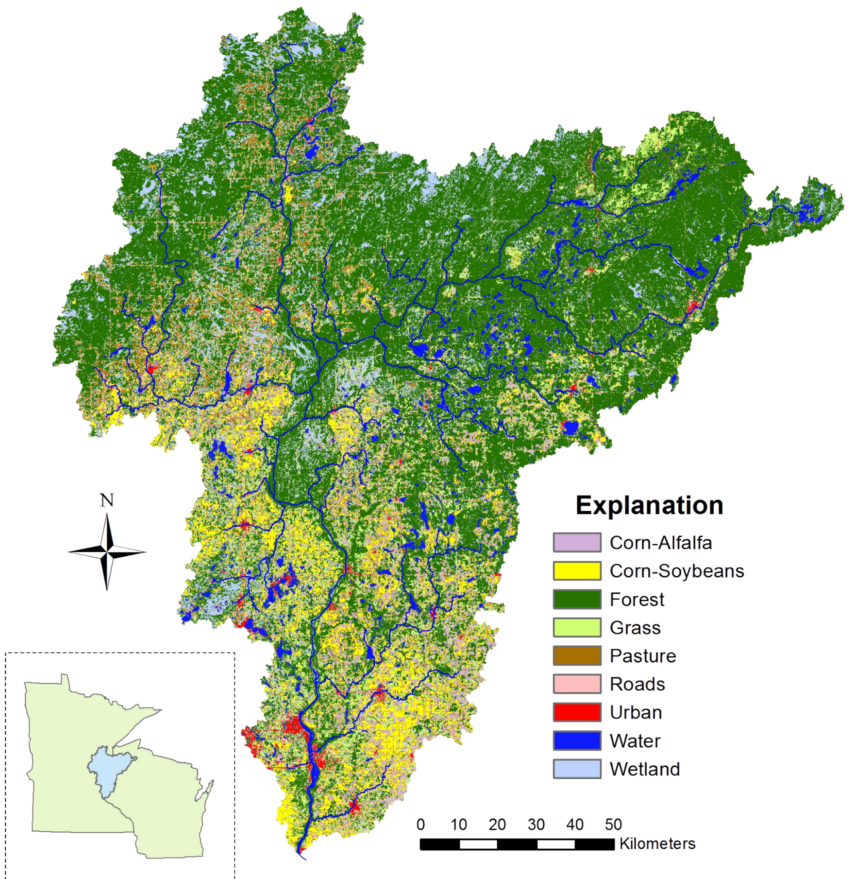


Figure 2. Land use in the St. Croix River Basin as used in the SWAT model.

The surficial geology of the St. Croix consists mostly of sandy glacial drift, much of which was deposited by ice from the Superior lobe of the Laurentide ice sheet. This ice lobe retreated from the basin by about 20,000 years ago, leaving behind a hummocky landscape of moraines interspersed with sandy outwash and lacustrine plains, many of which are occupied by peatlands today. Sometime near 18,000 years ago, an offshoot from the Des Moines ice lobe spilled into the southwest part of the basin and deposited a tongue of calcareous drift, much of which was outwash, extending to Grantsburg, WI (Wright 1972, Hobbs and Goebel 1982). From these parent materials, soils in the basin tend to be sands to sandy-loams and generally well drained. However, when flat, the landscape can be poorly drained despite the coarse soils. The pock-marked landscape and fairly permeable surficial deposits can create areas of closed surficial drainage with a strong influence of groundwater discharge on streamflow (Almendinger et al. 2014).

The climate of the St. Croix basin is strongly continental, with cold dry winters and warm humid summers. In Grantsburg, WI, near the basin centroid, the 1971-2000 normal mean temperature is -12.9 deg C (9 deg F) for January and 20.6 deg C (69 deg F) for July. The normal annual precipitation is 808 mm (31.8 inches), 42% of which falls during summer (Jun-Jul-Aug) and only 10% during winter (Dec-Jan-Feb) (NCDC 2011). Mean annual water yield differs across the basin by more than a factor of two, from about 6.6 inches the southwest part of the basin to 13.7 inches in the northeast part, with an average of 9.75 inches (248 mm) over the basin (data from D. Lorenz, U.S. Geological Survey, personal communication, 2010, based on data compiled for Lorenz et al. 2010). This volume equates to a mean annual flow at the outlet of the basin of 157 cms (cubic meters per second; about 5500 cubic feet per second [cfs]). If the mean annual precipitation at Grantsburg is representative of the basin, then mean annual evapotranspiration (ET) would be the difference between precipitation and water yield, or about 560 mm (22 inches).

Methods

SWAT Model Construction and Calibration

Model construction and calibrations are discussed thoroughly in Almendinger et al. (2014); what follows is a brief summary. The Soil and Water Assessment Tool (SWAT, specifically SWAT2012 for this project) is a watershed modeling program developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) (Arnold et al. 1998). Model construction requires inputs of hydrography, topography, soils, land cover, and agricultural management practices. Data input is facilitated by the program ArcSWAT (Winchell et al. 2013), an interface with ArcGIS geographic information systems (GIS) software (ESRI 2012). The St. Croix basin was subdivided into 419 subbasins, based on a high-density hydrologically corrected flow network (Vaughn 2010) burned into a 30-m digital elevation model (DEM; USGS 2010). Land cover, cropland areas, and livestock were determined from the digital Cropland Data Layer (CDL; NASS 2011) and countywide surveys of cropland and livestock populations (NASS 2009, 2010). Cropland areas were reproduced in the model by the use of two simple rotations: a two-year cash-crop rotation of alternating corn-grain and soybeans (CS) and a six-year forage rotation of one year of corn-grain, one year of corn-silage, and four years of alfalfa (CA). Based on the sequence of crops from 2006-10 CDL data sets, each cropland grid cell was assigned either a CS or CA rotation identifier. ArcSWAT intersected this rotation-specific land use, STATSGO soils (NRCS, 2008), slopes, and subbasin datasets to produce 3,010 hydrologic response units (HRUs) (Figure 3). Sub-rotations for CA and CS HRUs were constructed for each hydrologic soil group and with different crops starting in year-1 so that the landscape had a constant proportion of corn, soybeans, and alfalfa each year. Livestock was simplified to three major types (dairy cows, beef cattle, and horses) from which annual manure quantities were calculated (ASAE, 1998). Based on phosphorus content, manure from minor livestock types (sheep, hogs, poultry, red deer) was added to that of the major types to maintain the basin-wide total phosphorus load. Most dairy manure was applied to the CA rotations in three variants: no manure, seasonal applications (spring and fall), and monthly haul. Monthly-hauls were our model-simplified surrogate for daily-haul manure operations. All beef and horse manure was applied to grasslands via grazing operations in the model; only a small fraction of dairy manure was applied to grasslands. The 48 principal point sources, mostly waste-water treatment plants, were parameterized based on data summarized by Edlund et al. (2009) and Magdalene (2009). The 39 largest lakes were modeled as reservoirs, and smaller lakes and wetlands were modeled as aggregated pond and wetland features in SWAT (Almendinger et al.

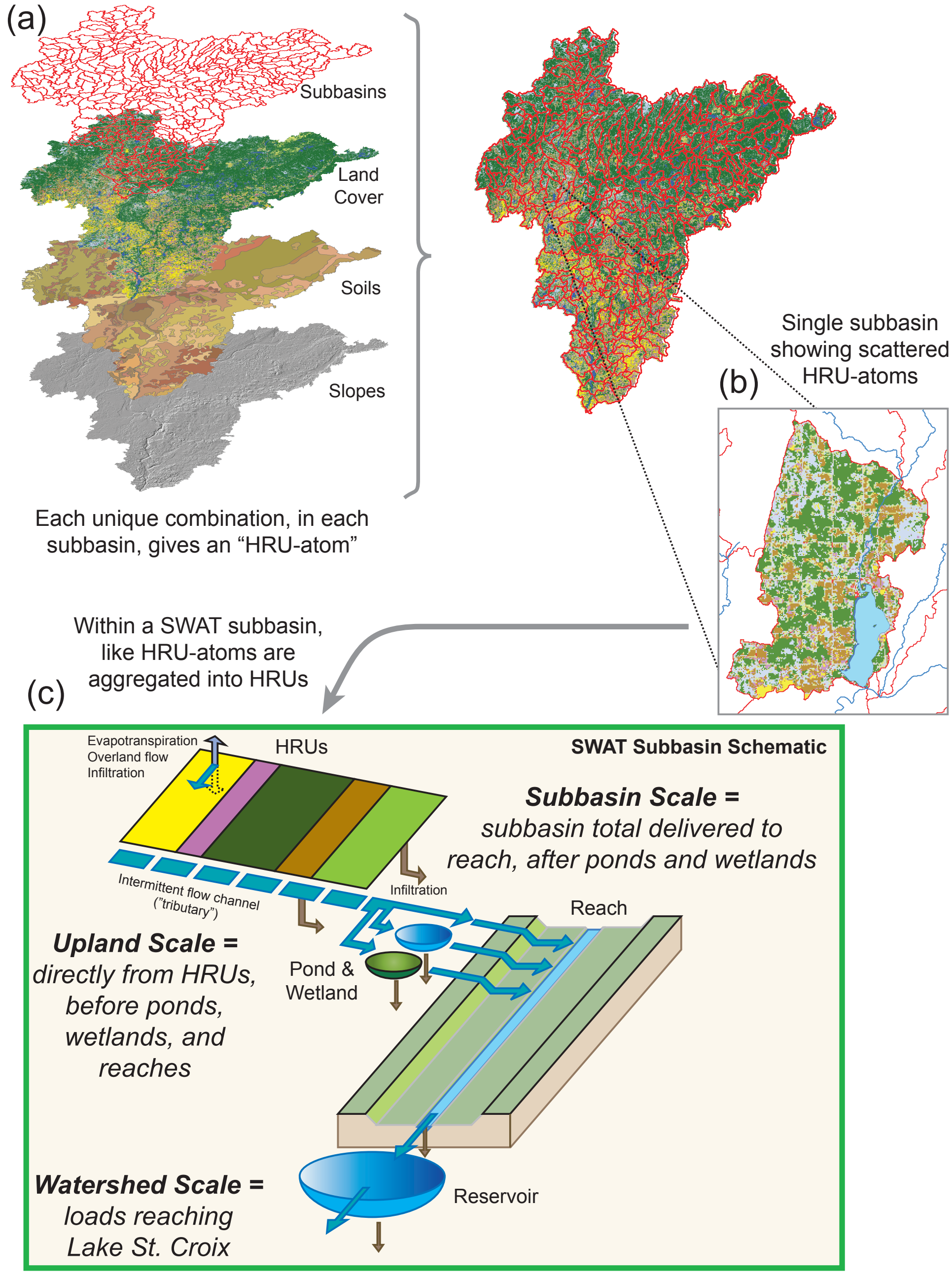


Figure 3. The hydrologic response unit (HRU) concept and spatial scaling in SWAT: (a) spatial layers intersected to identify HRU-atoms; (b) example subbasin showing mosaic of scattered HRU-atoms; (c) schematic of HRU aggregation, subbasin components, and conceptualized flow path in SWAT. The spatial scale of SWAT output depends on where along the flow path output is extracted.

2014). Climate data were obtained on-line from NCDC (2010) for 25 weather stations and daily data spatially smoothed over the basin by kriging analysis (Zhang and Srinivasan 2009).

The model was calibrated (2000-07) and validated (1990-99) principally with respect to monthly stream flows, sediment loads, and phosphorus loads. Flows of the St. Croix at Danbury, St. Croix Falls, Stillwater, and Prescott, and flows of the principal tributaries (Kettle, Snake, Sunrise, and Apple) were all calibrated with Nash-Sutcliffe efficiencies (NSE) exceeding 0.7, which is considered a good model fit (Nash and Sutcliffe 1970, Moriasi et al. 2007). Monthly sediment and phosphorus loads were available only at the Stillwater station for the full 18-year period of simulation. Sediment loads there were calibrated to an NSE of 0.76 and phosphorus loads to an NSE of 0.83. Total nitrogen loads were simulated as well, with a reasonably good NSE of 0.69 at the Stillwater station, but this constituent was not rigorously calibrated.

Spatial Scale of SWAT Output: Upland versus Watershed

Output from the St. Croix SWAT model is presented at three spatial scales in this report, the upland scale, the subbasin scale, and the watershed scale. In general, an “upland” load refers approximately to what is commonly called an “edge of field” load close to its source, “subbasin” load refers to what enters the channelized network, and “watershed” load refers to what is entering Lake St. Croix at the bottom of the watershed. Understanding the difference between these three scales requires understanding the flow path of constituents across the landscape, from source to sink, and how SWAT conceptualizes this flow path.

Transport factors alter the loads of nonpoint pollutants along the flow path between source and receiving water. Thus, the load ascribed to a source depends on where along that flow path the load is measured or estimated. SWAT, however does not track actual flow paths on the landscape. Instead, it is a “lumped parameter” model at the subbasin scale. Within a subbasin, ArcSWAT (the input data processor for SWAT) creates a series of unique “hydrologic response units” (HRUs; Figure 3c), each of which is an aggregation of land units with the same soil, slope, and land use (HRU-atoms; Figure 3a,b), regardless of where in the subbasin these scattered land units may occur. Each HRU is treated as a large flow plane of uniform slope, which simplifies SWAT’s calculations of the rainfall-runoff processes (interception, infiltration, percolation, evapotranspiration, runoff, and so forth). The fundamental assumptions of the HRU concept (i.e., of any lumped parameter model) are these:

(1) that each HRU functions hydrologically similarly to the disaggregated, distributed units (HRU-atoms) of which it is composed

(2) that the functional errors inherent in the previous assumption can be compensated for by parameterization, and

(3) that if assumptions (1) and (2) are adequately met, then the HRUs can be considered independent of each other and computationally processed individually.

