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Evaluation of the CERES-Maize water and nitrogen balances under tile-drained conditions☆

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Abstract

The CERES-Maize model was developed to investigate how variations in environmental conditions, management decisions, and genetics interact to affect crop development and growth. A tile drainage subroutine was incorporated into CERES-Maize to improve soil-water and nitrogen leaching under subsurface tile drainage conditions. The purpose of this work was to evaluate the soil-water, soil-nitrogen, tile drainage, and tile-nitrogen loss routines of CERES-Maize for tile-drained fields in Iowa. An analysis was conducted based on information collected from a study of 36 plots consisting of five management systems during a 4-year period from 1993 to 1996, at Nashua, IA. The model was calibrated for each plot using data from 1994 and 1995, and validated using data from 1993 and 1996. Temporal soil-water contents and water flow from tile drains were calibrated to an average root mean square error (RMSE) of 0.036 cm^3 cm^{-3} and 2.62 cm, respectively, compared to measured values. Validation trials gave an average RMSE for soil-water and tile drainage of 0.046 cm^3 cm^{-3} and 5.3 cm, respectively. Soil-nitrate and tile-nitrogen flows were calibrated, with an RMSE of 6.27 μg NO_3 g^{-1} $soil^{-1}$ and 3.21 kg N ha^{-1} $soil^{-1}$, respectively. For the validation trials, the RMSE for soil-nitrate content and cumulative tile-nitrate flow was 6.82 μg NO_3 g^{-1} $soil^{-1}$ and 8.8 kg N ha^{-1}, respectively. These results indicate that the new tile drainage algorithms describe water and nitrate movement reasonably well, which will improve the performance of CERES-Maize for artificially drained fields.

Keywords: Water balance; Nitrogen balance; Modeling; Maize; Drainage

1. Introduction

Iowa ranks in the top three out of eight Midwestern states which comprise a total of 20.6 million hectares utilizing artificial drainage systems (Fausey et al., 1995). Swoboda (1990) estimated that farmers spend $300–400 million a year in Iowa on nitrogen fertilization, with $100 million being spent on unnecessary applications. As a result, many fields in Iowa have a combination of nitrate-nitrogen loss through tile drains with water as it flows from the field and through leaching as large amounts of nitrogen may remain in the soil after the growing season. Soil-water and nitrogen management are important factors in determining

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profitability and possible risks for environmental contamination; therefore, modeling tools, such as CERES-Maize, are needed to evaluate these impacts of field and sub-field management (precision farming) (Paz et al., 1998, 1999).

The CERES-Maize model (Jones and Kiniry, 1986) calculates soil temperature, soil-water availability, nitrate transport, C and N turnover, and crop growth within the plant–soil environment (Gabrielle and Kengni, 1996). The model has been widely used to study the impacts of environmental conditions, management decisions, and genetics on corn growth and development. Recently, researchers in Iowa have used the model to investigate the role of water stress on plant development and growth and have developed methodologies to determine optimal variable rate prescriptions for nitrogen rate and population across several fields (Paz et al., 1999).

The CERES model currently does not account for tile drainage effects on soil-water movement. Many models are available that attempt to predict tile drainage flows and nitrogen losses through tile drains (Madramootoo et al., 1995; Singh and Kanwar, 1995a, b; Skaggs et al., 1995; Verma et al., 1995; Azevedo et al., 1997). A disadvantage of many of these models is that they require an accurate characterization of the location and geometry of the subsurface drainage that is not commonly known for most fields in Iowa. Shen et al. (1998) developed a simple tile drainage routine, which was incorporated into the CROPGRO model (Boote et al., 1998). They found that the model gave cumulative seasonal tile-water flow predictions with errors ranging from −37.42 to 5.74% between predicted and measured values for 36 plots at Nashua, IA, over two validation years.

Several attempts have been made to validate the soil-water and nitrogen predictions of CERES-Maize. Gabrielle et al. (1995) modified the original model by calculating a modified water flow routine, called CERES2wf, on silt loam and sandy loam soils in France. They modified the original CERES equation by calculating drainage and capillary fluxes, which resulted in incorporation of additional parameters dependent on the soil texture and saturated hydraulic conductivity. They found that the original CERES model predicted volumetric soil-water contents with a mean error ranging from −3.34 to 5.60%. CERES2wf gave a mean error range for soil-water contents from −1.65 to 5.60%. CERES2wf performed well for the poorly drained soil types in the study and the original CERES performed well on the well-drained soils.

