

ECONOMIC AND ENVIRONMENTAL IMPACTS OF LSNT AND COVER CROPS FOR NITRATE-NITROGEN REDUCTION IN WALNUT CREEK WATERSHED, IOWA, USING FEM AND ENHANCED SWAT MODELS

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ABSTRACT. Nitrate nitrogen (NO_3-N) enriched water originates from subsurface drains or “tiles” that underlay many fields in the Corn Belt and is the primary source of NO_3-N to surface waters in this region. To better assess the fate and transport of nutrients, such as NO_3-N , the tile drain and pothole components of SWAT (Soil and Water Assessment Tool) were enhanced and modified in the previous component of this study. In this study, the environmental and economic impacts of various best management practice (BMP) scenarios often adopted by local farmers to reduce sediment and nutrient loadings (in particular NO_3-N) were evaluated using the modified SWAT (SWAT-M) and FEM (Farm-level Economic Model) models. Measured values of water quality indicators from the Walnut Creek watershed (WCW) located in central Iowa were used to verify the capability of SWAT-M to predict the impact of late-spring nitrate test (LSNT) and rye cover crop management on NO_3-N reduction at the subbasin level. The results obtained from SWAT-M simulation results, similar to field measurement data, indicated a 25% reduction in NO_3-N under the LSNT scenario. FEM results indicated a corresponding increased annual cost of \$6/ha across all farms in the watershed. Simulation of other scenarios, including winter cover cropping and a combination of LSNT and cover cropping at different adoption rates within WCW, resulted in a progressive reduction in sediment and nutrient losses as adoption rates increased. Use of the rye cover crop added about \$25/ha to \$35/ha to the annual cost of the average farm, indicating that some cost-share support may be necessary to encourage farmers to use winter cover crops.

Keywords. Cover crop, Economics, LSNT, Modeling, Pothole, Subsurface flow, SWAT, Tile drainage, Water quality, Watershed.

To reduce nutrient losses from agricultural lands, many practices have been proposed, including nutrient management, manure storage, manure handling and utilization, tillage, land treatment, livestock feed management, and off-farm manure utilization options. The benefits of these practices depend on specific biophysical characteristics in the area of concern and the practices already in place. In many watersheds, field demonstrations of specific best management practices (BMPs) and educational initiatives have led to some reductions in agricultural nutrient loss (Jaynes et al., 2004a).

Unlike environmental impacts, economic effects of nutrient BMPs are generally mixed (i.e., some are costly and some are beneficial), and this is partly responsible for the

lower-than-expected adoption rates in some areas. However, even in areas where nutrient management is expected to benefit the environment and producers as well, there is evidence that most producers are not accounting, at least reasonably, for manure nutrients. As a result, fertilizer nutrient application often exceeds crop needs. This over-application is the case in spite of various demonstration trials and other studies that indicate clear financial benefits to farmers of reducing N application to meet crop needs. Several studies, such as Babcock (1992), suggest various reasons why producers tend to over-apply nutrients. It is evident from these studies that additional information confirming the benefits from nutrient management would help producers adopt cost-effective practices.

Similarly, reliable information on the economic and environmental effects of other managerial and structural practices will help producers adopt cost-effective alternatives to enhance downstream water quality. Some of the highest contributions of N to surface waters come from fields with subsurface drains (Gilliam et al., 1999). In general, agricultural sources primarily in the Upper Mississippi River Basin are implicated as a contributing source of hypoxia in the Gulf of Mexico (Rabalais et al., 1996). Because subsurface drainage systems are installed on farm fields, they profoundly affect watershed hydrology (Hewes and Frandson, 1952; Eidem et al., 1999; Jaynes et al., 1999). Another natural feature in the Midwest Corn Belt area is prairie potholes or enclosed shallow depressions, which

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periodically flood and delay water movement out of the watershed (Eidem et al., 1999; Jaynes et al., 1999). This prolonged wetness causes stress to crop growth because saturated soils do not provide sufficient aeration for crop root development. Cropping systems in pothole regions employing tile drainage systems have unique hydrologic and N transport characteristics (Eidem et al., 1999; Jaynes et al., 1999). Therefore, to accurately model water and agrochemical fate and transport in tile-drained soils, it is necessary to develop models capable of simulating landscapes with both tile drainage and pothole physiography. Recently, Du et al. (2005) modified the Soil and Water Assessment Tool (SWAT) model to better simulate pothole and tile drainage systems. The modification of SWAT by Du et al. (2005) resulted in better prediction of flow and nitrate nitrogen ($\text{NO}_3\text{-N}$) for landscapes with tile drains and potholes.

The timing of N fertilizer application can have a substantial effect on tile drainage $\text{NO}_3\text{-N}$ concentration. A major portion of Iowa corn land receives fall application of N, primarily as anhydrous ammonia (Hatfield et al., 1999; Shankar et al., 2000; Dinnes et al., 2002). This timing of N application can greatly increase the risk of N losses through leaching into the tile drain system due to fall and winter precipitation. Randall and Mulla (2001) have reported an increase of 36% in annual losses of $\text{NO}_3\text{-N}$ in tile drainage with fall application compared with spring application of N for corn production.

