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Sensitivity of tile drainage flow and crop yield on measured and calibrated soil hydraulic properties

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Abstract

Process-based agricultural system models require detailed description of soil hydraulic properties that are usually not available. The objectives of this study were to evaluate the sensitivity of model simulation results to variability in measured soil hydraulic properties and to compare simulation results using measured and default soil parameters. To do so, we measured soil water retention curves and saturated soil hydraulic conductivity (K_{sat}) from intact soil cores taken from a long-term experimental field near Nashua, Iowa for the Kenyon–Clyde–Floyd–Readlyn soil association. The soil water retention curves could be well described using the pore size distribution index (λ). Measured λ values from undisturbed soil cores ranged from 0.04 to 0.12 and the measured K_{sat} values ranged from 1.8 to 14.5 cm/h. These hydraulic properties were then used to calibrate the Root Zone Water Quality Model (RZWQM) for simulating soil water content, water table, tile drain flow, and crop yield (corn and soybean) by optimizing the lateral K_{sat} (LK_{sat}) and hydraulic gradient (HG) for subsurface lateral flow. The measured soil parameters provided better simulations of soil water storage, water table, and N loss in tile flow than using the default soil parameters based on soil texture classes in RZWQM. Sensitivity analyses were conducted for λ, K_{sat}, saturated soil water content (θ_s) or drainable porosity, LK_{sat}, and HG using the Latin Hypercubic Sampling (LHS) and for LK_{sat} and HG also using a single variable analysis. Results of sensitivity analyses showed that RZWQM-simulated yield and biomass were not sensitive to soil hydraulic properties. Simulated tile flow and N losses in tile flow were not sensitive to λ and K_{sat} either, but they were sensitive to LK_{sat} and HG. Further sensitivity analyses using a single variable showed that LK_{sat} in the tile layer was a more sensitive parameter compared to LK_{sat} in other soil layers, and HG was the most sensitive parameter for tile flow under the experimental soil and weather conditions.
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Keywords: Subsurface drainage; N loading; Tile flow; Agricultural systems modeling; Water table; Water balance; Nitrogen balance

1. Introduction

Agricultural system models require input of soil properties, weather data, plant parameters, and management practices, for all of which uncertainty has been a major concern. The more complex a model, the more parameters it requires and the more sensitive its simulation results are to uncertainty in input parameters. Among the major requirements for a process-based model are detailed soil hydraulic properties (e.g. soil water retention curve, hydraulic conductivity) for the study site. As a result, estimating soil hydraulic properties has been a significant subject of study for soil physicists and agricultural engineers. Rawls et al. (1982) compiled soil hydraulic properties for 11 soil texture classes, which was used as default soil database in the Root Zone Water Quality Model (RZWQM). Later, they refined these estimates based on a series of regression equations from soil texture, soil organic carbon, soil porosity, and soil bulk density (Rawls and Brakensiek, 1985), which were used to estimate soil hydraulic properties in GPFARM (Great Plains Framework for Agricultural Resources Management) (Andales et al., 2003).

Ahuja and Williams (1991) and Williams and Ahuja (2003) found that the soil water retention curves as described by the

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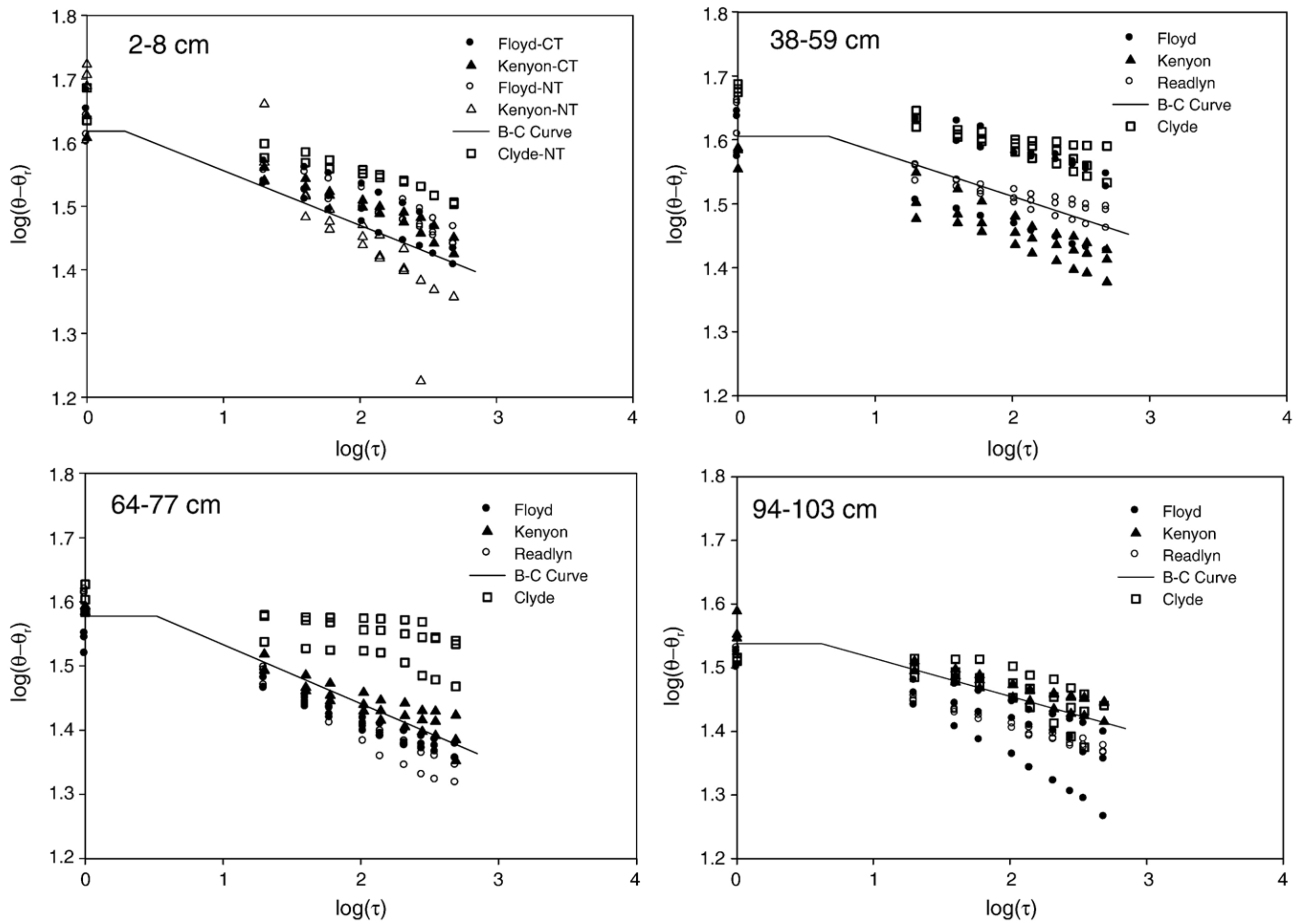

Fig. 1. Measured soil water retention curves for all the four soils and the lines are average Brooks–Corey curves for the Floyd, Kenyon, and Readlyn soils.

