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# MODELING ALTERNATIVE AGRICULTURAL MANAGEMENT PRACTICES FOR HIGH ISLAND CREEK WATERSHED IN SOUTH-CENTRAL MINNESOTA

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*Nonpoint source pollution from row crop land is a widespread problem in North America. Concerns include sediment, nitrate and phosphorus loadings to water bodies from row cropped lands. In this study, a spatial-process based water quality model was calibrated (2001-2002) for flow, sediment, nitrate and phosphorus losses from the High Island Creek, a 3856 ha agricultural watershed located in south-central Minnesota. The calibrated model was used to evaluate alternative tillage and fertilizer management practices such as adoption of conservation tillage practices, rate, timing and method of N– and P-fertilizer applications, and method of manure application. Statistical comparison of calibration results with observed data indicated excellent agreement with $r^2$ of 0.95, 0.96, 0.87, and 0.97 for flow, sediment, nitrate and phosphorus losses, respectively. The model simulated a 37.5% reduction in annual sediment losses can be achieved by adopting conservation tillage on all row cropped land in the watershed. Reductions in annual nitrate losses can be achieved by switching the timing of application from fall to spring and by reducing the rate of nitrogen fertilizer application. A 41% reduction in annual nitrate losses can be achieved if all farmers adopt injection as a method for animal manure application.*

## INTRODUCTION

High nitrate loadings in the Upper Mississippi River system are associated with tributaries from agricultural areas in the state of Minnesota, Indiana, Iowa, and Illinois, where a high percentage of agricultural land is in row crops which are managed with subsurface tile drainage systems. High nitrate losses are also associated with excessive applications of N-fertilizer (Baker and Johnson, 1981; Kanwar et al., 1988), especially fertilizer applied in the fall (Baker and Melvin, 1994). Roughly 26% of the total suspended sediment load and 33% of all the phosphorus entering the Upper Mississippi River System from the Minnesota River are contributed by the Lower Minnesota River watershed located at the mouth of the Minnesota River (Mulla and Mallawatantri, 1997). High P losses are primarily due to excessive soil P levels as a result of long term P fertilizer and manure applications and high soil erosion rates (Randall et al., 1997). In addition, rate of fertilizer application (Romkens and Nelson, 1974), method of application (broadcast or incorporated; Baker and Laflen, 1982) and type (organic or inorganic) of fertilizer (Eghball et al., 1996; Heathwaite, 1997) in combination with timing and magnitude of rainfall events (Burwell et al., 1975) dictate the magnitude of P losses.

The type and timing of farm management practices in combination with spatially varying soil types, topography, and climatic conditions have a major impact on the pattern and magnitude of nutrient losses. For this reason, many long term water quality monitoring studies have been conducted throughout the Midwest U.S. and Canada with emphasis on fertilizer application rates and timing, crop rotation, and climatic variability. Most of these studies have been conducted at plot and field scales to describe the effect of specific farming practices. However, there are only a few such studies at the watershed scale (Jaynes et al., 1999; Mulla et al., 2002). Watershed scale studies on the impacts of agricultural alternative management practices on water quality are difficult to carry out because many farmers must simultaneously be convinced to adopt new practices. Also, it is difficult to evaluate the impact of more than one or two farming practices in watershed scale studies, due to the difficulty in monitoring water quality impacts of each practice independently. Water quality simulation models can play a major role in filling this knowledge gap time and cost-effectively.

Based on the introductory information provided above, the objectives of this study were to 1) evaluate the reductions in sediment, nitrate, and phosphorus losses possible with several alternative agricultural management practices in a 3856 ha agricultural watershed (located in the High Island Creek watershed, south-central Minnesota); and 2) estimate how much of the reduction in pollutant loads could reasonably arise from controlling nonpoint source pollution. In this study, a dynamic watershed-scale modeling approach (Gowda et al., 1999) that uses the ADAPT (Agricultural Drainage and Pesticide Transport) field scale water table management model (Chung et al., 1992), and Geographic Information System (GIS) and remote sensing databases, was calibrated to predict monthly flow, sediment, nitrate and phosphorus losses. This model explicitly accounts for the effects of all typical agricultural management practices on water quality, including the effects of various tillage implements on crop residue, the impacts of changes in fertilizer and manure application rates and methods, crop rotation effects, and effects of tile drainage. The calibrated model was used to evaluate the improvement in water quality due to alternative agricultural management practices including changes in adoption of conservation tillage, rate and timing of N- and P-fertilizer applications and method of animal manure applications.

## MATERIALS AND METHODS

### *Study Area and Water Quality Data*

The study area comprises two minor watersheds in the High Island Creek watershed, MN (Figure 1). Hereafter, the study watershed is referred to as the High Island Creek watershed. From April 2001 until June 2002, the watershed was monitored for flow, sediment, nitrogen and phosphorus losses as part of the Clean Water Partnership Program involving the Minnesota Pollution Control Agency and Soil and Water Conservation District of Sibley County. Topography of the watershed is relatively flat, and soils are poorly drained. The Clarion-Nicollet-Canisteo (Typic Hapludolls - Aquic Hapludolls - Typic Haplaquolls) soil association predominates, with Webster (Typic Haplaquolls), Harps (Typic Calciaquolls), Okoboji (Cumulic Haplaquolls), and Klossner (Terric Medisaprists) soils occupying the closed depressions. About 70% of the land uses a corn (Zea Mays L.) and soybean (Glycine Max L.) crop rotation, and is tile drained. Twenty feedlots with 3072 animal units were found within the High Island Creek watershed, of which 56.8, 25.6 and 15.6 percent were hog, dairy and beef units, respectively. About 18% of the cropland received animal manure, and through a survey of farmers in a nearby watershed we estimated that 61.5, 14.2 and 24.2 percent of manure was applied using broadcast, incorporation or injection methods, respectively.

Discharges at the outlet were measured by a 1-stage measuring device which is connected to a Campbell Scientific Inc. (CSI) CR10[1] data logger. Flow measurements were made every 5 minutes. Water samples for water quality were collected automatically with ISCO peristaltic pump

