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# Evaluating and predicting agricultural management effects under tile drainage using modified APSIM

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## Abstract

An accurate and management sensitive simulation model for tile-drained Midwestern soils is needed to optimize the use of agricultural management practices (e.g., winter cover crops) to reduce nitrate leaching without adversely affecting corn yield. Our objectives were to enhance the Agricultural Production Systems Simulator (APSIM) for tile drainage, test the modified model for several management scenarios, and then predict nitrate leaching with and without winter wheat cover crop. Twelve years of data (1990–2001) from northeast Iowa were used for model testing. Management scenarios included continuous corn and corn–soybean rotations with single or split N applications. For 38 of 44 observations, yearly drain flow was simulated within 50 mm of observed for low drainage (<100 mm) or within 30% of observed for high drain flow. Corn yield was simulated within 1500 kg/ha for 12 of 24 observations. For 30 of 45 observations yearly nitrate-N loss in tile drains was simulated within 10 kg N/ha for low nitrate-N loss (<20 kg N/ha) or within 30% of observed for high nitrate-N loss. Several of the poor yield and nitrate-N loss predictions appear related to poor N-uptake simulations. The model accurately predicted greater corn yield under split application (140–190 kg N/ha) compared to single 110 kg N/ha application and higher drainage and nitrate-N loss under continuous corn compared to corn/soybean rotations. A winter wheat cover crop was predicted to reduce nitrate-N loss 38% (341 vs. 537 kg N/ha with and without cover) under 41-years of corn-soybean rotations and 150 kg N/ha applied to corn. These results suggest that the modified APSIM model is a promising tool to help estimate the relative effect of alternative management practices under fluctuating high water tables.

*Keywords:* N loading; Cover crop; Crop rotation; Water quality; Crop production; Modeling

## 1. Introduction

Proper nitrogen management is one of the important challenges facing the agricultural community. Poor nitrogen management in subsurface drained agricultural basins in the U.S. Midwest is a contributing factor to increased nitrate load in the Mississippi river and the subsequent effects on hypoxia (Dinnes et al., 2002). Among promising practices to reduce nitrate loss under tile drainage are appropriate timing of N application (Randall and Mulla, 2001; Jaynes et al., 2004) and planting of cover crops such as rye (Strock et al., 2004). Winter cover crops minimize soil nitrate before and after the growing season, when it is most subject to leaching (Eigenberg et al., 2002). Winter wheat and rye have been used as cover crops and the biomass nitrogen contents of the two crops are often similar (Odhiambo and Bomke, 2001; Weinert et al., 2002). In general, management strategies to reduce nitrate loss have only been tested over a few years and limited environmental and management conditions, therefore, quantifying the effects under the variety of expected conditions is difficult.

Developing quantitative performance measures for conservation practices may be among the most important challenges currently confronting the conservation science community (Cox, 2002). Short-term experiments allow qualitative analysis of treatments but are inadequate to quantify temporal variability

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due to climate (Keating et al., 2002). Agricultural models may be useful to fill in these experimental gaps. If properly validated against short-term data, models could be used to objectively quantify the potential effects of conservation practices under site specific climate and soil conditions.

The model APSIM is a component-based simulation framework that allows integration of various agricultural components in order to investigate the implications of management practices (McCown et al., 1995; Keating et al., 2003). APSIM has been used to investigate long-term corn production in Nebraska (Lyon et al., 2003) and long-term winter wheat production in China (Chen et al., 2004). To accurately predict crop yield in the Midwest a model should account for subsurface drainage (Shen et al., 1998; Paz et al., 1998). Therefore, to use APSIM to quantify the effects of conservation practices in the U.S. corn and soybean belt the model had to be modified to simulate tile drainage. Our objectives are to 1) modify APSIM for tile drainage; 2) test the modified model for several management scenarios; and 3) use the tested model to predict nitrate leaching with and without winter wheat cover crop after corn and soybean.

## 2. Materials and methods

### 2.1. Site description

To test the modified APSIM model, a 12-year (1990 to 2001) data set was used that included tile-drainage volume, nitrate concentrations in drainage water, corn yield, soybean yield, and N treatment information such as rates and timing of N application for each plot. The data were collected from 36, 0.4-ha plots located at the Iowa State University Northeast Research Station near Nashua, IA (43.0°N, 92.5°W). The field research site was initiated in 1977 with tillage (moldboard plow, chisel plow, ridge-tillage, and no-tillage) and cropping system (continuous corn and both phases of a corn/soybean rotation) treatments. From 1993 through 2001, chisel plow and no-till practices were evaluated using different N sources (swine manure or UAN — urea ammonium nitrate), times of N application (fall, spring, or split), and N rates (generally within 100 to 200 kg/ha). Each treatment was replicated three times using a randomized complete block design.

For our objectives, four plots were chosen that had different N management (split and single N application), included both phases of a corn/soybean rotation, and had different tillage (Table 1). To simplify model testing and parameterization, the plots chosen (2, 15, 24, and 25) had similar soil and drainage characteristics (Malone et al., 2007-this issue). The predominant soils from these four plots are Kenyon loam (Fine-loamy, mixed, superactive, mesic Typic Hapludolls) and Readlyn loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls). These soils have seasonally high water tables, and thus benefit from subsurface drainage (USDA–NRCS, 2001a,b).

### 2.2. Model description, input, testing, and application

The Agricultural Production Systems Simulator (APSIM) predicts daily water, soil, and plant variables in response to weather and management. Model input includes: daily rainfall, temperature, and solar radiation; soil properties; crop phenology characteristics, and management (planting and harvest dates, fertilizer application, tillage). Model output includes: drainage amount, nitrate concentration in drainage water, crop growth (grain, biomass, roots). More details on simulated drainage, soil water and N dynamics, and crop growth are described below.

For testing, the model was initialized in 1980 and run through 2001. Predicted crop yield, drainage flux, and nitrate flux in drainage from 1990 through 2001 were compared to observed data to evaluate the response of the modified model to year-to-year climate differences and plot-to-plot treatment differences. After testing, APSIM was run using actual climate records from 1951 through 2003 to estimate the long-term corn yield and nitrate leaching for split and single preplant N applications of 150 kg N/ha (Table 1). Treatment comparisons were started in 1963 to allow several years for model initialization. The tested model was then used to predict the long-term effects (1963–

Table 1
Field management scenarios

| Years | Tillage [a] | N application [b] (kg/ha) | Crop [c] |
|---|---|---|---|
| *Plot 25* | | | |
| 1980–1992 | NT | 202 | CC |
| 1993–1998 | NT | 110 | SC |
| 1999–2000 | NT | 30/139 | SC |
| *Plot 24* | | | |
| 1980–1992 | NT | 168 | SC |
| 1993–1998 | NT | 30/112; 30/141; 30/119 | SC |
| 1999–2000 | CP | 28/177 | SC |
| *Plot 2* | | | |
| 1980–1992 | MP | 168 | CS |
| 1993–1998 | NT | 110 | CS |
| 1999–2001 | NT | 126 | CS |
| *Plot 15* | | | |
| 1980–1992 | NT | 168 | CS |
| 1993–1998 | NT | 30/111; 30/161; 30/155 | CS |
| 1999–2001 | CP | 168 | CS |
| *Long-term single preplant N application (APSIM simulation only; observed data is not available)* | | | |
| 1951–2003 | NT | 150 | CS |
| *Long-term split N application (APSIM simulation only; observed data is not available)* | | | |
| 1951–2003 | NT | 30/120 | CS |
| *Long-term split N application and winter wheat planted on day 270 (after soybean) or 290 (after corn) [APSIM simulation only; observed data is not available]* | | | |
| 1951–2003 | NT | 30/120 | CWSW |

[a] NT is no-till; CP is chisel plow; MP is moldboard plow.