Gabrielle and Kengni (1996) also evaluated the nitrogen module of CERES-Maize in France. They found that CERES-Maize predicted nitrate leaching with a mean deviation (MD) of 12.3 to 5.9 kg N ha^{-1} and topsoil nitrogen content (0–30 cm depth) from −11.5 to 7.5 kg N ha^{-1}. Kovacs et al. (1995) found that CERES-Maize model, over a long simulation period, gave reasonable predictions of nitrogen transformation and transport, nitrogen plant uptake, nitrogen accumulation in soil, and soil profile nitrate distribution. No studies have been published that evaluate the CERES-Maize soil-water and nitrogen components for conditions typically found in the Midwestern USA, particularly those with tile drainage.

The objectives of this study were to: (1) modify the soil-water balance routines by adding a simple tile drainage flow component to the CERES-Maize model; and (2) evaluate the predicted soil-water and nitrate balance against measurements of soil-water contents, soil-nitrate contents, subsurface tile drainage, and tile-nitrogen losses over a 4-year period.

2. Methodology

2.1. Model modification

The CERES-Maize model calculates water infiltration and runoff using the Soil Conservation Service (SCS) curve number technique. The soil profile is divided into as many as 20 horizontal, homogenous layers with user-specified properties. These properties include the lower limit of water availability to plants (LL, cm^3 cm^{-3}), drained upper limit (DUL, cm^3 cm^{-3}), saturated water holding capacity (SSAT, cm^3 cm^{-3}), saturated hydraulic conductivity (K_{sat} , cm day^{-1}), and a root weighting factor (SRGF) for determining the relative partitioning of roots. Water flux from an individual layer occurs if the soil-water content in that layer is above the DUL. The drainage coefficient (SWCON, day^{-1}) and/or the saturated hydraulic conductivity controls water movement in free drainage or in saturated conditions, respectively. Perched water tables can occur when K_{sat} in the deep soil layers (typically 120–180 cm in depth) have values less than one-tenth to one-hundredth of the K_{sat} in the layers above.

Our criteria for modeling tile drainage was to use a minimal number of parameters that could be easily calibrated to mimic soil-moisture contents at any location in a field. We implemented the approach developed by Shen et al. (1998). Using this approach, drainage from the tile outlet is computed by:

$$q = H \times \frac{k_t}{\mathrm{d} \times 100},$$

where q = daily tile drainage flow (cm day^{-1}); H = the hydraulic head (cm); k_t = saturated hydraulic conductivity for the tile layer (cm day^{-1}); and d = effective drain spacing (m).

The inputs required to implement this algorithm are depth of the tile below the soil surface and effective drain spacing. Hydraulic head (H) is defined as the distance between the tile drain and the top of the uppermost saturated soil layer above the tile drain, and is computed daily in the model. Water flow from the soil through the tile drain is computed each day. As water is removed from the soil by the tile drain under saturated conditions, water in layers above are redistributed to allow for downward flow.

The crop model also calculates soil temperature, nitrate transport, C and N turnover, and crop growth (Jones and Kiniry, 1986). Nitrogen mineralization and immobilization due to crop residue and soil organic matter decomposition is calculated based on routines in the PAPRAN model (Seligman and van Keulen, 1981). The model assumes that two pools of organic matter exist, a fresh organic pool and a stable organic pool (humus). Of the fresh organic matter, 20% is partitioned to carbohydrates, 70% to cellulose, and 10% to lignin fractions. The decomposition rates for carbohydrates are 0.8 day^{-1}, cellulose (0.05 day^{-1}), lignin (0.0095 day^{-1}), and humus (8.3×10^{-5} day^{-1}) are considered, with a C/N ratio fixed at 10 (Jones and Kiniry, 1986; Gabrielle and Kengni, 1996). Solute movement through the soil profile is described with a purely convective method. Solute coming into a layer mixing with solute present in that layer and water leaves this layer at an average solute concentration (Gabrielle and Kengni, 1996).

The nitrogen balance routines were modified to allow nitrate to move with water out of the tile according to:

$$\mathrm{NLOSS} = \frac{\mathrm{SKGN}(L) \times \mathrm{CTDFL}}{\mathrm{SW}(L) \times \mathrm{DLAYER}(L) + \mathrm{CTDFL}},$$

where NLOSS = nitrate loss through tile drain today (kg N ha^{-1}); SKGN(L) = soil nitrate content in layer L (kg N ha^{-1}); CTDFL = cumulative tile drainage flow today (cm); SW(L) = water content in layer L (cm^3 cm^{-3}); and DLAYER(L) = thickness of layer L (cm). As nitrate moves through the bottom soil layer and into the tile drain, the remaining nitrate is redistributed with the remaining soil-water.

