Lake Pepin Watershed Full Cost Accounting Project

Final Report Prepared for the Minnesota Pollution Control Agency

July 2012

Brent Dalzell[2], Derric Pennington[1], Stephen Polasky[1], David Mulla[2], Steve Taff[1], Erik Nelson[3]

University of Minnesota:

[1] Department of Applied Economics

[2] Department of Soil, Water, and Climate

[3] Bowdoin College: Department of Economics

Table of Contents

Executive Summary

The citizens of the Upper Midwest prize their water resources, including the Great Lakes, the Mississippi River and other large rivers, along with countless smaller lakes, rivers and streams. The water quality of many lakes, rivers and streams, however, has been degraded from the combined effects of industrial effluents, municipal wastewater, erosion, and excess nutrients from agricultural lands. In 2002, Lake Pepin, a natural lake in the Mississippi River on the border of Minnesota and Wisconsin was placed on the list of impaired waters. The Lake Pepin Total Maximum Daily Load (TMDL) addresses impairments for turbidity and eutrophication in the Mississippi River between the confluence of the Mississippi and Minnesota Rivers to the confluence of the Mississippi and Chippewa Rivers and includes both Lake Pepin and Spring Lake. Improving water quality to meet standards required by the TMDL will require watershed load reductions of phosphorus and sediment of up to 50 percent from current levels. Since the Lake Pepin watershed comprises almost half the land area of Minnesota, these load-reduction requirements will have major implications for land management across the state.

This study analyzes the environmental and economic effects of actions to improve water quality by reducing phosphorus and sediment loads in selected watersheds in the Minnesota River Basin upstream of Lake Pepin. Two watersheds, Seven Mile Creek in central Minnesota near Mankato and West Fork Beaver Creek in western Minnesota, were used as case studies. We selected these watersheds because of the availability of flow and water quality monitoring data, their representation of different sources of sediment and phosphorus including field sources as well as non-field sources (failing streambanks and ravines). These watersheds allowed detailed modeling of land use and consequent modeling of effects on water quality, ecosystem services and economic returns. For the baseline calibration period, average sediment loads were 3,016 and 486 tons yr^{-1} for Seven Mile Creek and West Fork Beaver Creek, respectively. In Seven Mile Creek, roughly 77% of sediment observed at the watershed outlet is derived from non-field sources of sediment. In contrast, 39% of sediment exported from West Fork Beaver Creek is derived from non-field sources. This difference highlights the important role of non-field sources of sediment in watersheds where ravines and steep, exposed streambanks are present. Phosphorus export for baseline conditions was 3,216 and 2,941 kg yr^{-1} for Seven Mile Creek and West Fork Beaver Creek, respectively. In both watersheds, field sources are the main sources of phosphorus accounting for 68 and 97% of exported phosphorus from Seven Mile Creek and West Fork Beaver Creek.

This study links spatially-explicit biophysical models with economic models to trace the effects of changes in land use and land management in agricultural watersheds on subsequent changes in the environment, and traces the effects of changes in the environment on subsequent changes in the economic well-being. This study provides a comprehensive framework in which relevant biophysical and economic changes are arrayed and evaluated on a transparent and consistent basis. Combining biophysical analysis and economic analysis approaches allows assessment of the benefits and costs of alternative policy choices that include direct costs and benefits as measured by market transactions as well as non-market benefits and costs from changes in environmental conditions that lead to changes in the provision of ecosystem services.

We use the integrated approach to do a quantitative assessment of the benefits and costs of alternative land use and land management alternatives taken to achieve load-reduction goals for the Lake Pepin TMDL. In addition, the study also measures and reports biophysical measures related to habitat and biodiversity that are difficult to measure the benefit in monetary terms. We find efficient land-use and land-management decisions for a watershed that maximize gains in water quality for a given level of economic returns. By measuring the value of ecosystem services and agricultural crop production in monetary terms we can summarize the value of these outputs in a single measure of economic returns. We illustrate the tradeoffs between improvements in water quality and economic returns in a simple graph in two dimensions. By finding the maximum TMDL reduction for a given level of economic return, and then varying the economic return over its entire potential range, we can trace out the efficiency frontier The efficiency frontier illustrates what can be achieved in terms of water quality and economic returns by carefully arranging the spatial allocation of activities across the landscape and the necessary tradeoffs between the water quality and economic returns on the landscape. The efficiency frontier also illustrates the degree of inefficiency of other land-use patterns not on the frontier, showing the amount by which water quality improvements and/or economic returns could be increased.

Based on the biophysical watershed scale modeling coupled with ecosystem service valuation modeling for Seven Mile Creek and West Fork Beaver Creek watersheds, we find the following results:

- **Modest gains in water quality are possible without reducing current economic returns in both watersheds:** Relative to current levels, phosphorus may be reduced by from roughly 20 to 32% in Seven Mile Creek and West Fork Beaver Creek, respectively, without reducing economic returns of the watershed relative to baseline levels. Sediment may be reduced by from roughly 18 to 25% in

Seven Mile Creek and West Fork Beaver Creek, respectively, without diminishing current economic returns of the watersheds.

- **50% reductions in sediment and phosphorus are possible in both watersheds but this level of reduction requires moving substantial acreage out of row crops into perennial vegetation at substantial cost in terms of reduced economic returns.** Achieving a 50% reduction in phosphorus will generate from roughly $900,000 to $600,000 less per year in Seven Mile Creek and West Fork Beaver Creek watersheds, respectively. The cost to meet 50% phosphorus reductions is higher in Seven Mile Creek than West Fork Beaver Creek because more agricultural land must be converted to natural vegetation. In Seven Mile Creek, the in-channel loads of phosphorus represent the largest contribution to overall phosphorus loads, and in turn more land must be converted to practices that reduce phosphorus loads while also reducing overall water yield to the stream channel. In West Fork Beaver Creek, there is a more direct link between field practices and in-channel loads so changes to field parameters translate directly to water quality improvements. Achieving a 50% reduction in sediment will reduce net economic returns by $900,000 to $1,000,000 per year in both Seven Mile Creek and West Fork Beaver Creek watersheds.
- **When the value of non-market ecosystem services is incorporated into the economic accounting, 50% reductions of sediment and phosphorus occur at low costs to society.** For Seven Mile Creek watershed, a 50% reduction in phosphorus may be achieved at essentially no cost to society compared to current watershed economic returns. For West Fork Beaver Creek, at 50% reduction in phosphorus coincides with an *increase* in the total annual watershed returns by about $650,000 per year. For sediment, 50% reductions relative to current levels can be achieved for at roughly no net reduction in average annual returns for both Seven Mile Creek and West Fork Beaver Creek watersheds.
- **Maximizing the value of returns including the value of ecosystem services results in modest sediment and phosphorus reductions that fall short of 50% guidelines necessary to meet Lake Pepin water quality goals.** The landscape that maximizes net benefits results in sediment reductions of around 15% in both watersheds and phosphorus reductions of nearly 20% and 40% in Seven Mile Creek and West Fork Beaver Creek, respectively. Even when society includes the value of ecosystem service valuation in their watershed management decisions, 50% reductions in sediment and phosphorus are not optimal. This conclusion, however, is dependent upon current valuation of non-market ecosystem services. If the value of ecosystem services is doubled then it is optimal in some cases to achieve reduction levels exceeding 50%.
- **If crop prices fall, then the economic costs of achieving water quality goals are less burdensome.** With high agricultural crop prices, the value of agricultural crops is the dominant

factor in determining the shape of the efficiency frontiers. Given high crop prices, there is generally a substantial trade-off between water quality improvement and net economic value. If crop prices were to drop, however, to levels similar to pre-2007 values, the slope of the efficiency frontier becomes much steeper meaning that greater environmental gains can be realized without dramatic decreases in net annual returns from these watersheds.

- **Adoption of best management practices for achieving water quality goals will not by themselves be sufficient to achieve water quality goals and incur higher than necessary cost.** Employing conventional best management practices alone only achieves modest reductions in sediment and phosphorus (<20% reductions). In order to work towards goals of 50% reductions in sediment and phosphorus, conventional best management practices must be accompanied by transition of key landscape segments from row crops to perennial vegetation such as deciduous forest, prairie grasses, or switch grass. In addition, best management practices achieve reductions in phosphorus and sediment at higher costs in terms of reduced economic returns in comparison to alternatives that involve a mix of targeted land-use changes from row crops to perennial vegetation and changes in practices such as reduced phosphorus fertilizer application.

The results from this study highlight the potential policy shortfall in meeting the goals of the Lake Pepin TMDL. This shortfall is the difference between the amount the State of Minnesota is willing to pay out to meet a 50% TMDL reduction and the amount required to pay off any economic losses accrued by landowners to meet the TMDL goal. For example, based only on current agricultural prices and costs, meeting 50% reductions for sediment and phosphorus will cost the State $900,000 annually in Seven Mile Creek. However, if a mechanism were in place for paying landowners for the joint ecosystem service benefits they provided in addition to agriculture production then the policy shortfall would be near zero. Interestingly, the policy shortfall or economic costs to landowners would have been even less if the TMDL policy goal of meeting 50% water quality reductions had been implemented prior to in 2007. For Seven Mile Creek, the cost of meeting the TMDL goal of 50% would have been ~ $700,000 per year less pre-2007 compared with today's economic conditions. This dramatic change in agricultural returns since 2006 is largely the result of growing corn-ethanol demand that has resulted in a near tripling in corn prices and a modest rise in production costs from fossil fuel derived inputs. This economic trend is not expected to subside in the near future and likely represents a new economic baseline.

Background and Overview

The Mississippi River widens into a natural lake, Lake Pepin, along the border of Minnesota and Wisconsin below the confluence of the Mississippi, Minnesota and St. Croix Rivers. Lake Pepin is important resource for the area, used for recreation (boating and fishing), tourism, transportation, and is an important aquatic habitat. Water quality in Lake Pepin, however, has declined due to increases in sediment and nutrient loads. As a result, Lake Pepin was placed on the list of impaired waters (303(d)) in 2002.

The Lake Pepin Total Maximum Daily Load (TMDL) addresses impairments for turbidity and eutrophication in the Mississippi River between the confluence of the Mississippi and Minnesota Rivers to the confluence of the Mississippi and Chippewa Rivers and includes both Lake Pepin and Spring Lake. High levels of turbidity are due to high amounts of sediment from the upstream watershed. Eutrophication, especially severe at lower flows, results from excessive growth of algae, which in turn results from the superabundance of phosphorus in the lake. Improving water quality to meet standards required by the TMDL will require watershed load reductions of phosphorus and sediment in the range of 25-50 percent from current levels. Since the Lake Pepin watershed comprises almost half the land area of Minnesota, these load-reduction requirements by the Lake Pepin TMDL will have major implications for land management across the state (see Figure 1).

Water quality in Lake Pepin and the Mississippi River immediately upstream is a reflection of the climate, soils, vegetation and land uses within its watershed. Considerable variation exists across the watershed; land uses vary from heavily forested to the north and east, to mainly agricultural in the south and west, to highly urbanized in the Twin Cities metropolitan area immediately upstream of Lake Pepin.

Much of the phosphorus is attached to sediment that is transported from the watershed through tributaries to Lake Pepin. While in suspension, sediment contributes to the problem of turbidity in the river reach that includes Lake Pepin, particularly at higher flows. Sediment that settles to the lake bed releases considerable quantities of phosphorus and dissolved oxygen levels in the upper layer of sediments decline to near zero as a result of organic matter decomposition. Sestonic algae produced from this and other sources of phosphorus in the watershed may contribute somewhat to the problem of turbidity.

The Minnesota Pollution Control Agency has an obligation (Minn. Stats. 114D.25) to expand the scope of its TMDL analyses to include additional incurred or avoided impacts on the area's habitat, water quality, carbon budget, and agricultural production—from both point and non-point sources of pollution. Goal III of the 2nd Lake Pepin TMDL Work Plan involves estimating "potential reductions in watershed and non-watershed loads of sediment and phosphorus." Objective J under Goal III is to "Estimate economic benefits and costs associated with attainment of water quality standards resulting from changes in land use and wastewater management in the Lake Pepin watershed." Management and policy decisions that affect land use and water use have a range of important environmental, economic, and social consequences. Analysis of the full set of consequences of such decisions requires integrating economic analysis with hydrology and analysis of nutrient flows, and with other ecological assessments. A comprehensive assessment of the full set of consequences of these choices on water quality, agricultural production, biodiversity, carbon storage and other important outcomes will generate information that can be used to evaluate the effect of decisions on the welfare of the people of Minnesota and beyond.

Integrated assessment for full cost-accounting

This study uses an integrated modeling approach to assess the economic benefits and costs of land-use and land-management decisions that impact water quality as well as ecosystem functions and other aspects of environmental quality. Full-cost accounting refers to an economic approach that attempts to provide a complete accounting of both market and non-market costs and benefits including the value of changes in ecosystem services. The approach includes a physical accounting of the complete set of inputs and outputs and uses an economic accounting approach to put all inputs and outputs in a common (monetary) metric that allows for easy comparison across management and policy alternatives. This approach has been applied to analyze the effects of producing biofuels, such as corn-grain ethanol, soy biodiesel and energy from prairie biomass, compared to conventional fossil-fuels (Hill et al., 2006; Hill et al., 2009; Tilman et al., 2006), among other applications. Full cost accounting used in life-cycle assessments cover impacts over the complete production cycle of goods and services but typically do not do so in a spatially-explicit manner. A closely-related strand of literature on the value of ecosystem services takes account of benefits and costs in spatially-explicit models. Models of the value of ecosystem services link economic and biophysical models to analyze the costs and benefits of alternative land use/management and water management (Boody et al., 2005; Johnson et al., 2012; Nelson et al., 2009; Polasky et al., 2008; Polasky et al., 2005; Polasky et al., 2011). Ecosystem services are the goods and services provided by ecosystems that are of value to humans including direct provisioning services (e.g. timber, fish, agricultural crops) as well as more indirect regulatory services (e.g. carbon sequestration) and cultural and aesthetic values (MEA, 2005) . Estimating the value of ecosystem services requires biophysical analysis of the provision of ecosystem services ("ecological production function") as well as economic analysis of the values of various services((NRC), 2005).

This project links spatially-explicit biophysical models with economic models to trace the effects of changes in land use and land management in agricultural watersheds on subsequent changes in the environment, and traces the effects of changes in the environment on subsequent changes in the economic well-being. The goal of this work is to provide a comprehensive framework in which all relevant biophysical and economic changes are arrayed and evaluated on a transparent and consistent basis. Combining biophysical analysis and economic analysis approaches will allow us to assemble information about the full economic benefits and costs from alternative policy choices that include direct costs and benefits as measured by market transactions as well as non-market benefits and costs from changes in environmental conditions that lead to changes in the provision of ecosystem services. The final product of the project is a quantitative analysis of the economic benefits and costs of alternative land use and land management alternatives taken to achieve load-reduction goals for the Lake Pepin TMDL. In addition, the project also measures and reports biophysical measures related to habitat and biodiversity that are difficult to measure the economic value in monetary terms.

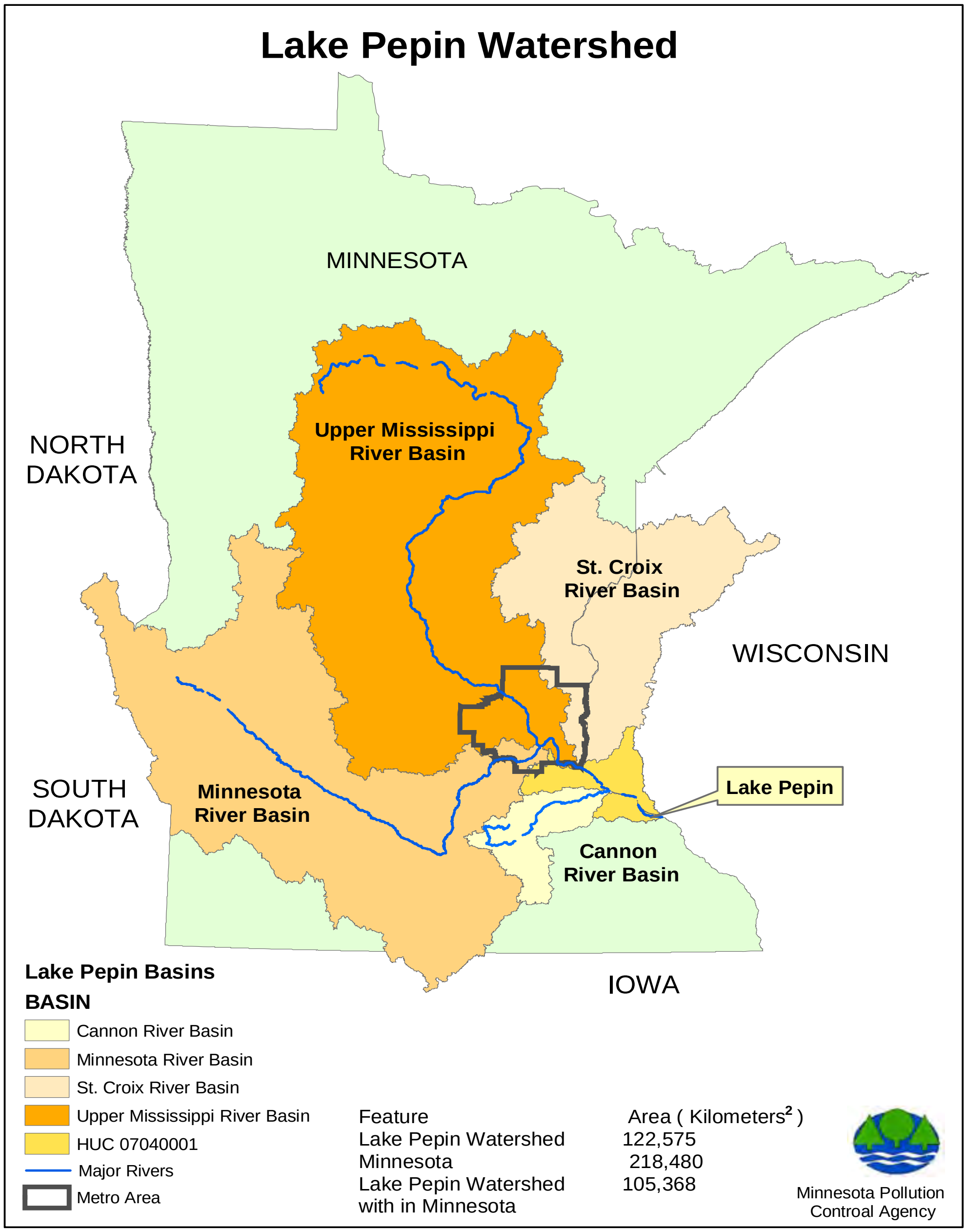


Figure 1. The Lake Pepin Watershed (including major sub basins).

Project Goals

1. Provide a comprehensive assessment of the benefits associated with alternative scenarios for achieving TMDL load-reduction goals through modified land use. This assessment includes an evaluation of which segments of society stand to gain or lose under the alternative scenarios.

2. Develop a template that describes a step-by-step process for applying a full-cost-accounting approach to other TMDLs in Minnesota. This template will primarily be focused on outlining the full-cost-accounting framework developed in this study; however, we will also explore the possibility of developing tools to make these models available in a way that permits outside users to evaluate additional alternative scenarios.

3. Explain the implications of this study for MPCA policies and programs, including watershed implementation planning, TMDL guidance, and pollutant trading in Minnesota as it applies to ongoing rule development.

Methological Approach

In order to evaluate the effectiveness of alternative scenarios on sediment and phosphorus export as well as both market and non-market ecosystem services, we developed a modeling approach that uses a biophysical model (SWAT – Soil and Water Assessment Tool) and an integrated biophysical and economic model (InVEST – Integrated Valuation of Environmental Services and Tradeoffs).
Water samples were collected periodically in the study watersheds and analyzed for sediment and phosphorus concentrations. These periodic water quality data were combined with continuous daily flow monitoring data via the FLUX model (Walker, 1996) in order to generate monthly values for sediment and phosphorus. Hereafter, these monthly loads are referred to as observed data. The SWAT (Soil and Water Assessment Tool) model was calibrated and validated to observed data in order to simulate the effects of land management on environmental quality over a range of weather conditions, soils, and slope classes. The InVEST model (Integrated Valuation of Ecosystem Services) integrates biophysical and economic models to quantify the provision and value of a number of ecosystem services (e.g., carbon sequestration, commodity production, biodiversity conservation, and recreation). For each model we collected watershed-specific data needed to parameterize the model and used the data to analyze impacts across multiple objectives of various land use and land management alternatives.

For this study, we used the SWAT model to provide data on water yield and quality, crop yields and vegetation biomass. We used InVEST to quantify and value carbon sequestration , quantify habitat for biodiversity conservation, value agricultural crop and biomass production, and value sediment and phosphorus reduction. We integrated outputs from both models to determine the roles that individual landscape units play in economic and environmental quality when under varying land cover and land management scenarios (Fig. 2)

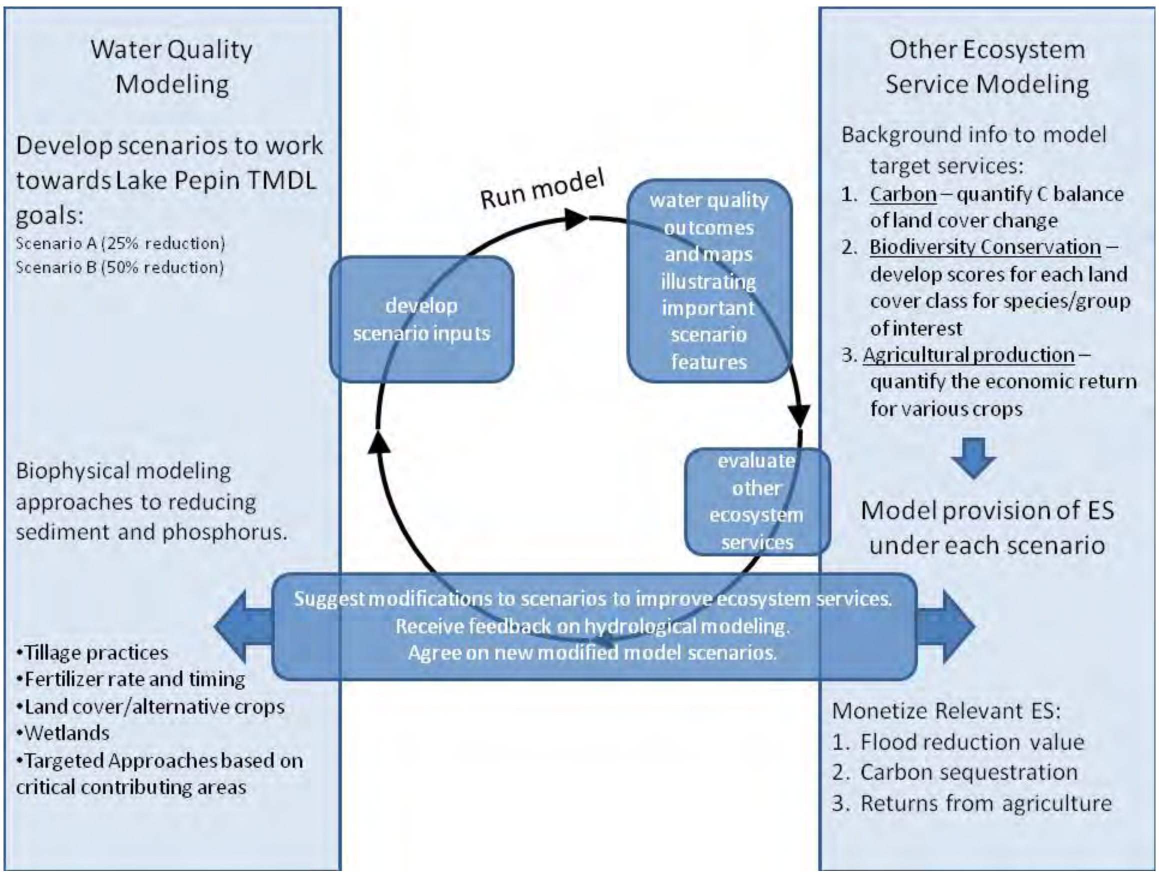


Figure 2. Schematic diagram showing the conceptual approach developed for this project in order to integrate results from water quality and ecosystem service models.

Study Areas

We applied this integrated biophysical and economic modeling approach to representative small watersheds in the Lake Pepin drainage to demonstrate what types of actions are needed to meet water quality objectives and to show what other social benefits or costs are associated with such changes. In consultation with MPCA personnel, two watersheds were selected for this study located within the agriculturally-dominated southern portion of the Lake Pepin Watershed. Both watersheds are located in the Minnesota River Basin: Seven Mile Creek Watershed and West Fork Beaver Creek Watershed (Fig. 3). We selected these watersheds because of the availability of flow and water quality monitoring data, their representation of different sources of sediment and phosphorus including field sources as well as non-field sources (failing streambanks and ravines) and they have active stakeholders involvement. Key watershed parameters are summarized in Table 1.

Seven Mile Creek Watershed: This watershed drains directly to the Minnesota River just north of Mankato, MN. Seven Mile Creek receives greater annual rainfall than West Fork Beaver Creek. Seven Mile Creek is located within the Wetter Clays and Silts agroecoregion of Minnesota and, similar to West Fork Beaver Creek, soils are generally characterized as fine-textured lacustrine deposits overlying glacial till. Although the average slope in the watershed is less than 2%, Seven Mile Creek is characterized by very flat upland portions and a quick transition into a ravine-zone before discharging to the Minnesota River. This watershed is important for demonstrating that, in some portions of the Minnesota River Basin, there can be very important non-field sources of sediment. While the SWAT model does not simulate non-field sediment sources, differences between observed and predicted data will be used in conjunction with model outputs to estimate non-field contributions. Results from Seven Mile Creek watershed are important for identifying what amounts of sediment reduction should be reasonably expected given the diversity of field and non-field sources.

West Fork Beaver Creek Watershed: This watershed is located in western Minnesota within the Minnesota River Basin. Like most of southern Minnesota, this watershed is dominated by corn and soybean row crop agriculture. Features unique to this watershed include sugarbeet crops and a local beet processing cooperative which has been active in promoting adoption of BMP’s in the area. West Fork Beaver Creek watershed is located within the Steeper Till agroecoregion of Minnesota, although soils in the immediate region of the watershed are characterized as lacustrine deposits overlying glacial till. The overall landscape is very flat and the mean slope is less than 2%.

Table 1. Summary characteristics and land use composition for Seven Mile Creek and West Fork Beaver Creek watersheds.

				area (%)				
Watershed	Area (km2)	Mean Slope (%)	Mean Annual Precip (mm)	Row Crop	Grass / Hay	Deciduous Forest	Water / Wetlands	Urban / Roads
Seven Mile Creek	89.9	1.72	754	83%	2%	4%	6%	5%
West Fork Beaver Creek	257.7	1.34	660	84%	3%	1%	5%	7%

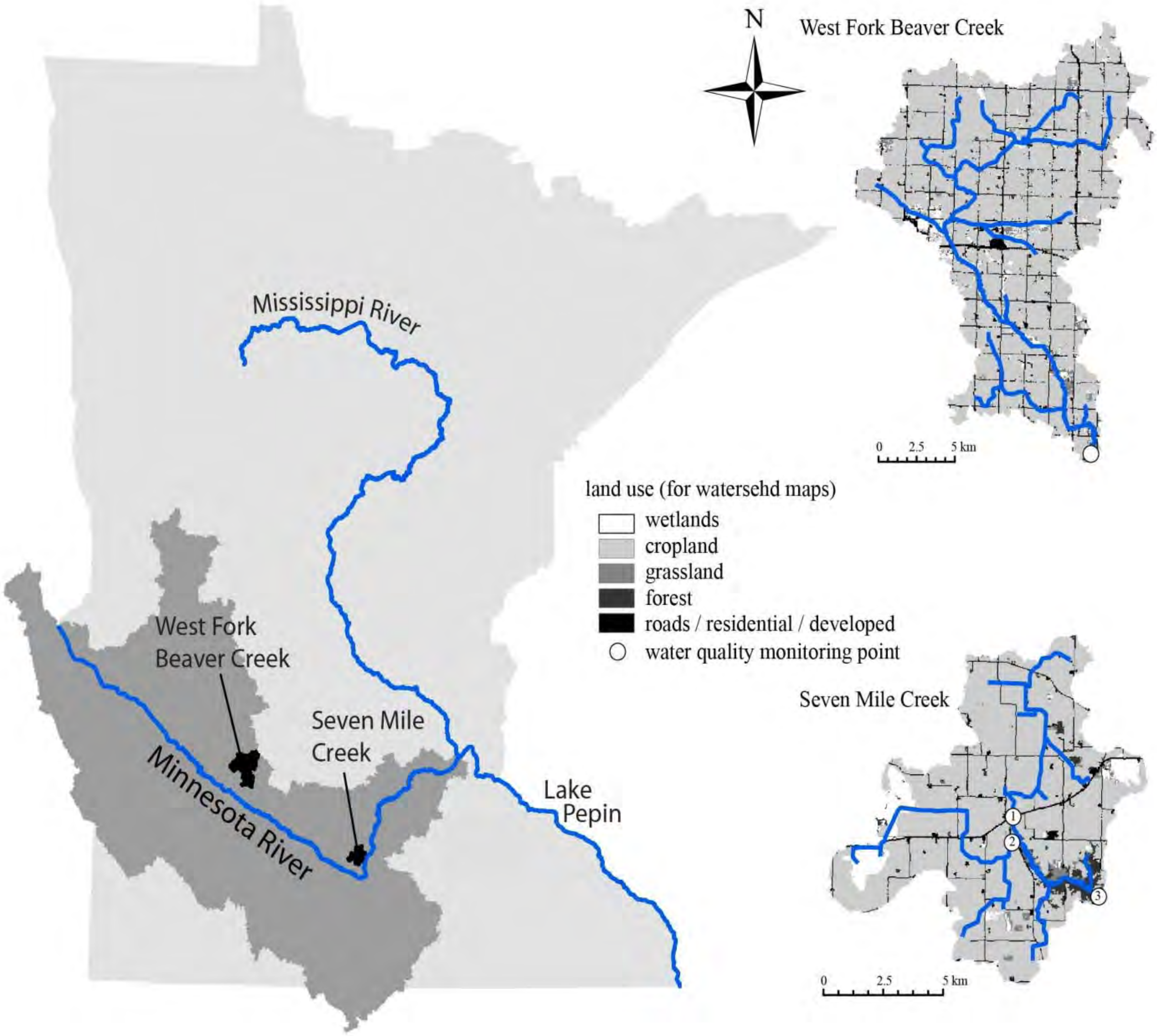


Figure 3. Minnesota map showing the watersheds selected for this study. The shaded region indicates the Minnesota River Basin. *Inset at right*: watershed maps showing Seven Mile Creek and West Fork Beaver Creek. Water quality monitoring points are shown for each watershed. For Seven Mile Creek, site numbers correspond to different monitoring locations discussed in the text.

Methods

Observed Monthly Watershed Pollutant Loads – FLUX Model

The SWAT biophysical model requires calibration of predicted sediment and phosphorus loads at the watershed scale. To obtain measured water quality data, continuous flow measurements and periodic water quality samples were input into the FLUX model (Walker, 1996) and used to generate monthly estimates of sediment, phosphorus and nitrogen loading from the watersheds. For Seven Mile Creek watershed, observed flow and water quality monitoring data used in this study were collected from 2002-2008 at three locations within the watershed. Two locations were in the upland portion of the watershed where slopes are very flat and land use is dominated by agriculture and one location near the watershed outlet that encompasses the steeper portion of the watershed. Flow monitoring did not occur during winter months in Seven Mile Creek watershed. In West Fork Beaver Creek watershed, flow and water quality monitoring occurred continuously from January 2006 to September 2008. In the FLUX model, sediment and phosphorus data were stratified based on season; a monthly load series was developed using regression method 6. FLUX model performance was evaluated by comparing predicted loads against observed data. Hereafter, these monthly loading estimates are referred to as “observed” loads, against which SWAT performance is evaluated. FLUX model output is contained in Appendix A.

SWAT model

The water quality model selected for this work is the Soil and Water Assessment Tool (SWAT2005). SWAT is a watershed-scale model that functions on a daily time step; it is primarily applied to predict and evaluate land cover and land management practices on the quantity and quality of water that is exported from watersheds with agricultural land use. The model is physically-based and relies on environmental parameters and plant growth to estimate the amount of water available in the landscape to contribute to stream flow and the delivery of sediment, nutrients, and pesticides to the watershed outlet. The SWAT model was selected for this work because it is freely available, it has a large user base and is actively being supported and developed. Further, it has a great degree of flexibility and supporting databases to allow simulation and evaluation of a wide variety of alternative crops and land management practices. SWAT has been used widely for the study of water quality in agricultural regions and has been applied to TMDL studies.

SWAT Model inputs

Several sources of data are required to build and calibrate the SWAT model in order to appropriately simulate conditions for a give watershed. In addition to physical data on climate, topography and soils, information about typical management practices are compiled from a wide variety of sources ranging from published documents to discussions with local stakeholders and expert knowledge. Key inputs to the model are summarized in Figure 4 and watershed-specific details are included in Appendix B.

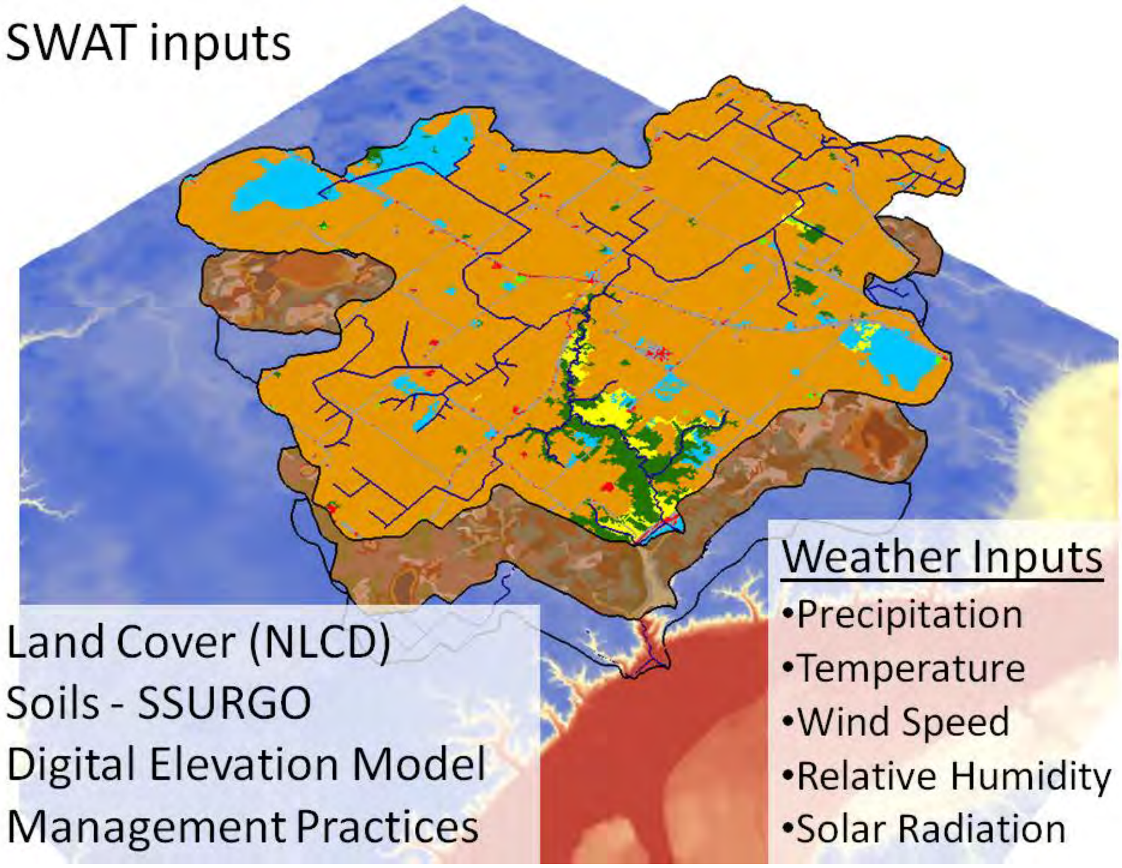


Figure 4. Schematic showing stacked layers of spatial data for SWAT model development.

In addition to standard inputs required to run the SWAT model (summarized in Fig. 4), we incorporated additional information into the land use layer in order to allow for greater flexibility with model calibration and to evaluate alternative land management scenarios:

- Sites of greater erosion potential due to focused overland flow.
- Buffers around the stream network.
- Wildlife management areas and other sites of potential importance for wildlife habitat.

Differentiating between field and non-field sources of sediment and phosphorus.

In the Minnesota River Basin, a significant proportion of total sediment is derived from non-field sources; primarily from the failure of bluffs, streambanks and ravines. In Seven Mile Creek watershed, ravine and streambank erosion that occurs in the lower portion of the watershed is an important contribution to the total sediment load. We calibrated the upland portions of the Seven Mile Creek watershed based on the assumption that sediment loads observed in this flat, agricultural portion of the landscape are derived from agricultural field sources. Assuming that the calibrated model is successfully simulating sediment from agricultural fields in the flat-upland portions of Seven Mile Creek, we determine non-field sources to be the difference between observed and predicted sediment loads at the watershed outlet.

In order to estimate non-field sources of sediment for each alternative land cover or land management practice in each functional model unit (hydrologic response unit, HRU), we developed a simple empirical approach based on a regression between mean monthly flow and monthly sediment loads observed at the watershed outlet. The regression takes the form of a power function $SS=kq^m$ after (Brooks et al., 1991)(pp 190) where SS is suspended sediment load, q is stream discharge, and k and m are constants for a given stream. This flow-based approach was used in conjunction with SWAT-predicted water yield for each HRU in order to quantify how the water generated by each HRU contributed to non-field sources of sediment (Fig 5). Sediment from streambank sources in the Minnesota River Basin has been shown to contain phosphorus (Sekely et al., 2002). Following the approach described here for partitioning sediment sources, we determined non-field sources of phosphorus based on the assumption that non-field sediment has a phosphorus content of 441 mg kg^{-1} after analysis of similar samples performed by (Sekely et al., 2002). This provided a valuable tool for helping to identify the importance of non-field sediment sources in this watershed.

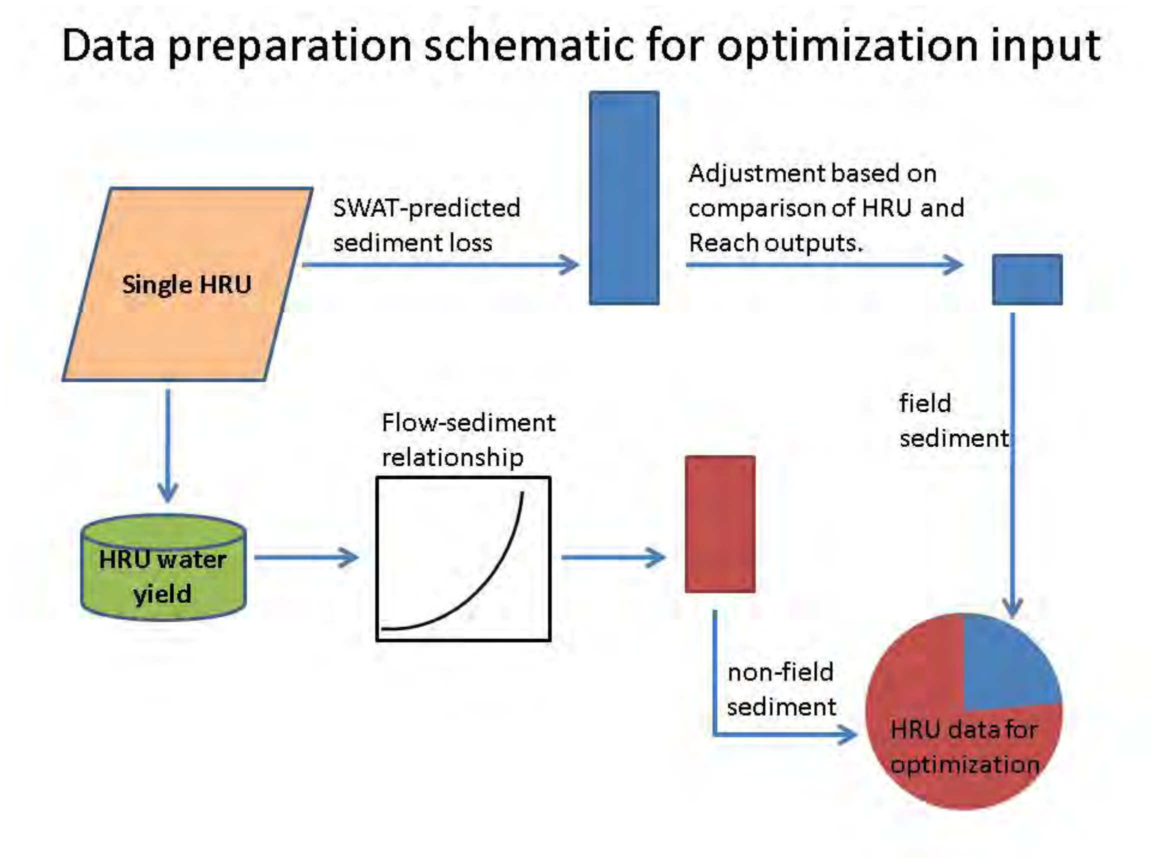


Figure 5. Schematic illustrating how SWAT model outputs are used to predict both field and non-field sources of sediment on an HRU basis. Non field phosphorus loads are based on the assumption that non-field sediment has a phosphorus content of 441 mg kg-1 after Sekely et al., (2002).

InVEST Ecosystem Service Models

To predict annual change in additional ecosystem services on the landscape for the various LULC types in a given HRU, we use the InVEST model (Integrated Valuation of Ecosystem Services and Tradeoffs; (Tallis et al., 2010), http://invest.ecoinformatics.org/) to calculate the provision and economic value of associated ecosystems services to meet either water quality or economic objectives. InVEST provides a consistent and transparent methodology for evaluating the tradeoffs across multiple ecosystem services from alternative land-use and land-management scenarios. Developed by researchers from the Natural Capital Project, a partnership between the University of Minnesota, Stanford University, The Nature Conservancy, and the World Wildlife Fund, the InVEST framework uses "ecological production functions" to predict the provision of ecosystem services, then combines these estimates with economic valuation methods to account for the value of the ecosystem services for a given landscape.

For this study, we consider a broad set of ecosystem services based on the availability of applicable data for Minnesota. Specifically we quantify and value the reduction in phosphorus and sediment, carbon sequestration, agricultural production (commodity and biofuel production systems), and recreation (big-game hunting, small-game hunting, migratory waterfowl hunting, and wildlife viewing). We also model habitat quality as a proxy for biodiversity conservation. We do not, however, attempt to estimate a monetary value for habitat quality. Below we describe the InVEST modules developed and used in this analysis: carbon sequestration, sediment and phosphorus retention value, habitat provision, and agricultural production. We also describe the data and models we use to estimate recreational hunting and wildlife viewing activity, which is currently not a part of the InVEST suite of models.

For each InVEST model we collected watershed-specific data needed to parameterize the model. All InVEST models require LULC maps in order to define and describe the study landscapes, in this case, watersheds. We use the Multi-Resolution Land Characteristics (MRLC) Consortium National Land Cover Database for 2001 (Homer et al., 2007) to assess baseline LULC conditions and to derive and create alternative scenarios for the two study watersheds: Seven Mile Creek and West Fork Beaver Creek. The land cover and land management categories we consider for our analyses are listed in Table 2.

Table 2. Selected land-management and land-cover types used to generate alternative scenarios.

Land-management practices	Land-cover types
50% lower application of P	Row crops – e.g., corn, soybeans, sugar beets
Manure application of N and P	Harvested switchgrass
Tillage practices – conservation and conventional	Harvested mixed-species grassland
	Deciduous forest

Carbon storage and sequestration

The carbon model accounts for carbon stored in the soil and in biomass. The amount of carbon stored in each of these pools depends primarily on LULC type (e.g., agriculture, forest, grassland, wetlands) but is also affected by land management (e.g., corn and soybean, switchgrass production). For carbon storage in the baseline landscape we assume that land use and land management had existed long enough in each HRU for carbon storage in the cell to reach its equilibrium (steady-state) level (Fig. 6). We assumed storage equilibrium because we lacked state-wide data on age class of forests and other LULC that would allow for a more exact estimation of carbon storage values in Minnesota. We estimated carbon sequestration that would be achieved under a given LULC type by calculating the differences in carbon storage under the LULC in a given HRU in question relative to the baseline. Steady-state levels for all LULC types are listed in Appendix C.

We convert a LULC scenario's carbon stock to an annualized flow of carbon sequestration by dividing the change in carbon stock with a change in land use by the average time it takes for carbon storage to reach equilibrium across LULC types, assumed here to be 50 years. This annualized sequestration from the carbon model can either be reported as tons of carbon sequestered, or it can be converted to a dollar value by using estimates of the social cost of carbon, carbon market prices, or estimates of the cost of carbon capture and storage (Hill et al., 2009). We calculated monetary values of the changes in carbon storage using estimates of the social cost of carbon (Tol, 2009). The social cost of carbon is the cost to society from the estimated present value of future damages from more intense climate change from an additional ton of carbon emitted to the atmosphere. Values for the social cost of carbon reported in the literature range from near $0 to over $500 per ton of carbon (Tol, 2009). In this paper, we used a base case estimate of $64 per ton carbon ($17.45 per ton CO_2) in constant 2011 dollars, based on a value of $45 in 1995 constant dollars for the 33rd percentile fitted distribution for social cost of assuming a 1% pure rate of time preference (Tol, 2009). To evaluate how the uncertainty in the value of ecosystem services could influence land-use decisions we calculated two additional estimates: 1) two times the ecosystem service value (2ESV), or $128 per ton carbon, and 2) eight times the ecosystem service value (8ESV), or $512 per ton carbon. We decided to use eight times the base case value since that reflects the spread from the 33rd and 95th percentile from a meta-analysis for the social cost of carbon reported in the literature (Tol, 2009).

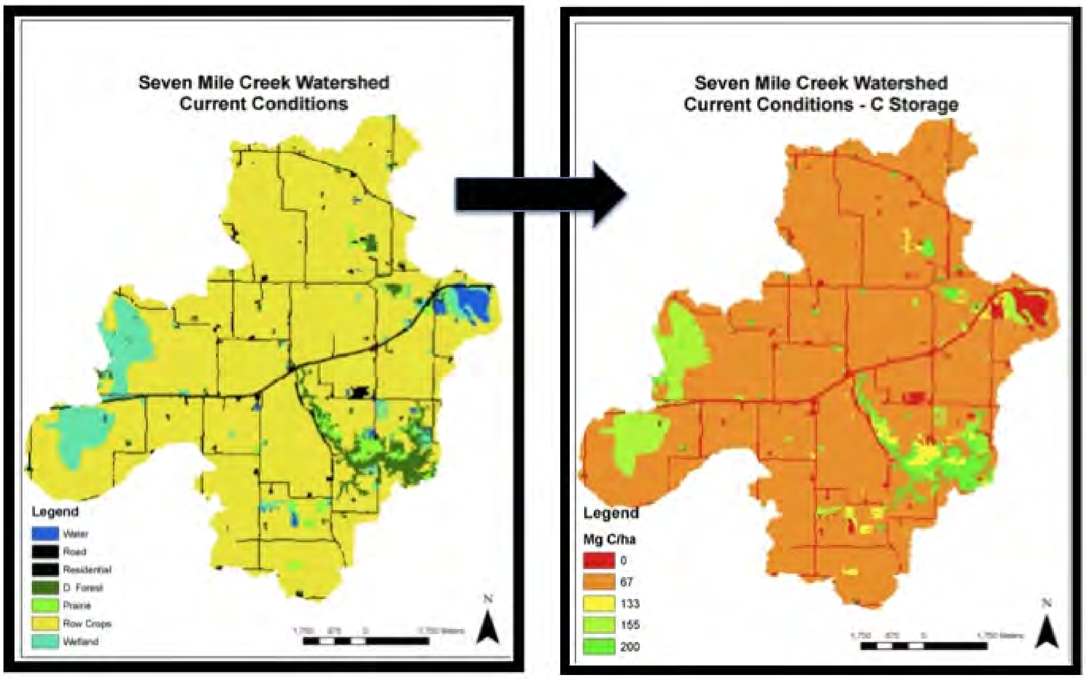


Figure 6. Land use/land cover (LULC) map and associated Carbon storage map for baseline or current conditions in Seven Mile Creek watershed. Biomass and soil carbon storage values based steady-state estimates.

Sediment and phosphorus valuation

The retention of polluting nutrients and filtration of water is an important service provided by functioning ecosystems. As described above, we use the SWAT model to estimate the sediment and phosphorus retention service provided by a landscape over the course of a year. For sediment we convert the ton reduction in the annual loadings at the mouth of Seven Mile Creek and West Fork Beaver Creek into monetary values using the methodology of (Hansen and Ribaudo, 2008); they generated a per-ton soil conservation benefit estimate of water quality and the subsequent impacts on industries, municipalities, and households. These values can be viewed as the prices people, businesses, and government agencies would be willing to pay for a 1-ton reduction in soil erosion. The per-ton benefit values are available on the ERS web site (www.ers.usda.gov) for the 2,111 8-digit Hydrologic Unit Code (HUC) watersheds within the contiguous States. This method assumes that benefits respond linearly as water quality improves.

We convert the annual loadings of phosphorous at the mouth of Seven Mile Creek and West Fork Beaver Creek into monetary values using results from (Mathews et al., 2002); they used a contingent valuation survey to estimate how households in the Minnesota River basin would value a 40% reduction in phosphorus loadings into the Minnesota River. They estimated an aggregate annual household willingness-to-pay of $141 million for a 40% reduction in 1997 dollars ($122.7million in $1992). The water quality benefits (or costs) for each LULC scenario are found by prorating the value of a 40% improvement in water quality to the water quality improvement in the LULC scenario. For example, a 10% reduction in phosphorus exports would generate an annual value of $30.7million ($122.7 times 0.25). We assume that the benefits of phosphorus reduction in Seven Mile Creek and West Fork Beaver Creek are dispersed across the entire Minnesota Basin. Therefore a unit reduction of phosphorus in Seven Mile Creek is benefits the everyone equally in the Minnesota Basin. This method is equivalent to assuming that water quality benefits are linear in water quality improvement. As we did for carbon, we also evaluate how the uncertainty in the value of ecosystem services could influence land-use decisions we calculated two additional estimates: 1) two times the ecosystem service value (2ESV), and 2) eight times the ecosystem service value (8ESV).