[b] A single N application indicates spring preplant; split application includes about 30 kg/ha spring preplant and larger application in late spring (around 40 days after corn planting). N was only applied to corn; soybean had no N application.

[c] CC is continuous corn; SC is soybean in even years and corn in odd years; CS is corn in even years and soybean in odd years; CWSW is corn in even years, soybean in odd years and wheat planted after corn and soybean harvest.

Table 2
Selected soil properties

| Soil depth [a] (mm) | SAT [b] (mm/mm) | DUL [c] (mm/mm) | LL [d] (mm/mm) | $K_{sat}$ [e] (mm/h) | Soil OC [f] (%) | Soil OC inert fraction [g] (g/g) |
|---|---|---|---|---|---|---|
| 0–10 | 0.434 | 0.345 | 0.134 | 50 | 2.0 | 0.4 |
| 600–700 | 0.39 | 0.31 | 0.185 | 300 | 0.6 | 0.8 |
| 900–1000 | 0.35 | 0.29 | 0.17 | 50 | 0.25 | 0.8 |
| 1100–1200 | 0.33 | 0.27 | 0.14 | 10 | 0.25 | 0.8 |
| 1800–3000 | 0.30 | 0.27 | 0.14 | 0.01 | 0.14 | 0.99 |

[a] Soil properties were gradually changed between selected layer and upper and lower layers.

[b] SAT is volumetric water content at saturation (porosity). These values were taken from Shen et al. (1998) with some minor adjustments.

[c] DUL is volumetric drained upper limit of soil water, which was assumed at 1000 mm (water equivalent) of soil tension. These values were from Shen et al. (1998) with some minor adjustment.

[d] LL is volumetric lower limit of soil water, which was assumed at 150,000 mm (water equivalent) of soil tension. This value was taken from Shen et al. (1998).

[e] $K_{sat}$ from 10 to 1000 mm soil depth measured from Ma et al. (2006a-this issue).

[f] Soil OC is soil organic carbon, which is taken from Singh and Kanwar (1995).

[g] Soil OC inert fraction is the fraction of soil carbon that is unavailable for mineralization. The selected values resulted in an average yearly mineralization of 113 kg N/ha for plot 25 in 1990 through 2001, which Ma et al. (2006c-this issue) deemed reasonable. Note that reported average mineralization value (96 kg N/ha) for plot 25 by Ma et al. (2006c-this issue) includes 1978–1990, which was continuous corn and has less overall mineralization than corn–soybean rotation (Ma et al., 2006b-this issue).

2003) of winter wheat cover crop planted after corn and soybean harvest. Winter wheat was planted on day 270 after soybean and on day 290 after corn; wheat was killed 10 days before corn planting and 1 day before soybean planting. Corn and soybean were planted on day 125 and 143, respectively.

### 2.2.1. Drainage

Each plot at Nashua is drained separately and the lines are at a depth of 1.2 m and a spacing of 28.5 m. To minimize soil disturbance, a trenchless drain plow was used to install the center drain, but drain lines between plots were installed using a trencher.

The drainage component inserted into APSIM is similar to that found in DRAINMOD (Skaggs, 1978, 1989) and RZWQM (Singh and Kanwar, 1995; Ahuja et al., 2000). APSIM is linked to a comprehensive soil water dynamics model (SWIMv2) that is based on Richards' equation and computes fluctuating water tables (Verberg et al., 1996). Drainage flux (mm/hr, $S_d$) is calculated by the steady-state Hooghoudt equation:

$$S_d = 4.0^* \mathrm{L}K_{sat}{}^* m^* (2.0 d_e + m)/L^2$$

where $\mathrm{L}K_{sat}$ is lateral saturated hydraulic conductivity (mm/h); $m$ is water table height above the drain measured midway between drains (mm); $d_e$ is equivalent depth from drain to bottom of restricting layer (mm); $L$ is distance between drains (mm). $\mathrm{L}K_{sat}$ and $L$ are model inputs, and $m$ is computed for each time increment by SWIMv2. At this time only a single value for $\mathrm{L}K_{sat}$ is input, which is the effective $\mathrm{L}K_{sat}$ for the saturated soil depth above the drains. The equivalent depth is used to correct drainage fluxes for convergence near the drain (Moody, 1967):

$$d_e = \frac{d}{1 + \frac{d}{L}\left[\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - 3.55 + \frac{1.6d}{L} - 2\left(\frac{d}{L}\right)^2\right]}, \qquad 0 < d/L < 0.3$$

$$d_e = \frac{L\pi}{8\left[\ln\left(\frac{L}{r}\right) - 1.15\right]}, \qquad d/L > 0.3$$

where $r$ is drain tube radius (mm) and $d$ is distance from drain to bottom of restricting layer (mm). The drain tube radius can be input as less than actual radius ($r_e$, effective tube radius) to account for additional head loss as soil water approaches real tubes that have only a finite number of openings. This added functionality is now available as part of APSIM V4.2.

### 2.2.2. Soil

The soils were similar, therefore, one set of soil parameters were input for the four plots (Table 2). Saturated water content (SAT), drained upper limit (DUL), and lower limit (LL) were obtained from Shen et al. (1998), with some minor adjustment. These soil properties and tools provided by the model developers were used to develop soil water retention and soil hydraulic conductivity as functions of soil tension. The SAT, DUL, and LL were used to construct a moisture characteristic using the approach of Cresswell and Paydar (1996) but modified to utilize the functional form suggested by Ross et al. (1991). Hydraulic conductivity was modeled as the sum of two pore spaces (Ross and Smettem, 1993). One pore space was created using the shape of the moisture characteristic (Campbell, 1974) and the requirement that conductivity at DUL was a nominal 0.1 mm/day. A second pore space was added to raise the near saturation conductivity such that the combination of the two pore spaces resulted in the desired conductivity at SAT.

The modified APSIM model predicts peak flow as a function of a single lateral saturated hydraulic conductivity ($\mathrm{L}K_{sat}$), which was adjusted to minimize the average annual difference between observed and predicted drainage for plot 25 over the simulation period (1990–2000). The end result was a 2-mm drainage difference with a calibrated $\mathrm{L}K_{sat}$ of 4000 mm/d (166 mm/h). Also, the regional water table depth was set to the lower water table values measured for plot 25 (1500 mm) and the deepest soil layer vertical $K_{sat}$ value was adjusted (0.01 mm/h; Table 2) to improve the predicted water table depth for plot 25. The soil parameters resulted in accurate plot 25 water table predictions [Root Mean Square Error, RMSE = 156 mm; average measured and predicted water table depths are 1254 and 1289 mm; predicted daily water table depth (mm) = 0.98 * measured daily water table depth−9.1 mm; $R^2=0.75$; $N=155$]. Plot 25 was used for soil parameter calibration because it included water table measurements generally taken weekly; the other three plots did not have water table measurements.