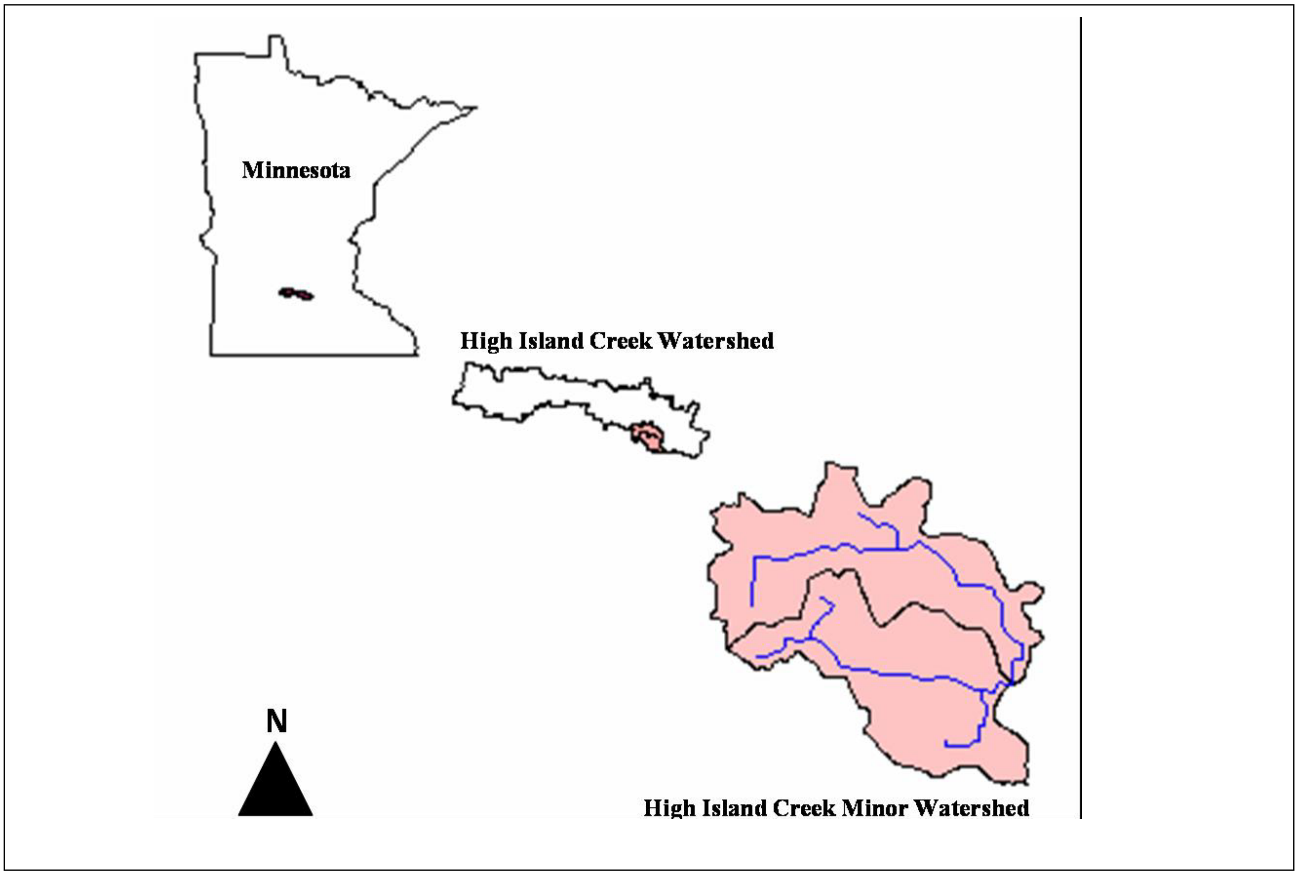

Figure 1. Location of the two Island Creek minor watersheds in Southern Minnesota

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samplers. Sampling interval for water quality was based on the rate of change in water level, with more frequent water samples during storm events. In addition to automated collection, water quality samples were collected manually on a biweekly basis and after major rainfall events by dipping sterilized glass bottles into stream flow.

### *ADAPT Model*

The ADAPT model is a daily time step field-scale water table management simulation model that was developed by integrating GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Leonard et al., 1987), a root zone water quality model, with subsurface drainage algorithms from DRAINMOD (Skaggs, 1982), a subsurface drainage model. More detailed information about ADAPT can be found in Chung et al. (1992), Ward et al. (1993), and Desmond et al. (1996). Additional enhancements to the model include potential evapotranspiration estimation with the Doorenbos and Pruitt method (1977) as an alternative to the Ritchie method (1972). Runoff was estimated using the SCS curve number method (SCS, 1972, 1985) with daily curve number updates dependent on antecedent moisture conditions. Soil erosion was estimated using the Universal Soil Loss Equation (Foster et al., 1980). Edge of field sediment losses were estimated by multiplying predicted erosion rates by a sediment delivery ratio (the ratio of sediment transported beyond the edge of field to the predicted rate of erosion). The nitrogen and phosphorus cycles used in the ADAPT model include routines for mineralization, immobilization, fertilization, animal waste application, and crop uptake. Nutrient losses are simulated at daily time-step based on rates of sediment loss and soil and runoff concentrations of nitrogen and phosphorus.

The ADAPT model was used here because of its ability to simulate the water quality effects of all typical agricultural management practices (tillage, crop rotation, fertilizer management), including subsurface drainage contributions to agricultural runoff. The ability to accurately simulate tile drainage effects is especially important in the Midwest where nearly 30% of all crop land has been improved using subsurface tile drainage systems (Zucker and Brown, 1998), which can have a significant impact on the quantity and quality of runoff and drainage from agricultural watersheds. Also, the ADAPT model was calibrated and validated for conditions in southern Minnesota using long-term monitoring data collected from an experimental plot with continuous corn (Davis et al., 2000). Recently, a frost depth algorithm developed by Benoit and Mostaghimi (1985) was incorporated to enhance the model’s capability to predict flow during spring and fall months (Dalzell, 2004).

### *Model Input*

Model inputs include information about land cover, soil, slope, type and timing tillage and nutrient management practices. In the summer of 2001, a detailed land use survey was conducted in the High Island Creek watershed to identify crop types at the field level. Aerial photos acquired by the USDA Farm Service Agency were used in conjunction with field survey to develop a land use map for the watershed. This information was stored in a GIS format. The SSURGO (Soil SURvey GeOgraphic) soil map of the High Island Creek watershed was used to derive soil input. Soil properties such as the depth of each horizon, particle size distribution, organic matter content, saturated vertical hydraulic conductivity, and soil water release curve for each of the SSURGO soil map units were derived from the Map Unit Use File (MUUF) soil database (Baumer et al., 1994). To avoid duplication and reduce the number of soil map units used in the model simulation, soil properties between the map units were compared and soil map units were merged whenever there was no difference in values of model sensitive parameters such as slope, saturated vertical hydraulic conductivity and soil water release curve.

Site-specific information on planting and harvesting dates and tillage management practices for 2001 were collected by the Soil and Water Conservation District of Sibley County for each field within the High Island Creek watershed. Also, data were collected on timing, method of application, and type of fertilizer or manure through a landowners-operators survey within the watershed, as well as from a detailed land owners-operators survey (as part of another watershed project) in the Huelskamp Creek watershed located on south-side of the study watershed. Land use attributes were linked to the tillage and nutrient management data associated with each field.