To reduce N losses in tile drainage, Magdoff et al. (1984) introduced the split application of N with the pre-sidedress $\text{NO}_3\text{-N}$ test (PSNT). With PSNT, the $\text{NO}_3\text{-N}$ quantity at the top 30 cm of the soil surface is determined when the corn is 15 to 30 cm tall. If the soil $\text{NO}_3\text{-N}$ content is below a critical level, additional N fertilizer is immediately sidedressed. Currently in the state of Iowa, PSNT, in the form of the late-spring nitrate test (LSNT), is the recommended practice for N fertilization of corn (Blackmer et al., 1997).

Fall cover crops can reduce N leaching (Owens et al., 1995; Aronsson and Torstensson, 1998; Shepherd and Webb, 1999) by extending the growing season and the uptake of N beyond that for corn and soybean. Small-grain cover crops take up residual N, released by mineralization during fall and spring, and N released from fall-applied anhydrous ammonia (NH_3) (Ditsch et al., 1993; Kessavalou and Walters, 1999). The cover crops then release this N as their residue decays the next spring or summer. Jaynes et al. (2004b), using a corn-soybean rotation with conventional management and subsurface drainage, compared this to the same rotation with

rye cover crop planted in the fall following each harvest. The results obtained from their study showed a significant reduction in $\text{NO}_3\text{-N}$ in tile drains due to the rye cover crop.

The main objective of the present study was to use the modified SWAT (SWAT-M) model and the Farm-level Economic Model (FEM) to evaluate the economic and environmental impacts of LSNT and use of winter cover crops as well as a combination of both scenarios when implemented in the Walnut Creek watershed (WCW).

METHODS AND MATERIALS

WATERSHED DESCRIPTION

The 5130 ha WCW, located in Story and Boone counties in central Iowa, is typical of the poorly drained, gently rolling landscapes of the Des Moines lobe landscape of central Iowa and southern Minnesota (Andrews and Dideriksen, 1981). This landscape was formed on a young till plane and contains numerous closed depressions or potholes as a result of a poorly developed, geologically young surface drainage network. These potholes often retain water for extended periods, especially during snowmelt and after heavy rainfall, which can result in a reduction in crop yields. The upland soils are underlain by a dense unoxidized till that restricts vertical drainage, resulting in poorly drained soils in lower elevation areas. A corn-soybean cropping system is predominately used in this area.

The watershed has an average elevation of about 300 m above sea level. The average annual precipitation during the eight years used to evaluate this model was approximately 820 mm, and the average monthly temperatures during crop growth seasons were between 9.0°C and 23.0°C. These beneficial weather conditions along with fertile soils result in high corn and soybean yields.

DATA MEASUREMENT

Weather and stream flows have been intensively monitored at a number of sites within the watershed since 1992 by the USDA-ARS National Soil Tilth Laboratory (Hatfield et al., 1999). Stream flows were calculated from continuous water-stage measurements and frequently updated rating curves. Water quality samples were collected at each site once a week when flow occurred, with additional samples collected during rainfall-runoff events. A more detailed description of hydrologic data measurements for WCW can be found in Jaynes et al. (1999). Precipitation data measured by 17 weather gauges within the watershed (fig. 1)

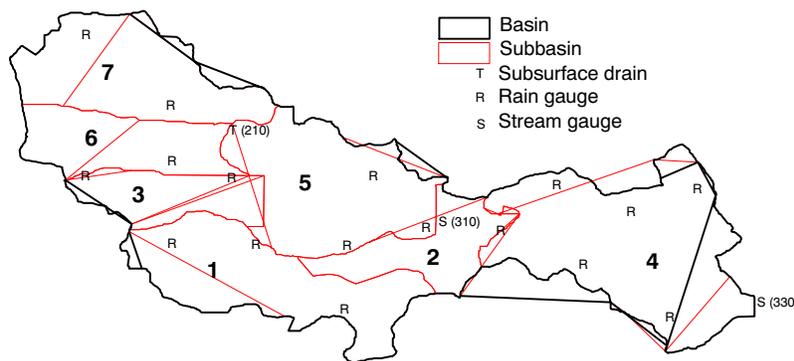


Figure 1. Walnut Creek watershed showing SWAT subbasins and measurement gauges.

were used in SWAT. The maximum and minimum temperature data sets were measured every day at two locations within the watershed. Solar radiation data were measured daily at one station.

INPUT DATA AND MODEL ASSUMPTIONS

Maps of digital elevation, land use, soils, measured daily precipitation, temperature, and solar radiation for the watershed were provided during the initial setup of the input data files for SWAT using the ArcView interface for SWAT2000 (AVSWAT). Other input data, such as daily wind speed and relative humidity, were generated by SWAT from long-term monthly statistics. The Penman-Monteith method within SWAT was selected for calculation of potential evapotranspiration (PET). Prices and other economic input data were obtained from sources in Iowa and USDA databases.