The value estimates for both sediment and phosphorus should be viewed with considerable caution. It is a difficult task to estimate the value of water quality improvements from either sediment reduction or reduction in nutrients. The estimates we used can be viewed as a "best guess" but the true value of water quality improvements could be far higher or lower. The current state of the economics literature on the value of clean water, however, does not permit precise estimation of this value at present.

Commodity agriculture production value

The agricultural production model produces estimates of expected gross value of net annual agricultural production value which is the expected agricultural production for a given crop in a given HRU (derived from SWAT) multiplied by commodity price less production costs. Using current and historical crop price and cost (less land rent) data (Lazarus, 2010; Minnesota State Colleges and Universities, 2012) we determined two estimates of price and cost for each agriculture enterprise (see Appendix D): 1) current price and cost based on mean values for the years 2007-2011, and 2) historical price and cost based on mean values for the years 2002-2006.

Habitat availability and quality

The InVEST habitat model accounts for the spatial extent and quality of habitat for a targeted conservation objective (e.g., forest birds). Maps of LULC are transformed into maps of habitat by defining what LULC counts as habitat for various species. Habitat quality in a grid cell is a function of the LULC in the grid cell, the LULC in surrounding grid cells, and the sensitivity of the habitat in the grid cell to the threats posed by the surrounding LULC. Whether a particular LULC type is considered species habitat depends on the objective of biodiversity conservation. For this application, we consider two different terrestrial conservation objectives: (i) functional group diversity focusing on breeding forest interior songbirds, and (ii) functional group diversity focusing on breeding grassland songbirds (based on (Ehrlich et al., 1988).

Each LULC type is given a habitat suitability score of 0 to 1 for general terrestrial biodiversity that includes all species with non-habitat scored as 0 and perfectly suitable habitat scored as 1. For example, grassland songbirds may prefer native prairie habitat above all other habitat types (habitat suitability = 1), but will also make use of a managed hayfield (habitat suitability = 0.5). See Appendix E for the definition of habitat suitability and quality across LULC types.

The habitat quality score in a grid cell can be modified by LULC in surrounding grid cells. We consider sources of degradation as those human modified LULC types (e.g., urban, agriculture, and roads) that cause edge effects (Forman, 1995; McKinney, 2002). Edge effects refer to changes in the biological and physical conditions that occur at a patch boundary and within adjacent patches (e.g., facilitating entry of predators, competitors, invasive species, toxic chemicals and other pollutants). The sensitivity of each habitat type to degradation is based on general principles of landscape ecology and conservation biology (e.g., (Lindenmayer et al., 2008) and is specific to each measure of biodiversity. See Appendix E for the sensitivity scores and the influence of threats determined from the literature and expert knowledge.

We generate a habitat quality score for each landscape with and without conservation by summing across all the grid cell degradation-adjusted habitat quality scores. Because of the influence of adjacent patches on quality scores, the spatial pattern of land use as well as the overall amount of habitat will matter in determining the landscape habitat quality score. Habitat quality scores should be interpreted as relative scores with higher scores indicating landscapes more favorable for the given conservation objective. The landscape habitat quality score cannot be interpreted as a prediction of species persistence on the landscape or other direct measure of species conservation in the same way that the output of the carbon model is an estimate of the actual carbon stored on the landscape. The InVEST habitat model does not convert habitat quality measures into monetary values.

Recreation activity value

To estimate changes in annual recreation value for a given LULC pattern, we employed the Wildlife Habitat Benefits Estimation toolkit (Loomis and Richardson, 2007). This is a suite of predictive models derived from empirical meta-analyses for estimating annual activity days and value as a function of land-use type and area, access, and state-level population and median income. The toolkit can be applied to private and public lands that are potential habitat for game species. (e.g., cropland, grasslands, forests). Specifically we sought to predict changes in annual state-level big-game hunting, small-game hunting, and wildlife viewing days and resultant economic value for each point along the efficiency frontiers and alternative scenarios for Seven Mile Creek and West Fork Beaver Creek (see appendix for model details).

The economic values for outdoor recreation are the average consumer surplus values for a day of big-game hunting, small-game hunting, migratory waterfowl hunting, and wildlife-viewing, which are $60, $33, $37, and $48, respectively (Loomis and Richardson, 2007); see Appendx-F). The hunting value per day is based on the average of 192 estimates from 21 studies of big game, small game, and migratory bird hunting value per day in the north and northeast regions. The wildlife-viewing value per day is the average of 81 estimates from nine studies of wildlife-viewing value per day in the Northeast. We estimate annual value per activity by multiplying the value of the activity per day by the annual activity days. The annual value per activity is summed to calculate the total annual value of recreation. Finally, we also evaluate how the uncertainty in the value of ecosystem services could influence land-use decisions we calculated two additional estimates: 1) two times the ecosystem service value (2ESV), and 2) eight times the ecosystem service value (8ESV).

Alternative land management practices

We explored a suite of alternative landscape land management practices that ranged from typical management practices to more dramatic shifts in vegetation at the landscape scale in order to evaluate a range of options for achieving sediment and phosphorus reduction goals:

- Conservation Tillage: Chisel and disk tillage practices are replaced with a conservation tillage practice that leaves 30% residue at the time of planting. Field cultivators are still used before planting.
- Reduced P Fertilizer Application: Fall application of P fertilizer is reduced by 50% from current levels. Manure application (only in Seven Mile Creek) is unchanged.
- Cropland Conversion to Grassland: Biomass is harvested. Previous tile drainage systems remain intact.
- Cropland Conversion to Switchgrass: Biomass is harvested. Previous tile drainage systems remain intact.
- Cropland Conversion to Forest: Previous tile drainage systems remain intact.
- Cropland Conversion to Wetlands: Croplands in low-lying areas converted to wetlands. Wetland characteristics (drainage area / volume) estimated from DEM. Tile drainage removed. This option was explored in Seven Mile Creek only, owing to the suitability of the landscape for wetland restoration and the historic presence of wetlands in that watershed. Cropland area in Seven Mile Creek was reduced by 9%.

Optimization Methods

The goal of the analysis is to combine results from SWAT for crop production and water quality, and InVEST for the value of ecosystem services and the value of agricultural output, to find efficient land-use and land-management decisions for a watershed that maximize gains in water quality for a given value of agricultural production and ecosystem services. By measuring the value of ecosystem services and agricultural crop production in monetary terms we can summarize the value of these outputs in a single measure of economic returns. We can then illustrate the tradeoffs between improvements in water quality and economic returns in a simple graph in two dimensions. By finding the maximum TMDL reduction for a given level of economic return, and then varying the economic return over its entire potential range, we can trace out the efficiency frontier (also called a production possibility frontier). The efficiency frontier illustrates what can be achieved in terms of water quality and economic returns by carefully arranging the spatial allocation of activities across the landscape and the necessary tradeoffs between the water quality and economic returns on the landscape. The efficiency frontier also illustrates the degree of inefficiency of other land-use patterns not on the frontier, showing the amount by which water quality improvements and/or economic returns could be increased.

Our water quality objectives are: (1) reductions in phosphorus loadings (P), and (2) reductions in sediment (S), compared to the baseline of the existing landscape. Our other objectives are: (1) the change in market returns (from agriculture), and (2) the change in market + non-market returns that include the value of all ecosystem services (carbon sequestration, phosphorus reduction, sediment reduction). The value of recreation was added into the totals for the landscape score but was not used in generating the efficiency frontier. The value of agricultural products as well as the value of ecosystem services is subject to considerable variation. For example, prices for corn went from $2 per bushel in 2005 to over $6 per bushel in 2011 (USDA ERS 2011; http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx). Estimates of the value of carbon sequestration range from near zero to several hundreds of dollars per ton of carbon (Tol 2009). Here we present several efficiency frontiers for both water quality objectives, reduction in P and reduction in S, and for six different measures of the economic returns that capture some of the variable in values of crops and ecosystem services: (1) current market returns (using 2007-2011 prices), (2) historical market returns (using 2002-2006 prices), (3) current market returns plus the value of ecosystem services, (4) historical market returns plus the value of ecosystem services, (5) current market returns plus two times the value of ecosystem services, and (6) current market returns plus eight times the value of ecosystem services. We index these various measures of the economic returns with $l = 1,\ldots,6$.

Let $j = 1,\ldots,J$ index the HRUs on the landscape of interest. Let k index LULC conversions on the landscape. LULC conversions from current use include “to conservation tillage” (k = 1); “to forest” (k = 2); “to switchgrass” (k = 3); “to prairie” (k = 4); “to low-phosphorous agriculture” (k = 5); and “no change” (k = 6). Let $x_{jk} = 1$ indicate that land in HRU j converts to LULC k and $x_{jk} = 0$ otherwise. Each HRU must either remain in the same land use or convert to one of the other options so that $\sum_{k=1}^{6} x_{jk} = 1$. We assume that all area in an HRU has the same LULC.

Let y_{jkl} indicate the annual net gain in monetary returns in HRU j when its land is converted to LULC k under the measure of the economic returns l. For example, $y_{jkl} = 4$ means that the conversion to LULC k in HRU j will generate an additional $4 per year in j compared to the current LULC assuming the measure of the economic returns l. A negative y_{jkl} indicates that the transition to k in j will generate less in annual net returns than the current LULC using l. The change in annual net economic returns in HRUs that do not transition LULC is equal to 0 for all measures of the economic returns (i.e., $y_{j6l} = 0$ for all j and all l).

Let P_{jk} indicate the annual reduction in metric tons of phosphorous emitted from HRU j given the LULC transition choice k (where negative numbers indicate an increase in phosphorous emissions). Let S_{jk} indicate the annual reduction in metric tons of sediment emitted from HRU j given the LULC transition choice k (where negative numbers indicate an increase in sediment emissions). The change in P and S is equal to 0 in HRUs that do not change LULC (i.e., $P_{j6} = S_{j6} = 0$ for all j).

Formally, the social planner's objective is to maximize annual reductions in the emissions of phosphorus or sediment across the landscape by choosing a LULC transition in each HRU in the landscape subject to a fixed annual budget, b, which fixes the level of change in the measure of the economic returns l. The optimal LULC choice, X*(b, l, z), that maximizes the reduction in pollutant z, where $z = P, S$, solves the following problem:

$$X^*(b,l,z) =_{\{x_{jk}\}} Max \sum_{j=1}^{J} \sum_{k=1}^{6} z_{jk} x_{jk}$$

Subject to:

$$x_{jk} = \{0,1\}\ for\ all\ j,k$$

$$\sum_{k=1}^{6} x_{jk} = 1\ for\ all\ j$$

$$\sum_{j=1}^{J} \sum_{k=1}^{6} y_{jkl} x_{jk} \geq b$$

$$y_{j6l} = 0\ for\ all\ l\ and\ all\ j; p_{j6} = 0\ for\ all\ j$$

For example, suppose $b = -6{,}000{,}000$. If $X^*(b = -6{,}000{,}000, l, z) = \sum_{j=1}^{J}\sum_{k=1}^{6} z_{jk} x_{jk}^{*} = 100$, then society must sacrifice at a minimum $6,000,000 a year in economic returns according to accounting method *l* to reduce annual emissions of pollutant *z* on the landscape by 100 tons a year.

Suppose the social planner considers a set of budgets, $b_1,\ldots,b_S$. The set of solutions given these budgets , forms the problem's efficiency frontier over the range $b_1,\ldots,b_S$. We graphically represent the efficiency frontier with a plot of $b_1,\ldots,b_S$ and corresponding $X^*(b_1, l, z),\ldots, X^*(b_S, l, z)$ where *b* values (representing economic returns) are on the *x*-axis and *X** values (representing water quality improvements) are on the *y*-axis.

Results

Watershed Flow, Sediment, and Phosphorus Contributions

Seven Mile Creek and West Fork Beaver Creek are similar in their land cover composition with the majority of the landscape devoted to row crop agriculture. Despite this similarity, the watersheds differ in two notable ways. Mean annual precipitation in Seven Mile Creek watershed is about 14% greater than in West Fork Beaver Creek and Seven Mile Creek watershed includes an area characterized by steep slopes as the stream transitions from the flat uplands down to its confluence with the Minnesota River. This steep region is an important source of sediment (and, to a lesser extent, phosphorus) in Seven Mile Creek watershed. This difference between the two watersheds is apparent when comparing area-normalized monthly sediment and phosphorus loads derived from water quality monitoring data (Fig. 7). The most direct comparison is for the period from 2006-2008 during which monitoring data were available for both watersheds. Area-normalized mean monthly flow and phosphorus export are comparable between both watersheds, indicating those water and phosphorus yields are driven by similar processes in both watersheds. In contrast, however, monthly loads of total suspended solids (area-normalized) are over an order of magnitude greater in Seven Mile Creek watershed than in West Fork Beaver Creek watershed. This difference is due to the importance of non-field sources of sediment (ravines, gullies, streambanks) that are prominent in the steeper portions of Seven Mile Creek watershed.

Water Balance

Water budgets for the study watersheds (Fig. 8) show only slight differences in the dominant sources of stream flow between Seven Mile Creek and West Fork Beaver Creek. In both watersheds, flow from subsurface tile drainage comprises the single largest component of total water yield. This contribution is much larger in Seven Mile Creek watershed, however, owing to the greater proportion of drainage present in this watershed. Surface runoff is an important component of water yield in both watersheds. Remaining contributions to total water yield are surface runoff (both watersheds), lateral soil flow (Seven Mile Creek) and shallow groundwater flow (West fork Beaver Creek). It is important to note that the model calibration and validation is performed on total water yield. Additional data sources are used to ensure that the proportion of water yields from tile drainage and losses to groundwater are realistic, but these components of flow are not measured directly in the study watersheds.

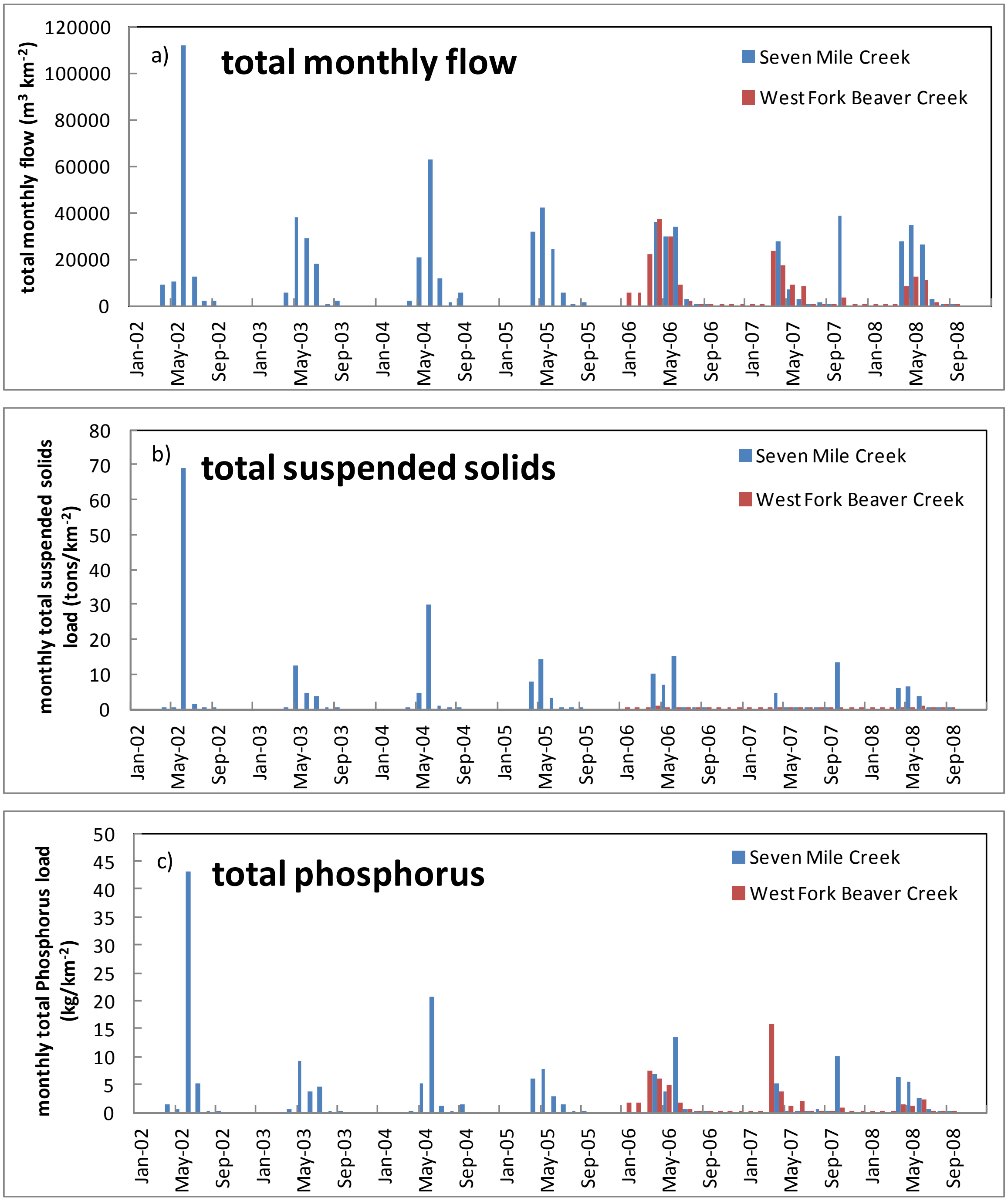
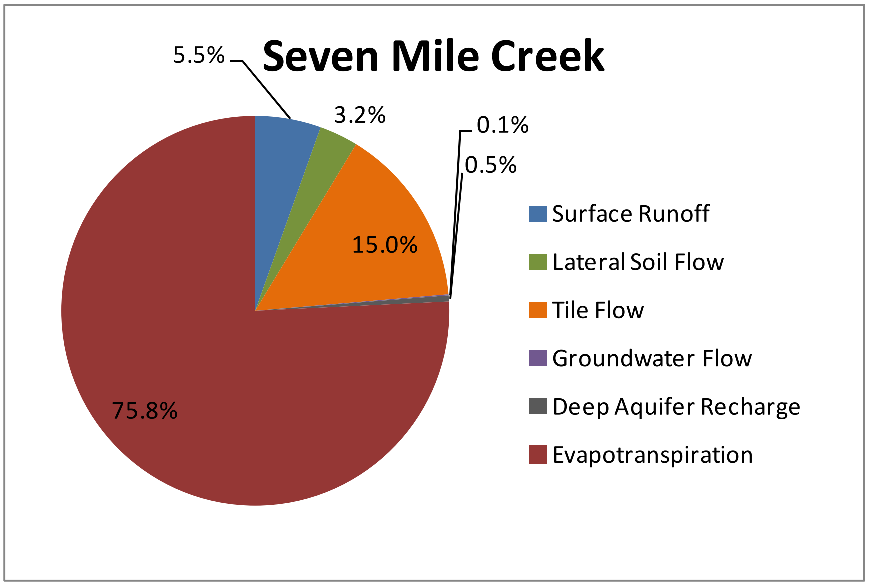


Figure 7. Bar graphs showing area-normalized a) water, b) sediment, and c) phosphorus loads at the watershed outlet under baseline conditions for the two study watersheds. Data shown reflect the period of monitoring data available for each watershed. Tabular data are contained in Appendix A.

.



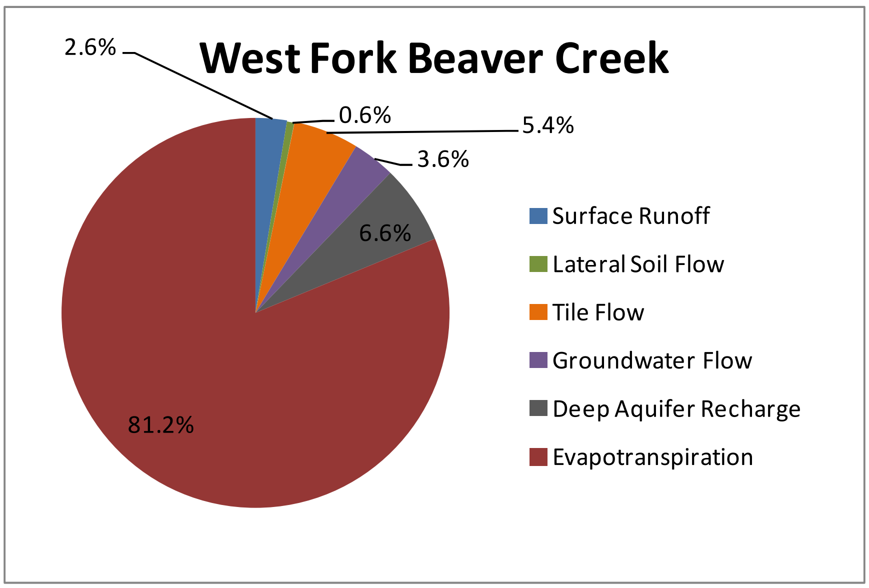


Figure 8. Water budgets for Seven Mile Creek and West Fork Beaver Creek watersheds. Results are based on SWAT model output for the calibration and validation period (Seven Mile Creek: 2002-2008; West Fork Beaver Creek (2006-2008).

Measuring model performance (model calibration and validation)

Performance of the SWAT model was assessed by comparing the models ability to match monthly values of observed flow (mean monthly discharge) and water quality parameters (total monthly loads of sediment and phosphorus).

In addition to comparing mean values for the calibration and validation periods, model performance is evaluated with the Nash-Sutcliffe Efficiency metric (NSE; (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{(Y_o - Y_m)^2}{(Y_o - \overline{Y_o})^2}$$

Where Y_o is the observed monthly value (discharge or load), Y_m is the modeled value of the same parameter, and $\overline{Y_o}$ is the mean value of the observed data. NSE values can range from $-\infty$ to 1. Perfect agreement between predicted and observed data results in NSE = 1; an NSE value of 0 indicates that the mean of the observed data is as accurate as the model predictions. For watershed scale modeling, NSE values of 0.36 to 0.50 are generally considered fair, values from 0.50 to 0.75 are considered good, while values greater than 0.75 indicate excellent model performance (Motovilov et al., 1999).

Allocating field and non-field sources of sediment and phosphorus in Seven Mile Creek and West Fork Beaver Creek watersheds.

Sediment loads observed at the outlet of Seven Mile Creek watershed were strongly correlated with observed flow and predicted by a power function ($r^2 = 0.99$; Fig. 9). For baseline watershed conditions, non-field sources comprise approximately 76% of the total sediment load at the outlet of Seven Mile Creek watershed. This flow-based approach is applied to the alternative scenarios in order to predict how the contribution of non-field sources will change under different flow regimes. A similar approach was applied to West Fork Beaver Creek watershed. However, the flow-sediment relationship was described by a linear regression (Fig. 10) rather than the more typical power function based on available observed data. This flow-based approach provided a valuable tool for helping to identify the importance of non-field sediment sources in this watershed.

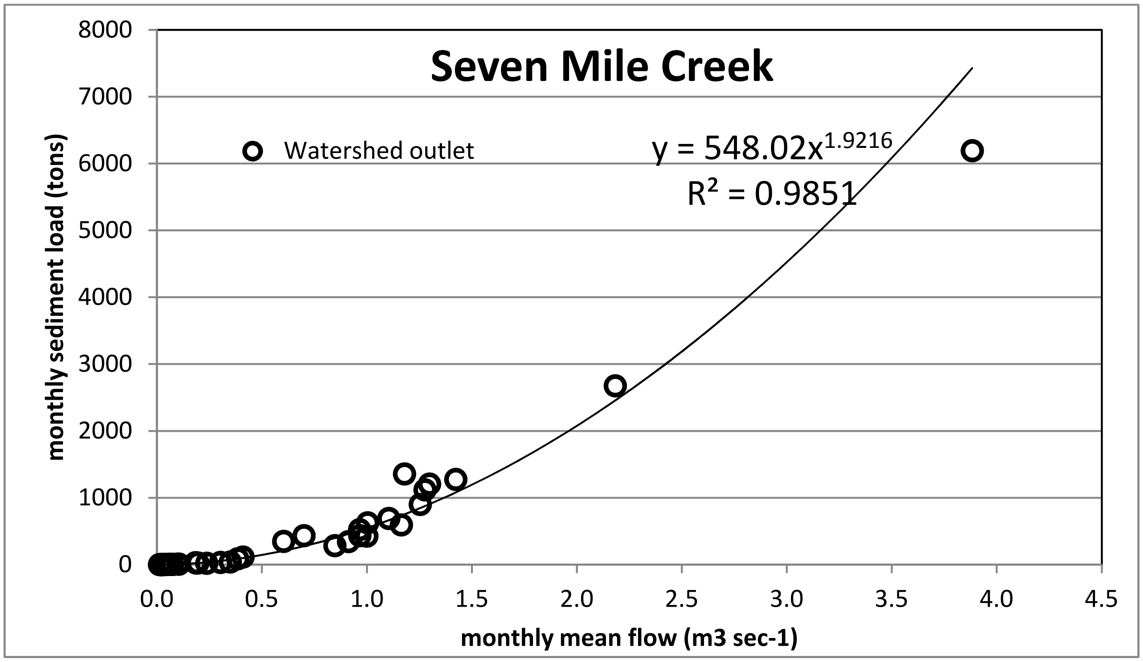


Figure 9. Relationship between monthly suspended sediment load and monthly mean stream flow at the outlet of Seven Mile Creek watershed. This relationship is based on observed flow and sediment data and is used in conjunction with SWAT-predicted sediment from field sources in order to partition sediment exported from Seven Mile Creek into field and non-field sources.

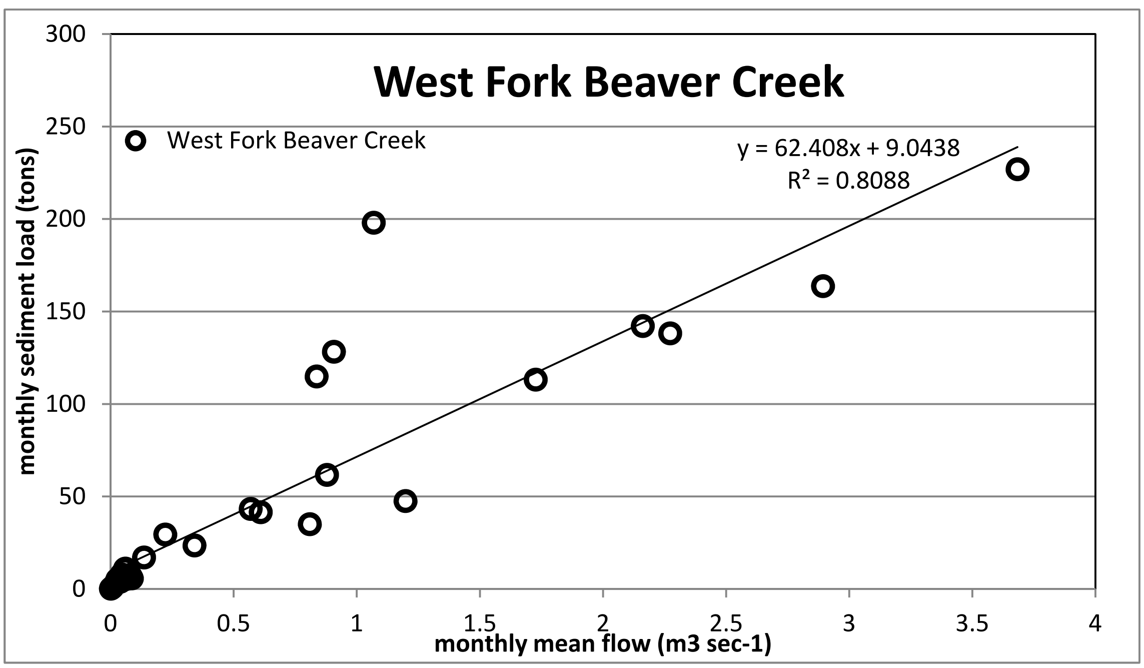


Figure 10. Relationship between monthly suspended sediment load and monthly mean stream flow at the outlet of West Fork Beaver Creek watershed. This relationship is based on observed flow and sediment data and is used in conjunction with SWAT-predicted sediment field sources in order to partition sediment exported from West Fork Beaver Creek into field and non-field sources.

Calibration and Validation – Seven Mile Creek

Flow

For Seven Mile Creek Watershed, the time period used for evaluation was from 2002 through 2008. For that seven-year period, 75.8% of precipitation left the watershed via evapotranspiration (ET) while 23.7% of precipitation contributed to streamflow at the watershed outlet (the remaining 0.5% was lost to deep aquifer recharge). This partitioning between ET and water yield is comparable to other reported values in the region and suggests that the calibrated SWAT model is doing an adequate job of simulating plant growth and water use. Of the water that reaches the outlet of Seven Mile Creek watershed, the largest proportion (63.1%) is comprised of subsurface tile drainage (15% of annual precipitation) with smaller amounts from surface runoff and lateral soil flow (23.0% and 13.6% of streamflow, respectively).

The calibrated SWAT model did a good job of predicting streamflow from Seven Mile Creek watershed. For the model validation conducted at the watershed outlet, mean monthly predicted streamflow was 0.66 m^3 sec^{-1}, slightly greater than the observed value of 0.58 m^3 sec^{-1}. The model did a very good job capturing the timing and magnitude of large flow events (Fig. 11) and the NSE value of 0.89 indicates excellent model performance. Additional summary statistics for model calibration and validation sites in Seven Mile Creek watershed are contained in Table 3 and final model calibration parameters are presented in Appendix B.

Table 3. Summary statistics for flow calibration and validation at three monitoring sites in Seven Mile Creek watershed.

Flow	Calibration			Validation			Overall Mean (2002-2008)	
Site	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})	NSE value	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})	NSE value	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})
1 - upland	0.27	0.33	0.85	0.16	0.22	0.52	0.21	0.27
2 - upland	0.28	0.31	0.95	0.26	0.19	0.61	0.26	0.24
3 - outlet	-	-	-	0.58	0.66	0.89	-	-

Sediment

For this study, the SWAT model was directly used to predict sediment losses from field sources only based on model calibration to monitoring stations located in the upper flat portion of Seven Mile Creek watershed and based on the assumption that non-field sources of sediment (streambank/ditch failure and ravines) are negligible in this portion of the watershed. When considering edge-of-HRU losses the average value from 2002-2008 was 0.82 tons $hectare^{-1}$. A large portion of this sediment does not reach the watershed outlet, however, and gets deposited in temporary waterways or ditches and stream channels. After accounting for in-channel deposition, only about 9.5% of sediment eroded from fields is delivered to the watershed outlet. This is in agreement with compiled sediment delivery ratio values for watersheds of similar size to Seven Mile Creek (compiled by (Boyce, 1975) and presented in (Haan et al., 1994).

When considering sediment delivered to the outlet of Seven Mile Creek watershed, contributions from non-field sources such as ravines, gullies, and streambanks present in the lower portion of the watershed are important considerations. Based on the observed sediment and streamflow data (Fig. 5) and SWAT-simulated streamflow for the seven year study period, roughly 77% of all sediment delivered to the watershed outlet is derived from non-field sources (Fig. 11).

SWAT model calibration for sediment was conducted at two monitoring locations located in the flat upper portion of the watershed in order to calibrate the model for sediment derived from field sources. Calibrating the model at these sites produced good agreement of predicted and observed mean monthly sediment loads with NSE values of 0.66 and 0.80 for the calibration period and NSE values of 0.40 and 0.47 for the validation period (Table 4) indicating good to fair model performance. When the calibrated model was applied to sediment data at the watershed outlet, however, the model greatly under predicted observed sediment loads and the NSE value of 0.23 indicates poor model performance, showing that non-field sources of sediment are important contributors in the lower portion of the watershed. When model flow data were used to predict sediment based on the sediment-discharge relationship (Fig. 9), predicted values showed excellent agreement with observed data (Fig. 11; Table 4). Final SWAT calibration parameters are contained in Appendix B.

Table 4. Summary statistics for sediment calibration and validation at three monitoring locations in Seven Mile Creek watershed.

Sediment	Calibration			Validation			Overall Mean (2002-2008)	
Site	Ave. Obs. (tons)	Ave. Pred. (tons)	NSE value	Ave. Obs. (tons)	Ave. Pred. (tons)	NSE value	Ave. Obs. (tons)	Ave. Pred. (tons)
1 - upland	29.3	23.1	0.80	7.8	10.6	0.47	16.8	15.9
2 - upland	45.6	47.4	0.66	22.0	18.8	0.40	31.8	30.8
3 - outlet	-	-	-	461	94.5	0.23	-	-
3* - outlet	-	-	-	461	452	0.95	-	-

* Total sediment determined based on monthly flow-sediment empirical relationship.

Phosphorus

Similar to sediment, phosphorus in Seven Mile Creek watershed was calibrated at the two upland sites based on the assumption that non-field contributions of phosphorus (from streambank/ditch failures and ravines) are negligible in this flat portion of the watershed. The calibrated model performed fair to excellent during the calibration and validation periods for the two upland sites (Table 5). Final model calibration parameters are presented in Appendix B. For the calibration period, NSE values ranged from 0.48 (site 2) to 0.90 (site 1) showing fair to excellent model performance. Model NSE values from the validation period were 0.42 (site 1) and 0.40 (site 2) indicating fair model performance. For model validation at the watershed outlet, when non-field sources of phosphorus are not included, NSE values are excellent (0.88) although the overall phosphorus loads are under predicted by roughly 28%. When non-field sources of phosphorus are included in the model prediction, NSE values diminish to 0.71 but still indicate good model performance and overall loads are closer to observed values (over predicted by roughly 15%).

Table 5. Summary statistics for phosphorus calibration and validation at three monitoring locations in Seven Mile Creek watershed.

Phosphorus	Calibration			Validation			Overall Mean (2002-2008)	
Site	Ave. Obs. (kg)	Ave. Pred. (kg)	NSE value	Ave. Obs. (kg)	Ave. Pred. (kg)	NSE value	Ave. Obs. (kg)	Ave. Pred. (kg)
1 - upland	138	99	0.90	45	41	0.42	84	65
2 - upland	170	187	0.48	103	70	0.40	131	119
3 - outlet	-	-	-	362	260	0.88	-	-
3* - outlet	-	-	-	362	418	0.71	-	-

* Total Phosphorus estimate includes non-field sources

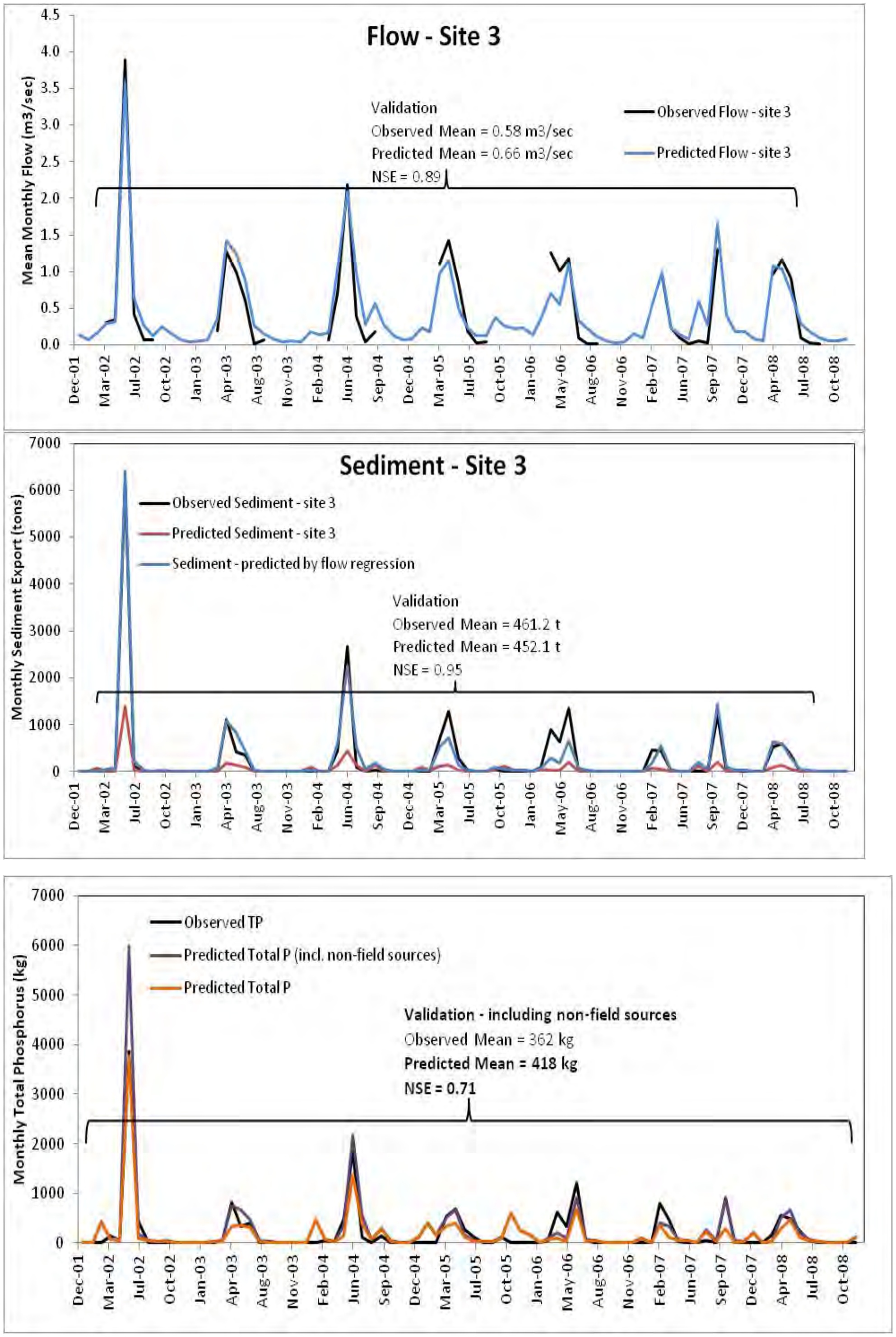


Figure 11. Observed and predicted flow, sediment, and phosphorus for the validation site at the outlet of Seven Mile Creek watershed.

Calibration and Validation – West Fork Beaver Creek

Flow

In West Fork Beaver Creek watershed, evapotranspiration accounted for roughly 81.2% of annual precipitation for the simulation period from 2006-2008. Water yield simulated at the watershed outlet was about 12.2% of precipitation while 6.6% of precipitation contributed to groundwater recharge. Similar to Seven Mile Creek watershed, surface runoff and tile flow comprise much of water yield. In contrast to Seven Mile Creek, simulation results suggest that flow from shallow groundwater also contributes to water yield. This is likely the result of more extensive subsurface drainage in Seven Mile Creek watershed, which intercepts soil water before it can become part of the shallow groundwater component of the SWAT model. Predicted mean monthly flow for the calibration period (2006; 0.74 m^3 sec^{-1}) was slightly less than the observed value (0.94 m^3 sec^{-1}). The NSE value of 0.85 indicated very good model performance. For the validation period from 2007-2008, predicted mean flow values were close to observed values (0.47 and 0.49 m^3 sec^{-1}, respectively; Fig. 12), although NSE decreased to 0.48 indicating good model performance (Table 6). Final model parameter calibration values are contained in Appendix B.

Table 6. Summary statistics for flow calibration and validation in West Fork Beaver Creek watershed.

Flow	Calibration			Validation			Overall Mean (2006-2008)	
Site	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})	NSE value	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})	NSE value	Ave. Obs. (m^3 sec^{-1})	Ave. Pred. (m^3 sec^{-1})
Outlet	0.94	0.74	0.85	0.47	0.49	0.48	0.64	0.58

Sediment

Sediment export from West Fork Beaver Creek watershed was roughly an order of magnitude less than from Seven Mile Creek watershed owing to the lack of steep ravines in West Fork Beaver Creek. Following calibration of West Fork Beaver Creek watershed to simulate edge-of-HRU sediment losses, a flow-sediment relationship approach similar to that applied to Seven Mile Creek was developed for West Fork Beaver Creek. It is important to note that West Fork Beaver Creek is only monitored at one location (as opposed to three locations for Seven Mile Creek). For West Fork Beaver Creek, sediment calibration was first performed to achieve suitable model agreement during the calibration period. Then, a sediment-discharge relationship based on observed data was used to estimate the proportion of sediment derived from non-field sources as described above. Applying this approach to West Fork Beaver Creek watershed suggests that field-derived sediment comprises roughly 61% of the load observed at the watershed outlet while the remainder is derived from non-field sources. This is in contrast to Seven Mile Creek, where approximately 23% of sediment observed at the watershed outlet is predicted to originate from field sources. It is important to note that the gauge location for West Fork Beaver Creek watershed is not located immediately adjacent to its confluence with the Minnesota River and there may be some important non-field sources of sediment that are not monitored at the current location nor represented in the watershed model.

SWAT model calibration for sediment was conducted for 2006 while the validation period was 2007-2008. SWAT predictions of sediment ranged from good to fair for the calibration and validation periods, respectively (NSE values of 0.79 and 0.48). For the duration of the model period (2006-2008), predicted mean monthly sediment loads (45 tons) were slightly less than observed loads (49 tons) but overall model performance was good (Table 7; Fig. 12). Final model parameter calibration values are contained in Appendix B.

Table 7. Summary statistics for sediment calibration and validation in West Fork Beaver Creek watershed.

Sediment	Calibration			Validation			Overall Mean (2006-2008)	
Site	Ave. Obs. (tons)	Ave. Pred. (tons)	NSE value	Ave. Obs. (tons)	Ave. Pred. (tons)	NSE value	Ave. Obs. (tons)	Ave. Pred. (tons)
Outlet	67	52	0.54	38	17	0.47	49	30
Outlet*	67	55	0.79	38	40	0.48	49	45

* Total sediment determined based on monthly flow-sediment empirical relationship.

Phosphorus

SWAT predictions of sediment did a good job of capturing the general timing and magnitude of observed data (Fig. 12) and NSE values for the calibration period were excellent (0.78) while values for the validation period were fair (NSE = 0.49). Final model parameter calibration values are presented in Appendix B. In general, SWAT under predicted monthly phosphorus loads and the mean predicted values were 38% lower than observed loads (Table 8). However, this was primarily due to two months (May 2006 and March 2007). The model also over predicted phosphorus loads in January 2007, which appears to be the result of flow over-predictions occurring during the same month.

Table 8. Summary statistics for phosphorus calibration and validation in West Fork Beaver Creek watershed.

Phosphorus	Calibration			Validation			Overall Mean (2006-2008)	
Site	Ave. Obs. (kg)	Ave. Pred. (kg)	NSE value	Ave. Obs. (kg)	Ave. Pred. (kg)	NSE value	Ave. Obs. (kg)	Ave. Pred. (kg)
Outlet	533	395	0.78	367	177	0.49	428	256
Outlet*	533	402	0.78	367	186	0.49	428	265

* Total Phosphorus estimate includes non-field sources

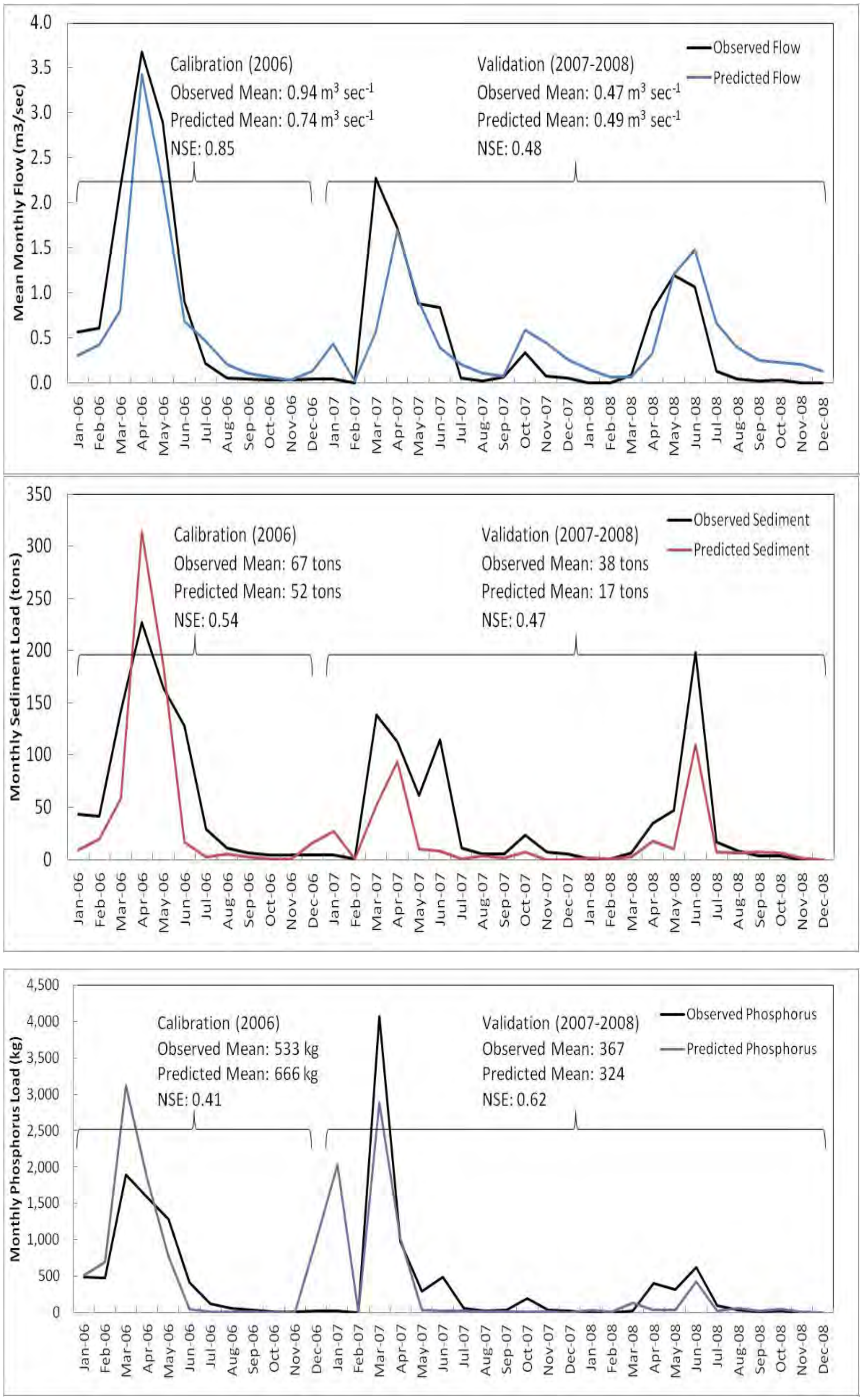


Figure 12. Observed and predicted flow, sediment, and phosphorus for the validation site at the outlet of West Fork Beaver Creek watershed .

Optimization Results

Using the methods described in Section 2 for Seven Mile Creek and West Fork Beaver Creek, we find efficiency frontiers for sediment and phosphorus reductions and economic returns for each watershed. Below we begin by summarizing the results for the Seven Mile Creek in detail. We then summarize results for West Fork Beaver Creek more briefly by highlighting important similarities and differences between the two watersheds.

Efficiency frontier for sediment reduction and current market returns for Seven Mile Creek

Solving the optimization problem shown above for a range of budget levels we find the efficiency frontier for the Seven Mile Creek Watershed. The efficiency frontier for sediment reduction (Fig. 13) shows the maximum level of sediment reduction for any given level of change in economic returns. Starting from the land use pattern that generates the maximum economic return, labeled as point A in Fig. 13, we find land-use changes that reduce sediment losses with minimal impact on the economic returns (the efficiency frontier is quite steep). At point A, both the sediment reduction and economic returns are improved relative to the baseline landscape. Compared to the baseline, the landscape for point A results in a 103 ton reduction in sediment (3.5% sediment reduction) and a $171,657 increase in annual economic returns (4% increase) (Table 9). This improvement in both dimensions relative to the baseline landscape (a “win-win” scenario) is accomplished by the conversion of 97% of conventional annual row crop production area to annual row crop production with 50% less phosphorus inputs, and a small area put into conservation tillage and diverse grassland (Fig. 14). The conversion of a small amount of area to conservation tillage and diverse grasslands in lower quality soils that are highly erodible reduces sediment losses and raises economic returns.

Point B in Fig. 13 increases the sediment reduction relative to the baseline by 750 tons, a 25% reduction in the baseline annual sediment loadings. Point B results in a modest reduction of the economic score relative to the baseline, a drop in annual economic returns of -$158,000, or 3.6% percent of the baseline economic returns for Seven Mile Creek. Among the first changes made to reduce sediment, which result in large reductions at low cost are to increase the amount of area in diverse grasslands along riparian areas and high erosion areas (Fig. 14). Doing so results in a large decrease in sediment per reduction in the value of marketed commodities.

Because there is some scope for “win-win” changes that both reduce sediment losses and increase economic returns (as shown by point A), there is potential to make reasonably large percentage reductions in sediment loadings at little to no cost relative to the baseline. For Seven Mile Creek, our results indicate that sediment reductions of approximately 19% can be made at no loss in economic returns relative to the baseline (Fig. 13).

Moving beyond 20-25% sediment reductions, however, come at increasingly higher costs. In moving from sediment reductions of 25% to 50%, a reduction in sediment loads relative to the baseline of 1,470 tons, requires a loss in the economic returns of $912,000 or 21% of the baseline economic returns (point C in Fig. 13; Table 9). The main land–use change in moving from point B to point C involves converting more annual cropland to diverse grassland production, mostly in the central and eastern region of the watershed (Fig. 14). There is also an increase in switchgrass production concentrated in the central and western portions of the watershed (Fig. 14). Because more land is shifted out of uses that generate high economic returns, such as corn and soy production, toward lower valued economic activity (perennial biomass for biofuel production), economic returns are reduced. Note that the cost of reducing sediment in terms of lower economic returns is higher in moving from B to C (25% to 50% reduction) than from A to B (5% to 25% reduction). The low-cost means of reducing sediment are done first (up to 25% reduction) leaving more costly methods of reducing sediment (from 25% to 50% reduction). The efficiency frontier becomes flatter as sediment reductions increases relative the baseline (Fig. 13). Reducing sediment losses above 50% requires still more costly changes in land use. Getting to a 75% sediment reduction (Point D in Fig. 13) and maximum sediment reduction (Point E, Fig. 13) requires increasingly shifting lands from annual row crop production to perennial biofuel production and natural forests. Much of this land becomes switchgrass production (83% of the land in the land-use pattern at point E), with other perennial vegetation types including diverse grassland and forest moderately expanding (Fig 14). The shift to dominance of land in perennial vegetation prevents from 1,470 to 2,230 tons (or 50% to 82.9%) of sediment from leaving the watershed, but comes at a steep economic cost. Annual economic returns are reduced by -$3,115,130 or 71.5% of the baseline economic returns for the land-use pattern at point E.