Spatial data development for watershed application of the ADAPT model consist of a two-part process; namely, (1) Hydrologic Response Unit (HRU) development, and (2) aggregation of HRUs into Transformed Hydrologic Response Units (THRUs). In the HRU formation process, spatial data layers of land cover, soils, slope (averaged by SSURGO map unit), tillage, and other spatially varied agronomic practices were overlain with Arcview 3.1[2] GIS software (ESRI, 2000). Also, a 50-meter buffer on each side of the ditches within the watershed was formed to vary sediment delivery ratio to account for differences in sediment trapping as a function of proximity to nearby streams. The region in close proximity to streams is hereafter referred to as the primary contributing corridor. The result is a GIS layer consisting of many polygons that each contains hydrologic characteristics that are unique from those around it. The number of HRUs that result from this initial definition can be quite large. High Island Creek, for example, has over 6,000 HRUs associated with it. However, there are many HRUs in a watershed that have the same hydrologic characteristics as other HRUs, but are different from each other by location only. These similar HRUs are then aggregated together to form Transformed HRUs (THRUs) – the functional modeling unit. It should be noted that THRUs do not retain the positional information initially present in the HRUs. This data arrangement is based on the assumption that the time of concentration in the study watershed is less than 24 hours, the time-step resolution of the model. This assumption is valid for High Island Creek watershed. GIS overlay analysis of land use, tillage, soil and slope layers for the High Island Creek watershed resulted in 224 THRUs.

Climatic data such as daily values of precipitation and mean temperature used in the water quality simulation were the daily averages of data recorded at four weather stations within the study watershed to account for spatial variability. Other climatic data such as average relative humidity, solar radiation and wind speed were obtained from a nearby weather station located in Jordan, MN.

### *Model Calibration*

The spatial process model was calibrated using water quality data measured at the outlet of the High Island Creek watershed from April to September in 2001 and from April to June in 2002. Calibration of the model for flow was achieved by adjusting initial depth of water table, soil water release curve, soil porosity, leaf area index, and saturated vertical hydraulic conductivity of the impeding layer. Sediment delivery ratios of 0.10 and 0.05 were used for THRUs outside and inside of the primary contributing corridor, respectively. These are consistent with algorithms for estimating sediment delivery ratio based on distance from surface water bodies (Ouyang and

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Bartholic, 1997). Improvements in nitrogen and phosphorus loss predictions were made by adjusting initial total nitrogen or phosphorus, and nitrate or labile phosphorus levels in the soil horizons. Statistical measures such as mean and Root Mean Square Error (RMSE), coefficient of determination ($r^2$) and slope and intercept of the least square regression line between measured and predicted values, and index of agreement (d), were used to evaluate the match between measured and predicted flow and nitrate discharges for the calibration period. The value of *d* reflects the degree to which the predicted variation accurately estimates the observed variation. The values of $r^2$, slope, intercept, RMSE, and index of agreement are 1.0, 1.0, 0.0, 0.0 and 1.0, respectively, when there is a perfect agreement between predicted and observed values.

### Adoption of Conservation Tillage Practices

The effects of various levels of adoption of conservation tillage practices on water quality in High Island Creek watershed were evaluated by changing the amount of row cropped land under conservation tillage for two years (2001-2003). Based on our field data and questionnaire surveys, adoption of conservation tillage (more than 30% of the topsoil covered with crop residue after planting) in the watershed was about 24.2%. About 61.5% of row cropped land in conventional tillage had a crop residue level of 0-15%, the remaining 14.3% had residue levels of 15-30%. Levels of adoption of conservation tillage used in the simulations include 0.0% (100% conventional tillage), 24.2% (existing), and 100% of the cropped land in the watershed. Under the 100% conventional tillage scenario, two separate simulations were made by changing the crop residue levels on all row cropped land to 0-15% and 15-30% to quantify the effect of commonly adopted crop residue levels on water quality in the watershed.

### N– and P-Fertilizer Application Rate and Timing

Several simulations were made for the period from 2001-2002 to determine the effect of variation in the rate and timing of fertilizer application on nitrogen and phosphorus losses. Input parameters used in the simulations for evaluating various practices were the same as those used in the model calibration, unless otherwise mentioned. Five N and P application rates (by changing the existing rate by -20, -10, 0, +10, and +20) and in addition, two application timings (fall and spring for N-fertilizer only) were used for this purpose. The use of multiple application rates and timings was to demonstrate the sensitivity of nitrogen and phosphorus losses to variation in precipitation as the application rate and timing changed.

### Method of Animal Manure Application

Three scenarios were developed to evaluate the impact of method of animal manure application on nitrate and phosphorus losses in the High Island Creek watershed. They were: 1) broadcast application of all of the animal manure, 2) all of the manure incorporated, and 3) all of the animal manure injected.

## RESULTS AND DISCUSSIONS

GIS overlay analysis resulted in 224 THRUs. Although the corn-soybean or soybean-corn rotation was practiced on about 70% of the cropland, the number of THRUs was increased as a result of more than one soil type within a crop or field boundary. Corn typically received a fall application of anhydrous ammonia at 163 or 170 kg N/ha with or without animal manure, respectively (Table 1).

Table 1. Baseline N– and P-fertilizer application rates for corn in the High Island Creek watershed from 2001 to 2002.

| **Crop** | **Baseline application Rate (kg/ha)** | | | |
|---|---|---|---|---|
| | Without Animal Manure | | With Animal Manure | |
| | N | P[1] | N | P[1] |
| Corn | 170 | 38 | 163 | 28 |
| Soybean | - | - | - | - |

[1] Applied to corn in corn-soybean rotation.

## *Model Calibration*

Table 2 shows excellent agreement between model predictions and measured flow, sediment, nitrogen and phosphorus losses for the calibration period. Attempts were made to minimize the RMSE and obtain $r^2$ and d values closest to a value of unity. Comparison of measured and calibrated values of monthly flow shows (Figure 2) that the magnitude and trend in the predicted monthly flows closely followed the measured data in most of the months. However, the model over predicted measured mean monthly flow (0.37 $m^3$/sec) by 24%. Statistical evaluation of the measured and predicted flow gave an $r^2$ value of 0.95, with a slope and intercept of 0.87 and -0.03 $m^3$/sec, respectively. The index of agreement was about 0.98 and the RMSE was 43% of the observed mean monthly flow.

The model predicted 96% of the variability in sediment losses observed at the outlet of the High Island Creek watershed. The trend in predicted monthly sediment losses (Figure 3) was similar to that in the measured data, and predicted mean monthly sediment losses (51.4 tons) closely matched with the measured losses (50.6 tons). The model gave an RMSE equivalent to 38% of the measured mean monthly sediment losses, with an index of agreement of 0.99. The higher RMSE is partly a result of over prediction of sediment losses for April of 2001.