Brooks–Corey equations could be simply described by the pore size distribution index (λ). In other words, if the value for λ is known for a soil, the soil water retention curve for the soil can be estimated with good confidence. For saturated soil hydraulic conductivity (K_{sat}), Ahuja et al. (1984) found that it could be estimated as a power function of effective porosity. In RZWQM, users can either use K_{sat} based on soil texture class given in Rawls et al. (1982) or estimate K_{sat} from effective

Table 1
Measured soil hydraulic properties of Clyde, Floyd, Kenyon, and Readlyn soils

Soil or tillage	Depth (cm)	θ (cm/cm)	λ*	K_{sat}* (cm/h)	Bulk density (g/cm^3)	Particle density (g/cm^3)	Sand (g/kg)	Silt (g/kg)	Clay (g/ka)
NT (C)	0–8	0.49	0.063	0.83	1.36	2.58	215	493	292
NT (K, F)	0–8	0.44	0.080	3.58	1.42	2.60	312	434	254
CT (K, F)	0–8	0.51	0.119	3.65	1.26	2.61			
Clyde	38–59	0.51	0.047	0.00079	1.30	2.64	257	412	331
Clyde	64–77	0.43	0.040	0.00064	1.55	2.72	304	405	291
Clyde	94–103	0.35	0.083	0.095	1.74	2.69	496	245	259
Floyd	38–59	0.44	0.063	28.92	1.50	2.69	252	442	306
Floyd	64–77	0.37	0.071	27.84	1.69	2.69	466	285	249
Floyd	94–103	0.36	0.082	1.17	1.71	2.66	472	308	220
Kenyon	38–59	0.40	0.078	6.89	1.62	2.71	447	295	258
Kenyon	64–77	0.41	0.062	12.97	1.58	2.69	340	326	334
Kenyon	94–103	0.39	0.048	0.704	1.65	2.71	320	304	376
Readlyn	38–59	0.47	0.043	4.71	1.43	2.67	395	336	269
Readlyn	64–77	0.47	0.103	8.15	1.50	2.68	469	242	289
Readlyn	94–103	0.36	0.056	3.84	1.71	2.65	449	254	297
Average F, K, R	0–8	0.442	0.086	3.60	1.45	2.60	312	434	254
Average F, K, R	38–59	0.430	0.070	8.05	1.51	2.65	365	357	278
Average F, K, R	64–77	0.405	0.092	14.50	1.60	2.69	425	285	290
Average F, K, R	94–103	0.372	0.060	1.80	1.69	2.69	413	289	298

*Geometric means were taken for λ and K_{sat}. C: Clyde; F: Floyd; K: Kenyon; R: Readlyn.

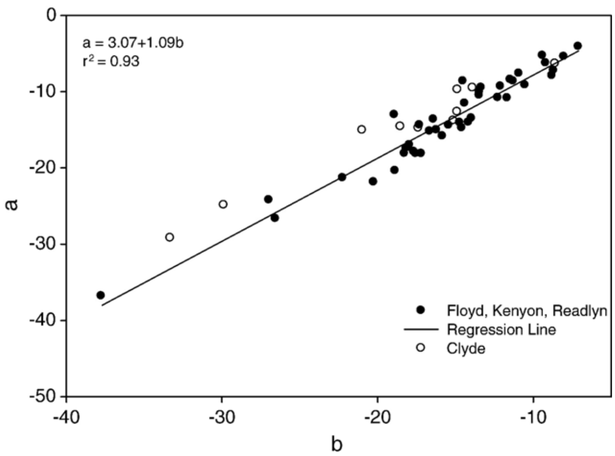

Fig. 2. Fitted one-parameter model based on measured soil water retention curves for all the soils and soil layers, where soil water retention curve is given by Eq. (3) [$\ln(\tau)=a+b\ \ln(\theta-\theta_r)$].

porosity (Ahuja et al., 2000). Users can also input measured K_{sat} if available.

These estimates of soil hydraulic properties were adequate in some applications of RZWQM (Ma et al., 1998; Starks et al., 2003), while they were inadequate under other conditions (Malone et al., 2004). Although it was recommended to use measured values whenever it was possible (Ma et al., 1998), it was a major concern for model users on how to deal with the experimental errors and spatial variability in soil hydraulic property measurements since most models took only one value rather than a distribution for a given parameter. Users also would like to know how the experimental errors in input parameters were transferred to errors in model outputs. Under semi-arid conditions of Colorado, Ma et al. (2000) found that N leaching loss and corn yield were more sensitive to average K_{sat} in the soil profile rather than individual K_{sat} of each layer. They attributed the lack of responses to K_{sat} to lower rainfall and infrequent irrigation. For an Illinois soil, Walker et al. (2000) found that K_{sat} (=LK_{sat}) was a sensitive parameter for tile flow, but not for crop yield (corn–soybean rotation). The Brooks–Corey soil water retention parameters also affected only tile flow not yield in their study. For Iowa conditions, Kumar et al. (1998, 1999) and Singh and Kanwar (1995) found that LK_{sat} and drainable porosity (soil porosity – soil water content at 1/3 bar) were the most sensitive variables in simulating tile drainage flow.

In most sensitivity analyses, model parameters are allowed to vary around their base values independently (Tiscareno-Lopez et al., 1993; Barnes and Young, 1994) or dependently (Silberbush and Barber, 1983). The range of the perturbation may be a specific percentage (Barnes and Young, 1994; Ferreira et al., 1995) or determined from experimental measurements (Fontaine et al., 1992; Gwo et al., 1996). The most common form of sensitivity analysis is independent parameter perturbation (IPP), in which parameters are varied individually by a fixed percentage around a base value (Ferreira et al., 1995). More recent approaches vary multiple parameters simultaneously

Table 2
Hydraulic parameters used to simulate the Nashua data (see Saseendran et al., 2007-this issue; Kumar et al., 1999)

Soil depth (cm)	Bulk density (g/cm^3)	θ_s (cm^3/cm^3)	λ	τ_b (cm)	K_{sat} (cm/h)	1/3 bar SW $\theta_{1/3}$ (cm^3/cm^3)	15 bar SW θ_{15} (cm^3/cm^3)	θ_r	LK_{sat}* (cm/h)
0–20	1.45	0.442	0.086	1.9	3.60	0.300	0.1451	0.027	3.60
20–41	1.51	0.430	0.070	4.6	6.05	0.270	0.1321	0.027	6.05
41–50	1.51	0.430	0.070	4.6	8.50	0.260	0.1278	0.027	8.50
50–69	1.60	0.405	0.092	3.3	11.50	0.234	0.1164	0.027	11.50
69–89	1.60	0.405	0.092	3.3	14.50	0.234	0.1164	0.027	14.50
89–101	1.69	0.372	0.060	4.2	1.80	0.260	0.1278	0.027	9.41
101–130	1.80	0.333	0.060	4.2	1.80	0.280	0.1365	0.027	17.22
130–150	1.80	0.333	0.060	4.2	0.01	0.280	0.1365	0.027	0.01
150–200	1.80	0.333	0.060	4.2	0.01	0.280	0.1365	0.027	0.01
200–252	1.80	0.333	0.060	4.2	0.01	0.280	0.1365	0.027	0.01

*LK_{sat} was fitted. Fitted lateral hydraulic gradient (HG) was 2.4×10^{-5}.

