Evaluation of DRAINMOD-DSSAT simulated effects of controlled drainage on crop yield, water balance, and water quality for a corn-soybean cropping system in central Iowa.

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Abstract:

Controlled drainage (CD) has been identified as a sustainable management practice whereby more soil water can be conserved and less nutrients are leached; alongside its potential benefit of alleviating drought stress and increasing yield. More than 12 million hectare of cropland in the US Midwest are suitable for implementing CD; however, the effectiveness of the practice can vary across the region with the variation in environmental conditions and management practices. The main objective of this study is to evaluate the performance of the integrated agro-ecosystem model; DRAINMOD-DSSAT, for simulating the effects of CD on drainage flow, nitrogen losses via drainage water and crop yield.

Herein, we utilized a 4-yr dataset (2006-2009) that was collected from a corn–soybean cropping system near Story City, Iowa. This site was artificially drained under free drainage (FD) and CD treatments. The model was calibrated using the data collected from the FD plots, and validated for the CD plots. DRAINMOD-DSSAT predictions of drainage flow and nitrate-nitrogen ($\text{NO}_3\text{-N}$) losses were in good agreement with measured values under FD and CD, with the former treatment showed slightly better performance. The modeling efficiencies (NSE's) for simulating monthly drainage flows were 0.81 and 0.60 for FD and CD, respectively. Monthly $\text{NO}_3\text{-N}$ mass losses were simulated with NSE's of 0.76 and 0.66 for FD and CD, respectively. DRAINMOD-DSSAT well simulated CD-induced percent reductions in annual drainage flow (measured = 24.6%, simulated= 27.1%), and $\text{NO}_3\text{-N}$ losses (measured=34.8%, simulated=33.5%). Low percent error (PE) values were associated with the model predictions of corn yields ($-1.3 \leq \text{PE} \leq 1.3$) and soybean yields ($-6.0 \leq \text{PE} \leq 12.6$). Overall, results obtained from this relatively short-term modeling study demonstrated the potential use of DRAINMOD-DSSAT as a management design tool. Yet, further model testing CD effectiveness under different conditions is critically needed to establish a higher credibility in model predictions and to allow for further model improvement and expansion.

Keywords. , controlled drainage, DRAINMOD-DSSAT, integrated modeling, crop production, water quality.

1. Introduction:

Food security and environmental sustainability represent one of the world's most pressing challenge facing human generations now and for the coming several decades (Baker et al., 2012; Hanson, 2013). World population reached 7 billion in 2012 and is projected to reach 9.6 billion by 2050 (The UN DESA report, 2015). Climate change and uncertain characterization of future climate pose profound challenges to assessing the scale of adaptation planning required for agriculture (Reidsma et al, 2010; Hatfield et al., 2011; Calzadilla et al., 2013; Rosenzweig et al., 2013). The ongoing intensification of agriculture has entailed considerable degradation of natural resources. In this context, agro-ecosystem engineers and scientists strive to reduce tradeoffs between meeting food demand and protecting environmental quality. Fostering innovation in agriculture requires merging experimental research; through which data is collected and hypotheses are tested, with computational modelling which is capable of extrapolating time-limited and/or site-specific measurements to different temporal and spatial scales. With the advancements in process-based agro-ecosystem modeling in terms of computational power and theoretical basis (Bastiaanssen et al., 2007; Ma et al., 2007; Zhang et al, 2015), proper model calibration and evaluation remains a necessity to establish model credibility (Rykiel, 1996; Grimm et al., 2014; Moriasi et al., 2015b). The later statement highlights the goal initiated in the current study.

The United States is one of the world's leading countries in agricultural production, with the U.S. Midwestern region, also known as the "Corn Belt", leads the U.S. in receipts for corn and soybean (i.e; $\geq 70\%$) (USDA Economic Research Services, 2014) and contributes more than 40% of corn and soybean grains to the world market (USDA FAS, 2013). However, cultivated land in the U.S. Midwest, where a large percentage is tile drained and commercial fertilizers are heavily applied, is well known as a major contributor to the hypoxic zone in the Gulf of Mexico (Goolsby et al., 1999; Mitsch et al., 2001; Rabalais et al., 2002; Nangia et al., 2010). This problem has gained prominent attention to develop scientifically guided conservation practices that reduce nutrient export from drained agricultural land to receiving water bodies such as the Gulf of Mexico (Rabalais et al., 2002; Nangia et al., 2010) and Great Lakes system (Scavia et al., 2014; Smith et al., 2015; Tian et al., 2016a). Controlled drainage (CD), sometimes referred to in the literature as drainage water management (DWM) or managed drainage, is a valuable cost-effective practice that involves the use of drainage water control structures equipped with a gate assembly to regulate drainage water flow from the field. Drainage is controlled to maintain accessibility for field operations (e.g. tillage, planting, and harvesting) and adequate level of soil water in the root zone during the crop growing season

while minimizing drainage outflow leaving the field to downstream surface waters during the non-growing season. Studies conducted to investigate the effectiveness of CD reported that the practice achieved reductions in flow rates and nitrogen (N) loads ranging from 18% to 80% (Evans et al., 1989; Fausey, 2005; Drury et al., 2008; Wesstrom et al., 2007; Luo et al., 2010; Adenya et al., 2012; Cooke and Verma, 2012; Helmers et al., 2012; Jaynes et al., 2012; Gunn et al., 2015). This variation in CD performance is mainly attributed to variations in soils, cropping systems, farming practices, climate conditions, drainage design, and control structure management across different studies.

Approximately, 12 million hectares of cropland spanning multiple climate divisions and numerous soil types within the Midwest region are suitable for CD (USDA NRCS – Maps and Spread Sheets). However, and until recently, CD has not been widely practiced in the US Midwest (Gunn et al., 2015). More studies are needed to synthesis the fate of the water and nitrogen that do not leave the field through the drain outlet because of CD implementation. And more research is needed to establish design standards and operation protocols of CD that maximizes soil water reserve, minimize nutrient losses, and benefit crop production (Delbecq et al., 2012). In addition, careful attention is needed to improve the performance of CD to cope with an increasing annual precipitation, more intensive rainfall events, and tendency of prolonged dry periods characterizing recent and near-future climate of the US Midwest (Hatfield et al., 2013; Hatfield et al., 2014; Pryor et al., 2014).