At the time of the study, corn and soybean occupied 87% of the total area, while other crops, roads, and forest occupied 13% of the area. Continuous corn production occurred on 15% of the total farmland, while 85% of the tilled area was in a corn-soybean rotation (Hatfield et al., 1999).

The seven predominant soils within the watershed were included in the model. The very poorly drained Okoboji and Harps soils were assigned as potholes. Based on the Hatfield et al. (1999) study, we estimated that about 75% of the total watershed area was tile drained and that 57% of the total surface runoff directly flowed into potholes. Pothole area occupied 9.7% of the watershed.

A standard tile drain depth of 1.2 m was used in this study. The initial number of soil layers in the soil files created from the State Soil Geographic (STATSGO) soils data for WCW varied from three to four, and the distribution of layer depths of soils also varied. To set up tile drains at a depth of 1.2 m, the number of soil layers was modified to seven for all soils. Tile drains are usually designed to reduce the water content to field capacity within 48 h, so the initial value of SWAT's tile drain parameter, *t_{drain}* (time to drain soil to field capacity), was set at 48 h.

DESCRIPTION OF MODELING SYSTEM

Brief descriptions of model components are provided below. Detailed description of CEEOT is provided in Saleh et al. (2005), Osei et al. (2000), and Gassman et al. (2002).

Farm-Level Economic Model (FEM)

FEM is a whole-farm annual time step model that simulates the economic impacts of various scenarios on agricultural operations (Osei et al., 2000). FORTRAN routines within FEM are used to estimate costs and returns of a representative farm based on livestock and crop operations, ownership and characteristics of structures, facilities and equipment, financing terms, land areas and uses, livestock nutrition, and manure production and handling. For all field operations performed by the farmer, the model calculates fixed and variable costs using several routines that utilize agricultural machinery management specifications tabulated in ASAE Engineering Practice EP496.1 (*ASAE Standards*, 1995a) and ASAE Data D497.1 (*ASAE Standards*, 1995b). Published custom rates are used for operations performed by custom operators. Many data layers used for environmental model simulations are also used to simulate farm-level economic impacts of alternative practices in FEM.

Table 1. Selected input data used for FEM simulations.^[a]

Input Variable	Value
Soil sampling intensity	1 sample per approximately 4 ha
Labor cost for soil sampling	1.5 h per sample @ \$8/h
LSNT N fertilizer rate	138 kg ha ⁻¹
LSNT corn yield	9.76 Mg ha ⁻¹
Non-LSNT N fertilizer rate	174.5 kg ha ⁻¹
Non-LSNT corn yield	10.03 kg ha ⁻¹
Glyphosate (herbicide) rate and cost	2.34 L ha ⁻¹ @ \$5.28/L

^[a] Sources: Jaynes et al. (2004a) and Jaynes (2004).

In this study, FEM was used to estimate the economic impacts of LSNT and winter cover crops in the WCW. FEM simulations accounted for increased soil sampling costs, decreased N fertilizer application rates, increased fertilizer application costs, and slightly reduced crop yields that come with LSNT compared to regular nutrient management practices. These impacts were based on research conducted in the watershed (Jaynes et al., 2004a; Jaynes, 2004). Selected watershed input data used for FEM simulations are shown in table 1. Costs simulated in FEM for the rye cover crop included the cost of the rye planting operation, as well as the cost of killing the rye crop with glyphosate herbicide before the next crop is planted. FEM simulations also accounted for the fact that farmers would harvest a portion of the rye crop before herbicide application and use that as seed for the next cover crop planting.

Soil and Water Assessment Tool (SWAT)

SWAT (Arnold et al., 1999) was developed to overcome several limitations to watershed simulations by allowing continuous-time simulations with a high level of spatial detail through the division of a watershed or river basin into hundreds or thousands of grid cells or subbasins.

SWAT operates on a daily time step and is designed to evaluate management effects on water quality, sediment, and agricultural chemical yield in large, ungauged basins (Arnold et al., 1999). The model operates on a command structure for routing runoff and chemicals through a watershed. These commands allow the user to route flows through streams and reservoirs, combine flows, and input measured data (e.g., weather) and point-source loading. The major components of SWAT include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The modified SWAT (SWAT-M) is used in the present study to provide improved characterization of the environmental impacts of several widely researched BMPs in the Midwest.

During the simulation of the corn-rye-soybean rotation, an error in SWAT for simulating the winter cover crop (e.g., rye) during winter was discussed. Therefore, SWAT-M was modified to simulate this condition correctly. For instance, figure 2 shows an example of the simulated annual consumption of NO₃-N by corn, rye, and soybean rotations before and after SWAT-M modification. Under this rotation, corn was planted on 26 April 1995 and harvested on 15 October 1995, and the rye cover crop was planted right after corn harvest. During the second rotation year, rye was harvested on 15 April 1996 and soybean was planted right after. As figure 2 indicates, the NO₃-N uptake by corn, rye, and soybean seem to be correctly simulated by the modified SWAT-M. However, the unmodified version of SWAT-M was not able to simulate the NO₃-N uptake by soybean