Table 2. Model performance statistics for predicted monthly flow, nitrate and phosphorus discharges in High Island Creek watershed for calibration period.

| **Statistic** | | **Calibration period (April 2001 to July 2002)** | | | |
|---|---|---|---|---|---|
| | | Flow ($m^3$/sec) | Sediment (ton) | Nitrogen (ton) | Phosphorus (ton) |
| Mean | Observed | 0.37 | 50.59 | 14.08 | 0.40 |
| | Predicted | 0.46 | 51.42 | 15.66 | 0.40 |
| RMSE[1] | | 0.16 | 19.25 | 7.63 | 0.12 |
| $r^2$ | | 0.95 | 0.96 | 0.87 | 0.97 |
| Slope | | 0.87 | 0.89 | 1.04 | 1.05 |
| Intercept | | -0.03 | 4.64 | -2.27 | -0.02 |
| d[1] | | 0.98 | 0.99 | 0.96 | 0.97 |

[1] RMSE - Root Mean Square Error, d - index of agreement

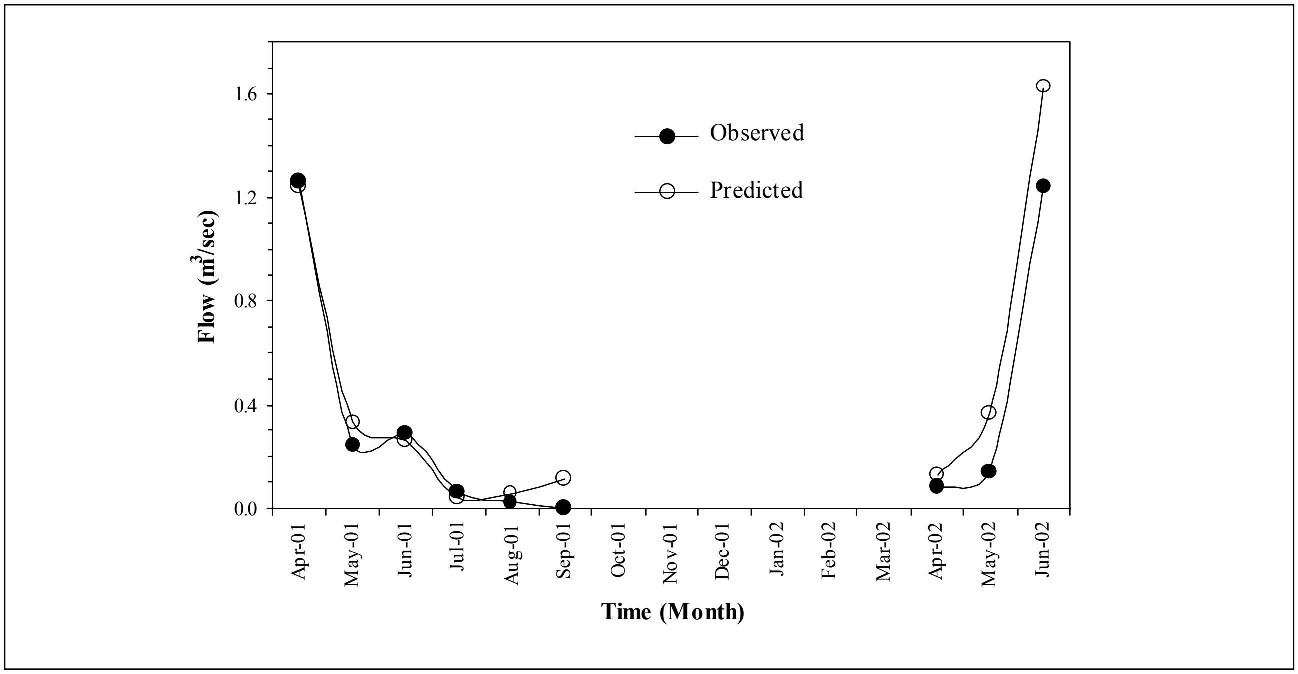

Figure 2. Comparison of predicted monthly flow against measured data (April 2001 – June 2002).

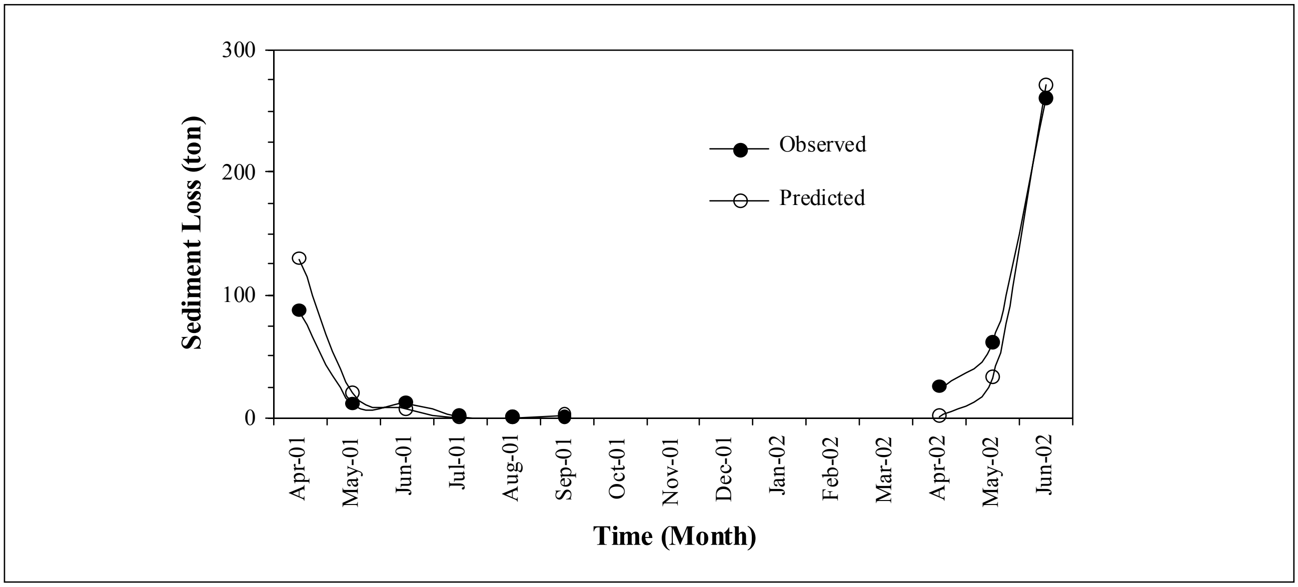

Figure 3. Comparison of predicted monthly sediment losses against measured data (April 2001 – June 2002).

Predicted monthly nitrate losses were in close agreement with the measured data (Figure 4). The predicted mean monthly nitrate loss was about 15.7 tons against a measured value of 14.1 tons. However, the model under predicted nitrate losses in April 2001 and over predicted for June 2002. Statistical evaluation of the predicted and measured nitrate losses gave an $r^2$ value of 0.87 with a slope and intercept of 1.04 and -2.27 tons, respectively. The index of agreement was about 0.96 and the RMSE was about 54% higher than the measured value. Overall, the model seems to predict nitrate losses reasonably well when the predicted monthly flows were in agreement with the measured data.