The consequence of the HRU concept is that, instead of tracking actual flow paths, SWAT tracks conceptual surficial flow paths that originate as overland flow in HRUs and form concentrated flow in an intermittent channel, which then leads to the main reach of a subbasin (Figure 3c). Groundwater flow is not tracked explicitly; instead the model keeps track of the amount of groundwater recharge and releases that water gradually to the stream reach at a rate determined by a recession parameter.

The independence of HRUs may be approximately true for many upland HRUs. I.e., there is no necessary reason to expect that one HRU-atom would pass water to another rather than to an intermittent channel carrying concentrated flow (which effectively by-passes all other HRU-atoms). However, independence is almost certainly not true for lowland HRUs, namely, wetlands and ponds (depressions with open water). Because of their low position in the landscape, wetlands are in fact likely to receive input from surrounding HRU-atoms as direct runoff, intermittent concentrated flow, and groundwater discharge. To compensate for this interaction between upland and lowland HRUs, SWAT has added features called "ponds" and "wetlands" at the subbasin level, where the user can route a selected fraction of water yield from the subbasin through a pond or wetland (Figure 3c, Ponds and Wetlands). These features alter both the flow of water by infiltration, evaporation, and storage, and the quality of water by settling of sediment and nutrients (Almendinger et al. 2014b). All lakes in SWAT directly connected to the modeled network of channels (reaches) are called "reservoirs." Lakes have a large impact on both the hydraulics of flood events and on water quality because flow from all upstream subbasins flow through them, and not just from the immediate subbasin.

Output from SWAT may be extracted at selected points along this conceptual flow path from HRU to receiving waters. To see the direct impact of implementing agricultural BMPs on cropland HRUs, output was extracted at the upland (HRU) scale, corresponding approximately to an edge-of-field scale (Figure 3c, HRU scale). Otherwise, modification of loads farther along the flow path by settling in ponds, wetlands, or reservoirs could mask the true impact of the BMP within the HRU (or field). However, precisely because ponds and wetlands can trap sediment and nutrients, they commonly have a significant influence on what is delivered to the reach and thus on which subbasins are the highest loaders. In this case managers would want model output at the subbasin scale in order to spatially target implementation efforts toward known hotspots (Figure 3c, subbasin scale). Finally, since the goal of the TMDL study was to reduce loads reaching Lake St. Croix (MPCA and WDNR 2012), output was also needed at the watershed scale (Figure 3c, watershed scale). It is crucial for the reader to understand the distinction between these scales and to not mix results because the magnitude of loads at these scales can be substantially different. Upland loads include all sediment and nutrients mobilized on the landscape and are generally larger than subbasin and watershed loads, which are what remains after parts of the upland load have been trapped by ponds, wetlands, reservoirs, and floodplains during transport.

BMP Scenario Runs

Implementation of agricultural BMPs in SWAT is flexible with significant latitude given to the modeler for parameterization. Because of this latitude, Arabi et al. (2008) and Waidler et al. (2009) give guidelines for the application of BMPs within SWAT to limit artifacts in model outputs resulting from different parameterizations. In general, these documents guided the application of BMPs in the St. Croix SWAT model. Six BMPs were selected for evaluation: no-till, vegetated filter strips, grassed waterways, soil-test phosphorus reduction, fall cover crops, and improved soil health. Specific details of how SWAT was parameterized to simulate these BMPs are given in Table 1 and will be further discussed with the results of each BMP implementation.

Table 1. Parameters altered to configure the St. Croix SWAT model for agricultural best-management practice (BMP) scenarios.

			Parameter		Values		
BMP	Table	Files	Abbreviation	Name	Baseline scenario or default value	BMP scenario	HRUs applied
No-Till (NT)							
	mgt2	mgt	TILLAGE_ID	Tillage practice in specified rotations	58 (chisel plow) 62 (disk plow) 63 (moldboard plow)	4 (zerotill)	CA and/or CS rotations
No-Till, modified (NT-mod)							
	hru	hru	OV_N	Manning's "n" value (roughness) for oveland flow	0.14	0.3	CA and/or CS rotations
	mgt1	mgt	BIOMIX	Biological mixing efficiency	0.2	0.5	CA and/or CS rotations
	mgt2	mgt	CNOP	Curve number for scheduled management operation	Calibrated CNOPs	0.95 * calibrated CNOP	CA and/or CS rotations
Vegetated Filter Strips (VFS)							
	ops	ops	MGT_OP	Management operation number (4 = VFS)	0	4	CA and/or CS rotations
	ops	ops	VFSI	Flag for simulating VFSs	0	1	CA and/or CS rotations
	ops	ops	VFSCON	Fraction of HRU draining to most concentrated 10% of VFS area	0.5	0.75	CA and/or CS rotations
	ops	ops	VFSRATIO	Ratio of field area to VFS area	40	50	CA and/or CS rotations
	ops	ops	VFSCH	Percent of flow in most concentrated 10% of VFS that is fully channelized	90	90	CA and/or CS rotations
Grassed Waterways (GWAT)							
	ops	ops	MGT_OP	Management operation number (7 = GWAT)	0	7	CA and/or CS rotations
	ops	ops	GWATI	Flag for simulating GWATs	0	1	CA and/or CS rotations
	ops	ops	GWATL	Length of GWAT (m); 0 => default.	0	0 (sq. root HRU area)	CA and/or CS rotations
	ops	ops	GWATW	Width of GWAT (m)	0	10	CA and/or CS rotations
Soil-Test Phosphorus (STP) reduction							
	chm	chm	SOL_LABP1	Initial soil labile phosphorus, layer 1	0.15 * STP, where STP = 20, 40, or 60	0.15 * STP, where STP = 60 cut to 40, or STP CA = 30, or STP CS = 20	CA and/or CS rotations, and barnyard rotations
Fall Cover Crops (FCC)							
	mgt2	mgt	harvesting, killing, planting, and tillage operations	CA and CS rotations were re-configured, where corn and soybeans were harvested & killed on 7 September, and winter wheat was planted on 8 September of each year. Each new rotation multiplied into specific versions for each hydrologic soil group.	Baseline CA and CS rotations	CA and CS rotations with fall cover crops (winter wheat)	CA and/or CS rotations
Improved Soil Health (ISH)							
	sol	sol	SOL_AWCi	Available water capacity of soil layer i, where i = 1, 2, and 3. ISH = FCC configuration, plus NT-mod, plus increased AWC Further scenario = ISH configuration, plus STP reduction	from soil database	1.5 * SOL_AWCi	CA and/or CS rotations

NOTES: CA, corn-alfalfa rotation; CS, corn-soybean rotation.

All scenario results were based on a 23-year model run from 1985 through 2007, with the first five years of output ignored as a model equilibration ("warm-up") period, yielding 18 years of usable model output. Average values from this 18-year time series then were assumed to represent "average annual" values for both loads (mass/time) and yields (mass/area/time). All BMP scenarios were compared to a "baseline" scenario. This scenario was identical to the calibrated model for the 2000-07 time period (the 2000s), with the exception that the time series of point-source inputs was replaced with constant values of point-source inputs that correspond to the current (2006-09) average inputs. This was done not only to eliminate point sources as an experimental variable, but also to make the baseline model correspond as closely as possible to the current state of the basin going forward from the present time.

Results and Discussion

In this section, SWAT output is presented at the three scales discussed above, namely the upland, subbasin, and watershed scales. However, the subbasin scale was used only for mapping spatial differences in sediment and nutrient yields across the basin. Most of the report is concerned with output of BMP implementation runs at the upland and watershed scales. These outputs were evaluated against the baseline run to assess percent change in load due to BMP implementation.

Upland-scale loads are presented as stacked bar plots, showing magnitude of loads under each scenario for each major land-use type or rotation. In each stacked bar, the lowermost parts for undeveloped, developed, and pasture land uses remained constant throughout the model runs because the BMPs were applied only to cropland, namely the corn-alfalfa (CA) and corn-soybean (CS) rotations. Commonly each group of runs for a BMP included a full implementation of that BMP to assess the maximum possible benefit. In most cases, the benefit from fractional implementation may be linearly scaled from the maximum end-member benefit, although local conditions may complicate the relation.

Watershed-scale loads are presented in tables, where loads are given for selected points or features in the watershed. From the perspective of the TMDL study, the critical load is what reaches Lake St. Croix from all of its surrounding sources. A few other selected points were included as well, namely the St. Croix River at Stillwater and near the outlets of the Apple, Willow, and Kinnickinnic rivers. These three tributaries on the Wisconsin side of the lower basin appear to be the most likely to be impacted by development pressure resulting from the construction of the new bridge at Stillwater.

Upland-Scale Sediment and Nutrient Sources

The upland sources of sediment and nutrients for the calibrated St. Croix SWAT model were reported earlier (Almendinger et al. 2014) but deserve being updated here as a point of reference for BMP scenario results. Agricultural lands occupied 17% of the basin but accounted for 96% of the sediment and 78% of the phosphorus mobilized in the uplands in the baseline model (Table 2). These results are somewhat biased because no other land-moving activities were included in the model, such as suburban development, highway construction, or erosive recreational activities. Also excluded were point sources and river bank erosion, since the SWAT

Table 2. Areas of selected landscape units and their average annual loads and yields of sediment, total phosphorus, and total nitrogen over 18 years of model runs (1990-2007) for the St. Croix SWAT model in baseline configuration. Quantities refer to amounts mobilized in the uplands, which are generally larger than what is delivered to receiving waters.

Land Cover	Area		Sediment			Total Phosphorus			Total Nitrogen		
			Load	Percent	Yield	Load	Percent	Yield	Load	Percent	Yield
	(km^2)	(%)	(metT)	(%)	(metT/ha)	(metT)	(%)	(kg/ha)	(metT)	(%)	(kg/ha)
Urban	**536**	**3%**	**1,199**	**1%**	**0.02**	**25**	**5%**	**0.46**	**314**	**6%**	**5.9**
Agriculture	**3,352**	**17%**	**201,394**	**96%**	**0.60**	**374**	**78%**	**1.12**	**2,874**	**51%**	**8.6**
Cropland	**2,258**	**11%**	**181,792**	**87%**	**0.81**	**321**	**67%**	**1.42**	**2,125**	**38%**	**9.4**
by crop:											
Corn-grain	*767*	*4%*	*73,658*	*35%*	*0.96*	*131*	*27%*	*1.70*	*897*	*16%*	*11.7*
Corn-silage	*181*	*1%*	*22,929*	*11%*	*1.27*	*37*	*8%*	*2.03*	*231*	*4%*	*12.8*
Soybeans	*586*	*3%*	*62,457*	*30%*	*1.07*	*117*	*24%*	*1.99*	*802*	*14%*	*13.7*
Alfalfa	*724*	*4%*	*22,748*	*11%*	*0.31*	*36*	*8%*	*0.50*	*195*	*3%*	*2.7*
by rotation:											
Corn-Soybeans (CS)	*1,172*	*6%*	*125,576*	*60%*	*1.07*	*231*	*48%*	*1.97*	*1,590*	*28%*	*13.6*
Corn-Alfalfa (CA)	*1,086*	*5%*	*56,216*	*27%*	*0.52*	*89*	*19%*	*0.82*	*535*	*10%*	*4.9*
CA, no manure	*745*	*4%*	*40,177*	*19%*	*0.54*	*50*	*11%*	*0.68*	*287*	*5%*	*3.8*
CA, daily-haul manure	*123*	*1%*	*8,390*	*4%*	*0.68*	*25*	*5%*	*2.03*	*145*	*3%*	*11.8*
CA, seasonal manure	*218*	*1%*	*7,649*	*4%*	*0.35*	*14*	*3%*	*0.64*	*104*	*2%*	*4.8*
Pastureland	**1,095**	**5%**	**19,602**	**9%**	**0.18**	**53**	**11%**	**0.49**	**748**	**13%**	**6.8**
Pasture	*1,042*	*5%*	*18,404*	*9%*	*0.18*	*33*	*7%*	*0.31*	*652*	*12%*	*6.3*
Beef	*414*	*2%*	*9,679*	*5%*	*0.23*	*18*	*4%*	*0.44*	*382*	*7%*	*9.2*
Dairy	*434*	*2%*	*6,179*	*3%*	*0.14*	*10*	*2%*	*0.22*	*191*	*3%*	*4.4*
Horse	*193*	*1%*	*2,547*	*1%*	*0.13*	*5*	*1%*	*0.24*	*79*	*1%*	*4.1*
Barnyard	*53*	*0.3%*	*1,198*	*1%*	*0.23*	*21*	*4%*	*3.93*	*96*	*2%*	*18.2*
Beef	*21*	*0.1%*	*709*	*0.3%*	*0.34*	*15*	*3%*	*7.15*	*62*	*1%*	*29.6*
Dairy	*22*	*0.1%*	*322*	*0.2%*	*0.15*	*4*	*1%*	*1.78*	*24*	*0.4%*	*10.9*
Horse	*11*	*0.05%*	*166*	*0.1%*	*0.16*	*2*	*0.4%*	*1.95*	*11*	*0.2%*	*10.8*
Grassland	**1,767**	**9%**	**1,174**	**1%**	**0.007**	**24**	**5%**	**0.14**	**445**	**8%**	**2.5**
Forest	**11,596**	**58%**	**4,214**	**2%**	**0.004**	**36**	**8%**	**0.03**	**1,577**	**28%**	**1.4**
Aquatic	**2,755**	**14%**	**950**	**0%**	**0.003**	**20**	**4%**	**0.07**	**381**	**7%**	**1.4**
Totals	***20,006***	***100%***	***208,931***	***100%***		***479***	***100%***		***5,590***	***100%***	

NOTE: Standard errors of the mean ranged from about 4-42% of load or yield value, and averaged about 11%.

results were extracted at the upland scale (Figure 3c) in order to clarify nonpoint sources independently from point sources and transport factors. Nonetheless, agriculture is clearly the principal source of nonpoint sediment and phosphorus mobilized in the basin. The values given in Table 1 correspond to the *baseline* configuration of the St. Croix SWAT model, and are thus slightly different then the values given in Almendinger et al. (2014; Table 27), which correspond to the *calibrated* model configuration. All BMP scenario runs were compared to the values given in Table 2 to assess their percent change in upland loads.