Table 3
Ranges of λ, θ_s, and K_{sat} sampled and their sampled mean values

Parameter sampled	Soil depth (cm)	Range of values sampled	Mean value
λ	0–20	0.077–0.147	0.107
	20–41	0.028–0.085	0.050
	41–50	0.028–0.085	0.050
	50–69	0.057–0.121	0.084
	69–89	0.057–0.121	0.084
	89–101	0.039–0.120	0.070
	101–130	Not sampled	–
θ_s (cm^3/cm^3)	0–20	0.426–0.556	0.491
		(0.141–0.244[a])	(0.188)
	20–41	0.385–0.484	0.435
		(0.092–0.162)	(0.124)
	41–50	0.385–0.484	0.435
		(0.086–0.170)	(0.130)
	50–69	0.357–0.443	0.400
		(0.082–0.150)	(0.114)
	69–89	0.357–0.443	0.400
		(0.071–0.150)	(0.111)
	89–101	0.344–0.415	0.379
		(0.032–0.101)	(0.067)
	101–130	Not sampled	–
K_{sat} (cm/h)	0–20	1.03–9.78	3.38
	20–41	Not sampled	–
	41–50	4.71–28.92	12.17
	50–69	Not sampled	–
	69–89	6.47–34.66	15.52
	89–101	0.46–18.02	3.41
	101–130	0.46–18.02	3.41
LK_{sat} (cm/h)	0–20	0.38–27.78	4.11
	20–41	0.005–29.84	1.00
	41–50	0.018–7.82	0.61
	50–69	0.079–3.47	0.63
	69–89	0.054–9.73	1.02
	89–101	0.057–32.04	2.25
	101–130	1.33–141.30	18.12
	130–150	0.0058–0.60	0.078
	150–200	0.00078–0.083	0.011
	200–252	0.0027–0.147	0.024
	HG	1.59×10^{-6}–2.34×10^{-4}	2.64×10^{-5}

[a]Values are for drainable porosity ($\theta_s-\theta_{1/3}$), $\theta_{1/3}$ is soil water content at 1/3 bar suction.
λ and K_{sat} are assumed to be log-normal distributed; θ_s is assumed to be normal distributed.

based on underlying probability distributions of the parameters, such as the Latin Hypercube Sampling (LHS) (Gwo et al., 1996; Ma et al., 2000). The output responses of a model to parameter perturbation may be quantified by percentage change of selected output variables (Barnes and Young, 1994; Ferreira et al., 1995), relative change of output versus input (Nearing et al., 1990; Larocque and Banton, 1994), sensitivity coefficients from linear regression analysis (Fontaine et al., 1992; Tiscareno-Lopez et al., 1993; Gwo et al., 1996), and graphic response curves or probability distributions (Haan and Zhang, 1996; Ellerbroek et al., 1998).

However, most sensitivity analyses were not designed to study variability in experimental measurements on model outputs, and could not be used to answer the question of what quantity of the experimental errors in input parameters was transferred to simulation output errors. In this study, variability in measured soil hydraulic properties was used to conduct sensitivity analyses of the RZWQM–DSSAT hybrid model (Ma et al., 2005, 2006) after it was calibrated for a long-term study in Nashua, Iowa of the USA (Saseendran et al., 2007-this issue). The objectives of this study were to conduct sensitivity analyses on how experimental errors in hydraulic parameter measurement affected simulation results of RZWQM, and to evaluate these model simulation results against those using the default soil parameters based on soil texture from Rawls et al. (1982) in RZWQM. Results from sensitivity analyses were used in subsequent studies to parameterize RZWQM for different fields with different drainage characteristics (Saseendran et al., 2007-this issue).

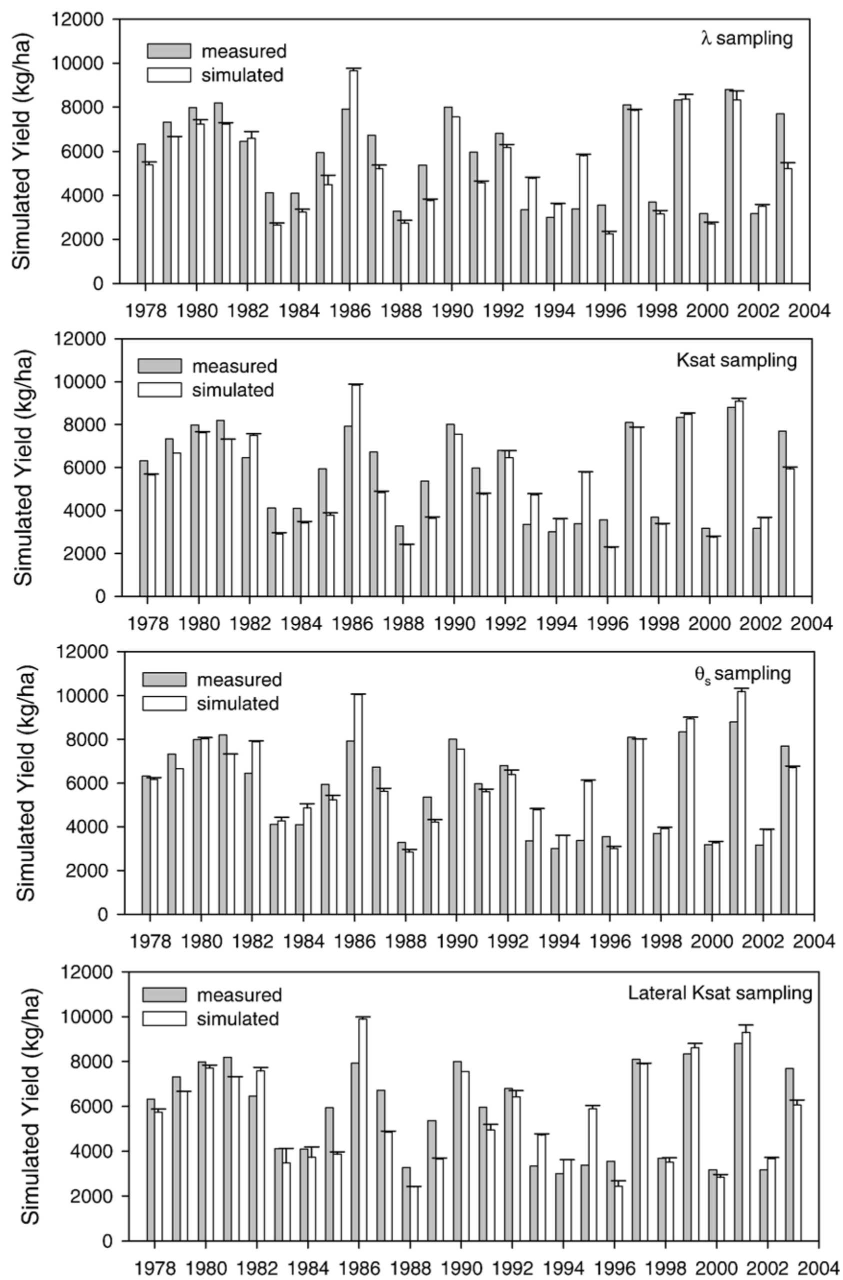

Fig. 3. Simulated crop yield responses to λ, θ_s, K_{sat}, and LK_{sat}+HG sampled from LHS soybean was planted in 1994, 1996, 1998, 2000, 2002; and corn was planted in other years.

2. Materials and methods

The water quality study from the Nashua, IA experiment station includes 36 one-acre plots across four soils: Clyde, Readlyn, Floyd, and Kenyon loam (Ma et al., 2007-this issue). The experiment was conducted at Iowa State University's Northeast Research Center in Nashua, IA. The three dominant soils at this site are Floyd loam (fine-loamy, mixed, mesic Aquic Hapludolls), Kenyon silty-clay loam (fine-loamy, mixed, mesic Aquic Hapludolls), and Readlyn loam (fine-loamy, mixed, mesic Aquic Hapludolls). These soils are moderately well to poorly drained and lie over loamy glacial till and belong to the Kenyon–Clyde–Floyd soil association. Seasonal water tables fluctuate from 20 to 160 cm below the surface. Subsurface drainage tiles (10 cm in diameter) were installed in the fall of 1979 at 120 cm depth and 29 m apart. A HOES trenchless drain plow was used to install the center tile in each plot and a HOES chain trencher was used to install the tiles between plots as buffer tiles. Tile drains from the center tile were collected from each plot and used for water quality analysis. Three phases of the study were conducted. From 1978–1993, the main focus of the study were tillage practices (moldboard plow, chisel plow,