The model predicted 97% of the variability in phosphorus losses observed at the outlet of the High Island Creek watershed. The trend in predicted monthly phosphorus losses (Figure 5) was

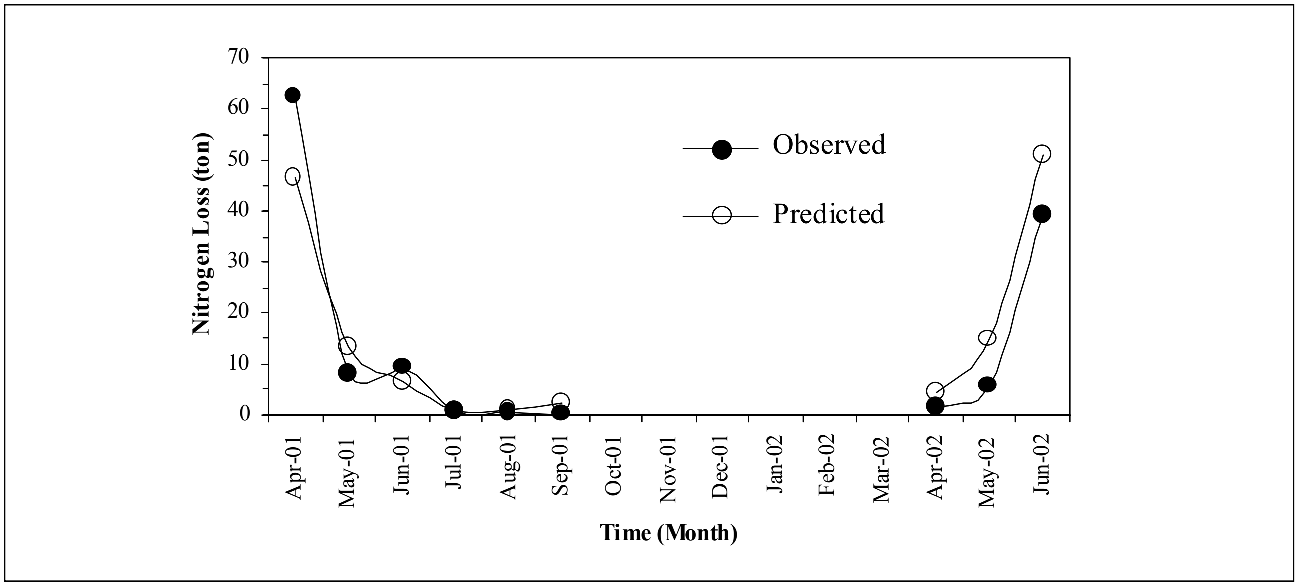

Figure 4. Comparison of predicted monthly nitrate losses against measured data (April 2001 – June 2002).

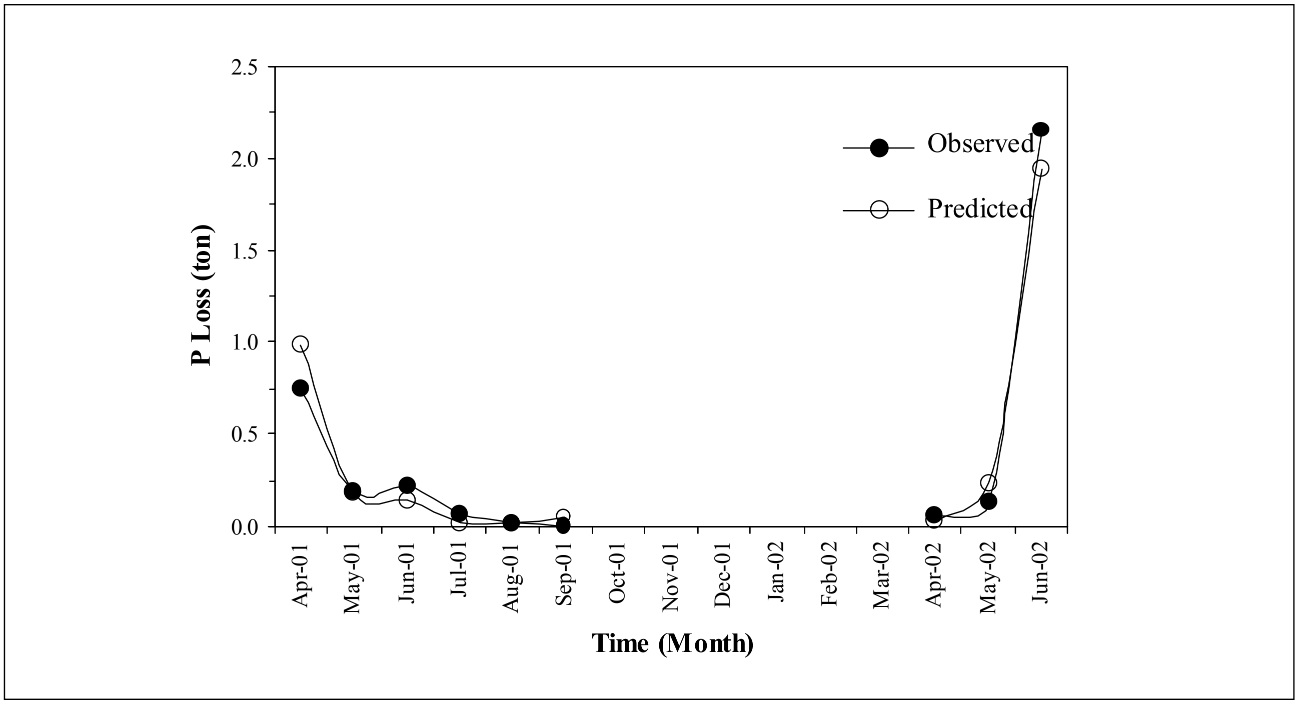

Figure 5. Comparison of predicted monthly phosphorus losses against measured data (April 2001 – June 2002).

similar to that in the measured data. The predicted mean monthly sediment losses (0.40) matched with the measured losses. The model gave an RMSE equivalent to 30% of the measured mean monthly sediment losses, with an index of agreement of 0.97 (Table 2).

### *Adoption of Conservation Tillage Practices*

Changes in the adoption rate of conservation tillage in High Island Creek watershed were simulated with the calibrated model. Table 3 presents annual sediment and nutrient losses for the High Island Creek watershed. Annual sediment losses delivered to the mouth of the watershed under existing tillage practices (24.2% conservation tillage) were about 0.08 ton/ha. Compared to this, if all land had crop residue levels of 0-15%, sediment losses would have increased by 12.5%.

Table 3**.** Predicted annual sediment, nitrogen, and phosphorus losses for 2001-2002.

| Water Quality Parameter | Loss |
|---|---|
| Sediment | 0.08 ton/ha |
| Nitrogen | 28.67 kg/ha |
| Phosphorus | 0.64 kg/ha |

On the other hand, if all cropland had 15-30% crop residue levels, sediment losses were reduced by 12.5% compared to existing conditions (Figure 6). Simulation results suggested that a 38% reduction in sediment losses is possible if all row cropped land is put into conservation tillage. Similarly, a 6% reduction in existing phosphorus losses is possible if all row cropland is put into conservation tillage. On the other hand, phosphorus losses would have been increased 3-5% if all row cropland was in conventional tillage.

