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Evaluation of EPIC for Three Minnesota Cropping Systems

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Abstract
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Keywords
modeling, water quality, crop rotation, tile drainage, nitrate leaching, fertilizer

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Abstract

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Key words: modeling, water quality, crop rotation, tile drainage, nitrate leaching, fertilizer.

EVALUATION OF EPIC FOR THREE MINNESOTA CROPPING SYSTEMS

Introduction

Pressure is growing worldwide to adopt agricultural cropping and management systems that ensure a safe food supply but avoid negative environmental externalities. As a result of this paradigm shift, agricultural policy makers and other decision makers are faced with an increasing need for timely information that can provide the data required to address these concerns. Research results from long-term field and monitoring studies, and applications of simulation models, are both playing key roles in supporting this need. An important contribution of simulation modeling is the ability to evaluate a variety of agricultural policy and management scenarios for many combinations of soils, landscapes, climates, and crops. This is especially useful in the context of integrated modeling systems that can provide both economic and environmental indicators in response to potential changes in agricultural policies.

One tool that has been widely used for agricultural policy analyses is the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1990; Williams, 1995) that consists of the following nine components: weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, tillage, and crop budgets (costs and returns). EPIC was originally developed to assess the long-term impacts of erosion upon soil productivity. However, more recent versions of EPIC have also been used to estimate nutrient losses from fertilizer and manure applications (Edwards et al., 1994; Phillips et al., 1993), climate change impacts on crop yield and soil erosion (Favis-Mortlock et al., 1991; Brown and Rosenberg 1999), edge-of-field leaching and runoff losses from simulated pesticide applications (Williams et al., 1992), and soil carbon sequestration as a function of cropping and management systems (Lee and Phillips, 1993).

EPIC has been adopted within the Resource and Agricultural Policy Systems (RAPS), an integrated modeling system designed to evaluate the economic and environmental impacts of agricultural polices for the north central United States (Babcock et al., 1997; Wu and Babcock, 1999). The primary use of EPIC within RAPS is to provide nitrogen loss, soil erosion, and crop production indicators in response to variations in tillage treatment and crop rotation. Testing and validation of EPIC using measured data obtained at specific sites is a key component of applying EPIC within RAPS; previous validation results at a site in southwest Iowa are described by Chung et al. (1999). The goal of this testing is to improve the accuracy of the environmental indicators estimated by the model for as many combinations of cropping and management systems, soil, climate, and landscape conditions as possible that exist within the RAPS study region (Gassman et al., 1998).

The objective of this study is to evaluate the performance and reliability of EPIC version 5300 in predicting subsurface drain flow (tile flow), nitrate-nitrogen (NO_3-N) loss in tile flow, residual NO_3-N in the soil profile, crop nitrogen uptake, and crop yield with measured data collected from 1990 through 1993 under three conventionally-tilled cropping systems at a site near Lamberton, Minnesota (Randall et al., 1997). Both statistics and graphical displays are used to compare the EPIC predictions with observed values to evaluate the long-term (annual and annual mean) and short-term (monthly) performance of the model.

Field Site Description and Input Data

Field Site

The study site is located at the University of Minnesota Southwest Experiment Station at Lamberton, Minnesota. The field study was conducted at the site from 1988 through 1993 to determine the effect of different cropping systems on aboveground biomass yield and nitrogen uptake, water content and residual NO_3-N in the soil profile, and NO_3-N loss through tile drainage water (Randall et al., 1997). Four cropping systems were established in the spring of 1988 after secondary tillage: continuous corn (Z*ea mays L.*), soybean (*Glycine max* L.)-corn, continuous alfalfa (*Medicago sativa* L.), and alfalfa-grass mixtures established on Conservation Reserve Program (CRP) land.

Each cropping system was replicated three times in a randomized, complete-block design. In this study, EPIC was tested against measured data averaged across three plots each for continuous corn (CC), soybean-corn (SC), and continuous alfalfa (CA).

Subsurface tile drainage systems (perforated, plastic 10-cm tubing) with separate drain outlets were installed in 1972 below 15 individual 13.7 by 15.3-m plots. Tile lines were spaced to simulate 28-m spacing and placed 1.2 m deep. Individual plots were hydrologically isolated to a depth of 1.8 m by trenching and installation of a 12-mil thick plastic sheet.

Soil Inputs

The soil at the experiment site is a moderately well-drained Nicollet clay loam (fine-loamy, mixed, mesic Aquic Haplustoll) that is classified as a hydrologic group B soil. An average slope of 1.5 percent, based on an estimated slope range of 1.0 to 2.0 percent, was assumed and input for each simulation. Soil profile data of up to 2 m was available to describe the Nicollet soil. However, a soil profile depth of 1.2 m was assumed to facilitate comparisons between predicted outputs and tile measurements further discussed in the Simulation Methodology section, which was divided into eight layers (Table 1). Up to 20 physical and chemical soil properties for each soil layer can be input into EPIC; required values include layer depth, bulk density, wilting point, field capacity, percentage sand, percentage silt, pH, and percentage organic carbon. The required soil layer inputs for the Lamberton site are listed in Table 1.

Weather Inputs

EPIC operates on a daily time step and requires daily climatic input data including precipitation, maximum and minimum air temperatures, solar radiation, average relative humidity, and average wind speed. Daily precipitation and maximum and minimum air temperature used for the simulations were measured at a site 700 m from the experimental plots. The other daily weather data were generated within EPIC using monthly weather statistics from the Tracy Power Plant, the nearest Minnesota climatic station available in the EPIC weather generator database. The Hargreaves method was used to estimate the potential evaporation because this method gives realistic results in most cases when wind speed, relative humidity, and solar radiation data are not available (Williams, 1995). Daily values of soil water evaporation and plant transpiration were then computed as a function of potential evaporation and leaf area index in the model.

Management Inputs

The EPIC management component requires information about different operations such as planting, fertilizer applications, tillage, and harvesting. Operation dates and fertilizer amounts entered in the model were based on those reported by Randall et al. (1997). Urea was broadcast applied for corn each spring and incorporated within 24 hours by cultivation. No nitrogen was applied to the CA or to soybeans within the SC cropping system. Nitrogen rates applied to corn within CC and SC were determined as a function of the previous crop (corn or soybean), soil NO_3 concentrations, and a yield goal of 8.8 t/ha.

Initial Condition Assumptions

Data on initial soil NO_3-N concentrations (g/t) for 1990 were estimated using the residual NO_3-N amounts (kg/ha) in the soil profile up to a 1.2 m depth that were measured in October of 1989 and in April of 1990. The estimated values for initial soil NO_3-N concentrations were 5, 3, and 1 g/t for CC, SC, and CA. Data for the initial soil water content, which is defined in EPIC as the soil water content normalized by field capacity of the soil (SW/FC), were not available for January of 1990. Thus it was assumed that an initial soil water content of 0.3 m/m was present for all cropping systems. This is a reasonable assumption because precipitation levels in the previous two years (1988 and 1989) were less than 500 mm, resulting in soil profiles near the wilting point.

Simulation Methodology

The EPIC runoff model simulates surface runoff volumes and peak runoff rates in response to daily precipitation inputs. A modified Soil Conservation Service (SCS) curve number method (Mockus, 1969; Williams, 1995) was used to partition precipitation between surface runoff volume and infiltration. A curve number value with antecedent moisture condition 2 (CN2) of 78 was chosen for CC and SC, reflecting row crops planted in straight rows and good hydrologic conditions under soil group B (Mockus, 1969). A CN2 of 75 was used for CA. The time-varying curve number or retention parameter estimate is re-calculated in the model based on land slope, soil water content and distribution and is adjusted for frozen soil (Williams, 1995).