2.2. *Field experiments*

The site for this investigation is the Iowa State University's Northeast Research Center located at Nashua, IA. Site soils consist of Kenyon (fine-loamy, mixed, mesic, Typic Hapludolls) and Readlyn (fine-loamy, mixed, mesic, Aquic Hapludolls). These soils range from moderately well-drained to poorly drained, consisting of loamy sediments overlying glacial till. Kenyon and Readlyn soils are located on upland flats, ridge crests, and side slopes (USDA-SCS, 1995). The topsoil is loamy with loam, clay loam, and sandy loam subsoils on slopes varying from 0 to 4%, but are generally less than 2% slope (Bjorneberg, 1995). Organic matter contents of the soils ranged from 3 to 4%. Table 1 contains a more detailed description of the physical characteristics for these soil types.

The site consists of 36 0.4-ha plots with long-term records for tillage and cropping history. In 1979 subsurface tile drains were installed at a

Table 1
Average soil profile characteristics at the ISU Research Center, Nashua, IA

Soil type	Depth (cm)								
	10	20	30	45	60	90	120	150	180
Kenyon									
Sand[a] (% by vol.)	44	34	37	45	45	45	46	45	N/A
Silt[a] (% by vol.)	37	42	38	28	28	26	27	28	N/A
Clay[a] (% by vol.)	19	24	25	27	27	29	27	27	N/A
PAWC[b] (cm cm^{-1})	0.21	0.21	0.18	0.18	0.18	0.18	0.18	0.18	N/A
Bulk density[a] (g cm^{-3})	1.50	1.50	1.50	1.52	1.55	1.65	1.72	1.77	1.80
Permeability[b] (cm hr^{-1})	1.52–5.08								
Readlyn									
Sand[a] (% by vol.)	36	36	37	46	46	44	45	45	N/A
Silt[a] (% by vol.)	41	41	40	27	27	28	29	33	N/A
Clay[a] (% by vol.)	23	23	23	27	27	28	26	22	N/A
PAWC[b] (cm cm^{-1})	0.21	0.21	0.18	0.18	0.18	0.18	0.18	0.18	N/A
Bulk density[a] (g cm^{-3})	1.45	1.45	1.45	1.45	1.45	1.60	1.65	1.67	1.70
Permeability[b] (cm hr^{-1})	1.52–5.08								

[a] Sand, silt, clay percent fractions and bulk density adapted from Weed (1992).
[b] Plant available water capacity (PAWC) and water permability adapted from USDA-SCS (1995).

depth of 1.2 m and at a spacing of 28.5 m. Tile lines were run down the middle and parallel to the edges of each plot. Plots have seasonally high water tables and benefit greatly from the installation of subsurface tile drainage. A more detailed history of site characteristics, operations, and methods are contained in other research reports (Singh and Kanwar, 1995a, b; Kanwar et al., 1996, 1997; Azevedo et al., 1997; Bjorneberg et al., 1998).

Data collected from 19 plots (Kenyon and Readlyn soils) were used in this study. Plots consisted of two tillage practices, no-tillage (NT) and chisel plow (CP) with four corn–soybean rotations and one continuous corn rotation from 1993 to 1996. Table 2 classifies each plot to the corresponding soil type and tillage practice. Generally, soil-moisture and nitrate contents were collected for at least four dates during the study period corresponding to: before planting, after planting, early growing season, and after harvest. Measurements for soil-moisture and nitrate contents were generally taken from depths of: 0–10, 10–20, 20–30, 30–45, 45–60, 60–90, and 90–120 cm, and were analyzed according to techniques described by Ahmed (1996). Tile drainage was monitored on a regular basis for each of the plots from 1993 to 1996. Drainage flows were sampled for nitrate concentrations which were used to calculate a tile-nitrogen outlet flows. Details for field operations are contained in Table 3. Table 4 lists the applied inorganic nitrogen rates for each management system.

Table 2
Plot classification based on soil type and tillage practice used in this study[a]

Treatment[b]	Plot number for each soil type	
	Kenyon	Readlyn
Soybean–corn rotation (NT)	10, 15, 29	2, 16
Corn–soybean rotation (NT)	24, 25, 28	3, 14
Soybean–corn rotation (CP)	9, 18	4, 33
Corn–soybean rotation (CP)	17, 34	6
Continuous corn rotation (CP)	26	5

[a] Adapted from Ahmed (1996).
[b] NT, no tillage, CP chisel plow.