### *N- and P-Fertilizer Application Rate and Timing*

Annual nitrate losses in the High Island Creek watershed were about 28.7 kg/ha (Figure 7) under prevailing management conditions. These conditions include a fall application of 170 kg N/ha as anhydrous ammonia (163 kg N/ha for manure-applied land) to corn fields and a spring application of 19 kg/ha (14 kg/ha for manure-applied land) of phosphorus as orthophosphate to corn fields

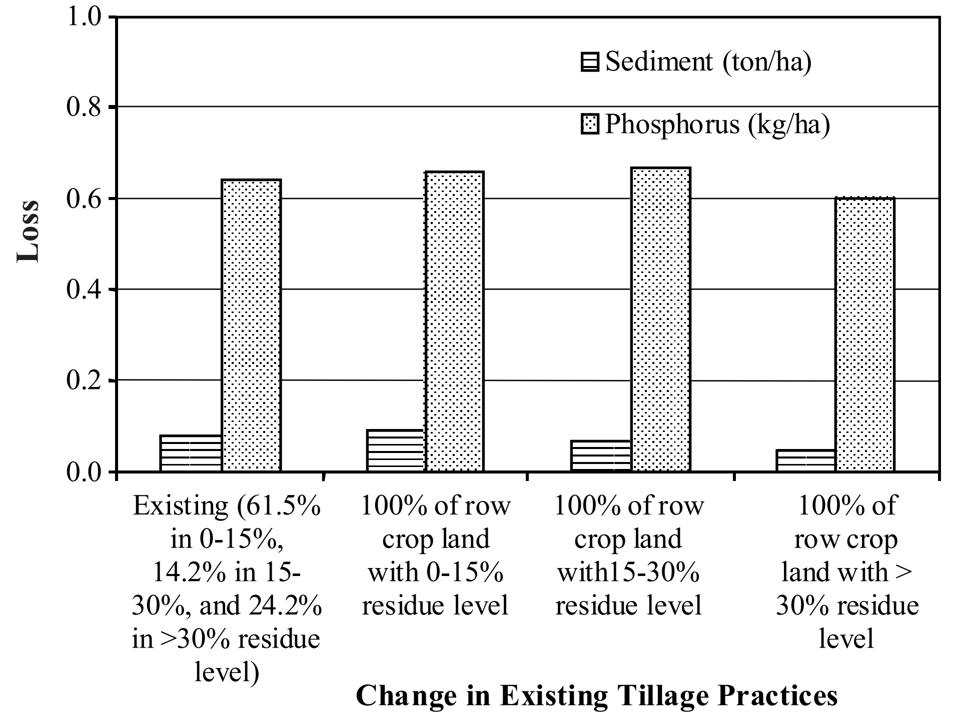

Figure 6. Predicted annual sediment and phosphorus losses to various crop residue levels in the High Island Creek watershed.

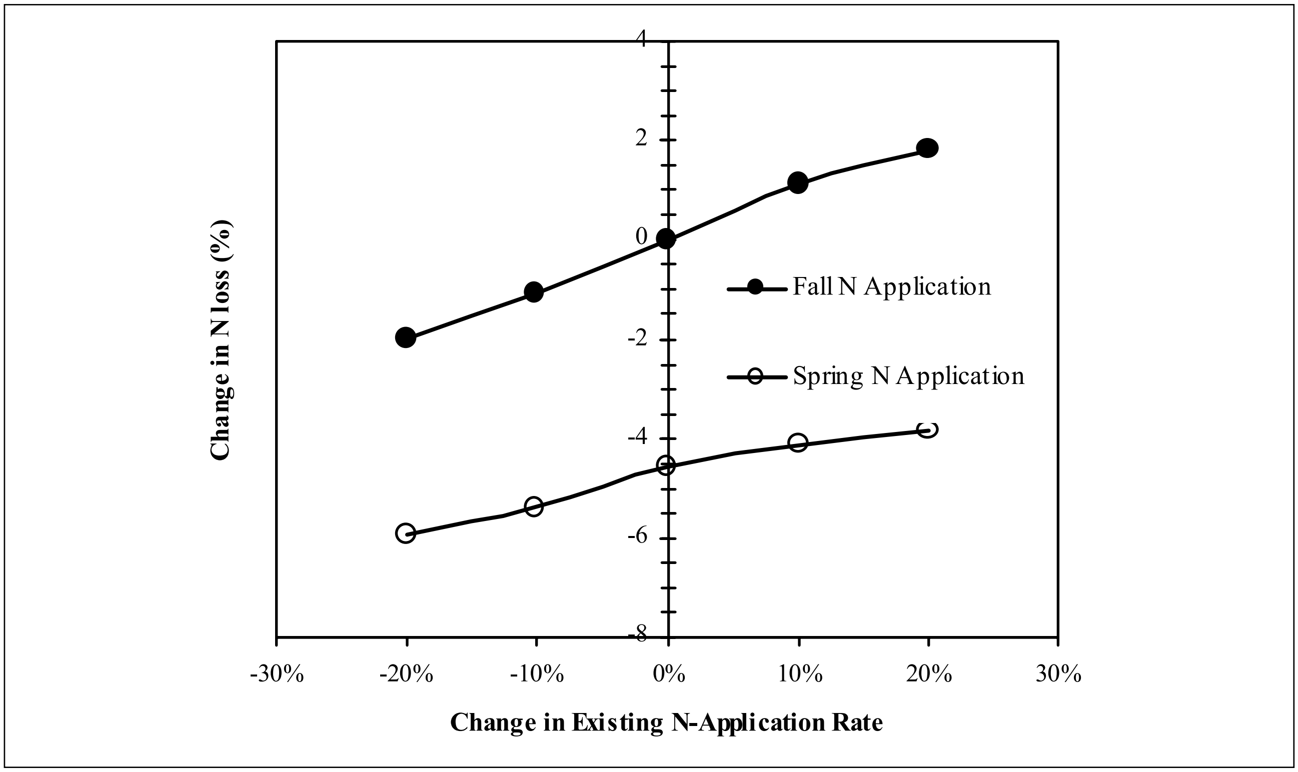

Figure 7. Predicted annual nitrogen losses for changes in baseline fertilizer application rate and timing in High Island Creek watershed.

(Table 1). Nitrate losses were sensitive to both application rate and timing of application (Figure 7). Reductions in nitrate losses were proportional to reductions in N fertilizer application rates. For example, annual nitrate losses were reduced from 29.2 to 28.1 kg/ha when fall applied N was reduced from +20 to -20% of the baseline rate. When the existing N application rate was kept constant, nitrate losses were 4.5% greater for fall application than for spring application. Of the simulated scenarios, the greatest reduction in nitrate losses was associated with a 20% reduction in applied fertilizer application rate combined with a switch from fall to spring application (6 percent). The greatest increases in nitrate loss were associated with fall applied fertilizer at a rate 20% greater than the baseline.