The original curve number tables consider only soil, land use, and management assuming that the tabulated CN2 value is appropriate for a 5 percent land slope. Thus, the EPIC model uses the following equation for adjusting that value for other slopes.

$$\mathrm{CN2}_S = \frac{1}{3}(\mathrm{CN3} - \mathrm{CN2})[1 - 2\exp(-13.86S)] + \mathrm{CN2} \tag{1}$$

where $\mathrm{CN2}_s$ is the tabulated CN2 value adjusted for slope, CN3 is the curve number for moisture condition 3 (wet), and S is the average slope of the field or watershed. The CN3 is determined as a function of CN2 by the following relationship:

$$\mathrm{CN3} = \mathrm{CN2}\exp[0.00673(100 - \mathrm{CN2})] \tag{2}$$

The assumed 1.5 percent slope at the experiment site is considerably less than the standard 5 percent assumed for the CN2. Two different curve number scenarios were used to evaluate EPIC's ability to replicate the measured data:

(1) using the standard table values of CN2 (Case 1), and

(2) adjusting the CN2 values at planting with a calibration process (Case 2).

Case 2 was included because initial results using Case 1 showed significant underprediction of tile flows, and overprediction of surface runoff for the CC and SC systems. Surface runoff has been observed to be negligible at the site due to the almost flat slope. Thus the CN2 calibration was intended to result in increased simulated drainage flows and reduced surface runoff. The calibration exercise was performed on the basis of matching the total predicted subsurface drainage flows as close as possible to those measured for 1990 to 1993. A CN2 of 65 was ultimately chosen for Case 2 versus the initial value of 78 that was selected for CC and SC from the standard table.

Nitrogen Transport and Transformations

Nitrogen transport and transformation processes simulated in EPIC include NO_3-N in surface runoff, organic-N transport by sediment, NO_3-N leaching, upward NO_3-N movement by soil water evaporation, denitrification, immobilization, mineralization, crop uptake, volatilization of NH_3, and fixation (Williams, 1995). Leguminous N-fixation was simulated for soybean and alfalfa; all other N processes were simulated for all three cropping systems. N-fixation occurs when nitrogen gas (N_2) is transformed via the interaction of microorganisms and a legume crop to form a chemical compound that can be used by that crop. This transformation is simulated in EPIC by accounting for the effects of early nodule development, nodule senescence late in the growth cycle, soil water in the top 30 cm, and soil mineral N in the root zone (Williams, 1995; Bouniols et al., 1991). The impact of these environmental factors upon fixation can be adjusted in EPIC with an empirical parameter denoted as parm(7). In this study, a sensitivity analysis for soybean within the SC system was conducted in which model output for two different parm(7) values (1.0 and 0.3) were compared. Setting parm(7) to 1.0 assumes that the effect of the environmental factors on the simulated fixation process will be fully accounted for. A parm(7) value of 0.25 was used for alfalfa because perennial legumes are not very sensitive to the above-mentioned factors.

The daily N-fixation was computed as a fraction of daily plant N uptake for soybean using the following relationship:

$$WFX_I = FXR_i \cdot UN_I, \quad WFX \le 6.0 \tag{3}$$

where WFX is the amount of daily N-fixation (kg/ha), FXR is the fraction of uptake for day i, and UN is the daily plant N uptake rate (kg/ha). The FXR value was estimated as a function of plant growth stage, soil water content, and soil NO_3-N amount. The soil water content factor reduces N-fixation when the water content in the top 30 cm of the soil profile is less than 85 percent of field capacity. The amount of NO_3-N in the root zone reduces N-fixation when it is greater than 100 $kgha^{-1}m^{-1}$ and prohibits N-fixation when it is greater than 300 $kgha^{-1}m^{-1}$. These bounds are based on measurements by Bouniols et al. (1985) as cited by Bouniols et al. (1991).

Model Output Comparisons with Tile Measurements

Applications of EPIC for simulating tile drainage dynamics have been very limited. This is likely due in part to the simplistic way in which tile drainage can be simulated in the model, which is performed as function of lateral subsurface flow and the time required for the drainage system to reduce plant stress (Williams 1995). Sabbagh et al. (1991) incorporated components of the DRAINMOD model into a modified version of EPIC called EPIC-WT to provide a more rigorous methodology for simulating drainage flow. However, this approach is more complex than necessary for many applications and is not used in EPIC 5300 or other standard versions of EPIC. For this study, it was assumed that the leached amounts predicted by EPIC at 1.2 m would be equivalent to the measurements at the tile line outlets for the monthly and annual comparisons. This is a reasonable assumption for the monthly and annual comparisons because the experimental plots (0.02 ha) and the tile line spacings (28.5 m) are small enough to carry the flow that enters the tile lines to the tile line outlets within several days. This assumption does ignore the possibility of water and nitrate losses that leach below the tile line depth. But these losses are likely minor at the Lamberton site.

Model Evaluation Methods

Statistical analyses were conducted to compare the observed and simulated values. The statistics used for the comparisons included the percentage error (E), modeling efficiency (EF), r-square (r^2), and paired t-test. The E, EF, and r^2 statistics were formulated as

$$E = \frac{(P_i - O_i)}{O_i} \times 100 \tag{4}$$

$$EF = [\sum_{i=1}^{n}(O_i - O_m)^2 - \sum_{i=1}^{n}(P_i - O_i)^2] / \sum_{i=1}^{n}(O_i - O_m)^2 \tag{5}$$

$$r^2 = \left[\frac{n(\sum_{i=1}^{n} O_i P_i) - (\sum_{i=1}^{n} O_i)(\sum_{i=1}^{n} P_i)}{(n\sum_{i=1}^{n} O_i^2 - (\sum_{i=1}^{n} O_i)^2)(n\sum_{i=1}^{n} P_i^2 - (\sum_{i=1}^{n} P_i)^2)} \right]^2 \tag{6}$$

where O_i and P_i are the observed and predicted values at each comparison point i, n is the number of observed and predicted values that are being compared, and O_m is the mean of the observed values.

The E value was mainly used to assess the error associated with the long-term (annual mean) performance of EPIC, while the other statistics were used for short-term (monthly) assessment. The EF describes the proportion of the variance of the observed values over time that are accounted for by the EPIC model, where the variance is relative to the mean value of the observed data (Nash and Sutcliffe, 1970; Martin et al., 1993). The EF can vary from 1 to negative infinity; an EF value of 1 indicates that the model predictions are exactly the same as the observed values. If EF is equal to or less than 0, it means that the observed mean value is as good an overall predictor as the model (or a better predictor of observed values than the model). The r^2 value indicates how accurately the model tracks the variation of observed values. The r^2 value can range from 0 to 1, where an r^2 value of 1 indicates that the model can completely explain the variations of the observed indicators. The main difference between the EF and the r^2 value is that the latter cannot interpret the model performance in replicating individual observed values while the EF can.

The null hypothesis (H_o) of the paired t-test between the observed and simulated monthly values was $\mu_d = \mu_o - \mu_s = 0$, in which μ_d is the difference between the mean values of the observed (μ_o) and simulated (μ_s) indicators. The alternative hypothesis (H_A) was $\mu_d \neq 0$. Thus, the acceptance of the null hypothesis indicates that the EPIC-predicted mean value is statistically the same as the observed one. The H_o was rejected when the significance value level (P-value) was less than half of a specific level of significance ($\alpha/2$). A significance level of $\alpha = 0.05$ (95 percent confidence level) was used for this study.