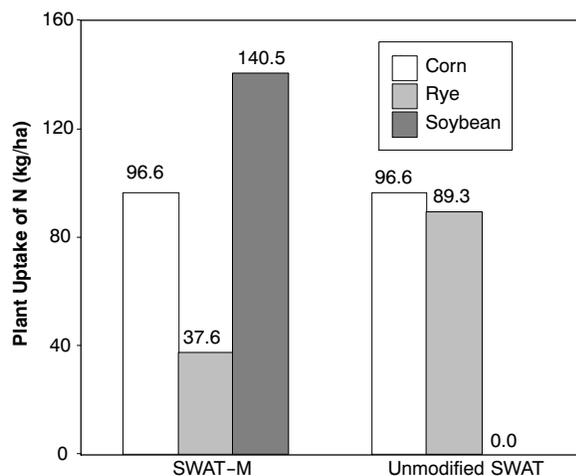


Figure 2. Example of NO₃-N uptake by corn, rye, and soybean during 1995-1996 rotation predicted by SWAT-M and unmodified SWAT.

during the second rotation year. This is because of lack of recognition of the termination (kill) operation for rye during the spring of 1996 by the unmodified SWAT. Consequently, the growth and NO₃-N uptake of rye continued throughout the 1996 season, and the planting operation of soybean was never simulated. The modification of SWAT-M included the changes needed in order to recognize the continuation of crop life cycle (e.g., rye) from one year to another. The modifications introduced in SWAT-M (Du et al., 2005) are publicly available in subsequent releases of SWAT, which can be accessed at the official SWAT web site.

VERIFICATION OF SWAT-M FOR SIMULATING LSNT

Jaynes et al. (2004a) reported a field study conducted from 1997 to 2000 to evaluate the effect of implementing LSNT for corn grown within a 400 ha, tile-drained subbasin (fig. 1) of WCW. They compared the surface water discharge and NO₃-N losses from the treated subbasin and two adjacent subbasins receiving primarily fall-applied anhydrous ammonia. Under the LSNT program, they applied 56 kg ha⁻¹ of N at or shortly before corn planting, and then soil samples were analyzed for NO₃-N content to determine the required N rate for sidedressing application after corn plants had grown to the height of 15 to 30 cm (typically mid-June). Table 2 presents the N fertilizer rates determined by the late-spring nitrate test (LSNT), proposed by the farmer-collaborators, and applied within subbasin 3 from 1997 through 2000.

The data presented by Jaynes et al. (2004a) for subbasin 3 was used to evaluate the capability of SWAT-M for simulating the LSNT management practice. SWAT-M was used to simulate the period from 1991 through 2000 using the

Table 2. Conventional nitrogen application rates and nitrogen fertilizer rates determined by the late-spring nitrate test (LSNT), proposed by the farmer-collaborators, and applied within WCW subbasin 3 during 1997-2000 (Jaynes et al., 2004a).

Year	Average N Application Rates (kg/ha)	
	Conventional	LSNT
1997	164	168
1998	164	118
1999	188	177
2000	182	109

conventional N application rates reported by local farmers for the baseline scenario and alternatively the values reported by Jaynes et al. (2004a) as LSNT during 1997 through 2000 (table 2) for the LSNT scenario.

MODELING METHODOLOGY FOR ALTERNATIVE SCENARIOS

SWAT-M was used to simulate three BMP scenarios including LSNT, cover crops (following corn and then following both corn and soybeans), and a combination of both at various rates of adoption within WCW. FEM simulations were performed independently for each BMP scenario for representative continuous corn and corn-soybean farms. The FEM model was also calibrated for the study area. Data from Iowa State University crop enterprise budgets and custom rates surveys were used to calibrate the economic model and verify data used for simulations. Information from the 2002 Agricultural Census was also used to determine model parameters and calibrate the model to ensure reasonable simulation of key economic indicators. Indicators considered while calibrating FEM for WCW included net cash farm income, labor costs, and various fixed and variable cost indicators for field operations.

The following nutrient and crop management BMPs were simulated for WCW. Each of these options is expected to reduce nutrient losses at the field and watershed levels:

Scenario 1: LSNT

The LSNT scenario, as described previously, deals with changes in fertilizer applications. It requires that nitrogen applications be made in the spring during two separate operations instead of one in the fall. This approach helps address the issue of timeliness of nitrogen availability to the crop. With LSNT, nitrogen applications are spread out to synchronize with crop needs better than with conventional methods. This scenario was applied at 15%, 29%, 42%, 62%, and 100% of continuous corn or corn-soybean land areas, reflecting various possible rates of adoption by farmers.

Under the LSNT scenario, a total annual N fertilizer rate of 118 kg ha⁻¹ was applied in two operations: once shortly before corn planting at 56 kg ha⁻¹ and the second time, a sidedressing application, of 62 kg ha⁻¹ after corn plants had grown to a height of 15 to 30 cm (June 13). The fertilizer application rate simulated for the LSNT scenario was based on the average of the fertilizer rates used by farmers who adopted LSNT (table 2). While in practice the LSNT rate varies from year to year and across farms based on soil test N levels, a fixed level was used for all farms and for all years of the simulations for the sake of simplicity. On average, the LSNT scenario results in about 27% lower N application as compared to the conventional method.