Overall, compared to the baseline landscape, points on the efficiency frontier have less conventional till agriculture and more natural cover. There is a shift from predominantly agricultural land toward natural land as sediment reduction is increased.

Comparing results from best management practices with the efficiency frontier for Seven Mile Creek

A standard approach for reducing nutrient and sediment loading is to introduce "best management" practices designed to improve environmental performance within the context of a working agriculture landscape. We analyzed the performance of several best management practices including grassland buffers along waterways of (25 m and 250 m), conversion of highly erodible areas to grasslands, and 250 m grassland buffers surrounding wildlife refuges. Two of these practices, 25 m grassland buffers along waterways and 250 m grassland buffers surrounding wildlife refuges, resulted in reductions of sediment of less than 5% compared to the baseline (Fig. 13 and Table 9). The other two best management practices, 250 m grassland buffers along waterways and conversion of highly erodible areas to grasslands, resulted in roughly 15% reductions compared to the baseline. Implementation of any single best management practice on its own is not capable of generating the types of sediment reductions necessary to meet TMDL standards. Generating 50% reductions or larger appears to require large-scale changes in land use (as under points C, D, or E on the efficiency frontier). Further, all of the best management practices were well inside the efficiency frontier (Fig. 13). In other words, the cost of achieving sediment reductions was higher using these best management practices than using optimal approaches to reduce sediment.

Efficiency frontier for sediment reduction and current market returns plus ecosystem services value, twice ecosystem services value, and eight times ecosystem services value for Seven Mile Creek

The addition of economic values that account for ecosystem services such as carbon sequestration, recreation, sediment and phosphorus reductions, and the value of agricultural crop production shifts the efficiency frontier to the right (Fig. 15) relative to the efficiency frontier for current market returns. A shift to the right means that there are economic gains for a given level of sediment of phosphorus reduction relative to the efficiency curve based on market returns only. The efficiency curve shifts to the right because adding the value of ecosystem services increases the overall value of economic returns. The shift to the right in the efficiency frontier is greater at higher levels of sediment reduction because actions taken to reduce sediment also tend to increase ecosystem services. For example, carbon sequestration is 7,460 tons higher than baseline with a 75% reduction in sediment while only 2,544 tons higher than baseline with a 25% reduction in sediment (Table 9) for the efficiency frontier for sediment reduction and economic returns that includes market returns and the value of ecosystem services. Similarly, phosphorus reductions, recreation and habitat for grassland and breeding birds all increase as the amount of sediment reduction is increased (Table 9). Including the value of ecosystem services raises the level of sediment reduction that occurs in the landscape that maximizes economic returns relative to the baseline (Point A in Fig. 15). At point A there is a reduction of 447 tons of sediment (15.2%) and a $359,618 (8.2%) increase in annual economic returns (Table 9). This improvement is accomplished by the conversion of 63% of conventional annual row crop production area to annual row crop production under a 50% less phosphorus input scheme and conversion of some crop are to forest. Including the value of ecosystem services also increases the level of sediment reduction that can occur without loss of economic returns relative to the baseline.

The efficiency curve shifts further to the right, indicating that sediment reductions are associated with higher economic returns as the value of ecosystem services is increased (two-times and eight-times the value; Fig. 16 and Table 9). In the case of twice the value of ecosystem services, sediment reductions up to 80% can be achieved without loss of economic returns relative to the baseline. In the case of eight times the value of ecosystem services, the value of economic returns is always higher than it is in the baseline.

Increasing the value of ecosystem services increases the level of sediment reduction associated with the landscape that maximizes economic returns. The maximum economic returns for the efficiency frontier for sediment reduction and current market returns plus ecosystem service value times 2 occurs at a sediment reduction of 1349 tons, or 46% reduction relative to baseline. This landscape also has an increase in annual economic return of $2,110,819, or a 48% increase from current baseline conditions. The amount of sediment reduction that can occur while keeping economic returns constant relative to the baseline also increases. When the value of ecosystem services is two-times or eight-times base case assumptions, the landscapes on the efficiency frontiers are often dramatically different than current landscapes (Fig. 17 and Fig. 18). Along Points A to C there is a shift from crops to forest while at higher levels of sediment reduction there is a shift to perennial grasslands. These results illustrate the importance of non-market values for ecosystem services on land-use changes to meet water quality and economic objectives.

Efficiency frontier for sediment reduction with historical market returns in Seven Mile Creek

The price of agricultural commodities, including corn and soybeans that are the dominant crops in the Seven Mile Creek Watershed, have increased dramatically in the recent few years (2007-2011) as compared to earlier years (2002-2006). Using historical market prices (2002-2006) results in a much steeper efficiency frontier compared to using current market prices (Fig 19 and Table 9). In general, historical market prices offered lower returns to agricultural and thus reduce the opportunity costs for shifting out of agriculture to other land uses. Using historical market prices, sediment reductions of 30% could be achieved with no loss of economic returns relative to the baseline (Fig. 13). At point E the cost of reaching maximum sediment reductions of 83% is $2,018,110, which is 60% less than when using current returns (Fig 19). The land uses associated with points along the efficiency curve are shown in Fig. 20 and 21. When the value of ecosystem services is added to market returns, the efficiency curve is shifted further to the right. Using historical market prices and adding in the value of ecosystem services means that under all levels of sediment reduction, economic returns are higher than they are under the baseline (Fig 19; Table 9). While it seems almost inconceivable at present, the optimal landscape would be quite different if: a) agricultural price are reduced to levels of the recent past (2002-2006), and b) the value of ecosystem services can be internalized and accounted for in economic returns.

Efficiency frontier for phosphorus reductions and current market returns for Seven Mile Creek

The efficiency frontier for phosphorus reductions is quite similar to the efficiency frontier for sediment reductions. The main differences are that the land use pattern that generates the maximum economic return (Point A in Fig. 22) does not generate any gains in phosphorus reduction, while it generated small reductions in sediment loadings (Fig. 13). At point A, water quality is not improved from baseline conditions but the economic score improves by $157,000 or a 7% increase (Table 10). This is accomplished by the conversion of 97% of conventional tilled annual cropland area to conventional tilled annual cropland production under a 50% less phosphorus input management scheme and a smaller amount of area to conservation tilled annual cropland area. Despite no water quality improvement at point A, there are rapid gains in phosphorus reduction at little cost. Approximately 20% reductions in phosphorus can be achieved with no loss in economic returns as compared to the baseline (Fig. 22), which is virtually the same level found in analyzing sediment reduction. At a 25% reduction in phosphorus compared to the baseline (Point B in Fig. 22), a reduction of 780 kg of phosphorus, results in a small decline in the economic returns relative to the baseline, -$95,500 or 2%. Among the first changes made to increase phosphorus reductions for the least cost are to increase the amount of row crop area under lower phosphorus inputs along with the targeted conversion of row crop area to grasslands along riparian areas especially along the main channel of the creek (Fig. 23).

To reduce phosphorus by 50%, 1,578 kg of phosphorus (Point C in Figure 22), results in a substantial reduction in economic returns, $902,000 or 21% of baseline economic returns. The main land–use change in going from 25% to 50% reduction involves placing a large block of diverse grassland production in the south central, eastern, and northern portions of basin (Fig 23). There is also some increase in switchgrass production throughout the basin.

Reducing phosphorus beyond 50% up to a maximum attainable reduction of just over 75% (Point E in Fig. 22), requires increasingly shifting lands from annual row crop production to perennial biofuel production and natural forests. Much of this land becomes switchgrass production (82 % of the land in the land-use pattern at point E; Fig. 23). Other perennial vegetation types expand but at a much lower level (e.g., diverse grassland constitutes 2% of the area at point E). The shift to dominance of land in perennial vegetation increases the phosphorus reduction score from 1,578 to 2,387 tons or 50% to 75%, but comes at a steep economic cost. Annual economic returns are reduced by -$3,115,130 or 71% of baseline for the land-use pattern at point E.

Efficiency frontier for sediment reduction and current market returns plus ecosystem services value, twice ecosystem services value, and eight times ecosystem services value for Seven Mile Creek

The effects of adding ecosystem service values to the economic returns for the efficiency frontier for phosphorus reductions were similar to what was seen above for sediment results. Overall, the addition of ecosystem service value to economic returns shifts the efficiency frontier up and to the right (Fig. 24). When the value of ecosystem services is added to market returns, the landscape that maximizes economic returns (Point A in Fig. 24) occurs with a reduction of 604 kg in phosphorus (19% reduction) in and a $359,618 increase (8%) in annual market returns compared to the baseline. This improvement is accomplished by the conversion of 63% of conventional annual row crop production area to annual row crop production under 50% less phosphorus input scheme (44% of the landscape) and forest (30% of the landscape). The shift to the right in the efficiency frontier is greater at higher levels of phosphorus reduction because actions taken to reduce phosphorus also tend to increase other ecosystem services. The shift to the right increases markedly when the value of ecosystem services is increased two-times or eight-times the value (Fig. 25 and Table 10). When the efficiency frontier includes ecosystem service value at twice value, Point A reduces phosphorus by 1,834 kg or 58%, and an increase in annual economic return of $2,110,819 or 48% from the baseline. When the efficiency frontier is constrained by current market returns plus eight-times the value of ecosystem service value, Point A has a phosphorus reduction of 1,931 kg or 61% along with an increase in economic returns of $21,188,820 or a 486% change from baseline. For the cases with large increases in the value of ecosystem services, optimal landscapes are composed of forests or perennial grasses as compared to annual crops (Fig. 26 and Fig. 27). These results show how the value of non-market ecosystem services values can greatly influence the spatial arrangement of land-use decisions to meet phosphorus reduction and economic objectives.

Efficiency frontier constrained by phosphorus reductions and historic market returns for Seven Mile Creek

Similar to the results shown above for sediment reduction frontiers, the efficiency frontier for phosphorus reduction is much steeper when historical market prices are used instead of current market prices (Fig. 28). Again, historical market returns reduce the opportunity costs for shifting out of annual row crop production to other land uses that result in reductions in phosphorus. For example, at Point E that results in maximum reduction in phosphorus the reduction in economic returns $1,097,150, which is only 35% of the reduction at in Point E using current market prices (Table 10).

Results for recreation value for Seven Mile Creek

In general, total recreation value increases with changes in land use targeted to improve water quality (Tables 11 and 12). However, different activities respond differently to land-use change (Appendix F). Annual hunting visits for big game and migratory waterfowl decreased as area was converted out of cropland whereas annual small-game hunting and wildlife viewing visits increase with natural land cover (Tables 11 and 12). Overall the increase in the opportunity to hunt small game drives recreation values for the basin. The addition of recreation value to selected points along the frontiers constrained by economic returns plus ecosystem service value marginally adds to economic returns at Point A for sediment $2,566 and for phosphorus $6,989. For point E this increases to an addition of $135,285. Across the frontiers that include ecosystem service value the contribution of recreation is relatively minor compared to the value for water quality improvements and carbon sequestration (Tables 11 and 12).

Results on habitat quality for Seven Mile Creek

In general, measures of habitat for both grassland birds and forest birds respond positively to changes in land use and land management aimed at reducing sediment or phosphorus. Changes in land use out of annual cropland into perennial vegetation types (perennial grassland or forest) increases habitat quality measures. The increase in habitat quality is quite dramatic compared to baseline conditions because much of Seven Mile Creek at present is devoted to annual crop production. Starting from a habitat quality score of around 500 units for grassland birds for the baseline landscape, the habitat quality score increases steadily in moving up the efficiency frontier towards higher levels of sediment or phosphorus reduction. For sediment reduction the habitat quality score for grassland birds increases by 190.8 units at Point A up to 15,003.8 units at Point D, before declining slightly to 14,104.6 units at the maximum sediment reduction at Point E (Table 9). It is interesting to note that habitat measures increased at Point A, which is the landscape that maximizes economic returns, suggesting that it is possible to increase species conservation and economic returns at least to some degree relative to the current landscape. Grassland species benefit from the increase in the availability of large blocks on intact diverse grassland that increase in area as sediment reduction levels are increased. Grassland birds do not benefit from the shift from diverse grasslands to switchgrass because the monoculture switchgrass habitat is less suitable to the majority of grassland species compared to diverse grassland. Yet both diverse grassland and switchgrass substantially improved habitat compared to annual cropland of corn, soybeans, or surgarbeets. Habitat quality scores for forest bird species follow the same pattern of increase as grassland species but to a lesser degree (Table 9). Grassland bird habitat and forest bird habitat increases in a similar fashion as phosphorus reductions are increased (Table 10). For best management practices, the 250 m riparian diverse grassland buffer scenario generated the greatest gains in habitat quality scores with grassland species benefiting more than forest species (Tables 9 and 10). This result occurs because this alternative involved the greatest conversion of cropland area to natural cover.

West Fork Beaver Creek efficiency frontiers

In general, the efficiency frontiers for West Fork Beaver Creek display similar patterns as shown above for Seven Mile Creek. Below we highlight key similarities and differences between the two basins.

Efficiency frontier for sediment reduction and current market returns for West Fork Beaver Creek

The efficiency frontier for sediment reduction in West Fork Beaver Creek shows the maximum level of sediment reduction for any given level of change in economic returns (Fig. 33). Similar to Seven Mile Creek, we find land-use changes that reduce sediment losses with minimal impact on the economic returns (the efficiency frontier is quite steep). At point A only annual economic returns are improved relative to the baseline landscape. Compared to the baseline, the landscape for point A results in no change in sediment loading but does contribute to a $306,213 increase in annual economic returns (4% increase) (Table 13). Moving along the frontier from point A to E results in similar changes in sediment reduction and changes in economic returns (Fig. 33; Table 13) as for Seven Mile Creek. Likewise among the first land-use changes made to reduce sediment are those that result in large reductions at low cost by shifting from conventional annual row crop production area to annual row crop production and increasing the amount of area in diverse grasslands and switchgrass (Fig. 34). The maximum sediment reduction that can be achieved is 351 tons or 79% of the baseline but, again at a steep cost. The annual economic returns are reduced by $4,443,720 or 50% of the baseline for the land-use pattern at point E, which is dominated by switchgrass and diverse grassland production. Compared to Seven Mile Creek, maximum reductions of sediment in West Fork Beaver Creek can be achieved for relatively smaller cost than for Seven Mile Creek, where point E resulted in a 72% reduction in economic returns.

Again we find opportunities for "win-win" changes that both reduce sediment losses and increase economic returns (as shown by frontier points between A to B). In West Fork Beaver Creek there is potential to make reasonably large percentage reductions in sediment loadings at little to no cost relative to the baseline. Sediment can be reduced by approximately 22% at no loss in economic returns relative to the baseline (Fig. 33).

Efficiency frontier for sediment reduction and current market returns plus ecosystem services value, twice ecosystem services value, and eight times ecosystem services value for West Fork Beaver Creek

The addition of ecosystem service values to the value of agricultural crop production shifts the efficiency frontier to the right (Fig. 35). As for Seven Mile Creek, the efficiency curve shifts to the right because adding the value of ecosystem services increases the overall value of economic returns. Likewise including the value of ecosystem services raises the level of sediment reduction that occurs in the landscape that maximizes economic returns relative to the baseline (Point A in Fig. 35). As for Seven Mile Creek, the improvement is accomplished by the conversion of the majority of conventional annual row crop production area to annual row crop production under a 50% less phosphorus input scheme and conversion of some crop area to forest. Despite no sediment reductions at point A, there are rapid gains in phosphorus reduction at little cost. This finding is the opposite of what we found for Seven Mile Creek where at point A there were no phosphorus reductions, but small sediment reductions (Table 9).

Again, including the value of ecosystem services also increases the level of sediment reduction that can occur without loss of economic returns relative to the baseline (Fig. 36). The West Fork Beaver Creek frontiers with ecosystem service values similarly shows that increasing the value of ecosystem services reduces sediment losses associated with the landscape that maximizes economic returns (two-times and eight-times the value; Fig. 35 and Table 13). When the value of ecosystem services is two-times or eight-times base case assumptions, the landscapes on the efficiency frontiers are often dramatically different than current landscapes (Fig. 37. and Fig. 38). Along points A to C there is a shift from crops to forest, while at higher levels of sediment reduction there is a shift to perennial grasslands. Interestingly, the point for maximum economic returns for the efficiency frontier for sediment reduction and current market returns plus ecosystem service value times 2 and times 8 results in a sediment reduction of 14.9% reduction relative to baseline, while at the same time yielding a phosphorus reduction of 92.4% from baseline. This result is driven by the dominance of forest cover in point A, which results both in significant phosphorus reduction and increased economic returns ($12,824,532 increase in carbon value from baseline; Table 15). This finding differs from the parallel tracking of sediment and phosphorus reductions across frontiers for Seven Mile Creek.

Efficiency frontier for sediment reduction with historical market returns in West Fork Beaver Creek

We see a similar change in the frontiers when using historical market prices (2002-2006) as for Seven Mile Creek which results in a much steeper efficiency frontier compared to using current market prices (Fig 39 and Table 11). Using historical market prices, sediment reductions of 46% could be achieved with no loss of economic returns relative to the baseline (Fig. 39). The land uses associated with points along the efficiency curve are shown in Fig. 40 and 41. As for Seven Mile Creek, using historical market prices and adding in the value of ecosystem services means that under all levels of sediment reduction, economic returns are higher than they are under the baseline (Fig 39; Table 13).

Efficiency frontier for phosphorus reductions and current market returns in West Fork Beaver Creek

As for Seven Mile Creek, the West Fork Beaver Creek efficiency frontier for phosphorus reductions is quite similar to the efficiency frontier for sediment reductions. The main differences are that the land use pattern that generates the maximum economic return (point A in Fig. 42) generates small phosphorus reductions, but no reductions in sediment loading (Fig. 33). Again, this is accomplished by the conversion of all conventional tilled annual cropland area to conventional tilled annual cropland production under a 50% less phosphorus input management scheme and a small area of diverse grassland. Approximately 30% reductions in phosphorus can be achieved with no loss in economic returns as compared to the baseline (Fig. 42), which is about 8% greater than found in analyzing sediment reduction.

Moving from point A to E results in similar changes in sediment reduction and changes in economic returns (Fig. 42; Table 14.) as for Seven Mile Creek. Likewise among the first changes made to increase phosphorus reductions for the least cost are to increase the amount of row crop area under lower phosphorus inputs along with the targeted conversion of row crop area to swichgrass along riparian areas especially along the main channel of the creek (Fig. 343). The shift to dominance of land in perennial vegetation at point E results in phosphorus reduction of 2,780 tons or 97%, but comes at a steep economic cost. Annual economic returns are reduced by $4,871,340 or 55% of baseline for the land-use pattern at point E. As for sediment reductions, the maximum reduction of phosphorus can be achieved for less cost than for Seven Mile Creek (Table 10).

Efficiency frontier for sediment reduction and current market returns plus ecosystem services value, twice ecosystem services value, and eight times ecosystem services value for West Fork Beaver Creek

The effects of adding ecosystem service values to the economic returns for the efficiency frontier for phosphorus reductions were similar to what was seen above for sediment results and for Seven Mile Creek. Overall, the addition of ecosystem service value to economic returns shifts the efficiency frontier up and to the right (Fig. 44). When the value of ecosystem services is added to market returns, the landscape that maximizes economic returns (point A in Fig. 44) occurs with a reduction of 39% reduction, roughly twice that seen for Seven Mile Creek (19% phosphorus reduction; Table 14) for the same increase (8%) in annual market returns compared to the baseline. Similarly, this improvement is accomplished by the conversion of conventional annual row crop production area to annual row crop production under 50% less phosphorus input scheme combined with a small area in forest. The shift to the right in the efficiency frontier is greater at higher levels of phosphorus reduction and also increases markedly when the value of ecosystem services is increased two-times or eight-times the value (Fig. 45 and Table 14).

Efficiency frontier constrained by phosphorus reductions and historic market returns for West Fork Beaver Creek

Similar to the results shown above for sediment reduction frontiers for West Fork Beaver Creek and for Seven Mile Creek, the efficiency frontier for phosphorus reduction is much steeper when historical market prices are used instead of current market prices (Fig. 48). Again, historical market returns reduce the opportunity costs for shifting out of annual row crop production to other land uses that result in reductions in phosphorus.

Results for recreation value for West Fork Beaver Creek

Similar to Seven Mile Creek, the total recreation value increases with changes in land use targeted to improve water quality (Tables 15 and 16). Likewise different recreation activities respond differently to land-use change. Across the frontiers that include ecosystem service value the contribution of recreation is relatively minor compared to the value for water quality improvements and carbon sequestration (Tables 15 and 16).

Results on habitat quality for West Fork Beaver Creek

Measures of habitat for both grassland birds and forest birds respond similarly to that of Seven Mile Creek. In general, habitat quality improved with land use and land management aimed at reducing sediment or phosphorus (Fig. 51 and 52). Likewise the increase is quite dramatic compared to baseline conditions because much of West Fork Beaver Creek at present is devoted to annual crop production. Habitat measures increased at point A, suggesting that it is possible to increase species conservation and economic returns at least to some degree relative to the current landscape. Both grassland and forest birds responded in the same fashion as seen for Seven Mile Creek. In general land-use changes to maximize water quality benefits is most beneficial to grassland species.

Table 9. Change in provision of ecosystem services and biodiversity conservation from baseline for sediment reductions and economic returns for Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

Land-use pattern	Sediment reduction (tons)	% sediment reduction	P reduction (kg)	% P reduction	Carbon sequestration (Mg)	Economic returns (2011$)	% economic returns	Recreation visits	Habitat quality score - grassland birds	% Habitat quality - grassland birds	Habitat quality score - forest birds	% Habitat quality - forest birds
Efficiency frontier for sediment reductions and current market returns												
A	103	3.5	-26	-0.8	447	171,657	3.9	83	190.8	37.5	75.1	16.1
B	750	25.4	695	21.8	1,625	-158,000	-3.6	764	283.4	55.7	450.5	96.9
C	1,470	49.8	1,461	45.8	3,273	-912,000	-20.9	1,957	6479.6	1273.7	1235.9	265.7
D	2,230	75.6	2,205	69.1	4,580	-2,206,000	-50.6	3,433	15003.8	2949.3	2621.5	563.7
E	2,446	82.9	2,390	74.9	1,475	-3,115,260	-71.5	4,059	14104.6	2772.5	3109.2	668.5
Scenarios												
F	79	2.7	101	3.2	195	-81,239	-3.6	120	744.2	146.3	106.2	22.8
G	451	15.3	470	14.7	1,508	-628,917	-28.2	788	1788.7	351.6	226.0	48.6
H	435	14.8	542	17.0	704	-217,726	-9.8	331	879.4	172.9	151.9	32.7
I	77	2.6	74	2.3	309	-112,265	-5.0	122	548.1	107.7	81.5	17.5
Efficiency frontier for sediment reductions and current market returns + ecosystem service value												
A	447	15.2	604	18.9	2,965	359,618	8.2	109	195.9	38.5	911.7	196.0
B	750	25.4	899	28.2	2,544	310,500	7.1	629	1630.8	320.6	691.8	148.8
C	1,470	49.8	1,544	48.4	4,673	8,600	0.2	1,891	6984.9	1373.0	1615.3	347.3
D	2,230	75.6	2,217	69.5	7,460	-826,000	-18.9	3,422	15215.8	2990.9	3145.9	676.4
E	2,446	82.9	2,390	74.9	1,475	-1,951,710	-44.8	4,059	14104.6	2772.5	3109.2	668.5

Scenarios												
F	79	2.7	101	3.2	195	-24,327	-0.6	120	744.2	146.3	106.181	22.8
G	451	15.3	470	14.7	1,508	-325,439	-7.5	788	1788.7	351.6	226.0	48.6
H	435	14.8	542	17.0	704	68,080	1.6	331	879.4	172.9	151.9	32.7
I	77	2.6	74	2.3	309	-60,177	-1.4	122	548.1	107.7	81.5	17.5
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x2)												
A	1349	45.7	1,834	57.5	29,901	2,110,819	48.4	568	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	1,470	49.8	1,912	60.0	29,857	2,000,000	45.9	832	…	…	…	…
D	2,230	75.6	2,257	70.8	11,613	802,000	18.4	3,222	…	…	…	…
E	2,446	82.9	2,390	74.9	1,475	-781,679	-17.9	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	33,957	1.5	120	…	…	…	…
G	451	15.3	470	14.7	1,508	-12,770	-0.6	788	…	…	…	…
H	435	14.8	542	17.0	704	359,144	16.1	331	…	…	…	…
I	77	2.6	74	2.3	309	-6,269	-0.3	122	…	…	…	…
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x8)												
A	1390	47.1	1,931	60.6	34,983	21,188,820	486.1	661	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	1,470	49.8	1,966	61.6	33,357	20,490,000	470.0	864	…	…	…	…
D	2,230	75.6	2,294	71.9	13,725	11,500,000	263.8	3,193	…	…	…	…
E	2,446	82.9	2,390	74.9	1,475	6,251,266	143.4	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	300,031	13.4	120	…	…	…	…
G	451	15.3	470	14.7	1,508	1,474,946	66.1	788	…	…	…	…
H	435	14.8	542	17.0	704	1,652,339	74.1	331	…	…	…	…
I	77	2.6	74	2.3	309	256,718	11.5	122	…	…	…	…
Efficiency frontier for sediment reductions and historical market returns												
A	136	4.6	20	0.6	461	157,000	7.0	94	…	…	…	…

B	750	25.4	650	20.4	1,583	71,500	3.2	798	…	…	…	…
C	1,470	49.8	1,413	44.3	2,906	-174,000	-7.8	1,987	…	…	…	…
D	2,230	75.6	2,202	69.0	4,083	-694,000	-31.1	3,432	…	…	…	…
E	2,446	82.9	2,390	74.9	1,475	-1,097,150	-49.2	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	30,895	1.4	120	…	…	…	…
G	451	15.3	470	14.7	1,508	-242,429	-10.9	788	…	…	…	…
H	435	14.8	542	17.0	704	-70,340	-3.2	331	…	…	…	…
I -	77	2.6	74	2.3	309	-41,052	-1.8	122	…	…	…	…
Efficiency frontier for sediment reductions and historical market returns + ecosystem service value												
A - min	1287	43.6	1,734	54.4	25,563	999,087	44.8	587	…	…	…	…
B -25	…	…	…	…	…	…	…	…	…	…	…	…
C - 50	1,469	49.8	1,863	58.4	24,408	976,500	43.8	995	…	…	…	…
D -75	2,230	75.6	2,239	70.2	10,088	714,000	32.0	3,296	…	…	…	…
E - max	2,446	82.9	2,390	74.9	1,475	66,402	3.0	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	26,107	1.2	120	…	…	…	…
G	451	15.3	470	14.7	1,508	61,049	2.7	788	…	…	…	…
H	435	14.8	542	17.0	704	215,465	9.7	331	…	…	…	…
I	77	2.6	74	2.3	309	11,036	0.5	122	…	…	…	…

Table 10. Change in provision of ecosystem services and biodiversity conservation from baseline for phosphorus reductions and economic returns for Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

Land-use pattern	Sediment reduction (tons)	% sediment reduction	P reduction (kg)	% P reduction	Carbon sequestration (Mg)	Economic returns (2011$)	% economic returns	Recreation visits	Habitat quality score - grassland birds	% Habitat quality - grassland birds	Habitat quality score - forest birds	% Habitat quality - forest birds
Efficiency frontier for phosphorus reductions and current market returns												
A	103	3.5	-26	-0.8	447	171,657	3.9	116	176.6	34.7	83.1	17.9
B	595	20.2	780	24.5	1,066	-96,500	-2.2	456	1181.1	232.2	325.5	70.0
C	1,344	45.6	1,578	49.5	3,082	-902,000	-20.7	1,686	6158.5	1210.6	1121.2	241.1
D	2,439	82.7	2,387	74.9	1,863	-3,050,000	-70.0	4,028	14577.3	2865.4	3108.4	668.4
	2,446	82.9	2,390	74.9	1,469	-3,115,130	-71.5	4,059	14188.5	2789.0	3129.7	672.9
Scenarios												
F	79	2.7	101	3.2	195	-81,239	-3.6	120	744.2	146.3	106.2	22.8
G	451	15.3	470	14.7	1,508	-628,917	-28.2	788	1788.7	351.6	226.0	48.6
H	435	14.8	542	17.0	704	-217,726	-9.8	331	879.4	172.9	151.9	32.7
I	77	2.6	74	2.3	309	-112,265	-5.0	122	548.1	107.7	81.5	17.5
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value												
A	447	15.2	604	18.9	2,965	359,618	8.2	109	195.9	38.5	668.0	143.6
B	530	18.0	752	23.6	4,067	350,000	8.0	190	379.8	74.7	1076.6	231.5
C	1,415	48.0	1,619	50.8	4,904	0	0.0	1,534	6405.2	1259.1	1717.5	369.3
D	2,439	82.7	2,387	74.9	2,389	-1,850,000	-42.4	4,004	14606.1	2871.1	3402.8	731.7
E	2,446	82.9	2,390	74.9	1,469	-1,951,950	-44.8	4,059	14188.5	2789.0	3129.7	672.9%
Scenarios												
F	79	2.7	101	3.2	195	-24,327	-0.6	120	744.2	146.3	106.181	22.8
G	451	15.3	470	14.7	1,508	-325,439	-7.5	788	1788.7	351.6	226.0	48.6

H	435	14.8	542	17.0	704	68,080	1.6	331	879.4	172.9	151.9	32.7
I	77	2.6	74	2.3	309	-60,177	-1.4	122	548.1	107.7	81.5	17.5
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x2)												
A	1349	45.7	1,834	57.5	29,901	2,110,819	48.4	568	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…	…	…
D	2,438	82.7	2,388	74.9	2,720	-600,000	-13.8	3,999	…	…	…	…
E	2,446	82.9	2,390	74.9	1,469	-782,314	-17.9	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	33,957	1.5	120	…	…	…	…
G	451	15.3	470	14.7	1,508	-12,770	-0.6	788	…	…	…	…
H	435	14.8	542	17.0	704	359,144	16.1	331	…	…	…	…
I	77	2.6	74	2.3	309	-6,269	-0.3	122	…	…	…	…
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x8)												
A	1390	47.1	1,931	60.6	34,983	21,188,820	486.1	661	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…	…	…
D	2,438	82.7	2,387	74.9	2,920	6,930,000	159.0	3,982	…	…	…	…
E	2,446	82.9	2,390	74.9	1,469	6,248,186	143.3	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	300,031	13.4	120	…	…	…	…
G	451	15.3	470	14.7	1,508	1,474,946	66.1	788	…	…	…	…
H	435	14.8	542	17.0	704	1,652,339	74.1	331	…	…	…	…
I	77	2.6	74	2.3	309	256,718	11.5	122	…	…	…	…
Efficiency frontier for phosphorus reductions and historical market returns												
A	136	4.6	20	0.6	461	157,000	7.0	94	…	…	…	…
B	704	23.9	780	24.5	1,240	61,500	2.8	650	…	…	…	…
C	1,453	49.3	1,579	49.5	2,973	-205,400	-9.2	1,898	…	…	…	…

D	2,439	82.7	2,387	74.9	1,974	-1,060,000	-47.5	4,028	…	…	…	…
E	2,446	82.9	2,390	74.9	1,469	-1,097,150	-49.2	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	30,895	1.4	120	…	…	…	…
G	451	15.3	470	14.7	1,508	-242,429	-10.9	788	…	…	…	…
H	435	14.8	542	17.0	704	-70,340	-3.2	331	…	…	…	…
I	77	2.6	74	2.3	309	-41,052	-1.8	122	…	…	…	…
Efficiency frontier for phosphorus reductions and historical market returns + ecosystem service value												
A	1287	43.6	1,734	54.4	25,563	999,087	44.8	587	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…	…	…
D	2,438	82.7	2,387	74.9	2,604	150,000	6.7	4,004	…	…	…	…
E	2,446	82.9	2,390	74.9	1,469	66,164	3.0	4,059	…	…	…	…
Scenarios												
F	79	2.7	101	3.2	195	26,107	1.2	120	…	…	…	…
G	451	15.3	470	14.7	1,508	61,049	2.7	788	…	…	…	…
H	435	14.8	542	17.0	704	215,465	9.7	331	…	…	…	…
I	77	2.6	74	2.3	309	11,036	0.5	122	…	…	…	…

Table 11. Change in economic value of ecosystem services from baseline for efficiency frontier for sediment and economic returns in Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

Land-use pattern	Sediment reduction (2011$)	P reduction (2011$)	Carbon sequestration (2011$)	Recreation (2011$)	Agriculture returns (2011$)	Total value - ag returns (2011$)	Total value (2011$)
Efficiency frontier constrained by sediment reductions and current market returns							
A	836	-11,454	28,161	3,235	171,657	20,779	192,436
B	6,090	306,161	102,375	25,828	-158,000	440,454	282,454
C	11,936	643,600	206,199	65,548	-912,000	927,283	15,283
D	18,108	971,347	288,540	114,631	-2,206,000	1,392,625	-813,375
E	19,862	1,052,843	92,925	135,285	-3,115,260	1,300,914	-1,814,346
Scenarios							
F	641	44,493	12,285	4,064	-81,239	61,483	-19,756
G	3,662	207,044	95,004	26,317	-628,917	332,027	-296,890
H	3,532	238,762	44,352	11,082	-217,726	297,728	80,002
I	625	32,598	19,467	4,113	-112,265	56,804	-55,461
Efficiency frontier constrained by sediment reductions and current market returns + ecosystem service value							
A	3,630	266,074	186,795	2,566	-96,881	459,064	362,184
B	6,090	396,027	160,272	16,670	-251,889	579,059	327,170
C	11,936	680,163	294,399	50,493	-977,898	1,036,991	59,093
D	18,108	976,633	469,980	91,503	-2,290,720	1,556,223	-734,497
E	19,862	1,052,843	92,925	108,706	-3,117,339	1,274,335	-1,843,004
Scenarios							
F	641	44,493	12,285	4,064	-81,746	61,483	-20,263
G	3,662	207,044	95,004	26,317	-631,150	332,027	-299,122
H	3,532	238,762	44,352	11,082	-218,566	297,728	79,162

I	625	32,598	19,467	4,113	-112,868	56,804	-56,064
Efficiency frontier constrained by sediment reductions and current market returns + ecosystem service value (x2)							
A	21,908	1,615,827	3,767,526	105,126	-3,294,442	5,510,387	7,621,206
B	…	…	…	…	…	…	…
C	23,873	1,684,548	3,761,982	121,358	-3,470,403	5,591,761	7,591,761
D	36,215	1,988,507	1,463,238	227,419	-2,685,960	3,715,379	4,517,379
E	39,723	2,105,686	185,850	270,569	-3,112,938	2,601,828	1,820,149
Scenarios							
F	1,283	88,985	24,570	8,128	-80,881	122,966	42,085
G	7,324	414,089	190,008	52,634	-624,191	664,055	39,864
H	7,064	477,524	88,704	22,164	-214,148	595,456	381,308
I	1,250	65,197	38,934	8,227	-111,650	113,608	1,958
Efficiency frontier constrained by sediment reductions and current market returns + ecosystem service value (x8)							
A	90,294	6,805,153	17,631,432	490,976	-3,338,059	25,017,855	21,679,796
B	…	…	…	…	…	…	…
C	95,491	6,928,499	16,811,928	526,180	-3,345,918	24,362,098	21,016,180
D	144,861	8,084,423	6,917,400	931,470	-3,646,684	16,078,154	12,431,470
E	158,892	8,422,742	743,400	1,082,278	-3,073,769	10,407,313	7,333,544
Scenarios							
F	641	44,493	12,285	32,513	242,612	89,932	332,544
G	3,662	207,044	95,004	210,535	1,169,235	516,245	1,685,481
H	3,532	238,762	44,352	88,656	1,365,693	375,302	1,740,995
I	625	32,598	19,467	32,907	204,027	85,598	289,625
Efficiency frontier constrained by sediment reductions and historical market returns							
A	1,104	8,810	29,043	3,629	157,000	42,586	199,586
B	6,090	286,338	99,729	27,008	71,500	419,165	490,665
C	11,936	622,455	183,078	66,582	-174,000	884,051	710,051
D	18,108	970,025	257,229	114,649	-694,000	1,360,010	666,010
E	19,862	1,052,843	92,925	135,285	-1,097,150	1,300,914	203,764

Scenarios							
F	641	44,493	12,285	4,064	-26,524	61,483	34,959
G	3,662	207,044	95,004	26,317	-548,140	332,027	-216,112
H	3,532	238,762	44,352	11,082	-356,986	297,728	-59,258
I	625	32,598	19,467	4,113	-93,743	56,804	-36,939
Efficiency frontier constrained by sediment reductions and historical market returns + ecosystem service value							
A	10,450	763,862	1,610,469	48,256	-1,385,694	2,433,037	1,047,343
B	…	…	…	…	…	…	…
C	11,928	820,689	1,537,704	59,622	-1,393,821	2,429,943	1,036,122
D	18,108	986,324	635,544	114,460	-925,976	1,754,436	828,460
E	19,862	1,052,843	92,925	135,285	-1,099,227	1,300,914	201,687
Scenarios							
F	641	44,493	12,285	4,064	-31,312	61,483	30,171
G	3,662	207,044	95,004	26,317	-244,662	332,027	87,366
H	3,532	238,762	44,352	11,082	-71,181	297,728	226,547
I	625	32,598	19,467	4,113	-41,655	56,804	15,149

Table 12. Change in economic value of ecosystem services from baseline for efficiency frontier for phosphorus and economic returns in Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

Land-use pattern	Sediment reduction (2011$)	P reduction (2011$)	Carbon sequestration (2011$)	Recreation (2011$)	Agriculture returns (2011$)	Total value - ag returns (2011$)	Total value (2011$)
Efficiency frontier for phosphorus reductions and current market returns							
A	836	-11,454	28,161	3,930	171,657	21,474	193,131
B	4,831	343,606	67,158	15,628	-96,500	431,223	334,723
C	10,913	695,141	194,166	56,556	-902,000	956,775	54,775
D	19,805	1,051,540	117,369	134,261	-3,050,000	1,322,975	-1,727,025
E	19,862	1,052,843	92,547	135,285	-3,115,130	1,300,536	-1,814,594
Scenarios							
F	641	44,493	12,285	4,064	-81,239	61,483	-19,756
G	3,662	207,044	95,004	26,317	-628,917	332,027	-296,890
H	3,532	238,762	44,352	11,082	-217,726	297,728	80,002
I	625	32,598	19,467	4,113	-112,265	56,803	-55,462
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value							
A	3,630	266,074	186,795	6,989	-96,881	463,488	366,607
B	4,304	331,271	256,221	11,003	-241,796	602,799	361,003
C	11,490	713,202	308,952	53,128	-1,033,644	1,086,772	53,128
D	19,805	1,051,521	150,507	134,096	-3,071,833	1,355,929	-1,715,904
E	19,862	1,052,843	92,547	135,285	-3,117,201	1,300,536	-1,816,665
Scenarios							
F	641	44,493	12,285	4,064	-81,746	61,483	-20,263
G	3,662	207,044	95,004	26,317	-631,149	332,027	-299,122
H	3,532	238,762	44,352	11,082	-218,566	297,728	79,162

I	625	32,598	19,467	4,113	-112,867	56,803	-56,064
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x2)							
A	21,908	1,615,827	3,767,526	105,126	-3,294,442	5,510,387	7,621,206
B	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…
D	39,593	2,103,924	342,720	267,949	-3,086,237	2,754,185	2,154,185
E	39,723	2,105,686	185,094	270,569	-3,112,817	2,601,072	1,818,758
Scenarios							
F	1,283	88,985	24,570	8,128	-80,881	122,966	42,085
G	7,324	414,089	190,008	52,634	-624,191	664,055	39,864
H	7,064	477,524	88,704	22,164	-214,148	595,456	381,308
I	1,250	65,197	38,934	8,227	-111,650	113,608	1,958
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x8)							
A	90,294	6,805,153	17,631,432	490,976	-3,338,059	25,017,855	21,679,796
B	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…
D	158,372	8,412,170	1,471,680	1,068,775	-3,112,222	11,110,998	7,998,775
E	158,892	8,422,742	740,376	1,082,278	-3,073,825	10,404,289	7,330,464
Scenarios							
F	5,132	355,940	98,280	32,513	-159,321	491,865	332,544
G	29,297	1,656,355	760,032	210,535	-970,738	2,656,219	1,685,481
H	28,258	1,910,095	354,816	88,656	-640,829	2,381,824	1,740,995
I	5,002	260,788	155,736	32,907	-164,808	454,433	289,625
Efficiency frontier for phosphorus reductions and historical market returns							
A	1,104	8,810	29,043	3,629	157,000	42,586	199,586
B	5,716	343,606	78,120	22,114	61,500	449,556	511,056
C	11,798	695,581	187,299	63,666	-205,400	958,345	752,945

D	19,805	1,051,521	124,362	134,261	-1,060,000	1,329,949	269,949
E	19,862	1,052,843	92,547	135,285	-1,097,150	1,300,536	203,386
Scenarios							
F	641	44,493	12,285	4,064	-26,524	61,483	34,959
G	3,662	207,044	95,004	26,317	-548,139	332,027	-216,112
H	3,532	238,762	44,352	11,082	-356,986	297,728	-59,258
I	625	32,598	19,467	4,113	-93,742	56,803	-36,939
Efficiency frontier for phosphorus reductions and historical market returns + ecosystem service value							
A	10,450	763,862	1,610,469	48,256	-1,385,694	2,433,037	1,047,343
B	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…
D	19,797	1,051,521	164,052	134,096	-1,085,370	1,369,466	284,096
E	19,862	1,052,843	92,547	135,285	-1,099,087	1,300,536	201,449
Scenarios							
F -	641	44,493	12,285	4,064	-31,312	61,483	30,171
G	3,662	207,044	95,004	26,317	-244,661	332,027	87,366
H	3,532	238,762	44,352	11,082	-71,181	297,728	226,547
I	625	32,598	19,467	4,113	-41,654	56,803	15,149

Table 13. Change in provision of ecosystem services and biodiversity conservation from baseline for sediment reductions and economic returns for West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

Land-use pattern	Sediment reduction (tons)	% sediment reduction	P reduction (kg)	% P reduction	Carbon sequestration (Mg)	Economic returns (2011$)	% economic returns	Recreation visits	Habitat quality score - grassland birds	% Habitat quality - grassland birds	Habitat quality score - forest birds	% Habitat quality - forest birds
Efficiency frontier for sediment reductions and current market returns												
A	0	0.0	249	8.7	152	306,213	3.5	116	4321.0	148.3	406.4	45.1
B	110	24.8	699	24.4	1,349	-29,500	-0.3	1,104	3305.4	113.5	447.8	49.7
C	222	50.1	1,269	44.2	4,351	-1,030,000	-11.8	4,361	16034.1	550.3	2401.4	266.7
D	333	75.2	1,932	67.3	7,715	-3,573,000	-40.8	10,143	42934.5	1473.7	6648.1	738.2
E	351	79.2	2,193	76.4	7,902	-4,442,720	-50.8	11,670	49176.6	1687.9	7766.9	862.4
Efficiency frontier for sediment reductions and current market returns + ecosystem service value												
A	75	16.9	1,116	38.9	22,604	672,984	7.7	444	729.9	25.1	7763.4	862.1
B	111	25.1	1,302	45.4	23,922	635,500	7.3	895	2781.0	95.5	8559.3	950.4
C	222	50.1	1,515	52.8	8,045	-125,000	-1.4	4,259	17085.9	586.4	4353.6	483.4
D	333	75.2	2,112	73.6	7,586	-2,180,000	-24.9	10,155	42616.1	1462.7	6742.2	748.7
E	351	79.2	2,193	76.4	7,902	-2,968,660	-33.9	11,670	49176.6	1687.9	7766.9	862.4
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x2)												
A	66	14.9	2,653	92.4	101,782	6,645,250	75.9	1,874	…	…	…	…
B	111	25.1	2,311	80.5	86,338	5,780,000	66.0	2,915	…	…	…	…
C	222	50.1	2,293	79.9	52,990	2,870,000	32.8	6,271	…	…	…	…
D	333	75.2	2,364	82.4	15,843	-530,000	-6.1	10,526	…	…	…	…
E	351	79.2	2,193	76.4	7,902	-1,494,590	-17.1	11,670	…	…	…	…
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x8)												
A	66	14.9	2,654	92.5	102,109	52,818,550	603.5	1,880	…	…	…	…
B	111	25.1	2,672	93.1	89,997	47,150,000	538.7	3,063	…	…	…	…

C	221	49.9	2,408	83.9	56,520	30,850,000	352.5	6,660	…	…	…	…
D	333	75.2	2,390	83.3	17,356	12,400,000	141.7	10,716	…	…	…	…
E	351	79.2	2,193	76.4	7,902	7,349,803	84.0	11,670	…	…	…	…
Efficiency frontier for sediment reductions and historical market returns												
A	60	13.5	330	11.5	2,733	212,106	2.4	1,794	…	…	…	…
B	111	25.1	597	20.8	3,309	201,750	2.3	3,121	…	…	…	…
C	222	50.1	1,234	43.0	4,376	-11,500	-0.1	4,953	…	…	…	…
D	333	75.2	1,945	67.8	7,554	-992,000	-11.3	10,990	…	…	…	…
E	351	79.2	2,193	76.4	7,902	-1,676,150	-19.2	11,670	…	…	…	…
Efficiency frontier for sediment reductions and historical market returns + ecosystem service value												
A	82	18.5	2,448	85.3	87,534	2,837,387	32.4	1,818	…	…	…	…
B	110	24.8	2,257	78.6	80,009	2,760,000	31.5	2,840	…	…	…	…
C	222	50.1	2,184	76.1	47,288	1,730,000	19.8	6,521	…	…	…	…
D	333	75.2	2,203	76.8	9,906	420,000	4.8	10,991	…	…	…	…
E	351	79.2	2,193	76.4	7,902	-202,097	-2.3	11,670	…	…	…	…

Table 14. Change in provision of ecosystem services and biodiversity conservation from baseline for phosphorus reductions and economic returns for West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

Land-use pattern	Sediment reduction (tons)	% sediment reduction	P reduction (kg)	% P reduction	Carbon sequestration (Mg)	Economic returns (2011$)	% economic returns	Recreation visits	Habitat quality score - grassland birds	% Habitat quality - grassland birds	Habitat quality score - forest birds	% Habitat quality - forest birds
Efficiency frontier for phosphorus reductions and current market returns												
A	0	0.0	249	8.7	152	306,213	3.5	116	242.1	8.3	-57.2	-6.3
B	71	16.0	717	25.0	381	129,500	1.5	569	1340.7	46.0	196.3	21.8
C	164	37.0	1,578	55.0	990	-571,000	-6.5	2,176	5620.7	192.9	1078.7	119.8
D	258	58.2	2,154	75.1	2,363	-2,000,000	-22.9	5,689	11559.9	396.8	2251.3	250.0
E	347	78.3	2,780	96.9	5,403	-4,871,340	-55.7	11,474	43141.6	1480.8	8313.4	923.1
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value												
A	75	16.9	1,116	38.9	22,604	672,984	7.7	444	729.9	25.1	7763.4	862.1
B	…	…	…	…	…	…	…	…	…	…	…	…
C	95	21.4	1,435	50.0	30,971	647,000	7.4	579	964.1	33.1	11603.0	1288.4
D	107	24.2	2,154	75.1	58,417	200,000	2.3	1,016	1365.1	46.9	29383.7	3262.8
E	347	78.3	2,780	96.9	5,403	-3,298,520	-37.7	11,670	43141.6	1480.8	8313.4	923.1
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x2)												
A	66	14.9	2,653	92.5	101,782	6,645,250	75.9	1,874	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…	…	…
D	…	…	…	…	…	…	…	…	…	…	…	…
E	347	78.3	2,780	96.9	5,403	-1,725,710	-19.7	11,474	…	…	…	…
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x8)												
A	66	14.9	2,654	92.5	102,109	52,818,550	603.5	1,880	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…

C	…	…	…	…	…	…	…	…	…	…	…	…
D	…	...	…	…	…	…	…	…	…	…	…	…
E	347	78.3	2,780	96.9	5,403	7,711,178	88.1	11,474	…	…	…	…
Efficiency frontier for phosphorus reductions and historical market returns												
A	60	13.5	330	11.5	2,733	212,106	2.4	1,794	…	…	…	…
B	120	27.1	718	25.0	3,214	193,300	2.2	3,200	…	…	…	…
C	200	45.1	1,435	50.0	3,330	22,400	0.3	4,324	…	…	…	…
D	267	60.3	2,154	75.1	2,808	-494,000	-5.6	7,087	…	…	…	…
E	347	78.3	2,780	96.9	5,403	-1,993,170	-22.8	11,474	…	…	…	…
Efficiency frontier for phosphorus reductions and historical market returns + ecosystem service value												
A	82	18.5	2,448	85.3	87,534	2,837,387	32.4	1,818	…	…	…	…
B	…	…	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…	…	…
D	…	…	…	…	…	…	…	…	…	…	…	…
E	347	78.3	2,780	96.9	5,403	-420,256	-4.8	11,474	…	…	…	…

Table 15. Change in economic value of ecosystem services from baseline for efficiency frontier for sediment and economic returns in West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

Land-use pattern	Sediment reduction (2011$)	P reduction (2011$)	Carbon sequestration (2011$)	Recreation (2011$)	Agriculture returns (2011$)	Total value - ag returns (2011$)	Total value (2011$)
Efficiency frontier for sediment reductions and current market returns							
A	0	109,689	9,576	3,930	306,213	123,195	429,408
B	893	307,923	84,987	36,896	-29,500	430,699	401,199
C	1,803	559,020	274,113	145,383	-1,030,000	980,319	-49,681
D	2,704	851,085	486,045	337,907	-3,573,000	1,677,741	-1,895,259
E	2,850	966,060	497,826	388,761	-4,442,720	1,855,497	-2,587,223
Efficiency frontier for sediment reductions and current market returns + ecosystem service value							
A	609	491,620	1,424,052	36,815	-1,243,297	1,953,096	709,799
B	901	573,557	1,507,086	52,225	-1,446,044	2,133,769	687,725
C	1,803	667,388	506,835	146,409	-1,301,025	1,322,434	21,409
D	2,704	930,378	477,918	338,403	-3,591,000	1,749,403	-1,841,597
E	2,850	966,060	497,826	388,761	-4,435,396	1,855,497	-2,579,899
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x2)							
A	1,072	2,337,399	12,824,532	-447,406	-8,517,753	14,715,597	6,197,844
B	1,803	2,036,083	10,878,588	-264,059	-7,136,474	12,652,416	5,515,941
C	3,605	2,020,225	6,676,740	157,001	-5,830,570	8,857,571	3,027,001
D	5,408	2,082,779	1,996,218	673,970	-4,614,404	4,758,375	143,970
E	5,700	1,932,121	995,652	802,720	-4,428,063	3,736,193	-691,870
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x8)							
A	4,287	9,353,121	51,462,936	-1,795,333	-8,001,794	59,025,011	51,023,217