Explicit standards for evaluating model performance with statistics such as the EF and r^2 are not well established, because the judgment of model results is highly dependent on the purpose of the model application. For this study, the target criteria used by Chung et al. (1999) were used to judge if the model results were satisfactory; i.e., EF > 0.3, r^2 > 0.5, and P-value > 0.025.

Results and Discussion

Case 1: Tile Flow

Monthly time-series comparisons between the observed and simulated tile flows are presented in Figure 1. The EPIC simulated tile flows followed the observed trends reasonably well under all crop management systems, especially for CC and SC. Small amounts of tile flow occurred in 1990, a year of normal precipitation, which was predicted well by the model using an initial soil water content (SW/FC) of 0.3. Following the two consecutive drought years (1988 and 1989), most of the infiltrated water during storm events in 1990 recharged the soil pores. However, the model consistently under-predicted the peak tile flows that occurred during the later spring and summer months in 1991 and 1993 under all cropping systems. In particular, the predicted peak tile flows were half of the observed values for all cropping systems in 1993 when precipitation was 60 percent greater than normal. The errors may be due in part to:

(1) the daily time step, and

(2) the lack of a preferential flow component in the EPIC model.

Preferential flow can occur through macropores after ponding during heavy storm events, resulting in quick movement of flow and nutrients from the soil surface to the bottom of root zone (Singh and Kanwar, 1995). This process cannot be simulated in EPIC.

Table 2 shows the observed and simulated annual tile flows for different cropping systems. Observed values indicate that the tile flow was influenced greatly by the cropping systems, i.e., greater levels of tile flow occurred under row-crops compared to alfalfa, while the simulated results show much less influence. According to the annual mean values, the observed drain flows under CC and SC are 85 percent and 100 percent greater than that under CA. However, only 47 percent and 55 percent greater drain flows were predicted by EPIC for the corresponding simulated scenarios. This error may be partly attributed to the unrealistic estimation of the curve number at this site, as well as the possibility of preferential flow. EPIC uses an empirical equation (Eq. 1) to estimate CN2 as a function of slope, which may have not accurately captured the effect of the very flat landscape and resulting negligible surface runoff.

Case 1: NO_3-N Loss via Tile Flow

Time-series comparisons between the observed and simulated monthly values of leached nitrogen are shown in Figure 2. Simulated values followed the observed trends reasonably well under CC and SC, but large deviations occurred for CA in 1990 and 1991. The EPIC model adequately replicated the effects of different cropping systems on the amount of nitrogen loss, i.e., greater nitrogen loss under row cropping systems compared to alfalfa. As noted for the tile flow comparisons, the model consistently under-predicted the amount of NO_3-N loss that occurred during the peak time periods under all cropping systems. This was at least partially a function of the under-predicted tile flows.

The model predictions in 1992 and 1993 were improved by using a parm(7) value of 0.3 for soybean within SC, compared to the results obtained with parm(7) set equal to 1. With the lower parm(7) value, the nitrogen fixation process was less restricted by the environmental conditions such as soil NO_3-N amount, water content, and crop growth stage, which resulted in greater amounts of leachable residual NO_3-N in the soil profile in late October 1991 and April 1992.

Observed and simulated annual NO_3-N tile losses under different cropping systems are listed in Table 3. The model performance varied greatly for the different simulated crop management systems. Based on the annual mean values, the model reasonably simulated the nitrogen loss for CC, but considerably under-predicted NO_3-N losses for the SC system. For CA, the predicted NO_3-N losses in 1990 and 1991 were much greater than the observed values. This can in part be attributed to the low magnitude of NO_3-N loss that occurred from the system. Overall, the model accurately captured the effect of different cropping systems on the nitrogen loss, i.e., much less NO_3-N losses under perennial crop rotation compared to continuous row cropping systems.

Case 1: Residual NO_3-N in Soil Profile

Observed and simulated soil profile residual NO_3-N amounts in April and late October of each year are listed in Tables 4 and 5, respectively. Although the model performance varied among years and among cropping systems, the model consistently simulated lower residual NO_3-N under CA than the other row crop rotations, which was consistent with the relative observed trends. The highest residual soil NO_3-N levels occurred in April of 1990 after the second consecutive dry year, which was accurately reflected by the model predictions because of the initial soil NO_3-N concentration estimates.

The use of parm(7) = 0.3 for the SC system greatly improved the model predictions of the soil residual NO_3-N in late October due to the greater nitrogen fixation simulated during the growing season. However, the model consistently over-predicted the SC residual NO_3-N in April. This is primarily attributed to errors in simulating complicated nitrogen transformation processes such as immobilization, nitrification, and denitrification that occur outside of the growing season. The model considerably under-predicted the CA residual NO_3-N in late October, but did predict the residual April NO_3-N well in 1990.

Case 1: Nitrogen Uptake and Crop Yield

Tables 6 and 7 list the observed and simulated nitrogen uptakes and crop yields, respectively. The model well predicted the amounts of nitrogen uptake and crop yield for all cropping systems, and captured the effect of different crops; i.e., the estimated nitrogen uptake was highest for alfalfa, followed by soybean, and was lowest for corn. The extended growing season and rooting depth of alfalfa provided a greater opportunity for season-long water use and nitrogen uptake compared to row crops, which was reflected in the EPIC estimates. The model over-predicted corn and alfalfa yield in 1993 because it could not adequately simulate the impacts of prolonged periods of saturated soil and cooler than normal temperatures that occurred during that year.

Case 2: Tile Flow

Monthly comparisons between the observed and simulated tile flows following curve number calibration are presented in Figure 3. The model performance in predicting peak tile drain flows was considerably improved by adjusting the CN2s after planting. The results support the hypothesis established for the Case 2 runs in this study that the curve number estimated as a function of slope in the EPIC model is not sufficient for taking into account the flat feature of the landscape in this site.

Table 8 shows the observed and simulated annual tile flows after CN2 calibration. The simulated CC and SC drainage flows were considerably improved, following the CN2 adjustment, resulting in four-year predicted mean values that were 8.5 and 12.2 percent below the CC and SC observed means. The simulated CC and SC drain flow averages were 98 percent and 106 percent greater than the predicted CA mean, which compared much more favorably with the corresponding observed differences of 85 and 102 percent.

Case 2: NO_3-N Fate and Crop Yield

Observed and simulated monthly time-series of NO_3-N loss in tile flow are shown in Figure 4. Definite improvement in the predicted CC NO_3-N losses occurred as a result of the calibrated CN2. Some improvement also resulted in the estimated SC losses with parm(7) set at 0.3 for the CN II scenario, but essentially no change was predicted following CN2 calibration with parm(7) set at 1.0. The observed and predicted annual tile flow NO_3-N losses are listed in Table 9. The estimated four-year mean CC NO_3-N loss was virtually identical to the measured mean. The predicted SC annual mean NO_3-N loss (with parm(7) equal to 0.3) was under-predicted by 24 percent, a definite improvement over the 41 percent under-prediction that occurred for the uncalibrated CN2 scenario.

For the most part, only slight changes in the April and October residual NO_3-N soil levels were predicted by EPIC following the curve number adjustment. The greatest changes were predicted for the CC April and October residual values, which decreased 10 and 16 percent relative to the Case 1 CN2 scenario mean annual residual values.