Soil, weather, and management inputs were collected from previous site reports (Weed, 1992; USDA-SCS, 1995; Ahmed, 1996; Kanwar et al., 1996, 1997) and measured field data were set up in the model input and graphical output files. Daily weather data included maximum and minimum temperatures, precipitation, and total solar radiation measured at the site from 1993 to 1996. Soil

Table 3
Field operation dates for all 36 plots at Nashua, IA[a]

Field operation	1993	1994	1995	1996
Corn variety	GH 2343[b]	GH 2343	GH 2343	GH 2343
Monitoring starts	Mar. 26	Mar. 14	Mar. 13	Mar. 29
Spring fertilizer applied	May 14	Apr. 24	May 12	May 3
Planting	May 17	May 2	May 16	May 21
Sidedress fertilizer applied	July 7	June 17	June 22	June 24
Cultivation	July 21	June 2	June 14	June 24
Approximate maturity	Sep. 1	Sep. 2	Sep. 7	Oct. 5
Harvest	Oct. 25	Sep. 28	Sep. 22	Oct. 21
End monitoring	Dec. 1	Dec. 8	Dec. 15	Dec. 13

[a] Adapted from Kanwar et al. (1997).
[b] GH 2343 is Golden Harvest 2343.

Table 4
Nitrogen application rates for Nashua, IA[a]

System	Applied nitrogen (kg N ha^{-1})			
	1993	1994	1995	1996
NT-LSNT[b]	144	169	193	195
NT-single	110	110	110	110
CP-LSNT[b]	93	160	160	169
CP-single	110	110	110	110
CC-single	135	135	135	135

[a] Taken from Kanwar et al. (1997).
[b] Amount for late spring nitrate test includes 30 kg N ha^{-1} applied with planter.

physical properties measured included percent sand, silt, clay, plant available water, and bulk density for the Kenyon and Readlyn soil types (Table 1). Initial estimates for these parameters were obtained from Ratliff et al. (1983) and Mirjat (1992). The plots in the soybean portion of the corn–soybean rotation were not analyzed with CERES-Maize. Shen et al. (1998) evaluated the CROPGRO-Soybean tile flow algorithm on the soybean rotation in these plots.

2.3. Parameter estimation

Data collected from 1994 and 1995 were used for model calibration and 1993 and 1996 were used for model validation. Initial estimates of the LL, DUL, saturated hydraulic conductivity, SCS runoff curve number, and effective drain spacing were calibrated in each grid to obtain the most accurate predicted soil-water contents and tile drainage flows. Some previously measured data were available from Mirjat (1992) for saturated hydraulic conductivity on some of the plots, and were used as a starting point for calibration. Soil-nitrogen mineralization rate, soil organic contents, and the tile drainage spacing were adjusted to fit the measured values of soil-nitrate contents by layer and tile-nitrate flows. Soil-nitrogen mineralization rates and soil organic contents were adjusted within ranges noted by the USDA-SCS Soil Survey for Floyd County, IA (1995).

2.4. Model evaluation

Predicted soil moisture and nitrate contents and tile-water and nitrate flows were analyzed using two statistical properties, the mean deviation (MD) and the root mean square for error (RMSE), computed according to Gabrielle et al. (1995).

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}(\text{measured} - \text{predicted});$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\text{measured} - \text{predicted})^2}{n}},$$

where n = number of observations. Measured corresponds to the field measured value for the particular property of interest and predicted represents the predicted value produced by the model.

3. Results

3.1. Soil-water content

Tables 5 and 6 show the MD and RMSE for eight Readlyn and 11 Kenyon plots. The MD averaged 0.009 $cm^3\ cm^{-3}$ over all plots in both soil types for the validation years. The range was −0.002 to 0.018 $cm^3\ cm^{-3}$, which indicated that the model slightly over-predicted soil-water content. The average RMSE for volumetric soil water content over all plots and soil types for the validation years was 0.046 $cm^3\ cm^{-3}$. The plots in the Readlyn soil type tended to have the best predictions for soil-water content over all of the years. For Readlyn soil, the model gave an MD of approximately 0.004 $cm^3\ cm^{-3}$ and 0.006 $cm^3\ cm^{-3}$ for calibration and validation years, respectively. The model tended to under-predict water contents early in the season for all years. This likely occurred because the model allowed water to move through the soil profile faster than what was observed in the field. Fig. 1a shows the prediction of water storage over the soil profile for Plot 5 over the entire season. The water storage represents an overall measurement of the water volume

Table 5
Average mean diviation (MD) and root mean square error (RMSE) of measured and simulated soil water ($cm^3\ cm^{-3}$) for eight Readlyn soil type plots

Depth (cm)	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
0–5	0.003	0.025	0.034	0.050	0.029	0.040	–	–
5–15	0.009	0.031	0.005	0.029	0.007	0.046	0.041	0.055
15–30	0.008	0.042	0.020	0.041	−0.003	0.046	0.031	0.049
30–45	0.003	0.029	−0.012	0.031	−0.019	0.040	0.012	0.046
45–60	−0.001	0.028	–	–	0.001	0.041	0.012	0.046
60–90	−0.006	0.032	−0.003	0.023	0.001	0.029	−0.008	0.031
90–120	−0.011	0.024	−0.008	0.025	−0.029	0.054	−0.008	0.031
Average	0.001	0.030	0.006	0.033	−0.002	0.042	0.013	0.043