Scenario 2: Use of a Winter Cover Crop

Winter cover crops provide ground cover on cultivated cropland after the growing season. Rye, oats, and alfalfa have been used as cover crops in cropland areas in the Midwest for a number of years. This scenario provided an opportunity to assess the economic and water quality impacts of using rye as a cover crop. In this scenario, rye was planted only after corn harvest in one simulation, and after both corn and soybean harvest in another simulation. The rye cover crop scenario was simulated for both continuous corn and corn-soybean rotations. Based on farm practices in WCW, harvest of the rye crop was not simulated; it was simply plowed in prior to corn or soybean planting, except that for FEM

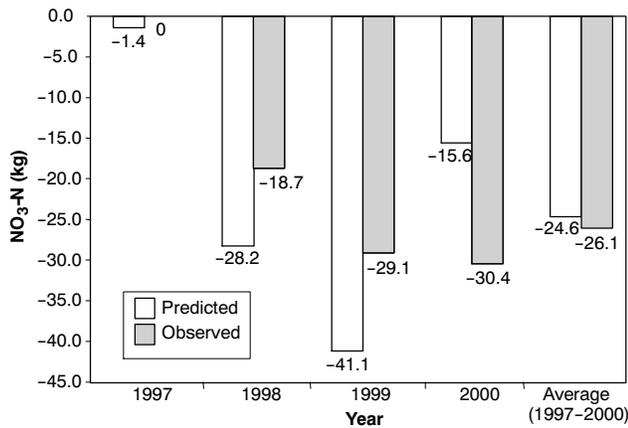


Figure 3. Observed and predicted reduction in NO₃-N due to LSNT treatment at subbasin 3 during 1997 through 2000.

simulations a small portion of the rye crop was harvested for use as seed in the following year. Two primary impacts expected from this scenario were nutrient uptake by the rye crop and reduction in erosion due to the existence of a crop cover on otherwise exposed cropland. The two variants of this scenario involved cover crop planting after corn only (CR) and cover crop planting after both corn and soybeans (CSR). This scenario was also applied at 15%, 29%, 42%, 62%, and 100% of continuous corn and corn-soybean land areas.

Scenario 3: LSNT and Winter Cover Crop

Scenario 3, a combination of scenarios 1 and 2, investigated the combined impacts of these scenarios on water quality and farm finances.

RESULTS AND DISCUSSIONS

VERIFICATION OF SWAT-M FOR SIMULATING LSNT MANAGEMENT

Figure 3 shows the NO₃-N reduction under LSNT as compared to the conventional scenario from 1997 through 2000. Jaynes et al (2004a) reported that the reduction in

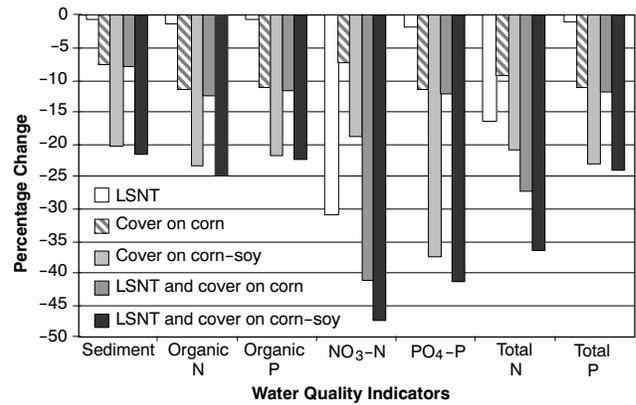


Figure 4. Simulated flow, sediment, and nutrient reduction at the outlet of WCW due to 100% adoption of alternative LSNT and cover crop treatments on corn or corn and soybean cropland.

NO₃-N losses for the LSNT-treated subbasin materialized about 10 to 14 months after ceasing the fall N fertilizer application. This delayed response is also demonstrated in the simulation results (fig. 3), where the SWAT-M results indicate that the NO₃-N reduction started to become significant in 1998, which is about 12 months after the treatment that began in 1997. Jaynes et al (2004a) also reported that the adoption of LSNT resulted in an average reduction of 26% in the NO₃-N level in the water from subbasin 3. As figure 3 indicates, the estimated reductions in NO₃-N from subbasin 3 by SWAT-M were overpredicted for 1998 and 1999 and underpredicted for 2000. This model overprediction could be, as reported by Jaynes et al. (2004a), because of some difficulties with producers in subbasin 3 not following the exact LSNT management practices from one year to another, whereas in the SWAT-M simulation it was assumed that all farmers followed the LSNT management practices during all simulation years. Nevertheless, the average reduction of 25% in NO₃-N from subbasin 3 obtained from SWAT-M during the period of 1997 to 2000 is very close to the 26% reduction reported by Jaynes et al. (2004a) (fig. 3). This indicates the capability of SWAT-M to simulate management practice scenarios such as LSNT.

Table 3. Farm-level economic impacts of LSNT and cover crop scenarios.