Very little change was predicted in crop yields between the Case 1 and II CN2 scenarios. This is because the hydrologic change effect (increased or decreased infiltration) on the simulated nitrogen uptake and crop yield is not significant as long as the soil water content and soil nitrogen level are not limiting. In EPIC, crop growth and yield are restricted because of constraints imposed by the plant environment such as water, nutrients, temperature, aeration, and radiation.

Model Evaluation

The long-term (annual and annual mean) and short-term (monthly) predictions were further evaluated using the E, EF, and r^2 statistics. Table 10 presents the percent errors (E) between the observed and simulated four-year mean values for each variable used to assess the long-term performance of EPIC model. Overall, the EPIC CC predictions were the most accurate. This was especially true for the CN2 II scenario, where the E values were all less than the target criteria of 20 percent except for the late October soil residual NO_3-N. The SC (Case 2 CN2 scenario) and CA drain flow, nitrogen uptake, and crop yield errors were also under the target level of 20 percent. However, large errors resulted between the measured and predicted SC and CA nitrogen loss and residual indicators. This could be due in part to the complicated nitrogen transformation processes that occur for leguminous crops, such as N fixation, which may not be adequately simulated by EPIC.

The r^2, EF, and t-test statistics used to assess the monthly (short-term) EPIC estimates are shown in Table 11. Very good performance is shown for the EPIC CC and SC monthly tile flow and N loss predictions. All of the statistics satisfied the target criteria, except for the SC NO_3-N loss t-test value for which the null hypothesis was rejected at the 95 percent confidence level. This was primarily due to the considerable under-prediction of the NO_3-N losses during the peak drainage flow time periods. However, the EPIC SC simulation clearly responded to the peak rainfall events and tracked the trend of observed NO_3-N losses as indicated by the high r^2 and EF values.

The CA monthly statistics, on the other hand, were generally poor. The model was unable to consistently track the observed monthly drainage flows and N losses. The exact reasons for the weaker EPIC CA results are unclear, although they could be a result of more complicated growth processes such as an extended growing season, frequent harvests, and a deeper rooting system. Randall et al. (1997) report that alfalfa extracted water and NO_3-N from depths of up to 3 m at the Lamberton site. This is considerably deeper than the maximum depth of 1.2 m that the alfalfa roots could extend in the EPIC simulations. Despite the weak monthly predictions, the predicted mean annual drain volumes and N losses were definitely of the same magnitude as the corresponding observed values, which were quite low relative to CC and SC. This is of ultimate concern for most regional modeling applications in which projections of likely long-term trends are the primary outputs.

Conclusions

The relative impacts of the three cropping systems upon the average annual tile flows and associated NO_3-N losses were correctly predicted by EPIC under the Case 1 scenario. However, the average annual tile drainage flows were underestimated by over 30 percent for CC and SC, which in turn led to an underestimation of the NO_3-N losses. The SC results were weaker than those obtained for CC; the observed average annual SC NO_3-N loss was only 12 percent less than the corresponding measured CC NO_3-N loss but the estimated SC NO_3-N losses were 59 (parm(7) = 0.1) and 48 percent (parm (7) = 0.3 percent) below the measured CC value. The predicted annual average CA tile drainage flows were about 14 percent below the measured levels, but the simulated NO_3-N losses were almost 100 percent greater than those measured. However, this overprediction of NO_3-N loss for the CA system must be considered within the context of the general magnitude of the CA NO_3-N losses, which are quite small relative to the CC and SC systems. In other words, EPIC was well able to reflect the minimal NO_3-N leaching impacts associated with CA.

The Case 1 monthly tile drainage flows and NO_3-N losses for CC and SC were captured very well by EPIC as evidenced by the generally strong r^2 and EF values that ranged from 0.71 to 0.91 for tile flow and 0.43 to 0.69 for N loss. Adjusting parm(7) from 1.0 to 0.3 resulted in improved r^2 and EF values for the SC system. The CA monthly predictions were much weaker, with r^2 and EF ranging from 0.19 to 0.27 (EF = -.26 for N loss). As noted previously, it is likely that EPIC has trouble capturing all the effects of the CA growth processes. While improvement of the CA monthly results are desirable, it is again clear that the model is reflecting the proper magnitudes of NO_3-N loss under CA which is the most important indicator for many integrated regional modeling systems such as RAPS. Under-prediction of peak tile flows and NO_3-N losses occurred for all three systems, which is the primary reason that the CC and SC average annual tile flows and NO_3-N losses were under-predicted.

Calibration of the CN2 for CC and SC (Case 2) resulted in definite improvements in the average annual tile drainage flow predictions. The predicted CC NO_3-N loss was almost identical to that observed; SC NO_3-N loss was only improved when parm(7) was set at 0.3. For the most part, predictions of the monthly tile flows and NO_3-N losses did not improve, except for the CC and SC EF values. The estimated Case 2 CC and SC peak drainage flows are closer to those observed as compared to the Case 1 results in Figure 1. Some improvement is also noticeable in the peak SC NO_3-N losses when parm(7) was set at 0.3.

The impacts of the different cropping systems on crop NO_3-N uptake and crop yield were accurately predicted by EPIC. The % errors ranged from 6.9 to 13.7, which were all below the target level of 20 percent. April and October soil residual NO_3-N levels were generally not well predicted, with the majority of the E values deviating from 25 to 84 percent of those measured. Only minor changes occurred between the Case 1 and Case 2 CN2 scenarios for the simulated crop N uptake, crop yield, and soil residual NO_3-N values.

The simulation results indicate that EPIC can generally replicate the long-term impacts of CC, SC, and CA on tile flow and NO_3-N losses. The fact that improved results occurred when the CN2 and/or parm(7) values were adjusted revealed the uncertainty regarding the best choice of initial values for these inputs. The ability to discern when such calibration would be useful can be difficult, especially when applying a model such as EPIC at a regional scale.

In general, using the standard table values is the best choice for CN2 selection unless specific information is available that warrants an adjustment such as the very level slope present at the Lamberton site, or the presence of crop residues under no- or reduced-tillage conditions that will result in the need to reduce the CN2 value (Rawls and Richardson, 1983; Rawls et al., 1980; Chung et al., 1999). The choice of parm(7) is a more difficult question than the CN2 selection. A parm(7) value of 1.0 is recommended in the EPIC Users Manual (Mitchell et al., 1996) for soybeans. However, improved results were clearly obtained when parm(7) was set at 0.3 for this study.

These CN2 and parm(7) questions underscore the need for additional testing of the EPIC modified curve number and legume N fixation routines. Specifically, insight is needed to: (1) determine if the EPIC curve number approach should be further refined to better reflect expected surface runoff volumes for level or nearly level conditions, (2) determine what the optimal choice of parm(7) is under a wide range of conditions, and (3) determine if the legume N fixation routine and/or other portions of the EPIC nitrogen cycling submodel need to be modified to provide better results. The latter may also provide further insight into the weakness that EPIC had in replicating the soil residual NO_3-N levels in this study.