Table 6
Average mean deviation (MD) and root mean square error (RMSE) of measured and simulated soil water ($cm^3\ cm^{-3}$) for 11 Kenyon soil type plots

Depth (cm)	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
0–5	0.015	0.035	0.021	0.052	0.047	0.072	–	–
5–15	0.008	0.033	0.004	0.037	0.019	0.043	0.037	0.054
15–30	0.015	0.037	0.026	0.051	0.026	0.053	0.027	0.056
30–45	0.010	0.030	−0.017	0.051	0.004	0.004	0.014	0.063
45–60	0.004	0.030	–	–	−0.014	0.059	0.014	0.063
60–90	0.006	0.040	−0.011	0.040	−0.015	0.037	0.008	0.044
90–120	−0.005	0.050	−0.011	0.044	−0.030	0.047	0.008	0.044
Average	0.008	0.036	0.002	0.046	0.005	0.045	0.018	0.054

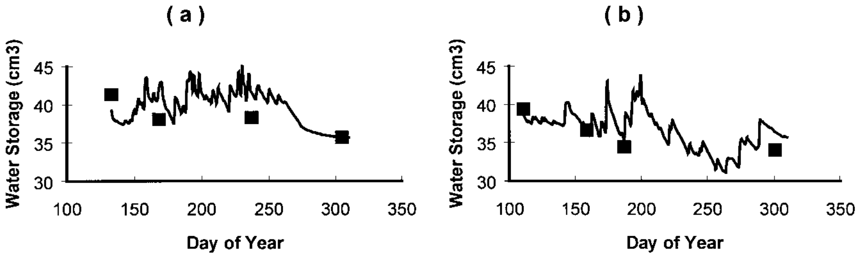

Fig. 1. Predicted and measured water storage for Plot 5 (Readlyn) for (a) the validation year 1993 and (b) the calibration year 1994. Solid line is simulated values and points are the field measurements.

contained in the profile. Since the model tended to over-predict some layers and under-predict other layers, the differences in error tended to cancel out, resulting in good predictions of water storage over the profile.

The model predicted volumetric soil-water contents for the Kenyon soil type with an average MD of approximately 0.005 $cm^3\ cm^{-3}$ for calibration years and 0.011$cm^3\ cm^{-3}$ for the validation years (Table 6), indicating a slight over-prediction of soil-water contents on average. The model tended to give poorer predictions in the upper and middle layers of the soil profile compared to Readlyn soil, as evidenced by the RMSE values in each layer (Tables 5 and 6). Although the differences are not large, this probably indicates that the calibrated soil-water holding capacities in the top and middle layers did not adequately describe the physical system.

3.2. Subsurface tile drainage

Table 7 shows the MD and RMSE values for cumulative tile-water flow averaged over the 11 Kenyon and eight Readlyn plots. The model gave an MD of 1.33 cm for calibration years and 0.03 cm for validation years, averaged over all soil types and years, indicating a tendency to over-predict tile flow. The RMSE was 2.62 and 5.30 cm averaged over the two calibration and validation years and two soil types, respectively (Table 7). Cumulative tile-water flow ranged from 0 to over 20 cm per year for the plots in this study, representing a large range of environments for testing the model. The model performed well in 1995 (calibration) and 1996 (validation) for both soil types and in 1994 (calibration) for Kenyon. The RMSE values tended to be high in 1993 for both soil types where relatively large tile flows were measured (up to 20 cm). The model also had difficulty in 1994 when relatively low tile flows were observed. In the worst calibration and validation years, the model tended to over-predict tile flows when low flows were observed, and under-predict tile flow when high flows were measured. Fig. 2a, b shows the example time series graphs for subsurface tile drainage flows for Plot 5 (Readlyn) for 1993 and 1994; the worst prediction by the model. However, the model gave very nice fits to measured data for many of the other plots and years.