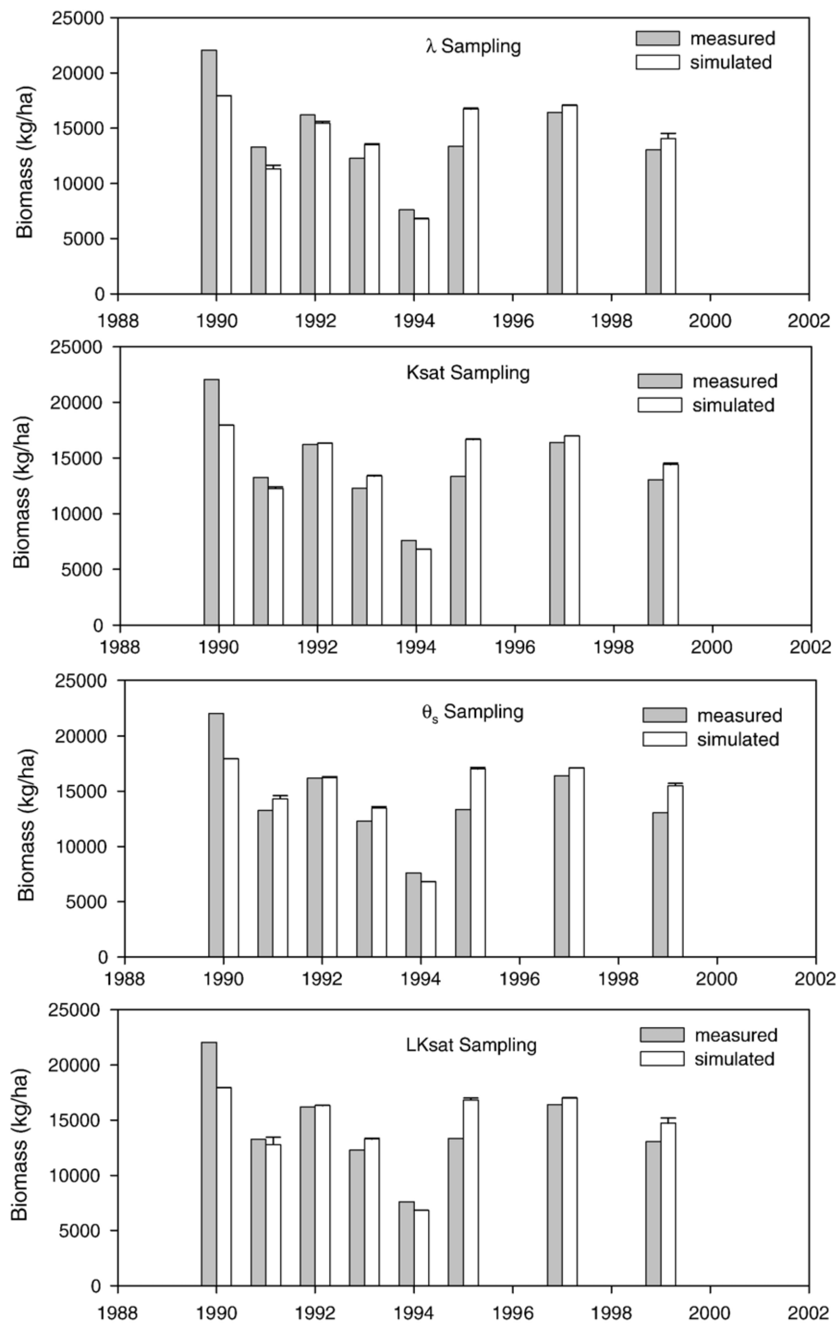

Fig. 4. Simulated crop biomass responses to λ, θ_s, K_{sat}, and LK_{sat}+HG sampled from LHS soybean was planted in 1994, 1996, 1998, 2000, 2002; and corn was planted in other years.

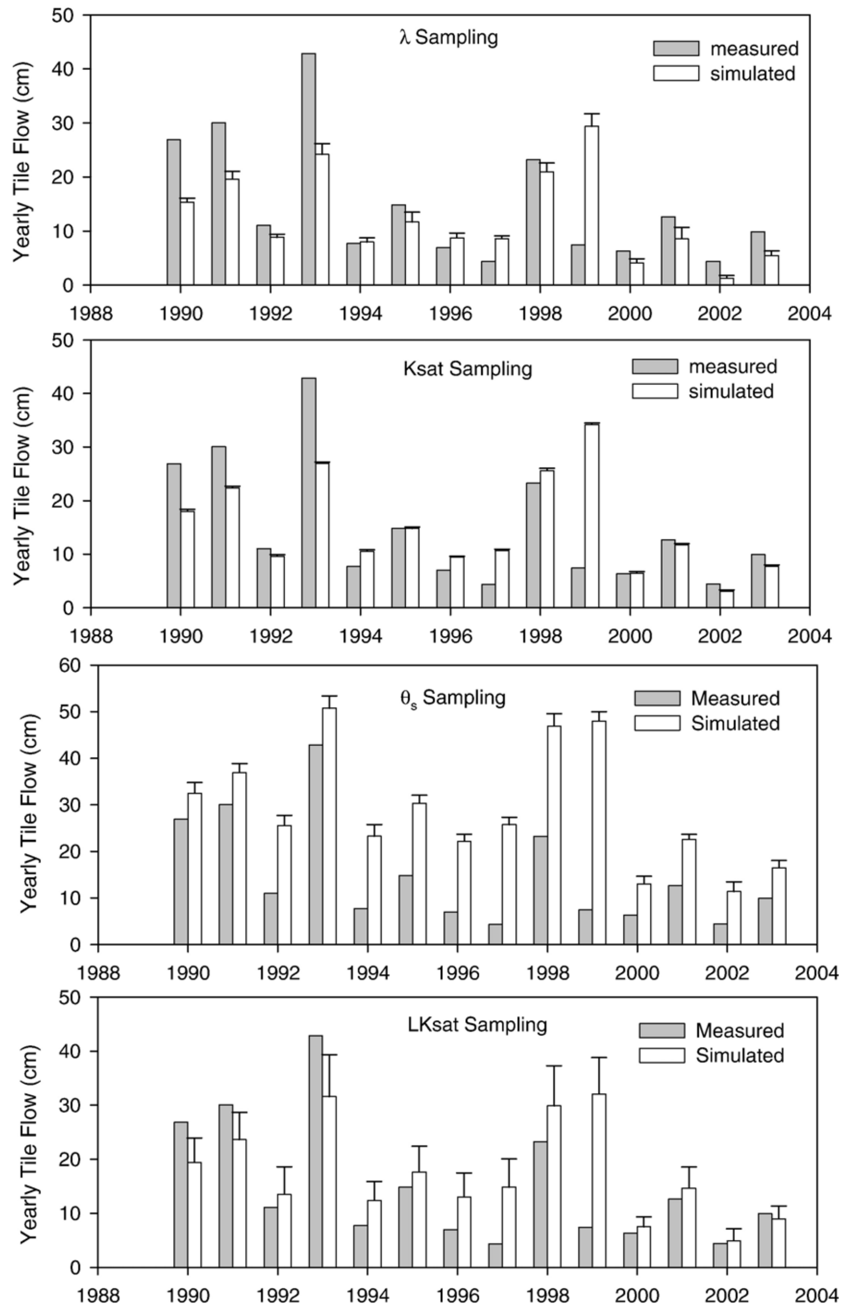

Fig. 5. Simulated yearly tile flow responses to λ, K_{sat}, θ_s, and LK_{sat}+HG sampled from LHS soybean was planted in 1994, 1996, 1998, 2000, 2002; and corn was planted in other years.

ridge-till, and no-till) and crop rotations (continuous corn, corn–soybean). From 1993–1998, the main focus of the study was on N management, including liquid swine manure, N application rate, and late spring N test. Tillage was reduced from four practices to two (Chisel plow and no-till). From 1998–2003, the main focus of the study was on manure application rate, timing, and method (Ma et al., 2007-this issue).