Table 1. Properties of the Nicollet clay loam used for the Lamberton, MN, simulations

	Soil layer number							
Soil properties	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Lower boundary (m)	0.01	0.15	0.25	0.51	0.66	0.89	1.07	1.20
Bulk density (Mg/m^3)	1.15	1.15	1.25	1.30	1.35	1.35	1.45	1.45
Wilting point (m^3/m^3)	0.14	0.14	0.14	0.12	0.13	0.13	0.11	0.11
Field capacity (m^3/m^3)	0.27	0.27	0.26	0.22	0.24	0.24	0.24	0.24
Sand content (%)	39.1	39.1	33.8	42.3	41.8	42.2	40.1	40.1
Silt content (%)	34.3	34.3	30.8	30.4	29.1	31.0	36.9	36.9
Soil pH	6.1	6.1	6.2	6.4	6.8	7.0	7.8	7.8
Organic carbon (%)	2.55	2.55	1.80	0.80	0.42	0.38	0.0	0.0

Table 2. Observed and simulated annual subsurface drain flows (mm) for three different cropping systems at Lamberton, MN

		Tile flow					
	Rainfall	**CC**†		**SC**‡		**CA**§	
Year	(mm)	Observed	Simulated	Observed	Simulated	Observed	Simulated
1	623	20	37	19	27	0.0	17
1	812	179	119	220	166	40	91
1	766	132	96	124	72	55	31
1	102	443	275	480	293	323	221
M	807	193	132	211	139	105	90

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.

Table 3. Observed and simulated annual NO_3-N loss (kg/ha) for different cropping systems at Lamberton, MN

	NO_3-N loss (kg/ha)						
	CC†		**SC‡**			**CA§**	
Year	Observed	Simulated	Observed	Simulated#	Simulated*	Observed	Simulated
1990	0	19	0	12	12	0.0	4.1
1991	70	55	81	62	62	1.3	3.2
1992	50	37	32	2	15	2.1	2.7
1993	84	71	67	10	17	3.5	3.8
Mean	51	46	45	22	27	1.7	3.4

†Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# Simulated results with N-fixation sensitivity parameter, parm(7) = 1.0.
* Simulated results with N-fixation sensitivity parameter, parm(7) = 0.3.

Table 4. Observed and simulated residual NO_3-N (kg/ha) in soil profile in April of each year at Lamberton, MN

	Residual soil NO_3-N (kg/ha)						
Year	**CC†**		**SC‡**			**CA§**	
	Observed	Simulated	Observed	Simulated#	Simulated*	Observed	Simulated
1990	177	170	75	137	137	47.0	50.1
1991	115	206	73	158	158	N.D.∞	1.8
1992	86	164	61	34	108	N.D.	4.8
1993	91	111	40	30	57	N.D	11.3
Mean	117	163	62	90	115	-¶	17.0

†Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# Simulated results with N-fixation sensitivity parameter, parm(7) = 1.0.
* Simulated results with N-fixation sensitivity parameter, parm(7) = 0.3.
∞ Observed residual soil NO_3-N values were not determined in 1991-93.
¶ Observed mean is not known.

Table 5. Observed and simulated residual NO_3-N (kg/ha) in soil profile in late October of each year at Lamberton, MN

	Residual soil NO_3-N (kg/ha)						
	CC†		**SC‡**			**CA§**	
Year	Observed	Simulated	Observed	Simulated#	Simulated*	Observed	Simulated
1990	180	181	169	128	128	101	2
1991	94	148	63	14	67	18	2
1992	107	99	66	14	21	18	16
1993	70	50	59	12	38	28	33
Mean	113	120	89	42	63	41	13

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# Simulated results with N-fixation sensitivity parameter, parm(7) = 1.0.
* Simulated results with N-fixation sensitivity parameter, parm(7) = 0.3.

Table 6. Observed and simulated nitrogen uptake (kg/ha) at Lamberton, MN

	Nitrogen uptake (kg/ha)						
	CC†		**SC‡**			**CA§**	
Year	Observed	Simulated	Observed	Simulated#	Simulated*	Observed	Simulated
1990	106	110	119	108	108	375	280
1991	136	126	227	169	175	380	270
1992	157	165	122	157	164	344	346
1993	108	141	187	145	151	272	319
Mean	127	136	164	145	150	342	304

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# Simulated results with N-fixation sensitivity parameter, parm(7) = 1.0.
* Simulated results with N-fixation sensitivity parameter, parm(7) = 0.3.

Table 7. Observed and simulated crop yield (t/ha) at Lamberton, MN for 1990-1993

	Crop yield (t/ha)						
	Rainfall	**CC**†		**SC**‡		**CA**§	
Year	(mm)	Observed	Simulated	Observed	Simulated	Observed	Simulated
1990	623	6.4	6.0	6.5	6.0	11.6	11.9
1991	812	7.8	7.0	2.5	2.6	11.9	11.8
1992	766	8.3	9.1	7.1	8.9	11.5	14.5
1993	1028	5.2	7.8	2.0	2.2	10.3	13.3
Mean	807	6.9	7.5	4.5	4.9	11.3	12.9

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.

Table 8. Observed and simulated annual tile flow (mm) for different cropping systems at Lamberton, MN after CN2 calibration

	Tile flow (mm)						
	Rainfall	**CC**†		**SC**‡		**CA**§	
Year	(mm)	Observed	Simulated	Observed	Simulated	Observed	Simulated
1990	623	20	47	19	37	0	17
1991	812	179	162	220	212	40	87
1992	766	132	153	124	127	55	32
1993	1028	443	345	480	364	323	221
Mean	807	193	177	211	185	105	90

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.

Table 9. Observed and simulated annual NO_3-N loss (kg/ha) for different cropping systems at Lamberton, MN after CN_2 calibration

Year	**NO$_3$-N loss (kg/ha)**						
	CCR†		**SCR**‡			**CA**§	
	Observed	Simulated	Observed	Simulated#	Simulated*	Observed	Simulated
1990	0	25	0	12	16	0.0	4.1
1991	70	70	81	52	74	1.3	3.2
1992	50	48	32	4	19	2.1	2.8
1993	84	62	67	15	27	3.5	4.1
Mean	51	51	45	21	34	1.7	3.6

† Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# Simulated results with N-fixation sensitivity parameter, parm(7) = 1.0.
* Simulated results with N-fixation sensitivity parameter, parm(7) = 0.3.

Table 10. Percent errors (%) between EPIC long-term (4-year means) predictions and observed values over 1990-1993 at Lamberton, MN.

	CC[†]		SC[‡]		CA[§]
Indicator	**CASE 1[#]**	**CASE 2[*]**	**CASE 1[#]**	**CASE 2[*]**	
Tile flow	-31.7 [∞]	-8.6	-33.8	-12.2	-14.1
NO_3-N loss	-10.5	0.6	-52.2 (-41.2)	-54.1 (-24.3)	98.7
Residual NO_3-N in April	38.7	24.9	44.2 (84.3)	37.3 (71.4)	44.5
Residual NO_3-N in October	6.1	-10.7	-53.0 (-28.9)	-54.5 (-33.6)	-68.1
N-uptake by crop	6.9	7.5	-11.6 (-8.7)	-12.1 (-8.7)	-11.6
Crop yield	7.9	7.9	8.8	8.8	13.7

[†] Continuous corn.
[‡] Soybean-corn (corn was planted in 1990).
[§] Continuous alfalfa.
[#] CASE 1 : CN2 was not calibrated.
[*] CASE 2: CN2 was calibrated (adjusted from 78 to 65 after planting) for CC and SC to better reflect the observed average annual tile flow for 1990-93.
[∞] Underlined value is outside of target criteria (E = 20%).
[¶] Values outside and inside the parentheses represent results obtained with parm(7) set to 1.0 and 0.3.