Modeling studies are essential for advancing our understanding of the effect of CD on the hydrologic cycle and nitrogen cycle, which in turn influence the efficacy of controlled drainage as an edge-of-field conservation practice. DRAINMOD-DSSAT (Negm et al., 2014a) is a comprehensive, processes-based model developed to simulate the response of hydrological, biogeochemical and plant growth processes to variation in environmental conditions and farming practices. It represents one of the recent advancements added to the DRAINMOD suite of models (e.g.: Tian et al., 2012; Negm et al., 2014a; Tian et al., 2016b) aiming to improve its vegetation component critically needed to support and expand the model use in resolving complex challenges facing agricultural systems in the current century (Ma et al., 2007). DRAINMOD-DSSAT was evaluated against experimental data collected from drained agricultural fields located in two Midwestern states that implemented different drainage design in terms of drain spacing (Negm et al., 2014b) and different nutrient management in terms of nitrogen fertilization rate (Negm et al., 2014a). Model evaluation results were promising and indicated the model's potential success for achieving the goal it has been developed for; a whole system model for agricultural systems supported by artificial drainage.

Nevertheless, the model has not been tested yet against experimental data comparing controlled drainage to free drainage. Drainage processes under CD are driven by factors not all the same as FD, and the algorithms implemented in the model to describe its operation and impact need to be explicitly evaluated. Youssef et al. (in review) compared CD performance across the U.S Midwest predicted by DRAINMOD and RZWQM models. The comparison revealed that CD-induced reduction in drainage flow predicted by both models was significantly different. Same finding was for reductions in N-losses caused by CD. This divergence in model predictions of the hydrologic and water quality impact of controlled drainage occurred despite a very close agreement between predictions of DRAINMOD and RZWQM during model calibration and validation against same data set for a corn-soybean production system under free drainage. Therefore, they underscored the importance of model testing using data sets that provide a side by side comparison of controlled drainage and free drainage before using a model in a predictive mode.

It justifiable to state that a model structure and its theoretical basis largely influences how it predicts the impacts of controlled drainage or any other management practice on a given agro-ecosystem. The objective of this study was to evaluate the performance of DRAINMOD-DSSAT for predicting the effect of CD on drainage flow, nitrogen loss, and crop yield using a four-year dataset (2006-2009) collected from an agricultural field located near Story City, Iowa. The model testing reported in this paper is one of a series of DRAINMOD-DSSAT testing studies using field measured data on CD performance at different locations within the Midwestern region of the United States.

2. Methods:

2.1. DRAINMOD-DSSAT Model:

DRAINMOD-DSSAT (Negm et al., 2014a) is a comprehensive agro-ecosystem model with emphasis on assessing the effects of environmental conditions and farming management practices on hydrologic cycle, water quality, and crop growth and yield on high water table soils that normally require artificial drainage for crop production. The model merged CERES-Maize (Jones and Kiniry 1986), CROP-GRO (Boote et al.1998), and CROPSIM-CERES (Ritchie and Otter 1985) deterministic crop growth models with the hydrologic model DRAINMOD (Skaggs 1978, 1999) and the soil carbon and nitrogen dynamics model DRAINMOD-NII (Youssef 2003; Youssef et al. 2005a). DRAINMOD-DSSAT is fully integrated allowing for data transfer and feedback among different model components on a daily time step (Figure 1).

On each simulated day, DRAINMOD predicts hydrologic variables (i.e.; infiltration, surface runoff, evapotranspiration, soil water distribution in the unsaturated zone, groundwater table, drainage flow, and seepage (if any)). Infiltration rate is modeled using Green-Ampt method, and surface runoff occurs when ponded water exceeds a user-defined surface storage depth. Drainage rates are calculated using the steady-state Hooghoudt equation when the water table is below ground surface. Under ponded conditions, the model applies Kirkham equations (1957) to calculate drainage rates. By default, potential evapotranspiration (PET) is computed internally by the model using the temperature-based Thornthwaite method. Alternatively, the model can be set to read an input file of daily PET, calculated externally using other PET methods. Darcy's Law is used to simulate vertical and lateral seepage. DRAINMOD simulates daily soil temperatures along the soil profile, enabling simulation of the effects of soil freezing/thawing and snow accumulation and melt on hydrologic predictions under cold conditions (Luo et al. 2000, 2001). The model provides management options including CD, sub-irrigation (SI), or both combined. It utilizes built-in subroutines capable of simulating feedback operation of these water table management systems by tracking water level in drain outlets at each time increment; taking into account the storage capacity of the outlet ditch, the control gate elevation, drainage flux, and sub-irrigation flux (if any) (Skaggs, 1980; Fouss, 1985, Skaggs 1999).

DRAINMOD-NII simulates a detailed soil-N cycle. The model numerically solves a multiphase form of the one-dimensional advection-dispersion-reaction equation to simulate N reactive transport midway between two parallel drains. DRAINMOD-simulated hydrologic variables that are required for simulating N transport are transferred to DRAINMOD-NII. Nitrogen transformation processes simulated by the model include atmospheric deposition, the application of mineral N fertilizers and animal manure, mineralization of organic nitrogen (ON), immobilization of mineral N, nitrification, denitrification, ammonia volatilization, and N losses via lateral subsurface drainage, vertical seepage, and surface runoff. Required plant biogeochemical composition and daily N-uptake; previously defined through a set of empirical inputs and equations, are predicted by the crop modules and transferred to DRAINMOD-NII. The model also simulates the effect of tillage and plant residue management on soil carbon and nitrogen. The soil carbon model of DRAINMOD-NII is based on the CENTURY model (Parton et al. 1987).

The crop component simulates daily plant growth and development by reading crop-specific genetic coefficients, soil water and N available for plant uptake simulated by DRAINMOD and DRAINMOD-NII, along with daily measured and computed weather parameters (i.e.; solar radiation, max and min. temperatures, PET). Atmospheric

CO₂ concentration, a critical factor affecting plant carbon balance and total water use (Morison and Lawlor, 1999; Ewert, 2004), can be adjusted as needed by the model user.

The basis of simulating plant development is founded on dividing the plant life cycle into phenological stages; each stage requires a number of predefined heat units or photothermal days. These units are computed based on the difference between daily average temperature and a base temperature below which plant development ceases. Water or nutrient related stresses could negatively impact the rate of development.