Annual phosphorus losses in the High Island Creek watershed were about 0.64 kg/ha (Figure 8) Reductions in phosphorus losses were proportional to reductions in P fertilizer application. For example, annual phosphorus losses were reduced from 0.68 to 0.60 kg/ha when spring applied phosphorus was reduced from +20 to -20% of the baseline rate. In other words, a 12.6% reduction in phosphorus losses resulted from a 40% reduction in phosphorus fertilizer application rate in the watershed.

### *Method of Animal Manure Application*

Annual nitrate and phosphorus losses in the High Island Creek watershed were about 28.7 kg/ha and 0.64 kg/ha, respectively under baseline conditions. Under baseline conditions, 18% of the cropland receives animal manure, and on land receiving animal manure, the primary application methods were broadcast, incorporation or injection on 61.5, 14.2 or 24.2% of the area, respectively. Of the simulated scenarios, the highest nitrate and phosphorus losses were associated with a scenario in which all of the animal manure was broadcast applied to the surface. In this scenario, annual nitrate and losses were increased by 10% above baseline conditions, whereas annual

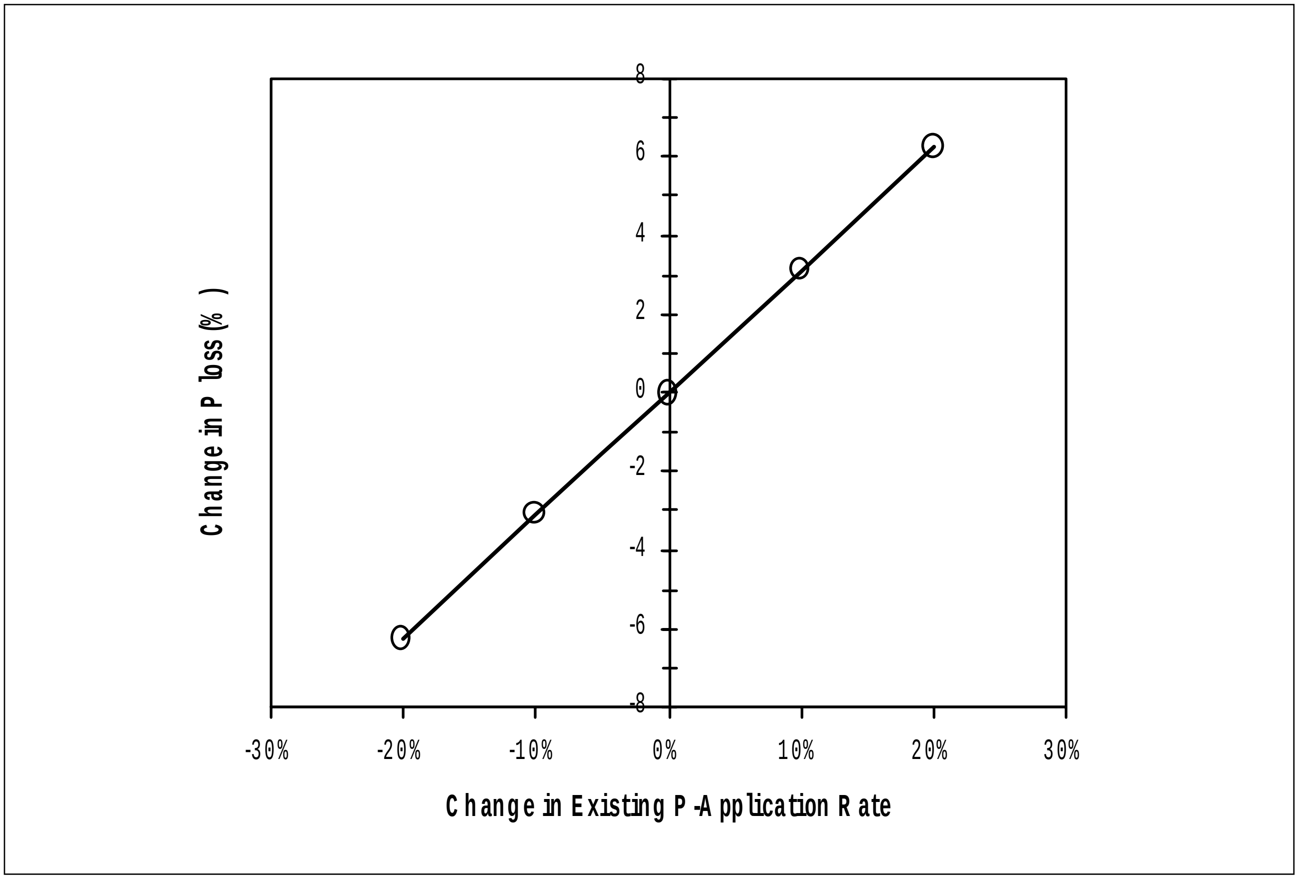

Figure 8. Predicted annual phosphorus losses for changes in baseline spring-applied fertilizer application rate in High Island Creek watershed.

phosphorus losses were increased by 30% (Figs. 9 and 10). Greatest reductions in nitrate and phosphorus losses were associated with a scenario in which all of the animal manure was injected. In this scenario, annual nitrate losses were reduced by 13.6%, whereas annual phosphorus losses were reduced by 41%.

## SUMMARY

A spatial-process model that uses GIS and the ADAPT, a field scale daily time-step continuous water table management model, was calibrated for flow sediment, nitrate and phosphorus discharges from the High Island Creek watershed. For the calibration period, the observed and predicted flow, sediment, nitrate and phosphorus discharges were in excellent agreement, with $r^2$ values of 0.95, 0.96, 0.87, 0.87, and 0.97, respectively. The calibrated model was used to investigate sediment, nitrate and phosphorus loss responses to alternative tillage and nutrient management scenarios such as adoption rate of conservation tillage, and rate, timing and method of fertilizer applications. The simulated results suggested a 37.5% reduction in annual sediment losses can be achieved by adopting conservation tillage on all row cropped land in the watershed. Reductions in annual nitrate losses can be achieved by switching the timing of application from fall to spring and by reducing the rate of nitrogen fertilizer application. Phosphorus losses were sensitive to rate and method of application. A 41 percent reduction in annual phosphorus losses in the High Island Creek watershed can be achieved if all farmers adopt injection as a method for animal manure application. Further reductions in phosphorus losses require reductions in the rate of phosphorus fertilizer application and increases in the adoption rate of conservation tillage.