To obtain soil hydraulic properties of these soils for RZWQM simulations, we dug four pits outside of the plot area from representative locations: one pit per soil type. Intact soil cores (5.4 cm in diameter and 6 cm long) were obtained from three subsurface depths down to the tile (approximately 38–59 cm; 64–77 cm; 94–103 cm) from each pit. Since the soil horizon delineation in RZWQM was finer than the soil depths measured in the field, the measured soil properties were mapped approximately to the finer soil horizon in RZWQM. Surface samples (2–8 cm) were obtained on the experimental plots from no-till Clyde, Floyd, and Kenyon soils. Surface samples were also obtained from Floyd and Kenyon with chisel till. Three replicates were obtained from each subsurface soil-depth combination and from each surface soil-tillage combination, respectively. The cores were saturated in flow cells with a screen mesh at the bottom of the cores and at least three falling head saturated hydraulic conductivity measurements were obtained from each core. The screen mesh from each saturated core was then replaced with a 600 mbar membrane and

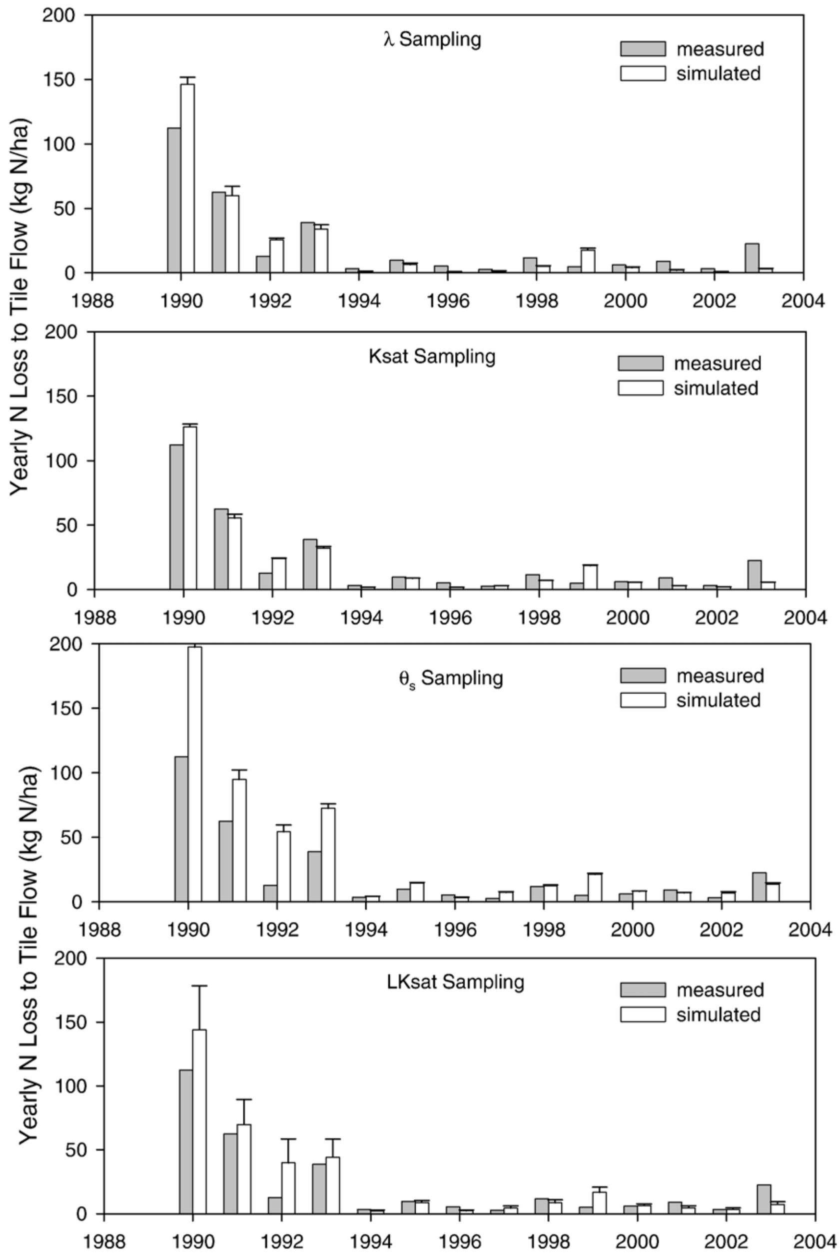

Fig. 6. Simulated yearly N losses to tile flow responses to λ, K_{sat}, θ_s, and LK_{sat}+HG sampled from LHS soybean was planted in 1994, 1996, 1998, 2000, 2002; and corn was planted in other years.

increasing pressure was applied to the cores at 20, 40, 60, 105, 140, 210, 279, 349, 489, and 699 cm water. At each pressure head, the cells were allowed to equilibrate (48 h minimum) before taking a measurement. At the end of the experiment, the cores were removed from the cells and oven dried at 105 °C. Soil bulk density of each core was determined from the dry soil mass divided by the core volume. Oven-dried soil was then ground and the particle density determined.

The obtained pairs of volumetric water content θ ($cm^3\ cm^{-3}$) and pressure head τ (cm) were fitted to the Brooks–Corey equation (Brooks and Corey, 1964):

$$\begin{aligned} \theta(\tau) &= \theta_s & \tau \le \tau_b \\ \theta(\tau) &= \theta_r + B\tau^{-\lambda} & \tau > \tau_b \end{aligned} \tag{1}$$

where $B=(\theta_s-\theta_r-A_1 * \tau_b)\ \tau_b{}^{\lambda}$. θ_s and θ_r are the saturated soil water content and residual soil water content, respectively. λ is a pore size distribution index. To derive the corresponding curves for soil hydraulic conductivity, we assumed the same bubbling pressure (τ_b) and λ as for the soil water retention curves to be applicable to the $K(\tau)$ function:

$$\begin{aligned} K(\tau) &= K_{sat} & \tau \le \tau_b \\ K(\tau) &= K_{sat}\tau^{-N_2} & \tau > \tau_b \end{aligned} \tag{2}$$

where K_{sat} is soil hydraulic conductivity (cm/h) and $N_2=2+3\lambda$ (Ahuja and Ma, 2002). To compare the soil water retention curves, we invoked the one-parameter model, in which the

Table 4
Percentage change in tile flow (cm) and nitrate loss to tile flow (kg N/ha) based on 50% increase or decrease in lateral K_{sat} and lateral hydraulic gradient

Variables	Soil depth (cm)	Plot 25			
		−50%		+50%	
		Tile flow	N loss to tile flow	Tile flow	N loss to tile flow
LK_{sat} (cm/h)	0–20	−0.04	−0.05	0.05	0.06
	20–41	−0.04	−0.08	0.02	0.02
	41–50	−0.07	−0.07	0.08	0.11
	50–69	−0.08	−0.10	−0.15	−0.22
	69–89	−0.50	−0.60	0.48	0.58
	89–101	−1.90	−2.01	1.66	1.74
	101–130	19.09	22.85	−11.93	−11.63
	130–150	0.13	0.16	−0.13	−0.09
	150–200	0.09	0.09	−0.11	−0.11
	200–252	0.26	0.18	−0.28	−0.22
HG		37.03	38.68	−23.32	−23.47

Brooks–Corey equation can be described by the parameter λ (Ahuja and Williams, 1991). Rearranging Eq. (1), we have:

$$\ln(\tau) = a + b\ln(\theta - \theta_r) \quad (3)$$

where $a = \ln(B)/\lambda$ and $b = -1/\lambda$. Ahuja and Williams (1991) found that:

$$a = p_c + q_c b \quad (4)$$

where p_c and q_c are constant for each soil texture class. This concept was further extended across different soil texture classes (Williams and Ahuja, 2003). Thus, if b is known from λ, a can be calculated, and then B and τ_b, which define the Brooks–Corey equations (Eqs. (1) and (2)) (Williams and Ahuja, 2003). The importance of λ was satisfactorily exemplified later for scaling water infiltration and redistribution (Kozak and Ahuja, 2005) and for scaling evaporation and transpiration across soil textures (Kozak et al., 2005).