Subbasin-Scale Sediment and Nutrient Yields

Yields of nonpoint source pollutants (annual loads per unit area, or kg/ha/yr) were extracted at subbasin scale to show spatially the net results of the source and transport factors acting within subbasins across the St. Croix basin. Figures 4-6 show the average annual subbasin yields of sediment, total phosphorus, and total nitrogen, respectively, over the 2000-07 period. These maps represent the delivery of sediment and nutrients from the landscape to the stream network after ponds and wetlands have processed the upland loads coming from the HRUs. The maps do not, however, account for the trapping of sediment and nutrients by lakes connected to the stream network. These maps can help guide implementation efforts by locating “hot spots” of sediment and nutrient sources and delivery. Because both source and delivery are considered, such maps should be superior to those based on source (land use) alone, where export coefficients are used to translate land use into area-weighted yields and annual loads. When compared to the land-use map (Figure 2), these maps show that the largest yields of sediment and nutrients correspond to those parts of the basin with the most agriculture and urbanization, and with the least wetland area.

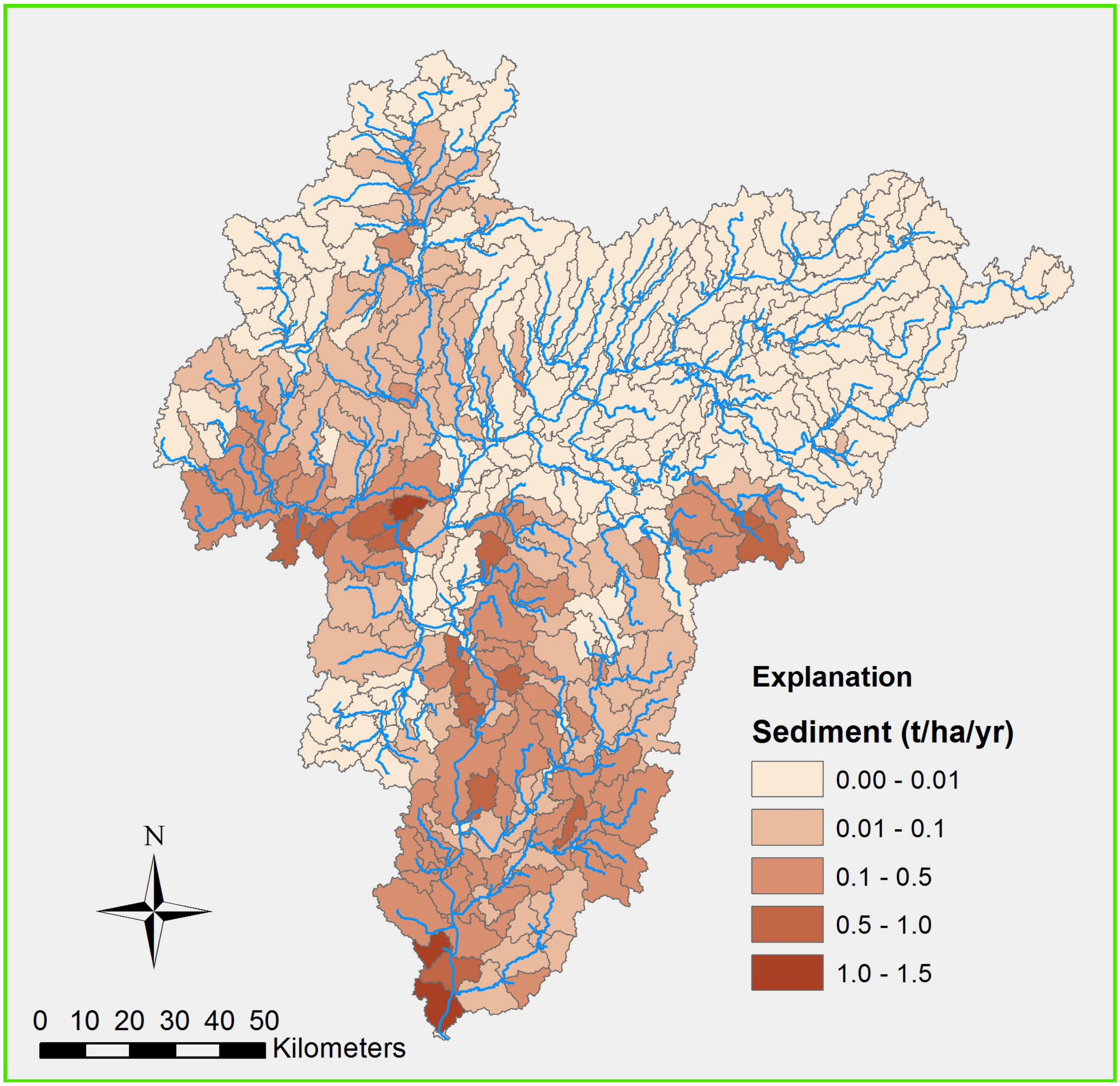


Figure 4. Average annual sediment yield at the subbasin scale in the St. Croix SWAT model, 2000-07.

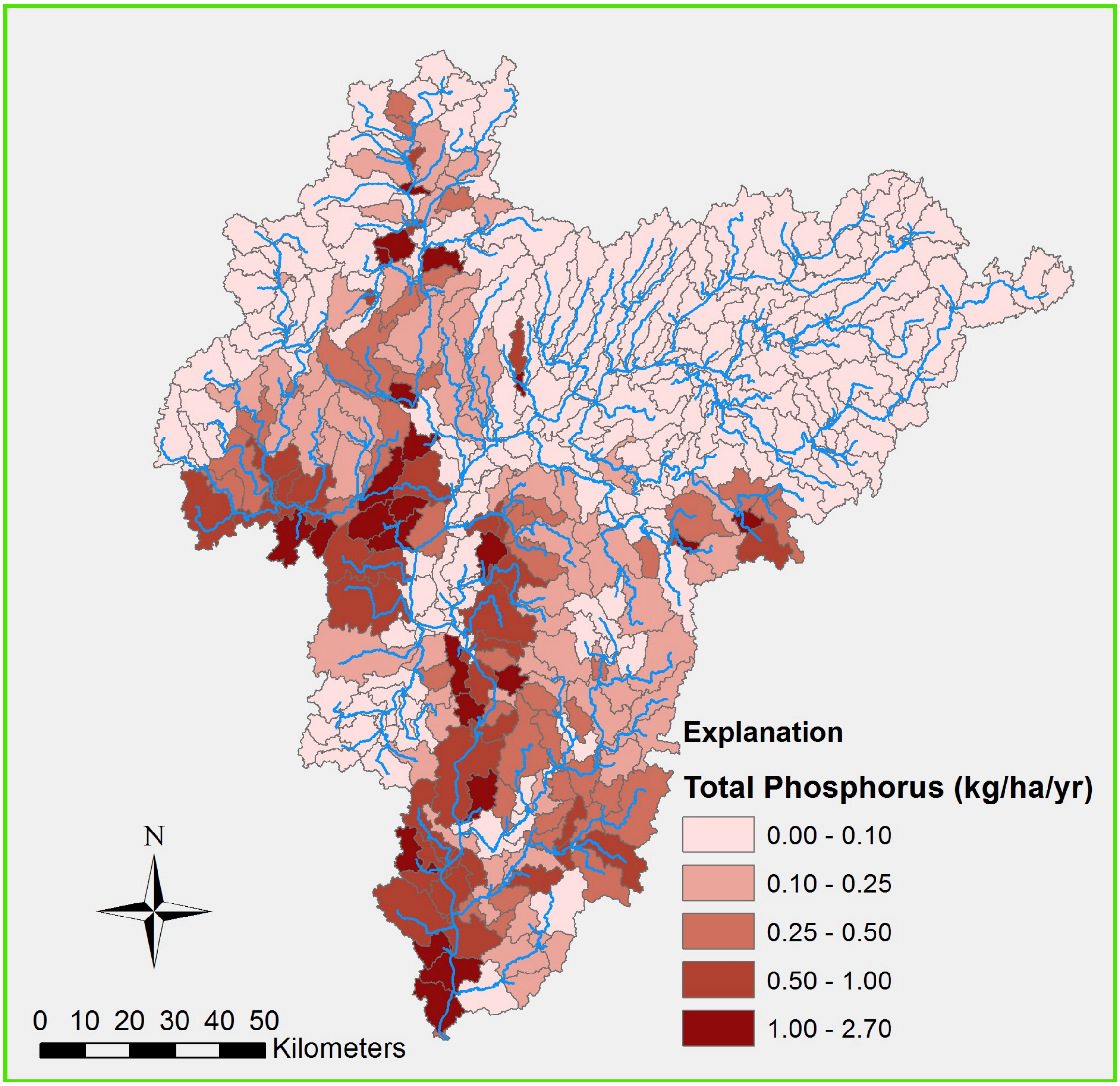


Figure 5. Average annual total phosphorus yield at the subbasin scale in the St. Croix SWAT model, 2000-07.

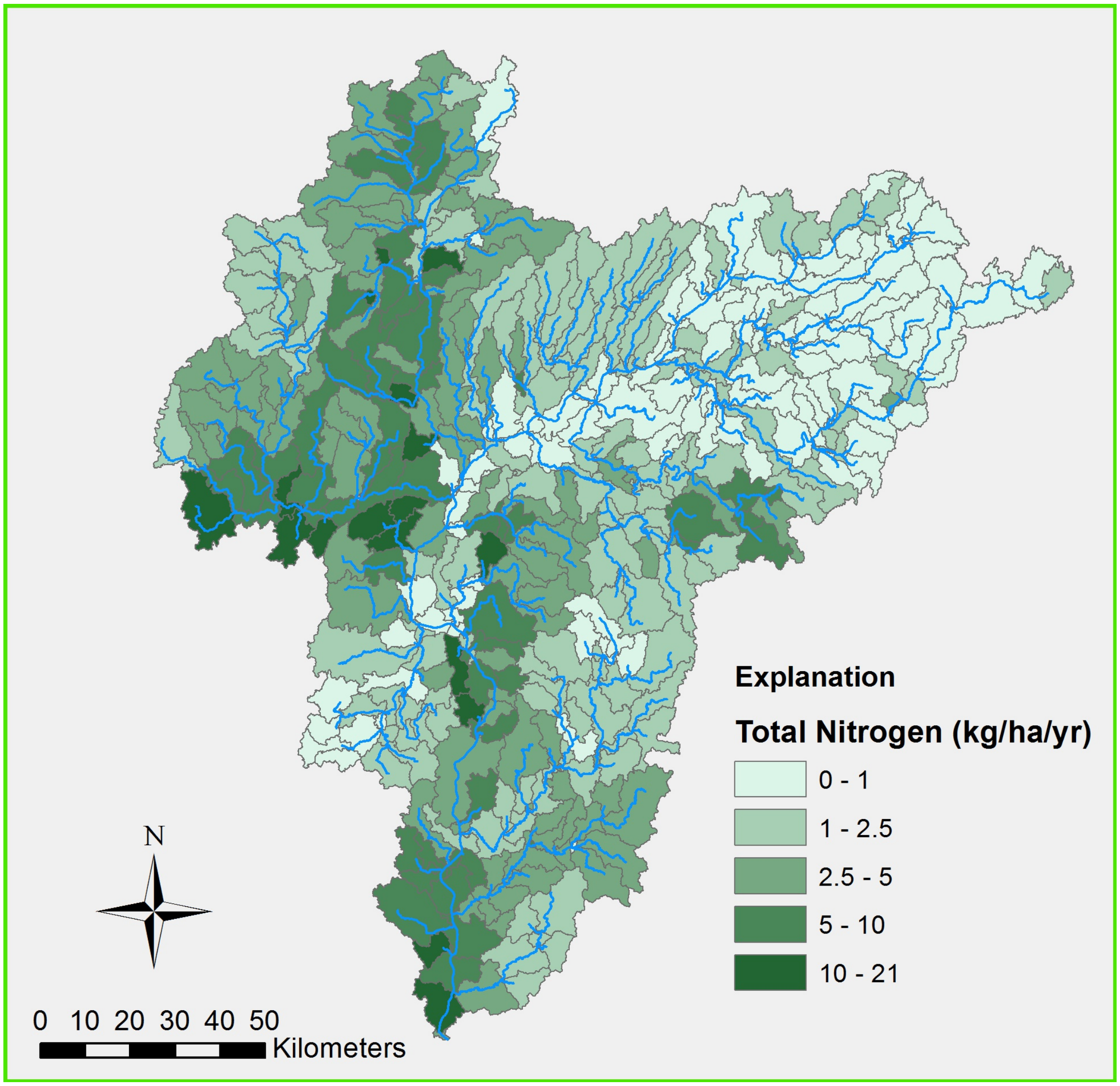


Figure 6. Average annual total nitrogen yield at the subbasin scale in the St. Croix SWAT model, 2000-07.

No-Till (NT) Scenarios

In SWAT, the principal effect of tillage practices is to mix crop residue and nutrients deeper into the soil column, exposing more bare soil to erosion. To implement a simple no-till (NT) scenario in the St. Croix SWAT model, all plowing and disking operations were replaced with a no-till operation, which is an operational placeholder with minimal downward mixing. NT was implemented first on half of the cropland, split evenly between corn-alfalfa (CA) and corn-soybean (CS) rotations, and then on all of the cropland.