B	7,211	9,416,556	45,358,488	-1,187,241	-7,632,254	53,595,013	45,962,759
C	14,356	8,486,177	28,486,080	648,746	-6,136,613	37,635,360	31,498,746
D	21,632	8,422,742	8,747,424	2,716,116	-4,791,798	19,907,914	15,116,116
E	22,801	7,728,483	3,982,608	3,210,879	-4,384,089	14,944,771	10,560,682
Efficiency frontier for sediment reductions and historical market returns							
A	0	109,689	9,576	59,810	212,106	179,075	391,181
B	901	262,990	208,467	104,071	201,750	576,429	778,179
C	1,803	543,602	275,688	165,094	-11,500	986,187	974,687
D	2,704	856,811	475,902	366,158	-992,000	1,701,575	709,575
E	2,850	966,060	497,826	388,761	-1,676,150	1,855,497	179,347
Efficiency frontier for sediment reductions and historical market returns + ecosystem service value							
A	666	1,078,393	5,514,642	169,896	-3,756,314	6,763,597	3,007,283
B	893	994,254	5,040,567	191,091	-3,275,714	6,226,805	2,951,091
C	1,803	962,096	2,979,144	268,987	-2,213,042	4,212,029	1,998,987
D	2,704	970,466	624,078	369,197	-1,177,248	1,966,445	789,197
E	2,850	966,060	497,826	388,761	-1,668,833	1,855,497	186,664

Table 16. Change in economic value of ecosystem services from baseline for efficiency frontier constrained by phosphorus and economic returns in West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

Land-use pattern	Sediment reduction (2011$)	P reduction (2011$)	Carbon sequestration (2011$)	Recreation (2011$)	Agriculture returns (2011$)	Total value - ag returns (2011$)	Total value (2011$)
Efficiency frontier constrained by phosphorus reductions and current market returns							
A - min	0	109,689	9,576	3,931	306,213	123,197	429,410
B -25	577	315,853	24,003	19,079	129,500	359,511	489,011
C - 50	1,332	695,141	62,370	72,587	-571,000	831,429	260,429
D -75	2,095	948,880	148,869	189,610	-2,000,000	1,289,454	-710,546
E - max	2,818	1,224,646	340,389	383,256	-4,871,340	1,951,108	-2,920,232
Efficiency frontier constrained by phosphorus reductions and current market returns + ecosystem service value							
A - min	609	491,620	1,424,052	36,816	-1,243,297	1,953,098	709,800
B -25	…	…	…	…	…	…	…
C - 50	771	632,146	1,951,173	49,558	-1,937,091	2,633,649	696,558
D -75	869	948,880	3,680,271	94,515	-4,430,020	4,724,535	294,515
E - max	2,818	1,224,646	340,389	388,761	-4,866,372	1,956,613	-2,909,759
Efficiency frontier constrained by phosphorus reductions and current market returns + ecosystem service value (x2)							
A - min	1,072	2,337,399	12,824,532	351,453	-8,517,753	15,514,456	6,996,703
B -25	…	…	…	…	…	…	…
C - 50	…	…	…	…	…	…	…
D -75	…	…	…	…	…	…	…
E - max	5,635	2,449,291	680,778	766,512	-4,861,414	3,902,216	-959,198
Efficiency frontier constrained by phosphorus reductions and current market returns + ecosystem service value (x8)							
A - min	4,287	9,353,121	51,462,936	1,410,279	-8,001,794	62,230,623	54,228,829
B -25	…	…	…	…	…	…	…

C - 50	…	…	…	…	…	…	…
D -75	…	…	…	…	…	…	…
E - max	22,541	9,797,165	2,723,112	3,066,048	-4,831,640	15,608,866	10,777,226
Efficiency frontier constrained by phosphorus reductions and historical market returns							
A - min	487	145,372	172,179	59,811	212,106	377,849	589,955
B -25	974	316,293	202,482	106,651	193,300	626,400	819,700
C - 50	1,624	632,146	209,790	144,136	22,400	987,697	1,010,097
D -75	2,168	948,880	176,904	236,181	-494,000	1,364,133	870,133
E - max	2,818	1,224,646	340,389	383,256	-1,993,170	1,951,108	-42,062
Efficiency frontier constrained by phosphorus reductions and historical market returns + ecosystem service value							
A - min	666	1,078,393	5,514,642	169,896	-3,756,314	6,763,597	3,007,283
B -25	…	…	…	…	…	…	…
C - 50	…	…	…	…	…	…	…
D -75	…	…	…	…	…	…	…
E - max	2,818	1,224,646	340,389	383,256	-1,988,108	1,951,108	-37,000

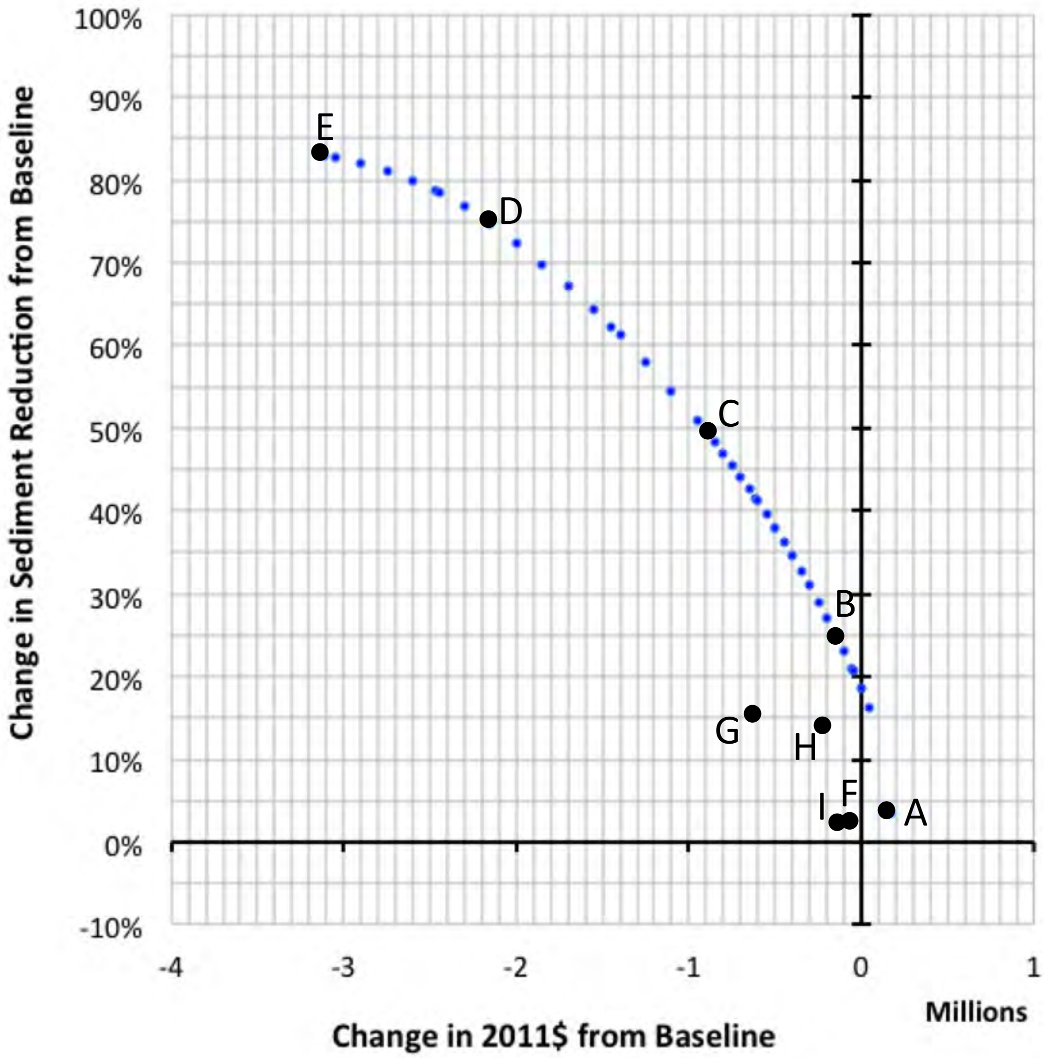


Figure 13. Efficiency frontier for sediment reduction and current market returns for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis. The efficiency frontier is outlined by solutions shown as blue circles. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

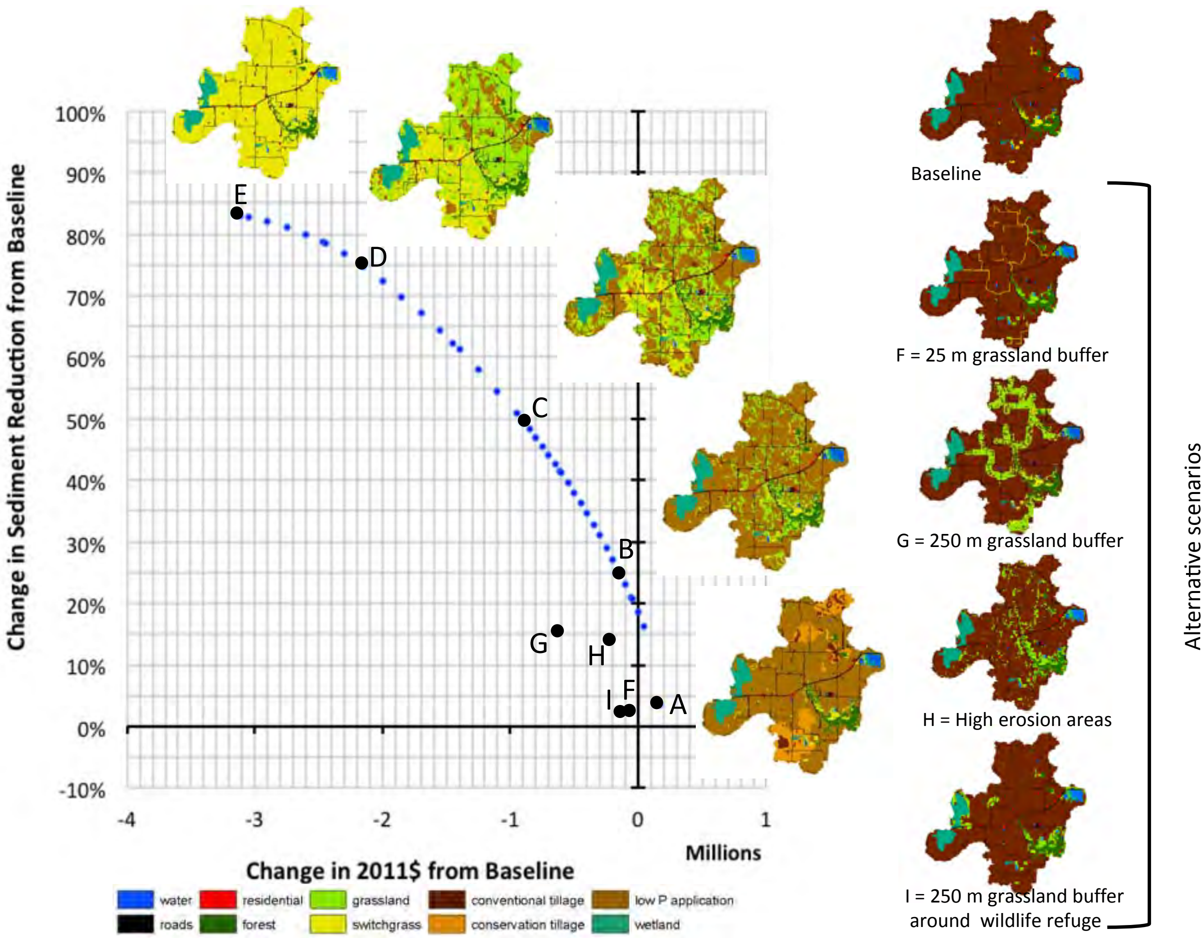


Figure 14. Land-use patterns for the baseline, best management practices and specific points along the efficiency frontier for sediment reduction and current value of market returns for Seven Mile Creek. The lettered points correspond to the points in Fig. 13.

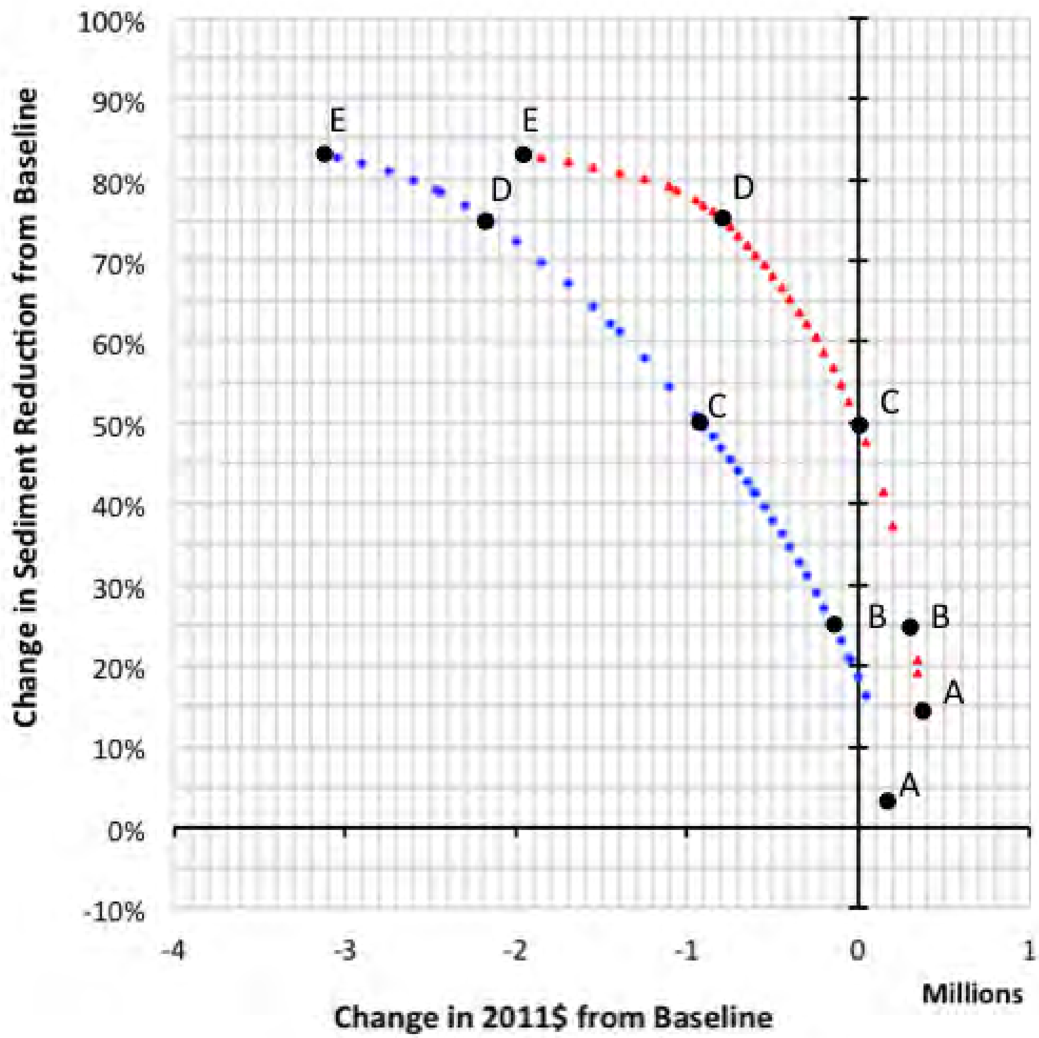


Figure 15. Efficiency frontiers for sediment reduction and current market returns (blue circles) and for sediment reduction and current market returns plus ecosystem service value (red triangles) for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum returns; B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

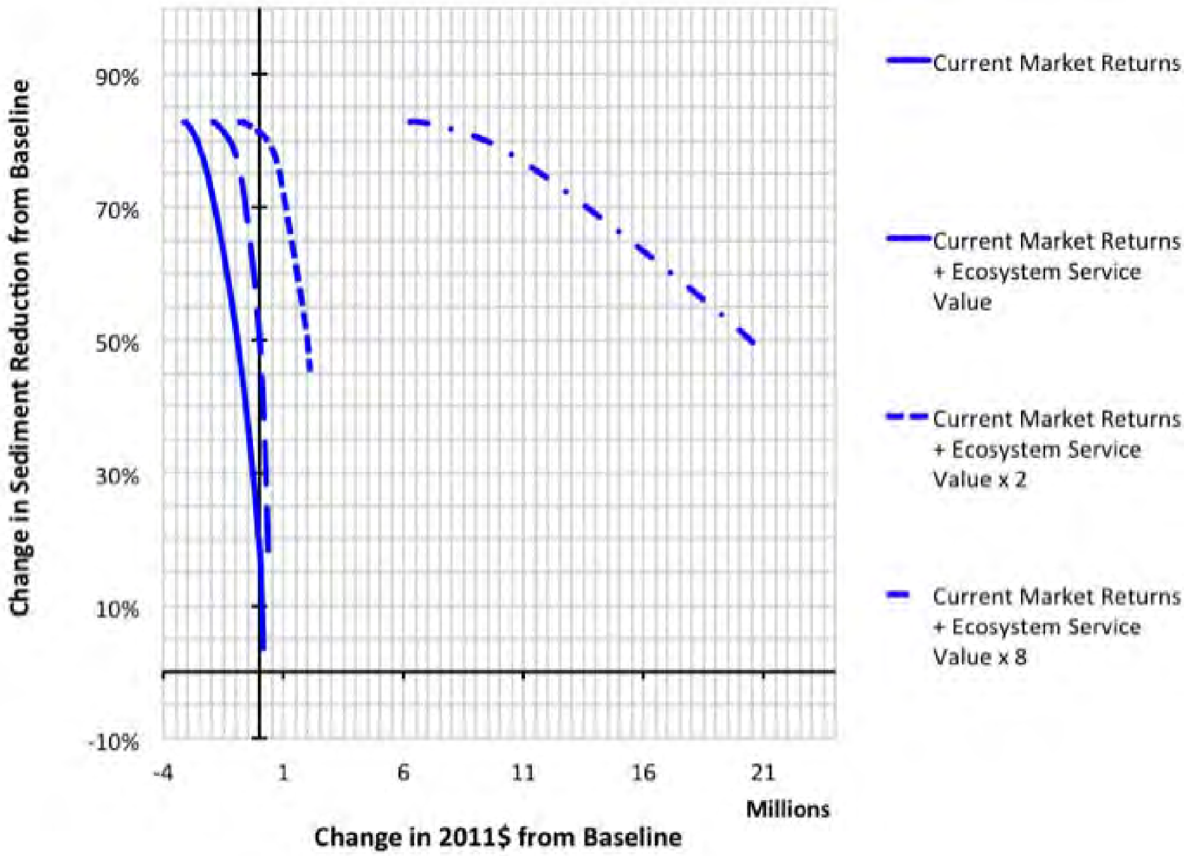


Figure 16. Efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

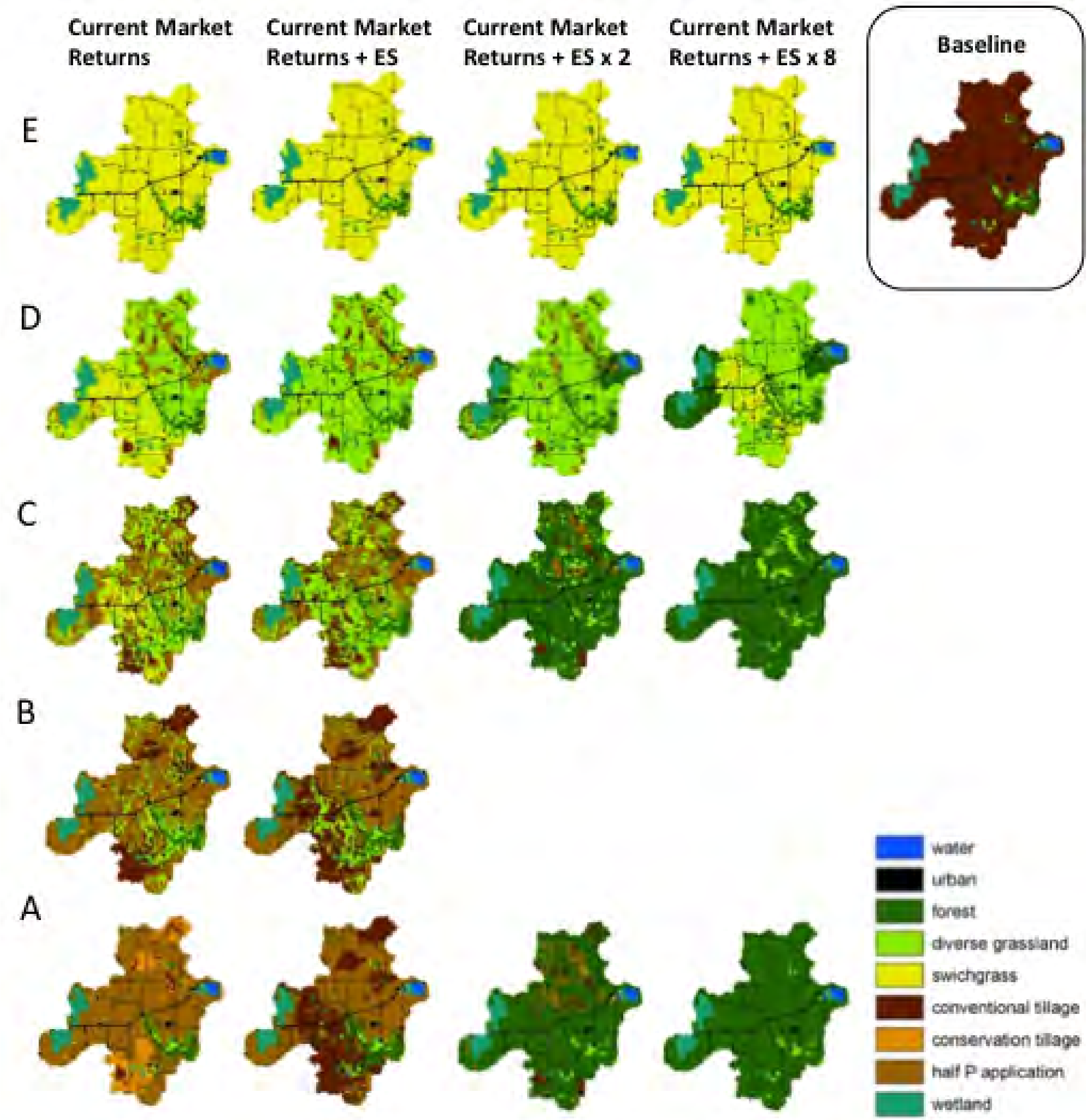


Figure 17. Land-use patterns associated with specific points along the efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

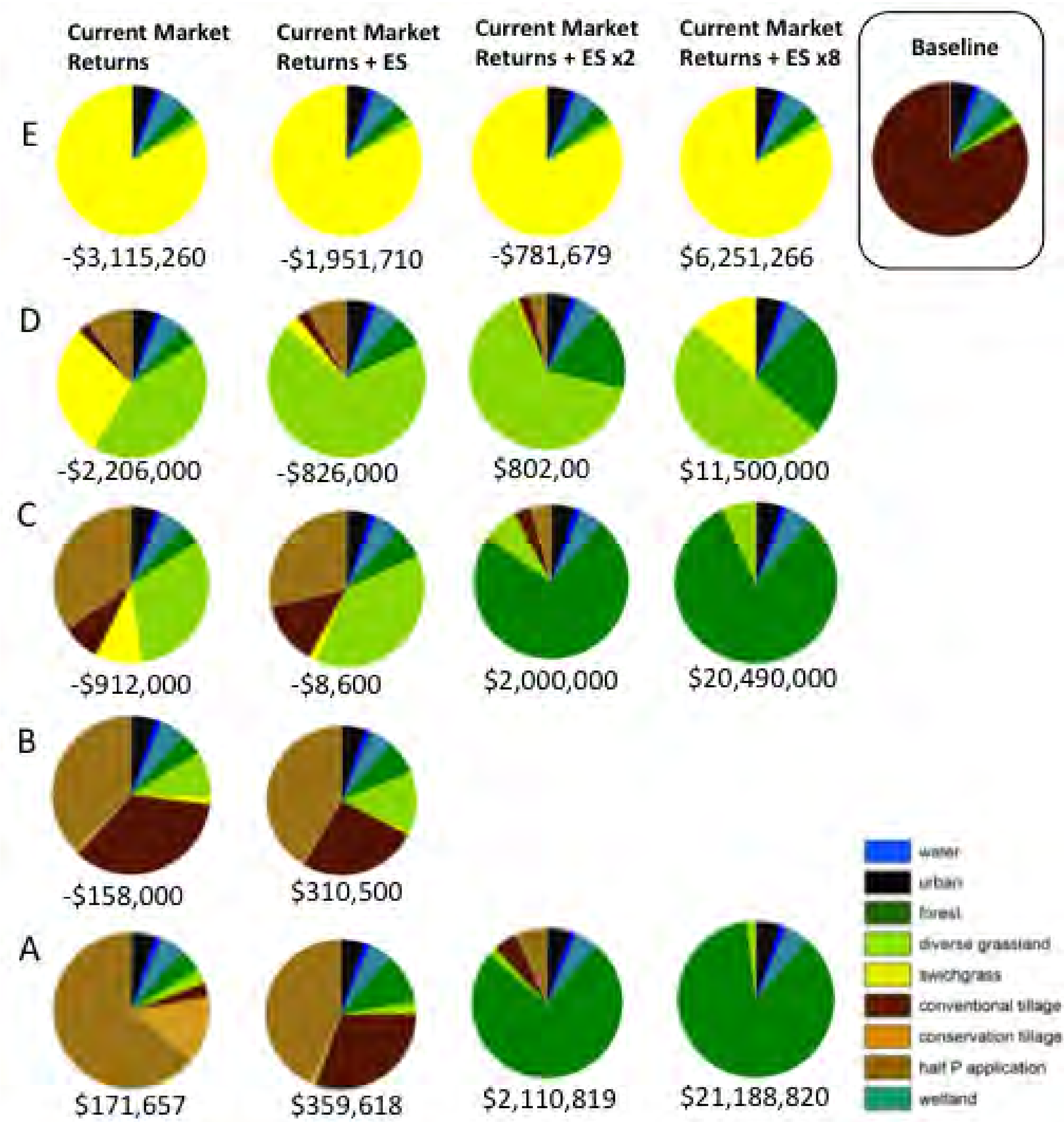


Figure 18. Fraction of land use associated with specific points along the efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

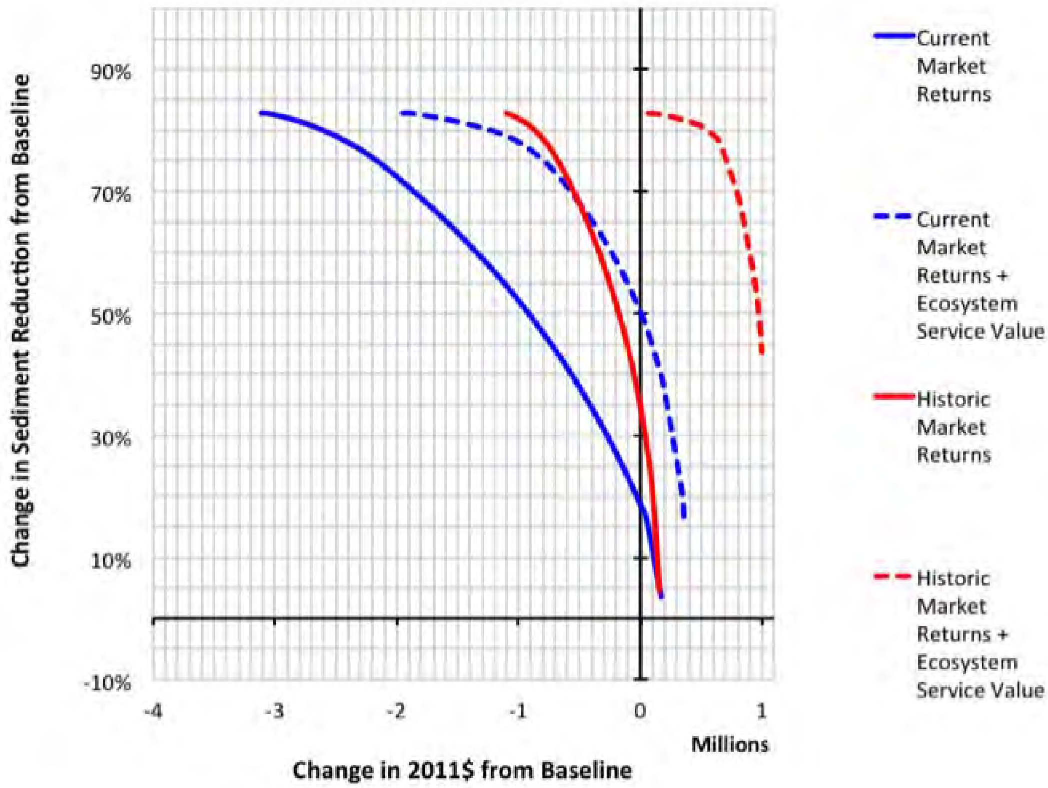


Figure 19 . Efficiency frontiers for sediment reduction and current market returns (blue solid line), historical market returns (red solid line), current market returns plus ecosystem service value (blue dotted line), and historical market returns plus ecosystem services (red dotted line), for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

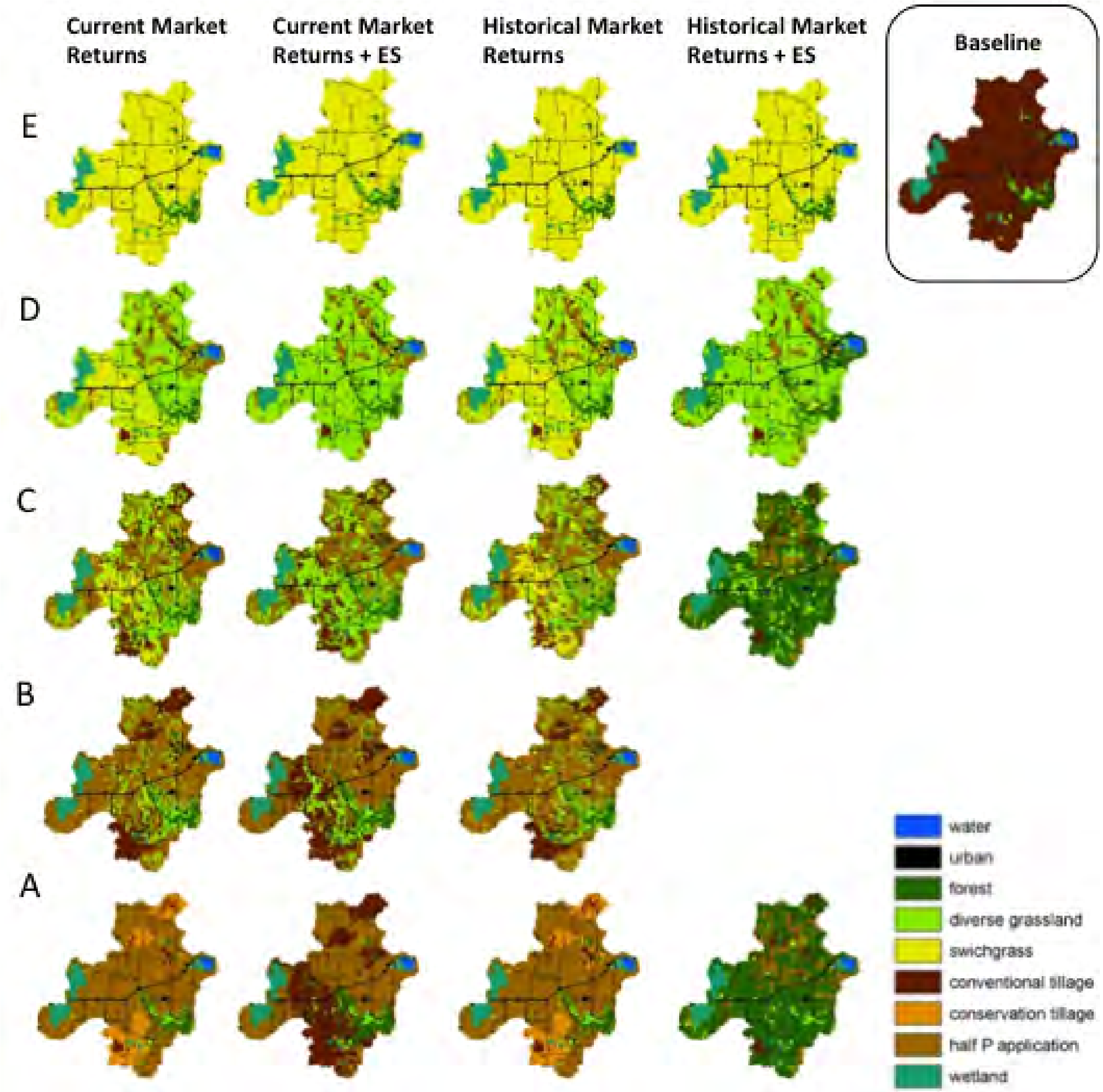


Figure 20. Land-use patterns associated with specific points along the efficiency frontiers for sediment reduction and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for Seven Mile Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

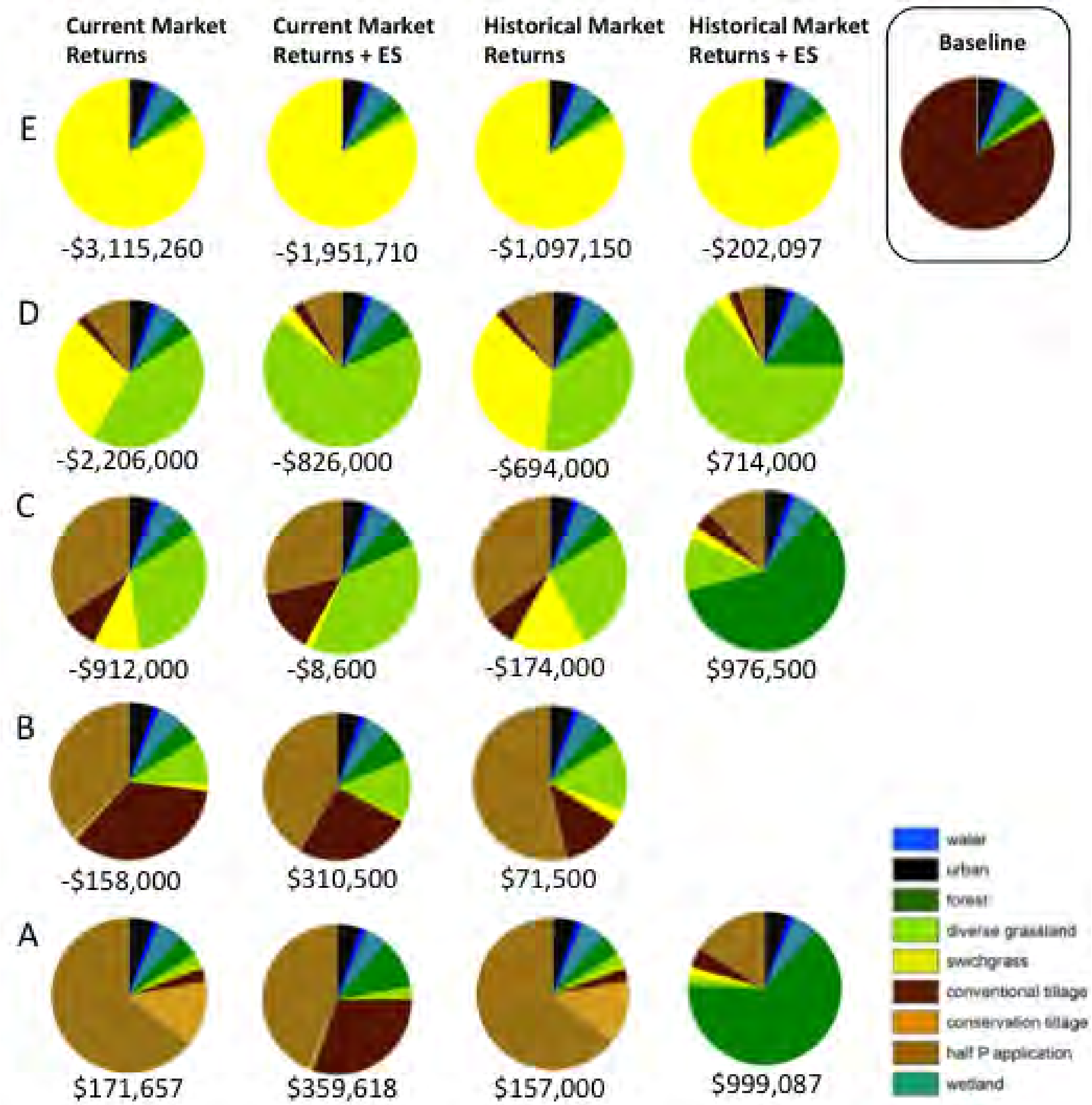


Figure 21. Fraction of land use associated with specific points along the efficiency frontiers for sediment and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for Seven Mile Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

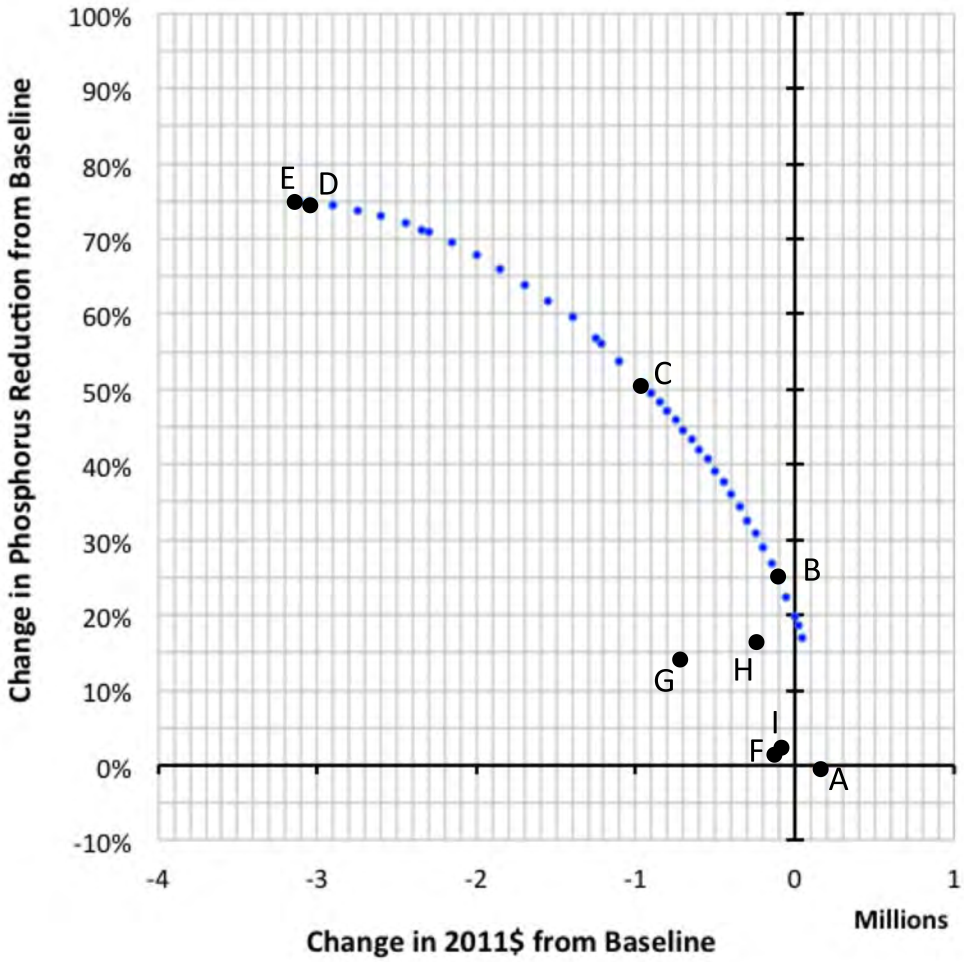


Figure 22. Efficiency frontier for phosphorus reduction and current market returns for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis. The efficiency frontier is outlined by solutions shown as blue circles. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

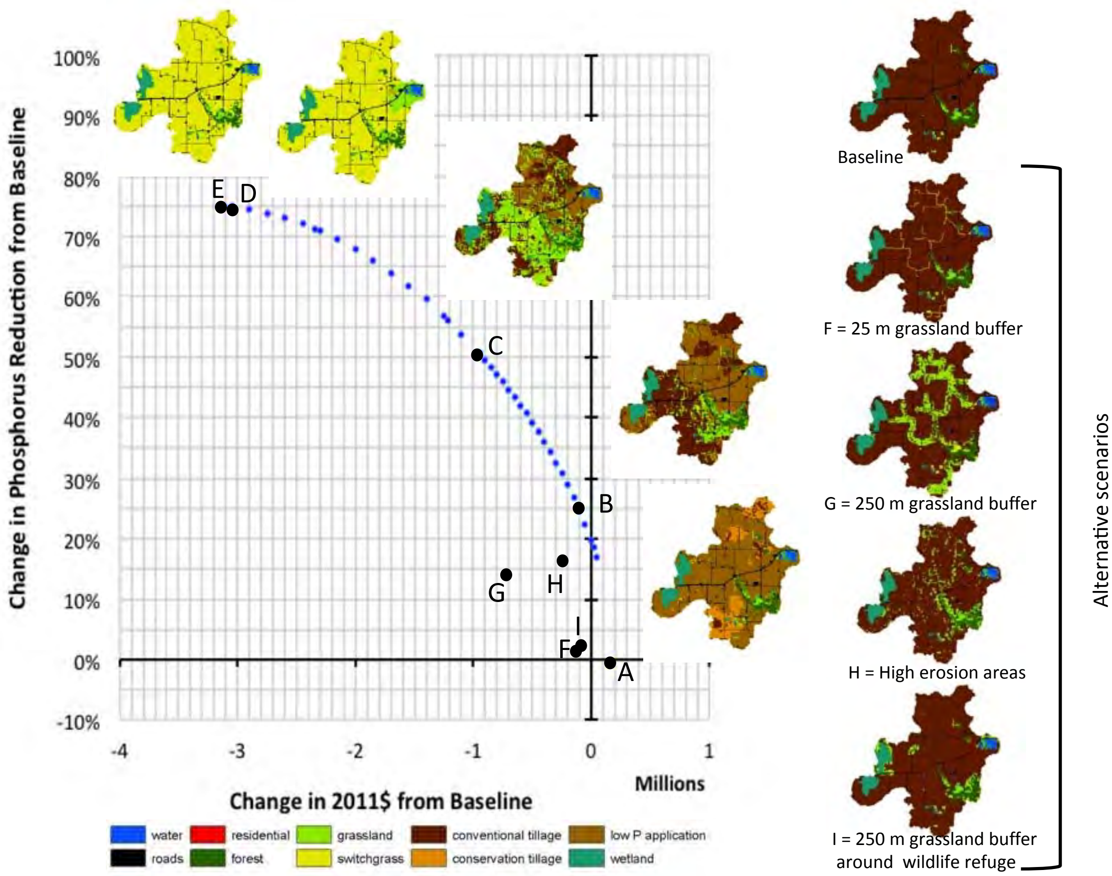


Figure 23. Land-use patterns for the baseline, best management practices and specific points along the efficiency frontier for phosphorus reduction and current value of market returns for Seven Mile Creek. The lettered points correspond to the points in Fig. 22.

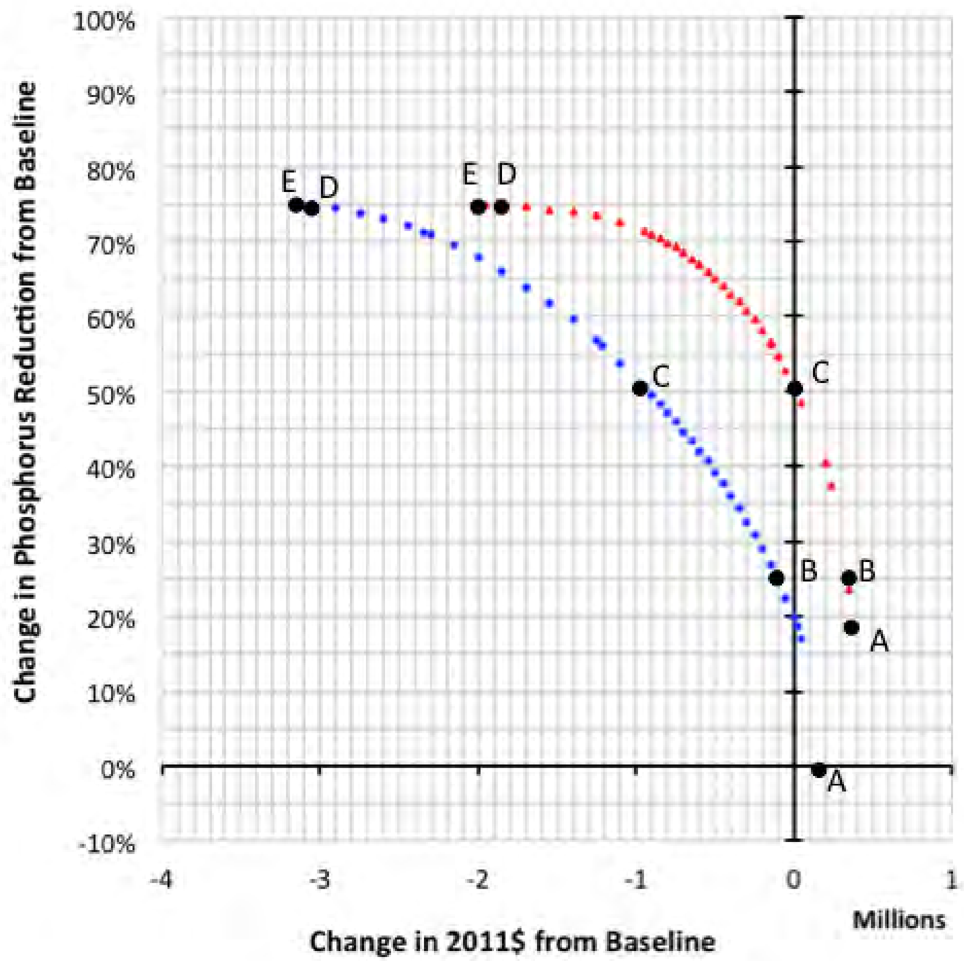


Figure 24. Efficiency frontiers for phosphorus reduction and current market returns (blue circles) and constrained by historical market returns (red triangles) for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum economic returns; B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

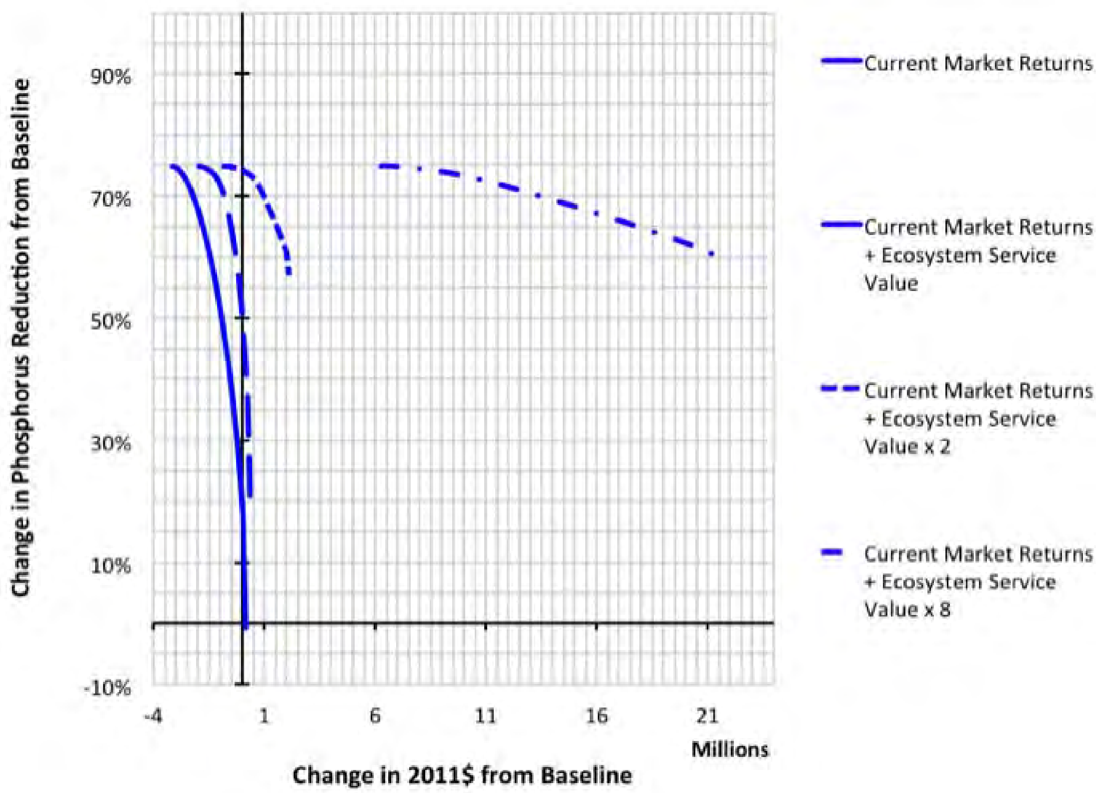


Figure 25. Efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis.