Table 7
Mean deviation (MD) and root mean square error (RMSE) between measured and simulated cumulative subsurface tile drainage (cm) for Kenyon and Readlyn soil types at Nashua, IA

Soil type	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
Kenyon	−0.04	1.40	0.04	0.32	0.72	5.40	0.31	3.47
Readlyn	4.93	7.95	0.35	0.80	−3.33	9.08	2.41	3.25
Average	2.45	4.68	0.20	0.56	−1.31	7.24	1.36	3.36

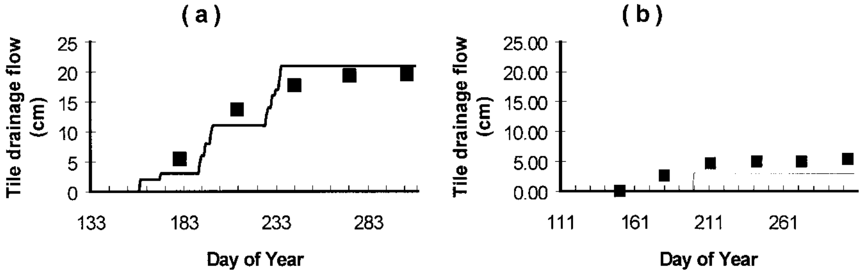

Fig. 2. Predicted and measured cumulative subsurface tile drainage flow for Plot 5 (Readlyn soil) for (a) the validation year 1993 and (b) the calibration year 1994. Solid line is simulated values and points are the field measurements.

Subsurface tile flow was predicted well in 1993, but in 1994 the model underestimated tile flow by approximately 2 cm (Fig. 2).

3.3. Soil-nitrate content

The mean difference between predicted and measured soil-nitrate contents is shown in Tables 8 and 9. For the validation years, the MD values ranged from an average of −2.53 μg NO_3 g^{-1} $soil^{-1}$ for the Readlyn soil type to −1.17 μg NO_3 g^{-1} $soil^{-1}$ for the Kenyon soil type. The RMSE averaged 6.83 μg NO_3 g^{-1} $soil^{-1}$ across the two soil types for validation years. For Kenyon, the model gave MD values of −0.99 μg NO_3 g^{-1} $soil^{-1}$ (RMSE 5.5 μg NO_3 g^{-1} $soil^{-1}$) and 1.17 μg NO_3 g^{-1} $soil^{-1}$ (RMSE 6.0 μg NO_3 g^{-1} $soil^{-1}$) for calibration and validation years, respectively. This indicates that the model generally under-predicted overall soil-nitrate contents, although it over-predicted nitrate in some layers (Table 8). Fig. 3 shows the time series soil-nitrate for Plot 26, which is a continuous corn system with Kenyon soil type for the 1993 validation year. The model tended to over-predict soil-nitrate for Plot 26, especially in the upper layers, during the early growing season. In this plot, the soil-water contents were also not predicted as well as other plots. Fig. 4 shows the prediction of the total nitrate storage in the soil profile over the entire season for Plot 26. Although there were errors in predicted nitrate in each soil layer, the total storage of nitrate in the soil profile (above the tile drain) was predicted very well.

For the Readlyn soil, the model gave an MD of −1.95 μg NO_3 g^{-1} $soil^{-1}$ (RMSE 7.1 μg NO_3 g^{-1} $soil^{-1}$) and 2.53 μg NO_3 g^{-1} $soil^{-1}$ (RMSE 7.6 μg NO_3 g^{-1} $soil^{-1}$) for calibration and validation years, respectively, over all of the soil layers. Highly variable infiltration was likely the primary

Table 8
Mean deviation (MD) and root mean square error (RMSE) of measured and simulated soil nitrate (μg NO_3 g^{-1} $soil^{-1}$) for Kenyon soil type

Depth (cm)	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
0–5	4.00	12.5	−5.11	16.1	−2.22	18.3	–	–
5–15	−4.63	7.78	−5.14	12.5	−2.63	13.1	−8.87	20.6
15–30	−0.54	6.72	−1.06	2.56	0.61	3.77	−0.71	5.45
30–45	0.08	2.11	−0.77	2.84	0.12	4.46	−1.06	3.85
45–60	−0.03	2.49	–	–	−0.26	1.67	−1.06	3.85
60–90	0.36	1.72	0.29	1.48	0.50	1.27	0.31	0.72
90–120	0.29	0.69	0.33	1.18	0.48	1.06	0.31	0.72
Average	−0.07	4.86	−1.91	6.11	−0.49	6.23	−1.85	5.86

Table 9
Mean deviation (MD) and root mean square error (RMSE) of measured and simulated soil nitrate (μg NO_3 g^{-1} $soil^{-1}$) for Readlyn soil type

Depth (cm)	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
0–5	−0.87	10.3	−11.3	27.5	−10.9	27.4	–	–
5–15	−3.77	17.2	−8.40	18.3	−8.69	18.0	−7.16	20.5
15–30	−2.15	5.62	−0.53	1.86	−2.59	7.16	0.09	5.76
30–45	0.54	1.26	−0.53	2.37	−2.29	5.05	−1.64	4.54
45–60	0.55	1.44	–	–	−0.81	2.46	−1.64	4.54
60–90	0.46	1.16	0.72	1.26	0.33	2.06	0.52	1.02
90–120	0.40	0.62	0.84	1.18	0.38	0.83	0.52	1.02
Average	−0.69	5.37	−3.20	8.75	−3.51	8.99	−1.55	6.23