Probert et al. (1998) presents details of the APSIM soil nitrogen dynamics. The soil organic matter in APSIM is treated as a three-pool system: fresh organic matter, such as crop residue and roots; soil microbial biomass; and the fairly stable humus pool. Nitrogen dynamics are then determined by a user-defined inert fraction of the humus pool, mineralization, immobilization, nitrification, denitrification, and urea hydrolysis. Most soil N parameters were maintained at default values except the user-defined inert fraction (Table 2). Also, the potential decomposition rate for crop residue was set to 0.08/day, which always resulted in more than 90% of corn and soybean residue decomposed by September 1 of the year following harvest.

### *2.2.3. Crop*

Keating et al. (2003) outlined the crop module, which provides references for more detailed crop simulation descriptions. Corn and soybean emergence (75%), corn silking, and soybean maturity data were used from 1980 through 2000 to parameterize the crop component. Only data from 1990 through 2001 were presented because drainage was not reported prior to 1990. The standard “usa_18leaf” maize and “Buchanan” soybean were selected as varieties and thermal time targets for phenological development were adjusted to best fit available observations of emergence, flowering, and maturity.

Table 3
Observed and APSIM simulated N in grain (kg N/ha)

| Corn | | | Soybean | | |
|---|---|---|---|---|---|
| Year | Observed | APSIM | Year | Observed | APSIM |
| *Plot 25* | | | | | |
| 1990 | 74 | 91 | | | |
| 1991 | 95 | 64 | | | |
| 1993 | 39 | 36 | 1994 | 103 | 279 |
| 1995 | 46 | 102 | 1996 | 206 | 218 |
| 1997 | 102 | 133 | 1998 | 247 | 190 |
| 1999 | 101 | 158 | 2000 | 190 | 220 |
| *Plot 24* | | | | | |
| 1991 | 123 | 71 | | | |
| 1993 | 80 | 43 | 1994 | 103 | 279 |
| 1995 | 66 | 111 | 1996 | 206 | 218 |
| 1997 | 114 | 139 | 1998 | 247 | 190 |
| 1999 | 114 | 161 | 2000 | 190 | 220 |
| *Plot 15* | | | | | |
| 1994 | 90 | 155 | 1995 | 147 | 198 |
| 1996 | 121 | 103 | 1997 | 187 | 257 |
| 1998 | 159 | 113 | 1999 | 190 | 202 |
| 2000 | 104 | 131 | | | |
| *Plot 2* | | | | | |
| 1994 | 69 | 147 | 1995 | 149 | 198 |
| 1996 | 99 | 85 | 1997 | 203 | 257 |
| 1998 | 102 | 104 | 1999 | 218 | 202 |
| 2000 | 89 | 125 | | | |
| RMSE (all data) | 41 | | | 77 | |
| RMSE (1994 and 1995 excluded) | 34 | | | 41 | |
| Average (all data) | 94 | 109 | | 185 | 223 |
| Average (1994 and 1995 excluded) | 101 | 104 | | 208 | 217 |

Default wheat parameters were used for the most part to simulate winter wheat growth and N uptake. Phyllochron and cumulative vernalization days were set at 76 and 50 (Saseendran et al., 2004), and vernalization was set to the default Australian winter wheat (5.0).

Early in this research we realized that using the default extra supply fraction (0.5) resulted in overprediction of N uptake, lack of model response to lower observed corn yield on plots with lower N rates (e.g., plots 2 and 25 had lower N application 1993–1998; Table 1), overprediction of overall corn yield, and underprediction of N concentration and loss in tile drainage. Therefore, the extra supply fraction was reduced. The corn model computes N uptake via mass flow from the crop root zone transpiration stream plus the N acquired by active uptake. Active uptake is calculated using a user-defined extra supply fraction. The extra supply fraction was set at 0.09, which supplies 9% of the daily corn N deficit after accounting for N uptake through transpiration. We used 0.09 because this resulted in the lowest RMSE between observed and predicted N removal in corn grain excluding 1994 and 1995 data (Table 3). Data from 1994 and 1995 were excluded because of possible localized crop damage (e.g., hail, wind; Malone et al., 2006-this issue) that was not simulated.

## 3. Results and discussion

### *3.1. Yield*

Corn yield was simulated within 1500 kg/ha for 12 of 24 observations (Fig. 1). The 1994 simulated soybean and corn yield was much greater than the observed yield for all four plots (Fig. 1). In 1994 very high average Iowa corn and soybean yields were reported (9192 and 3394 kg/ha; www.nass.usda.gov). Because both corn and soybean yield were substantially overpredicted and 1994 was an excellent growing year across most of Iowa, local crop damage may have occurred but was not recorded (e.g., hail, wind, etc.). Corn yield was also overpredicted in 1995 when hail damage was recorded to reduce grain yield (Andales et al., 2000). Corn yield was underpredicted in 1993 for plot 24 when seasonal rainfall was excessive throughout much of the Midwest. Hail damage effects were not simulated and the adverse effects of excessive rain in 1993 (e.g., oxygen deficit) were overpredicted for plot 24 possibly because of small scale elevation and surface drainage conditions. Plot 24 is at a high elevation among the 36 plots at Nashua.

Low corn yield predictions in 1990 reflect very high simulated N stress at floral initiation, flag leaf, and flowering; 1990 observed corn yields were among the highest (Fig. 1). Poorly simulated corn yield in some years may be due to the relatively simple N-uptake routine within the model. In fact, the APSIM Soil N module development team evaluated the model during fallow to avoid complications arising from N uptake by a crop