	Cropping System	Economic Indicator	LSNT	Cover Crop After:		LSNT and Cover Crop After:	
				Corn Only	Corn and Soybeans	Corn Only	Corn and Soybeans
Operations performed by farmer	Continuous corn	Fixed cost	-1.63	10.27	10.27	8.62	8.62
		Variable cost	12.22	30.10	30.10	42.78	42.78
		Economic return	-10.59	-40.37	-40.37	-51.41	-51.41
	Corn-soybeans	Fixed cost	-0.18	5.80	9.21	5.63	9.05
		Variable cost	6.14	16.52	21.03	21.98	26.65
		Economic return	-5.96	-22.32	-30.24	-27.61	-35.70
Operations performed by custom operator	Continuous corn	Fixed cost	0.00	0.00	0.00	0.00	0.00
		Variable cost	10.02	47.23	47.23	57.25	57.25
		Economic return	-10.02	-47.23	-47.23	-57.25	-57.25
	Corn-soybeans	Fixed cost	0.00	0.00	0.00	0.00	0.00
		Variable cost	5.01	23.62	35.36	28.63	40.38
		Economic return	-5.01	-23.62	-35.36	-28.63	-40.38
Average for entire watershed	Fixed cost	-0.20	3.24	4.68	3.04	4.49	
	Variable cost	6.41	22.86	29.77	29.01	35.99	
	Economic return	-6.21	-26.09	-34.45	-32.05	-40.48	

ALTERNATIVE NUTRIENT MANAGEMENT RESULTS

All scenarios reported here were simulated with SWAT-M and FEM over a 10-year horizon. Results are annual averages over the 10-year simulation period for various BMP adoption rates in WCW. FEM results are only reported here for the 100% adoption rate, since the economic model results for all the lower adoption rates are simple proportions of those for the 100% adoption rate. As mentioned above, FEM calculates fixed and variable costs of field operations using agricultural machinery coefficients reported in *ASAE Standards* (1995a, 1995b) and prevailing fuel and equipment prices. Fixed and variable costs reported here were generated from FEM simulations. SWAT-M results are shown for all scenarios in figure 4 for the 100% adoption rate. FEM results for all scenarios are summarized in table 3.

Scenario 1: LSNT

Environmental Impact: The results obtained from this scenario indicate a 31% reduction in $\text{NO}_3\text{-N}$ for the whole watershed when all farms adopt LSNT (fig. 4). Similar to reports by Randall and Mulla (2001) and Jaynes et al. (2004a), the results obtained from the SWAT-M simulations indicated that the other nutrients along with sediment losses did not seem to be affected much by this scenario.

Economic Impact: FEM estimates of economic impacts of LSNT are shown in table 3 for typical corn-soybean and continuous-corn farms, which have an average size of 810 ha in WCW. The table shows economic results for the case where the farm operator performs all field operations, as well as for the case where a custom operator performs all field operations. The results reported here are in dollars per total cropland area per year across all farms in the watershed using a 10-year time horizon. Average results for the entire watershed, shown in the last three rows of the table, were computed as weighted averages of the output for the individual representative farms. It was assumed that 50% of farms perform farm operations themselves, while the other 50% pay to have it done. Furthermore, it was also assumed that 85% of cropland in the watershed is planted in corn-soybeans and 15% in continuous corn. As mentioned above, the results tabulated here assume a 100% adoption rate for the farms in the watershed. The economic impacts on a watershed basis would be proportionately lower if fewer farms adopted the practice. For instance, the impact for a 50% adoption rate would simply be 50% of the impact indicated for 100% adoption. In essence, the adoption rates refer to percentages of farms on which the practice was simulated.

The results shown in table 3 indicate that the LSNT practice will cost about \$6 and \$10 per hectare per year over a 10-year horizon for all corn-soybean and continuous-corn farmers, respectively, who implement the practice. Since about 85% of cropland in the watershed is corn-soybean acreage, the average cost across all farms in the watershed would be about \$6/ha. LSNT entails a net cost because increased soil sampling costs, increased fertilizer application equipment costs, and slightly reduced crop yields more than offset reduced commercial fertilizer expenses.

Scenario 2: Use of a Winter Cover Crop

Environmental Impact: The sediment and nutrient loss reductions under the CR and CSR scenarios are shown in figure 4 for the case where the cover crop is planted on 100% of corn (CR) and corn-soybean (CSR) acreage. As expected,

the nutrient reductions were higher when rye was planted after corn and soybean crops than after corn only (fig. 4). This is because of the existence of ground cover during the winter months after both corn and soybean harvests, and not just after corn harvest. Due to the slightly lower reduction in runoff and higher infiltration under the rye cover crop, as compared to no winter cover, sediment losses were reduced. The lower sediment loss resulted in reduction of organic N and organic P. The $\text{NO}_3\text{-N}$ and orthophosphate phosphorous ($\text{PO}_4\text{-P}$) uptake by rye also resulted in reduction of these nutrients in subsurface and surface waters (fig. 5). Small grain cover crops, such as rye, used with a corn-soybean rotation have the potential to reduce erosion and prevent nutrient losses, as suggested by Jaynes et al. (2004b).