The consequence of this simple no-till scenario was to leave more residue on the surface, thereby reducing erosion, but also to allow phosphorus to become enriched in the upper soil and thus more available for transport by overland runoff. Indeed, upland phosphorus loads increased 9-16% from the half and full implementation of NT (Figure 7, bars 1 and 2), while upland sediment declined 4-8% (Figure 8, bars 1 and 2). This increase in soil-surface phosphorus, called phosphorus stratification (Robbins and Voss 1991, Sharpley 2003), has been implicated as a cause of the recent eutrophication of Lake Erie and its toxic algal blooms.

However, NT should change other soil characteristics beyond just the downward mixing of nutrients. When the NT parameters were adjusted to increase infiltration, surface roughness, and biomixing (downward mixing of surface nutrients by soil organisms), phosphorus loads were reduced by 4-10% (Figure 7, bars 3 and 4) and sediment declined even further, by 16-31% (Figure 8, bars 3 and 4). The response in both cases was reasonably linear, meaning that applying the scenario to all (100%) of the cropland approximately doubled the change in loads compared to applying the scenario to half (50%) of the cropland. The conclusion is that NT agriculture could increase or decrease phosphorus loads depending on how other soil characteristics (infiltration, roughness, and biomixing) change in concert with the removal of tillage practices. SWAT will need to be informed of these soil changes to better improve its predictive ability concerning phosphorus transport. The literature is likewise equivocal in the effect of NT on nutrient loss, with examples of both phosphorus load increases (Gaynor and Findlay 1994) and decreases (Andraski et al. 1985).

Because of transport factors between fields and the channelized network, the changes in total phosphorus (TP) and sediment loads to Lake St. Croix were muted compared to the upland loads. Implementation of simple NT could increase TP loads to Lake St. Croix by 4-7%, whereas modified NT practices could reduce TP loads by 2-4% (Table 3). Sediment loads to Lake St. Croix decreased in all cases, only 1-3% for simple NT practices but up to 15% for modified NT (Table 4).

Figure 7. Upland phosphorus loads for no-till (NT) scenarios: simple no-till on 50% (NT_half) and 100% (NT_all) of the cropland in the basin, and modified no-till on 50% (NTmod_half) and 100% (NTmod_all) of the cropland. Modified no-till included increased infiltration, surface roughness, and soil biomixing.

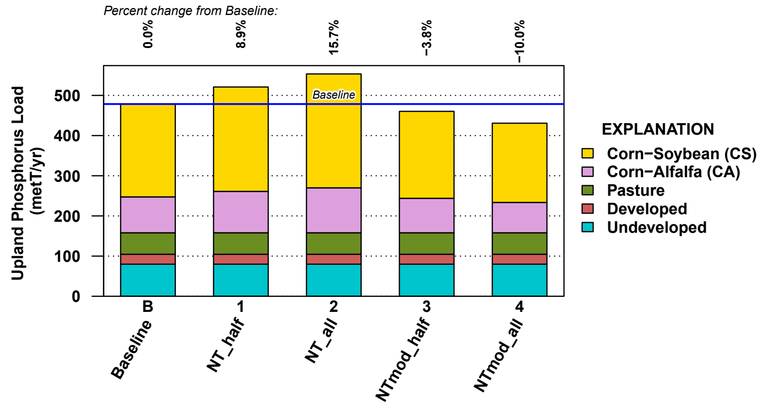


Table 3. Total phosphorus loads delivered to selected sites in the St. Croix basin under no-till agriculture scenarios. Modified no-till included increased infiltration, surface roughness, and soil biomixing.

	Baseline	**No-Till (simple)**				**No-Till (modified)**			
		50% of cropland		*100% of cropland*		*50% of cropland*		*100% of cropland*	
Site	**TP (metT)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**
St. Croix River at Stillwater	253.4	264.9	4.5%	275.4	8.7%	251.8	-0.6%	249.0	-1.7%
Apple River near Somerset	20.1	21.3	5.9%	23.3	15.6%	19.4	-3.7%	19.1	-5.1%
Willow River below Little Falls Lake	2.9	3.1	8.8%	3.3	14.9%	2.7	-4.7%	2.6	-10.3%
Kinnickinnic River at mouth	6.1	6.6	7.6%	6.9	12.6%	5.7	-8.0%	5.3	-14.1%
Lake St. Croix									
Input load	326.0	338.3	3.8%	349.6	7.2%	320.9	-1.6%	312.6	-4.1%
Trapped	116.3	120.4	3.5%	124.2	6.8%	115.2	-1.0%	113.1	-2.7%
Output load	209.7	218.0	3.9%	225.4	7.4%	205.7	-1.9%	199.5	-4.9%

Figure 8. Upland sediment loads for no-till (NT) scenarios: simple no-till on 50% (NT_half) and 100% (NT_all) of the cropland in the basin, and modified no-till on 50% (NTmod_half) and 100% (NTmod_all) of the cropland. Modified no-till included increased infiltration, surface roughness, and soil biomixing.

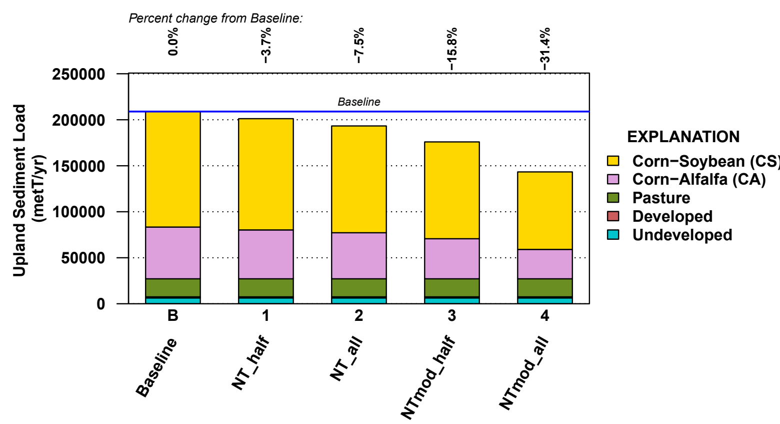


Table 4. Sediment loads delivered to selected sites in the St. Croix basin under no-till agriculture scenarios. Modified no-till included increased infiltration, surface roughness, and soil biomixing.

	Baseline	**No-Till (simple)**				**No-Till (modified)**			
		50% of cropland		*100% of cropland*		*50% of cropland*		*100% of cropland*	
Site	**Sed (metT)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**
St. Croix River at Stillwater	39,668	39,292	-0.9%	38,863	-2.0%	37,464	-5.6%	35,149	-11.4%
Apple River near Somerset	6,812	6,580	-3.4%	6,338	-7.0%	5,840	-14.3%	4,996	-26.7%
Willow River below Little Falls Lake	8,352	8,351	0.0%	8,353	0.0%	8,128	-2.7%	7,904	-5.4%
Kinnickinnic River at mouth	1,369	1,359	-0.7%	1,343	-1.8%	1,215	-11.2%	1,042	-23.9%
Lake St. Croix									
Input load	64,072	63,276	-1.2%	62,209	-2.9%	59,817	-6.6%	54,201	-15.4%
Trapped	58,019	57,313	-1.2%	56,338	-2.9%	54,174	-6.6%	48,955	-15.6%
Output load	6,054	5,963	-1.5%	5,871	-3.0%	5,644	-6.8%	5,246	-13.3%

Vegetated Filter Strip (VFS) and Grassed Waterway (GWAT) Scenarios

SWAT has explicit tools to simulate vegetated filter strips (VFSs) and grassed waterways (GWATs) and their mechanism is similar. Sediment is settled out of overland flow because of a loss of velocity as water moves through standing vegetation, especially dense grasses. Particle-bound phosphorus is thus trapped along with the sediment. A VFS in SWAT is placed along the downgradient edge of an HRU and treats approximate one slope-length of the HRU above the VFS. The rest of the runoff effectively by-passes or cuts through the VFS as concentrated flow, which is known to reduce the effectiveness VFSs (Dillaha et al. 1989). Earlier versions of SWAT without the option to allow by-pass of concentrated flow resulted in overestimates of sediment and nutrient removal by VFSs. A GWAT in SWAT is conceptually a vegetated overland flow channel in an HRU, as if the HRU were an open book. Overland runoff from the HRU enters the GWAT transversely from both sides, where sediment and particulate phosphorus are settled out as in a VFS. In addition, sediment and phosphorus are further settled out as flow continues longitudinally down the GWAT axis, at least partially because the slope of the GWAT is generally less than that of the contributing HRU. GWATs are expected to give greater reductions in sediment and phosphorus loads than do VFSs because of being able to treat more area of the contributing HRU, all other factors being equal.

In the St. Croix SWAT model, we set the area of the VFS to 2% of the HRU area and assumed 75% of the HRU runoff breached the VFS as concentrated flow. Implementation of VFSs in half (50%) and all (100%) cropland could reduce upland phosphorus loads by 3-8% (Figure 9, bars 1 and 2), and sediment loads by 9-17% (Figure 10, bars 1 and 2). The watershed response was essentially linear, meaning that implementing VFSs on half the cropland produced about half the reductions in loads. Transport factors muted these reductions to Lake St. Croix, where TP loads were reduced by only 1-3% (Table 5) and sediment loads by 3-7% (Table 6).

The area of each GWAT was set to to 2.5% of its HRU area, with a length equivalent to one side of a square HRU (i.e., GWAT length was set to the square root of the HRU area). GWATs in half to all cropland reduced upland TP loads by 7-15% (Figure 9, bars 3 and 4) and sediment loads by 15-30% (Figure 10, bars 3 and 4). Again, the watershed response was essentially linear, where implementing GWATs on half the cropland produced about half the reduction in loads. At the watershed scale, TP loads to Lake St. Croix were reduced by 3-6% (Table 5) and sediment loads by 5-14% (Tables 6). As surmised from the mechanisms of action within SWAT, the effect of GWATs was about double that of VFSs, although different parameterizations may give different results.

Figure 9. Upland phosphorus loads for vegetated filter strip (VFS) and grassed waterway scenarios: vegetated filter strips on 50% (VFS_half) and 100% (VFS_all) of the cropland in the basin, and grassed waterways on 50% (GWAT_half) and 100% (GWAT_all) of the cropland.

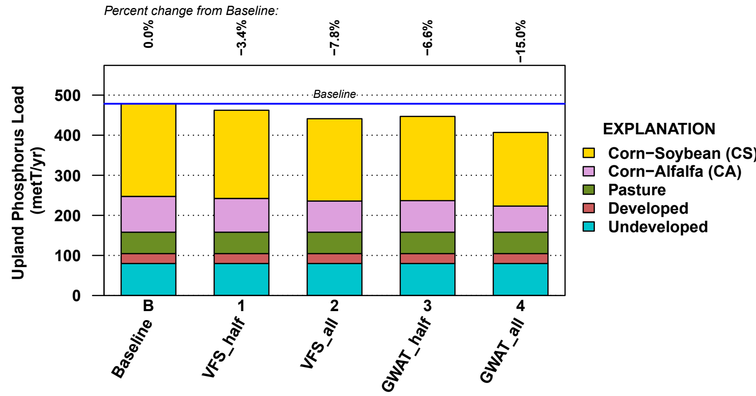


Table 5. Total phosphorus loads delivered to selected sites in the St. Croix basin under vegetated filter strip (VFS) and grassed waterway (GWAT) scenarios.

Site	Baseline	Vegetated Filter Strips (VFSs)				Grassed Waterways (GWATs)			
		50% of cropland		*100% of cropland*		*50% of cropland*		*100% of cropland*	
	TP (metT)	TP (metT)	(% diff)	TP (metT)	(% diff)	TP (metT)	(% diff)	TP (metT)	(% diff)
St. Croix River at Stillwater	253.4	249.9	-1.4%	245.6	-3.1%	246.8	-2.6%	238.5	-5.9%
Apple River near Somerset	20.1	19.7	-2.4%	19.1	-5.0%	19.2	-4.8%	18.1	-10.0%
Willow River below Little Falls Lake	2.9	2.8	-2.2%	2.7	-4.4%	2.8	-4.0%	2.6	-8.1%
Kinnickinnic River at mouth	6.1	6.1	-1.4%	6.0	-2.3%	5.9	-3.5%	5.8	-5.6%
Lake St. Croix									
Input load	326.0	321.5	-1.4%	315.1	-3.4%	317.2	-2.7%	304.8	-6.5%
Trapped	116.3	115.0	-1.1%	113.1	-2.7%	113.8	-2.1%	110.2	-5.2%
Output load	209.7	206.5	-1.5%	202.0	-3.7%	203.4	-3.0%	194.6	-7.2%

Figure 10. Upland sediment loads for vegetated filter strip (VFS) and grassed waterway scenarios: vegetated filter strips on 50% (VFS_half) and 100% (VFS_all) of the cropland in the basin, and grassed waterways on 50% (GWAT_half) and 100% (GWAT_all) of the cropland.

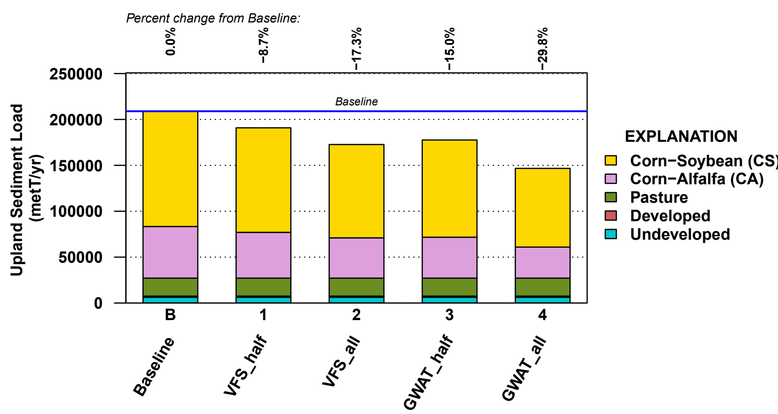


Table 6. Sediment loads delivered to selected sites in the St. Croix basin under vegetated filter strip (VFS) and grassed waterway (GWAT) scenarios.