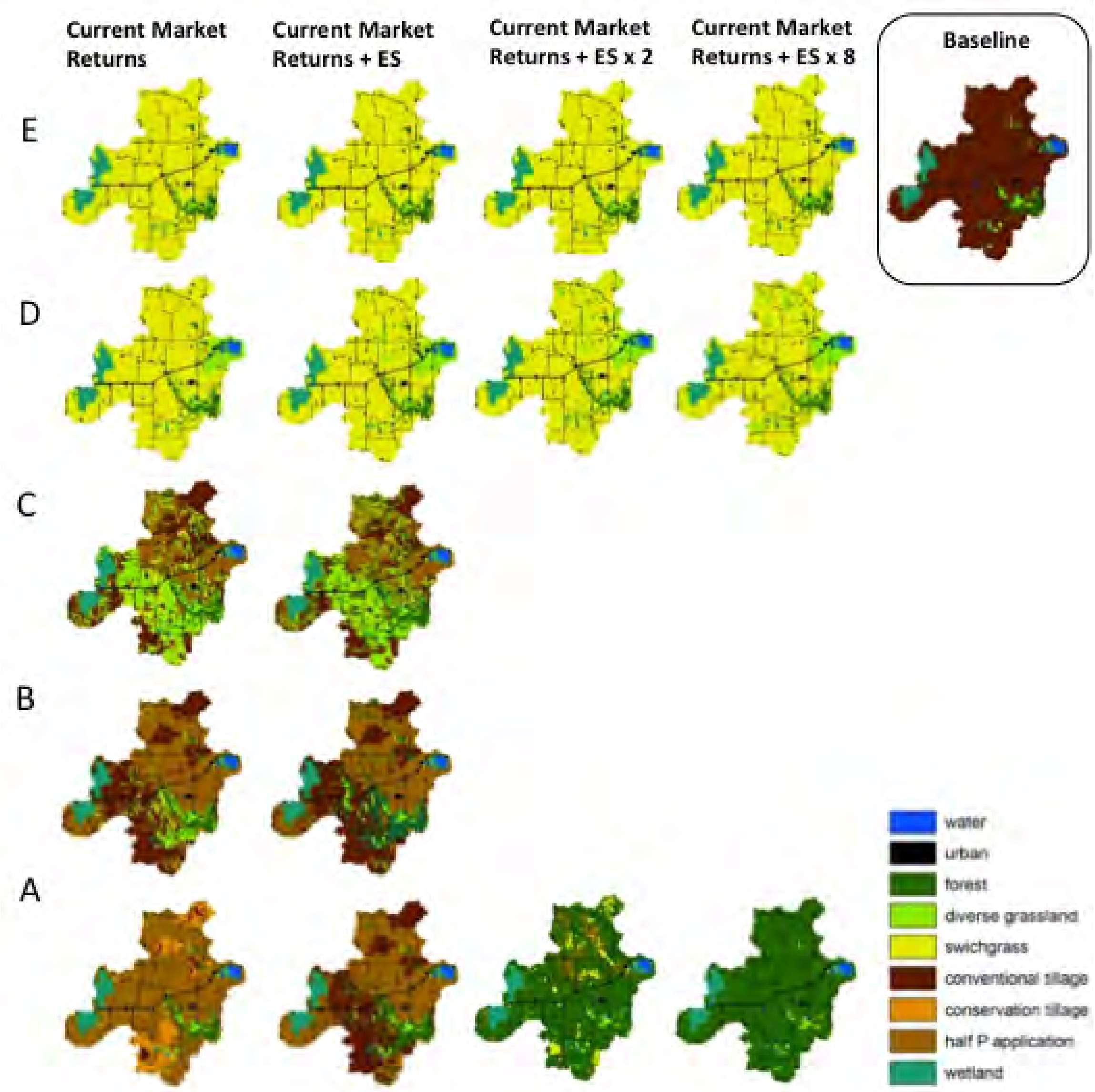


Figure 26. Land-use patterns associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

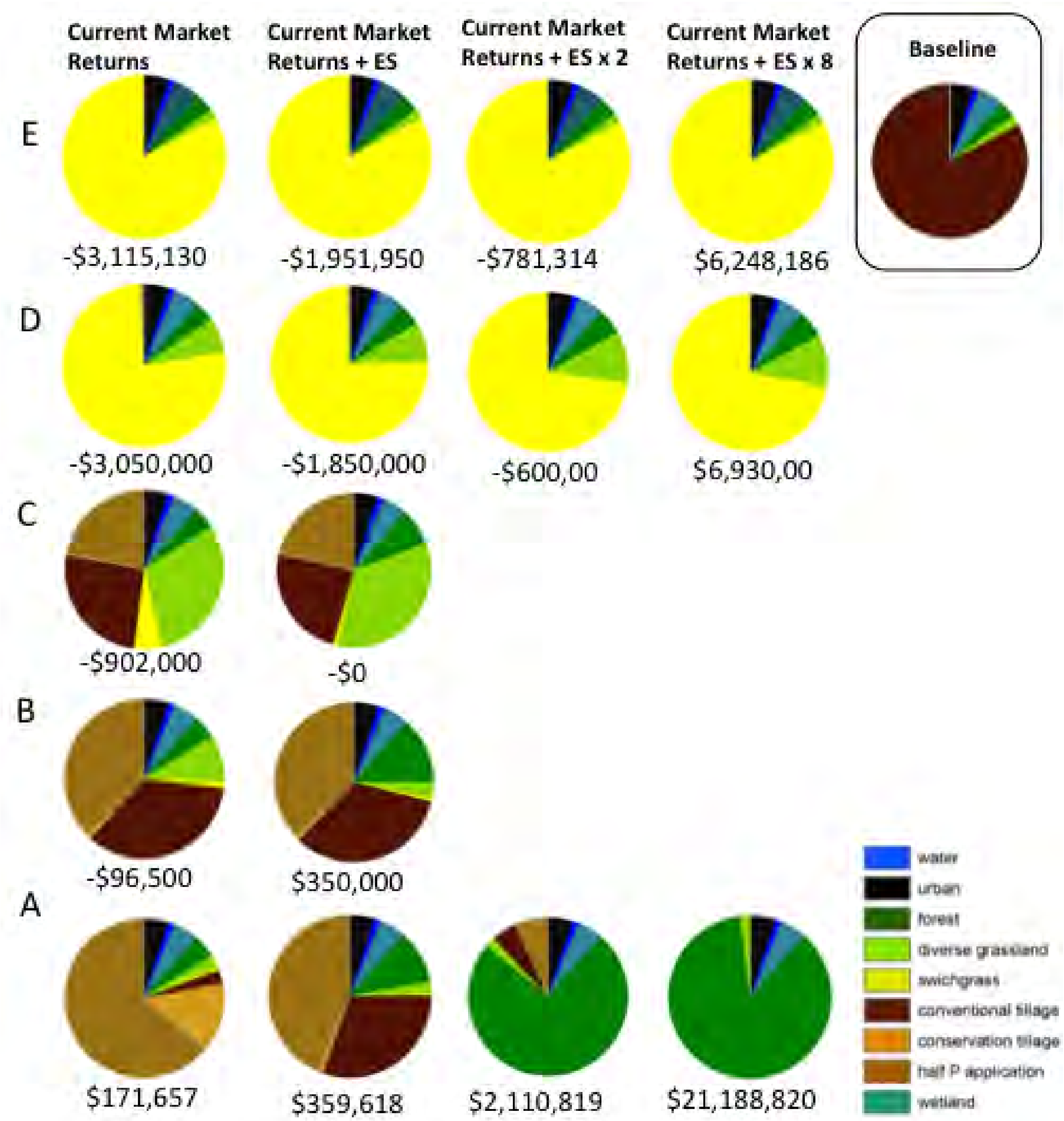


Figure 27. Fraction of land use associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

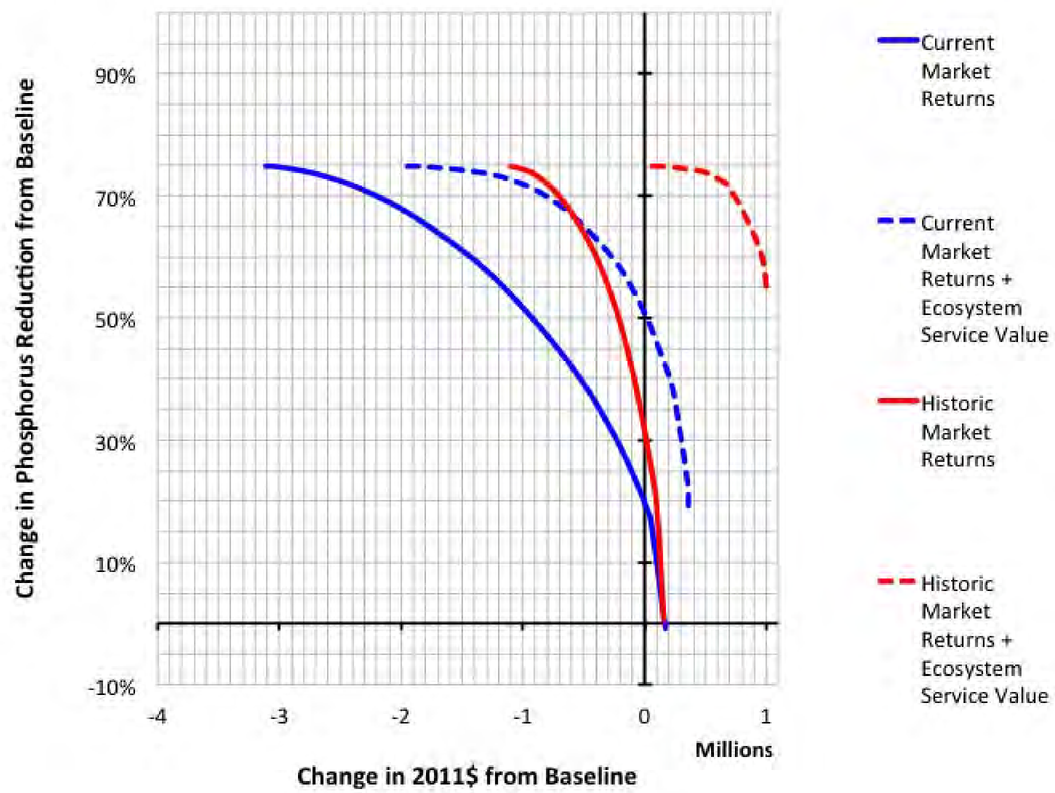


Figure 28. Efficiency frontiers for phosphorus reduction and current market returns (blue solid line), historical market returns (red solid line), current market returns plus ecosystem service value (blue dotted line), and historical market returns plus ecosystem services (red dotted line), for Seven Mile Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

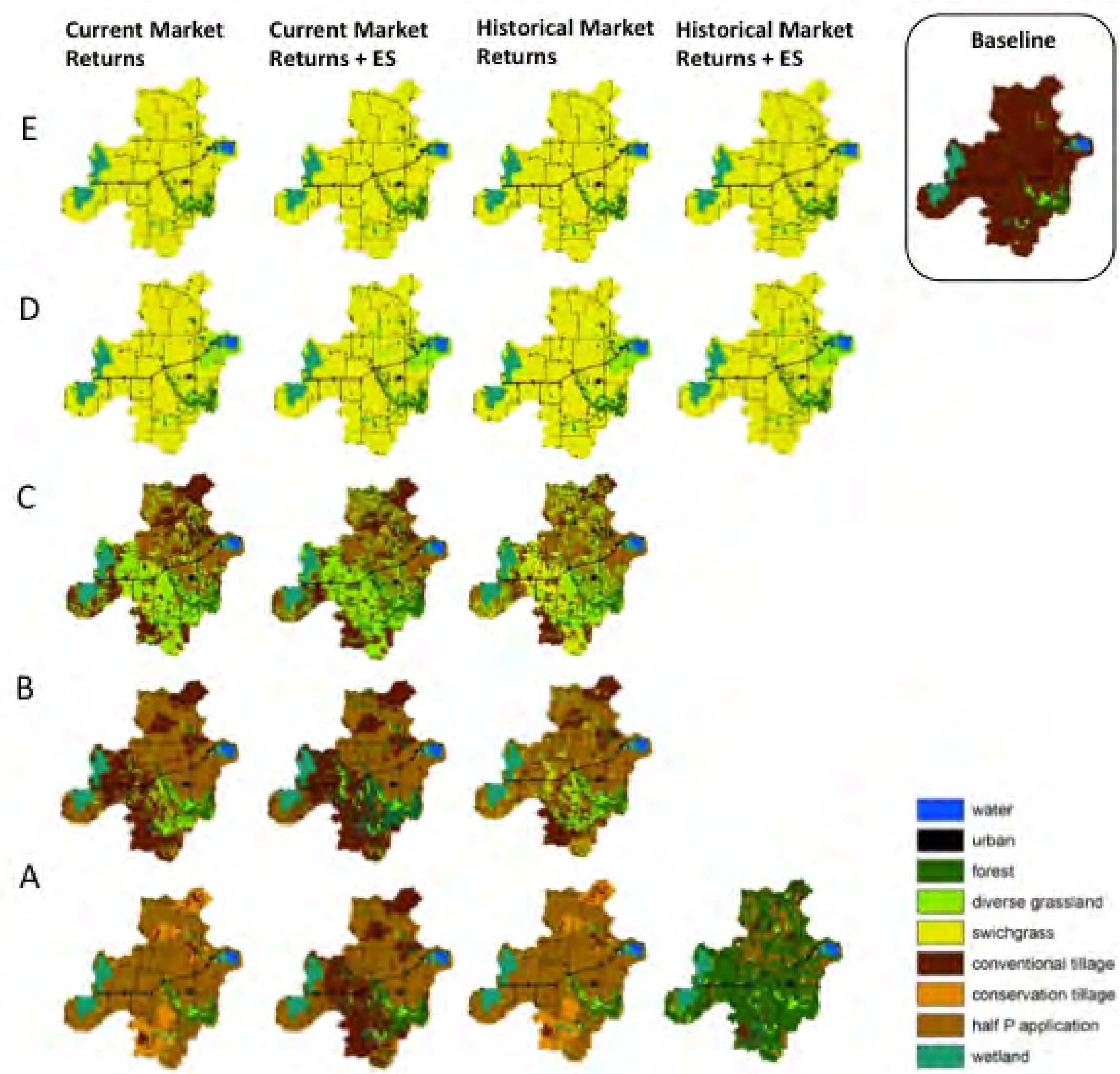


Figure 29. Land-use patterns associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction (not shown here since the max reduction is near 75%); E = maximum phosphorus reduction.

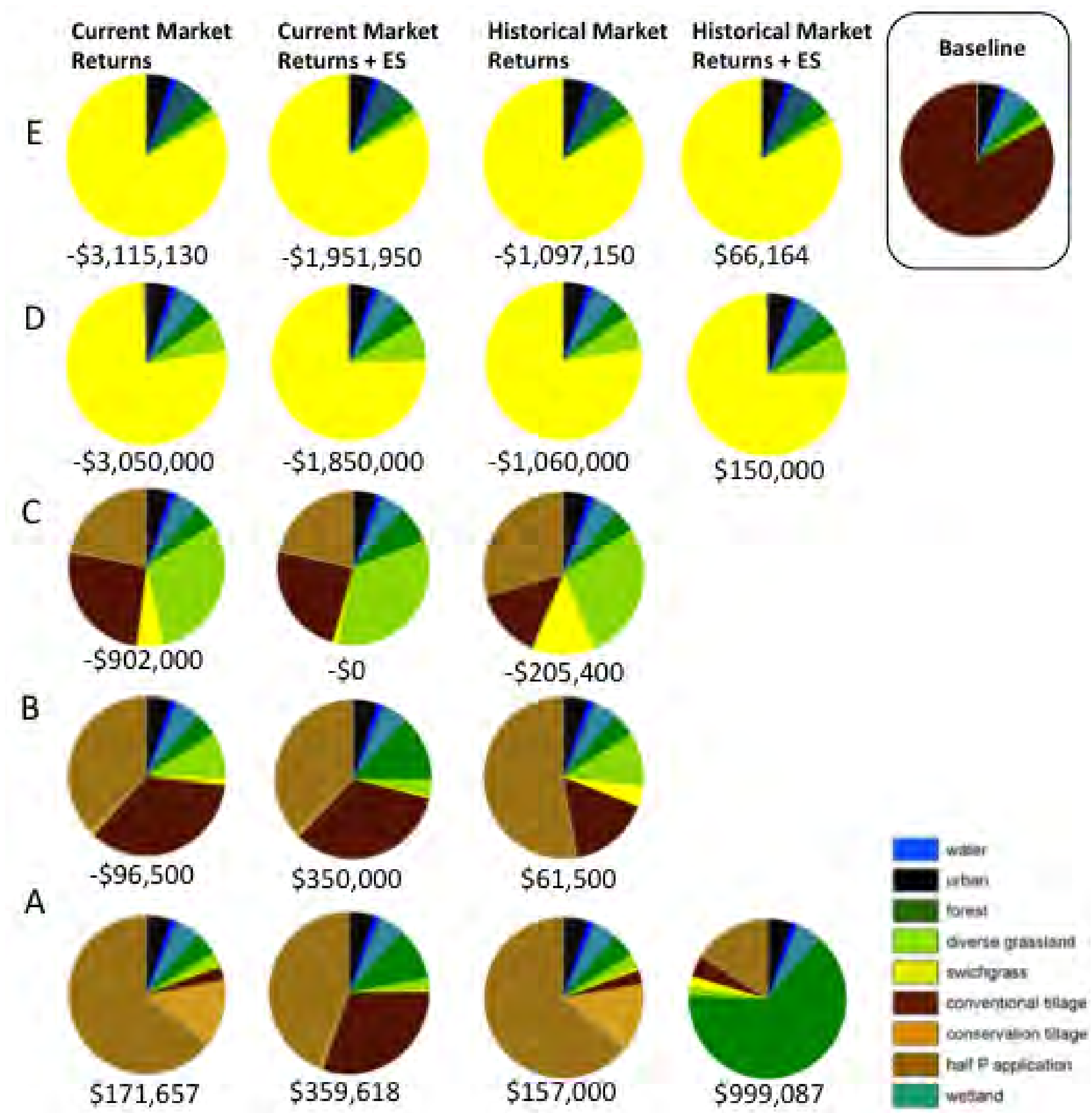


Figure 30. Fraction of land use associated with specific points along the efficiency frontiers for phosphorus and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

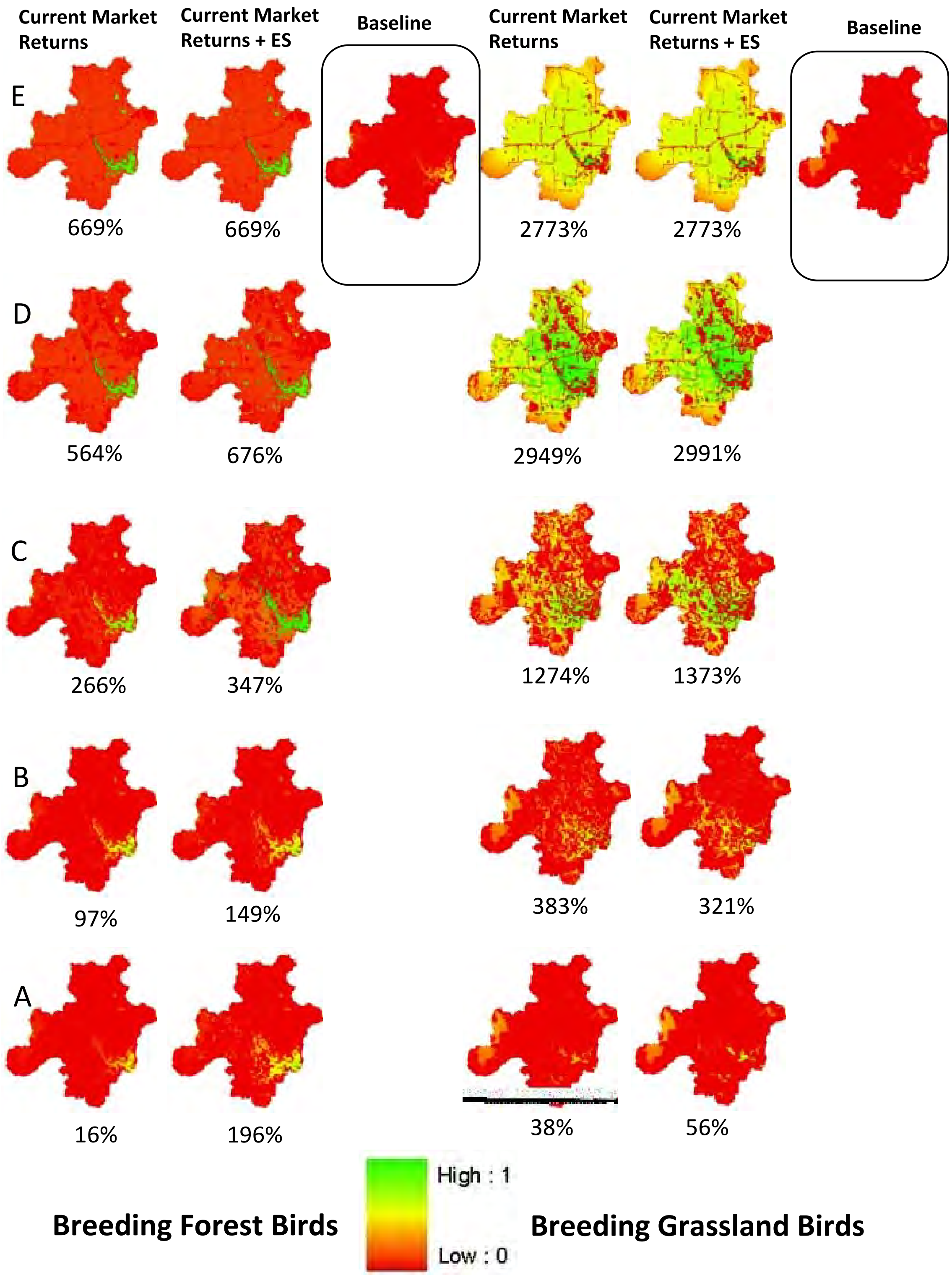


Figure 31. Change in habitat quality score from baseline for specific points along efficiency frontiers for sediment and current market values and sediment and current market values plus ecosystem service value for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

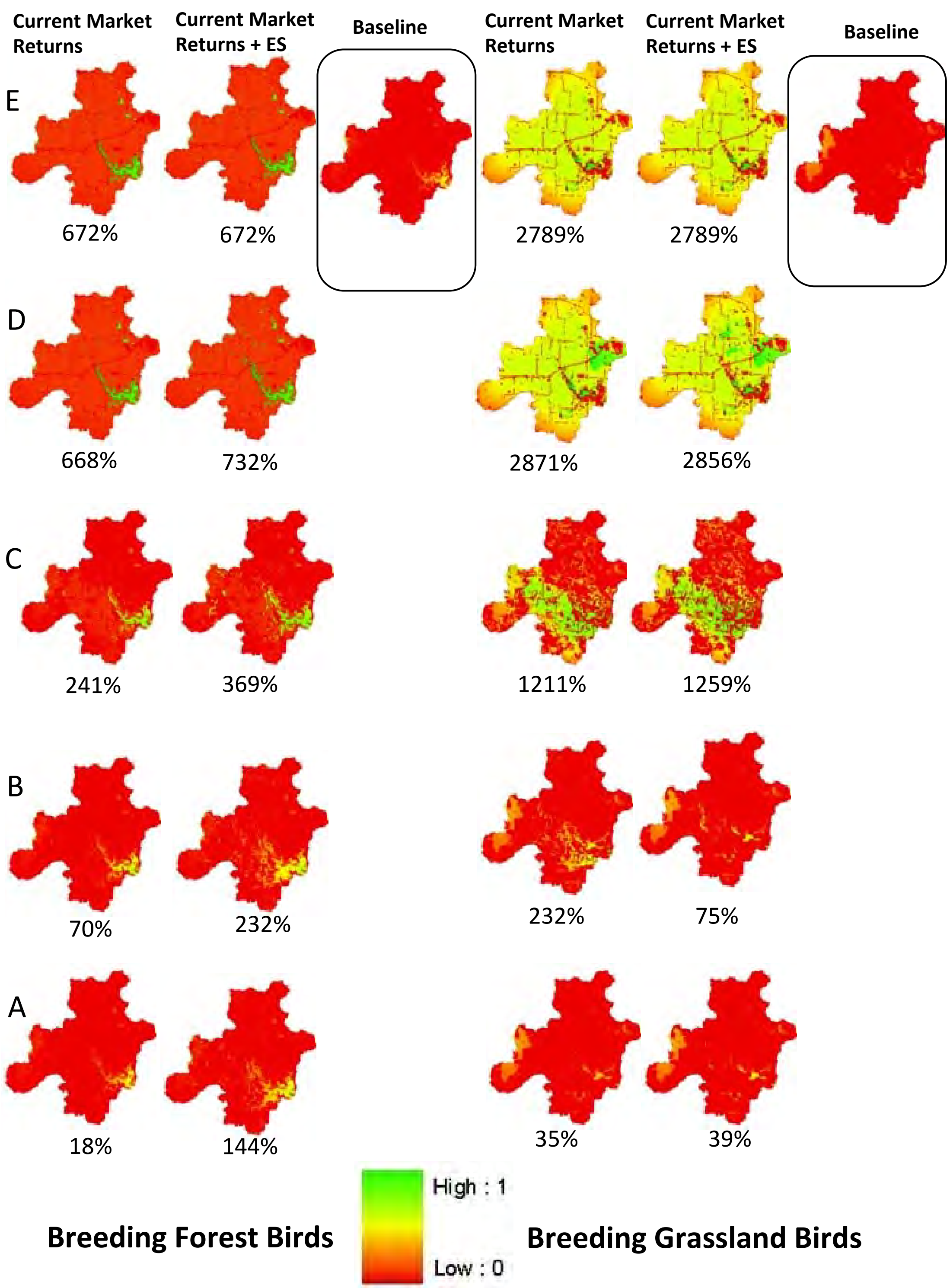


Figure 32. Change in habitat quality score from baseline for specific points along efficiency frontiers for phosphorus and current market values and sediment and current market values plus ecosystem service value for Seven Mile Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

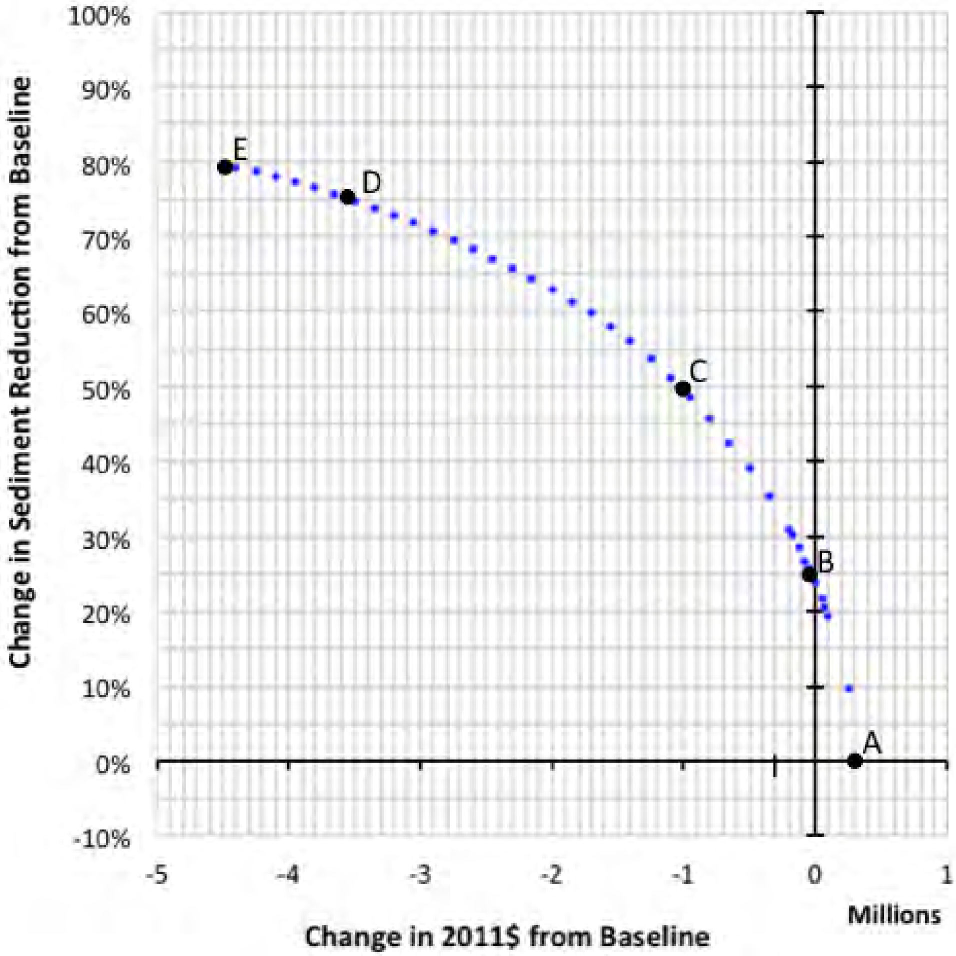


Figure 33. Efficiency frontier for sediment reduction and current market returns for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis. The efficiency frontier is outlined by solutions shown as blue circles. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

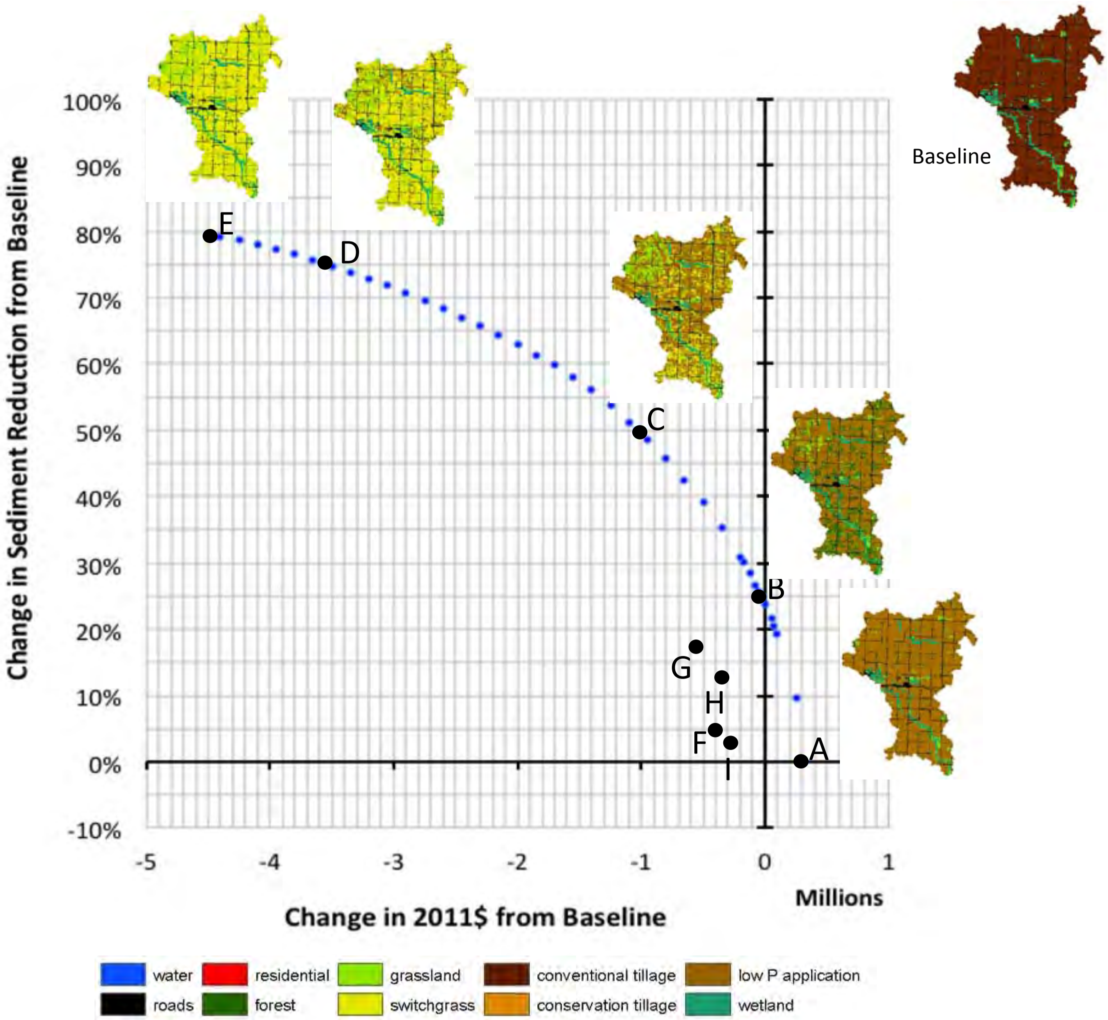


Figure 34. Land-use patterns for the baseline, best management practices and specific points along the efficiency frontier for sediment reduction and current value of market returns for West Fork Beaver Creek. The lettered points correspond to the points in Fig. 33.

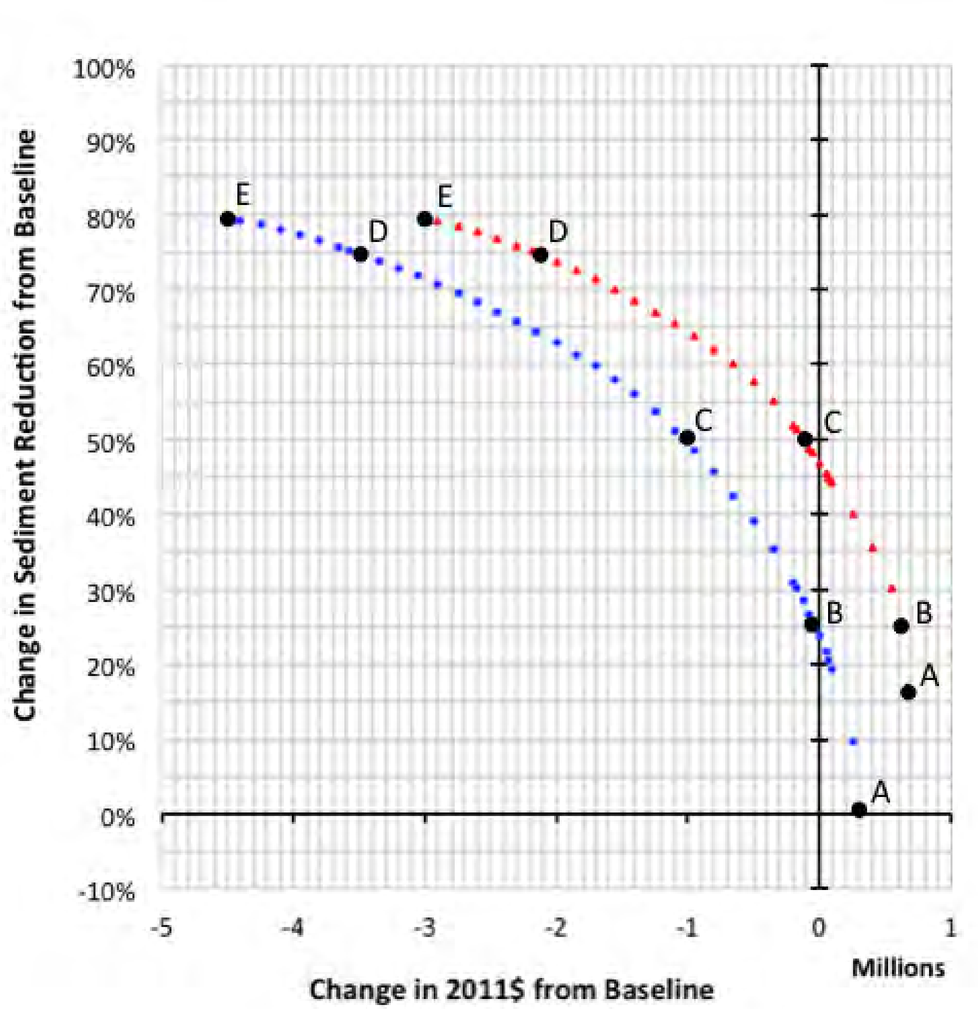


Figure 35. Efficiency frontiers for sediment reduction and current market returns (blue circles) and for sediment reduction and current market returns plus ecosystem service value (red triangles) for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum returns; B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

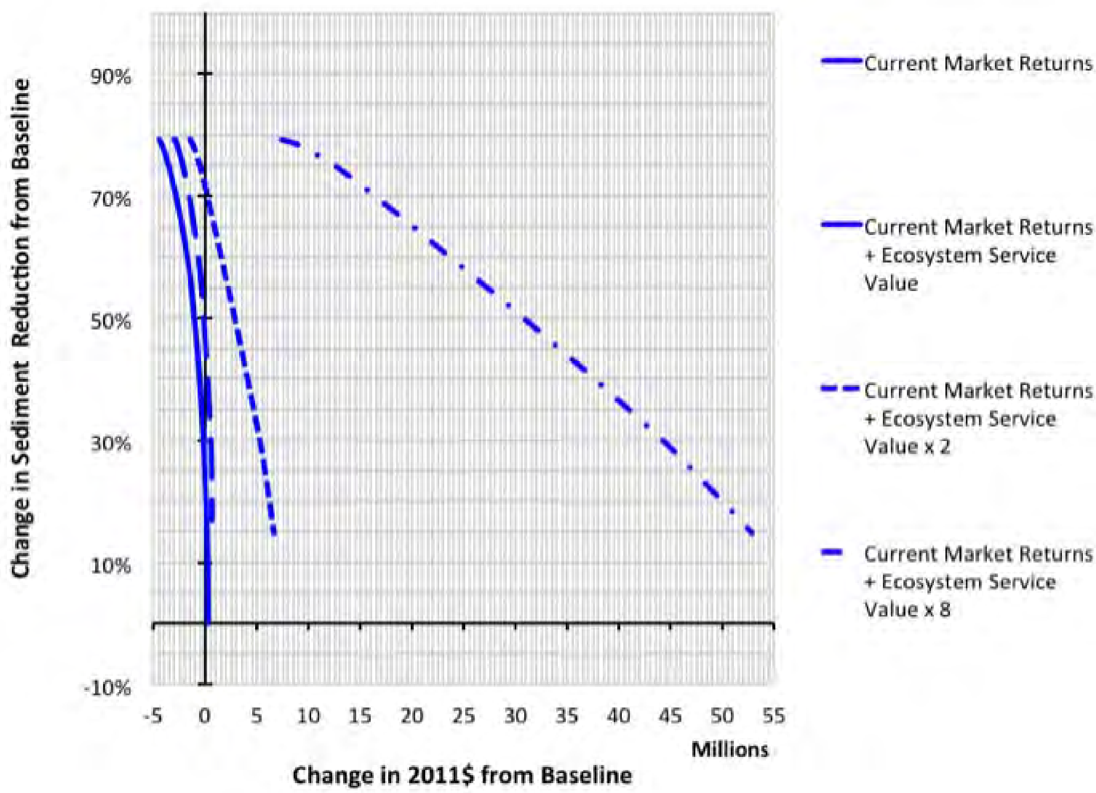


Figure 36. Efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

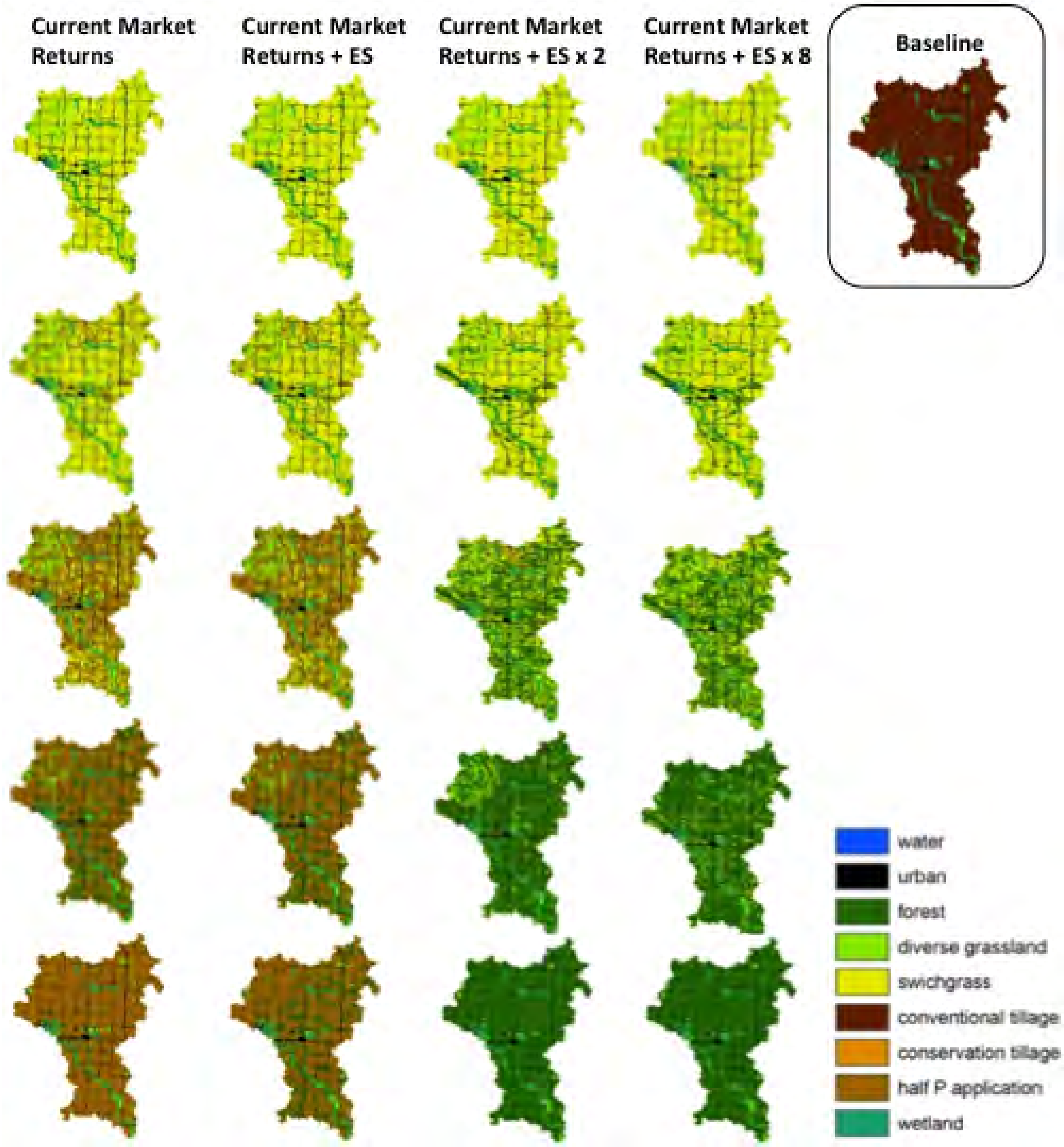


Figure 37. Land-use patterns associated with specific points along the efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

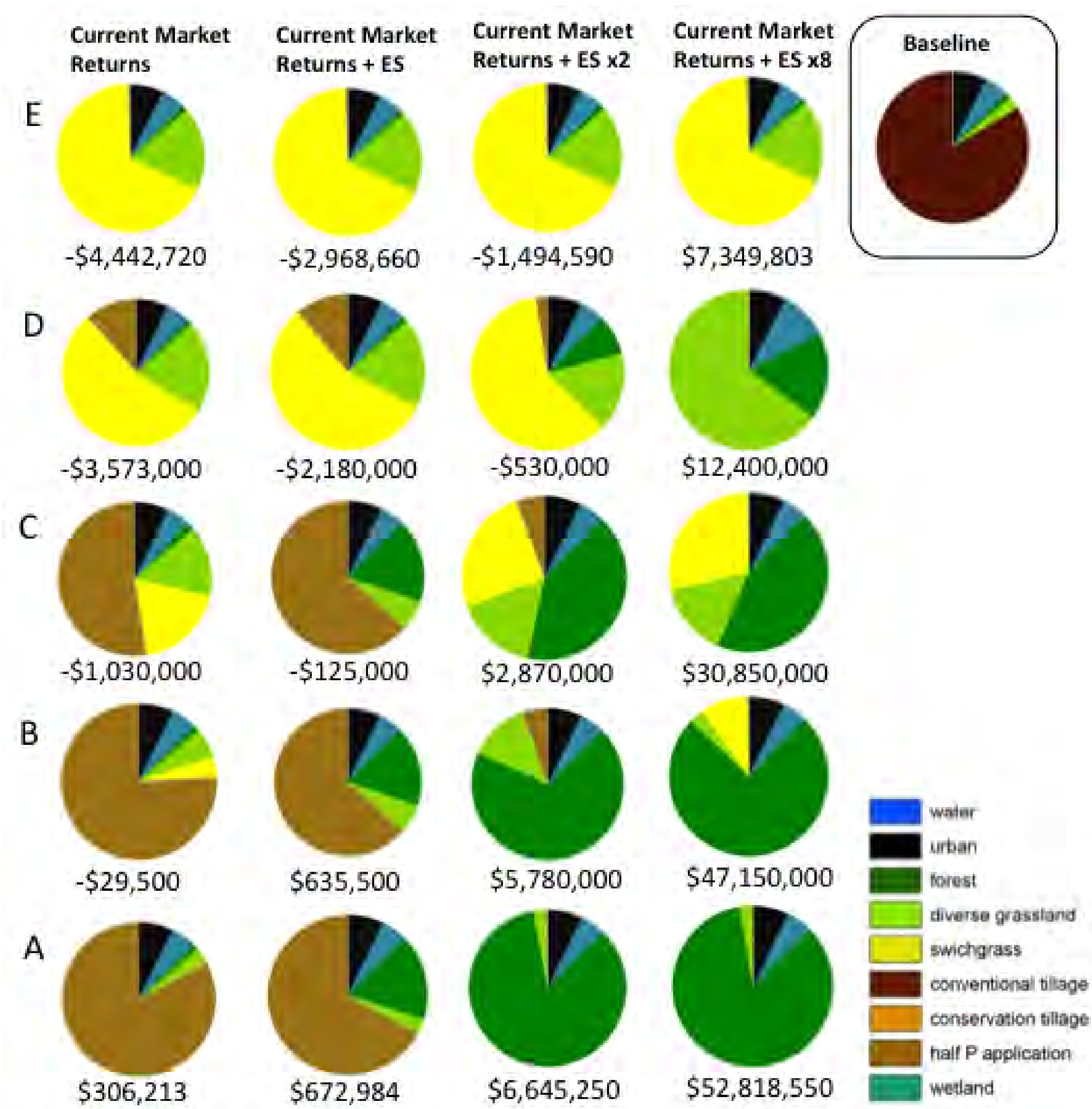


Figure 38. Fraction of land use associated with specific points along the efficiency frontiers for sediment reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

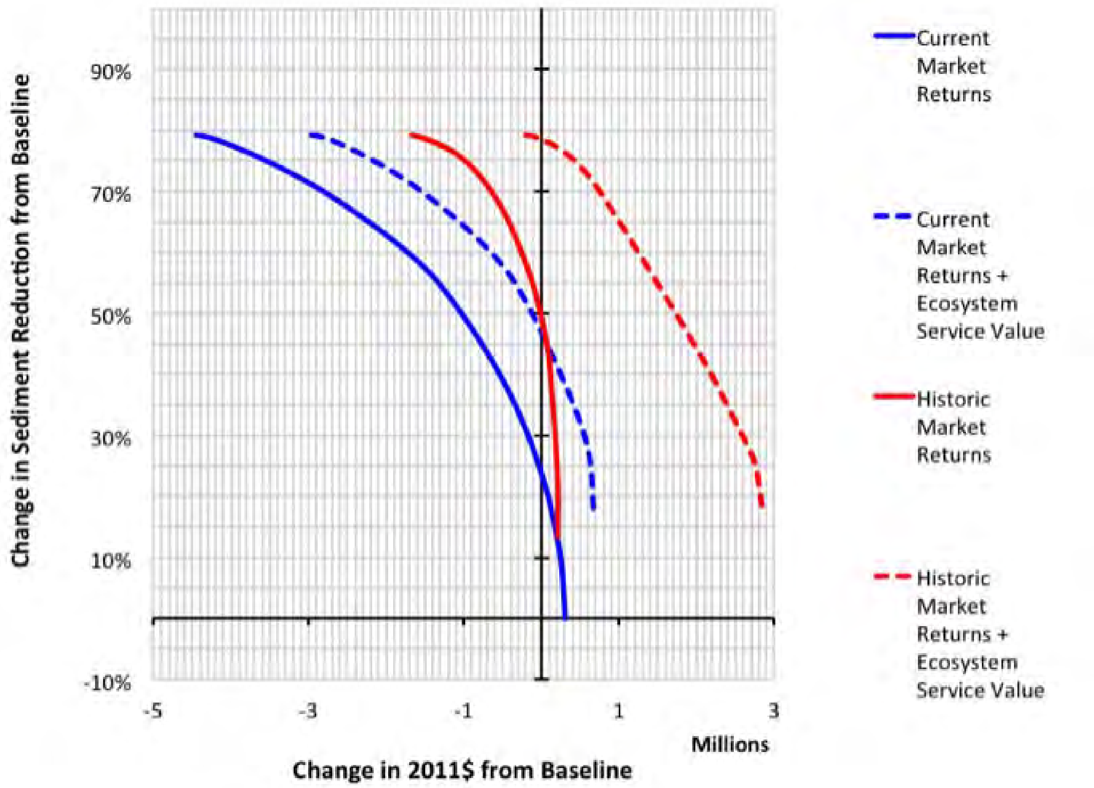


Figure 39. Efficiency frontiers for sediment reduction and current market returns (blue solid line), historical market returns (red solid line), current market returns plus ecosystem service value (blue dotted line), and historical market returns plus ecosystem services (red dotted line), for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

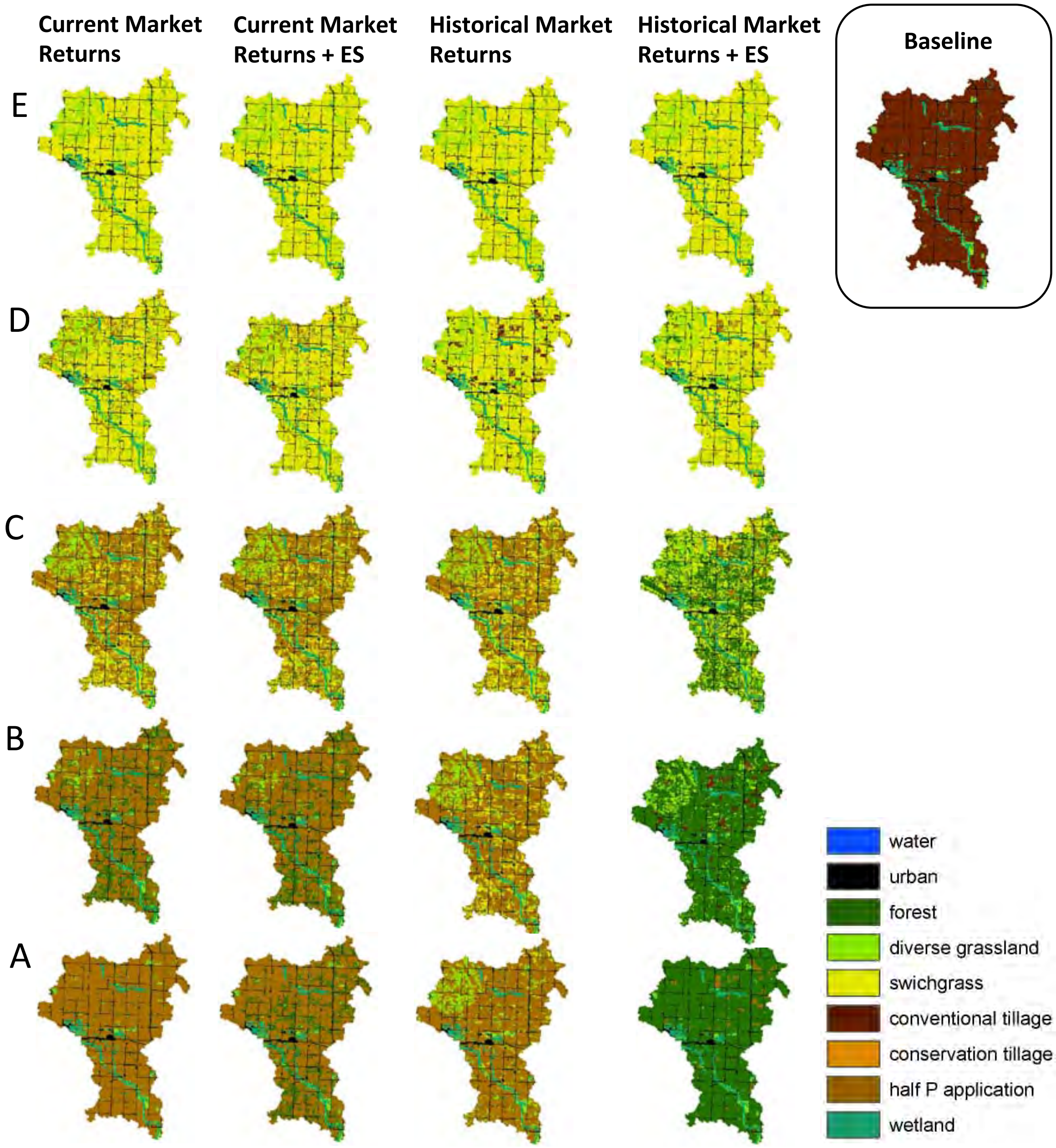


Figure 40. Land-use patterns associated with specific points along the efficiency frontiers for sediment reduction and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for West Fork Beaver Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

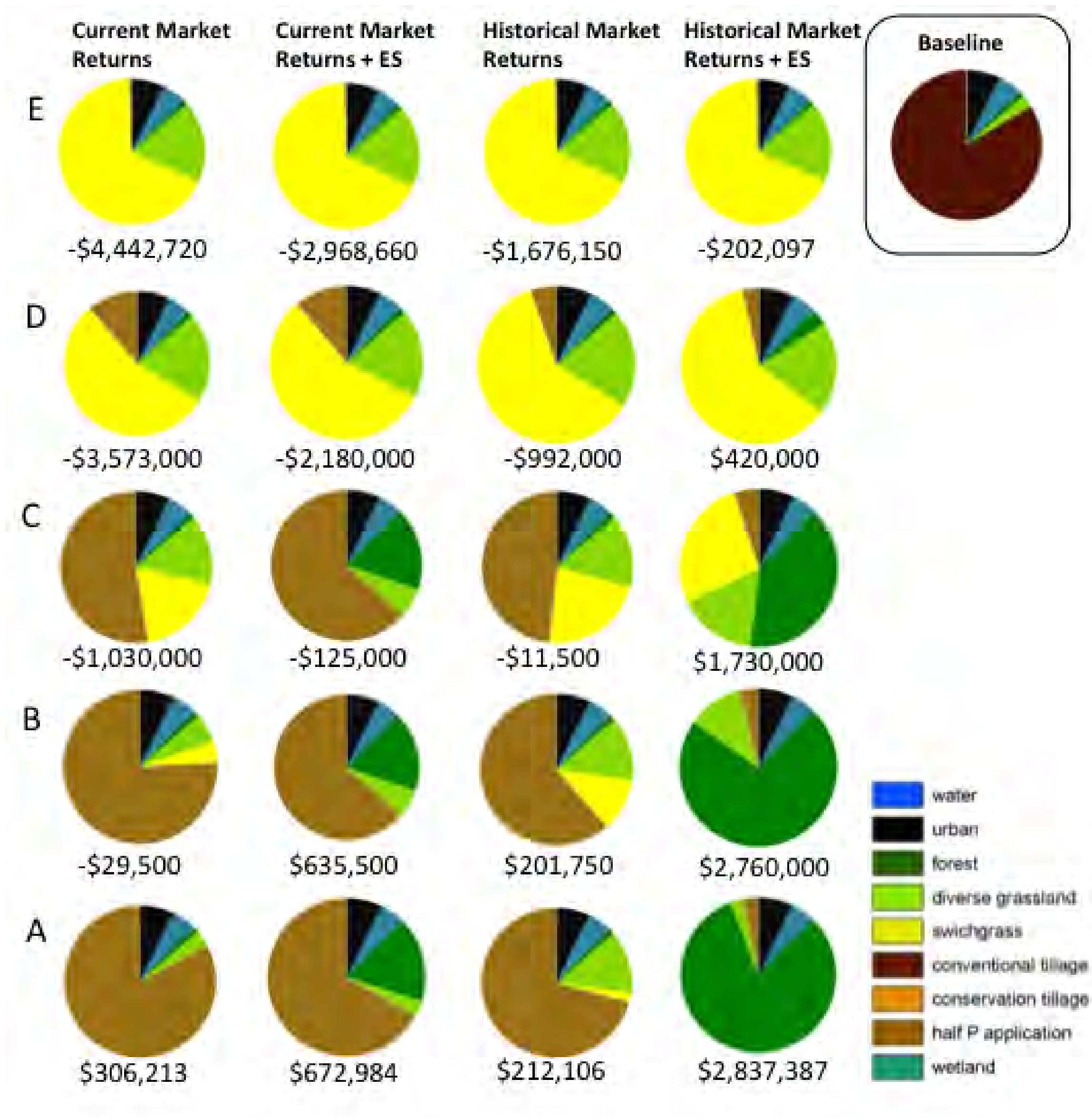


Figure 41. Fraction of land use associated with specific points along the efficiency frontiers for sediment and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for West Fork Beaver Creek. A = maximum economic value; B = 25% sediment reduction; C = 50 % reduction; D = 75% reduction; E = maximum sediment reduction.