Economic Impact: Table 3 also summarizes the farm-level economic impacts of an annual rye cover crop planted after corn only, and then after corn and soybeans, per hectare of total cropland in the watershed. Results are shown for 810 ha continuous-corn and corn-soybean farms.

The results indicate that planting a rye cover crop after corn harvest will cost corn-soybean and continuous-corn farmers an average of about \$23 and \$40 per hectare per year, respectively, over a 10-year time horizon if all farmers in the watershed implement the practice. The watershed average across the two cropping systems is about \$26/ha. When the rye cover crop is planted after soybeans as well instead of just after corn only, the cost increases to about \$30/ha for corn-soybeans, with a watershed average of about \$34/ha. The table shows that the results depend somewhat on whether farmers perform field operations themselves or contract them out. The results in the table also reflect savings of between \$10 and \$15 per hectare of cover crop area because farmers use seed they harvested from the previous rye crop rather than purchasing the seed.

Scenario 3: LSNT and Winter Cover Crop

Environmental Impact: Figure 4 also shows the results of combining scenarios 1 and 2 on 100% of cropland. As expected, the combination of cover cropping and LSNT is extremely effective in reducing the loss of nutrients through surface and subsurface waters. As was discussed for the previous scenario, the nutrient reductions, especially for $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$, are significantly greater under the LSNT and CSR scenario than under the LSNT and CR scenario. This difference is due to the combined effect of constant ground cover and lower and timely application of fertilizer with CSR. Nevertheless, a reasonable reduction in nutrients, especially for $\text{NO}_3\text{-N}$, was also obtained with the LSNT and CR scenario.

Economic Impact: The economic impacts of the combined LSNT and rye cover crop BMP are also shown in table 3. The costs to corn-soybean and continuous-corn farmers when the cover crop is planted only after corn are about \$28 and \$51 annually per hectare, respectively, implying a watershed average of about \$32/ha/year.

Table 3 shows that implementing the combined BMP on soybean fields as well adds about \$8 per hectare per year to the costs for corn-soybean operations, thus increasing the watershed average to \$40/ha/year. In all cases, the average annual costs when operations are performed by the farmer are somewhat lower for the typical 810 ha farm in the watershed. Here, too, the results reflect savings of between \$10 and \$15 per hectare of planted cover crop area annually for farmers,

Table 4. Cost-effectiveness coefficients for alternative scenarios.

Indicator	Units	LSNT	Cover Crop on		LSNT and Cover Crop on	
			Corn Only	Corn-Soybeans	Corn Only	Corn-Soybeans
Sediment	\$/ton	243.56	81.86	40.13	94.28	44.51
Organic N	\$/kg	30.07	14.41	9.31	16.27	10.28
Organic P	\$/kg	407.80	108.04	72.64	125.92	83.07
NO ₃ -N	\$/kg	1.20	21.64	11.06	4.67	5.11
PO ₄ -P	\$/kg	1,923.96	1,276.28	512.31	1,477.13	546.60
Total N	\$/kg	1.15	8.69	5.05	3.62	3.41
Total P	\$/kg	329.65	99.82	63.61	115.35	71.93

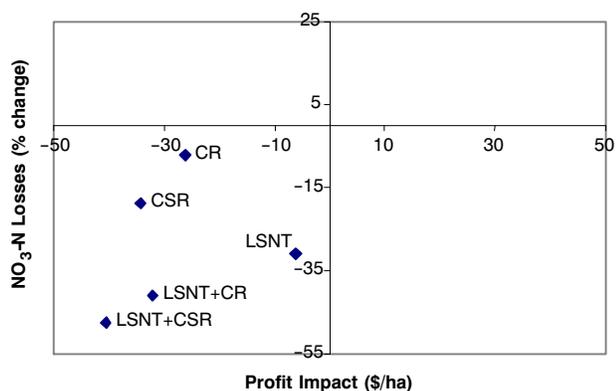


Figure 5. Tradeoff plot showing impact of scenarios on NO₃-N.

assuming that they use their own farm-grown seed for the rye crop.

The economic and environmental impacts presented above for the scenarios can be integrated in a number of ways to provide more useful insights. Cost-effectiveness coefficients show the cost per unit change in each relevant indicator for the scenarios simulated. Cost-effectiveness coefficients are tabulated for the water quality indicators in table 4. The table shows that the cost of NO₃-N loss reduction ranges from \$1.20/kg when LSNT is used as the option to \$21.64/kg when cover cropping after corn only is used instead. Similarly, the least expensive option for PO₄-P loss reduction is cover cropping after both corn and soybean harvests. Similar inferences can be made for other indicators. It should be noted that the most cost-effective option may not

be the scenario of choice in a given situation since it might not necessarily lead to the desired load reductions for the indicator.

Trade-off plots are also a convenient method of combining economic and environmental impacts. A trade-off plot for NO₃-N loss reduction is shown in figure 5, where percentage reductions in NO₃-N loss are plotted against costs for each scenario. The figure shows that the cover crop after the corn and soybean harvest scenario (CSR) is inferior to LSNT in terms of cost-effectiveness for NO₃-N because LSNT yields greater NO₃-N loss reductions and costs less than the CSR scenario.