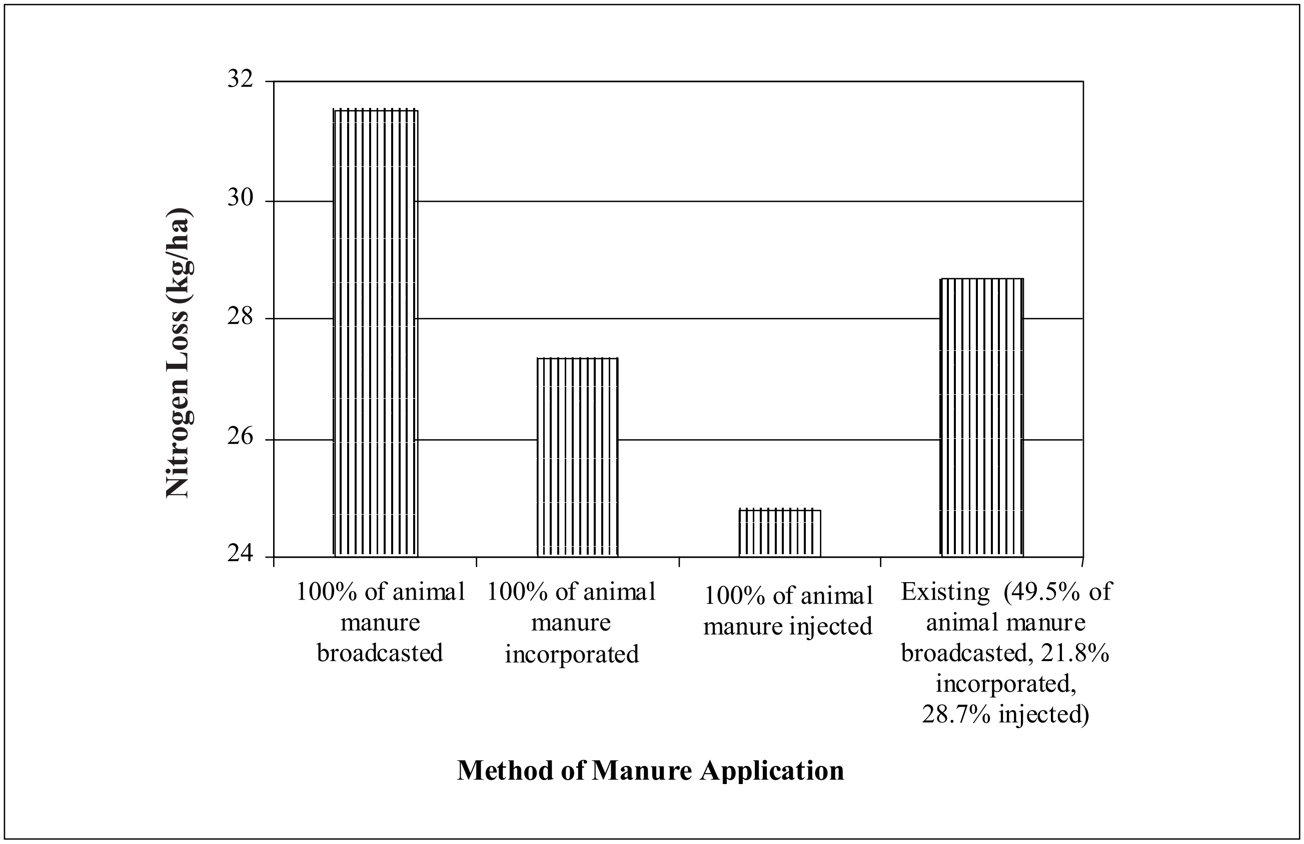

Figure 9. Predicted annual nitrogen losses for changes in the method of animal manure application in the High Island Creek watershed.

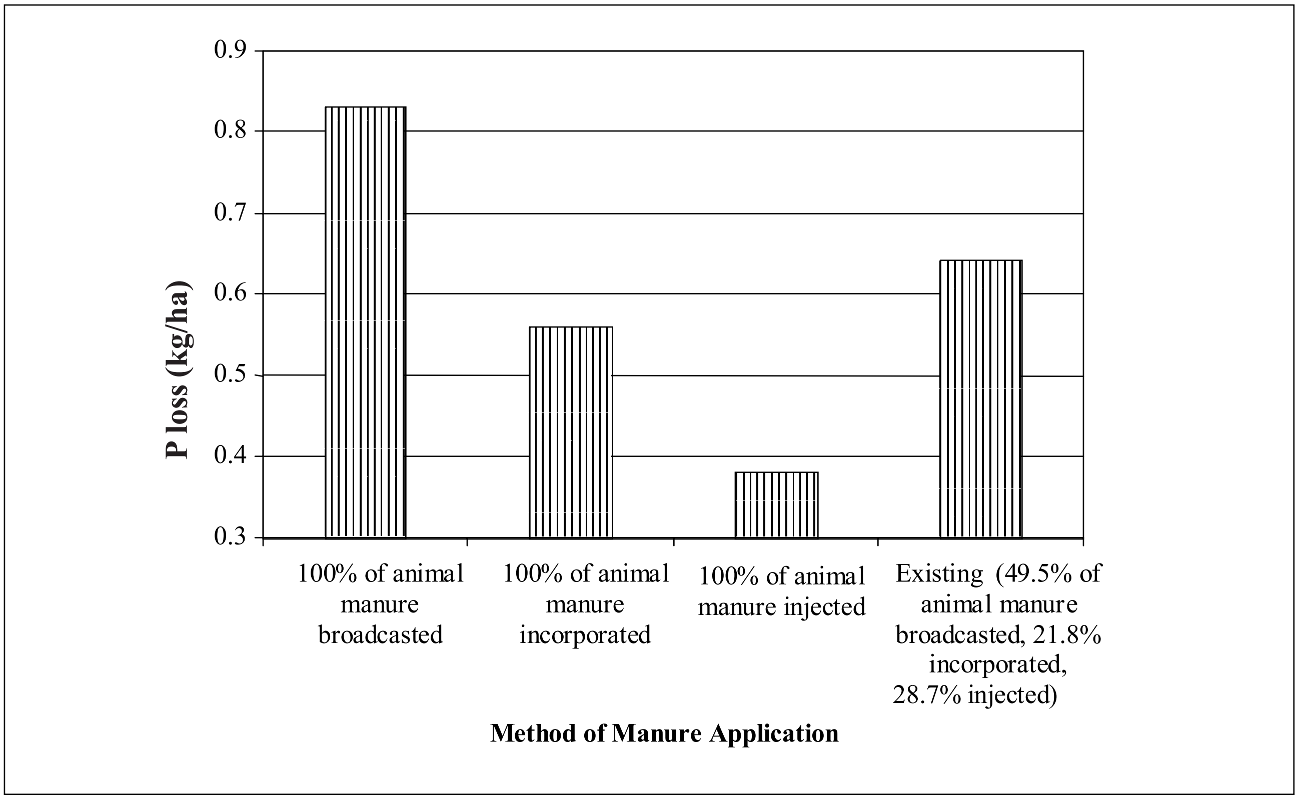

Figure 10. Predicted annual P losses for changes in the method of animal manure application in the High Island Creek watershed.

## ACKNOWLEGMENTS

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