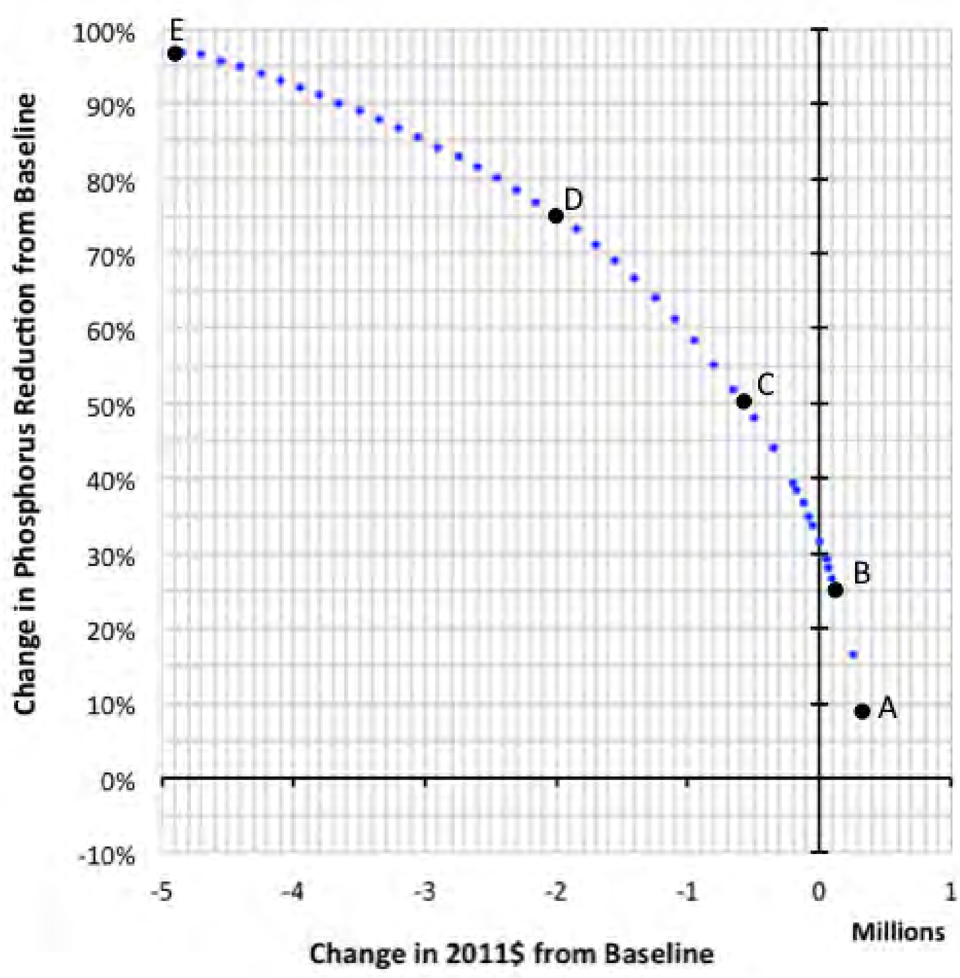


Figure 42. Efficiency frontier for phosphorus reduction and current market returns for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis. The efficiency frontier is outlined by solutions shown as blue circles. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

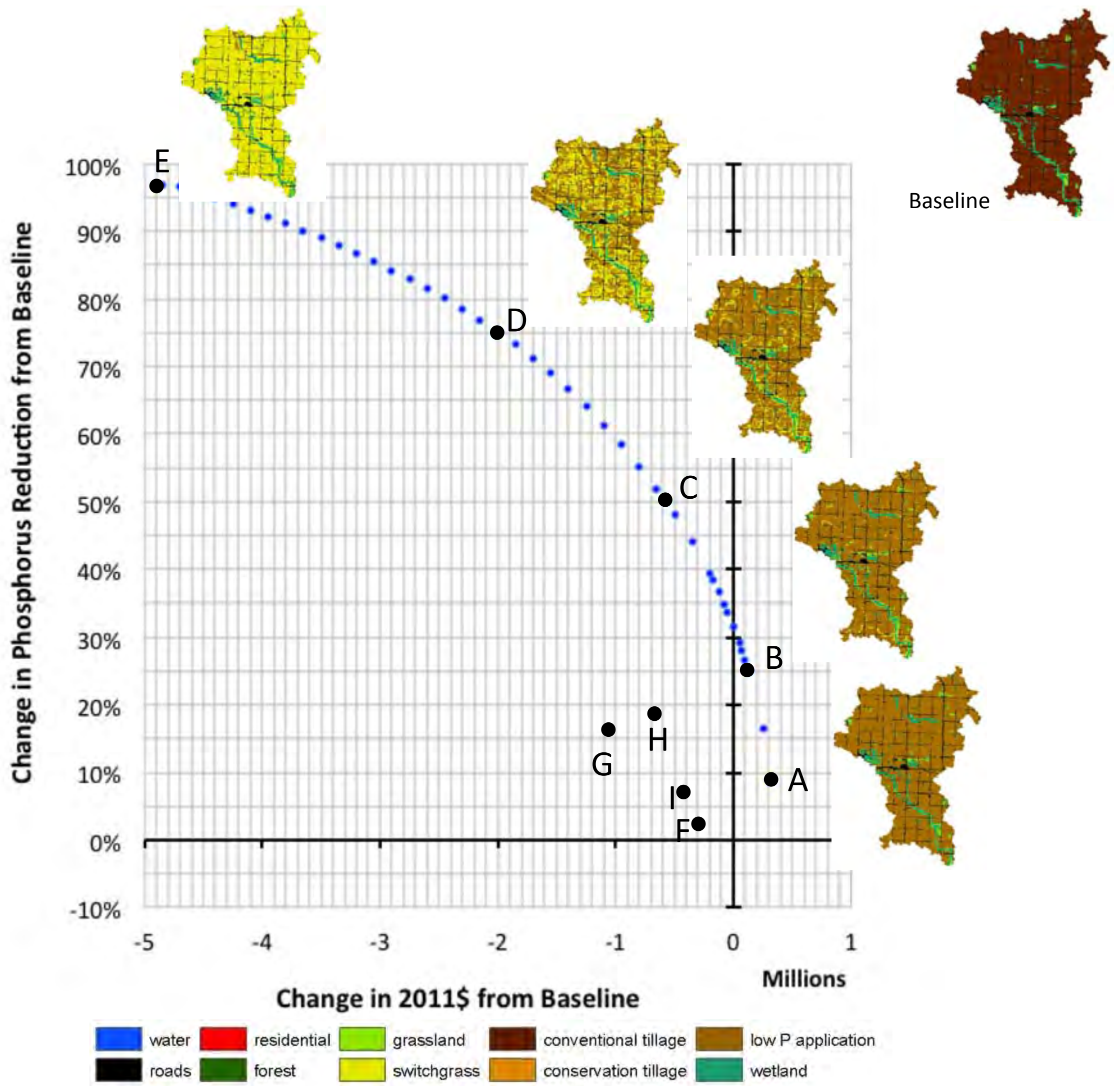


Figure 43. Land-use patterns for the baseline, best management practices and specific points along the efficiency frontier for phosphorus reduction and current value of market returns for West Fork Beaver Creek. The lettered points correspond to the points in Fig. 42.

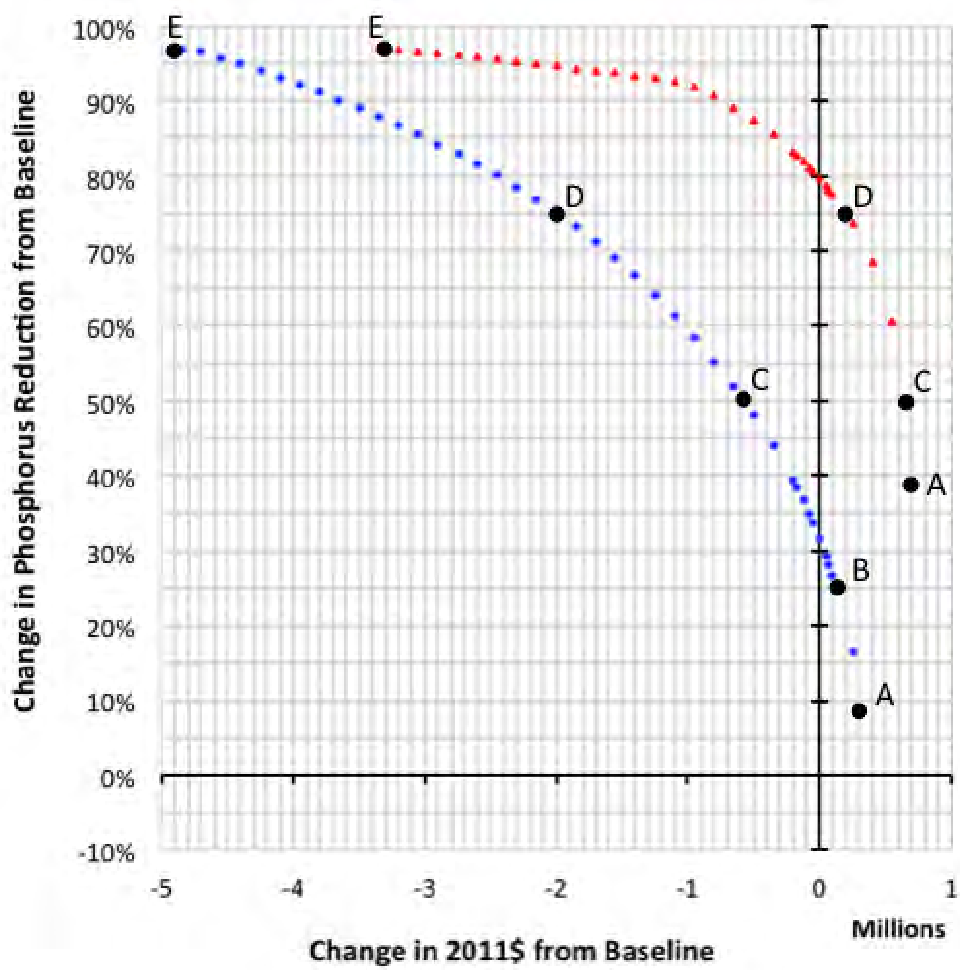


Figure 44. Efficiency frontiers for phosphorus reduction and current market returns (blue circles) and constrained by historical market returns (red triangles) for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis. The lettered circles represent specific land-use patterns along the frontier: Point A represents the maximum economic returns; B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

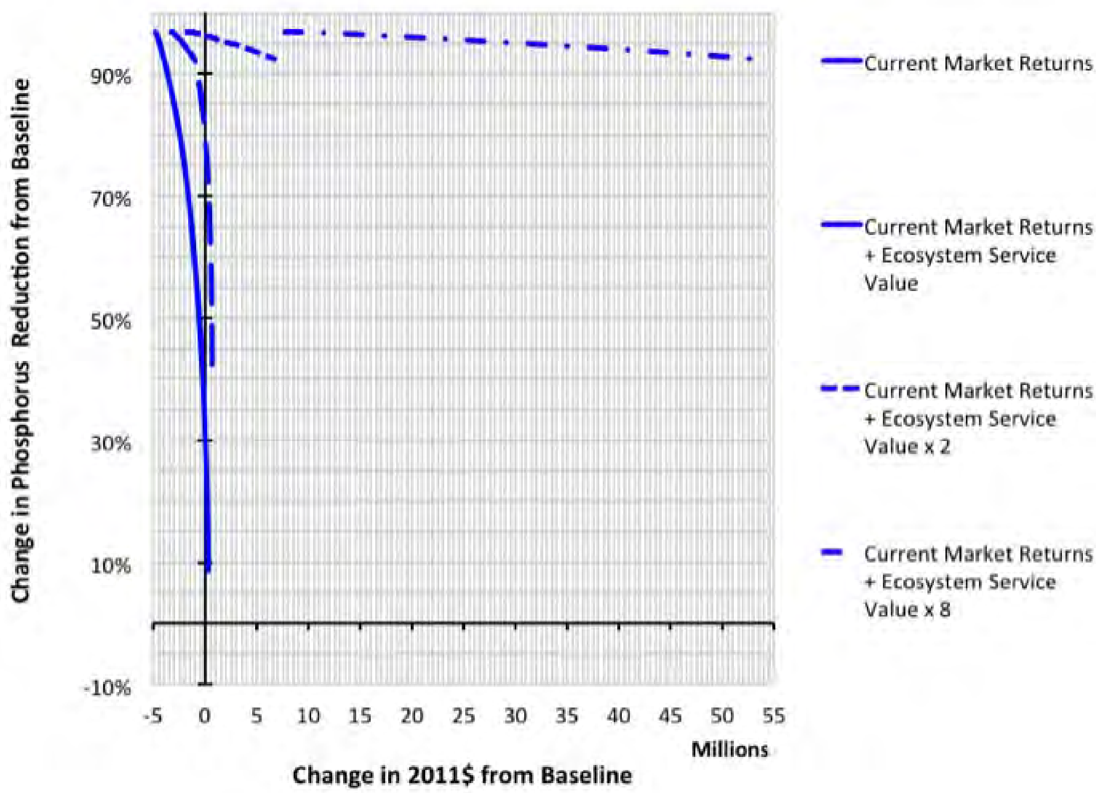


Figure 45. Efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in phosphorus is shown on the vertical axis.

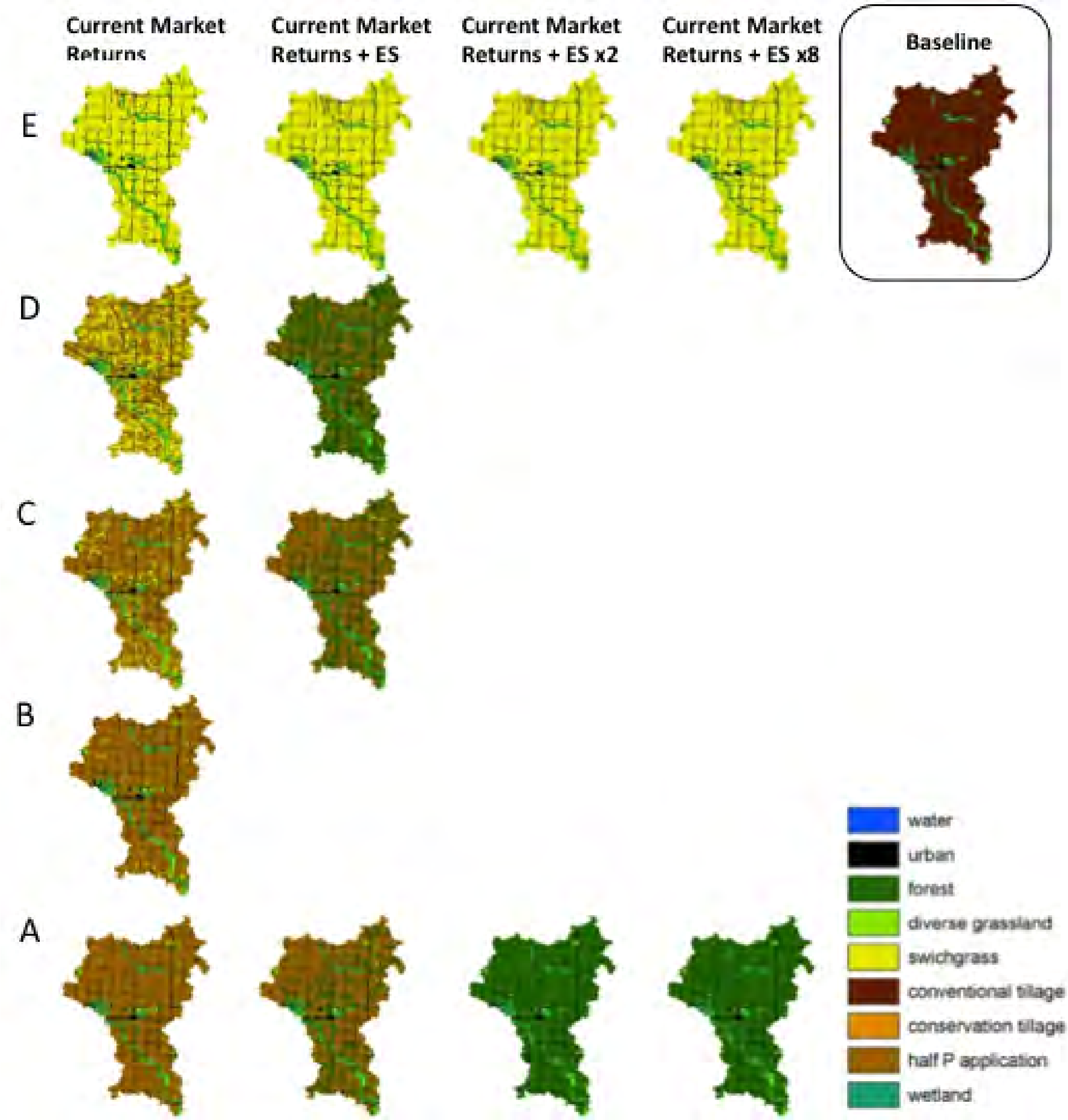


Figure 46. Land-use patterns associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

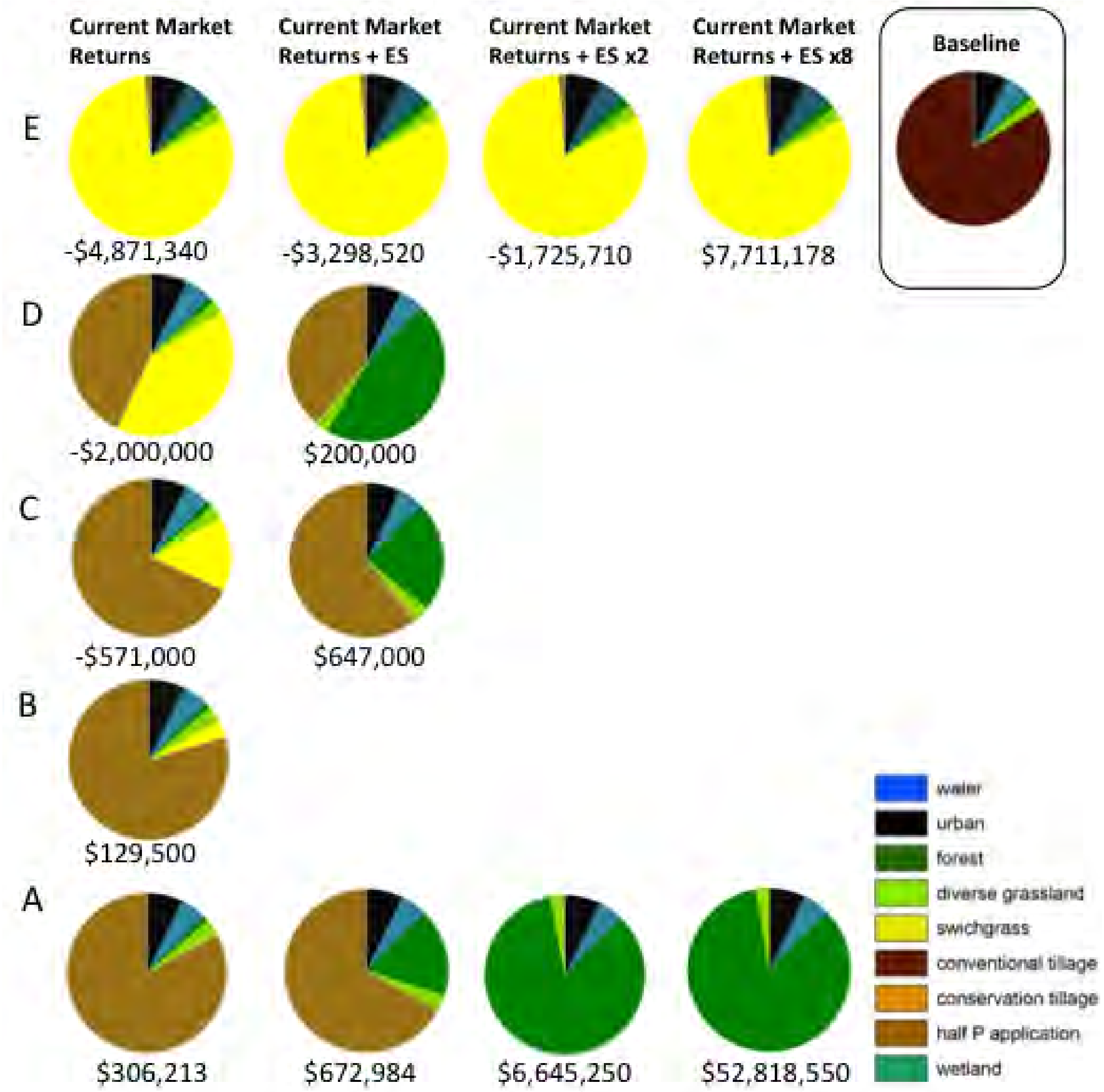


Figure 47. Fraction of land use associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, current market returns plus ecosystem service value, current market returns plus ecosystem service value times two, and current market returns plus ecosystem service value times eight, for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

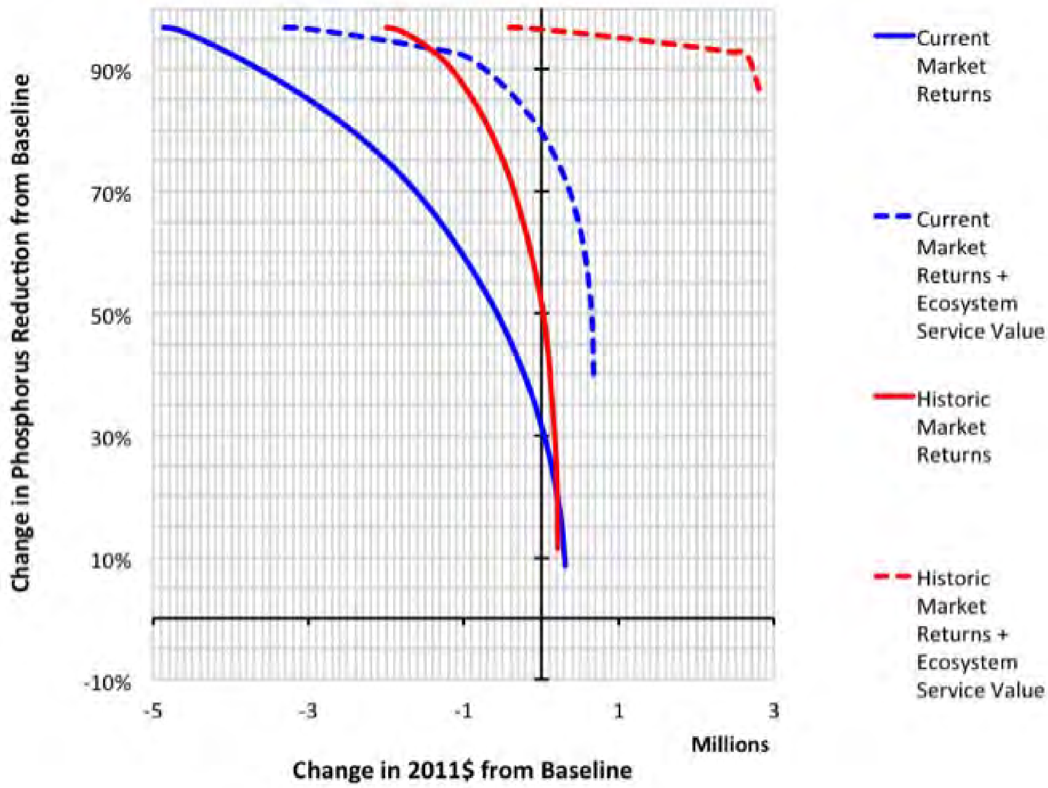


Figure 48. Efficiency frontiers for phosphorus reduction and current market returns (blue solid line), historical market returns (red solid line), current market returns plus ecosystem service value (blue dotted line), and historical market returns plus ecosystem services (red dotted line), for West Fork Beaver Creek. The graph's origin represents the baseline. The change from baseline in the value of economic activity generated by a land-use pattern is shown on the horizontal axis. The percent reduction in sediment is shown on the vertical axis.

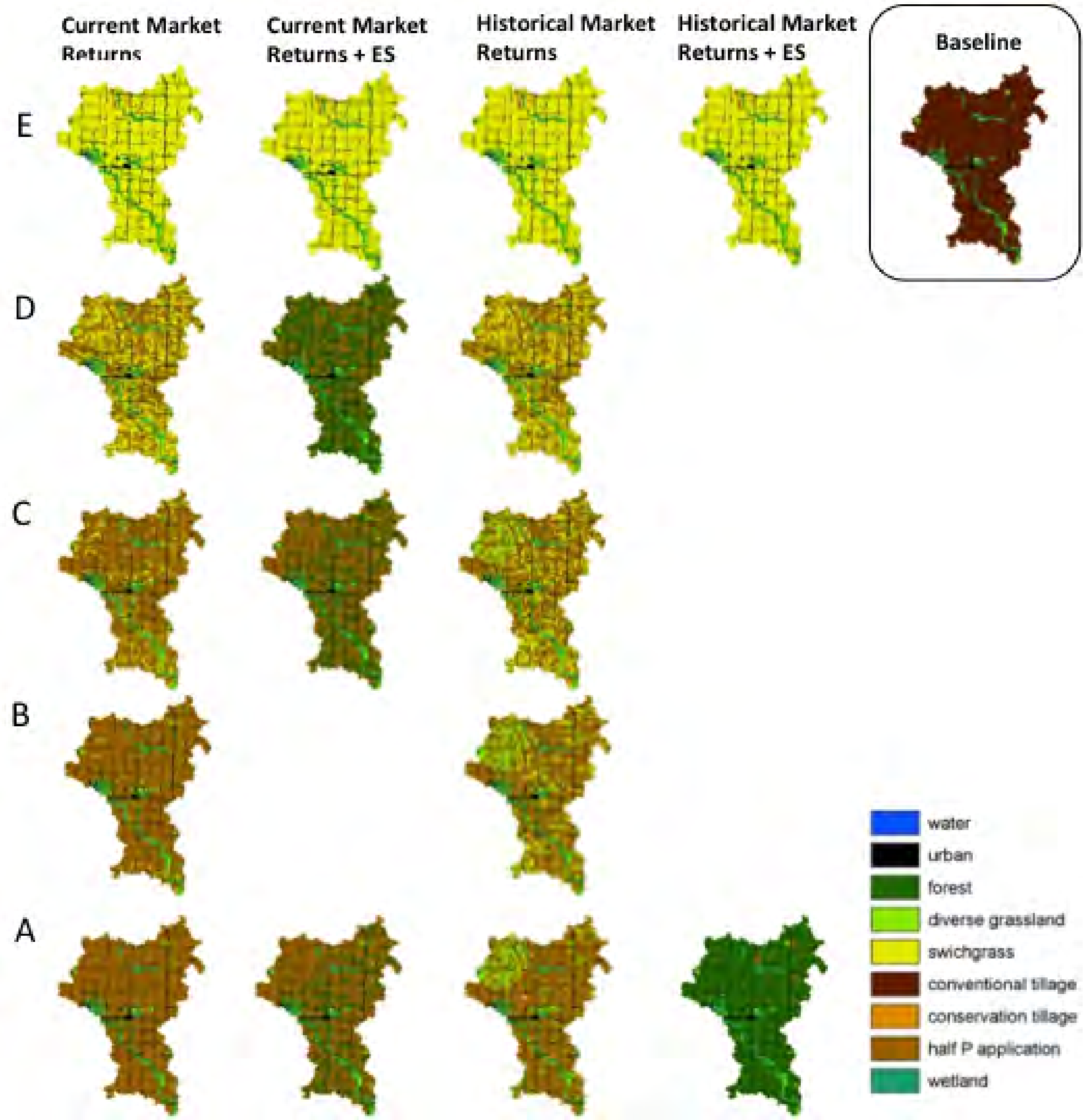


Figure 49. Land-use patterns associated with specific points along the efficiency frontiers for phosphorus reduction and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services, for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction (not shown here since the max reduction is near 75%); E = maximum phosphorus reduction.

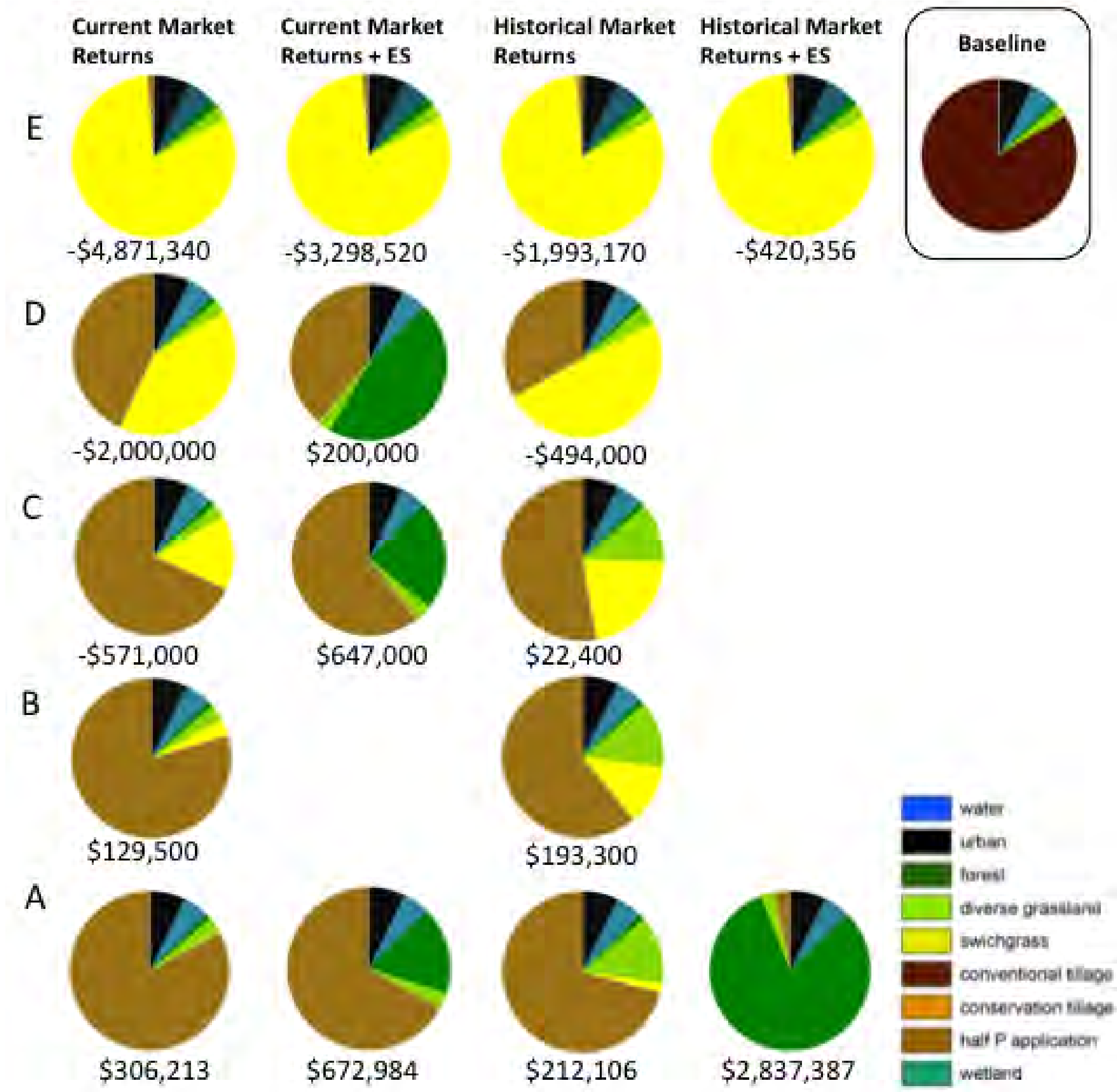


Figure 50. Fraction of land use associated with specific points along the efficiency frontiers for phosphorus and current market returns, historical market returns, current market returns plus ecosystem service value, and historical market returns plus ecosystem services for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

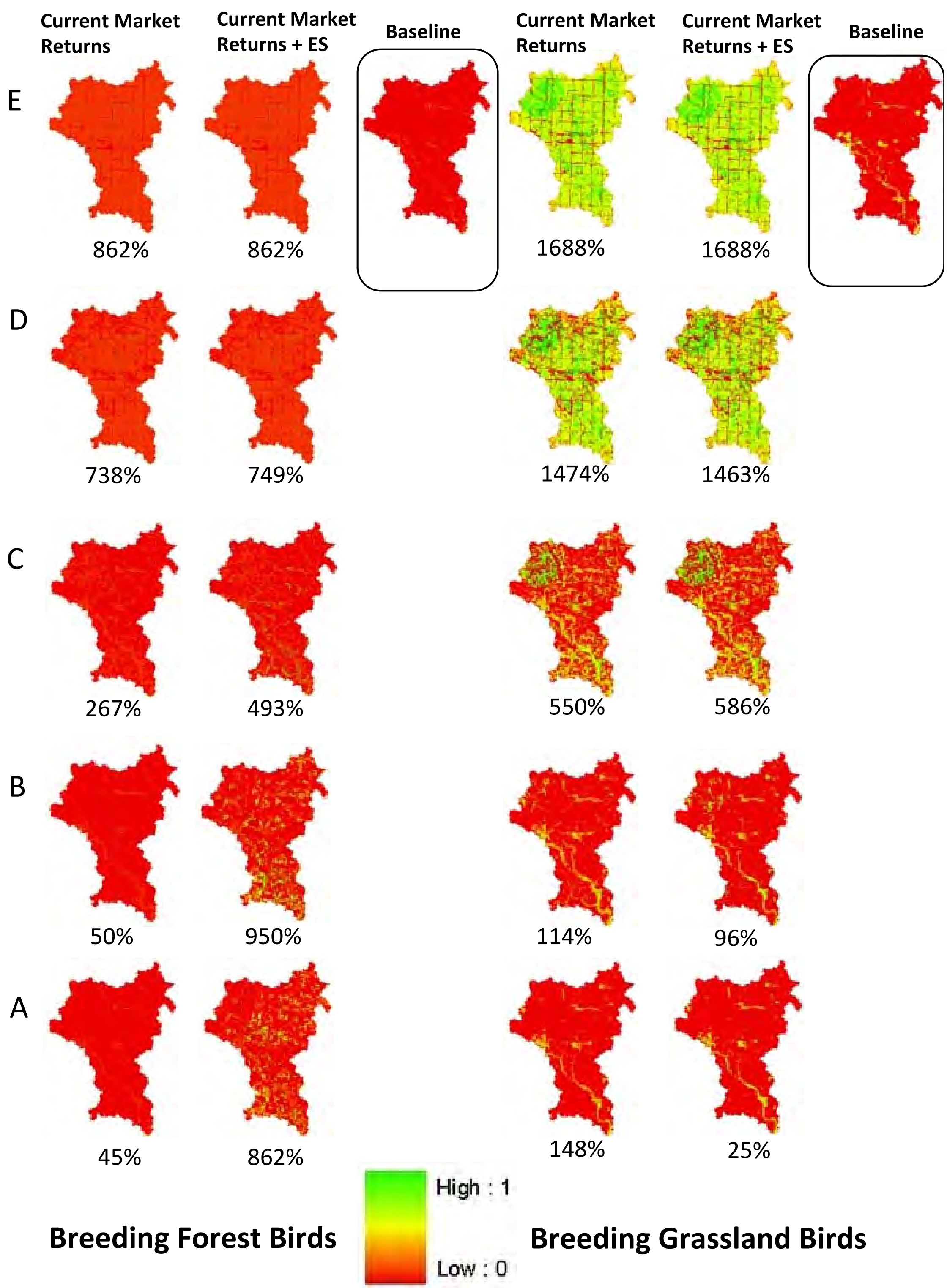


Figure 51. Change in habitat quality score from baseline for specific points along efficiency frontiers for sediment and current market values and sediment and current market values plus ecosystem service value for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

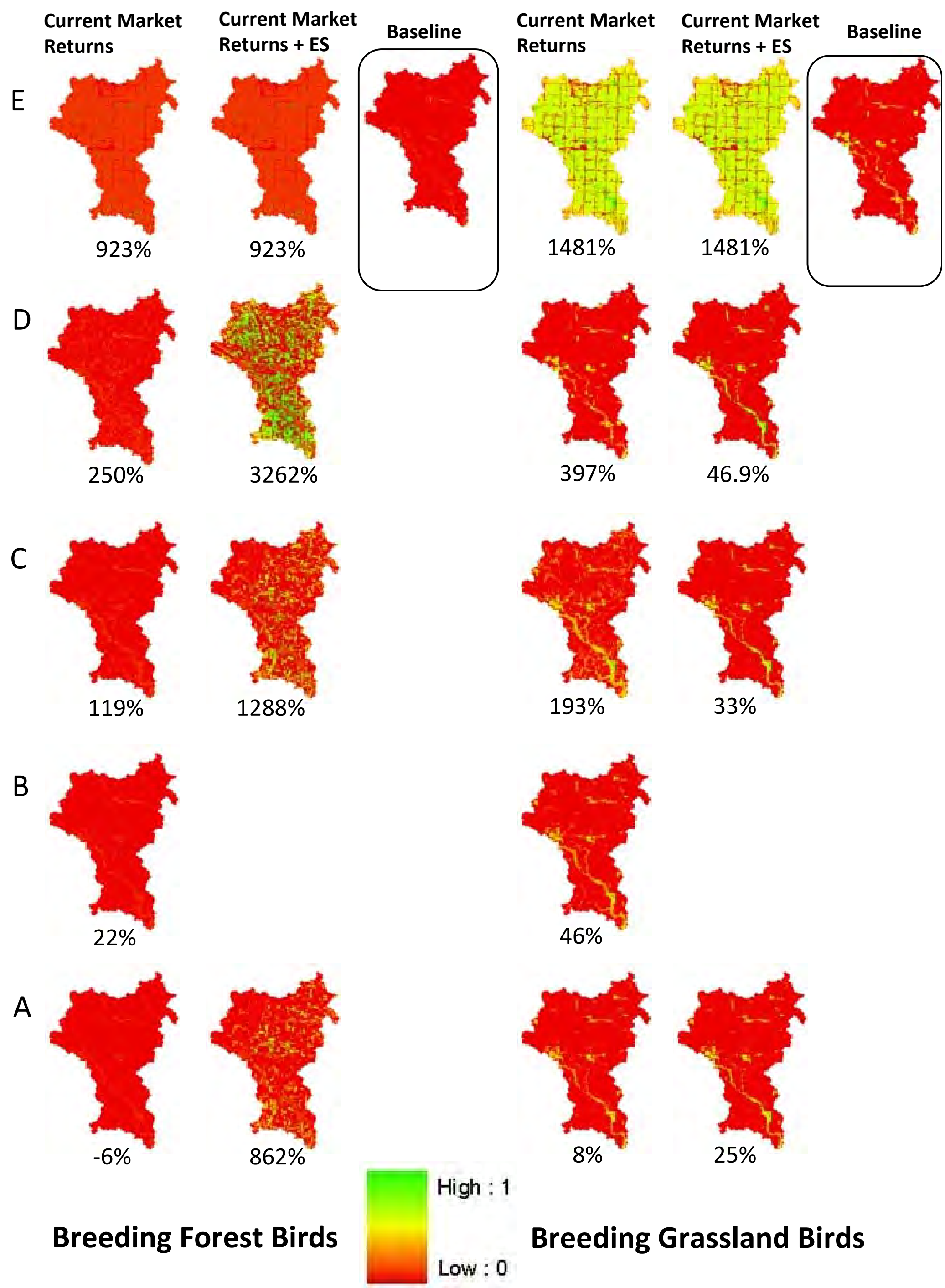


Figure 52. Change in habitat quality score from baseline for specific points along efficiency frontiers for phosphorus and current market values and sediment and current market values plus ecosystem service value for West Fork Beaver Creek. A = maximum economic value; B = 25% phosphorus reduction; C = 50 % reduction; D = 75% reduction; E = maximum phosphorus reduction.

Implications of results for pollutant trading in Minnesota

We discuss elsewhere potential MPCA use of the approach and results of this study for purposes such as SONAR studies and investment analysis. This study also has relevance for further development of the state's existing and proposed water quality trading systems. The state already has experience with point-nonpoint trading in the Minnesota River Basin, based upon early work by Senjem (1997). Water quality trading has also been done in other states and countries (Breetz et al. 2004, Shortle and Horan 2006). Fang et al. (2005) discuss the experience up to the middle of the last decade, Kling (2011) discusses practical strategies based on observable actions to get efficient water quality improvements in agricultural settings, and Kieser and Associates (Associates, 2009) lay out a possible expanded water pollutant trading program in detail. The state also permits point-point phosphorus trading under certain circumstances. To date, no additional trading regulations have been put into place, although draft rules were proposed in April 2011.

Water quality trading allows different entities that contribute to the same water quality problem to exchange the right to pollute. Done right such trading allows water quality targets to be achieved at lowest possible cost because those entities for whom it is expensive to reduce pollution will trade with entities for whom reducing pollution is cheaper. It is important to note that markets are not strictly required for trading or for achieving cost-effective pollution reduction; the current point-nonpoint trading system in Minnesota is administratively managed.

The methods outlined in the present report could be used to provide necessary measurements for how land management and land use actions lead to changes in water quality. These measurements can essentially be used to score land management and land use actions in terms of their contribution to water quality, which could then be used as a basis for trade. For example, if switching from corn and soybean rotation to perennial vegetation on one hectare reduces nutrient inputs by the same amount as putting in a 50 m riparian buffer for a 100 m stretch of a stream then these practices can be traded on a 1 for 1 basis. While accurate measurements are important for making sure that trades truly are equivalent in terms of water quality, having such measurements is not sufficient in and of themselves to address the significant institutional difficulties faced by water quality trading systems, first addressed by (Taff and Senjem, 1996) and more recently revisited by Coggins and Taff (2011).

For any water quality trading scheme to work, a unit of trade—a “commodity”—must be sanctioned. Trades in most such systems are denominated in terms of physical volumes of pollutants; a pound of phosphorus in one location is permitted if a pound (or some multiplier thereof) of phosphorus in another location is removed from the system. Such a scheme implicitly assumes that the location of the pollution doesn’t matter, that a pound of pollution is a pound of pollution wherever it occurs. We have shown in this report that this is not true of the *value* of a pound of pollution. Location and downstream context can matter greatly. We have also shown that rarely is the effect of a change in cropping system or crop management restricted to strictly one environmental cost or benefit: we need to consider all changes in environmental services if we are to determine the full economic value of a proposed change.

The methods used in the present report could be used by the Pollution Control Agency in its efforts to improve water quality in a cost-effective manner, however, they should be used with suitable caution. Briefly, we argue (1) the numbers we have developed here are better than no numbers at all (the status quo); (2) There are no other available full economic cost assessment technologies other than those we employ here; (3) the state would be well served if MPCA were to start to move in the direction of full-value assessment; and (4) the assessment process must be constantly monitored and updated as our assessment knowledge increases.

The value of a unit of pollution (a pound of phosphorus, say) is reflected in the slope of an efficiency frontier such as those developed in this report. (Strictly speaking, the frontiers that we chose to display in the report reflect the value of a percentage change in pollution; the vertical axis in a frontier diagram could be easily rescaled to physical volumes such as pounds.) The slope is the change in full economic value that society would gain/lose if pollution were to be reduced/increased. If Minnesota were to use this information in a pollutant trading system, the unit of transaction would be economic value, not pollutant volume. The state would authorize the reduction of a state full economic value at one location, in exchange for an increase (or multiplier thereof) in full economic value at another location (or even at another time).