Tile drainage (S_d) was simulated by the Hooghoudt's steady state equation in RZWQM (Ahuja et al., 2000).

$$\begin{aligned} S_d &= \frac{8LK_{sat}d_e m + 4LK_{sat}m^2}{CL^2\Delta Z} & \omega > d \\ S_d &= 0 & \omega \le d \end{aligned} \quad (5)$$

where z is depth of drain (cm); ω is distance from the water table to the bottom of the restricting layer (cm); d is distance from drain to the bottom of the restricting layer (cm); m is water table height above the drain (cm); LK_{sat} is effective saturated lateral hydraulic conductivity (cm/hr); L is distance between two drains; C is the ratio of the average flux between drains to the flux midway between drains (set to 1.0); and Δz is soil-depth increment at z (cm). The equivalent depth d_e from drain to bottom of restricting layer (cm) is given by:

$$\begin{aligned} d_e &= \frac{d}{1 + \frac{d}{L}\left(\frac{8}{\pi}\ln\left(\frac{d}{r}\right) - \alpha\right)} & 0 < \frac{d}{L} < 0.3 \\ d_e &= \frac{L\pi}{8\left(\ln\left(\frac{L}{r}\right) - 1.15\right)} & \frac{d}{L} \ge 0.3 \end{aligned} \quad (6)$$

$$\alpha = 3.55 - \frac{1.6d}{L} + 2\left(\frac{d}{L}\right)^2 \quad (7)$$

where r is drain tube radius (cm).

Since RZWQM is a point scale model and does not simulate lateral flow between plots, we assume two ways for groundwater to be lost: one is tile flow when groundwater is above the tile and the other is lateral flow from layers below the tile. Wahba et al. (2001) showed that lateral flow below tiles could be as much as tile flow itself. In this study, a simple equation is used to estimate lateral flow (Todd, 1980):

$$Q = LK_{sat}h\frac{dh}{dx} \quad (8)$$

where dh/dx is hydraulic gradient (HG) in the direction of lateral flow; x is direction of flow; and h is the distance from the water table to the bottom of soil profile.

In this study, we used the calibrated RZWQM–DSSAT hybrid model with data collected on plot 25 to examine the sensitivity of soil hydraulic properties on tile drainage flow and plant growth. This plot had water table measurements and typical tile flow characteristics. It also had both continuous corn and corn–soybean rotation and manure applications. Simulation results of this plot were documented in detail and compared to experimental measurements by Saseendran et al. (2007-this issue) in this issue.

3. Results and discussion

3.1. Measured soil hydraulic properties

Measured soil water retention curves are shown in Fig. 1 for the four soils (Floyd, Kenyon, Readlyn, and Clyde). Each curve was then fitted using the Brooks–Corey Eq. (1) and average (geometric means) pore size distribution index (λ) for the soils are listed in Table 1, along with measured saturated hydraulic conductivity, soil texture, bulk density and particle density. Calculated a and b values from Eq. (3) are plotted in Fig. 2, which shows a strong linear relationship between a and b. Therefore, the

Table 5
Default hydraulic parameters from Rawls et al. (1982)

Soil depth (cm)	Bulk density (g/cm^3)	θ_s (cm^3/cm^3)	λ	τ_b (cm)	K_{sat} (cm/h)	1/3 bar SW $\theta_{1/3}$ (cm^3/cm^3)	15 bar SW θ_{15} (cm^3/cm^3)	θ_r	LK_{sat}[a] (cm/h)
0–20	1.42	0.463	0.220	11.1	1.30	0.234	0.116	0.027	1.32
20–41	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	0.23
41–50	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	0.23
50–69	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	0.23
69–89	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	0.23
89–101	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	14.40
101–130	1.42	0.463	0.194	25.8	0.23	0.312	0.188	0.075	10.40
130–150	1.42	0.463	0.194	25.8	0.01	0.312	0.188	0.075	0.01
150–200	1.42	0.463	0.194	25.8	0.01	0.312	0.188	0.075	0.01
200–252	1.42	0.463	0.194	25.8	0.01	0.312	0.188	0.075	0.01

[a]LK_{sat} was fitted. Fitted lateral hydraulic gradient was 1.5×10^{-5}.

one-parameter model using λ (with measured θ_s and θ_r) to describe soil water retention curves is valid for the soils. Thus, to conduct a statistic analysis for the water retention curves, only an ANOVA analysis of the λ values needs to be conducted to compare the soil water retention curves among soils and soil depths. When the Clyde soil was included in the statistics, there were significant differences among soils ($p=0.0026$) and soil depths ($p=0.037$). However, when the Clyde soil was removed from the statistical analysis, no significant differences were found among the three soils (Kenyon, Readlyn, and Floyd) ($p=0.257$), but differences among soil depths still existed ($p=0.009$). Therefore, we used averaged soil properties from the three soils for each soil depth as input for RZWQM simulations. Statistical analysis for ln[K_{sat}] was also conducted. Again, when the Clyde soil was included in the ANOVA, there were significant differences among soils ($p<0.0001$) and soil depths ($p=0.008$). Removing the Clyde soil from the ANOVA resulted in no significant differences between soils ($p=0.160$), but a depth effect was found ($p=0.027$).

Although the measured soil water retention curves had lower λ values compared to the average values listed by Rawls et al. (1982) for similar soil classes (loam and clay loam), the λ values in this study did fall within the range (0.070–0.418) given by Rawls et al. (1982). The measured K_{sat} values were much higher than the 1.32 cm/h value reported by Rawls et al. (1982) for a loam soil. For RZWQM simulation study, we took

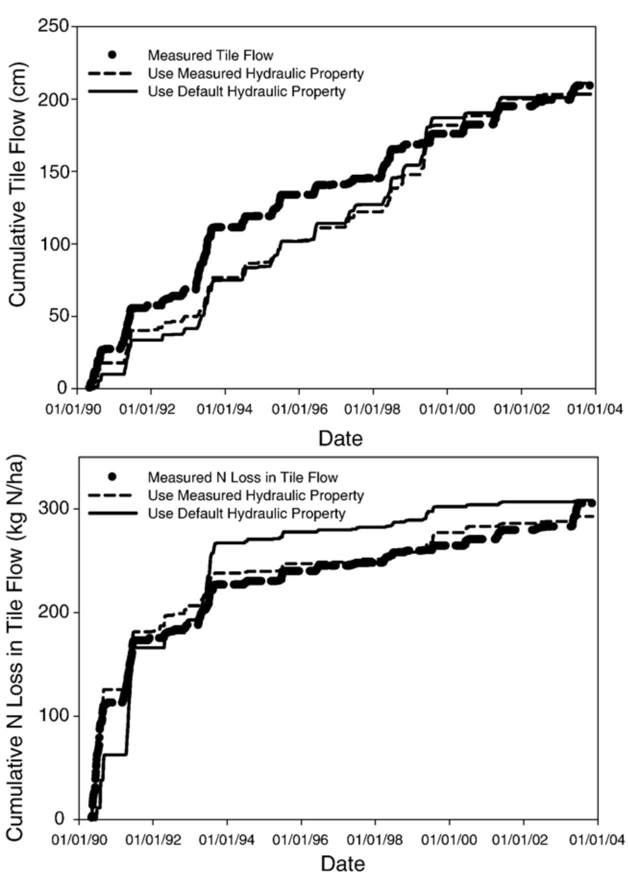

Fig. 7. Cumulative tile flow and N loss in tile flow using measured and default soil parameters.

the average (geometric means for λ and K_{sat}, and arithmetical mean for others; Table 1) of the soil hydraulic properties from the three soils (Floyd, Kenyon, and Readlyn). By fitting Eq. (4) to the three soils in Fig. 2, we obtained $p_c=3.07$ and $q_c=1.09$ with $r^2=0.93$. The q_c value was within the range listed by Williams and Ahuja (2003), but the p_c value was much higher. The high p_c value may be due to the lower λ values estimated for the undisturbed soil cores. It is interesting to notice also that a and b values obtained for the Clyde soil fell close to the same fitted line in Fig. 2, which was not surprising because soil water retention curves were not too much different for soil layers 2–8, 38–59, and 94–103 cm. The only noticeable difference in water retention curves existed for soil depth 64–77 cm.