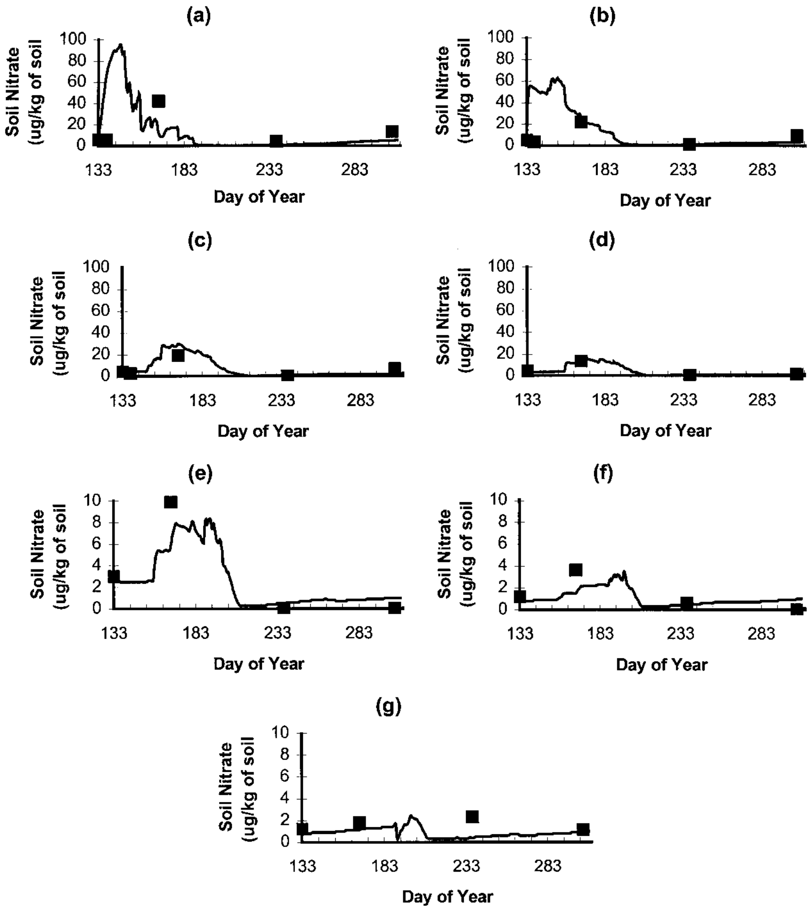

Fig. 3. Predicted and measured soil-nitrate for depths of: (a) 0–5 cm, (b) 5–15 cm, (c) 15–30 cm, (d) 30–45 cm, (e) 45–60 cm, (f) 60–90 cm, and (g) 90–120 cm for Plot 26 (Kenyon soil) at Nashua, IA, for 1993. Solid lines are the simulated values and points are the field measurements.

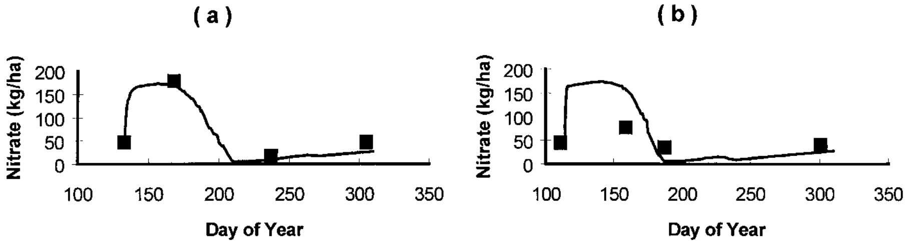

Fig. 4. Predicted and measured nitrate in soil profile for Plot 26 (Kenyon soil) for (a) validation year 1993 and (b) calibration year 1994. Solid lines are the simulated values and points are the field measurements.

cause for the difficulties in predicting soil-nitrate movement in some of the upper soil layers. The measured soil-nitrate content reached a steady state in the deeper layers throughout the growing season. The model reflected this trend.