Pollutant values could be traded as easily as could pollutant volumes (assuming that the Agency resolves the several tricky institutional and contract issues that bedevil trading systems in general). There would be some unique issues to creating such a system, issues that need to be fully addressed in subsequent research. For example, the same pollutant volume will likely have different values in different locations across the landscape, whether because of differences in the land itself or differences in the population affected by the landscape change. While this is true in the current pollutant quantity trading schemes as well, the differences are essentially assumed away, as discussed above, because the recipient of the pollution is largely not considered. A pollutant value system might result in much larger differences in values, making it more likely that the actual changes in pollutant quantity would vary greatly, for the same amount of pollutant value. The same heterogeneity could become apparent over time, as well, because of changing relative prices for marketed goods or changing assignment of values for non-marketed goods. This could result in the same landscape change being associated with quite different economic values at two different trading dates. This would mean that the value of the pollution permit itself would change over time, making re-trades (if permitted by the state) more or less lucrative to the permit holder at some future date. (This is true, of course, but perhaps to a lesser degree, of the value of pollutant permits under a quantity trading system as well, assuming that re-trades are allowed.)

These concerns make it all the more important that the MPCA, if it wants to pursue a pollutant value trading system, invest in developing and maintaining a suite of physical and economic models that permit rapid reassessment at appropriate intervals. Single-watershed models, developed at significant cost and requiring significant investment of staff time—such as the present effort—will not suffice. One possible approach would be to use the protocol developed here and apply it to “many” watersheds and look to the distribution of economic values for guidance about an appropriate “average” value, conditioned upon location and type of landscape, that could be assigned by law to various pollutants. Another approach would be to standardize the models sufficiently that they could be immediately run for any given proposed trade, using then-current scientific and economic knowledge. These and other trading structures are discussed further (for thermal trading, but the analysis can be generalized) in Konishi et al. (2008).

Guidance for MPCA

In order that a similar framework may be successfully applied to meet water quality goals in different Minnesota watersheds, we have outlined the key steps and data requirements for the main components of this project. This guidance is based on the assumption that MPCA will have access to personnel who are capable of using the following models: SWAT, InVEST, and GAMS (to generate the efficiency frontier).

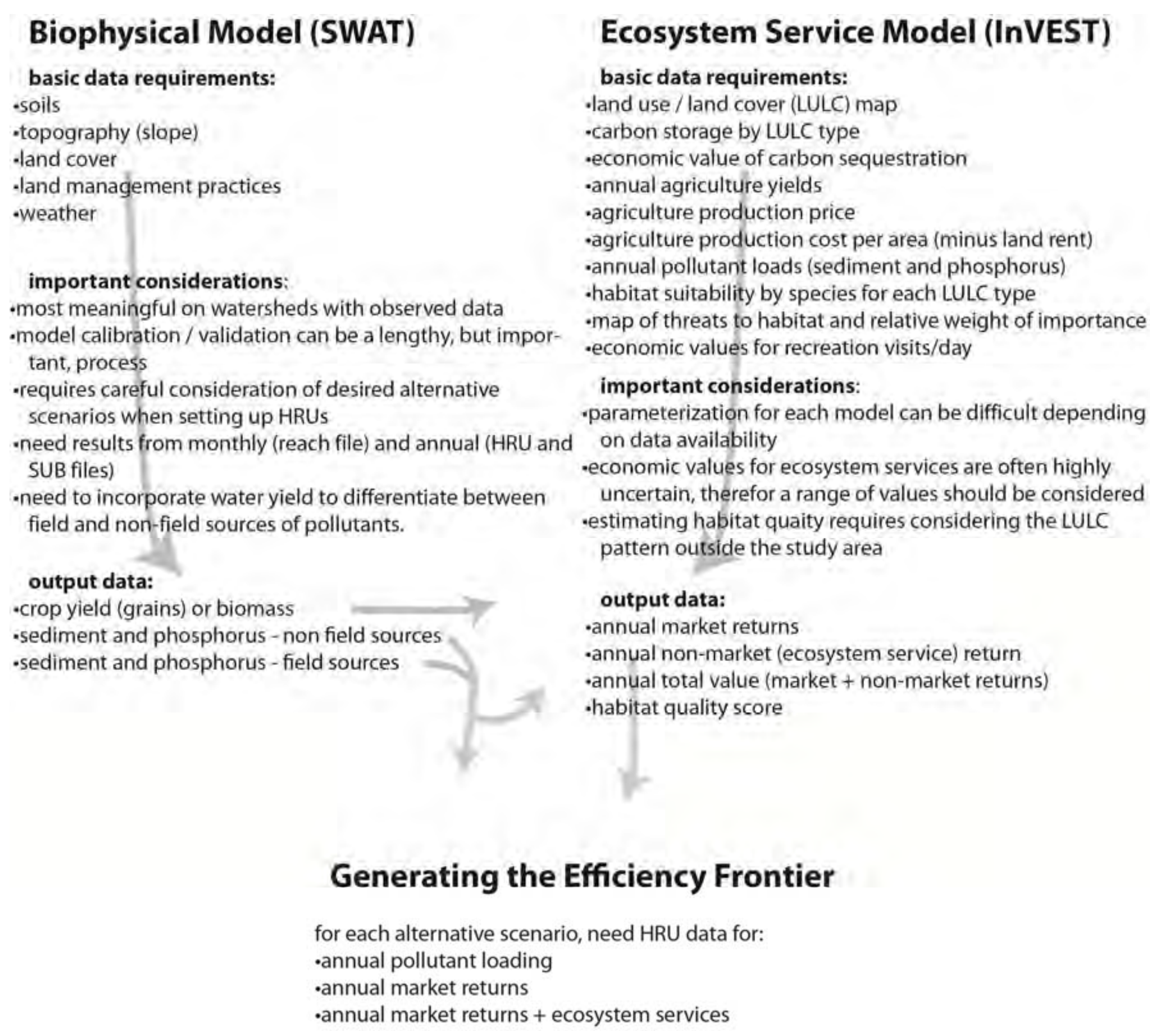


Figure 53. Schematic diagram outlining key data requirements and considerations involved in applying the approach developed for this study to similar water quality goals in other Minnesota watersheds.

Biophysical watershed scale modeling (SWAT)

Key input requirements for the SWAT model are described in the materials and methods section and summarized in Figure 53. Additional details for alternative land cover scenarios are described in the appendix. To incorporate the SWAT model into the full cost accounting framework, it is necessary to generate model outputs at both monthly and annual timesteps. The monthly timestep (only reach-level outputs are required) is necessary to estimate total sediment loading based on the flow-sediment relationship and differentiate between field and non-field sources of sediment. At the annual timestep, detailed HRU-level results are required in order to assign values of crop yield, sediment, and phosphorus production to each unique landscape combination of soils, percent slope, and land use.

In order to prepare SWAT model outputs for use with the InVEST model, the following data fields are required at an annual timestep for each HRU:

- Sediment from field sources after correcting for in-channel deposition (tons/year). In-channel deposition is determined to be the difference between the sum of all HRU loading and the load delivered by the stream at the watershed outlet.
- Sediment from non-field sources based on each HRUs contribution to water yield (tons/year)
- Phosphorus from field sources after correcting for in-channel deposition (kg/year). In-channel deposition is determined to be the difference between the sum of all HRU loading and the load delivered by the stream at the watershed outlet.
- Phosphorus from non-field sources based on non-field sediment (kg/year)
- Crop yield (tons/year)
- Aboveground biomass for prairie grass and switchgrass (tons/year)

Additionally, management information is required for crop fields (or any other land use requiring management). More specifically, details about typical rates of fertilizer application and tillage practices so that management input costs can be realistically represented. While the approach outlined here is specific to sediment and phosphorus, a similar framework could be applied to nitrogen (although non-field sources would likely not be a factor for nitrogen).

Step-by-Step approach to apply SWAT model within this framework.

1) Collect model input data for study watershed. This includes spatial data for soils, topography, and land cover as well as climate data including precipitation, temperature, solar radiation, wind speed, and relative humidity. Data sources used in this study are provided in Appendix B and detailed instructions about SWAT model data requirements and formatting are available in the SWAT model user’s manual. An important consideration here is the intended length of the model simulation period. All climate data must be input early in the model development process. Even if the observed data reflect a short period, it’s advantageous to develop a longer climate record at the beginning of the model development process.

2) Develop model inputs based on best available local information about field management including planting and harvest dates, tillage practices, and fertilizer application rates. Useful information sources include weekly crop reports, contacts with local soil and water conservation district personnel and farmers, state documents such as the FANMAP surveys (Farm Nutrient Management Assessment Program) as well as expert knowledge from University and Extension personnel.

3**) Calibrate and validate the SWAT model based on available flow and water quality monitoring data.** The model calibration process can be lengthy and will depend on the experience of the model user. The entire period of observed data is typically divided into a calibration period and a validation period. The calibration and validation periods don't need to be arranged chronologically but should be divided to represent the range of climate and management conditions available (this task is often limited by the availability of observed data).

4) Run the model two times for each scenario: (1) monthly, and (2) yearly. For each management scenario, the validated model will need to be run two times in order to generate model output for monthly and annual time steps in order to have the date necessary to evaluate scenario performance generate appropriate model outputs. When running the model at an annual time step it is important to generate model results for every HRU (this is not the default setting).

5) Monthly outputs (.rch file) are used to determine total flow, sediment, and phosphorus delivered to the watershed outlet. These values are most useful for comparing total loading under different management scenarios.

6) Annual outputs (.hru file) are used to calculate actual loading for each HRU. These water yield, sediment, and phosphorus values are corrected for their watershed outlet contributions by adjusting them proportionately to match the total load reflected by the reach file.

7) HRU specific values are multiplied by HRU area to determine actual load for each HRU (tons of sediment, kg of phosphorus, tons of crop yield, tons of biomass). These loads are used as input for the InVEST and GAMS models in order to determine valuation and develop the efficiency frontier.

Ecosystem service valuation modeling (InVEST)

Descriptions of the InVEST models are summarized in the materials and methods. A detailed description can be found in Tallis et al (2010). We provide details on Minnesota relevant parameters in the Appendix. However, if more geographically pertinent information exists for the study area in question you can easily substitute values using the more relevant data. Fundamental to InVEST, and this modeling approach in general, is spatially explicit information on land-use/land cover (LULC) types in the study landscape. Consequently, a map that can be used in a Geographic Information System is needed. Ultimately, the models provide estimates of how ecosystem service provision changes in a given LULC type. With this information you can evaluate infinite scenarios of LULC change and evaluate how the spatial arrangement of these LULC types on the landscape influences the ecosystem service provision. For the purposes of this study we consider all output in annualized terms (e.g., carbon sequestered per year).

Key data inputs:

- Map to assess amount and spatial arrangement of LULC types
- Carbon storage estimates for each LULC type
- Estimate on the value of carbon sequestration
- Estimate on the value of water quality improvement by lake or stream reach
- Estimate on the value of a recreation visitor day by location
- Agricultural price per unit production and production cost per unit area (minus land rent)
- Estimates of habitat suitability for a specific biodiversity objective (e.g., game species, species of conservation concern)
- Estimate of potential threats on biodiversity objective

Step-by-Step approach to apply the InVEST model within this framework.

InVEST Carbon model

1) Collect data on land use/land cover (LULC) to serve as the "current" or "baseline" map

2) Collect data on carbon storage estimates for each LULC type

3) Develop LULC maps of desired alternative scenarios (e.g., BMP regimes, agriculture to natural land covers)

4) Run InVEST Carbon Model as specified in Tallis et al. 2011 (page 202) and in Methods section above. Basically, carbon storage is estimated for the baseline and alternative LULC scenarios then the model calculates the difference between the two scenarios to give the change in carbon storage.

5) InVEST Carbon Model output is summarized as Mg C/ha sequestered annually. Carbon sequestration could be annualized over 50 years, assuming sequestration reaches a steady-state in 50 years across LULC types, or by another assumption given data availability. This output should provide you with an estimated annual carbon sequestration value per parcel (e.g., HRU or pixel) from baseline conditions

6) Collect data on the value of a per unit reduction in carbon emissions (e.g., avoided costs, willingness-to-pay, social cost of carbon, see Methods section for details)

7) Calculate the estimated annual non-market value of carbon sequestration applying the following generic equation:

Non-market value carbon sequestration = $CS = V*C$

V = non-market value per unit of carbon sequestration or emission

C = total carbon sequestration or emission for a given parcel area

8) Output should be the non-market economic return of carbon sequestration/emission for a given parcel (e.g., HRU) for a given change in LULC type (alternative scenario) from baseline conditions

Economic returns from agriculture production

1) Collect price per unit production and cost (minus land rental costs) per unit area data for all agricultural production practices considered

2) Calculate the total net economic return per parcel (e.g., HRU) by taking the relevant crop yield per parcel as estimated by SWAT (or some other approach) and applying the following equation:

Agricultural returns per parcel = $\pi = P*Y - (C*A)$

P = price of agricultural crop

Y = yield per area for a given parcel

C = production cost per area

A = parcel's area

3) Output should be the annual economic return to the land for a given parcel (e.g., HRU) under a given agricultural production regime

4) Change in annual economic returns per parcel can be calculated by subtracting the alternative LULC scenario score from the baseline LULC condition score

<u>**Non-market economic returns from sediment and phosphorus reductions**</u>

1) Collect data on the non-market value per unit reduction of sediment and non-market value per unit reduction of phosphorus (e.g., avoided costs, willingness-to-pay, see Methods section for details)

2) Calculate the estimated non-market value separately for each pollutant by taking the relevant annual pollutant load information per parcel as estimated by SWAT (or some other approach) and applying the following generic equation:

Non-market value of pollutant in a parcel = *WV* = Q*L

Q = non-market value per unit of pollutant reduction

L = total pollutant load reduction for a given parcel area

3) Output should be the annual non-market economic return from water quality improvements for a given parcel (e.g., HRU) under a given LULC type

4) Change in annual non-economic returns per parcel can be calculated by subtracting the alternative LULC scenario score from the baseline LULC condition score

<u>**Habitat quantity and availability model**</u>

1) Collect data on relevant LULC to serve as the "current" or "baseline" map

2) Determine biodiversity objective to model habitat quality (e.g., game species, threatened or endangered, ecological guilds)

3) Collect relevant data on habitat suitability estimates for each LULC type and potential threats along with an estimated impact distance of threat on each LULC type considered (see page 187 in Tallis et al. 2011 for more details)

4) Run InVEST Habitat Quality Model as specified in Tallis et al. 2011 and in Methods section above.

5) InVEST Habitat Quality Model output is a unitless score between 1 and 0 for highest quality to lowest quality, respectively.

6) Change in habitat quality score per parcel can be calculated by subtracting the alternative LULC scenario score from the baseline LULC condition score

Benefit Transfer and Visitor Use Estimating Models of Wildlife Recreation, Species and Habitats

Loomis' State level Wildlife Recreation Use

To download these models please visit http://dare.colostate.edu/tools/benefittransfer.aspx. Each model is represented as an excel spreadsheet.

1) Estimate the current acres of each relevant LULC type for the model.

2) Provide an estimate of state population and state median income

3) Enter the above data into the model then calculates the State Wildlife Visitor Days (e.g., angler days if fishing, hunter days if hunting or viewer days)

4) Next add data for the new level of LULC area for each type for a given scenario then calculate the change in State Wildlife Visitor Days from baseline conditions

5) Collect data on estimates of the value of a visitor day for each selected activity then multiply by the change in visitor days for the change in the economic value for the given activity

Generating the efficiency frontier

The goal of this analysis is to combine results from SWAT that describe water quality, and InVEST that describe the value of ecosystem services and agricultural output, to find efficient land-use and land-management decisions for a watershed that maximize gains in water quality for a given level of outcomes in other dimensions. The frontier is determined using The General Algebraic Modeling System (GAMS), which is a high-level modeling system for mathematical programming problems. For the approach developed for this project, it is important to have designated units or parcels in a map that are spatially explicit (like HRUs). For each HRU, data requirements include land use effects on water quality, carbon sequestration, and agricultural returns. Following generation of the efficiency frontiers, GAMS outputs must be converted into LULC maps for specified points along frontier.

Step-by-Step approach to apply the GAMS model within this framework.

The General Algebraic Modeling System (GAMS)

According to its website "The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows you to build large maintainable models that can be adapted quickly to new situations." (http://www.gams.com/).

In our case we used the CPLEX solver to solve a binary integer maximization program. The objective was to maximize the aggregate reduction in phosphorous or sedimentation across a landscape by choosing the spatial pattern of LULC. The spatial units are parcels, in our case, HRUs, and there are 6 LULC options (e.g., conservation tillage, 50% P fertilizer application, switch grass, prairie, forest, including no LULC change).

1) To solve the problem in GAMs we inputted the following information in tabular form (e.g., .xls) with HRUs in rows, LULC in columns, and data in the appropriate cells

- Sediment reduced (tons) compared to the current LULC in the HRU;
- Phosphorous reduced (kg) compared to the current LULC in the HRU;
- Carbon sequestered (Mg) compared to the current LULC in the HRU; and
- Six alternative net annual monetary returns (for our study – current market returns, current market returns + ecosystem service value, current market returns + ecosystem service value *2, current market returns + ecosystem service value *8, historic market

returns, and historic market returns + ecosystem services) compared to the current LULC in the HRU

2) Input a 100-element vector of various budget constraints where the constraint indicates the minimum aggregate net change in annual monetary returns allowed for a solution

3) Create a binary variable for each HRU, LULC combination. In the optimization routine each HRU has one LULC binary variable made equal to 1 and the remaining 5 LULC variables remain equal to 0. CPLEX does this such that the landscape maximizes sediment or phosphorous reduced subject to aggregate net change in annual returns being equal to or greater than the budget constraint. For each pollutant and alternative net annual monetary return measure combination we ran the model 100 times, once for each budget constraint level.

4) The resulting output is a LULC map that indicates LULC in each HRU, pollutants reduced over the landscape compared to the current landscape, change in aggregate net annual monetary returns compared to the current landscape, and carbon sequestered over the landscape.

Conclusions

Based upon biophysical watershed scale modeling coupled with ecosystem service valuation modeling for Seven Mile Creek and West Fork Beaver Creek watersheds, we reach the following conclusions about steps necessary to meet water quality goals aimed at reducing sediment and phosphorus in Lake Pepin:

Modest gains in water quality are possible without reducing current economic returns in both watersheds. Relative to current levels, phosphorus may be reduced by from roughly 20 to 32% in Seven Mile Creek and West Fork Beaver Creek, respectively, without reducing economic returns of the watershed relative to baseline levels. These phosphorus reductions are accomplished in both watersheds primarily by reducing the application rate of commercial phosphorus fertilizer and transitioning marginally-productive croplands to prairie grass, switch grass, or deciduous forest. Similarly, sediment may be reduced by from roughly 18 to 25% in Seven Mile Creek and West Fork Beaver Creek, respectively, without diminishing annual economic returns of the watersheds.

50% reductions in sediment and phosphorus are possible in both watersheds but this level of reduction requires moving substantial acreage out of row crops into perennial vegetation at substantial cost in terms of reduced economic returns. To achieve 50% sediment and phosphorus reductions from the study watersheds will require moving substantial acreage out of row crops into alternative cover types such as prairie grass and/or switch grass. At current market prices these alternative crops generate less profit than corn and soybeans (and sugarbeets in West Fork Beaver Creek). Relative to current watershed annual economic returns, achieving a 50% reduction in phosphorus will generate from roughly $900,000 to $600,000 less per year in West Seven Mile Creek and Fork Beaver Creek watersheds, respectively. The cost to meet 50% phosphorus reductions is higher in Seven Mile Creek than West Fork Beaver Creek because more agricultural land must be converted to natural vegetation. In Seven Mile Creek, the in-channel loads of phosphorus represent the largest contribution to overall phosphorus loads, and in turn more land must be converted to practices that reduce phosphorus loads while also reducing overall water yield to the stream channel. In West Fork Beaver Creek, there is a more direct link between field practices and in-channel loads so changes to field parameters translate directly to water quality improvements. Similarly, 50% reductions in sediment will reduce economic returns by $900,000 to $1,000,000 per year in both Seven Mile Creek and West Fork Beaver Creek watersheds.

When the value of non-market ecosystem services is incorporated into the economic accounting, 50% reductions of sediment and phosphorus occur at low costs to society. For Seven Mile Creek watershed, a 50% reduction in phosphorus may be achieved at essentially no cost to society compared to current watershed economic returns. For West Fork Beaver Creek, at 50% reduction in phosphorus coincides with an *increase* in the total annual watershed returns by about $650,000 per year. For sediment, 50% reductions relative to current levels can be achieved for at roughly no net reduction in average annual returns for both Seven Mile Creek and West Fork Beaver Creek watersheds.

Maximizing the value of returns including the value of ecosystem services results in modest sediment and phosphorus reductions that fall short of 50% guidelines necessary to meet Lake Pepin water quality goals. The landscape that maximizes net benefits results in sediment reductions of around 15% in both watersheds and phosphorus reductions of nearly 20% and 40% in Seven Mile Creek and West Fork Beaver Creek, respectively. Even when society includes the value of ecosystem service valuation in their watershed management decisions, 50% reductions in sediment and phosphorus are not optimal. This conclusion, however, is dependent upon current valuation of non-market ecosystem services. If the value of ecosystem services is doubled then it is optimal in some cases to achieve reduction levels exceeding 50%.

If crop prices fall, then the economic costs of achieving water quality goals are less burdensome. With current crop prices being near their historic highs, the value of agricultural crops is the dominant factor in determining the shape of the efficiency frontiers. Given high prices, there is generally a substantial trade-off between environmental quality and net economic value of each study watershed. If crop prices were to drop, however, to levels more similar to pre-2007 values, the slope of the efficiency frontier becomes much steeper meaning that greater environmental gains can be realized without dramatic decreases in net annual returns from these watersheds.

Adoption of best management practices for achieving water quality goals will not by themselves be sufficient to achieve water quality goals and incur higher than necessary cost. Employing conventional best management practices such as conservation tillage, reduced fertilizer application rates, and non-targeted implementation of grassed buffer strips can achieve modest improvements in water quality. However, employing best management practices alone only achieves modest reductions in sediment and phosphorus (<20% reductions). These practices alone do not come close to achieving the 50% reductions in sediment and phosphorus prescribed to improve water quality in Lake Pepin. In order to work towards goals of 50% reductions in sediment and phosphorus, conventional best management practices must be accompanied by transition of key landscape segments from row crops to perennial vegetation such as deciduous forest, prairie grasses, or switch grass. In addition, best management practices achieve reductions in phosphorus and sediment at higher costs in terms of reduced economic returns in comparison to alternatives that involve a mix of targeted land-use changes from row crops to perennial vegetation and changes in practices such as reduced phosphorus fertilizer application.

Appendices

Appendix A: summary of observed flow, sediment, and phosphorus data for Seven Mile Creek and West Fork Beaver Creek watersheds.

Data are derived from continuous daily flow monitoring and periodic samples of sediment and phosphorus and monthly loads are computed with the FLUX model (Walker, 1996). Data are not presented for months with incomplete flow records.

Seven Mile Creek			
Month -Year	Mean Flow (m3 sec-1)	Total Suspended Solids Load (tons)	Total Phosphorus Load (kg)
Jan-02	n.d.	n.d.	n.d.
Feb-02	n.d.	n.d.	n.d.
Mar-02	n.d.	n.d.	n.d.
Apr-02	0.30	33	135.2
May-02	0.35	39	53.7
Jun-02	3.88	6193	3872.2
Jul-02	0.41	113	454.3
Aug-02	0.07	2	20.1
Sep-02	0.07	2	15
Oct-02	n.d.	n.d.	n.d.
Nov-02	n.d.	n.d.	n.d.
Dec-02	n.d.	n.d.	n.d.
Jan-03	n.d.	n.d.	n.d.
Feb-03	n.d.	n.d.	n.d.
Mar-03	n.d.	n.d.	n.d.
Apr-03	0.19	22	47.9
May-03	1.28	1118	829.7
Jun-03	1.00	426	348
Jul-03	0.60	348	409.4
Aug-03	0.02	0	2.7
Sep-03	0.06	2	37.1
Oct-03	n.d.	n.d.	n.d.
Nov-03	n.d.	n.d.	n.d.
Dec-03	n.d.	n.d.	n.d.
continues...			

Seven Mile Creek (continued)			
Jan-04	n.d.	n.d.	n.d.
Feb-04	n.d.	n.d.	n.d.
Mar-04	n.d.	n.d.	n.d.
Apr-04	0.07	2	26.9
May-04	0.70	433	476.4
Jun-04	2.18	2675	1860.1
Jul-04	0.38	87	117.3
Aug-04	0.04	1	5
Sep-04	0.18	29	140.6
Oct-04	n.d.	n.d.	n.d.
Nov-04	n.d.	n.d.	n.d.
Dec-04	n.d.	n.d.	n.d.
Jan-05	n.d.	n.d.	n.d.
Feb-05	n.d.	n.d.	n.d.
Mar-05	n.d.	n.d.	n.d.
Apr-05	1.10	690	535.7
May-05	1.42	1274	689.9
Jun-05	0.85	284	273
Jul-05	0.19	24	123.6
Aug-05	0.03	1	7
Sep-05	0.04	2	20.5
Oct-05	n.d.	n.d.	n.d.
Nov-05	n.d.	n.d.	n.d.
Dec-05	n.d.	n.d.	n.d.
Jan-06	n.d.	n.d.	n.d.
Feb-06	n.d.	n.d.	n.d.
Mar-06	n.d.	n.d.	n.d.
Apr-06	1.25	900	620.8
May-06	1.00	625	339.5
Jun-06	1.18	1356	1207
Jul-06	0.10	9	44.2
Aug-06	0.01	1	8.2
Sep-06	0.02	0	1.8
Oct-06	n.d.	n.d.	n.d.
Nov-06	n.d.	n.d.	n.d.
Dec-06	n.d.	n.d.	n.d.
continues...			

Seven Mile Creek (continued)			
Jan-07	n.d.	n.d.	n.d.
Feb-07	n.d.	n.d.	n.d.
Mar-07	n.d.	n.d.	n.d.
Apr-07	0.97	433	476.6
May-07	0.24	20	28.2
Jun-07	0.10	6	9.7
Jul-07	0.01	0	0.9
Aug-07	0.05	5	43.8
Sep-07	0.02	0	2.5
Oct-07	1.30	1205	909.1
Nov-07	n.d.	n.d.	n.d.
Dec-07	n.d.	n.d.	n.d.
Jan-08	n.d.	n.d.	n.d.
Feb-08	n.d.	n.d.	n.d.
Mar-08	n.d.	n.d.	n.d.
Apr-08	0.97	524	557.8
May-08	1.16	594	493.1
Jun-08	0.91	344	245.6
Jul-08	0.10	7	58.1
Aug-08	0.03	1	5.1
Sep-08	0.02	0	1.8
Oct-08	n.d.	n.d.	n.d.
Nov-08	n.d.	n.d.	n.d.
Dec-08	n.d.	n.d.	n.d.

West Fork Beaver Creek			
Month -Year	Mean Flow (m3 sec-1)	Total Suspended Solids Load (tons)	Total Phosphorus Load (kg)
Jan-06	0.57	43	482.3
Feb-06	0.61	42	478.9
Mar-06	2.16	142	1896.4
Apr-06	3.68	227	1586.1
May-06	2.89	164	1280.0
Jun-06	0.91	128	414.1
Jul-06	0.22	29	124.6
Aug-06	0.06	11	54.4
Sep-06	0.04	6	29.4
Oct-06	0.04	4	14.2
Nov-06	0.04	4	14.2
Dec-06	0.05	5	19.4
Jan-07	0.05	5	21.5
Feb-07	0.00	1	0.9
Mar-07	2.27	138	4067.6
Apr-07	1.73	113	981.9
May-07	0.88	62	295.0
Jun-07	0.84	115	490.7
Jul-07	0.06	11	52.6
Aug-07	0.03	5	27.8
Sep-07	0.07	5	30.5
Oct-07	0.34	24	190.8
Nov-07	0.08	7	36.0
Dec-07	0.05	5	22.5
Jan-08	0.01	1	2.2
Feb-08	0.00	0	0.2
Mar-08	0.09	6	27.8
Apr-08	0.81	35	398.5
May-08	1.20	48	310.2
Jun-08	1.07	198	617.6
Jul-08	0.14	17	89.6
Aug-08	0.04	8	38.0
Sep-08	0.02	3	14.4
Oct-08	n.d.	n.d.	n.d.
Nov-08	n.d.	n.d.	n.d.
Dec-08	n.d.	n.d.	n.d.

Appendix B. Detailed Description of SWAT model inputs.

Seven Mile Creek Watershed

Climate Data

Precipitation and Temperature data were obtained from the Minnesota Climatology Working Group website: http://climate.umn.edu/ for the period from Jan-1975 to Jan -2008. Data were collected from 5 gauge locations around Seven Mile Creek Watershed: Gaylord, Le Sueur, New Ulm, St. Peter, and Winthrop. The data were converted to metric units: precipitation in mm and temperature in degrees C and missing values were filled-in with data from the nearest available station.

Note: *After inputting climate data into SWAT, only one station (St. Peter) is closer to the watershed than all other stations. As a result, only the St. Peter Data will be used by the model for temperature and precipitation inputs.*

Solar Radiation data were obtained from Dave Ruschy with the MN Climatology Working Group. The data were recorded on the UMN St. Paul Campus.

Wind Speed and Relative Humidity data were collected from the gauge located at the Minneapolis/St. Paul International Airport and available via the NOAA national climate data center website: http://www.ncdc.noaa.gov/oa/ncdc.html. All data were converted to a dbf format as specified in the ArcSWAT documentation.

Digital Elevation Model

A 10-meter digital elevation model (1/3 arc second) was downloaded from the USGS national map seamless server: http://seamless.usgs.gov/. The DEM was clipped with a watershed boundary obtained from MN-DNR minor watersheds. The watershed boundary was buffered to include adjacent cells. The clipped DEM was projected in utm coordinates (NAD 1983, zone 15N) and input into the SWAT model. Slope (%) was determined from the 10-m DEM by using the “Slope” tool in ArcGIS (spatial analyst).

Land Cover/Land Use Data

Basic land cover was collected from the 2001 National Land Cover Dataset. The original data were projected as: Albers Equal Area Conic USGS, the data were re-projected as: NAD_1983_UTM_Zone_15N and clipped with the Seven Mile Creek watershed boundary.

Identifying Areas that could serve as potential sites for wetland restoration (CTI) and sites of likely sediment contributions (SPI)

In order to identify landscape features that may be important contributors to water quality or valuable sites for wetland restoration, terrain analysis was performed as part of the development of model inputs. Starting with the 10m DEM, the compound topographic index (CTI) and stream power index (SPI) were determined as described in Moore et al., (1993). Briefly:

CTI (aka wetness index, w)

$$CTI = \ln\left(\frac{A_s}{\tan\beta}\right)$$

SPI (aka stream power, Ω)

$$SPI = A_s \tan\beta$$

The TAUDEM software package was used to determine slope (in radians) and specific contributing area (refer to TAUDEM online documentation). The slope layer (in radians) is substituted into the equations above at the *ß* term. The specific contributing area layer is substituted into the above equations as the A_s term. Stream Power Index in a given watershed is dominated by many pixels with very small values and few pixels with very large values. In order to better visualize the data, the SPI layer was ln-transformed resulting in an approximately normal distribution. The resulting layer contains many small-isolated pixels and linear features that appear to be artifacts of the calculations (these features are less prominent when a coarser DEM is used). The layers were smoothed 3 times with a low-pass filter in order to minimize these effects.

Two CTI cut points were identified: (1) one standard deviation – and (2) two standard deviations above the mean SPI value of 9.41. cutoffs = 10.81 and 12.21, respectively. These cutoffs were applied to extract CTI values for 2 scenarios.

Similar to the example shown for the Compound Topographic Index (above), the equation to determine Stream Power Index (SPI) was applied to Seven Mile Creek watershed. The SPI map was low-pass filtered twice (as opposed to 3 times with the CTI layer; this is because there was a negligible difference between the 2x filter and the 3x filter). Areas of the watershed that had SPI values 1 and 2 standard deviations greater than the mean value (ln-transformed) are more likely to contribute runoff during overland flow events.

Sites of Biodiversity Significance and Wildlife Management Areas (WMAs)

These data were collected from the DNR Data Deli for Nicollet County. Sites of biodiversity significance and WMAs essentially surround the wetland areas and Seven Mile Creek County Park. This information is included in the final HRU delineation.

Two Layers were created based on the **Sites of Biodiversity Significance**

1) Current sites of biodiversity significance.
2) Same as #1 (above) with a 250 m buffer (potential area of habitat recovery).

CRP land

CRP land (shown above) comprises a very minor portion of current land cover in Seven Mile Creek so it was not treated individually for model calibration or validation. CRP areas were classified as wetlands or rangeland as appropriate.

Note: future scenarios may certainly include CRP lands – but will probably be modeled as grasslands unless there is a specific reason for treating them differently from a modeling perspective.

Final HRU considerations

SWAT uses the following information when identifying HRU's for separate model treatment:

Land Cover

Slope

Soils

In order to include several more HRU classes within the model, additional information was incorporated based on:

Areas likely to receive dairy manure

Cropland likely to receive manure as described above.

Buffers around the stream network

25m (taken as an average value of buffers designed for water quality purposes)

250m (identified by ecosystem services collaborators as meaningful buffer/corridor width for wildlife benefits.

Wildlife Management Areas (WMAs) and sites of biodiversity significance

These sites are already contained within the wetland or forest classifications within the model. A 250m buffer around these areas is considered as a potential alternative scenario.

Sites of potential wetland restoration

Step 1 wetland restoration: sites with CTI values greater than 2 standard deviations above the mean CTI value (see CTI and SPI discussion above). These represent the first tier of likely wetland restoration sites.

Step 2 wetland restoration: sites with CTI values greater than 1 standard deviation above the mean CTI value. These represent the second tier of likely wetland restoration sites.

Sites of potential high sediment delivery to the stream network

Step 1 SPI sites: sites with SPI values greater than 2 standard deviations above the mean SPI value. These represent the greatest potential sources of sediment delivery to the stream.

- Step 2 SPI sites: sits with SPI values greater than 1 standard deviation above the mean SPI values. These represent the second tier of near-stream sites that should be targeted for erosion control.

Drainage Network

The clipped DEM (described above) was input into SWAT watershed delineation tool. When delineating Seven Mile Creek, there was some difficulty in incorporating some of the upland (flat) areas in the model to produce agreement with minor watershed boundaries (MN-DNR). This is due to a combination of DEM resolution and poorly-organized drainage in the flat upland portions of the watershed. However, the presence of ditches and subsurface tile drainage are known to connect these portions of the watershed to the main drainage network. The MN-DNR watershed boundary was used as a mask in the SWAT watershed delineation tool. Further, the current stream-ditch drainage network was incorporated into the DEM to receive flow (Fig. B-1).

Figure 54.. Digital Elevation Model of the Seven Mile Creek watershed showing the location of the stream and ditch network.

This still resulted in the omission of some of the watershed area from delineation based on topography. The drainage network was updated to include public subsurface drainage (which extends into portions of the landscape not reached by ditches; Fig. B-2). This resulted in some specific improvements but some portions of the watershed were still excluded.

Figure B-2. Map showing the location of public subsurface drainage (yellow) which was used to aid in watershed delineation.

Subwatershed boundaries were delineated in SWAT based on the following criteria:

Location of DNR minor watershed boundaries

1) Locations of water quality monitoring stations
2) Transitions between drainage types (tile-to-ditch; ditch-to-natural channel)
3) Natural breaks based on tributaries and area.
4) Size. Based on comments from collaborators (ecosystem services), subwatersheds were selected such that most were about 1mi^2.

West Fork Beaver Creek Watershed

DEM – 30m DEM from the seamless data server (did a better job of agreeing with DNR watershed boundaries than the 10m DEM)

Land Use – 2006 Crop Data Layer, simplified to remove land use classes that comprised very small portions of the watershed (generally less than 1%).

Soils – SSURGO, map units missing from the database have been re-named to existing map units with similar soil texture and drainage characteristics.

Point Sources in West Fork Beaver Creek Watershed

There are 3 point sources in WFBC watershed that have been discharging into SFBC since 1999 (according to the MPCA website). Those data have been summarized in to monthly averages in order to add their contribution to the SWAT predictions for WFBC.

Site Name	Lat	Lon
MN0040665-SD-1	44.8037	-95.16083
MN0040665-SD-3	44.79452	-95.15236
MN0040665-SD-4	44.7837	-95.13818

If point source concentrations (CalMoAvg) were listed as being below a threshold (e.g., <0.2), then a value of ½ that threshold was used for calculation purposes. This typically meant that <0.2 was replaced with 0.1. (occasionally, <0.3 and <0.1 were encountered).

Months that had no value reported were assumed to have no discharge during that time.

In SWAT, the point sources were located on the delineated stream channel closest to where their reported location was (according to MPCA EDA website).

Only one point source is allowed per sub basin. SD-1 and SD-3 will be combined in SubBasin 18.

Precipitation from Olivia and Redwood Falls
Temperature from Olivia
Humidity from MSP
Wind Speed from MSP
Solar Radiation from St Paul – UMN

Calibration and Validation Years

Observed Daily Flow Data are available from 2006 to 2008. Calibration Period = 2006 Validation Period = 2007-2008

Developing Typical Crop Rotations for West Fork Beaver Creek

Assumptions:

The amount of soybeans reflects the number of acres in corn/soybean rotation
The amount of sugarbeets reflects the area in corn/corn/sugarbeets rotation

Points of increased overland flow indicated by elevated stream power index (SPI) values were identified as described above for Seven Mile Creek.

Parameterization of grasslands in SWAT

In order to ensure that alternative grassland scenarios in SWAT are realistic, I have compiled information from a variety of data sources to help constrain ET rates and biomass production. Below is a summary of those data and a description of modifications to SWAT inputs necessary to “grow” realistic grasslands.

Evapotranspiration:

The primary sources of data for grassland ET rates are Daily measurements of grassland sites located near Brookings, South Dakota and at FermiLab in Northern Illinois. At both sites, approximately 5 years of water flux data are available from 2005-2009 with partial year data in 2004 and 2010. http://public.ornl.gov/ameriflux/

These water flux data (collected at 30 minute intervals) were downloaded into MS Excel for additional processing. Briefly, a pivot table was used to convert 30-minute data into daily average water flux (mmol/m2/sec). Units were converted into mm/day in order to allow comparison to SWAT output. Data from all years at each site were used to determine average daily ET.

For the available data, average cumulative annual ET was:

FermiLab: 636 mm/yr

Brookings: 703 mm/yr

Grasslands ET within SWAT was calibrated based on the assumption that Minnesota Grasslands will represent some intermediate value between Illinois and South Dakota. More weight is given to the Fermilab site because the S. Dakota site is managed as active pasture. The FermiLab ET rates were more conservative than those measured in South Dakota. Predicted ET (SWAT output) show good agreement with mean observed values for both daily and annual ET (Figs. B-3 and B-4).

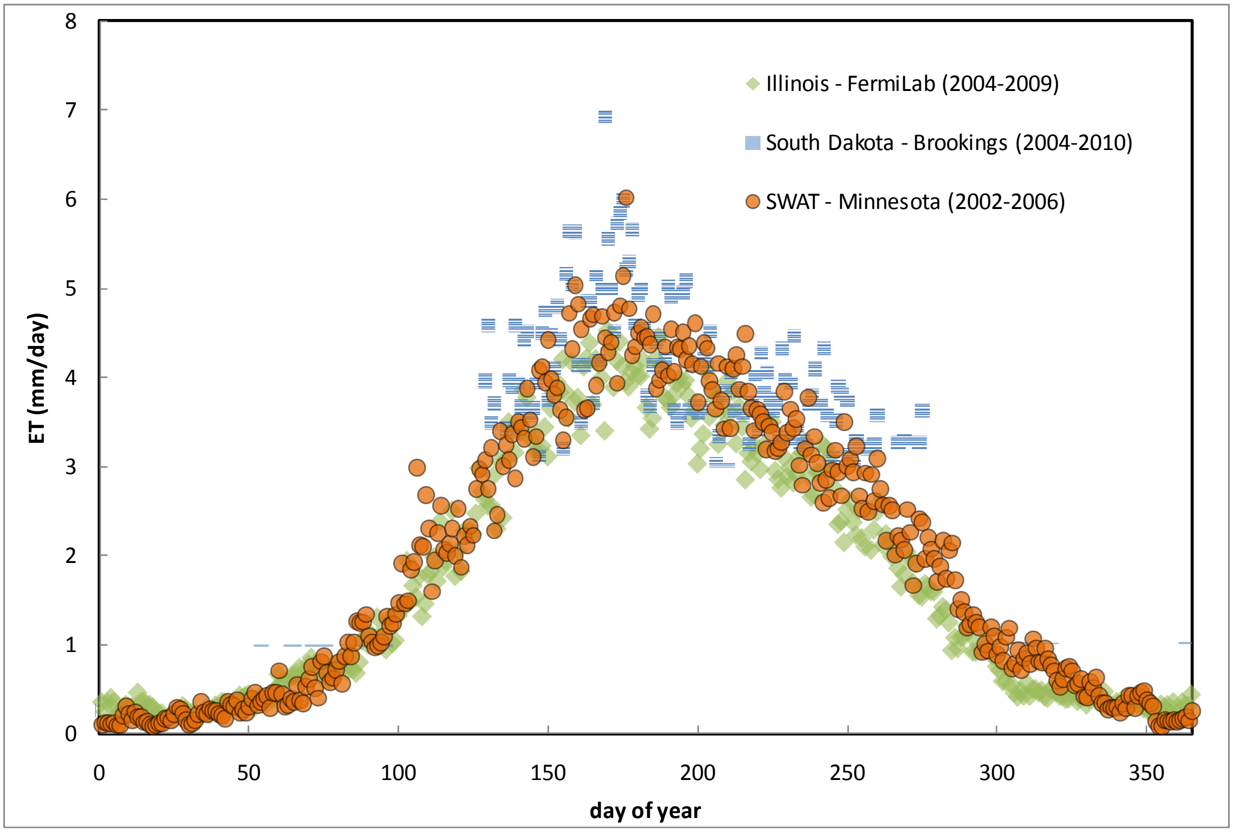


Figure B-3. Comparison of observed mean daily ET for sites in Illinois (Fermi Lab) and South Dakota (Brookings) against Grasslands calibrated for SWAT use in Minnesota.

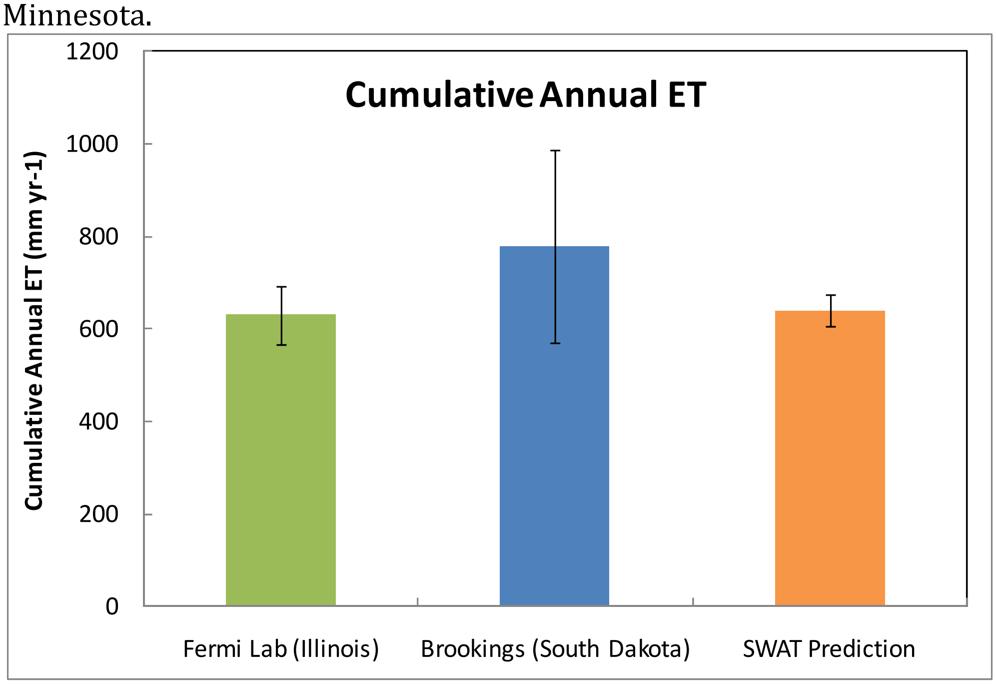


Figure B-4. Comparison of Annual Cumulative ET values for two measured sites and SWAT model predictions. Colors correspond to Fig. B-3.

Biomass:

Realistic biomass estimates are needed for evaluation of grasslands as biofuel sources as well as water use. Biomass calibration was based on reported numbers for aboveground biomass (the output that SWAT reports when run at an annual time step).

Table B-1. Summary of reported biomass values for prairie grass.

Site	Aboveground Biomass (t/ha)	Root Biomass (t/ha)	Total Biomass (t/ha)	Source	notes
generic - national	7.7	32.7	40.4	Fargione et al., 2008	supplementary data - Marginal Cropland
cedar creek	2.4		10	Tilman et al., 2001	high diversity plots
lamberton, st. paul, and waseca	8.0			Don Wyse pers. Comm.	Ave. 2009 & 2010 values from 3 minnesota sites
Northfield, MN	5.5	5.5	11	Camill et al, 2004	Fig 7., control treatment, >3yrs old
average	5.9				
stdev	2.6				

Sources: (Fargione et al., 2008; Tilman and Elhaddi, 1992; Tilman et al., 2001)The biomass of prairie grass in SWAT was calibrated such that the watershed average value was within the range of values reported in the literature. The calibrated average prairie grass biomass simulated by SWAT was 5.4 t/ha/yr. This is slightly less than the average of values summarized above, but very similar to data from a field-scale prairie restoration conducted in S. Central Minnesota (Camill et al., 2004). Following calibration, the distribution of prairie grass yields from SWAT outputs was explored (Fig. B-5), showing a range of predicted biomass yields that compared reasonably with reported data (Table B-1).

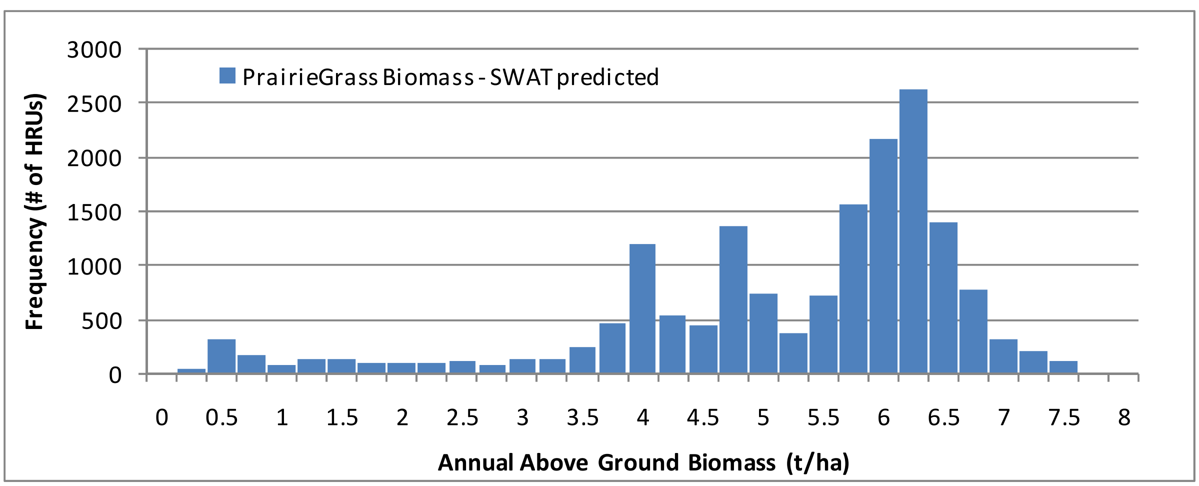
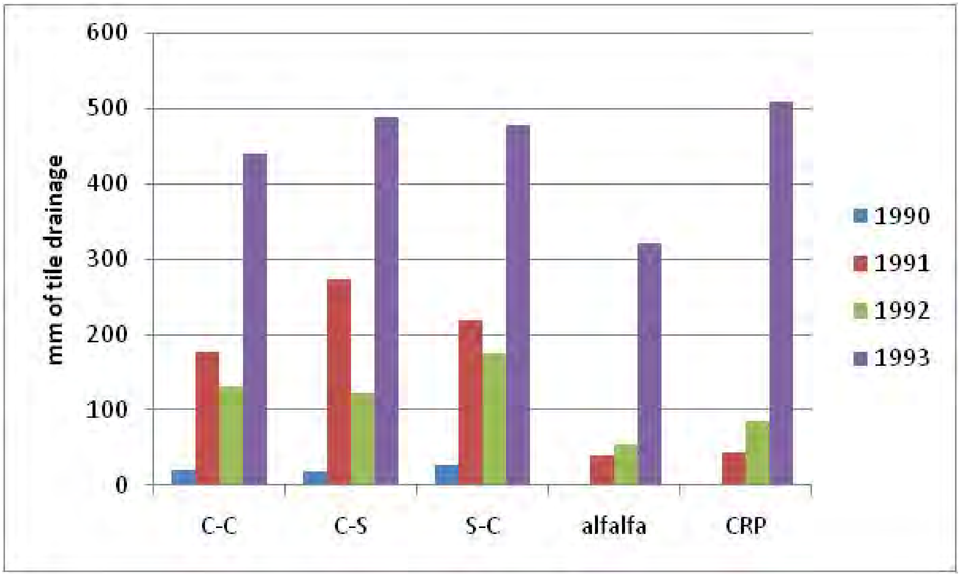


Figure B-5. Histogram of SWAT-predicted prairie grass yields (above ground biomass)

Other calibration considerations:

Base Temperature (temp. at which seeds germinate and grass starts growing) = 4.9 °C; (Jordan and Haferkamp, 1989)**Additional Lines of Evidence for relative differences between ET rates of cropland and grassland:**

Tile water flow below CRP plots was less than tile flow under crop plots during normal rainfall years. (Tile flow was marginally greater during a wet year, 1993; (Randall et al., 1997).



Data re-plotted from Randall et al., 1997.