Based on previous studies on this experimental site (Kumar et al., 1999), the soil was divided into 10 layers to improve the numerical solution of the Richards equation (Table 2). Higher soil bulk densities were used below the tile (120 cm) based on literature reports since no bulk density was measured below 100 cm soil depth (Kumar et al., 1999). The deepest three soil layers were assumed to have the same λ values as that for the layer 94–103 cm. A very low saturated hydraulic conductivity of 0.01 cm/h was necessary for the deepest three soil layers to maintain a water table. A default residual soil water content of 0.027 cm^3/cm^3 was assumed for all the layers based on Rawls et al. (1982). Lateral K_{sat} (LK_{sat}) and hydraulic gradient (HG) for lateral flow were fitted based on measured soil water content, tile flow, and water table measurement using an optimization scheme (Table 2) (Ma et al., 1999). Detailed model calibration and results are shown in Saseendran et al. (2007-this issue).

3.2. Sensitivity of hydraulic properties on simulated results

Most simulation models do not take into account the effect of variation in input parameters (e.g., soil hydraulic properties) on simulation results, although large spatial variability is commonly encountered in measurements. An average value is also used for each hydraulic property in this Nashua study (Saseendran et al., 2007-this issue) and distributed input to RZWQM is not feasible at this time. In this study, we tested the associated variability in hydraulic properties listed in Table 1 and Fig. 1 on simulation results, using the Latin Hypercubic Sampling (LHS) technique (Ma et al., 2000). Here we assumed log-normal distributions of λ and K_{sat} and used the LHS to obtain 500 sets of λ and K_{sat} values for soil layers 0–130 cm (Ma et al., 2000), while keeping soil hydraulic properties the same for deep soil layers (130–252 cm). The parameters λ and K_{sat} were independently sampled. For the soil depth 101–130 cm, λ was not varied because much higher bulk density was used for that layer. We also did not vary K_{sat} for soil layers 20–41 cm and 50–69 cm because no K_{sat} was measured for these two layers. Instead, an average (arithmetic mean) K_{sat} was calculated from K_{sat} of layers above and below. We also found that K_{sat} for layers from 130–252 cm depth cannot be randomly sampled. Otherwise, a valid water table depth cannot be maintained. Table 3 lists the range of values sampled and their mean values. Since for each plot, lateral K_{sat} (LK_{sat}) and hydraulic gradient had to be calibrated (Saseendran et al., 2007-

this issue), the range of LK_{sat} calibrated for all plots was also used to conduct a sensitivity analysis of model outputs to LK_{sat} and HG using the LHS sampled values and assuming a log-normal distribution (Table 3).

The RZWQM–DSSAT hybrid model was used to conduct sensitivity analyses. Simulated yield and biomass were not sensitive to variations in λ, K_{sat}, θ_s, and LK_{sat} (Figs. 3 and 4). Similar results were reported by Walker et al. (2000). In addition, minimum responses were observed for yearly tile flow and yearly N losses in tile flow to λ and K_{sat} (Figs. 5 and 6). The reasons for lack of response were that λ was sampled within a small range and that a low K_{sat} of 0.01 cm/h was maintained for soil layers below the tile in order to maintain a reasonable water table during the years of simulation. However, we did see substantial responses of tile flow and N loss in tile flow to changes in θ_s, LK_{sat} and HG (Figs. 5 and 6). As shown by Kumar et al. (1998, 1999) and Singh and Kanwar (1995), LK_{sat} and θ_s (or drainable porosity; $\theta_s - \theta_{1/3}$) were the most important variables controlling tile flow.

The low sensitivity of simulation results to measured λ and K_{sat} provided confidence of simulated management effects without interference from variability in soil parameters due to experimental errors. However, it was important to maintain a low K_{sat} below the tiles to maintain a water table. For the soils studied, there were restrictive layers below the tiles, which may or may not be within the 252 cm soil profile. Compared to the λ and K_{sat} values reported for a loam soil by Rawls et al. (1982), we measured a much lower λ and higher average K_{sat}. We found that the lower λ and higher K_{sat} were necessary to reflect dynamic changes in both water table and tile flow as shown in the next section.

It was important to notice that LK_{sat} was a sensitive parameter for obtaining correct tile flow as reported by others (Singh and Kanwar, 1995; Kumar et al., 1998, 1999). As shown in Saseendran et al. (2007-this issue), tile flow varied considerably from plot to plot under the same weather conditions and tile design, being of course independent of soil and crop management. Some of the hydrological reasons for the large variability in tile flow among plots were: (1) tiles in each plot may have had different water drainage capacity due to clogging over the years or sloping of the tile; (2) the uneven drainage capacity between center tiles within the plot (trenchless) and buffer tiles between plots (open ditch installation) (Kanwar et al., 1986; Mirjat and Kanwar, 1992); (3) spatial variability of soil layer structure that contributes to lateral subsurface flow. Therefore, it was necessary to calibrate the difference in tile drainage capacity among plots so that soil and crop management effects could be identified (Kumar et al., 1998, 1999; Bakhsh et al., 1999, 2001).

In previous LHS studies, we grouped LK_{sat} and HG together because they were closely related to each other. Single variable sensitivity analysis was necessary to find out which parameter was more important. To further understand which soil layer LK_{sat} was more sensitive, each LK_{sat} was increased or decreased by 50% while LK_{sat} in other soil layers were kept unchanged (Table 4). We found that LK_{sat} in soil layers (101–130 cm) where tile was installed had the highest sensitivity, followed by the layer immediately above (89–101 cm) in terms of tile flow and N loss to tile flow. The other soil layers were insensitive to changes in LK_{sat} (Table 4). Although biomass and yield followed the same pattern as tile flow and N loss in tile flow,