Potential dry biomass accumulation is estimated as a function of the intercepted photosynthetically active radiation. Reductions in potential values may occur due to environmental stressors including excess and deficit soil water, nutrient deficit, as well sub-optimal temperatures and CO₂ concentrations. Daily accumulated dry biomass is then allocated to different plant organs; a process that depends on the developmental stage of the crop (Jones et al., 2003)

CROPGRO (Boote et al. 1998), a generic model for grain legumes, incorporates additional algorithms to simulate nodule growth, N-fixation rate, and other related nitrogenous activities (Boote et al. 2008). On the day of harvest, DRAINMOD-NII amends plant residues simulated by the crop modules as added fresh organic matter. Afterwards, DRAINMOD and DRAINMOD-NII continue to simulate the hydrologic and N/C balance throughout the fallow season until the following growing season when the crop modules become active again. The reader is referred to the cited references for additional information on the different component models of DRAINMOD-DSSAT.

Figure 1. DRAINMOD-DSSAT model, major component, key processes and interactions.
(GWT: ground water table, PET: potential evapotranspiration,)

2.2. Site description and data collection:

Field measurements for four years (2006-2009) were utilized herein to evaluate DRAINMOD-DSSAT. This dataset was part of data collected from a drainage experimental site initiated in 1992 near Story City (42° 11' 48.2" N, 93° 35' 51.0" W), Iowa (Jaynes et al., 2001; Jaynes and Colvin, 2006; Jaynes, 2012). The field is a 22 ha of crop production with corn and soybean grown in rotation (normally corn planted in even years and soybean planted in odd years). Dominant soils within the field are Kossuth silty clay loam (fine-loamy, mixed, mesic Typic Endoaquoll) and Ottosen clay loam (fine-loamy, mixed, superactive, mesicTypic Calciaquoll); both classified as naturally poorly drained soils with relatively high organic carbon in the top layer (2.96%). The ground surface is slightly sloped at 0.8% on average. The drainage system consists of twelve subsurface drainage lines installed at two different spacings (Figure 2). The southern four tiles were spaced at 36.5 m and were the only tiles retrofitted with control structures during the years of 2006-2009. The other eight tiles were spaced at 27.4 m and were continuously managed under a conventional drainage mode. Recent field observations indicated that the drain depth varied

between 122 cm and 145 cm along the length of the tiles. An average drain depth of 130-cm was assumed based on DRAINMOD simulations of daily drainage rates for different drain depths and comparing predicted drainage rates to measured values. For controlled drainage plots, the control structures at the drain outlets were adjusted to 0.7 m below the soil surface several weeks after planting when all field operations have been completed. The outlets remained raised until two weeks before harvest when lowered back to the tile elevations. After harvest and fall tillage operations, the outlets were raised to 0.30 m below the soil surface throughout the fallow season and until the next growing season approached.

Fertilizer was injected to the soil as 32% urea ammonium nitrate (UAN) at a rate of 134 kg N ha⁻¹ in 2006, and at a rate of 157 kg N ha⁻¹ in 2008. No fertilization occurred in soybean years (i.e.; 2007 and 2009). Primary tillage was normally performed after harvest with chisel plow. In addition, a field cultivator was used to prepare the soil one day prior to planting. Exceptions occurred when no tillage was performed in the fall of 2008 corn year and the spring of 2009 soybean year.

Weather parameters including precipitation, temperature, and solar radiation were obtained from a weather station located less than 0.5 km (0.31 mi) from the site. Precipitation records coincided with freezing temperature were obtained from a rain gage, operated by the National Climatic Data Center and located 2 km (1.25 mi) away from the field.

Subsurface drain flow was measured by a digital flow meter and recorded with a CR10X datalogger. Flow weighted composite water samples were normally collected on a weekly basis, or more frequently when drainage flow become more intense. Grain yield as well as grain-nitrogen content were measured on the day of harvest. It worth noting that measurements reported herein represent the average of observed values for each tile and grouped into two treatments: free drainage versus controlled drainage. For more detailed description of the current, as well as previous site management and data collection, the reader is referred to Jaynes et al. (2001), Jaynes and Colvin (2006), and Jaynes (2012).

Figure 2. Schematic of site layout showing tile arrangement, sumps, and locations of control structures (Adapted from Negm et al., 2014a).

2.3. Model parametrization and calibration:

DRAINMOD-DSSAT, as a whole-system model, requires a large set of input parameters to adequately describe hydrological, physiological, and bio-geochemical processes, and the interactions occurring among different processes. In a recent study (Negm et al., 2014a), DRAINMOD-DSSAT was calibrated and evaluated using an older data set (1996-2005) collected from the same experimental field. During this 10-year period, different nutrient management practices were implemented by changing N-fertilizer application rate: 1) plots receiving high N rate, 2) plots receiving medium N rate (comparable to N rates of the current study period), and 3) plots received low N rate. However, drainage management was limited to free drainage only, and the model was run for the plots with the narrow drain spacing (i.e.; drains spaced at 27.4 m). Overall, model predictions in that modelling study were in excellent agreement with measured values for all plot-years in terms of drainage flow rates, crop yield, and N leaching losses. However, it is not at all certain that the model would perform equally well under CD mode. Youssef et al. (in review) argued that an excellent model performance under free drainage mode does not mean a comparable performance under the controlled drainage scenario. The testing of DRAINMOD-DSSAT using the new data set will provide evidence of the model's capability of simulating the effects of controlled drainage on the hydrology,

biogeochemistry, and plant growth for agro-ecosystems on artificially drained soil. Model parameters used by Negm et al. (2014a) were used to parameterize the model for the current simulation exercise. Only a few parameters were redefined through the calibration phase in order to improve model predictions. Further model calibration through the adjustment of some parameters that cannot be accurately measured is justified, and parameter optimization can be usually improved by an increasing experience with the model and by an increasing knowledge of the study site (Daggupati et al., 2015b).

In the current study we obtained the 2006-2009 measured data of daily drainage flow, NO₃-N leaching losses, and crop yields from three plots with FD and two plots with CD. All plots per treatment were managed under the same drainage design, fertilizer application rate, and cropping practices; therefore, measured data were combined and averaged for each treatment. Data from FD was utilized for model calibration, while data of CD were assigned for model validation.

Although differences in N treatment in terms of fertilizer application date between plots under the same drainage mode did exist (Jaynes, 2012), such difference was not presented in the current modelling work since our objective is to assess the model capability of capturing the impact of CD and does not include testing DRAINMOD-DSSAT for nitrogen fertilizer management, as this has been already done by the study of Negm et al. (2014a).

We briefly discuss key model inputs herein, and the reader is referred to the cited references for additional information. Table 1 lists main non-default hydrologic parameters required for modeling the soil water balance. Inputs describing drainage system configuration were set according to the current drainage design implemented on site as described in the previous section (see Table 1). Additional inputs required to run the model under CD mode are the values defining date and elevation of control gate adjustment (described in the previous section). The dimension of the “hypothetical” ditch characteristic required to simulate water table at drain outlets was set to a low value (bottom width = 0.01 cm) proposing inconsiderable water storage within the drainage system, while the major of water conserved by CD will be allowed in the soil profile (Skaggs, 1999). This parameter adjustment was based on the nature of the drain laterals (tiles not open ditches), and based on the placement of the control structure relative to the drain laterals (Figure 2).