Site	Baseline	Vegetated Filter Strips (VFSs)				Grassed Waterways (GWATs)			
		50% of cropland		*100% of cropland*		*50% of cropland*		*100% of cropland*	
	Sed (metT)	Sed (metT)	(% diff)	Sed (metT)	(% diff)	Sed (metT)	(% diff)	Sed (metT)	(% diff)
St. Croix River at Stillwater	39,668	38,668	-2.5%	37,558	-5.3%	37,779	-4.8%	34,690	-12.5%
Apple River near Somerset	6,812	6,306	-7.4%	5,876	-13.7%	6,135	-9.9%	5,560	-18.4%
Willow River below Little Falls Lake	8,352	8,284	-0.8%	8,211	-1.7%	8,215	-1.6%	8,069	-3.4%
Kinnickinnic River at mouth	1,369	1,352	-1.2%	1,325	-3.2%	1,348	-1.5%	1,312	-4.1%
Lake St. Croix									
Input load	64,072	62,261	-2.8%	59,624	-6.9%	60,928	-4.9%	55,297	-13.7%
Trapped	58,019	56,360	-2.9%	53,892	-7.1%	55,122	-5.0%	49,739	-14.3%
Output load	6,054	5,901	-2.5%	5,733	-5.3%	5,805	-4.1%	5,559	-8.2%

Soil-Test Phosphorus Reduction Scenarios

The literature has demonstrated that TP losses from fields are proportional to soil-test phosphorus (STP) levels, which are commonly above levels needed to maintain crop yields (Sharpley et al. 1994, Sharpley 1995, Vadas et al. 2005). Critical STP values, i.e., below which crop yield is reduced, are about 15 parts per million (ppm) for corn and soybeans and about 25 ppm for alfalfa (Vitosh et al. 1995). We here assume that optimal STP levels are 5 ppm above these critical levels, namely, about 20 ppm for corn and soybeans and 30 ppm for alfalfa. Available data from a few counties in the St. Croix basin indicated that average STP was around 40 ppm, but also highly variable. In the model, 25% of cropland was set to an STP = 20 ppm, 50% to 40 ppm, and 25% to 60 ppm, to provide some variability in STP values while maintaining an average of 40 ppm. In SWAT, these values represent the initial concentration of labile phosphorus in the soil at the beginning of the model run. During the 23 years of model run, SWAT keeps track of the nutrient balance in the soil based on additions of fertilizers and losses to crop removal, overland runoff, and leaching. By the end of the run, the STP values could be quite different than the initial values. For a typical corn-soybean rotation on different soils, Dodd and Mallarino (2005) found that eliminating phosphorus fertilizer reduced STP by 0.7-1.5 ppm/year, adding 13-17 kg P/ha/yr maintained STP near optimal levels, and adding 17-28 kg P/ha/yr increased STP by 1 ppm/yr. In the St. Croix SWAT model, the corn-soybean (CS) rotations received about 19 kg P/ha/yr and the corn-alfalfa (CA) rotations without manure received 15 kg P/ha/yr during the corn years. These application rates are at or just above maintenance levels, and we expect that STP levels in the soils of these rotations were fairly stable in the model. In contrast, the CA rotations with manure applications received 30-95 kg P/ha/yr, and STP levels probably increased over the 23 years of model runs.

Four scenarios of reducing initial model STP values were run (Figure 11, bars 1-4). The first was reducing all 60 ppm cropland down to 40 ppm, which reduced upland TP loads by only 3%. The second was to reduce all barnyards from 60 to 40 ppm, which had a negligible effect because of the small area of barnyards, but also because application rates are so high as to overwhelm any minor change in initial STP concentrations. Likewise, reduction of all CA rotations to 30 ppm had only a small reduction (2%), again because of additions overwhelming the effect of a change in initial concentration. Reduction in TP loads from these rotations will require a reduction in manure application and not just a change in initial concentrations. The only substantial impact came from changing the initial STP in all CS rotations down to 20 ppm, giving an 11% reduction in upland TP load. Here, because of the relatively stable STP values over time (because of approximately balanced inputs and outputs), a reduction of initial STP values influenced model yields over the full 23-year period of model runs.

As in the other BMP runs, the TP load reductions at Lake St. Croix were about half of those seen in the uplands. Loads were reduced by only 0.1-5% for the four scenarios discussed above (Table 7).

As one might expect, changing only STP levels alone had completely negligible impact on sediment loads (Figure 12 and Table 8).

Figure 11. Upland phosphorus loads for soil-test phosphorus (STP) reduction scenarios: reduction of high STP values in cropland to moderate (STP_Crop60to40), reduction of high STP values in barnyards to moderate (STP_BrnYd60to40), reduction of STP values in corn-alfalfa rotations to optimal (STP_CAto30), and reduction of STP values in corn-soybean rotations to optimal (STP_CSto20).

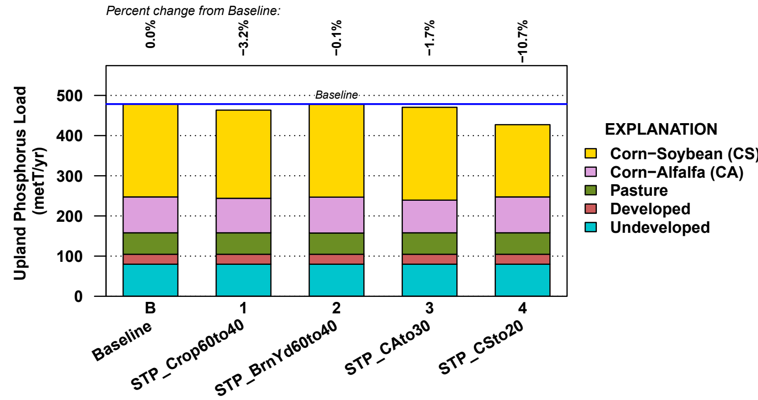


Table 7. Total phosphorus loads delivered to selected sites in the St. Croix basin under reduced soil-test phosphorus (STP) scenarios.

	Baseline	Reduction of Soil-Test Phosphorus (STP)							
		Cropland 60 to 40 ppm		*Barnyard 60 to 40 ppm*		*CA to 30 ppm*		*CS to 20 ppm*	
Site	**TP (metT)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**
St. Croix River at Stillwater	253.4	250.6	-1.1%	253.2	-0.1%	251.7	-0.7%	243.2	-4.0%
Apple River near Somerset	20.1	19.9	-1.1%	20.1	-0.1%	19.9	-1.4%	19.1	-5.2%
Willow River below Little Falls Lake	2.9	2.8	-2.7%	2.9	-0.1%	2.8	-1.4%	2.6	-8.2%
Kinnickinnic River at mouth	6.1	6.1	-0.4%	6.1	-0.3%	6.1	-1.4%	6.0	-2.7%
Lake St. Croix									
Input load	326.0	321.2	-1.5%	325.8	-0.1%	324.0	-0.6%	308.5	-5.4%
Trapped	116.3	114.9	-1.2%	116.2	-0.1%	115.6	-0.6%	111.3	-4.3%
Output load	209.7	206.3	-1.7%	209.6	-0.1%	208.4	-0.7%	197.2	-6.0%

Figure 12. Upland sediment loads for soil-test phosphorus (STP) reduction scenarios: for same scenarios as given in Figure 8. Changing STP had essentially no effect on sediment loads.

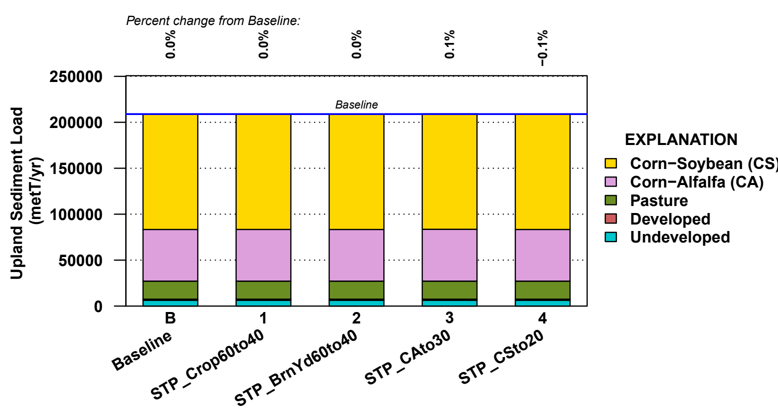


Table 8. Sediment loads delivered to selected sites in the St. Croix basin under reduced soil-test phosphorus (STP) scenarios.

	Baseline	Reduction of Soil-Test Phosphorus (STP)							
		Cropland 60 to 40 ppm		*Barnyard 60 to 40 ppm*		*CA to 30 ppm*		*CS to 20 ppm*	
Site	**Sed (metT)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**
St. Croix River at Stillwater	39,668	39,674	0.0%	39,668	0.0%	39,691	0.1%	39,648	-0.1%
Apple River near Somerset	6,812	6,815	0.0%	6,812	0.0%	6,823	0.2%	6,810	0.0%
Willow River below Little Falls Lake	8,352	8,351	0.0%	8,352	0.0%	8,345	-0.1%	8,352	0.0%
Kinnickinnic River at mouth	1,369	1,369	0.0%	1,369	0.0%	1,369	0.1%	1,368	0.0%
Lake St. Croix									
Input load	64,072	64,066	0.0%	64,072	0.0%	64,096	0.0%	63,991	-0.1%
Trapped	58,019	58,015	0.0%	58,019	0.0%	58,040	0.0%	57,947	-0.1%
Output load	6,054	6,052	0.0%	6,054	0.0%	6,056	0.0%	6,044	-0.2%

Fall Cover Crop (FCC) Scenarios

A critical aspect of implementing fall cover crops (FCCs) is to plant the cover crop early enough in the fall so that it can become established before winter arrives and the plants either go dormant or die. For the St. Croix basin, cover crops should be planted by early to mid-September (S. Olson, St. Croix County Land and Water Conservation Department, WI, personal communication, January 2016). For crops like corn silage that are harvested this early, planting a cover crop following harvest is straightforward. For corn-grain and soybeans that do not mature until October, the cover crop has to be over-seeded into the standing crop, either aerially or with a modified high-boy planter, with the hope that the cover crop can become established in between the crop rows.

SWAT does not have a specific module for simulating fall cover crops, but it does allow sequential harvesting and killing of one crop and planting of another crop immediately afterwards. Thus planting a cover crop following the harvest of corn silage in early to mid-September can be modeled directly. However, SWAT does not allow two crops to grow simultaneously in the same HRU, and so it cannot simulate overseeding of a cover crop into a standing crop, such as corn-grain or soybeans. For these cases, the only modeling option was to simply kill and harvest the standing crop early and plant the cover crop immediately afterwards. In this case, the modeled crop yields will be greatly compromised and not representative of reality, but the purpose of these model scenarios is to determine the effect of cover crops on soil erosion and nutrient yields, not crop yields.

Before running the FCC scenarios, a number of test runs were used to assess which cover crop to use. Winter wheat seemed be become established well enough before winter set in, attaining about 1 metT/ha biomass by early December. Rye and winter pasture were both tried as well, and both attained slightly lower biomass than winter wheat but had a similar effect in reducing erosion. For uniformity among modeling runs, we chose a single cover crop (winter wheat), which functioned as required and was representative of the other options. Furthermore, winter wheat seemed to be a more conservative choice than grassland, from a hydrological modeling point of view. Grassland has a much lower curve number, and thus greater infiltration, than does a small grain like winter wheat, which has a curve number intermediate between a row crop and grassland. In SWAT, a transition from row crop (corn or soybeans) to grassland (on 8 September in our model) would result in an abrupt and large change in curve number, which is unrealistic. The change from row crop to small grain (winter wheat) is less abrupt and (we hypothesize) more realistic, especially given how a cover crop may struggle to become established during the autumn, as temperatures fall and daylight declines.

Five FCC scenarios were run: two in CA rotations alone, two in CS rotations alone, and one in all CA and CS rotations together. In the CA rotations, the first scenario was for the FCC to follow corn-silage only, and the second scenario added the FCC following corn-grain as well. (It seemed unlikely for a FCC to be planted after corn-grain alone and not after corn-silage as well.) Upland TP load reductions were substantial, from 7-12% (Figure 13, bars 1 and 2, purple part), and upland sediment load reductions even larger, from 10-17% (Figure 14, bars 1 and 2, purple part). In the CS rotations, FCCs were planted first following soybeans, and then added to follow corn-grain as the second scenario. Upland load reductions were quite substantial for these

Figure 13. Upland phosphorus loads for fall cover crop (FCC) and improved soil health (ISH) in corn-alfalfa (CA) rotations scenarios: fall cover crop after corn-silage (FCC_CA_afterCsil), after both corn-silage and corn-grain (FCC_CA_afterCsil.Corn), and further modified with improved soil health (ISH_CA).

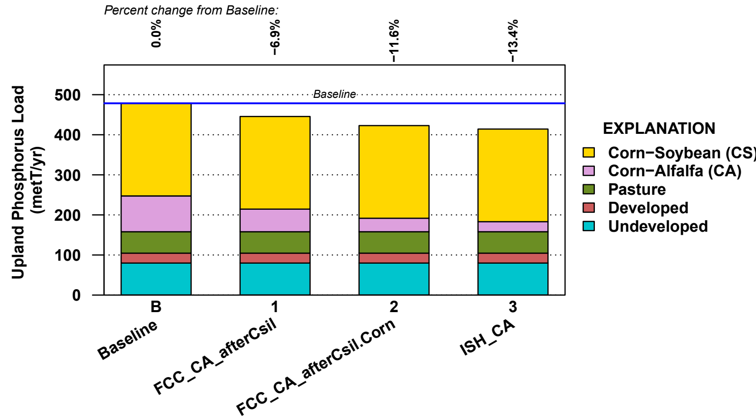


Table 9. Total phosphorus loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios implemented in the forage Corn-Alfalfa (CA) rotation.