Drainage (measured via equilibrium-tension lysimeter) was less under a prairie ecosystem than under crop systems (sites in Wisconsin): (Brye et al., 2000)

Prairie = 199 mm drainage

No-till maize = 563 mm drainage

Chisel plow maize = 793 mm drainage

In the same Study, (Brye et al., 2000) observed that deep soil water storage was greater under prairie than under croplands. A conservative estimate based on Fig 5 from that paper would be 10% soil water under prairies for soils between 0.8 and 1.4 meters deep.

Contrary evidence:

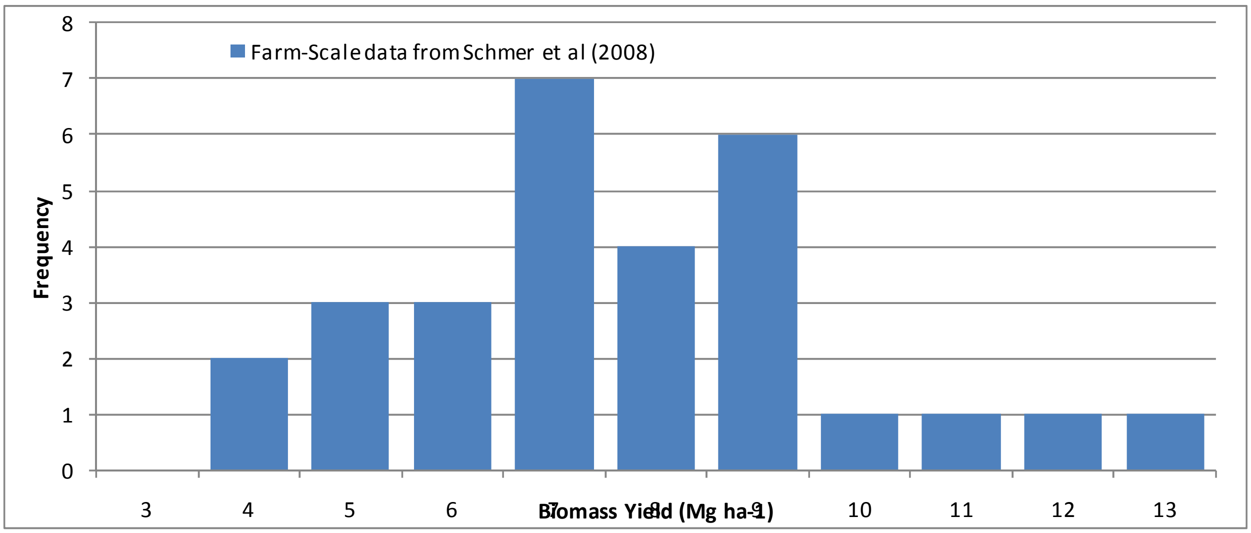
During 2008, Ameriflux ET data from the Brookings grassland site was less than, ET measured for a nearby corn site (Sioux Falls). During other years, however, grassland ET was much greater.

(Twine et al., 2004), showed that grassland water demands were less than cropland water demands in the Mississippi River basin. These were results of model simulations, however, and not constrained by observed water use data (Twine, pers. Communication).

Parameterization of Switchgrass in SWAT

Switchgrass yields were primarily calibrated to data published by Schmer et al., 2008. These data were selected because they represent farm-scale yields from three years of growth (following two years of establishment). Other reported values are typically from smaller plots where yields may benefit from more focused management.

Yield



The mean yield reported by Schmer et al., (2008) was 7.1 Mg ha-1.

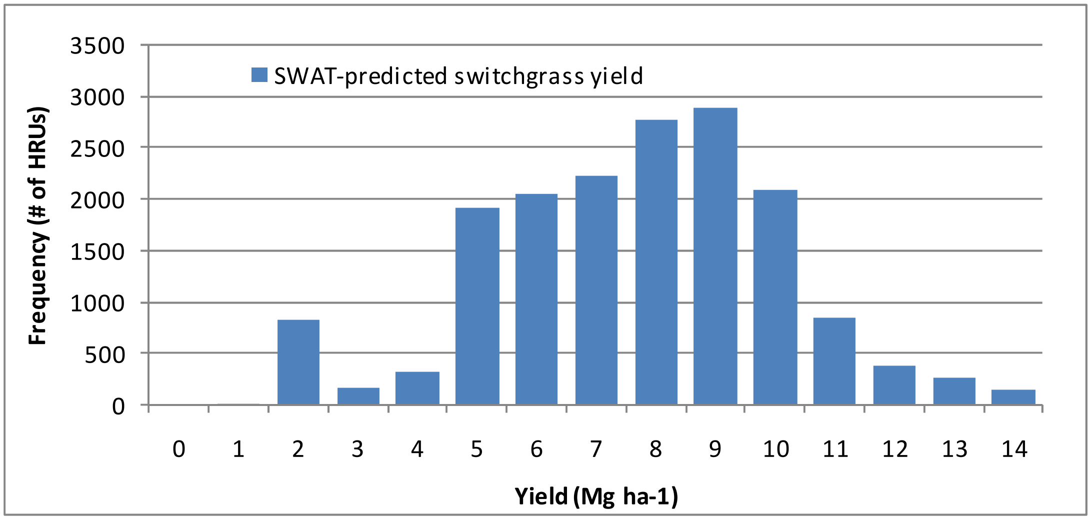
These mean yields are lower than those reported reported for sites in Iowa and Nebraska by (Vogel et al., 2002) (from 10.5 to 12.6 Mg/ha) and (Lemus et al., 2002) (9.0 Mg/ha).

Additionally, they are lower than yield data provided by Don Wyse (dept of agronomy).

	Dry Matter (tons / acre / yr)							
	Lamberton		St. Paul		Waseca		Mean	
	2009	2010	2009	2010	2009	2010	2009	2010
Switchgrass (*Sunburst*)	5	3.9	4.8	6.6	5.3	4.3	6.4	5

2009 and 2010 Average = 5.7 tons/ac = **14.1 t/hectare**

Following calibration, mean switchgrass yield predicted by SWAT was 7.4 Mg ha1- yr-1. I opted to keep SWAT-predicted switchgrass yields in this range because the overall range of SWAT-predicted values included higher yields that agreed with values reported elsewhere and I wanted to keep yield estimates conservative.



Other Switchgrass calibration parameters

Base Growing Temperatures for Switchgrass **[5 oC]** were based on the average of temperatures reported by (Madakadze et al., 2003).

Maximum canopy height of 1.8 m after (Lemus et al., 2002).

Maximum Leaf Area Index of 5.0 after (Mitchell et al., 1998).

Evapotranspiration rates for Switchgrass were based on values reported by (Hickman et al., 2010) for sites in Illinois. **(Switchgrass ET = 764 mm; Corn ET = 611mm).** It is assumed that this value is greater than ET for switchgrass grown in Minnesota owing to a shorter growing season and lower annual precipitation. Additionally, model data from Kiniry et al., (2008) showed switchgrass ET to range from 611 to 759 (mean = 661 mm yr-1). SWAT-predicted mean ET for the calibrated switchgrass was approximately 616 mm yr-1). This is on the low end of reported values, but is reasonable based on conservative predicted yields and measured ET from prairie grasses. (As of this writing, there are no Ameriflux data available for switchgrass to allow additional confirmation of ET rates).

Because switchgrass is a perennial grass with a base growing temperature similar to that of cool season grasses (Jordan and Haferkamp, 1989), my switchgrass annual ET curve was calibrated to be similar to that of prairie grasses (for which I was able to find measured daily ET data from the Ameriflux network).

.

Table of SWAT calibration parameters for Seven Mile Creek and West Fork Beaver Creek watersheds.

Parameter	Default Value	Seven Mile Creek Calibrated Value	West Fork Beaver Creek Calibrated Value
	.bsn file		
SFTMP	1	1	-1.25
SMTMP	0.5	-2	-1
SMFMX	4.5	4.5	6.9
SMFMN	4.5	4.5	1.4
TIMP	1	1	0.85
SNOCOVMX	1	1	1
SNO50COV	0.5	0.5	0.5
PET Method	Penman/Monteith	Penman/Monteith	Penman/Monteith
ESCO	0.95	1	0.99
EPCO	1	0.15	0.2
FFCB	0	0.5	0.5
DEP_IMP	0	2000	3450
ICN	Soil Moisture Method	Plant ET Method	Plant ET Method
CNCOEF	1	0.68	0.7
CN_FROZ	Inactive	Inactive	Inactive
SURLAG	4	4	1
ADJ_PKR	0	2	0
TB_ADJ	0	0	0
PRF	1	2	1
SPCON	0.0001	0.0002	0.0002
SPEXP	1	1	1
CMN	0.0003	0.003	0.002
CDN	0	0.01	0.05
SDNCO	0	0.99	0.999
NPERCO	0.2	0.2	1
PPERCO	10	10	10
PHOSKD	175	100	175
PSP	0.4	0.6	0.4
RSDCO	0.05	0.05	0.05
PERCOP	0.5	0.5	0.5
	.sub file		
CO2	0	380	380
	.hru file (crop)		
OV_N	0.14	0.14	0.2
LAT_TIME	0	4	3

CANMX	0	2	3
ESCO	0	0	0
EPCO	0	0	0
RSDIN	0	1000	500
ERORGP	0	1	0
.hru file (prairie grass)			
OV_N	0.15	0.3	0.2
LAT_TIME	0	4	3
CANMX	0	4	4
ESCO	0	0.8	0.8
EPCO	0	1	1
RSDIN	0	1000	500
ERORGP	0	1	0
.hru file (switchgrass)			
OV_N	0.15	0.3	0.2
LAT_TIME	0	4	3
CANMX	0	4	4
ESCO	0	0.8	0.8
EPCO	0	1	1
RSDIN	0	1000	500
ERORGP	0	1	0
.hru file (forest)			
OV_N	0.1	0.3	0.2
LAT_TIME	0	4	3
CANMX	0	4	4
ESCO	0	0.7	1
EPCO	0	0.5	0.2
RSDIN	0	1000	500
ERORGP	0	1	0
.rte file			
CH_N2	0.014	0.05	0.045
CH_K2	0	17	15
.gw file			
SHALLST	0.5	500	800
DEEPST	1000	1000	1000
GW_DELAY	31	15	31
ALPHA_BF	0.048	0.1	0.15
GWQMIN	0	500	800
REVAPMN	1	500	500
RCHRG_DP	0.05	0.01	0.5
GWHT	1	10	10
.mgt file (crop HRUs with drainage)			
DDRAIN	0	1220	1220

TDRAIN	0	48	36
GDRAIN	0	24	48

Table of SWAT Crop Rotation Parameters for all crops and vegetation types grown in Seen Mile Creek and West Fork Beaver Creek watersheds.

Seven Mile Creek: Corn/Soybean Rotation with commercial fertilizer				
Year	**Month**	**Day**	**Operation**	**Crop**
1	5	1	Tillage - field cultivator	
1	5	4	Plant - begin growing season	Corn
1	10	21	Harvest and kill	
1	10	28	Tillage - chisel plow	
2	5	12	Tillage - field cultivator	
2	5	18	Plant - begin growing season	Soybeans
2	10	7	Harvest and kill	
2	10	14	Tillage - chisel plow	
2	11	1	Fertilizer Application: Anhydrous Ammonia 168 kg ha-1	
2	11	1	Fertilizer Application: Phosphate, 25 kg ha-1 (as elemental P)	

Seven Mile Creek: Corn/Soybean Rotation with manure				
Year	**Month**	**Day**	**Operation**	**Crop**
1	5	1	Tillage - field cultivator	
1	5	4	Plant - begin growing season	Corn
1	10	21	Harvest and kill	
1	10	28	Tillage - chisel plow	
2	5	12	Tillage - field cultivator	
2	5	18	Plant - begin growing season	Soybeans
2	10	7	Harvest and kill	
2	10	14	Tillage - chisel plow	
2	11	1	Fertilizer App: Dairy Manure (wt. equivalent rate: 157052 kg ha-1)	

West Fork Beaver Creek: Corn/Soybean Rotation				
Year	**Month**	**Day**	**Operation**	**Crop**
1	5	1	Tillage - field cultivator	
1	5	4	Plant - begin growing season	Corn
1	10	21	Harvest and kill	
1	10	28	Tillage - chisel plow	
2	5	12	Tillage - field cultivator	
2	5	18	Plant - begin growing season	Soybeans
2	10	7	Harvest and kill	
2	10	14	Tillage - chisel plow	
2	11	1	Fertilizer Application: Anhydrous Ammonia 193.4 kg ha-1	
2	11	1	Fertilizer Application: Phosphate, 29 kg ha-1 (as elemental P)	

West Fork Beaver Creek: Corn/Sugarbeet/Corn Rotation				
Year	**Month**	**Day**	**Operation**	**Crop**
1	5	1	Tillage - field cultivator	
1	5	4	Plant - begin growing season	Corn
1	10	21	Harvest and kill	
1	10	28	Tillage - chisel plow	
1	11	1	Fertilizer Application: Anhydrous Ammonia 78 kg ha-1	
1	11	1	Fertilizer Application: Phosphate, 15 kg ha-1 (as elemental P)	
2	4	15	Tillage - field cultivator	
2	4	16	Tillage - field cultivator	
2	4	20	Plant - begin growing season	Sugarbeets
2	10	21	Harvest and kill	
2	10	28	Tillage - chisel plow	
2	11	1	Fertilizer Application: Anhydrous Ammonia 168 kg ha-1	
2	11	1	Fertilizer Application: Phosphate, 29 kg ha-1 (as elemental P)	
3	5	1	Tillage - field cultivator	
3	5	4	Plant - begin growing season	Corn
3	10	21	Harvest and kill	
3	10	28	Tillage - chisel plow	
3	11	1	Fertilizer Application: Anhydrous Ammonia 168 kg ha-1	
3	11	1	Fertilizer Application: Phosphate, 29 kg ha-1 (as elemental P)	

Both Watersheds: Deciduous Forest			
Year	**Heat Units**	**Operation**	**Crop**
1	0.15	Begin Growing Season	Deciduous Forest
1	1.2	End of Growing Season	

Both Watersheds: Deciduous Forest			
Year	**Heat Units**	**Operation**	**Crop**
1	0.15	Begin Growing Season	Cool Range Grasses
1	1.2	End of Growing Season	

Both Watersheds: Developed Low Density			
Year	**Heat Units**	**Operation**	**Crop**
1	0.15	Begin Growing Season	Bermudagrass
1	1.2	End of Growing Season	

Both Watersheds: Wetlands			
Year	**Heat Units**	**Operation**	**Crop**
1	0.15	Begin Growing Season	Wetlands - non forested
1	1.2	End of Growing Season	

Both Watersheds: Switchgrass			
Year	**Heat Units**	**Operation**	**Crop**
1	0.14	Fertilizer application, Nitrogen: 50 kg ha-1 as elemental N	
1	0.15	Begin Growing Season	Switchgrass
1	1.2	End of Growing Season	

Appendix C. InVEST carbon model.

Table C-1. Carbon sequestration model and carbon estimates

Table C-1. Estimates for soil organic carbon within the first meter of soil as determined from the literature (Midwestern U.S. studies were used when available).

LULC	SOC Mg ha^{-1} Mean (SD)	N of estimates	Assumptions	Source
Wetland - prairie pothole	123.8 (45.1)	3	Assumed all wetlands 75 years old.	Slobodian et al. 2002, Bedard-Haughn et al. 2006, Euliss et al. 2006
Forest - unmanaged	155.6	6	Assumed all unmanaged forests 95 years old.	Smith et al. 2006
High-diversity grassland or prairie	120.5 (40.6)	5	Assumed in high-diversity grassland for 50 years old.	Frank et al. 1995, Frank et al. 2002, McLauchlan et al. 2006, Omonode et al. 2007
Low-diversity grassland or switchgrass	77.0 (39.6)	7	Assumed in low-diversity grassland for ~ 20 years old.	Zan et al. 2001, Coleman et al. 2004, Al-Kaisi et al. 2005, Liebig et al. 2005, Omonode et al. 2007
Row crop (corn/soybean rotation)	66.6 (32.3)	24	Assumed in agricultural for 20 years. Corn and soybean rotation using conventional agricultural practices and average fertilizer applications.	Hansen and Strong 1993, Yang and Wander 1999, Halvorson et al. 2002, DeGryze et al. 2004, Al-Kaisi et al. 2005, Liebig et al. 2005, Russell et al. 2005, Euliss et al. 2006, Venterea et al. 2006, Gál et al. 2007, Kucharik 2007, Morris et al. 2007, Omonode et al. 2007

Table C-2. Estimates for biomass carbon pools as determined from the literature (Midwestern U.S. studies were used when available).

LULC	Biomass Mg ha^{-1} Mean (SD)	N of estimates	Assumptions	Source
Wetland - prairie pothole	n/a	n/a		
Forest - unmanaged	159.0	6	Assumed all forests ~ 95 years old.	Smith et al. 2006
High diversity	11.8 (2.3)	3	Assumed in high-diversity grassland for >	Baer et al. 2002, Tilman et al. 2006, Nelson et

grassland or prairie			50 years old. Belowground biomass is the only source of biomass carbon considered.	al. 2009
Low diversity grassland or switchgrass	8.3 (1.5)	7	Assumed in low-diversity grassland for ~ 50 years. Belowground biomass is the only source of biomass carbon considered.	Risser et al. 1981, Bransby et al. 1998, Oesterheld et al. 1999, Zan et al. 2001 Therefore, only roots and litter contribute to soil C in this system (Bransby et al., 1998).
Row crop (corn/soybean)	1.1 (n/a)	1	Assumed in agricultural production for 20 years.	IPCC 2006

Appendix D. Price and cost estimates for crops used to determine market returns.

Crop	**Price (2011 $)**		**Cost (less land rent; 2011 $)**		**Source**
Current (2007-2011)					
Corn w/chemical fertilizer	4.70	per bushel	532.00	per acre	Lazarus 2011; FINBIN 2011
Corn (less 50% P Chemical application)	4.70	per bushel	519.00	per acre	Lazarus 2011; FINBIN 2011
Corn w/ manure	4.70	per bushel	550.95	per acre	Lazarus 2011; personal communication with Al Larson, Davis Family Dairy
Soybeans	11.00	per bushel	264.00	per acre	Lazarus 2011
Sugar Beets	45.70	per ton	845.00	per acre	FINBIN 2011
Switchgrass	75.67	per ton	148.00	per acre	Price based on bromgrass hay, FINBIN 2011; cost annualized over 10 year stand, Lazarus 2011
High-diversity grassland	75.67	per ton	85.00	per acre	Price based on bromgrass hay, FINBIN 2011; cost annualized over 10 year stand, Lazarus 2011

Historical (2002-2006)					
Corn w/chemical fertilizer	2.77	per bushel	333.00	per acre	Lazarus 2011; FINBIN 2011
Corn (less 50% P Chemical application)	2.77	per bushel	320.00	per acre	Lazarus 2011; FINBIN 2011
Corn w/ manure	2.77	per bushel	352.00	per acre	Lazarus 2011; personal communication with Al Larson, Davis Family Dairy
Soybeans	6.92	per bushel	195.00	per acre	FINBIN 2011
Sugar Beets	45.50	per ton	693.00	per acre	FINBIN 2012
Switchgrass	61.89	per ton	125.00	per acre	Price based on bromgrass hay, FINBIN 2011; cost annualized over 10 year stand, Lazarus 2011
High-diversity grassland	61.89	per ton	76.00	per acre	Price based on bromgrass hay, FINBIN 2011; cost annualized over 10 year stand, Lazarus 2011

Appendix E. InVEST habitat quality model.

Table E-1. Habitat Suitability and sensitivity table for breeding grassland bird species. Higher numbers indicate more sensitivity or more suitable habitat.

LULC Code	LULC Name	Row Crops	Urban	Primary road	Secondary road	Habitat suitability
11	WATER	0	0	0	0	0
20	ROADS	0	0	0	0	0
21	RESIDENTIAL/URBAN	0.2	0.4	0.5	0.4	0
31	BARREN	0	0	0	0	0
41	DECIDUOUS FOREST	0.7	0.8	0.8	0.6	0
71	GRASSLAND_HERB	0.6	0.7	0.7	0.5	1
72	SWITCHGRASS	0.6	0.6	0.7	0.5	0.6
82	ROW CROPS - CONVT. TILLAGE	0.2	0.5	0.4	0.4	0.05
83	ROW CROPS - CONSRV. TILLAGE	0.2	0.5	0.4	0.4	0.05
84	ROW CROPS - LOW P INPUT	0.2	0.5	0.4	0.4	0.05
95	HERBECEOUS WETLANDS	0.6	0.7	0.7	0.5	0.6

Table E-2. Habitat Suitability and sensitivity table for breeding forest bird species. Higher numbers indicate more sensitivity or more suitable habitat.

LULC Code	LULC Name	Row Crops	Urban	Primary road	Secondary road	Habitat suitability
11	WATER	0	0	0	0	0
20	ROADS	0	0	0	0	0
21	RESIDENTIAL/URBAN	0	0	0	0	0
31	BARREN	0	0	0	0	0
41	DECIDUOUS FOREST	0.7	0.8	0.8	0.6	1
71	GRASSLAND_HERBACEOUS	0.6	0.7	0.7	0.5	0.1
72	SWITCHGRASS	0.5	0.6	0.6	0.4	0.1
82	ROW CROPS - CONVT. TILLAGE	0.2	0.5	0.4	0.4	0
83	ROW CROPS - CONSRV. TILLAGE	0.2	0.5	0.4	0.4	0
84	ROW CROPS - LOW P INPUT	0.2	0.5	0.4	0.4	0

95	HERBECEOUS WETLANDS	0.6	0.7	0.7	0.5	0.1

Table E-3. Weights and effective distances for degradation sources.

Degradation source	Maximum effective distance of degradation source (km)	Weight
Row crop	4	0.8
Urban	5	0.8
Primary road	3	0.8
Secondary road	2	0.7

Appendix F. InVEST Recreation Model

The following model details were adapted from Loomis and Richardson (2008). For these models, days of hunting (big game, small game, and migratory bird) and days of nonresidential wildlife-watching activity were obtained from the 2001 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation, U.S. Fish and Wildlife Service. Land use characteristics, including nonfederal land, federal land, and water areas, land cover/use of nonfederal rural land (cropland, CRP land, pastureland, rangeland, and forestland), as well as wetland acres were obtained from the U.S. Department of Agriculture's1997 National Resources Inventory Summary Report. Population and median income by state were taken from the U.S. Census Bureau, Census 2000, to match visitation data.

Big Game Hunting Days- Days of big game hunting by state in the continental U.S. in 2001; includes antelope, bear, deer, elk, moose, wild turkey, and similar large animals which are hunted (U.S. Fish and Wildlife Service, 2002).

Migratory Bird Hunting Days- Days of migratory bird hunting by state in the continental U.S. in 2001; includes birds that regularly migrate from one region or climate to another. The survey focused on migratory birds, which may be hunted, including bandtailed pigeons, coots, ducks, doves, gallinules, geese, rails, and woodcocks (U.S. Fish and Wildlife Service, 2002).

Small Game Hunting Days- Days of small game hunting by state in the continental U.S. in 2001; includes grouse, partridge, pheasants, quail, rabbits, squirrels, and similar small animals and birds for which many states have small game seasons and bag limits (U.S. Fish and Wildlife Service, 2002).

Wildlife-Watching Activity Days- Days of an activity engaged in primarily for the purpose of feeding, photographing, or observing fish or other wildlife by state in the continental U.S. in 2001. In previous years, this was also termed non-consumptive activity (U.S. Fish and Wildlife Service, 2002).

Big Game Hunting Days
Dependent Variable: Big Game Hunting Days per
Method: Least Squares
Observations: 48

Variable	Coefficient	Std. Error	Std. Error	Prob.
Constant	0,0299	0.0060	4.9826	0.0000
Ln Federal Land	8.98E-05	5.22E-05	1.7212	0.0926
Ln State Forest Land	0.0001	6.53E-05	1.8148	0.0767
Ln Private Forest Land	-0.0001	9.07E-05	-1.1461	0.2582
Ln Private Rangeland	-5.67E-05	2.55E-05	-2.2245	0.0315

Ln Median Income	-0.0027	0.0005	-5.0847	0.0000
R-squared	0.4599	Mean dependent var		0.0008
Adjusted R-squared	0.3956	S.D. dependent var		0.0006
S.E. of regression	0.0005	F-statistic		7.1520
Log likelihood	302.1791	Prob(F-statistic)		0.000064

Small Game Hunting Days
Dependent Variable: Ln Small Game Hunting Days
Method: Least Squares
Observations: 48

Variable	Coefficient	Std. Error	Std. Error	Prob.
Constant	8.4253	0.8226	10.2427	0.0000
State Forest Land	0.0003	0.0001	2.2418	0.0305
Cropland	4.26E-05	1.53E-05	2.7806	0.0082
Private Pastureland	0.0001	4.70E-05	2.5406	0.0149
Private Rangeland	-1.95E-05	7.41E-06	-2.6235	0.0122
Population	4.54E-08	1.88E-08	-2.4170	0.0202
Median Income	-5.52E-05	1.73E-05	-3.2014	0.0026
R-squared	0.5815	Mean dependent var		6.7201
Adjusted R-squared	0.5203	S.D. dependent var		1.0503
S.E. of regression	0.7274	F-statistic		9.4964
Log likelihood	-49.0499	Prob(F-statistic)		0.000002

Migratory Bird Hunting Days:
Dependent Variable: Ln Migratory Bird Hunting Days
Method: Least Squares
Observations: 41

Variable	Coefficient	Std. Error	Std. Error	Prob.
Constant	-7.5023	1.2280	-6.1091	0.0000
Ln Federal Land	0.0914	0.0469	1.9496	0.0593
Ln Private Forest Land	-0.32711	0.0769	-4.2515	0.0001

Ln Total Wetlands	0.1492	0.0799	1.8677	0.0702
Median Income	-5.62E-05	1.36E-05	-4.1385	0.0002
R-squared	0.6325	Mean dependent var		-9.0302
Adjusted R-squared	0.5800	S.D. dependent var		0.8263
S.E. of regression	0.5355	F-statistic		12.048
Log likelihood	-29.3235	Prob(F-statistic)		0.000001

Wildlife-Watching Activity Days
Dependent Variable: Ln Wildlife-Watching Activity Days
Method: Least Squares
Observations: 48

Variable	Coefficient	Std. Error	Std. Error	Prob.
Constant	3.7016	0.8926	4.1472	0.0002
Ln State Forest Land	0.2021	0.0640	3.1583	0.0029
Ln Private Forest land	0.1886	0.0892	2.1143	0.0403
Population	5.67E-08	1.26E-08	4.4995	0.0001
Median Income	4.09E-05	1.12E-05	3.6592	0.0007
R-squared	0.7465	Mean dependent var		8.6082
Adjusted R-squared	0.7229	S.D. dependent var		0.8684
S.E. of regression	0.4571	F-statistic		31.6553
Log likelihood	-27.8934	Prob(F-statistic)		0.00000

Values per trip day for wildlife viewing, total hunting, and freshwater fishing

Values of fishing, hunting and viewing days come from the recent U.S. Forest Service database and publication by Loomis (2005). Rosenberger provided a listing of very recent studies up to and including January 2007 that had not been entered into the Loomis (2005) database. Studies in the database have the most updated values per hunter day and viewer day tables by geographic region: three types of hunting (big game, small game and waterfowl) and two types of viewing (general wildlife viewing and bird viewing). Table F-1 indicates the average values per day for hunting and wildlife viewing.

Table F-1. Average values per day for hunting and wildlife viewing.

Species category	Average value per day for the Northeast	Number of estimates
Hunting		
Big game	60.29	142
Small game	33.42	11
Waterfowl	37.13	39
Wildlife viewing	47.95	88

Values are reported in 2011$.

Table F-2. Change in annual recreational activity visits and value from baseline for efficiency frontiers for sediment reductions and economic returns for Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

	Visitor days per year					Consumer surplus (2011$)				
Land-use pattern	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total
Efficiency frontier for sediment reductions and current market returns										
A	12	-7	35	42	83	456	-404	1,167	2,015	3,235
B	-8	-5	744	33	764	-291	-315	24,873	1,561	25,828
C	-44	-5	1,975	31	1,957	-1,646	-303	65,994	1,503	65,548
D	-89	-4	3,501	24	3,433	-3,304	-235	117,014	1,156	114,631
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for sediment reductions and current market returns + ecosystem service value										
A	-12	-51	-154	327	109	-315	-1,371	-4,137	8,388	2,566
B	-14	-26	506	164	629	-385	-688	13,545	4,198	16,670
C	-51	-21	1,827	137	1,891	-1,363	-575	48,926	3,504	50,493
D	-97	-20	3,413	126	3,422	-2,597	-530	91,399	3,230	91,503
E	-106	0	4,164	2	4,059	-2,850	-12	111,515	52	108,706
Scenarios										

F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x2)										
A	-272	-523	-1,985	3,347	568	-20,181	-63,055	-132,646	321007	105,126
B	…	…	…	…	…	…	…	…	…	…
C	-274	-513	-1,663	3,282	832	-20,384	-61,817	-111,146	314704	121,358
D	-132	-99	2,820	633	3,222	-9,811	-11,936	188,470	60696	227,419
E	-106	0	4,164	2	4,059	-7,902	-54	278,330	196	270,569
Scenarios										
F	15	0	105	0	120	1,082	0	7,046	0	8,128
G	-6	0	794	0	788	-439	0	53,073	0	52,634
H	3	0	328	0	331	258	0	21,906	0	22,164
I	10	0	112	0	122	735	0	7,492	0	8,227
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x8)										
A	-321	-612	-2,321	3,915	661	-95,314	-295,010	-620,659	1501960	490,976
B	…	…	…	…	…	…	…	…	…	…
C	-308	-575	-1,935	3,682	864	-91,515	-277,429	-517,295	1412420	526,180
D	-161	-156	2,512	999	3,193	-47,835	-75,300	671,512	383093	931,470
E	-106	0	4,164	2	4,059	-31,607	-218	1,113,321	782	1,082,278
Scenarios										
F	15	0	105	0	120	4,330	0	28,183	0	32,513
G	-6	0	794	0	788	-1,757	0	212,292	0	210,535
H	3	0	328	0	331	1,033	0	87,623	0	88,656
I	10	0	112	0	122	2,939	0	29,967	0	32,907

Efficiency frontier for sediment reductions and historical market returns										
A	12	-7	47	42	94	442	-404	1,575	2,015	3,629
B	-9	-6	776	37	798	-344	-358	25,928	1,782	27,008
C	-46	-6	2,003	35	1,987	-1,690	-333	66,949	1,656	66,582
D	-89	-5	3,498	28	3,432	-3,316	-273	116,888	1,350	114,649
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for sediment reductions and historical market returns + ecosystem service value										
A	-232	-446	-1,592	2,857	587	-8,628	-26,909	-53,191	136,985	48,256
B	…	…	…	…	…	…	…	…	…	…
C	-227	-412	-1,002	2,635	995	-8,423	-24,820	-33,480	126,344	59,622
D	-120	-72	3,029	459	3,296	-4,466	-4,334	101,231	22,029	114,460
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113

Table F-3. Change in annual recreational activity visits and value from baseline for efficiency frontiers for phosphorus reductions and economic returns for Seven Mile Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction. Points F to I represent outcomes under best management practices: F = 25 m grassland buffer along waterways; G = 250 m grassland buffer along waterways; H = conversion of high erosion areas to grassland; I = 250 m grassland buffer surrounding wildlife refuges.

	Visitor days per year					Consumer surplus (2011$)				
Land-use pattern	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total
Efficiency frontier for phosphorus reductions and current market returns										
A	15	0	101	0	116	546	0	3,384	0	3,930
B	1	-6	423	38	456	44	-361	14,146	1799	15,628
C	-36	-6	1,693	35	1,686	-1,347	-334	56,578	1658	56,556
D	-106	-1	4,131	4	4,028	-3,920	-43	138,049	176	134,261
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value										
A	-12	-51	-154	327	109	-436	-3,086	-5,163	15675	6,989
B	-25	-72	-173	460	190	-930	-4,339	-5,782	22054	11,003
C	-30	-30	1,403	191	1,534	-1,115	-1,810	46,876	9177	53,128
D	-110	-10	4,058	66	4,004	-4,084	-603	135,618	3165	134,096
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317

H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x2)										
A	-272	-523	-1,985	3,347	568	-20,181	-63,055	-132,646	321007	105,126
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	-110	-11	4,050	70	3,999	-8,178	-1,340	270,728	6739	267,949
E	-106	0	4,164	2	4,059	-7,902	-54	278,330	196	270,569
Scenarios										
F	15	0	105	0	120	1,082	0	7,046	0	8,128
G	-6	0	794	0	788	-439	0	53,073	0	52,634
H	3	0	328	0	331	258	0	21,906	0	22,164
I	10	0	112	0	122	735	0	7,492	0	8,227
Efficiency frontier for phosphorus reductions and current market returns + ecosystem service value (x8)										
A	-321	-612	-2,321	3,915	661	-95,314	-295,010	-620,659	1501960	490,976
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	-111	-14	4,016	91	3,982	-33,059	-6,938	1,073,775	34997	1,068,775
E	-106	0	4,164	2	4,059	-31,607	-218	1,113,321	782	1,082,278
Scenarios										
F	15	0	105	0	120	4,330	0	28,183	0	32,513
G	-6	0	794	0	788	-1,757	0	212,292	0	210,535
H	3	0	328	0	331	1,033	0	87,623	0	88,656
I	10	0	112	0	122	2,939	0	29,967	0	32,907
Efficiency frontier for phosphorus reductions and historical market returns										
A	12	-7	47	42	94	442	-404	1,575	2015	3,629

B	-5	-6	622	39	650	-182	-377	20,793	1880	22,114
C	-43	-6	1,910	38	1,898	-1,598	-361	63,827	1799	63,666
D	-106	-1	4,131	4	4,028	-3,920	-43	138,049	176	134,261
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113
Efficiency frontier for phosphorus reductions and historical market returns + ecosystem service value										
A	-232	-446	-1,592	2,857	587	-8,628	-26,909	-53,191	136985	48,256
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	-110	-10	4,058	66	4,004	-4,084	-603	135,618	3165	134,096
E	-106	0	4,164	2	4,059	-3,951	-27	139,165	98	135,285
Scenarios										
F	15	0	105	0	120	541	0	3,523	0	4,064
G	-6	0	794	0	788	-220	0	26,537	0	26,317
H	3	0	328	0	331	129	0	10,953	0	11,082
I	10	0	112	0	122	367	0	3,746	0	4,113

Table F-4. Change in provision of ecosystem services and biodiversity conservation from baseline for efficiency frontier for sediment reductions and economic returns for West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% sediment reduction; C = 50 % sediment reduction; D = 75% sediment reduction, Point E represents the highest sediment reduction.

	Visitor days per year					Consumer surplus (2011$)				
Land-use pattern	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total
Efficiency frontier for sediment reductions and current market returns										
A	15	0	101	0	116	546	0	3,384	0	3,930
B	-16	-1	1,115	6	1,104	-599	-65	37,268	291	36,896
C	-116	-1	4,472	6	4,361	-4,307	-68	149,455	304	145,383
D	-293	0	10,436	0	10,143	-10,864	0	348,771	0	337,907
E	-339	0	12,010	0	11,670	-12,599	0	401,360	0	388,761
Efficiency frontier for sediment reductions and current market returns + ecosystem service value										
A	-174	-342	-1,229	2,189	444	-6,447	-20,621	-41,078	104961	36,815
B	-191	-348	-795	2,229	895	-7,082	-20,999	-26,581	106887	52,225
C	-149	-70	4,029	449	4,259	-5,531	-4,239	134,634	21545	146,409
D	-294	-2	10,438	13	10,155	-10,917	-129	348,831	618	338,403
E	-339	0	12,010	0	11,670	-12,599	0	401,360	0	388,761
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x2)										
A	-958	-1,763	-6,694	11,289	1,874	-71,171	-212,567	-447,406	1082595	351,450
B	-812	-1,421	-3,951	9,098	2,915	-60,307	-171,335	-264,059	872534	376,833
C	-612	-839	2,349	5,373	6,271	-45,433	-101,202	157,001	515290	525,656
D	-384	-153	10,083	980	10,526	-28,536	-18,481	673,970	94021	720,975
E	-339	0	12,010	0	11,670	-25,198	0	802,720	0	777,521
Efficiency frontier for sediment reductions and current market returns + ecosystem service value (x8)										
A	-962	-1,768	-6,715	11,325	1,880	-285,610	-852,979	-1,795,333	4344189	1,410,267
B	-885	-1,553	-4,441	9,942	3,063	-262,980	-748,843	-1,187,241	3813645	1,614,582
C	-658	-906	2,426	5,797	6,660	-195,544	-436,754	648,746	2223875	2,240,323

D	-403	-178	10,159	1,138	10,716	-119,697	-85,819	2,716,116	436658	2,947,258
E	-339	0	12,010	0	11,670	-100,794	0	3,210,879	0	3,110,086
Efficiency frontier for sediment reductions and historical market returns										
A	-37	0	1,830	0	1,794	-1,365	0	61,174	0	59,810
B	-78	-1	3,194	6	3,121	-2,895	-65	106,740	291	104,071
C	-134	-1	5,082	6	4,953	-4,980	-65	169,848	291	165,094
D	-319	-1	11,305	5	10,990	-11,843	-58	377,806	252	366,158
E	-339	0	12,010	0	11,670	-12,599	0	401,360	0	388,761
Efficiency frontier for sediment reductions and historical market returns + ecosystem service value										
A	-925	-1,701	-6,450	10,894	1,818	-34,328	-102,567	-215,571	522362	169,896
B	-852	-1,501	-4,421	9,614	2,840	-31,626	-90,518	-147,743	460978	191,091
C	-602	-806	2,772	5,157	6,521	-22,347	-48,564	92,629	247269	268,987
D	-343	-48	11,077	305	10,991	-12,752	-2,882	370,199	14632	369,197
E	-339	0	12,010	0	11,670	-12,599	0	401,360	0	388,761

Table F-5. Change in provision of ecosystem services and biodiversity conservation from baseline for efficiency frontier for phosphorus reductions and economic returns for West Fork Beaver Creek. Point A represents the maximum market returns possible based on current price and cost data, B = 25% phosphorus reduction; C = 50 % phosphorus reduction; D = 75% phosphorus reduction, Point E represents the highest phosphorus reduction.

	Visitor days per year					Consumer surplus (2011$)				
Land-use pattern	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total	Hunting - waterfowl	Hunting - big game	Hunting - small game	Wildlife viewing	Recreation total
Efficiency frontier for phosphorous reductions and current market returns										
A	15	0	101	0	116	546	0	3,385	0	3,931
B	0	-1	564	6	569	0	-65	18,853	291	19,079
C	-49	-1	2,220	6	2,176	-1,819	-65	74,180	291	72,587
D	-157	-1	5,841	6	5,689	-5,818	-65	195,202	291	189,610
E	-342	-16	11,727	105	11,474	-12,694	-994	391,924	5019	383,256
Efficiency frontier for phosphorous reductions and current market returns + ecosystem service value										
A	-174	-342	-1,229	2,189	444	-6,447	-20,621	-41,077	104961	36,816
B	…	…	…	…	…	…	…	…	…	…
C	-245	-470	-1,717	3,011	579	-9,086	-28,360	-57,370	144375	49,558
D	-505	-944	-3,577	6,042	1,016	-18,746	-56,894	-119,542	289697	94,515
E	-339	0	12,010	0	11,670	-12,599	0	401,360	0	388,761
Efficiency frontier for phosphorous reductions and current market returns + ecosystem service value (x2)										
A	-958	-1,763	-6,694	11,289	1,874	-71,172	-212,567	-447,403	1082595	351,453
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	…	…	…	…	…	…	…	…	…	…
E	-342	-16	11,727	105	11,474	-25,387	-1,988	783,848	10039	766,512
Efficiency frontier for phosphorous reductions and current market returns + ecosystem service value (x8)										

A	-962	-1,768	-6,715	11,325	1,880	-285,611	-852,979	- 1,795,321	4344189	1,410,279
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	…	…	…	…	…	…	…	…	…	…
E	-342	-16	11,727	105	11,474	-101,549	-7,950	3,135,393	40154	3,066,048
Efficiency frontier for phosphorous reductions and historical market returns										
A	-37	0	1,831	0	1,794	-1,365	0	61,176	0	59,811
B	-80	0	3,280	0	3,200	-2,966	0	109,616	0	106,651
C	-115	-1	4,434	6	4,324	-4,264	-65	148,175	291	144,136
D	-200	-1	7,282	6	7,087	-7,408	-65	243,364	291	236,181
E	-342	-16	11,727	105	11,474	-12,694	-994	391,924	5019	383,256
Efficiency frontier for phosphorous reductions and historical market returns + ecosystem service value										
A	-925	-1,701	-6,450	10,894	1,818	-34,328	-102,567	-215,571	522362	169,896
B	…	…	…	…	…	…	…	…	…	…
C	…	…	…	…	…	…	…	…	…	…
D	…	…	…	…	…	…	…	…	…	…
E	-342	-16	11,727	105	11,474	-12,694	-994	391,924	5019	383,256

References

Authro, 2009. A Scientifically Defensible Process for the Exchange of Pollutant Credits under Minnesota's Proposed Water Quality Trading Rules. Prepared for Minnesota Pollution Control Agency.

Authro, 2010. Minnesota Crop Cost & Return Guide for 2011., St. Paul, MN.

Boody, G., Vondracek, B., Andow, D.A., Krinke, M., Westra, J., Zimmerman, J., Welle, P., 2005. Multifunctional agriculture in the United States. Bioscience 55, 27-38.

Boyce, R.C., 1975. Sediment routing with sediment delivery ratios., Present and Prospective Technology for Predicting Sediment Yields and Sources. U.S. Department of Agriculture. ARS-S-40., pp. 61-65.

Breetz, H.L., K. Fisher-Vanden, L. Garzon, H. Jacobs, K. Kroetz and R. Terry. 2004. Water Quality Trading and Offset Initiatives in the U.S.: A Comprehensive Survey. Hanover, NH: Dartmouth College. http://www.dep.state.fl.us/water/watersheds/docs/ptpac/dartmouthcomptradingsurvey.pdf

Brooks, K.N., Ffolliott, P.F., Gregersen, H.M., Thames, J.L., 1991. Hydrology and the Management of Watersheds. Iowa State Press, Ames, IA.

Brye, K.R., Norman, J.M., Bundy, L.G., Gower, S.T., 2000. Water-budget evaluation of prairie and maize ecosystems. Soil Science Society of America Journal 64, 715-724.

Camill, P., McKone, M.J., Sturges, S.T., Severud, W.J., Ellis, E., Limmer, J., Martin, C.B., Navratil, R.T., Purdie, A.J., Sandel, B.S., Talukder, S., Trout, A., 2004. Community- and ecosystem-level changes in a species-rich tallgrass prairie restoration. Ecological Applications 14, 1680-1694.

Coggins, J.S., Taff, S.J., 2011. Water Quality: Trading and the Effects of Agricultural and Energy Policy., in: Easter, K.W., Perry, J. (eds.), Water Policy in Minnesota: Issues, Incentives, and Action. Resources for the Future, New York, NY.

Ehrlich, P.R., Dobkin, D.S., Wheye, D., 1988. Birder's fieldbook: a field guide to the natural history of North American Birds. Simon and Schuster, New York, NY.

Fang, F., Easter, K.W., Brezonik, P.L., 2005. Point nonpoint source water quality trading: A case study in the Minnesota River Basin. Journal of the American Water Resources Association 41, 645-658.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319, 1235-1238.

Forman, R., 1995. Land Mosaics: The Ecology of Landscapes and Regions. Cambridge University Press, New York NY.

Haan, C.T., Barfield, B.J., Hayes, J.C., 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press Inc., San Diego 588 pp.

Hansen, L., Ribaudo, M., 2008. Economic Measures of Soil Conservation Benefits: Regional Values for Policy Assessment. TB-1922. USDA, Economic Research Service.

Hickman, G.C., Vanloocke, A., Dohleman, F.G., Bernacchi, C.J., 2010. A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. Global Change Biology Bioenergy 2, 157-168.

Hill, J., Nelson, E., Tilman, D., Polasky, S., Tiffany, D., 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proceedings of the National Academy of Sciences of the United States of America 103, 11206-11210.

Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwig, L., Neumann, J., Zheng, H.C., Bonta, D., 2009. Climate change and health costs of air emissions from biofuels and

gasoline. Proceedings of the National Academy of Sciences of the United States of America 106, 2077-2082.
Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., Wickham, J., 2007. Completion of the 2001 National Land Cover Database for the conterminous United States. Photogrammetric Engineering and Remote Sensing 73, 337-341.
Johnson, K.A., Polasky, S., Nelson, E., Pennington, D., 2012. Uncertainty in ecosystem services valuation and implications for assessing land use tradeoffs: An agricultural case study in the Minnesota River Basin. Ecological Economics in press.
Jordan, G.L., Haferkamp, M.R., 1989. TEMPERATURE RESPONSES AND CALCULATED HEAT UNITS FOR GERMINATION OF SEVERAL RANGE GRASSES AND SHRUBS. Journal of Range Management 42, 41-45.
Kling, C. 2011. Economic incentives to improve water quality in agricultural landscapes: Some new variations on old ideas. American Journal of Agricultural Economics 93(2): 297-309.
Konishi, Y., J. S. Coggins and S. J. Taff. On the Key Elements of the Vermillion Thermal Trading Program: What Do We Still Need to Figure Out? A report to the Vermillion River Watershed Joint Powers Organization. University of Minnesota Department of Applied Economics. March 2008.
Lemus, R., Brummer, E.C., Moore, K.J., Molstad, N.E., Burras, C.L., Barker, M.F., 2002. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. Biomass & Bioenergy 23, 433-442.
Lindenmayer, D., Hobbs, R.J., Montague-Drake, R., Alexandra, J., Bennett, A., Burgman, M., Cale, P., Calhoun, A., Cramer, V., Cullen, P., Driscoll, D., Fahrig, L., Fischer, J., Franklin, J., Haila, Y., Hunter, M., Gibbons, P., Lake, S., Luck, G., MacGregor, C., McIntyre, S., Mac Nally, R., Manning, A., Miller, J., Mooney, H., Noss, R., Possingham, H., Saunders, D., Schmiegelow, F., Scott, M., Simberloff, D., Sisk, T., Tabor, G., Walker, B., Wiens, J., Woinarski, J., Zavaleta, E., 2008. A checklist for ecological management of landscapes for conservation. Ecology Letters 11, 78-91.
Madakadze, I.C., Stewart, K.A., Madakadze, R.M., Smith, D.L., 2003. Base temperatures for seedling growth and their correlation with chilling sensitivity for warm-season grasses. Crop Science 43, 874-878.
Mathews, L.G., Homans, F.R., Easter, K.W., 2002. Estimating the benefits of phosphorus pollution reductions: An application in the Minnesota River. Journal of the American Water Resources Association 38, 1217-1223.
McKinney, M.L., 2002. Urbanization, biodiversity, and conservation. Bioscience 52, 883-890.
MEA, 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-Being. Synthesis. Island Press, Washington D.C.
Minnesota State Colleges and Universities, M.R.C.C., Farm Business Management, Farm Financial Database (FINBIN).
Minnesota State Colleges and Universities, M.R.C.C., 2012. Farm Business Management, Farm Financial Database (FINBIN).
Mitchell, R.B., Moser, L.E., Moore, K.J., Redfearn, D.D., 1998. Tiller demographics and leaf area index of four perennial pasture grasses. Agronomy Journal 90, 47-53.
Motovilov, Y.G., Gottschalk, L., Engeland, K., Rodhe, A., 1999. Validation of a distributed hydrological model against spatial observations. Agricultural and Forest Meteorology 98-9, 257-277.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. Journal of Hydrology 10, 282-290.
National Research Council. (NRC), N.R.C., 2005. Valuing Ecosystem Service: Towards Better Environmental Decision-making. National Academies Press.

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D.R., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., Shaw, M.R., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Frontiers in Ecology and the Environment 7, 4-11.

Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A., Tobalske, C., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biological Conservation 141, 1505-1524.

Polasky, S., Nelson, E., Lonsdorf, E., Fackler, P., Starfield, A., 2005. Conserving species in a working landscape: Land use with biological and economic objectives. Ecological Applications 15, 1387-1401.

Polasky, S., Nelson, E., Pennington, D., Johnson, K.A., 2011. The Impact of Land-Use Change on Ecosystem Services, Biodiversity and Returns to Landowners: A Case Study in the State of Minnesota. Environmental & Resource Economics 48, 219-242.

Randall, G.W., Huggins, D.R., Russelle, M.P., Fuchs, D.J., Nelson, W.W., Anderson, J.L., 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop systems. Journal of Environmental Quality 26, 1240-1247.

Sekely, A.C., Mulla, D.J., Bauer, D.W., 2002. Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the Blue Earth River, Minnesota. Journal of Soil and Water Conservation 57, 243-250.

Senjem, N. 1997. Pollutant trading for water quality improvement: A policy evaluation. Minnesota Pollution Control Agency.

Shortle, J. and R. Horan. 2006. Water quality trading. Penn State Environmental Law Review

Taff, S.J., Senjem, N., 1996. Increasing Regulators' Confidence in Point-Nonpoint Pollutant Trading Schemes. Water Resources Bulletin 32, 1187-1194.

Tallis, H.T., Rickets, T., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Lonsdorf, E., Kennedy, C., 2010. InVEST 1.0004 beta User's guide. The Natural Capital Project. Stanford University.

Tilman, D., Elhaddi, A., 1992. DROUGHT AND BIODIVERSITY IN GRASSLANDS. Oecologia 89, 257-264.

Tilman, D., Hill, J., Lehman, C., 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314, 1598-1600.

Tilman, D., Reich, P.B., Knops, J., Wedin, D., Mielke, T., Lehman, C., 2001. Diversity and productivity in a long-term grassland experiment. Science 294, 843-845.

Tol, R.S.J., 2009. The Economic Effects of Climate Change. Journal of Economic Perspectives 23, 29-51.

Twine, T.E., Kucharik, C.J., Foley, J.A., 2004. Effects of land cover change on the energy and water balance of the Mississippi River basin. Journal of Hydrometeorology 5, 640-655.

Vogel, K.P., Brejda, J.J., Walters, D.T., Buxton, D.R., 2002. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. Agronomy Journal 94, 413-420.

Walker, W.W., 1996. Simplified procedures for eutrophication assessment and prediction: User Manuan, Instruction Report W-96-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.