Weather parameters were set to reflect the measured data, and daily PET was internally calculated using the Thornthwaite temperature-based method.

Soil hydraulic parameters was formed for a profile divided into 5 layers, extended to 300 cm, with its bottom bounded by a restrictive layer permitting deep vertical seepage. But lateral seepage (another water loss pathway DRAINMOD can handle) was assumed to be negligible in the current study. With one exception, soil profile hydraulic parametrization including soil water characteristic, drainage volume-upward flux relationships, infiltration parameters, deep seepage parameters, as well as lateral saturated hydraulic conductivity (K_{sat}) were set as defined by Thorp et al., 2009 based on measurement by Bakhsh et al. (2000). The exception was for the value of K_{sat} of the fourth layer containing the tile drains that was defined during model calibration and assigned a value of 2.0 cm/hr (Table 1); lower than 3.5 cm/hr defined in previous studies. Such adjustment lessens the model's over prediction of high peak flows following intense rainfall that was common in the considered period. Haan and Skaggs (2003) discussed DRAINMOD sensitivity to the K_{sat} value of layers bounding the tile drain. Table 1 also lists parameters required to simulate soil temperature, snow melt and accumulation, and a rain-snow partitioning threshold temperature. Among these parameters, the temperature at which snow starts to melt was adjusted from Negm et al. (2014a) to improve model prediction of daily flow at winter periods.

Nitrogen transport and transformation parameters were mostly defined similar to Thorp et al. (2009) and Negm et al. (2014a) (Table 2). Through model calibration, values of longitudinal dispersivity and the empirical exponent of soil organic function that reduces denitrification rate with depth were redefined. Parameters of environmental response functions of C and N transformations were adapted from Youssef et al. (2006) and Thorp et al. (2009). Organic matter parameters including decomposition rates and C:N ratios of different organic matter pools were specified according to default values adapted from the CENTURY model (Parton et al., 1993). Management inputs for tillage were set according to actual practices implemented on site. Tillage plowing depths and intensity factors were set to 20 cm and 0.6 for chisel plow, and 10 cm and 0.25 for the field cultivator operations, respectively.

292 **Table 1. Non-default hydrologic and drainage management parametrization.**

<u>Drainage system parameters</u>			293
Drain depth (cm)	130		294
Drain Spacing (m)	27.4 (FD), 36.5 (CD)		295
Drainage coefficient (cm day ⁻¹) ^a	1.3		
Effective drain radius (cm)	1.1		296
Maximum surface storage (cm)	0.5		297
<u>Deep seepage parameters</u>			298
Restrictive layer thickness (cm)	200		
Piezometric aquifer head (cm)	200		299
Restrictive layer conductivity (cm hr ⁻¹)	0.0005		300
<u>lateral saturated hydraulic conductivity (Ksat)</u>	Depth (cm)	K_{sat} (cm hr⁻¹)	301
Layer 1	0 – 15	3.5	
Layer 2	15 – 60	3.5	302
Layer 3	60 – 120	3.5	303
Layer 4 ^a	120 – 150	2.0	
Layer 5	150 – 299	3.5	304
<u>Soil temperature parameters</u>			305
Soil thermal conductivity function	TKA = 0.39, TKB = 1.33		306
Air temperature below which precipitation is snow (°C)	0.0		
Snowmelt base temperature (°C) ^a	0.0		307
Critical ice cover at which infiltration stops (cm ³ cm ⁻³)	0.2		308
Temperature at profile bottom (°C)	9.11		
Snow melt Coefficient (mm d ⁻¹ °C ⁻¹)	5.00		309
			310

311 ^a Calibrated parameter

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313 Adequate simulations of crop development and yield production using the crop modules adapted from DSSAT

314 requires reasonable definition of the crop cultivar coefficients and planting characteristic (row spacing and plant

315 population). Soybean physiological traits of maturity group II (MG 02) (Table 3) were selected for the current study

316 similar to Negm et al. (2014a) and based on a previous 17-year CROPGRO-Soybean simulations for a nearby site

317 located in Ames, Iowa (Boote et al., 2003). Soybean was planted in 18 cm spaced rows at a population of 370,000

318 plants/ha.

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320 **Table 2. DRAINMOD-NII input parameters**

<u>Nitrogen Transport and Transformation</u>		
Longitudinal dispersivity (cm) ^a	40.0	
Tortuosity	0.5	
Fertilizer dissolution rate (d ⁻¹)	2.0	
Threshold soil water content (cm ³ cm ⁻³)	0.36	
	<u>Nitrification</u>	<u>Denitrification</u>
Maximum reaction rate (µg N g ⁻¹ soil)	24.0	0.75
Half saturation constant (Km)	9.0	40.0
Optimum temperature (°C)	25.0	30.0
Shape factor	0.413	0.186
Empirical exponent SOM depth function (α)	1.0	1.3 ^a
<u>Organic matter decomposition</u>		
Mineral N content at which litter enters the SOM	50	
Optimum temperature	28	
Optimum water-filled pore space range	0.5-0.6	
	<u>K_{dec} (d⁻¹)</u>	<u>C:N ratio</u>
<u>Litter Pools</u>		
Surface structural	1.068 X 10 ⁻²	150
Surface metabolic	4.055 X 10 ⁻²	15
Surface microbial	1.644 X 10 ⁻²	10
Below ground structural	1.342 X 10 ⁻²	150
Below ground metabolic	5.068 X 10 ⁻²	15
<u>SOM Pools</u>		
Active	2.00 X 10 ⁻²	8
Slow	5.479 X 10 ⁻⁴	16
Passive	1.233 X 10 ⁻⁵	10

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327 Table 3. Cultivar coefficient used to simulate corn and soybean growth