	Baseline	**Fall Cover Crop (FCC) in CA rotations**				**Improved Soil Health (ISH) in CA rotations**	
		After corn-silage		*After both corn-silage & corn-grain*		*After both corn-silage & corn-grain*	
Site	**TP (metT)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**
St. Croix River at Stillwater	253.4	247.3	-2.4%	242.7	-4.2%	240.7	-5.0%
Apple River near Somerset	20.1	19.2	-4.8%	18.2	-9.8%	17.7	-12.1%
Willow River below Little Falls Lake	2.9	2.7	-7.3%	2.6	-10.0%	2.5	-13.5%
Kinnickinnic River at mouth	6.1	4.9	-19.8%	4.6	-25.5%	4.4	-28.6%
Lake St. Croix							
Input load	326.0	317.7	-2.6%	312.3	-4.2%	310.0	-4.9%
Trapped	116.3	114.2	-1.8%	112.6	-3.2%	112.0	-3.7%
Output load	209.7	203.5	-3.0%	199.7	-4.8%	198.0	-5.6%

Figure 14. Upland sediment loads for fall cover crop (FCC) and improved soil health (ISH) in corn-alfalfa (CA) rotations scenarios: fall cover crop after corn-silage (FCC_CA_afterCsil), after both corn-silage and corn-grain (FCC_CA_afterCsil.Corn), and further modified with improved soil health (ISH_CA).

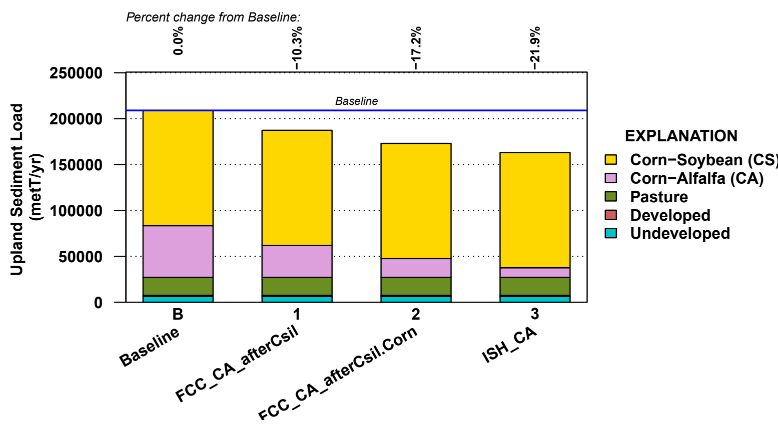


Table 10. Sediment loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios implemented in the forage Corn-Alfalfa (CA) rotation.

	Baseline	**Fall Cover Crop (FCC) in CA rotations**				**Improved Soil Health (ISH) in CA rotations**	
		After corn-silage		*After both corn-silage & corn-grain*		*After both corn-silage & corn-grain*	
Site	**Sed (metT)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**
St. Croix River at Stillwater	39,668	38,861	-2.0%	38,124	-3.9%	37,362	-5.8%
Apple River near Somerset	6,812	6,077	-10.8%	5,455	-19.9%	5,093	-25.2%
Willow River below Little Falls Lake	8,352	8,047	-3.6%	7,795	-6.7%	8,182	-2.0%
Kinnickinnic River at mouth	1,369	1,146	-16.3%	1,088	-20.5%	1,028	-24.9%
Lake St. Croix							
Input load	64,072	62,402	-2.6%	61,242	-4.4%	60,216	-6.0%
Trapped	58,019	56,453	-2.7%	55,328	-4.6%	54,360	-6.3%
Output load	6,054	5,949	-1.7%	5,914	-2.3%	5,857	-3.3%

scenarios: 22-37% for TP (Figure 15, bars 1 and 2, yellow part) and 28-46% for sediment (Figure 16, bars 1 and 2, yellow part). The load reductions were greater in the CS rotations than in the CA rotations because the CA rotation already had four out of six years in alfalfa, whereas the CS rotation had a FCC added for every year that stabilized large areas that were formerly protected from erosion by only crop residue. Not surprisingly, implementing the full FCC scenarios for both CA and CS rotations produced reductions that were the sums of individual reductions, 49% for upland TP loads (Figure 17, bar1) and 63% for upland sediment loads (Figure 18, bar 1).

Load reductions to Lake St. Croix were more modest than in the uplands (edge of field). Implementation of FCC in CA rotations could reduce input loads of both phosphorus and sediment by 3-4% (Tables 9 and 10). Load reductions from FCC in the CS rotation were more substantial: 11-18% for phosphorus and 18-32% for sediment (Tables 11 and 12). Full implementation of FCC in both CA and CS rotations resulted in load reductions that were approximately the sums of the individual reductions within rounding: 23% for phosphorus and 38% for sediment (Tables 13 and 14).

Improved Soil Health (ISH) Scenarios

Soil health management requires minimizing soil disturbance, diversifying crop rotations, maintaining living root systems throughout the year, and keeping a cover of residue on the soil surface (NRCS 2016). These management goals demonstrate that improving soil health is not an independent BMP, but rather a combination of BMPs. The main emphasis appears to be to increase soil infiltration capacity and soil organic matter (SOM), which will facilitate nutrient and water availability (Hamblin and Davies 1977, Carter 2002).

To implement improved soil health (ISH) in SWAT, we simply started with the full implementations of fall cover crops (FCC) for selected rotations (CA, CS, and both) and removed tillage practices as for the NT scenarios, modified with increased infiltration, roughness, and biomixing. In addition, available water capacity (AWC) of the soil was increased by 50% as a consequence of a presumed increase in soil organic matter (SOM). Hudson (1994) reported that increasing SOM from 0.5 to 3% could increase AWC by more than 100%, but it remains uncertain about what factors allow SOM to increase and persist (Schmidt et al. 2011). We therefore chose a 50% increase in AWC as a more achievable and conservative configuration for the St. Croix SWAT model runs. Increasing AWC has the effect of making more moisture available for plant transpiration, thereby increasing infiltration and reducing overland runoff, and thus generally reducing erosion and the attendant transport of nutrients.

In short, in the St. Croix SWAT model runs, the ISH scenario had all the benefits of the combined NT and FCC scenarios, plus the benefit of increased AWC. As a consequence, the ISH scenarios had the greatest reductions in upland phosphorus and sediment loads of all the BMP scenarios run. However, the reductions were only slightly greater than for the FCC scenarios (due to increased AWC), and so the ISH results were plotted alongside the FCC results for easy comparison (Figures 13-18). For example, the full FCC scenario for CA rotations reduced upland phosphorus loads by about 12% and adding the ISH component reduced loads by only another percent or so, to about 13% (Figure 13, bars 2 and 3). The full CS FCC scenario reduced upland phosphorus loads by 37%, and adding the ISH component reduced loads by another 4%, up to 41% (Figure 15, bars 2 and 3). ISH had a somewhat larger effect on sediment loads than on

Figure 15. Upland phosphorus loads for fall cover crop (FCC) and improved soil health (ISH) in corn-soybean (CS) rotations scenarios: fall cover crop after soybeans (FCC_CS_afterSoyb), after both soybeans and corn (FCC_CS_afterSoyb.Corn), and further modified with improved soil health (ISH_CS).

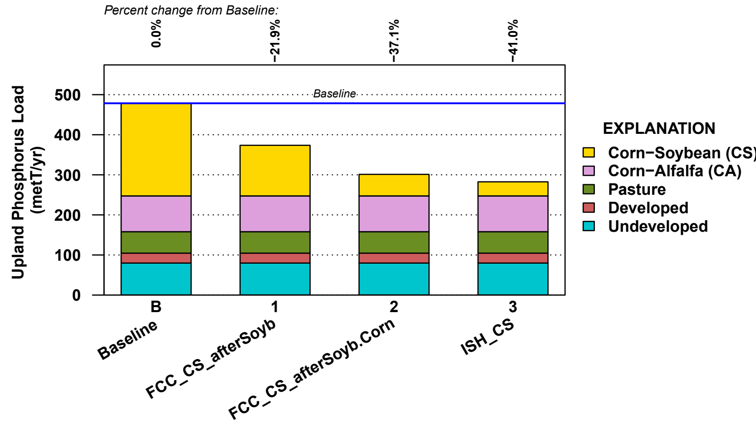


Table 11. Total phosphorus loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios implemented in the Corn-Soybean (CS) rotation.

Site	Baseline	Fall Cover Crop (FCC) in CS rotations				Improved Soil Health (ISH) in CS rotations	
		After soybeans		*After both soybeans & corn-grain*		*After both soybeans & corn-grain*	
	TP (metT)	TP (metT)	(% diff)	TP (metT)	(% diff)	TP (metT)	(% diff)
St. Croix River at Stillwater	253.4	231.6	-8.6%	218.6	-13.7%	215.6	-14.9%
Apple River near Somerset	20.1	17.6	-12.5%	15.9	-20.9%	15.6	-22.7%
Willow River below Little Falls Lake	2.9	2.4	-16.0%	2.1	-25.1%	2.1	-27.9%
Kinnickinnic River at mouth	6.1	5.8	-5.5%	5.5	-11.0%	5.4	-12.9%
Lake St. Croix							
Input load	326.0	289.7	-11.1%	265.8	-18.5%	259.4	-20.4%
Trapped	116.3	106.5	-8.4%	100.7	-13.4%	99.2	-14.7%
Output load	209.7	183.2	-12.7%	165.0	-21.3%	160.2	-23.6%

Figure 16. Upland sediment loads for fall cover crop (FCC) and improved soil health (ISH) in corn-soybean (CS) rotations scenarios: fall cover crop after soybeans (FCC_CS_afterSoyb), after both soybeans and corn (FCC_CS_afterSoyb.Corn), and further modified with improved soil health (ISH_CS).

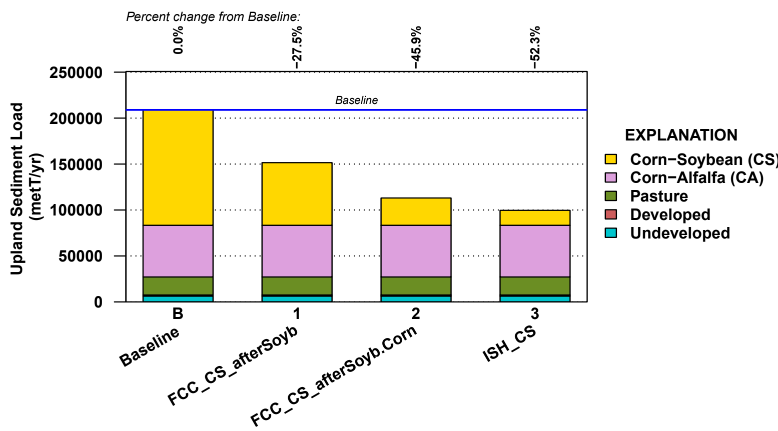


Table 12. Sediment loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios implemented in the cash-crop Corn-Soybean (CS) rotation.

Site	Baseline	Fall Cover Crop (FCC) in CS rotations				Improved Soil Health (ISH) in CS rotations	
		After soybeans		*After both soybeans & corn-grain*		*After both soybeans & corn-grain*	
	Sed (metT)	Sed (metT)	(% diff)	Sed (metT)	(% diff)	Sed (metT)	(% diff)
St. Croix River at Stillwater	39,668	35,122	-11.5%	31,451	-20.7%	29,806	-24.9%
Apple River near Somerset	6,812	5,455	-19.9%	4,453	-34.6%	4,141	-39.2%
Willow River below Little Falls Lake	8,352	7,880	-5.6%	7,217	-13.6%	7,428	-11.1%
Kinnickinnic River at mouth	1,369	1,239	-9.4%	1,105	-19.3%	1,074	-21.6%
Lake St. Croix							
Input load	64,072	52,586	-17.9%	43,496	-32.1%	39,454	-38.4%
Trapped	58,019	47,760	-17.7%	39,645	-31.7%	35,848	-38.2%
Output load	6,054	4,826	-20.3%	3,852	-36.4%	3,606	-40.4%

phosphorus loads, because of NT having a greater impact on sediment than on phosphorus. Sediment loads in ISH scenarios were reduced by an extra 5% in the CA rotations (Figure 14, bars 2 and 3) and an extra 6% in CS rotations (Figure 16, bars 2 and 3), relative to the FCC scenarios. The full combined implementation of ISH in the CA and CS rotations could reduce upland phosphorus loads by 54% (Figure 17, bar 2) and sediment loads by 74% (Figure 18, bar 2). A final stacked scenario was run wherein soil-test phosphorus (STP) levels were reduced by the maximum amounts (CA rotations to 30 ppm and CS rotations to 20 ppm). This scenario slightly improved upon the full ISH scenario, with upland phosphorus loads reduced by 56% and no change in the sediment load (Figures 17 and 18, bar 3).

As in all the other BMP scenarios, load reductions to Lake St. Croix were muted relative to the upland load reductions. Implementation of ISH in CA rotations could reduce input total phosphorus loads to Lake St. Croix by 5% (Table 9), implementation in CS rotations by 20% (Table 11), and a combined implementation by 25% (Table 13). Adding the STP reductions would decrease phosphorus loads by only an additional percent, to 26% (Table 13), the maximum achieved in all model runs. Input sediment loads to Lake St. Croix were reduced by 6%, 38%, and 50% for the ISH implementation in CA, CS, and combined rotations, respectively (Tables 10, 12, and 14).