Table 11. Statistics used to assess EPIC short-term (monthly) predictions relative to observed values over 1990-1993 at Lamberton, MN

Indicator	Statistics	CC†		SC‡		CA§
		CASE 1#	CASE 2*	CASE 1#	CASE 2*	
Drain flow	r^2	0.86	0.88	0.91	0.90	0.27∞
	EF	0.71	0.83	0.73	0.84	0.27
	t-test	0.092	0.557	0.068	0.407	0.704
NO_3-N loss	r^2	0.69	0.65	0.52 (0.62)¶	0.56 (0.65)	0.19
	EF	0.68	0.65	0.43 (0.54)	0.42 (0.63)	-0.26
	t-test	0.427	0.895	0.024 (0.024)	0.020 (0.020)	0.020

†Continuous corn.
‡ Soybean-corn (corn was planted in 1990).
§ Continuous alfalfa.
# CASE 1 : CN2 was not calibrated.
* CASE 2: CN2 was calibrated (adjusted from 78 to 65 after planting) for CCR and SCR to better reflect the observed average annual tile flow for 1990-93.
∞ Underlined value is outside of target criteria (r^2 = 0.5, EF = 0.3, and P-value = 0.025).
¶ Values outside and inside the parentheses represent results obtained with parm(7) set to 1.0 and 0.3.

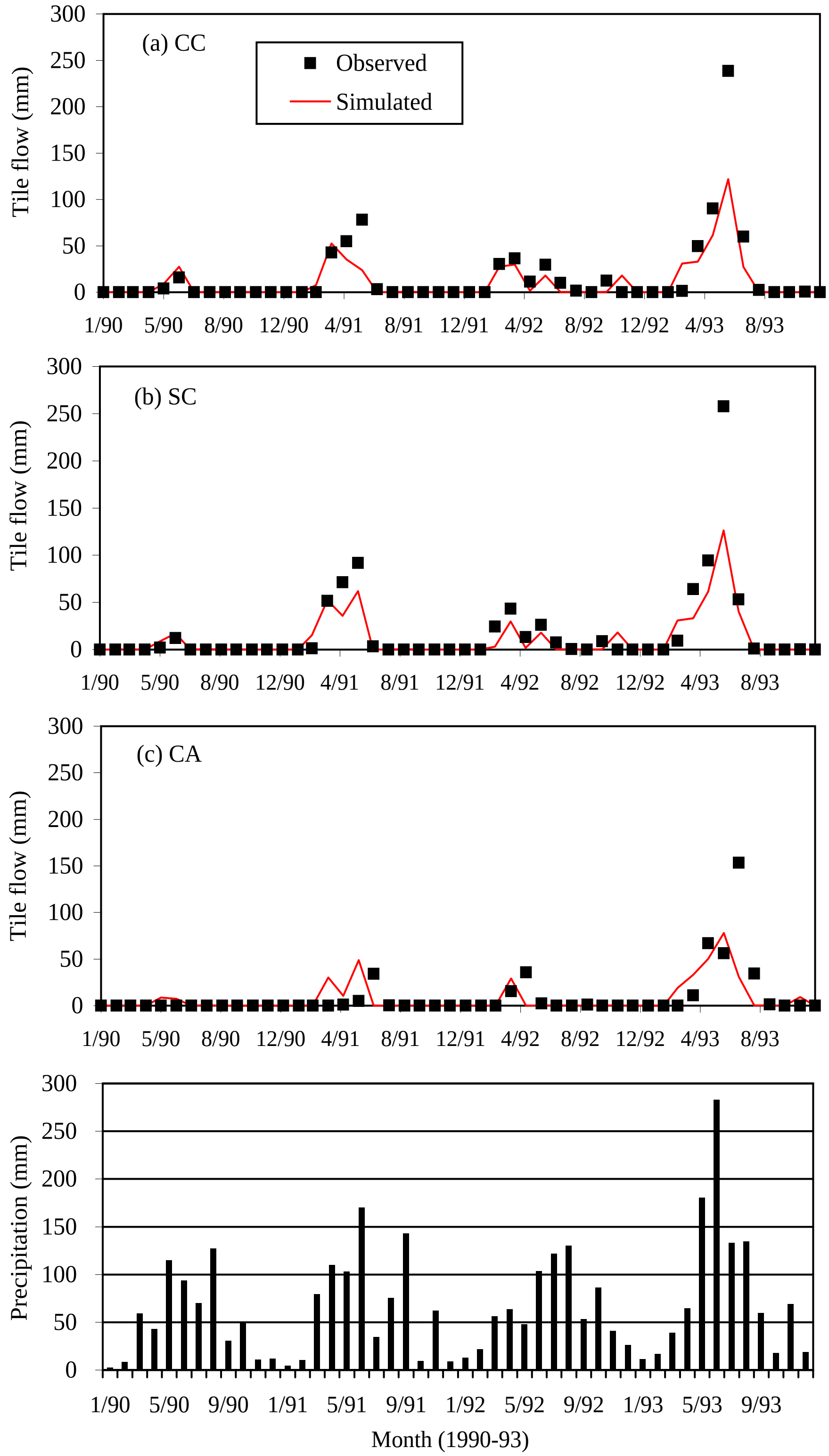

Figure 1. Observed and simulated monthly tile flows over 1990-93 at Lamberton, MN, prior to curve number calibration (CN2=78), for (a) CC, (b) SC, and (c) CA.