Coefficient	Value
<i>Corn growth parameters</i>	
Thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod (GDD ₈). ^[b]	220
Photoperiod sensitivity coefficient.	0.75
Thermal time from silking to physiological maturity (GDD ₈). ^[b]	800
Maximum possible number of kernels per plant.	750
Kernel filling rate during the linear grain filling stage under optimum conditions (mg d ⁻¹). ^[b]	7.05
Phytochron interval between successive leaf tip appearances (DD).	55.0
<i>Soybean growth parameters</i>	
Critical short day length below which reproductive development progresses with no day length effect (h)	13.5
Relative response of development to photoperiod with time (h ⁻¹)	0.29
Time from plant emergence to first flower (PD) ^[a]	17.4
Time from first flower and first pod (PD)	6.0
Time from first flower and first seed (PD)	13.5
Time from first seed to physiological maturity (PD)	32.0
Time between first flower and end of leaf expansion (PD)	26.0
Time required for cultivar to reach final pod load under optimal conditions (PD)	12.0
Maximum leaf photosynthesis rate (mg CO ₂ m ⁻² s ⁻¹)	0.70
Specific leaf area of cultivar under standard growth conditions (cm ² g ⁻¹)	375
Maximum size of fully expanded leaf (cm ²)	180
Maximum fraction of daily growth portioned to seed and shell	1.0
Maximum weight per seed (g)	0.19
Average seeds per pod under standard growing conditions	2.2
Standard seed-filling duration for pod cohort (PD)	23.0

328 ^[a] GDD₈ = growing degree days above a base temperature of 8 °C, DD=degree days, PD: photothermal day.

329 ^[b] Calibrated parameters

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331 Cultivar parameters used for simulating corn growth and phenological development were initially set according to

332 values estimated by Negm et al. (2014a). However, some parameters were redefined through model calibration to

333 improve model predictions. Efforts focused mainly on the adjustment of the development traits presenting thermal

334 time from seedling emergence to the end of the juvenile phase and thermal time from silking to physiological

335 maturity. Besides improving yield estimation at harvest, such adjustments guaranteed physiological maturation

336 before harvest. The corn growth trait describing Kernel filling rate during the linear grain filling stage under

optimum conditions was also adjusted (Table 3). Corn was planted in 75 cm spaced rows at a population of 75,000 plants/ha. Note that the upper limit of grain N concentration was maintained at 1.5% instead of 1.8% (internally in the code) as suggested by Negm et al. (2014a) to avoid the overestimation of corn grain N removal by the CERES-Maize model as reported by Thorp et al. (2007), Negm (2011), and Fang et al. (2012).

2.4. Model evaluation criteria:

The adequacy of a model performance can be demonstrated by both statistical performance measures and graphical performance measures (Moriasi et al., 2015). Among the statistical performance measures recommended by Moriasi et al. (2007, 2015) as well other modeling studies (Tian et al., 2012), we selected:

$$1) \text{ Nash-Sutcliffe model efficiency (NSE)} = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2}$$

$$2) \text{ Relative Error or Percent Error (PE)} = \frac{P_i - O_i}{O_i} \times 100$$

$$3) \text{ Normalized Percent Error (NPE)} = \frac{\sum_{i=1}^n P_i - O_i}{\sum_{i=1}^n O_i} \times 100$$

where O and P are the observed and predicted values, respectively; O_{avg} is the average of observed values; and n is the number of data pairs. The NSE was used to evaluate model predictions of daily and monthly drainage flow, as well as monthly N drainage losses. PE was used to assess predictions of annual drainage flow, annual N losses, and crop yields. Unlike Moriasi et al. (2015) who assessed PE in absolute form, we computed the values of PE as signed numbers to distinguish between cases of model over- or under-predictions and mark systematic errors (if any). NPE is a preferred performance measure to assess how well a model represents the average magnitude of a specific response variable.

Alongside the statistical performance measures, graphical methods were used to highlight and provide visual insights of temporal mismatch often overlooked by quantitative comparisons (Daggupati et al., 2015; Moriasi et al., 2015).

Beside model evaluation indices against measured or “hard” data, non-measured data or “soft” data that represents key processes of the hydrologic cycle or N cycle have to play a role in model evaluation to ensure model realism and

to avoid over-calibration that normally results from calibration efforts targeted towards maximizing evaluation criteria indices leading to getting a right answer but for a wrong reason (Harmel et al., 2010; Arnold et al., 2015).

3. Results:

3.1. Hydrology

The long-term (40-yr) average annual precipitation for the site is reported as 853 mm (Jaynes, 2012). Years of 2006-2009 received precipitation exceeding the long term average (i.e.; 4-yr average = 1010 mm) (Table 4). Annual precipitation was close to normal in 2006 (anomalies of +3.7%), relatively higher than normal in 2009 (anomalies of +11%), and considerably higher than normal in 2007 and 2008 (+21.6% and +38.3%; respectively). The wettest growing season was the 2008 corn season (anomalies of 31.1% for May–September rainfall) (Figure 3). However, rainfall of the 2009 soybean growing season; a wet year based on annual values, was considerably below normal (anomalies of -22.0% for May–September rainfall) (Figure 3). Both annual and inter-annual variations in precipitation patterns appeared to have influenced measured annual flow volumes under both FD and CD treatments.

DRAINMOD-DSSAT well represented variations in measured annual drainage flow under both FD and CD treatments with an absolute PE ranging from 3.1% to 18.4% (Table 4). The NSE values of the monthly drainage flow predictions were 0.81 and 0.63 for FD and CD treatments, respectively. Cumulative drainage over the 4-year study period was slightly over-predicted with a NPE of 1.6% for FD treatment, and slightly under-predicted with a NPE of -1.8% for CD treatment. Based on these statistical measures and corresponding performance evaluation criteria proposed by Moriasi et al. (2007 and 2015) and Skaggs et al. (2012), the model performance can be rated as “good” to “very good”. Visual assessment of model performance indicated predictions with no consistent over- or under-prediction of monthly drainage flow for a given month of the year or throughout the simulation period.

Simulated annual drainage flow reductions caused by CD agreed well with measured values (Table 4) except for one year. The exception was for 2006 when the model over-predicted flow reduction (measured = 22.0%; predicted = 40.4%) (Table 4). On average, measured and predicted flow reductions were 24.6% and 27.1%, respectively.

Figure 3. Monthly rainfall during April through August for the year 2006-2009 compared to the 40 year average.

Table 4. Measured and predicted annual drainage flow (cm) for free drainage (FD) and controlled drainage (CD) treatment plots.