Summary of Upland Phosphorus Loads and Input Loads to Lake St. Croix

To summarize the effect of BMPs on upland phosphorus loads in the St. Croix, we here include the tabulated values (Table 15) used to generate the previous figures (Figures 7, 9, 11, 13, 15, and 17). This table also includes the input loads to Lake St. Croix, the same as was given in Tables 3-14, for easy reference. Because of the importance of loading to Lake St. Croix in addressing the goals of the TMDL, both the phosphorus and sediment loads entering Lake St. Croix under each BMP scenario are shown in Figures 19 and 20. The changes in phosphorus and sediment loads in response to different BMP implementations follow a very similar pattern, with load reductions for sediment being generally larger than those for phosphorus.

Figure 17. Upland phosphorus loads for fall cover crop (FCC) and improved soil health (ISH) in corn-alfalfa (CA) and corn-soybean (CS) scenarios: full implementation of fall cover crops after corn-silage, corn-grain, and soybeans (FCC_CA.CS_afterCsil.Corn.Soyb), further modified with improved soil health (ISH_CA.CS), and further modified with soil-test phosphorus reductions to optimal levels in cropland (ISH_CA.CS_STP).

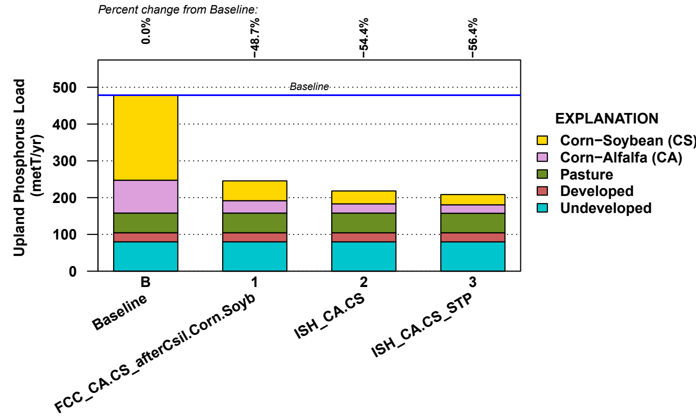


Table 13. Total phosphorus loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios fully implemented in Corn-Alfalfa (CA) and Corn-Soybean (CS) rotations. In addition, soil-test phosphorus levels (STP) were reduced to optimal levels.

	Baseline	Fall Cover Crop (FCC) in CA & CS rotations		Improved Soil Health (ISH) in CA & CS rotations		ISH plus STP reduction in CA & CS rotations	
		After soybeans, corn-silage, & corn-grain		*After soybeans, corn-silage, & corn-grain*		*After soybeans, corn-silage, & corn-grain*	
Site	**TP (metT)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**	**TP (metT)**	**(% diff)**
St. Croix River at Stillwater	253.4	208.0	-17.9%	202.9	-19.9%	200.9	-20.7%
Apple River near Somerset	20.1	14.0	-30.5%	13.2	-34.4%	13.0	-35.3%
Willow River below Little Falls Lake	2.9	1.8	-36.2%	1.7	-42.0%	1.6	-42.9%
Kinnickinnic River at mouth	6.1	3.9	-36.2%	3.6	-41.1%	3.6	-41.5%
Lake St. Croix							
Input load	326.0	252.2	-22.7%	243.5	-25.3%	240.5	-26.2%
Trapped	116.3	97.0	-16.6%	94.8	-18.5%	93.8	-19.4%
Output load	209.7	155.2	-26.0%	148.7	-29.1%	146.7	-30.1%

Figure 18. Upland sediment loads for fall cover crop (FCC) and improved soil health (ISH) in corn-alfalfa (CA) and corn-soybean (CS) rotations scenarios: full implementation of fall cover crops after corn-silage, corn-grain, and soybeans (FCC_CA.CS_afterCsil.Corn.Soyb), further modified with improved soil health rotations (ISH_CA.CS), and further modified with soil-test phosphorus reductions (ISH_CA.CS_STP).

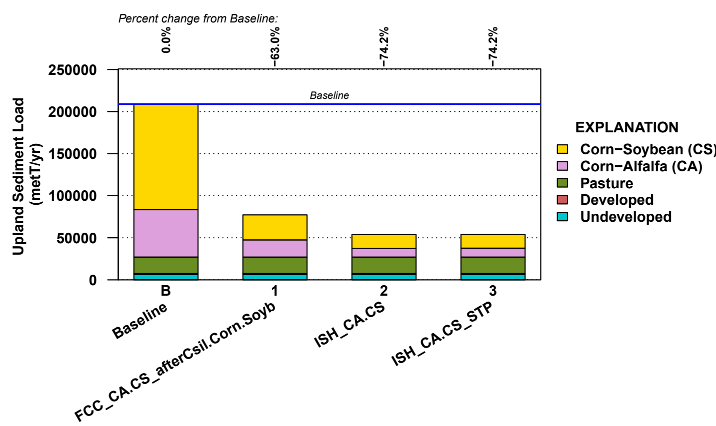


Table 14. Sediment loads delivered to selected sites in the St. Croix basin under fall cover crop (FCC) and improved soil health (ISH) scenarios fully implemented in Corn-Alfalfa (CA) and Corn-Soybean (CS) rotations. Reduction of soil-test phosphorus levels (STP) had negligible influence on sediment loads.

	Baseline	Fall Cover Crop (FCC) in CA & CS rotations		Improved Soil Health (ISH) in CA & CS rotations		ISH plus STP reduction in CA & CS rotations	
		After soybeans, corn-silage, & corn-grain		*After soybeans, corn-silage, & corn-grain*		*After soybeans, corn-silage, & corn-grain*	
Site	**Sed (metT)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**	**Sed (metT)**	**(% diff)**
St. Croix River at Stillwater	39,668	28,726	-27.6%	24,043	-39.4%	24,064	-39.3%
Apple River near Somerset	6,812	2,865	-57.9%	2,100	-69.2%	2,103	-69.1%
Willow River below Little Falls Lake	8,352	6,677	-20.1%	7,244	-13.3%	7,250	-13.2%
Kinnickinnic River at mouth	1,369	779	-43.1%	664	-51.5%	664	-51.5%
Lake St. Croix							
Input load	64,072	39,440	-38.4%	32,075	-49.9%	32,097	-49.9%
Trapped	58,019	35,720	-38.4%	28,634	-50.6%	28,655	-50.6%
Output load	6,054	3,720	-38.5%	3,441	-43.2%	3,442	-43.1%

Table 15. Summary of (a) upland total phosphorus loads for selected land-cover types and (b) total phosphorus loads into Lake St. Croix (annual averages) for each agricultural best-management practice (BMP) scenario relative to baseline conditions, and (c) areas of selected land-cover types for reference.

	(a) Total Phosphorus Upland Load							(b) Total Phosphorus Load into Lake St. Croix	
Land Cover	*Undeveloped* (t/yr)	*Developed* (t/yr)	*Pasture* (t/yr)	*Corn-Alfalfa* (t/yr)	*Corn-Soybean* (t/yr)	Total (t/yr)	Change from baseline (%)	Whole basin (t/yr)	Change from baseline (%)
Baseline	80	25	53	89	231	479	0%	326	0%
No Till									
half of cropland	80	25	53	103	260	521	9%	338	4%
all of cropland	80	25	53	112	283	553	16%	350	7%
half of cropland, modified	80	25	53	86	216	460	-4%	321	-2%
all of cropland, modified	80	25	53	76	197	431	-10%	313	-4%
Vegetated Filter Strip									
half of cropland	80	25	53	84	220	462	-3%	322	-1%
all of cropland	80	25	53	78	205	441	-8%	315	-3%
Grassed Waterways									
half of cropland	80	25	53	79	210	447	-7%	317	-3%
all of cropland	80	25	53	65	184	407	-15%	305	-7%
Soil-Test Phosphorus Reduction									
cropland 60 ppm to 40 ppm	80	25	53	86	219	463	-3%	321	-1%
barnyard 60 ppm to 40 ppm	80	25	53	89	231	478	0%	326	0%
corn-alfalfa land to 30 ppm	80	25	53	81	231	471	-2%	324	-1%
corn-soybean land to 20 ppm	80	25	53	89	180	427	-11%	309	-5%
Fall Cover Crops in Corn-Alfalfa Rotations									
after corn-silage	80	25	53	56	231	446	-7%	318	-3%
after corn-silage and corn-grain	80	25	53	34	231	423	-12%	312	-4%
ditto, plus improved soil health	80	25	53	25	231	414	-13%	310	-5%
Fall Cover Crops in Corn-Soybean Rotations									
after soybeans	80	25	53	89	126	374	-22%	290	-11%
after soybeans and corn-grain	80	25	53	89	54	301	-37%	266	-18%
ditto, plus improved soil health	80	25	53	89	35	282	-41%	259	-20%
Fall Cover Crops in Corn-Alfalfa & Corn-Soybean Rotations									
after all row crops (all corn & soybeans)	80	25	53	34	54	246	-49%	252	-23%
ditto, plus improved soil health	80	25	53	25	35	218	-54%	244	-25%
ditto, plus soil-test phosphorus reduction	80	25	53	23	28	208	-56%	240	-26%

	(c) Land-Cover Area					
Land Cover	*Undeveloped* (km^2)	*Developed* (km^2)	*Pasture* (km^2)	*Corn-Alfalfa* (km^2)	*Corn-Soybean* (km^2)	Total (km^2)
Area	16,117	536	1,095	1,086	1,172	20,006
Percent	81%	3%	5%	5%	6%	100%

Figure 19. Total phosphorus loads (metric tons per year) entering Lake St. Croix under selected agricultural best-management practices (BMPs), relative to baseline scenario. [NT, no-till; VFS, vegetated filter strip; GWAT, grassed waterway; STP soil-test phosphorus reduction; FCC, fall cover crop; ISH, improved soil health, CA, corn-alfalfa rotation; CS, corn-soybean rotation.]

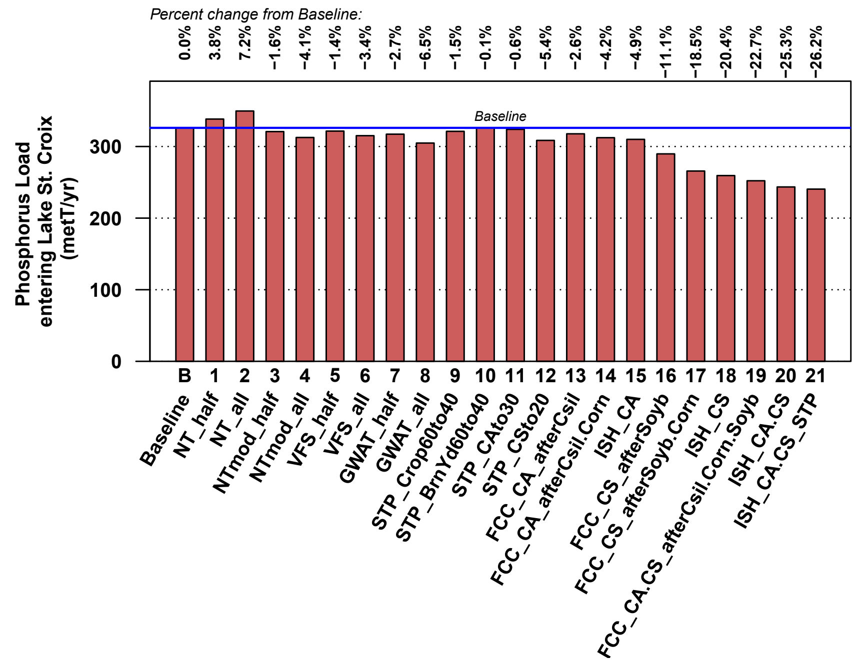
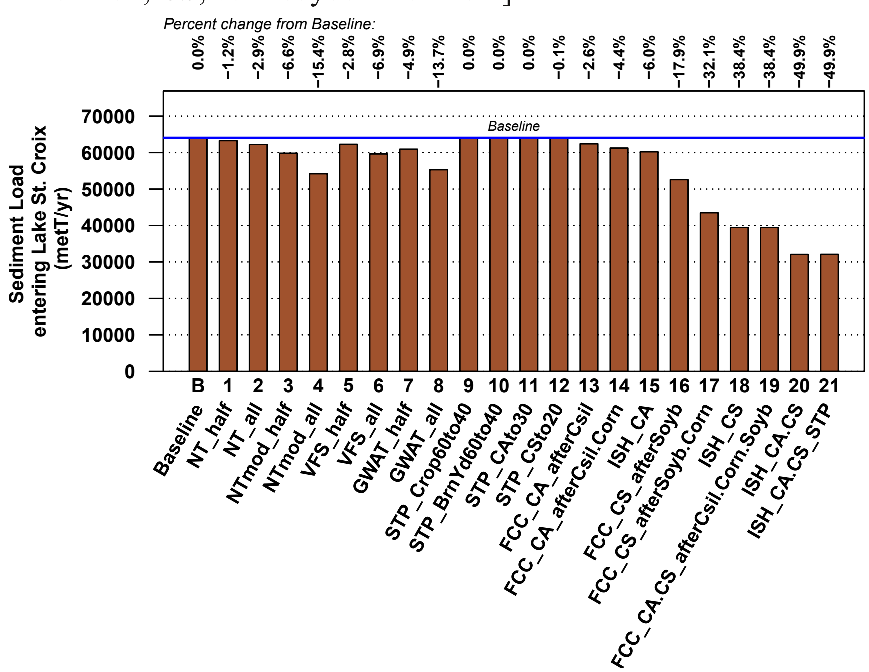


Figure 20. Sediment loads (metric tons per year) entering Lake St. Croix under selected agricultural best-management practices (BMPs), relative to baseline scenario. [NT, no-till; VFS, vegetated filter strip; GWAT, grassed waterway; STP soil-test phosphorus reduction; FCC, fall cover crop; ISH, improved soil health, CA, corn-alfalfa rotation; CS, corn-soybean rotation.]