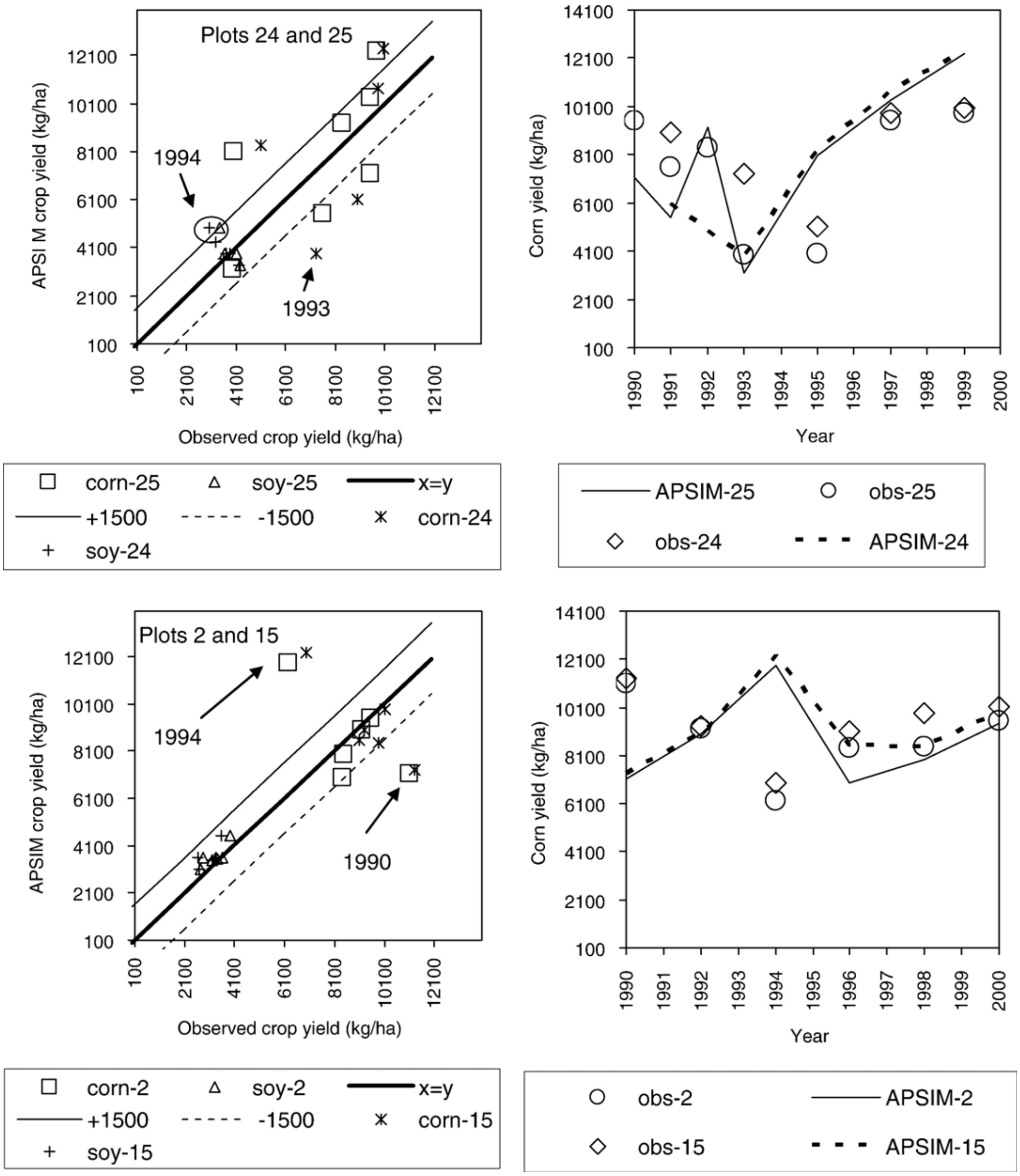

Fig. 1. Yearly observed and APSIM simulated crop yield.

(Probert et al., 1998). A more realistic N-uptake routine may improve corn yield predictions. Jeuffroy et al. (2002) reviews methods of varying complexity to account for N demand and uptake by crop models.

Although the predicted corn yield should be improved, the model accurately predicted higher yield from split and/or higher N application (Fig. 2 and Table 1); Bakhsh et al. (2002, 2000) also reported significant corn yield differences between these two treatments. The poorest predicted difference was for the very wet 1993 season (Fig. 2); near saturated soil water reduces APSIM predicted photosynthesis. Plot 24 is at a higher elevation than plot 25 possibly increasing the unsaturated soil column and resulting in less water stress from saturated soil and higher observed yield on plot 24 compared to plot 25 in 1993. Soil parameters were similar for all four plots (Table 2), therefore, the effect of soil profile water saturation differences between plots was not simulated.

Higher predicted corn yield under split N application was partially because N application coincided with corn demand. With equal N rates applied to corn for 41 years (Table 1), the average predicted corn yield was 8852 and 9396 kg/ha for single and split N applications. In 1996, 1998, and 2000 the average simulated yield was 9080 and 10264 kg/ha for single and split N applications. For those three years, the single application generally had more N stress predicted for floral initiation through grain fill while the split application had higher predicted N stress for the emergence and juvenile stages. Field studies suggest that corn yield is more dependent upon N accumulation after silking than during vegetative development (Singer and Cox, 1998). Predicting that the split N-application treatment had less N stress at critical growth stages than the single N application with equal N-application rates (Table 1) illustrates a useful application of agricultural system models. That is, models can be used in conjunction with field data as a tool to more thoroughly understand agricultural systems. The Nashua field results, on the other hand, were insufficient to quantify the contribution of N-application timing and rate on corn yield (Bakhsh et al., 2000).

### *3.2. Drain flow*

For 38 of 44 observations, yearly drain flow was simulated within 50 mm of observed for low drainage or within 30% of observed for high drainage (Fig. 3). Some predictions were inaccurate because tillage effects on infiltration were not simulated. No-till (NT) drained more than moldboard plow (MP) from the Nashua fields possibly because increased plant residue reduced evaporation and rainfall infiltration increased (Weed and Kanwar, 1996). For example, 1990 drainage from plot 2 (MP) was overpredicted while the 1990 drainage from plot 15 (NT) was more accurately predicted (Fig. 3). Tillage resulted in increased predicted soil evaporation because of lower predicted surface plant residue but infiltration differences were not simulated.

Inaccurate yield simulations also contribute to inaccurate drainage predictions. The predicted difference is about 20 mm of transpiration for each 1000 kg of corn yield and about 40 mm of transpiration for each 1000 kg of soybean yield. Therefore, overpredicted drainage in 1990 (plots 2 and 15) and 1998 (plot 15) were partially the result of underpredicted corn yield (Figs. 1 and 3).

The cause of overpredicted drainage in 1995 is less certain but it is mostly from late May through June (Fig. 4). Soil parameter calibration for each plot would improve drainage predictions, but daily and yearly drainage simulations are generally reasonable (Figs. 3 and 4). Also, the average soil water content prediction to a depth of 300 mm across all four plots between 1990 and 2000 was similar to average measured soil water content where data was available (0.31 mm/mm for both predicted and observed) suggesting that the overall soil water parameters (Table 2) are reasonable. Approximately 38 soil water content measurements were available for each plot between 1990 and 2000. More drainage from plot 25 under continuous corn was accurately predicted compared to plot 24 under corn/soybean rotation because of higher residue (i.e., less soil evaporation) and lower transpiration on plot 25 from 1990 through 1993 (Fig. 5). The slope of the best fit line in Fig. 5 is 0.56, suggesting the rotation effect was only partially simulated and some effects such as increased infiltration due to additional surface residue (Weed and Kanwar, 1996) were not simulated. Greater drain flow from no-till continuous corn compared to no-till corn–soybean rotations at Nashua was previously reported (Weed and Kanwar, 1996; Kanwar et al., 1997). These results suggest that the modified APSIM model is a promising tool to simulate daily tile drainage, average soil water fluctuation, and some management effects on yearly drainage.

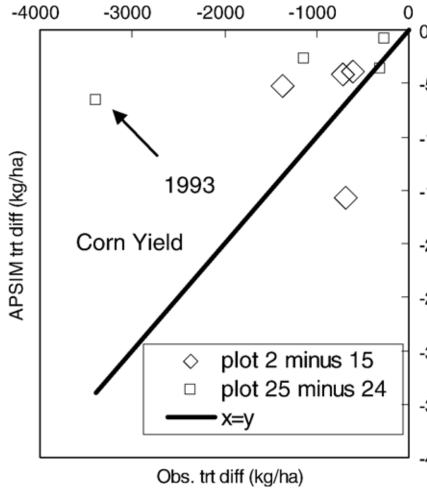

Fig. 2. Yearly APSIM predicted and observed corn yield difference between treatments for 1993 through 2000. Plots 24 and 25 were soybean in even years; plots 2 and 15 were corn in even years (see Table 1).