3.4. Subsurface tile-nitrogen flow

The tile-nitrate-nitrogen flow was predicted based on nitrate concentration in the water flowing out the tile. Calibration was performed by adjusting the soil organic carbon contents within a range suggested by the USDA-SCS (1995) Soil Survey for Floyd County, IA, to give the best predictions of soil nitrate. Table 10 shows the MD and RMSE for the Kenyon and Readlyn soil types for calibration and validation years. Kenyon had the lowest MD (1.79 and 6.31 kg ha^{-1}) for subsurface tile-nitrogen flow followed by Readlyn (4.03 and 8.48 kg ha^{-1}) for calibration and validation, respectively. Errors in predicted tile-water flow resulted in errors in predicting nitrate flow from the tile drain; thus the model generally overpredicted tile-nitrate flow. The RMSE values for the calibration and validation years averaged over both soils were 3.2 and 8.8 kg ha^{-1}, respectively. In one case (1994), the measured data indicated water and nitrogen tile flow, where the model predicted no flow. There were many cases where the model gave excellent predictions of tile-nitrate flows. Fig. 5a, b shows the graphs for subsurface tile-nitrogen flow for Plot 26 for 1993 (validation) and 1994 (calibration) as examples. Combining Fig. 5 with results shown in Table 10 gives an indication of how the MD and RMSE values appear in terms of time series total nitrate storage in the soil profile (above the drain). Generally, the model gave good predictions of total soil-nitrate above the tile line, even though it was not always accurate for a given soil layer.

4. Discussion

A tile drainage network imposes spatial variability in the soil-water and nitrogen dynamics across a field. In many cases, the geometry of the tile is not known; thus, classical approaches for

Table 10
Mean deviation (MD) and root mean square error (RMSE) between measured and simulated cumulative subsurface tile-nitrogen flow (kg ha^{-1}) for Kenyon and Readlyn soil types at Nashua, IA

Depth (cm)	Calibration				Validation			
	1994		1995		1993		1996	
	MD	RMSE	MD	RMSE	MD	RMSE	MD	RMSE
Kenyon	1.35	2.21	2.23	2.56	9.27	12.4	3.34	5.77
Readlyn	5.50	5.50	2.55	2.55	11.3	11.3	5.65	5.65
Average	3.43	3.86	2.39	2.56	10.3	11.9	4.50	5.71

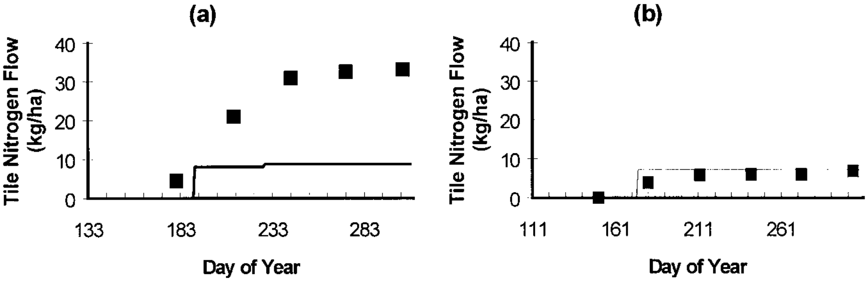

Fig. 5. Predicted and measured cumulative subsurface tile-nitrogen flow for Plot 26 (Kenyon soil) for (a) validation year 1993 and (b) calibration year 1994. Solid lines are the simulated values and points are the field measurements.

modeling tile drainage cannot be employed effectively. The method developed in this paper requires the estimate of two parameters (conductivity and effective drain spacing) to describe tile flow, and subsequently soil-water dynamics. In this example, these parameters were estimated based on detailed soil-water content and cumulative tile flow measurements. By calibrating water flow, the model gave good predictions of cumulative tile-nitrate flow and soil-nitrate concentrations. This provides a level of confidence for using the model to predict environmental impacts of nitrogen applications. The strength of this approach is that tile geometry and conductivity need not be known. However, the parameters in this model must be calibrated using field measurements of soil-moisture, nitrate content, tile-water, and nitrate flow.

This method of computing tile drainage may be advantageous when the model is implemented in situations where above-ground measurements can be used to estimate soil properties. Recently, Paz et al. (1999) attempted to overcome limitations of soil and tile field measurements by using above-ground biomass measurements to estimate the tile drainage parameters in the model. They calibrated tile drain spacing and the saturated hydraulic conductivity at 2 m to impose subsurface water dynamics that minimized error between predicted and measured corn yields in 224 grids in a 40-ha field over a 3-year period. Above-ground biomass is an excellent integrator of water and nitrate stress. While calibrating tile drainage properties using above-ground biomass has been shown to work reasonably well (Paz et al., 1998, 1999), there is still some uncertainty in parameter estimation. It is likely that integration of spatial images indicating surface wetness (before emergence) and within-season vegetative index, coupled with final yield will refine estimates of the tile model parameters, improving the certainty of parameter estimates. The tile-water and nitrogen flow methods outlined in this paper may prove to be a foundation for improving spatial representation of soil-water and nitrogen dynamics.

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