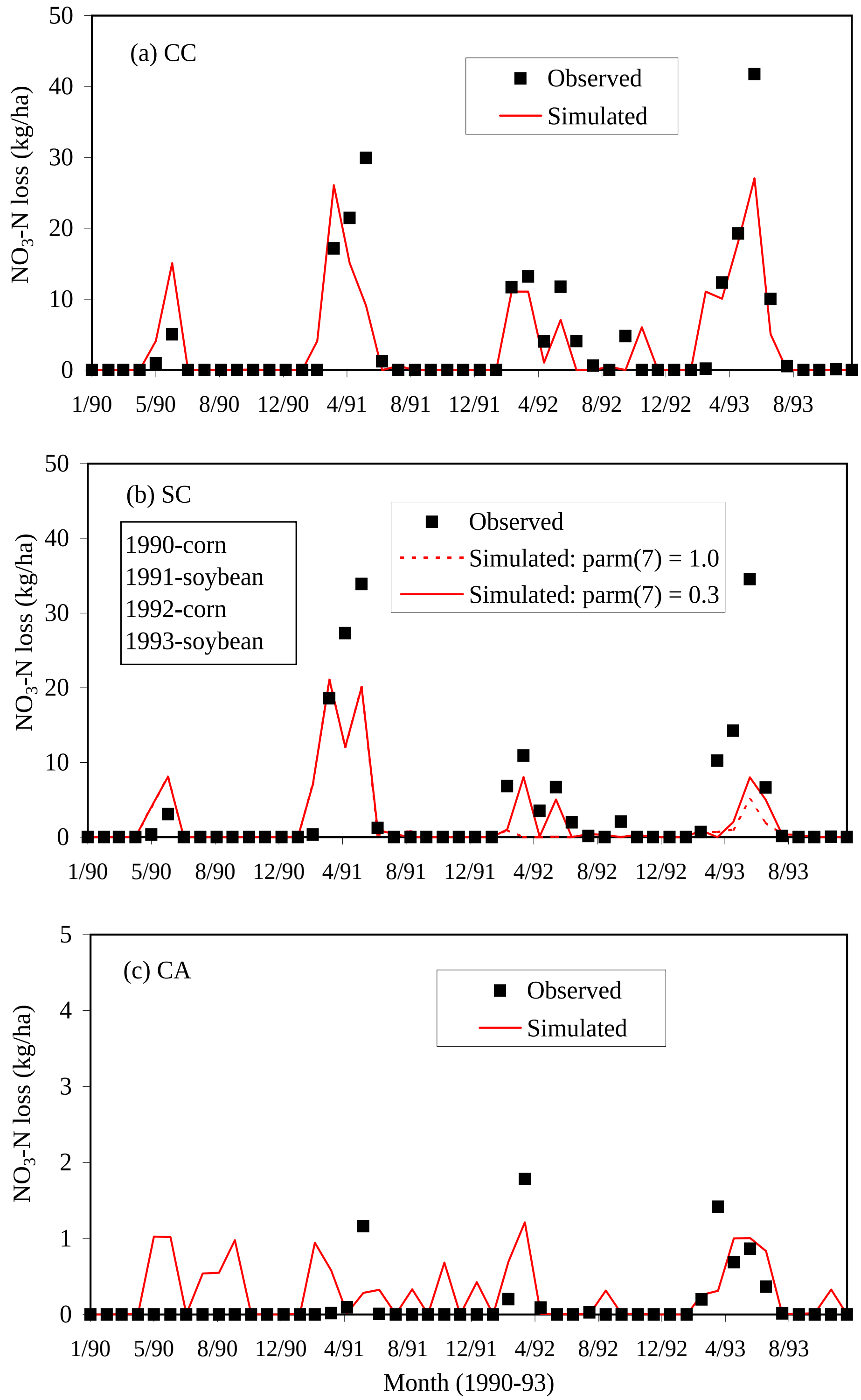

Figure 2. Observed and simulated monthly NO_3-N losses over 1990-93 at Lamberton, MN, prior to curve number calibration (CN2=78), for (a) CC, (b) SC, and (c) CA

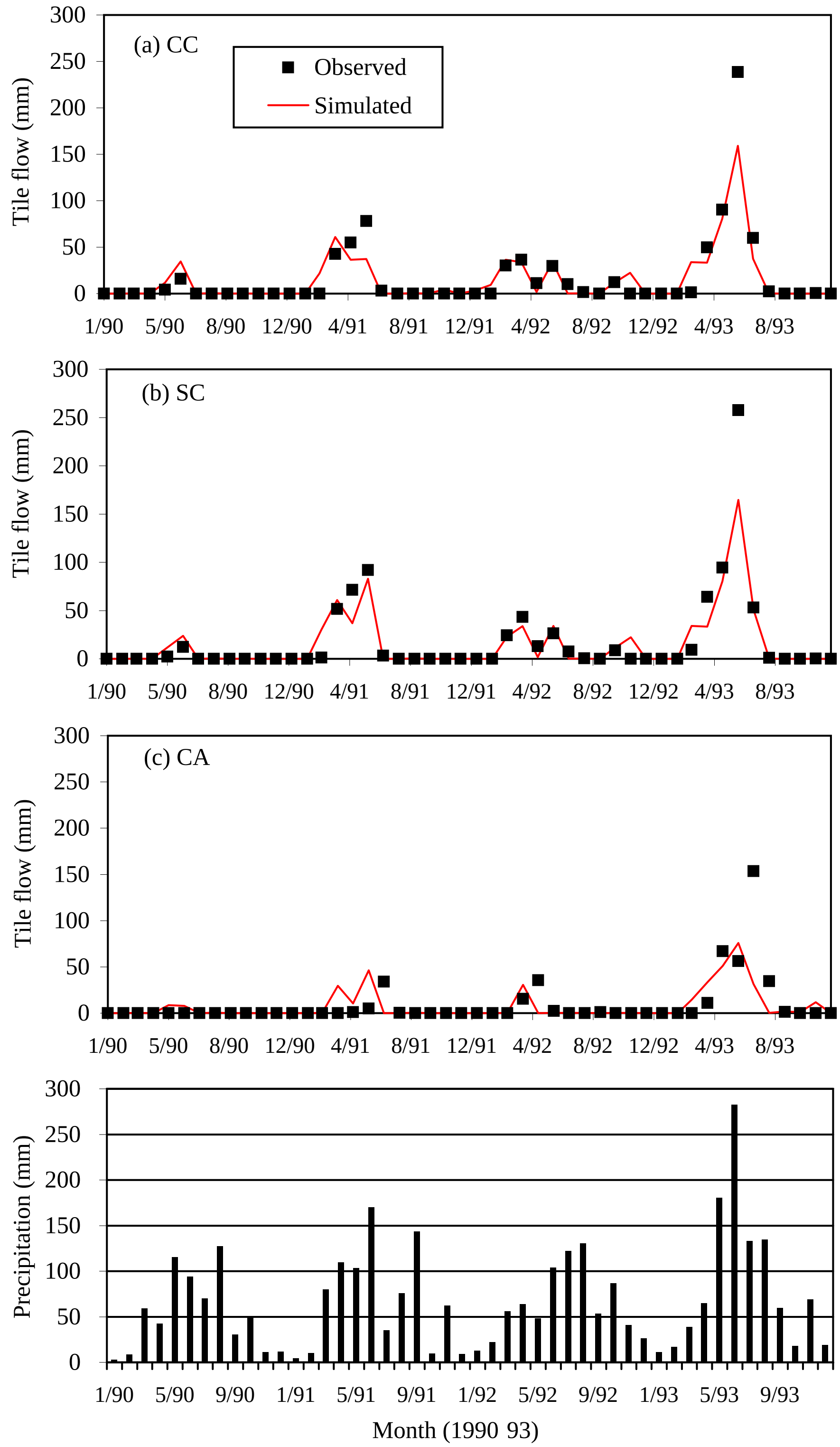

Figure 3. Observed and simulated monthly tile flows over 1990-93 at Lamberton, MN, after curve number calibration (CN2=65), for (a) CC, (b) SC, and (c) CA