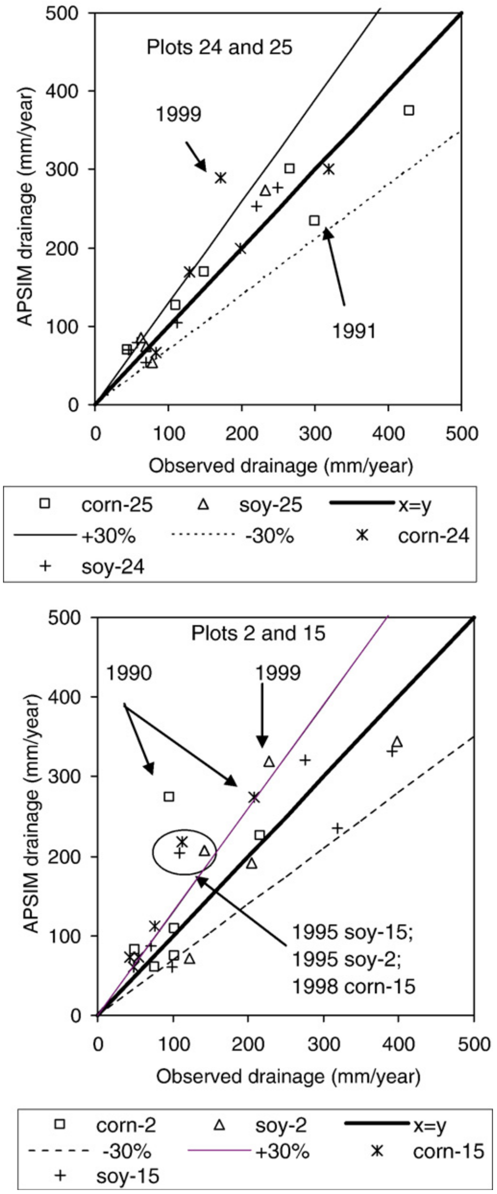

Fig. 3. Yearly observed and APSIM simulated drainage amount.

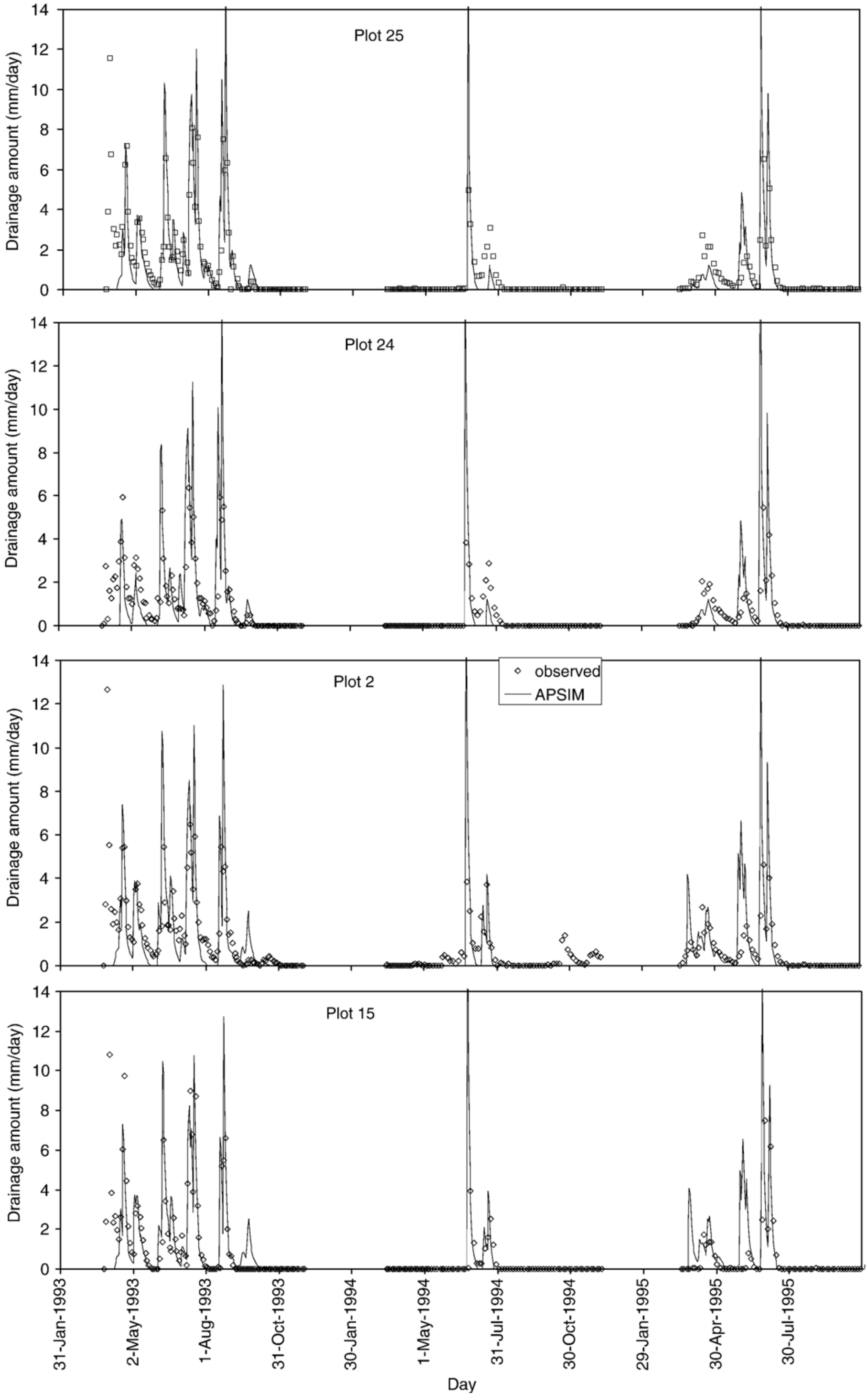

Fig. 4. Daily simulated and observed drainage amount.

### 3.3. Nitrate loss and concentration in tile drains

Annual nitrate loss from plots 25 and 24 is predicted reasonably well (Fig. 6). The largest absolute nitrate loss difference is in 1991 from plot 25 where 63 kg N/ha was observed and 43 kg N/ha was predicted (Fig. 6). The differences were mostly due to errors in simulated drainage amount rather than nitrate concentration (Figs. 3 and 7).

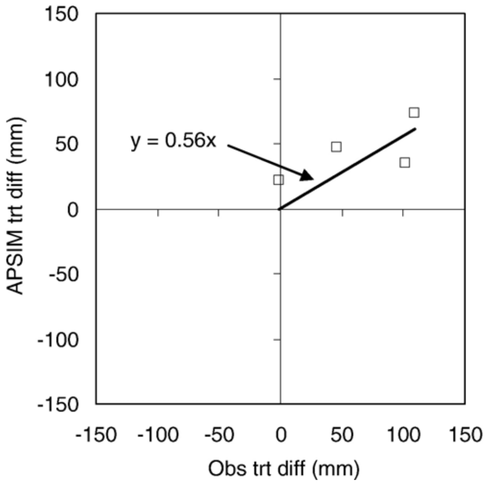

Fig. 5. Yearly APSIM predicted and observed drainage amount difference between plot 25 and 24 (plot 25–24) for 1990 through 1993 when plot 25 was in continuous corn and plot 24 was in a corn–soybean rotation (Table 1).