GENERAL SCENARIO EQUATIONS FOR SELECTED WATER QUALITY INDICATORS

SWAT-M results for alternative rates of scenario adoption were used to generate predictive equations that can be used to determine the likely water quality impacts associated with any adoption rate between 0% and 100%. A set of linear equations was generated for each indicator: $Y = AX + B$, where A and B are regression coefficients, and X represents the adoption rate (percent of land area affected by the scenario). The regression coefficients are shown in table 5. The significant (≥ 0.97) R^2 values obtained from these equations demonstrate the applicability of using these equations to estimate the percent change in sediment and nutrient loading caused by implementing the simulated scenarios at any given coverage at the watershed level. For instance, the estimated reduction in NO₃-N under the LSNT management scenario for 50% of corn acreage within the

Table 5. Coefficients A and B and R^2 values obtained from linear regression equations ($Y = AX + B$) relating the percent change in sediment and nutrient loading to (a) LSNT, CR, and CSR, and (b) LSNT + CR and LSNT + CSR.

(a)	LSNT			CR			CSR		
	A	B	R^2	A	B	R^2	A	B	R^2
Sediment	-0.01	0.12	0.99	-0.07	0.36	1.00	-0.16	1.14	1.00
NO ₃ -N	-0.35	-3.06	1.00	-0.09	-0.48	1.00	-0.16	0.20	1.00
Organic N	-0.02	0.12	0.99	-0.10	0.52	1.00	-0.23	1.63	0.99
Total N	-0.19	-1.52	1.00	-0.09	0.01	1.00	-0.19	0.89	1.00
PO ₄ -P	-0.03	0.17	1.00	-0.19	0.90	0.99	-0.51	2.25	1.00
Organic P	-0.01	0.09	1.00	-0.10	0.49	1.00	-0.22	1.55	0.99
Total P	-0.01	0.10	1.00	-0.11	0.52	1.00	-0.24	1.60	1.00
(b)	LSNT + CR			LSNT + CSR					
	A	B	R^2	A	B	R^2			
Sediment	-0.08	0.43	1.00	-0.10	-0.26	1.00			
NO ₃ -N	-0.30	-5.53	0.99	-0.02	-6.93	0.99			
Organic N	-0.13	0.84	1.00	-0.02	-0.25	1.00			
Total N	-0.22	-2.43	1.00	0.52	-30.04	0.20			
PO ₄ -P	-0.20	1.09	0.99	-0.70	8.62	0.99			
Organic P	-0.13	0.82	1.00	-0.14	-0.18	1.00			
Total P	-0.13	0.84	1.00	-0.16	-0.14	1.00			

WCW would be about 20.6% ($-0.35 \times 50 - 3.06 = -20.6$). The regression coefficients presented in table 5 were developed based on WCW conditions and are possibly useful for watersheds with similar conditions.

CONCLUSIONS

In this study, SWAT-M and FEM were used to evaluate the impacts of LSNT and a fall and winter cover crop (rye) on the water quality for WCW. SWAT-M was tested successfully against the actual measured data from a subbasin within WCW where LSNT was implemented from 1997 to 2000. The simulation results, similar to the field results reported by Jaynes et al. (2004a), showed a 25% reduction in $\text{NO}_3\text{-N}$ due to the LSNT scenario. This verified the capability of SWAT-M for simulation of the scenarios.

SWAT-M and FEM were then used to simulate several scenarios. The application of these two models to WCW provided a robust method of evaluating the environmental and economic impacts of adopting a range of alternative management practices to part or all of the cropped acreage in the watershed. The results showed that the three strategies designed to reduce the loss of nutrients were effective. As anticipated, the effectiveness of these scenarios was more pronounced as the area of crop coverage increased from 15% to 100%. The application of LSNT resulted in significant reduction (31%) of $\text{NO}_3\text{-N}$ for the whole watershed at a cost of about \$6/ha. Using rye as cover crop during fall and winter resulted in reduction of sediment and all nutrients (including particulate-P, $\text{PO}_4\text{-P}$, organic-N, $\text{NO}_3\text{-N}$, total-P, and total-N) at a cost of about \$26/ha if planted after corn harvest only (CR) and about \$34/ha if planted after both corn and soybean harvests (CSR). Greater $\text{NO}_3\text{-N}$ loss reduction was obtained from CSR, due to higher infiltration, as compared to CR. The simulation of combined cover crop and LSNT scenarios resulted in higher reduction in loss of nutrients compared to the impacts of the individual LSNT or cover crop scenarios. The cost of the combined BMP scenario was also correspondingly higher, largely being an additive cost of the two component BMPs.

The high cost of using the cover crop indicates that significant cost-share dollars may be required to promote this practice. The cost of the rye cover crop would have been even higher if farmers had purchased the seed rather than using their own farm-grown seed. On the other hand, the cost would be less if the full rye crop had been harvested and used on the farm or sold. Harvest of the full rye crop would also reduce the need for the herbicide application to kill the rye crop before corn or soybean planting during the next growing season.

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