Year	<u>Drain flow, FD</u>				<u>Drain flow, CD</u>			<u>Flow reduction</u>	
	<u>Precip. (cm)</u>	<u>Meas. (cm)</u>	<u>Pred. (cm)</u>	<u>PE (%)</u>	<u>Meas. (cm)</u>	<u>Pred. (cm)</u>	<u>PE% (%)</u>	<u>Meas. (%)</u>	<u>Pred. (%)</u>
2006	89	21.2	22.8	7.3	16.5	13.5	-18.4	22.0	40.7
2007	104	43.0	38.7	-10.0	29.4	26.4	-10.1	31.7	31.8
2008	118	36.9	40.5	10.0	29.4	32.9	12.0	20.3	18.8
2009	95	24.9	26.0	4.1	19.7	20.5	3.8	20.9	21.1
Avg.	101	31.5	32.0	1.6	23.8	23.3	-1.8	24.6	27.1

Figure 4. Measured and predicted daily drainage flow from 2006 through 2009 for a) free drainage (FD) treatment, and b) controlled drainage (CD) treatment.

Figure 4 presents the time series diagram of the measured daily drainage flow in comparison to DRAINMOD-DSSAT predicted values. Under the FD treatment, the majority of predicted flow events agreed well with measured values in terms of timing and magnitude with a NSE = 0.66; a value rated as “good” (Skaggs et al., 2012b). For the CD treatment, the NSE equaled to 0.38; a value that can be rated as “acceptable” (Skaggs et al., 2012b). Nevertheless, the model predictions of daily drainage deviated from measured values in some instances, mainly during winter months when soil freezing and thawing, and snow accumulation and melt normally occur. For example, 4.38 cm of drainage were measured from the FD treatment during the first 10 days of January 2007, while the model predicted only 1.72 cm of drainage flow from FD during same period. During this period maximum air temperature ranged between 1.6 °C to 10.3 °C, while minimum temperatures remained below freezing. The warm daytime temperatures could have resulted in snowmelt that yielded such measured drainage values. However, the model under-predicted drainage flow rates during the same period presumably due to poor prediction of soil freezing conditions, which influences infiltration and subsurface water movement to drains. Similar findings were reported by Luo et al. (2010) who applied the model for a Minnesota drainage field. This discrepancy did not occur for CD due to the raised gate that reduced measured drainage rates at the same period.

Conversely, the model predicted drainage flow between late January and early February of 2008 for FD, as well in early March of the same year for both FD and CD. However, measured values were practically zero during the same periods. Measured air temperature raised to a maximum value of 7.6 °C and 3.8 °C on January 28 and 29; respectively, besides, minimum temperature remained above freezing on the 28th. On this day, DRAINMOD predicted a snowmelt due to this warm spell equivalent to 2.74 cm of rainfall, raising groundwater table to 25 cm below soil surface and initiating drainage flow for several following days. Similarly, and during the warm winter day of March 2nd (maximum temperature = 12.9 °C), DRAINMOD predicted 2.8 cm of snowmelt raising groundwater table to the soil surface and yielding considerable sub-surface drainage rates while measured values approached zero under both treatments.

Flow events within the growing season were predicted mostly well; yet, there were a few events the model did not accurately predict such as the flow event in late July of 2008, and that of late October 2009 when the model under-predicted drainage for both FD and CD treatments. Such errors could be a result of less accurate estimation of ET; a major pathway of water loss in vegetated systems (Luo et al., 2010). However, such postulation cannot be confirmed without available ET measurements.

Over all, the model performed well in assessing the impact of CD on flow reductions from year to year as affected by variation in annual and inter-annual precipitation, crop cover, and the length of the growing season. Note that it is understandable that the reduction in flow rates in the CD treatment could be, in part, due to the placement of the tile drains at a wider spacing. According to DRAINMOD prediction, such wider spacing would have caused an average reduction in drainage flow equivalent to 25% of the reduction caused by CD and the wider spacing combined.

ET is another major pathway by which water leaves the agro-ecosystem. Simulated annual ET by DRAINMOD-DSSAT averaged at 54.5 cm and 56.8 cm for FD and CD treatments, respectively. These values indicate that 54.8%, on average, of annual precipitation left the system back to the atmosphere via ET. To justify the rational of the model estimation of annual ET, we compared it to the ET data derived from the MODIS algorithm available at 1-km spatial resolution over the 109.03 × 106 km² global vegetated land areas (Mu et al., 2007 and 2011). The comparison demonstrated a very close agreement between simulated values and MODIS-estimated values, with the later provided annual ET of 54.9 cm averaged for the same period. The previous DRAINMOD-DSSAT simulations for the period 1996-2005 (Negm et al., 2014a) yielded a slightly lower average annual ET ($ET_{avg} = 51.6$ cm [67% of

annual precipitation]). The difference is mainly attributed to variation in measured precipitation between both time periods. The earlier 10 years were characterized on average as normal to dry years (anomalies of -10.0%); dissimilar to the current 4-yr period characterized as wet years. It is well documented that ET is controlled by PET demands (energy) and precipitation (water availability) (Zhang et al., 2004).

According to model simulation, reoccurring high-intensity rainfall events initiated considerable amount of surface runoff for both FD treatment (annual average = 10 cm), and CD treatment (annual average = 16 cm). Surface runoff was not measured onsite to validate model predictions. According to model predictions, deep seepage was a minor pathway of water loss with a 4-yr average of 3.7 cm and 4.5 cm for FD and CD treatments, respectively.

3.2. Crop Growth and Yield:

Measured corn and soybean yields for the current 8 treatment plots (4 years x 2 drainage treatments) surpassed the average yields previously measured for this field over the past ten years including treatments receiving high N fertilizer application rate. On the other hand, measured crop yields compared well to the 10-year average corn and soybean yields reported for Story County and for Central Iowa district (Johanns 2016 a and b). Measured corn yields of 2008 was 18% above average corn yields reported for Story County in the same year (Johanns 2016 a). Such deviation could be mainly attributed to interaction between local environmental, crop hybrids, and management conditions.

DRAINMOD-DSSAT maintained a very good performance in predicting crop yields that compared well to what had been reported for the previous 10-year study by Negm et al. (2014a), although the current crops were grown under somewhat contrasting climate conditions (wetter than average), different water management practices in some plots (wider drain spacing and controlled drainage), and different fertilizer management.

Table 5 presents a comparison between measured and simulated corn and soybean yields under FD and CD treatments. Percent errors (PE's) in predicting corn yield were at 0.4% for FD, and were within $\pm 1.3\%$ for CD. These values proved that the model performed similarly for the calibration (FD) treatment and the validation (CD) treatment. Both measured and simulated corn yields indicated that controlled drainage had no measureable benefit nor harm on corn production in the current study period. DRAINMOD-DSSAT simulation showed that corn plants exposure to water related stresses was minor for both years and under both drainage treatments. On the other hand,

simulated N related stresses were relatively high in both corn years, but similar for FD and CD treatments. Such level of N stresses compared well to what was estimated previously by Negm et al. (2014a) under comparable N-fertilizer application rate.