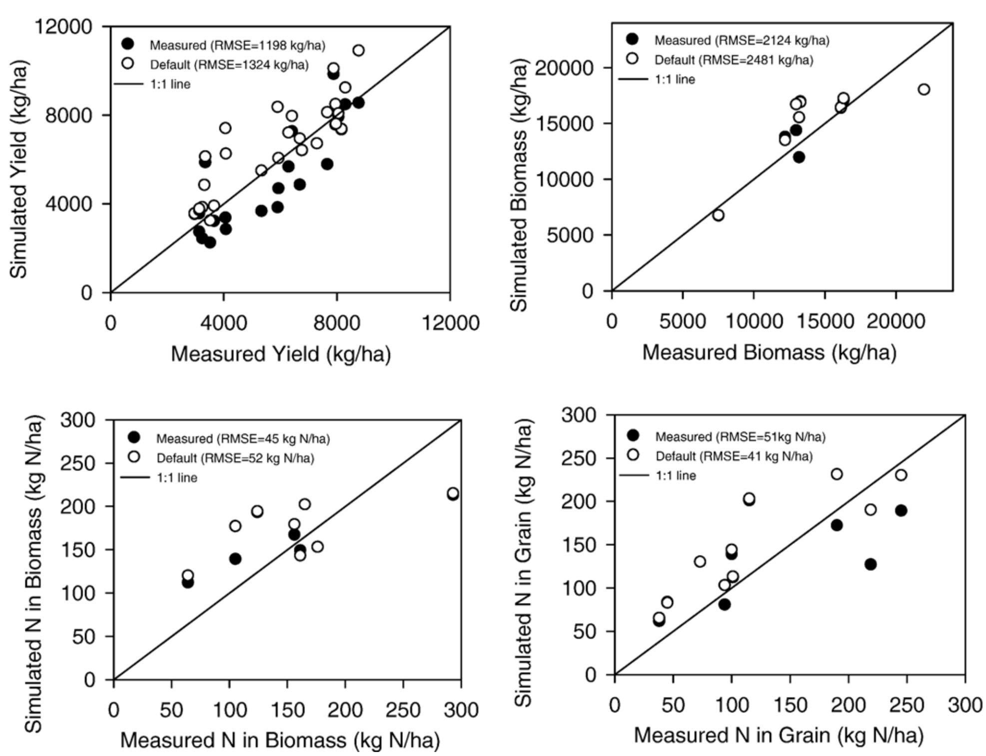

Fig. 8. Simulated and measured grain yield, biomass, N in biomass and N in grain (corn and soybean) using measured and default soil parameters.

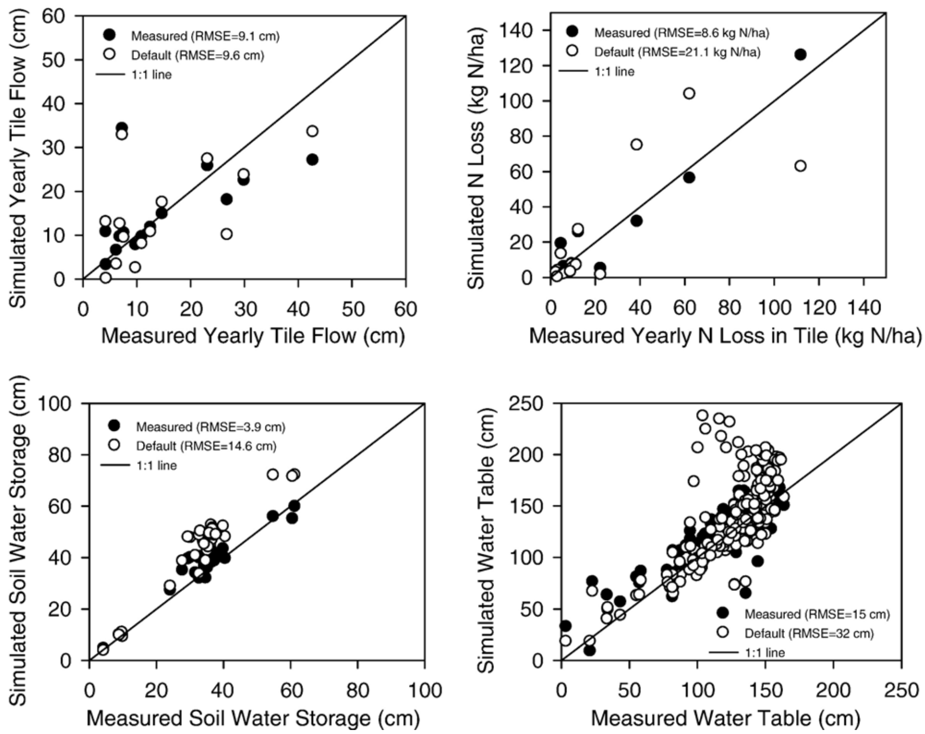

Fig. 9. Simulated and measured yearly tile flow, yearly N loss in tile flow, soil water storage and water table using measured and default soil parameters.

they were much less sensitive to LK_{sat}. HG was the most sensitive parameter in simulating tile flow and N loss in tile flow (Table 4). Again, yield and biomass were much less sensitive to lateral HG under the Iowa weather condition. Therefore, it was only necessary to calibrate LK_{sat} for soil layers 89–101 cm and 101–130 cm and HG.

3.3. Measured versus default soil parameters

Detailed soil parameters are usually not available for many soils. Thus, it is very helpful to know how much errors are introduced when default soil parameters are used. In this study we used the default soil hydraulic properties based on Rawls et al. (1982) (Table 5), where a lower soil hydraulic conductivity was again assumed for the last three soil horizons to maintain a valid water table. Lateral K_{sat} for the two horizons at and above the tile was fitted as previously discussed along with lateral hydraulic gradient (HG) (Table 5). Calibration was based on yearly tile flow, soil water storage, and water table (Saseendran et al., 2007-this issue). Mineralization was reduced slightly by increasing the inter-pool transfer coefficient from R_{14} (fraction of slow residue pool converted to intermediate soil humus pool) from 0.3 to 0.8 (Ma et al., 1998), so that total N loss in tile flow matched measured data from 1990 to 2003 (308 vs. 305 kg N/ha, Fig. 7). Otherwise, simulated N loss in tile flow would be much higher (421 kg N/ha) than measured when default soil parameters were used (305 kg N/ha). The same plant parameters were used for both sets of soil parameters.

Cumulative tile flow was similar using either set of soil parameters after calibration (Fig. 7). However, cumulative N loss in tile flow was much different although total loss was similar after calibration (Fig. 7). Plant growth simulations were not too much different as evidenced by the Root Mean Square Errors (RMSE) in Fig. 8, neither was calibrated yearly tile flow (Fig. 9). Simulated yearly N loss, soil water storage, and water table were better when measured soil parameters were used than when default soil parameters were used (Fig. 9). Simulated water and N balances are shown in Table 6 for both sets of soil parameters. Major differences between the results from the two

Table 6
Total water and nitrogen balance simulated using measured and default soil parameters during the simulation period

	Measured soil parameters	Default soil parameters
N balance (kg N/ha)		
Fertilizer application	3766	3766
N fixation	1194	1363
Net mineralization	2255	1846
Denitrification	91	77
Volatilization	7	7
N uptake	5494	6144
N loss in tile flow	600	466
N loss in lateral flow	942	241
Change in soil N storage	80	40
Runoff + deep seepage	1	0
Water balance (cm)		
Rainfall	2267	2267
Tile flow	324	293
Lateral flow	431	142
Runoff	184	202
Evapotranspiration	1333	1645
Change in soil water storage	−5	−14

sets of soil parameters were lateral water flow and N loss in later flow. The measured soil hydraulic properties required higher HG (2.4×10^{-5}) compared to HG of 1.5×10^{-5} for the default soil parameters. Because of lower N loss to lateral flow, more N was available to plant growth when default soil parameters were used as shown by high actual evapotranspiration and high N uptake, in spite of lower mineralization (Table 6). Therefore, based on soil parameters used, a system model may cause different results and implications of the results may also differ due to inadequate calibration and incomplete dataset used.

4. Summary and conclusion

In this study, we measured and analyzed the soil hydraulic properties needed to simulate management effects using RZWQM–DSSAT model. The measured soil hydraulic properties provided much better model simulations for soil water content, N loss in tile flow, and water table simulation, compared to the default soil hydraulic properties in RZWQM based on soil classes (Rawls et al., 1982). Therefore, we recommend using local soil information whenever possible. Also, a sensitivity analysis using the Latin Hypercubic Sampling (LHS) showed that simulated yield, biomass, yearly tile flow, and N losses in tile flow were not sensitive to the variability in measurements. However, tile flow and N losses in tile flow were sensitive to lateral K_{sat} (LK_{sat}), θ_s, and HG. The results also showed that it was less important to have accurate λ and K_{sat} measurement for plant growth simulation under Iowa soil and weather conditions, as long as they were within the range of experimental measurements. However, it was important to have a correct bulk density measurement because that defined the magnitude of the saturated soil water content which in turn determined drainable porosity.

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