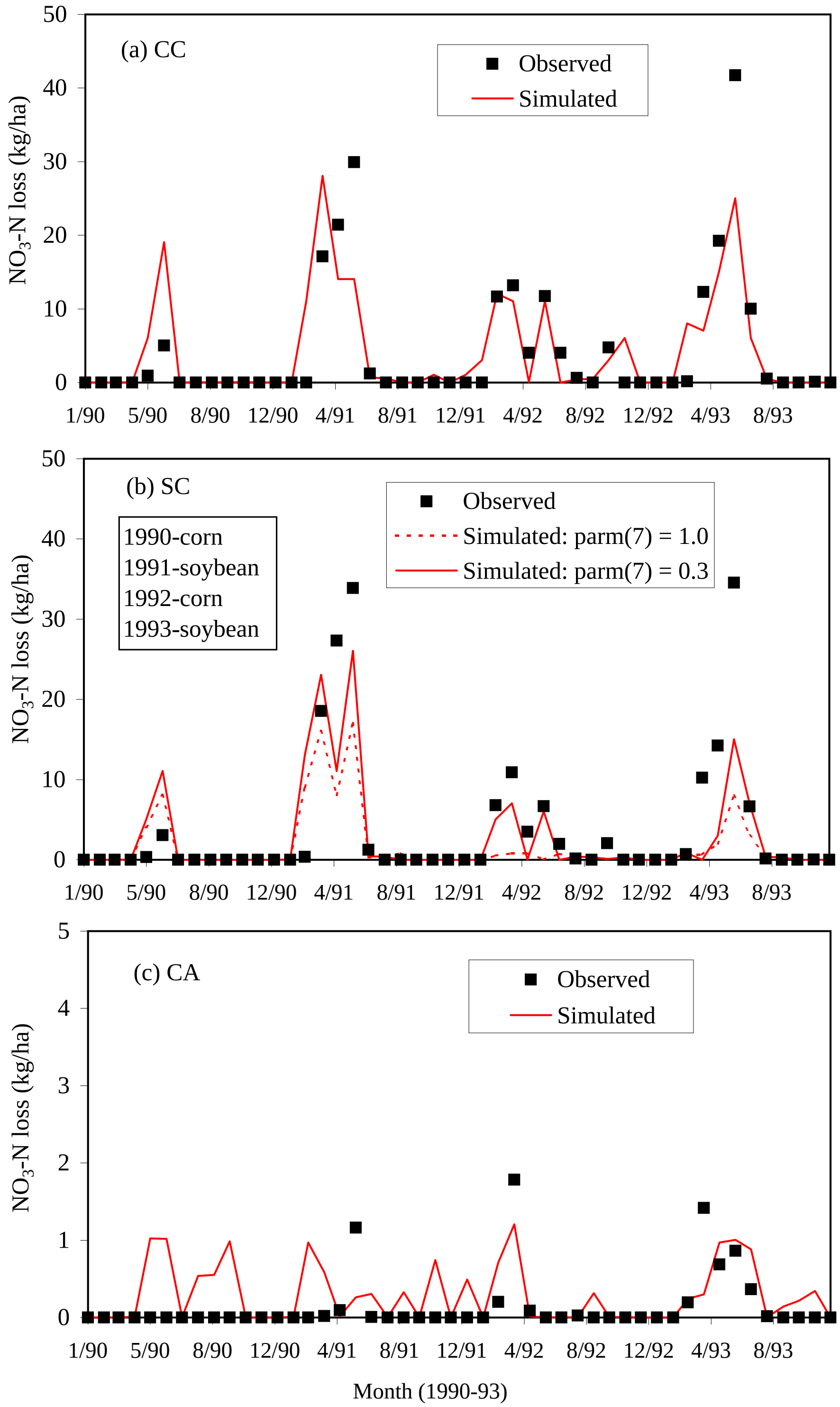

Figure 4. Observed and simulated monthly NO_3-N losses over 1990-93 at Lamberton, MN, after curve number calibration (CN2=65), for (a) CC, (b) SC, and (c) CA

References

Babcock, B. A., J. Wu, T. Campbell, P. W. Gassman, P. D. Mitchell, T. Otake, M. Siemers, T. M. Hurley. 1997. RAPS 1997: Agricultural and environmental outlook: Resource and agricultural policy systems. Center for Agricultural and Rural Development, Iowa State University, Ames, IA.

Bouniols, A., J. Puech, A. Chalamet, and A. M. Mondies. 1985. Influence des conditions d'alimentation hydrique ou (et) azotee a differents stades du développement sur la production de grains et la nutrition azotee du soja. *Eurosoya* 3:55-61.

Bouniols, A., M. Cabelguenne, C. A. Jones, A. Chalamet, J. L. Charpenteau, and J. R. Marty. 1991. Simulation of soybean nitrogen nutrition for a silty clay soil in southern France. Field *Crops Res*. 26:19-34.

Brown, R. A. and N. J. Rosenberg. 1999. Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. *Climatic Change* 41:73-107.

Chung, S. W., P. W. Gassman, L. A. Kramer, J. R. Williams, and R. Gu. 1999. Validation of EPIC for two watersheds in southwest Iowa. *J. Envr. Qual.* 28(3):971-79

Edwards, D. R., V. W. Benson, J. R. Williams, T. C. Daniel, J. Lemunyon, and R. G. Gilbert. 1994. Use of the EPIC model to predict runoff transport of surface-applied inorganic fertilizer and poultry manure constituents. Trans. *ASAE* 37 (2):403-09

Favis-Mortlock, D. T., R. Evans, J. Boardman, and T. M. Harris. 1991. Climate change, winter wheat yield and soil erosion on the English South Downs. *Agric. Syst*. 37:415-33.

Gassman, P. W., J. Wu, P. D. Mitchell, B. A. Babcock, T. M. Hurley, and S. W. Chung. 1998 Impact of U.S. agricultural policy on regional nitrogen losses. p. 115-122. *In* Proceedings of the 3rd International Conference on Diffuse Pollution (Poster Papers), 31 Aug.-4 Sept., Edinburgh, Scotland. IAWQ, London, England.

Lee, J. J. and D. L. Phillips. 1993. The effect of trends in tillage practices on erosion and carbon content of soils in the U.S. Corn Belt. *Water, Air, and Soil Pollution* 70:389-401.

Martin, S. M., M. A. Nearing, and R. R. Bruce. 1993. An evaluation of the EPIC model for soybeans grown in southern piedmont soils. Trans. *ASAE* 36(5):1327-31.

Mitchell, G., R. H. Griggs, V. Benson, and J. Williams. 1996. EPIC user's guide (draft) version 5300: the EPIC model environmental policy integrated climate (formerly erosion productivity impact calculator). The Texas Agric. Expt. Stn., Blacklands Res. Center, Temple, Texas.

Mockus, V. 1969. Hydrologic soil-cover complexes. p. 10.1-10.24. *In* SCS National Engineering Handbook, Section 4, Hydrology. USDA, Soil Conser. Ser., Washington, D.C.

Nash, J. E. and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part I, A discussion of principles. J. *Hydr.* 10:282-90.

Phillips, D. L., P. D. Hardin, V. W. Benson, and J. V. Baglio. 1993. Nonpoint source pollution impacts of alternative agricultural management practices in Illinois: a simulation study. *J. Soil and Water Conser.* 48(5):449-57.

Randall, G. W., D. R. Huggins, M. P. Russelle, D. J. Fuchs, W. W. Nelson, and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in Conservation Reserve Program, alfalfa, and row crop system. *J. Envr. Qual*. 26:1240-47.

Rawls, W. J., C. A. Onstad, and H. H. Richardson. 1980. Residue and tillage effects on SCS runoff curve numbers. *Trans. ASAE* 23:357-61.

Rawls, W. J. and H. H. Richardson. 1983. Runoff curve number for conservation tillage. *J. Soil and Water Conser.* 38:494-96.

Sabbagh, G. J., R. L. Bengston, and J. L. Fousa. 1991. Modification of EPIC to incorporate drainage systems. *Trans. ASAE* 34(2):467-72

Singh, P. and R. S. Kanwar. 1995. Modification of RZWQM for simulating subsurface drainage by adding a tile flow component. *Trans. ASAE* 38(2):489-98.

Williams, J. R. 1990. The erosion productivity impact calculator (EPIC) model: a case history. Phil. Trans. R. Soc. Lond. 329: 421-28.

__________ 1995. The EPIC Model. p. 909-1000. In V.P. Singh (ed.) *Computer Models of Watershed Hydrology*. Water Resources Publ., Highlands Ranch, CO.

Williams, J. R., C. W. Richardson, and R. H. Griggs. 1992. The weather factor: incorporating weather variance into computer simulation. *Weed Technol.* 6:731-35.

Wu, J. and B. A. Babcock. 1999. Metamodeling potential nitrate water pollution in the central United States. *J. Envr. Qual*. 28(6):1916-28.

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