We suspect that CD would have exhibited greater impacts on crop growth and yields if the experiment was ran for more growing seasons with different weather patterns.

Table 5. Measured and predicted corn and soybean yields for free drainage (FD) and controlled drainage (CD) treatments from 2006 to 2009. (Yield units are all in Mg ha^{-1} based on dry mass)

Year	Crop	Crop yield, FD			Crop yield, CD		
		Meas.	Pred.	PE	Meas.	Pred.	PE
		(Mg ha^{-1})			(Mg ha^{-1})		
2006	Corn	9.7	9.7	0.4	10.0	9.9	-1.3
2008		11.8	11.9	0.3	11.7	11.9	1.3
Avg.		10.8	10.8	0.3	10.9	10.9	0.1
2007	Soybean	3.4	3.9	12.9	3.7	4.1	11.3
2009		3.4	3.5	1.5	3.5	3.3	-6.0
Avg.		3.4	3.7	7.2	3.6	3.7	2.8

Soybean yields were adequately predicted by the model as well. In 2007, the model slightly over-predicted yields under both FD (PE = + 12.9%) and CD (PE = + 11.3%). In this year, CD resulted in yield increases 7.1% greater than the FD yields, and DRAINMOD-DSSAT simulated a comparable yield increment of 5.5%. Soybean yield in 2009 was predicted pretty well for both FD (PE = + 1.5%) and CD (PE = - 6.0%). However, the measured yield increment of 2.8% in the same year due to CD implementation was not captured by DRAINMOD-DSSAT; instead the model estimated reduction in soybean yield due to CD implementation (Table 5). In an effort to understand why the model estimated higher yield for FD plots under the dry growing season of 2009, we investigated the detailed crop growth output provided by CROPGRO module. Our findings were that the model simulated higher biomass partitioning for the root system to create longer and denser root at the vegetation stage to adapt the plant to drought conditions that were more intense under FD than CD. Although such adaptation mechanism agreed well with other experimental studies (e.g.: Garcia et al, 2010), different performance to be expected under site-specific soil physical and chemical properties. Besides, model predictions of soil moisture at this phenological period were not validated since measurements were not available neither for FD nor for CD plots.

Overall, the 2009 soybean yield under-prediction for CD also lead the model to underestimate the averaged soybean yield increase due to CD (measured = + 4.9%, simulated = + 0.6%). Over all, measured and simulated average corn and soybean yields were in excellent agreement (corn: $0.1\% \leq \text{NPE} \leq 0.3\%$; soybean: $2.8\% \leq \text{NPE} \leq 7.2\%$).

Corn and Soybean grain N content was measured, and this measurement was utilized herein as another set of “hard data” to validate the overall model performance. Nevertheless, N content in other plant shoot and root organs was not measured to compare total plant N uptake.

Table 6. Measured and predicted nitrogen (N) removal for corn and soybean for free drainage (FD) and controlled drainage (CD) treatment plots from 2006 to 2009.

Year	Crop	Grain N, FD			Grain N, CD		
		Meas.	Pred.	PE	Meas.	Pred.	PE%
		(kg N ha ⁻¹)	(%)		(kg N ha ⁻¹)	(%)	
2006	Corn	144	126	-12.4	146	128	-11.8
2008		149	133	-10.9	139	132	-5.2
Avg.		147	129	-11.6	142	130	-8.6
2007	Soybean	223	240	7.6	228	253	10.7
2009		200	201	0.5	211	193	-8.5
Avg.		212	221	4.3	220	223	1.5

Table 6 presents a side-by-side comparison between the 4-year measured and simulated crop grain N for FD and CD treatments. On average, corn grain N was under-predicted by 11.6% and 8.6% for FD and CD, respectively. For soybean, grain N was slightly over-predicted on average by 4.3% and 1.5% for FD and CD, respectively. The method of simulating crop N uptake by DRAINMOD-DSSAT depends on soil nitrogen availability and a set of default species-specific parameters that control the variation of N concentration in different plant organs throughout its life cycle. Although the later parameters were not included in the calibration process, and although the simulation of crop N uptake by DSSAT crop modules has generally been a challenge (Thorp et al., 2007; Fang et al., 2012; Negm et al., 2014a), the current DRAINMOD-DSSAT estimations of grain N are very reasonable.

3.3. Nitrate losses:

Measured $\text{NO}_3\text{-N}$ losses were mainly affected by the rates of drained groundwater under both FD and CD; i.e., high rates of N losses were measured along with high rates of drainage flow and vice versa. Crop and related fertilizer management seemed not to be a major contributor to variations in annual $\text{NO}_3\text{-N}$ leaching losses. Over all, CD resulted in significant reductions in the magnitude of measured $\text{NO}_3\text{-N}$ losses (Jaynes, 2012).

DRAINMOD-DSSAT accurately predicted the variation in measured annual $\text{NO}_3\text{-N}$ losses in most of the plot-years. For the FD treatment, absolute PE ranged from 4.6% to 9.8% (a “very good” performance evaluation criteria), except for the year 2008 when PE reached -22.8% (a “satisfactory” performance evaluation criteria) (Table 7). Similar results were obtained for the validation CD treatment where absolute PE ranged from 0.5% to 3.3% (a “very good” performance evaluation criteria), with the same exception of the year 2008 when PE equaled to -20.9% (a “satisfactory” performance evaluation criteria) (Table 7). For FD, the model’s under-prediction of $\text{NO}_3\text{-N}$ losses in 2008 could be attributed to the under-prediction of $\text{NO}_3\text{-N}$ concentration in the soil solution especially during the months of April and May when measured values exceeded model predictions by 5.6 kg N ha^{-1} although drainage flow predictions were in excellent agreement with measured values in these two months. In addition, flow under prediction in the month of October in the same year resulted in model under-prediction of $\text{NO}_3\text{-N}$ losses in the same month by another 5.0 kg N ha^{-1} . Similarly, flow under-prediction for the CD treatment in October and November of 2008 were associated with predicted $\text{NO}_3\text{-N}$ losses 4.2 kg N ha^{-1} lower than measured values (Figure 7). Overall, the predicted monthly $\text{NO}_3\text{-N}$ loss time-series agreed well with the measured curves in terms of timing and magnitude for both FD (NSE = 0.76) and CD (NSE = 0.66) (Figure 7). Cumulative $\text{NO}_3\text{-N}$ losses for the 4-year study period was under-predicted with a NPE of 8.5% and 6.8% for FD and CD treatments, respectively. Measured and simulated CD-caused reductions in annual $\text{NO}_3\text{-N}$ losses averaged at 34.8% and 33.5%, respectively, in addition, year-to-year reductions were predicted well by the model (Table 7).