Summary and Conclusions

Implementing agricultural best-management practices (BMPs) in the St. Croix basin could substantially reduce upland-scale and watershed-scale loads of phosphorus and sediment, depending on the practice and the level of compliance. Here, upland load refers to the amount of phosphorus and sediment mobilized in the uplands, or approximately at the "edge of field" scale, whereas watershed load refers to the loads entering Lake St. Croix at the bottom of the St. Croix basin.

While no-till (NT) agriculture decreased sediment loads (up to 31% in the uplands and 15% at Lake St. Croix), it may or may not decrease phosphorus loads, depending on how infiltration may change in concert. Without increased infiltration, NT could actually increase phosphorus loads by up to 16% in the uplands and 7% at Lake St. Croix. However, if infiltration increases under NT, then phosphorus loads could decrease, by up to 10% in the uplands and by 4% at Lake St. Croix. Vegetated filter strips (VFSs) could decrease upland loads of phosphorus and sediment by 8% and 17%, respectively, and could decrease phosphorus and sediment loads entering Lake St. Croix by 3% and 7%, respectively. Grassed waterways (GWATs) gave nearly twice the load reductions than did VFSs, reducing upland loads of phosphorus and sediment by 15% and 30%, and loads of phosphorus and sediment entering Lake St. Croix by 6% and 14%, respectively. Reducing initial concentrations of soil-test phosphorus (STP) to optimal levels (20 ppm) in all corn-soybean (CS) rotations could reduce upland phosphorus loads by 11% and loads entering Lake St. Croix by 5%. However, reducing STP in corn-alfalfa (CA) rotations that received manure had little effect because manure additions overwhelmed any change in initial conditions during the model runs. Reduction in phosphorus loads from these rotations will require reducing the manure application rate so that phosphorus losses to crop removal and hydrologic transport equals or exceeds additions from manure and other fertilizers.

Fall cover crops (FCC) and its variant, improved soil health (ISH), produced the largest reductions in phosphorus and sediment loads, which is not surprising. When large portions of the landscape that were formerly tilled and protected only by scattered crop residue are replaced with living cover crops (here, winter wheat) during the fall and through the spring runoff season, both sediment erosion and loss of nutrients to runoff and leaching will decline substantially. Full implementation of cover crops in CA rotations (winter wheat following both corn-silage and corn-grain) could reduce loads of phosphorus and sediment by 12% and 17% respectively in the uplands, and by 4% each at Lake St. Croix. Greater reductions were effected in the CS rotations (winter wheat following both corn and soybeans), where loads of phosphorus and sediment were reduced by 37% and 46% in the uplands, and by 18% and 32% at Lake St. Croix, respectively. Full implementation in both CA and CS rotations were approximately the sum of these results, reducing phosphorus and sediment loads by 49% and 63% in the uplands and by 23% and 38% at Lake St. Croix, respectively. Improved soil health (ISH) only incrementally improved (reduced) phosphorus and sediment loads, relative to those from FCC implementations, by increasing soil available water capacity, which reduces runoff and losses to leaching. Implementing ISH on the full FCC scenario further reduced phosphorus and sediment loads by a few percentage points. Stacking a reduction in STP on top of the full FCC-ISH implementation resulted in further incremental improvement and the lowest loads of all scenarios, relative to baseline conditions:

56% and 74% reductions in phosphorus and sediment loads in the uplands, and 26% and 50% reductions entering Lake St. Croix.

In conclusion, implementing agricultural best-management practices (BMPs) would move the St. Croix basin closer to achieving the goal in the TMDL study of reducing phosphorus loads to Lake St. Croix by 27% (MPCA and WDNR 2012). While the largest modeled load reductions came close to this goal, they required full compliance by all farmers to incorporate cover crops in all row-crop rotations. This result reinforces the message that large reductions in nonpoint source pollution from agricultural landscapes will almost certainly require greater extent of living cover, either as cover crops or as perennial vegetation.

On the other hand, more conventional BMPs gave modest but useful reductions in phosphorus and sediment loads, and these improvements should not be dismissed. Even if the 27%-reduction goal of the TMDL study is not met entirely, implementation efforts will still work towards protecting Lake St. Croix from further degradation. In the face of commodity prices and government policies that encourage expansion of row crops, and probable urban development resulting from the new bridge at Stillwater, Lake St. Croix will likely degrade further without efforts at curbing phosphorus loads from all sources. Still, remember that model results are, in the end, hypotheses of possible reductions. While great effort was expended to make these hypothetical results as quantitatively meaningful as possible, there remain unknown errors in the modeled scenarios, and actual BMP implementations may give lesser (or greater) reductions. Finally, the model did not account for how internal cycling of legacy phosphorus from past decades may delay the response by Lake St. Croix to reduced external loads. In short, the protection, maintenance, and possible improvement in the trophic status of Lake St. Croix will take continued effort on all fronts and may take a long time to become evident.

References

Almendinger, J.E., Deb, D., Ahmadi, M., Zhang, X., and Srinivasan, R. 2014a. Constructing a SWAT model of the St. Croix River basin, eastern Minnesota and western Wisconsin. Final report to the National Park Service, Centennial Challenge Cost Share Program. St. Croix Watershed Research Station, Science Museum of Minnesota, 83 pp.

Almendinger, J.E., Murphy, M.S., and Ulrich, J.S. 2014b. Use of the Soil and Water Assessment Tool to scale sediment delivery from field to watershed in an agricultural landscape with topographic depressions. Journal of Environmental Quality 43: 9-17.

Andraski, B.J., Mueller, D.H., and Daniel, T.C. 1985. Phosphorus losses in runoff as affected by tillage. Soil Science Society of America Journal 49(6): 1523–1527.

Arabi, M., Frankenberger, J.R., Engel, B.A., and Arnold, J.G. 2008. Representation of agricultural conservation practices with SWAT. Hydrological Processes 22(16): 3042–55.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. 1998. Large area hydrologic modeling and assessment part I: Model development. Journal of the American Water Resources Association (JAWRA) 34(1): 73-89.

ASAE (American Society of Agricultural Engineers). 1998. Manure production and characteristics, p. 646-648 in ASAE Standards 1998, 45th edition, Section D384.1. ASAE, St. Joseph. As cited by Arnold et al. 2011.

Borah, D.K., and Bera, M. 2004. Watershed-scale hydrologic and nonpoint-source pollution models: Review of applications. Transactions of the American Society of Agricultural Engineers (ASAE) 47(3): 789-803.

Carter, M.R. 2002. Soil quality for sustainable land management. Agronomy Journal 94: 38–47.

Dillaha, T.A., Reneau, R.B., Mostaghimi, S., and Lee, D. 1989. Vegetative filter strips for agricultural nonpoint source pollution control. Transactions of the ASAE (American Society of Agricultural Engineers) 32(2): 0513–0519.

Dodd, J.R., and Mallarino, A.P. 2005. Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn-soybean rotations. Soil Science Society of America Journal 69: 1118-1128.

Edlund, M.B., Triplett, L.D., Tomasek, M.D., and Bartilson, K. 2009. From paleo to policy: partitioning the historical point and nonpoint phosphorus loads to the St. Croix River, Minnesota-Wisconsin, USA. Journal of Paleolimnology 41(4): 679-689.

ESRI (Environmental Systems Research Institute). 2012. ArcGIS Desktop: Release 10.1 (build 3035). Redlands, CA.

Gaynor, J.D., and Findlay, W.I. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. Journal of Environment Quality 24(4): 734-741.

Hamblin, A.P., and Davies, D.B. 1977. Influence of organic matter on the physical properties of some East Anglian soils of high silt content. Journal of Soil Science 28: 11–22.

Hobbs, H.C., and Goebel, J.E. 1982. Geologic Map of Minnesota, Quaternary Geology, Map S-1. Minnesota Geological Survey, St. Paul, MN.

Holmberg, K.L., Perry, J., Ferrin, R.S., and Sharrow, D.L. 1997. Water Resources Management Plan-St. Croix National Scenic Riverway. 155 p. plus appendices.

Hudson, B.D. 1994. Soil organic matter and available water capacity. Journal of Soil and Water Conservation 49: 189–194.

Lorenz, D.L., Sanocki, C.A., and Kocian, M.J. 2010. Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on data through water year 2005: U.S. Geological Survey Scientific Investigations Report 2009–5250, 54 p.

Magdalene, S. 2009. Lake St. Croix Total Phosphorus Loading Study. Report to St. Croix Basin Water Resources Planning Team. St. Croix Watershed Research Station, Science Museum of Minnesota, 43 p. plus appendices.

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

MPCA (Minnesota Pollution Control Agency) and WDNR (Wisconsin Department of Natural Resources). 2012. Lake St. Croix Nutrient Total Maximum Daily Load. Minnesota Pollution Control Agency and Wisconsin Department of Natural Resources, with St. Croix Basin Water Resources Planning Team, Science Museum of Minnesota St. Croix Watershed Research Station, and Barr Engineering Company, Report wq-iw6-04e. St. Paul, MN, 93 p.

Nash, J.E., and Sutcliffe, J.V. 1970. River flow forecasting through conceptual models: Part I – A discussion of principles. Journal of Hydrology 10: 282-290.

NASS (National Agricultural Statistics Service). 2009, 2010. Crop data accessed 2009 and livestock data accessed 2010 from http://www.nass.usda.gov/Data_and_Statistics/.

NASS (National Agricultural Statistics Service). 2011. Minnesota and Wisconsin Cropland Data Layers, 2006-10. U.S. Department of Agriculture. Accessed 2011 from http://nassgeodata.gmu.edu/CropScape/.

NCDC (National Climatic Data Center). 2010. Cooperative station data online. Accessed 2010 from http://www.ncdc.noaa.gov/oa/ncdc.html.

NCDC (National Climatic Data Center). 2011. Climate Data Online. Accessed 2011 from http://cdo.ncdc.noaa.gov/climatenormals/clim60/states.

NPS (National Park Service). 1995. Interpretive Prospectus: St. Croix National Scenic Riverway, Minnesota/Wisconsin.

NRCS (Natural Resource Conservation Service). 2008. U.S. General Soil Map (State Soil Geographic Database, STATSGO) for Minnesota. U.S. Department of Agriculture. Accessed 2010 at http://soildatamart.nrcs.usda.gov.

NRCS (Natural Resoures Conservation Service). 2016. Soil Health Management. NRCS Soils [WWW Document]. URL http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/mgnt/ (accessed 2.23.16).

Robertson, D.M., and Lenz, B.N. 2002. Response of the St. Croix River pools, Wisconsin and Minnesota, to various phosphorus-loading scenarios. U.S. Geological Survey, Water-Resources Investigations Report 02-4181, 36 p.

Robbins, S.G., and Voss, R.D. 1991. Phosphorus and potassium stratification in conservation tillage systems. Journal of Soil and Water Conservation 46(4): 298–300.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S., and Trumbore, S.E. 2011. Persistence of soil organic matter as an ecosystem property. Nature 478: 49–56.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. Journal of Environmental Quality 24(2): 920–926.

Sharpley, A.N. 2003. Soil mixing to decrease surface stratification of phosphorus in manured soils." Journal of Environmental Quality 32(4): 1375-1384.

Sharpley, A.N., Chapra, S.C., Wedepohl, R., Sims, J.T., Daniel, T.C., and Reddy, K.R. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and Options. Journal of Environmental Quality 23(3): 437–451.

Triplett, L.D., Engstrom, D.R., and Edlund, M.B. 2009. A whole-basin stratigraphic record of sediment and phosphorus loading to the St. Croix River, USA. Journal of Paleolimnology 41(4): 659-677.

USGS (U.S. Geological Survey). 2010. Seamless Data Distribution System (now The National Map: Viewer and Download Platform). For digital elevation models (DEMs) and National Land Cover Dataset (NLCD). Accessed 2010 at http://seamless.usgs.gov/ (now at http://nationalmap.gov/viewer.html).

Vadas, P.A., Kleinman, P.J.A., Sharpley, A.N., and Turner, B.L. 2005. Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. Journal of Environmental Quality 34(2): 572–580.

Vaughn, S.R. 2010. DNR Watershed Delineation: Project History, Methodology, Terminology & Data Attribution. Draft manuscript. Minnesota Department of Natural Resources - Waters.

Vitosh, M.L., Johnson, J.W., and Mengel, D.B. (Eds.). 1995. TH-state Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa. Extension Bulletin E-2567, Michigan State, Ohio State, and Purdue Universities. 21 p.

Waidler, D., White, M., Steglich, E., Wang, S., Williams, J., Jones, C.A., and Srinivasan, R. 2009. Conservation Practice Modeling Guide for SWAT and APEX. Temple, TX: U.S. Department of Agriculture, Agricultural Research Service, 78 p.

Waters, T.F. 1977. The Streams and Rivers of Minnesota. University of Minnesota Press, Minneapolis, MN, 373 p.

Winchell, M., Srinivasan, R., Di Luzio, M., and Arnold, J. 2013. ArcSWAT Interface for SWAT2012 User's Guide. Blackland Research and Extension Center, Texas AgriLife Research, Temple, TX; and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, TX, 459 p.

Wright, H.E., Jr. 1972. Quaternary history of Minnesota. In: Sims, P.K. and Morey, G.B. (Editors). Geology of Minnesota: A Centennial Volume. Minnesota Geological Survey, p. 515–578.

Zhang, X., and Srinivasan, R. 2009. GIS-based spatial precipitation estimation: a comparison of geostatistical approaches. Journal of the American Water Resources Association (JAWRA) 45(4): 894-906.