Yearly nitrate loss from plot 2 and plot 15 is not simulated as well as plots 24 and 25 (Fig. 6). In 1990, APSIM overpredicts yearly drainage from plot 2 and to a lesser degree plot 15 (Fig. 3), which contributes to overpredicted nitrate loss (Fig. 6). Predicted nitrate concentration in 1990 from plots 2 and 15 was reasonable (Fig. 7). In 1993, drainage amount is predicted within 20% of observed data for plots 2 and 15, but the nitrate concentration is underpredicted (Fig. 7) resulting in underpredicted nitrate loss (Fig. 6). Even though nitrate concentration was underpredicted in 1993, the lowest flow weighted yearly nitrate concentration in drainage was accurately predicted in 1993 out of 46 observations (Fig. 7).

Three of the least accurate nitrate loss predictions were for 1998 and 1999 (Fig. 6). The drainage is substantially overpredicted in 1998 for plot 15 (Fig. 3), but is only slightly overpredicted in 1999 (321 and 275 mm for predicted and observed, respectively). The overprediction in 1999 for plot 15 is mostly because of predicted nitrate concentration (Fig. 7). Biomass N was not recorded in 1998 or 1999, but corn grain N was underpredicted in 1998 by 46 kg N/ha (113 vs. 159 kg N/ha). Predicted grain N is generally higher than observed for plots 2 and 15 and in 1998 grain N was underpredicted more than any other year (Table 3). This is further evidence that improved N-uptake predictions may contribute to more accurate subsurface drainage nitrate loss predictions.

Although the yearly nitrate loss predictions may be improved, the model accurately predicted the trend for higher loss with higher N application on plot 25 compared to plot 24 (Fig. 8). The excellent correlation confirms that APSIM accurately responds to treatment differences from 1988 through 1991. A drought in 1988 and 1989 resulted in no observed drainage and low observed corn yields, and thus a buildup of soil nitrate (Bjorneberg et al., 1996). Plot 25 leached much more nitrate in 1990 and 1991 than plot 24 because plot 25 was under continuous corn through 1993 and received higher N application each year; plot 24 was under a soybean corn rotation through 1992 (Table 1).

Nitrate loss differences in plots 2 and 15 were not accurately predicted (Fig. 8). The poor correlation is partly due to 1998 and 1999, where inaccurate N-uptake predictions may contribute to poor nitrate in drainage predictions as discussed above. Also, 1990 contributes to the poor correlation and plots 2 and 15 had equal amounts of N applied in 1988 through 1992 (Table 1), therefore 1990 nitrate leaching differences between plots should be small if soil differences are not significant among the two plots. In 1990, drainage is predicted to be nearly equal among plots 2 and 15, whereas plot 2 had more than twice the observed drainage as plot 15 (Fig. 3).

Nitrate loss differences from both sets of plots after 1991 were not accurately predicted (Fig. 8). However, the observed data did not clearly indicate that split N application resulted in statistically different nitrate loss than the single application, and observed nitrate loss differences were mostly due to drainage amount (Bakhsh et al., 2002).

### 3.4. Overall predicted and observed results

The overall predicted yield, drainage, and nitrate loss between plots generally agreed with observed data throughout the simulation period (Table 4). For example, plot 25 produced the

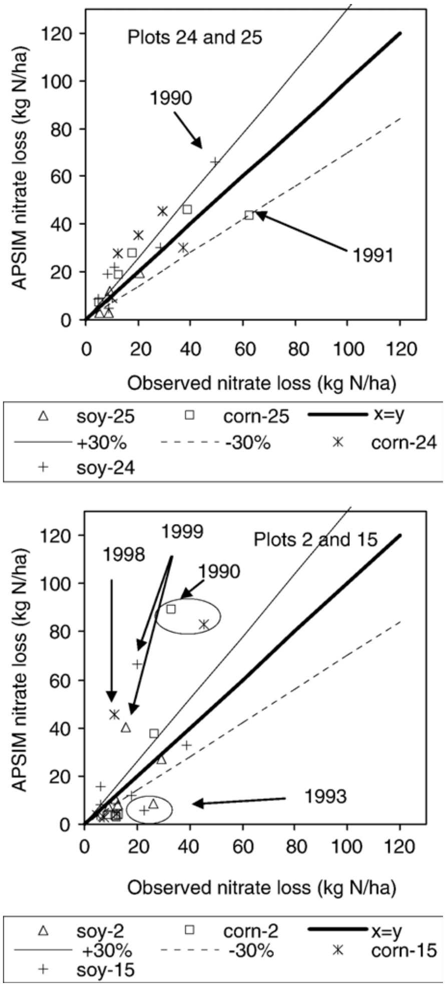

Fig. 6. Observed and APSIM simulated yearly nitrate-N loss in tile drains.