Table 7. Measured and predicted annual NO₃-N losses (kg N ha⁻¹) for free drainage (FD) and

Year	NO ₃ -N losses, FD			NO ₃ -N losses, CD			NO ₃ -N reduction	
	Meas.	Pred.	PE	Meas.	Pred.	PE	Meas.	Pred.
	(kg N ha ⁻¹)			(kg N ha ⁻¹)			(%)	
2006	25.7	26.9	4.6	17.9	17.8	-0.5	30.3	33.7
2007	44.9	40.9	-9.0	25.0	25.5	1.9	44.3	37.6
2008	44.3	34.2	-22.8	31.6	25.0	-20.9	28.5	26.7
2009	17.5	19.2	9.8	11.7	12.1	3.3	32.8	36.8
Avg.	33.1	30.3	-8.5	21.6	20.1	-6.8	34.8	33.5

controlled drainage (CD) treatment plots.

Figure 5. Measured and simulated monthly nitrate N losses for a) free drainage (FD) treatment and b) controlled drainage (CD) treatment for the years 2006-2009.

Other non-measured N processes predicted by the model comprise denitrification, net mineralization, N losses via surface runoff and deep seepage, as well as N atmospheric deposition as a minor source of mineral N. The later was predicted to add, on average, 10.1 kg N ha⁻¹ annually to the system. This value is slightly higher than values published by Thorp et al. (2009) and Negm et al. (2014) due to higher values of annual precipitation for the current

period. Predicted denitrification averaged 9.9 kg N ha^{-1} under FD and increased to $14.2 \text{ kg N ha}^{-1}$ under CD. This indicates that 7.0% to 10.0% of applied fertilizer was lost via denitrification; a reasonable value under such environmental and management conditions (Mehnert et al., 2007; Thorp et al. 2009; Gentry et al., 2009; Fang et al., 2012).

Annual net mineralization ranged from 69.7 to $100.8 \text{ kg N ha}^{-1}$ under FD, and from 66.8 to $94.7 \text{ kg N ha}^{-1}$ under CD with higher values simulated in soybean years. The same findings of slight reduction in net-mineralization caused by CD was observed by Fang et al. (2012) who ran RZWQM-DSSAT for the same current dataset. Predicted N losses through deep seepage averaged 3.4 kg N ha^{-1} for FD and 3.6 kg N ha^{-1} for CD. On average, predicted N losses via surface runoff increased from 1.8 kg N ha^{-1} for FD to 3.0 kg N ha^{-1} for CD. Plant uptake and N fixation, processes predicted by crop component, were not substantially affected by implementing CD which could be mainly attributed to similar crop production under both treatments as affected by uniform fertilizer management. It is well known that plant N uptake is the major sink of available mineral N within the soil matrix.

Overall, the predicted impact of CD on mean annual nitrogen transformation processes was not pronounced except for denitrification and $\text{NO}_3\text{-N}$ losses via sub-surface drainage. Similar findings were reported by Thorp et al. (2008) and Fang et al. (2012) who conducted long-term simulations for the same site using RZWQM-DSSAT and assessed the impact of CD on soil N transformation processes under uniform N fertilization rates. Different results might be obtained if the model is applied for different environmental conditions (i.e.; different soil type, different climate) and nutrient management practices.

Table 8. DRAINMOD-DSSAT predicted mean annual nitrogen transformation processes for free drainage (FD) and controlled drainage (CD) treatments.

	Drainage Mode	
	FD	CD
Fertilizer	146	146
Fixation	320.4	328.2
Net-mineralization	90.7	87.4
Wet deposition	10.1	10.1
Plant uptake		
<i>Corn</i>	209.3	210.1
<i>Soybean</i>	74.8	72.2
Denitrification	9.9	14.2
Seepage	3.4	3.6
Runoff	1.8	3.0
Leaching Losses		
<i>Predicted</i>	30.8	20.1
<i>Measured</i>	33.1	21.6

4. Conclusion and summary:

The current study evaluated DRAINMOD-DSSAT, for the first time since developed, to simulate CD impacts on soil water balance, soil C and N dynamics, as well as crop production. We used a 4-year data set (2006-2009) measured for a corn-soybean cropping system on a tile-drained field in central Iowa (42.2 ° N, 93.6° W), and managed under both FD and CD. Measured data included: daily weather records, daily drainage flow rates, NO₃-N concentration in drainage water, crop yield, and crop N uptake. To parameterize the model for this simulation study, we utilized a previous DRAINMOD-DSSAT application on the same site that spanned a 10-year period (1996-2005). That study did not comprise any CD management either on actual field settings or from a modeling application prospective, which by its turn necessitated the use of the current data to insure comparable model performance under both drainage modes. Only few parameters required some re-adjustment herein through model calibration using data collected from the FD plots. Data collected from CD plots was hold for model validation.

Statistical performance measures and graphical comparison showed that predicted drainage flows were in good agreement with measured values at different temporal scale (daily, monthly, annually) for both FD and CD treatment plots. The impact of CD on flow rate reduction was well predicted by the model (measured average

reduction = 24.6%; simulated average reduction = 27.1%). Similarly, model predictions of monthly and yearly NO₃-N losses were adequately predicted for FD and CD treatment plots, leading to accurate prediction of the reduction in NO₃-N losses due to CD implementation. Annual rates of simulated water balance components and nitrogen processes varied over reasonable ranges compared with previous modeling studies and published experimental data. Measured and simulated corn and soybean yields were in good agreement. However, the model under-predicted CD benefits in terms of increasing soybean yields for the simulated period. Nitrogen accumulation in grains was adequately predicted for soybean but slightly under-predicted for corn. Nitrogen accumulation in other plant organs (shoot and root) was not measured to validate total plant N uptake and its partitioning. Yet, this was beyond the scope of the current study. The availability of more detailed data for a longer period of time may have resulted in different system response and/or model performance.

Overall, results presented herein are promising and showed the potential use of the whole system model; DRAINMOD-DSSAT, as a research tool that can predict sustainability of agricultural systems on poorly drained soils. This modeling research represents the first among a series of studies aiming to evaluate the model for simulating the impact of CD on water yield and quality, as well as crop production across the U.S. Midwest where CD can potentially be applied to millions of hectares of drained cropland. Validating model algorithms that simulate CD is an essential step that must precede any application of the model for developing design standards and operation protocols.

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