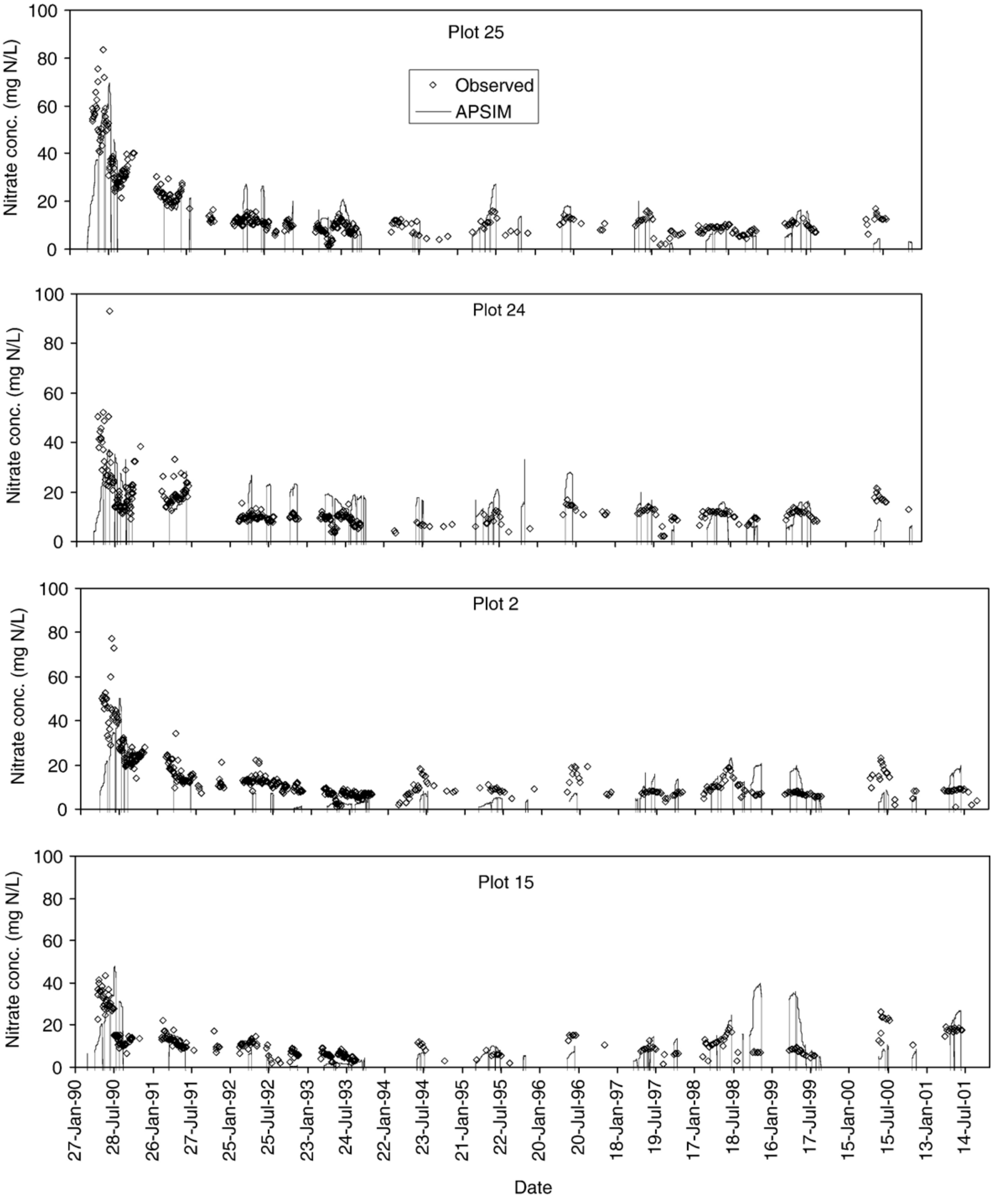

Fig. 7. Observed and APSIM simulated daily nitrate-N concentration in tile drainage.

highest predicted and observed nitrate leaching and drainage amount over the simulation period because it was under continuous corn prior to 1993. Also, plot 15 produced the highest predicted and observed corn yield over the simulation period partially because it received the highest N application from 1993–1998 (Table 1) and soybean was planted during the excessively wet 1993 season rather than corn. Plot 25 produced the lowest predicted and observed corn yield over the simulation period partially because of the low N application from 1993–1998 and excessive rainfall in 1993. The low slope for the predicted and observed drainage (0.27 mm/mm; Table 4) over the simulation period reflects that some conditions affecting drainage were not predicted. For example, soil properties were assumed equivalent for the four plots and infiltration difference between treatments due to tillage was not simulated.

### 3.5. APSIM predicted winter wheat cover crop effect

Predicted total nitrate loss in subsurface drainage was reduced 38% (341 vs. 537 kg/ha) when averaged for 41 years by incorporation of a winter wheat cover crop into a corn and soybean rotation (Fig. 9). Neither corn nor soybean yield was

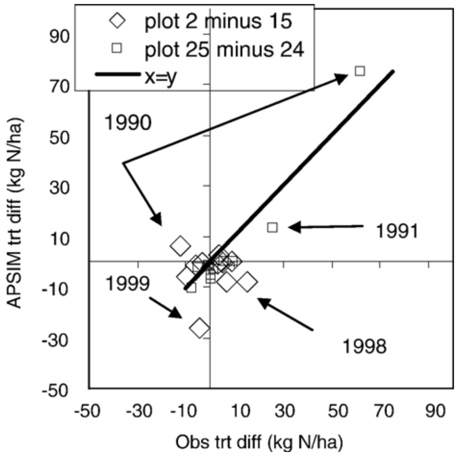

Fig. 8. Yearly APSIM predicted and observed nitrate-N loss difference between treatments for 1990 through 2001.

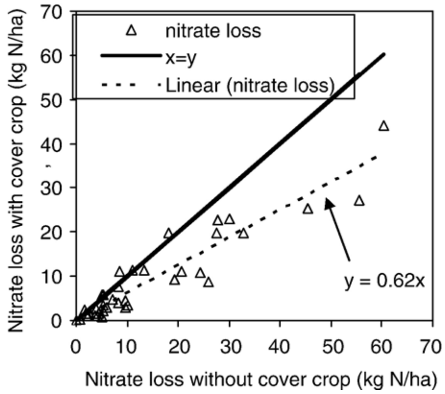

Fig. 9. APSIM predicted nitrate-N loss with vs. without winter wheat cover crop planted after corn and soybean harvest for a 41-year simulation using observed weather data (1963–2003). 30 kg/ha of N is applied at corn planting (day 125) and 120 kg/ha of N is applied 40 days later. The winter wheat is killed 10 days prior to corn planting and 1 day prior to soybean planting.

predicted to decrease due to N or soil water deficiency after the cover crop (e.g., 9427 kg/ha vs. 9396 kg/ha corn yield for cover and no cover crop). Corn yield reductions from other factors such as allelopathy and physical interference were not simulated. The reduced nitrate loss was due to cover crop N uptake because drainage was not affected. Predicted wheat transpiration exceeded 50 mm in only 3 of 41 years (average transpiration was 27 mm/year). Wheat added shade and residue cover and wheat transpiration replaced some soil evaporation, which reduced soil evaporation on average about 33 mm/year.

The 38% nitrate loss reduction was predicted with median wheat biomass production of about 1.5 Mg/ha and average N concentration of 1.61% for 1.5 Mg/ha of biomass (Table 5; Fig. 10a). Strock et al. (2004) applied 134 kg N/ha of Urea to corn and measured southwestern Minnesota winter rye cover crop biomass of 2.7 Mg/ha in spring of 1999 and 1.0 Mg/ha in spring of 2000 with nitrogen concentration of 2.5% and 2.7%, respectively. Also, Odhiambo and Bomke (2001) and Weinert et al. (2002) found N concentration in rye and wheat cover crop of 2.9% to 2.2% for biomass of 2.1 to 3.8 Mg/ha. Therefore, the above ground biomass critical and/or minimum N concentration limits used in APSIM may be too low considering that the terminal crop stage for the wheat was floral initiation. The current values may provide acceptable biomass N concentration for “mature” wheat but may be low for earlier stages. Increasing both the stem and leaf minimum N concentration limits to 25% over the original wheat leaf N concentration limits for emergence through flowering and increasing the stem critical N concentration limits results in increased N concentration in biomass (2.1% for biomass production of 1.5 Mg/ha, Table 5). The nitrate loss in drainage was slightly increased above the base scenario because increased nitrogen concentration in biomass was countered by reduced biomass production. Therefore, precise nitrogen concentration limits may not be critical to accurately model nitrogen leaching in cover crop systems over the long-term. Instead, accurate yearly N uptake by winter cover crop may be the most important element necessary to accurately predict the overall effect of winter cover crops on nitrate leaching. The standard critical concentrations during crop establishment were already higher than 1.6% (Fig. 11) so N uptake was supply limited rather than demand limited in the base scenario. The results suggest that under our conditions, choice of a more demanding species does not reduce N leaching.

Table 4
Average annual summary of observed and APSIM simulated results over the simulation period for the four treatments (see Table 1)[a]

| | Corn yield (kg/ha) | | Soybean yield (kg/ha) | | Drainage (mm) | | Nitrate-N loss in drainage (kg N/ha) | | Flow-weighted nitrate concentration in drainage (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Plot | Observed | APSIM | Observed | APSIM | Observed | APSIM | Observed | APSIM | Observed | APSIM |
| 25 | 7535 | 7985 | 3857 | 4000 | 174 | 176 | 29.2 | 32.2 | 16.8 | 18.2 |
| 24 | 8266 | 8286 | 3602 | 3998 | 150 | 169 | 20.0 | 27.1 | 13.3 | 16.0 |
| 2 | 8830 | 8722 | 3291 | 3638 | 157 | 170 | 16.6 | 20.1 | 10.6 | 11.8 |
| 15 | 9442 | 9240 | 3131 | 3637 | 150 | 171 | 15.1 | 23.6 | 10.0 | 13.8 |
| Intercept[b] | 2909 | | 1740 | | 129 | | 10.9 | | 4.5 | |
| Slope[b] | 0.66 | | 0.60 | | 0.27 | | 0.74 | | 0.83 | |
| $R^2$ | 0.97 | | 0.86 | | 0.89 | | 0.83 | | 0.85 | |
| RMSE | 252.5 | | 372.0 | | 15.5 | | 6.0 | | 2.5 | |

[a] The simulation period for plots 2 and 15 was from 1990–2001; the simulation period for plots 24 and 25 was from 1990–2000 (Table 1).

[b] The best fit line of observed and APSIM predicted average annual results summary.

Table 5
APSIM predicted winter wheat cover crop results for 41 years with selected parameter changes

| Scenario description | Wheat biomass N concentration limits[a] (% of biomass) | XF[b] (unitless) | Average root depth with 1.5 Mg/ha biomass on day 115[c] (mm) | Median wheat biomass production at spring kill date (Mg/ha) | Average N concentration of wheat biomass at 1.5 Mg/ha (% of biomass) | Total wheat N-uptake over 41 year simulation (kg N/ha) | Total nitrate-N loss to drains over 41 year simulation (kg N/ha) |
|---|---|---|---|---|---|---|---|
| Base scenario | Original | 0.99 | 898 | 1.50 | 1.61 | 1028 | 341 |
| Wheat N concentration limits | Increased | 0.99 | 946 | 1.09 | 2.06 | 1031 | 352 |
| Rooting depth | Original | 0.60 | 608 | 1.04 | 1.41 | 722 | 425 |
| Rooting depth | Original | 1.2 | 1029 | 1.68 | 1.65 | 1130 | 308 |

[a] Plant nitrogen demand is determined by the critical N concentration limits and nitrogen stress occurs if this demand is not obtained. For the second scenario (Wheat N concentration limits), both the stem and leaf minimum N concentration limits were increased 25% over the original wheat leaf minimum N concentration limits for emergence through the flowering stage. Also, the stem critical and maximum N concentration limits were raised to the leaf critical N concentration limits for floral initiation through maturity. Note that wheat growth never exceeded the flowering stage and did not exceeded floral initiation the vast majority of years. The APSIM original minimum, critical, and maximum N concentration limits (%) are illustrated in Fig. 11.

[b] XF is input for each soil layer and lower values slow rate of root growth. The maximum root depth for all scenarios never exceeded 1250 mm.

[c] This was determined on day 115 for both corn and soybean years. See Fig. 10b for illustration of relationship between predicted winter wheat biomass production and rooting depth on day 115.

Decreasing the average root depth from 898 to 608 mm (1.5 Mg/ha biomass production) over the 41 year simulation increases total nitrate loss from 341 kg/ha in the base scenario to 425 kg/ha (Table 5). The model sensitivity to rate of root growth agrees with the observations of Thorup-Kristensen (2001), where deep soil layer N uptake and root growth of winter cover crops significantly affected nitrogen leaching. The rate of root growth for the base scenario appears reasonable. Late April 2004 winter rye rooting depths of about a meter were measured with biomass production of 1.5 Mg/ha in central Iowa (Tom Kaspar, plant physiologist, USDA-ARS, personal communication, April 2005).

Parameters such as critical N concentration limits, extra supply fraction, and relative rate of root growth may be important to realistically simulate winter cover crops and their effects on nitrate leaching. Determining the correct values for some important parameters associated with simulating winter cover crops requires thorough model testing with several years of field specific data

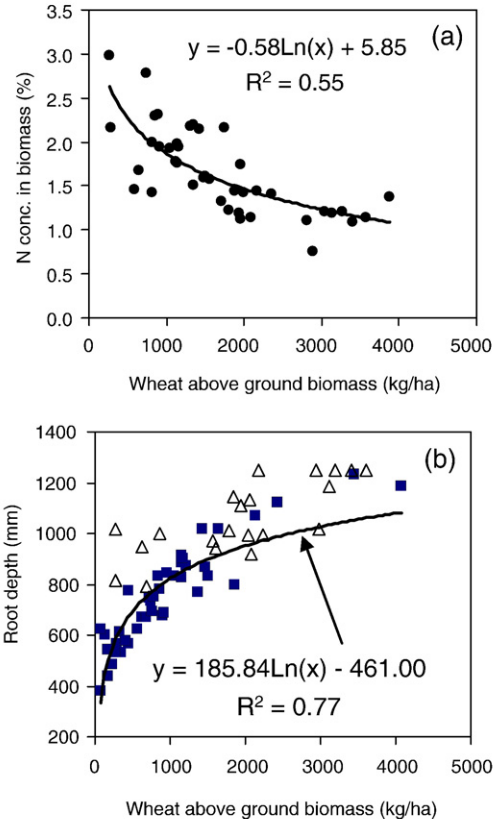

Fig. 10. APSIM predicted wheat N concentration and root depth as a function of above ground wheat biomass for a 41-year simulation using observed weather data (1963–2003). Note that predicted winter wheat biomass and N concentration was determined at kill date in the spring prior to corn or soybean planting (solid circles). Also note that root depth was determined as a function of wheat biomass on day 115 for both soybean and corn years (solid squares), and that root depth is also presented on day 142 prior to soybean planting (open triangles).

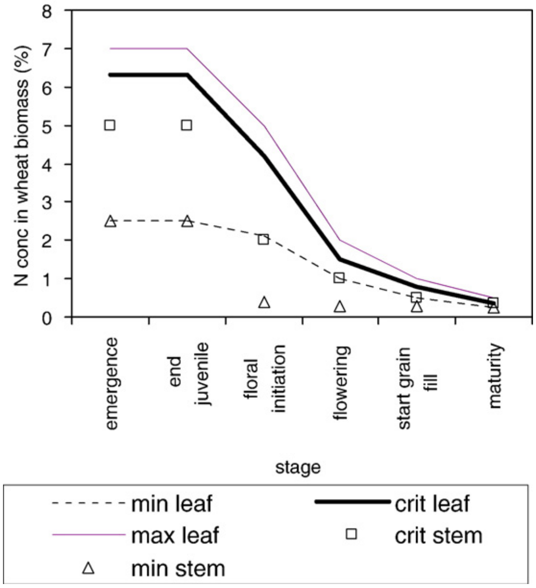

Fig. 11. The minimum, critical, and maximum APSIM N concentration limits for wheat stem and leaf.

such as biomass production, N concentration of biomass, and rooting depth, which is beyond the scope of this study. The cover crop scenario, however, illustrates the potential of the modified APSIM model to estimate the relative impact of alternative management strategies on nitrate loss in tile drainage.

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