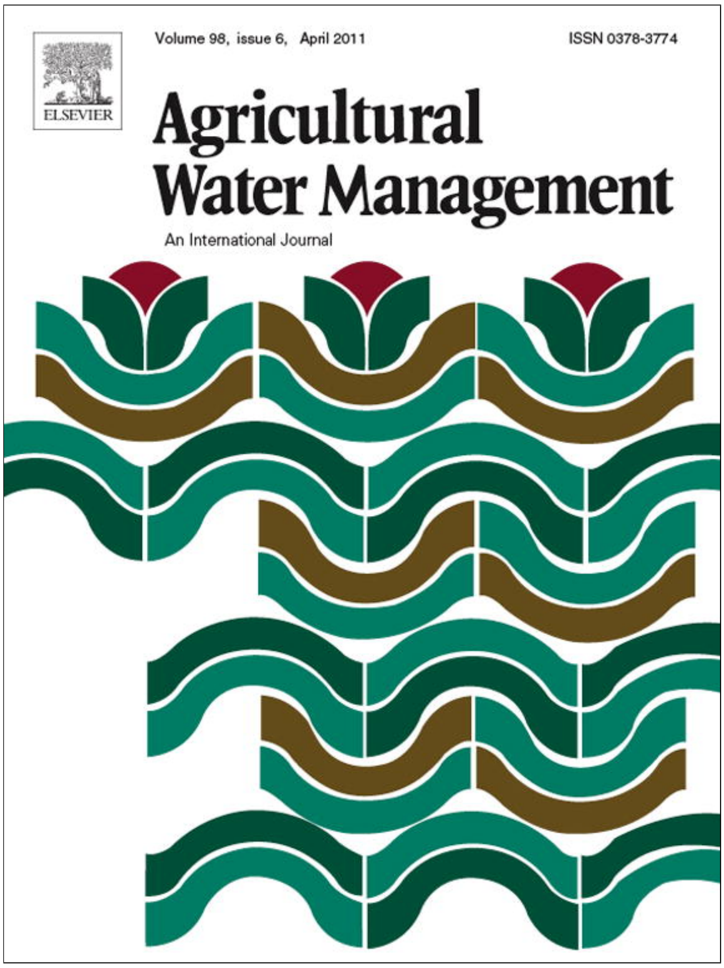
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Simulating water content, crop yield and nitrate-N loss under free and controlled tile drainage with subsurface irrigation using the DSSAT model

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ABSTRACT

In southwestern Ontario, rain-fed crop production frequently fails to achieve its yield potential because of growing-season droughts and/or uneven rainfall distribution. The objective of this study was to determine if the Decision Support System for Agrotechnology Transfer (DSSAT) v4.5 model could adequately simulate corn and soybean yields, near-surface soil water contents, and cumulative nitrate-N losses associated with regular free tile drainage (TD) and controlled tile drainage with optional subsurface irrigation (CDS). The simulations were compared to observations collected between 2000 and 2004 from both TD and CDS field experiments on a Perth clay loam soil at the Essex Region Conservation Authority demonstration farm, Holiday Beach, Ontario, Canada. There was good model-data agreement for crop yields, near-surface (0–30 cm) soil water content and cumulative annual tile nitrate-N loss in both the calibration and validation years. For both TD and CDS, the CENTURY soil C/N model in DSSAT simulated water content and cumulative tile nitrate-N loss with normalized root mean square error (*n-RMSE*) values ranging from 9.9 to 14.8% and 17.8 to 25.2%, respectively. The CERES-Maize and CROPGRO-Soybean crop system models in the DSSAT simulated corn and soybean yields with *n-RMSE* values ranging from 4.3 to 14.0%. It was concluded that the DSSAT v4.5 model can be a useful tool for simulating near-surface soil water content, cumulative tile nitrate-N losses, and corn and soybean yields associated with CDS and TD water management systems.

1. Introduction

One of the main challenges of field-crop production on the flat, fine-textured soils in southwestern Ontario, Canada, is to remove excess water in/on the soil during the critical spring planting and fall harvesting periods (Tan and Reynolds, 2003). This is achieved most effectively by installing networks of subsurface drainage tile to quickly route water off the field and into drainage ditches. Unfortunately, this approach also enhances non-point source agricultural pollution in the region by increasing the translocation of sediments, nutrients and pesticides from fields to streams and lakes, especially during the non-growing season and after heavy summer rains (Drury et al., 1996; Drury et al., 2009; Gaynor et al., 1995; Ng et al., 2002; Rudolph and Goss, 1993; Tan et al., 1993; Tan et al., 1998). In addition, the tile-drained water is no longer available for irrigation, and crop yields in the region are often reduced because of droughts and/or poor rainfall distribution during the growing season (Tan and Reynolds, 2003).

It has recently been shown for the region that a combination of controlled tile drainage and subsurface irrigation of captured drainage water decreases agricultural pollution and increases crop yields (Tan et al., 2007). In this system, tile outflow is restricted to conserve root zone moisture, and surface runoff and tile drainage waters are captured in a small reservoir for later use as surface/subsurface irrigation during moisture deficit periods. Although the short-term benefits of this system have been clearly demonstrated, the long-term impacts on the environment, soil water, nutrient and pesticide dynamics, and crop yield are still open to debate, and thus in need of further investigation.

Process-based simulation models are being increasingly used as a means for simulating the medium- and long-term effects of agricultural management practices. For example, Chen et al. (2010) simulated climate and water management for a winter wheat and summer corn rotation on the North China Plain using the Agri-

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cultural Production System Simulator (APSIM) model, and Geerts et al. (2009) simulated the yield potential of quinoa under varying water availability scenarios in the Bolivian Altiplano region using the AquaCrop model. Van der Laan et al. (2010) used the Soil Water Balance Model (SWB-Sci) to simulate soil nitrate leaching, and Bastiaanssen et al. (2007) reviewed the state-of-the-art models for irrigated and drained soils. In India, subsurface drip irrigation under an onion crop was simulated using the Hydrus-2D model (Patel and Rajput, 2008), and subsurface drainage under a pearl millet–wheat rotation was simulated using the WaSim model (Hirekhan et al., 2007).

The DSSAT (Decision Support System for Agrotechnology Transfer) model is particularly well suited for simulating agricultural practices (Jones et al., 2003). The DSSAT v4.5 model integrates several crop system models, two soil carbon and nitrogen models, a daily water models, and a range of crop/land management options to simulate crop growth/yield and environmental impacts. The model has been widely and successfully used throughout the world. (e.g. Hoogenboom et al., 2009; Jeffrey et al., 2010; Gijsman et al., 2002; Jones et al., 2003; Sarkar, 2009), and was recently used by Liu et al. (2010) to simulate corn yield and nitrogen cycling on a 50-year corn production experiment in southwestern Ontario, Canada. However, to the author's knowledge, the DSSAT model has never been applied to controlled tile drainage-subsurface irrigation systems. The objective of this study was consequently to calibrate and evaluate the DSSAT v.4.5 model for simulating near-surface soil water dynamics, crop yields, and tile nitrate-N losses from a crop production system using regular free tile drainage and controlled tile drainage with optional subsurface irrigation.

2. Materials and methods

2.1. Field site and experimental design

The field site is located on the Essex Region Conservation Authority demonstration farm at Holiday Beach, Ontario, Canada (42°13′N, 82°44′W). The soil is a poorly drained Perth clay loam/silty clay loam (Gleyed Grey Brown Luvisol), with basic soil properties as indicated in Table 1. The experiment was conducted from spring of 2000 to fall of 2004, and the cropping practice (including varieties, planting dates and rates, fertilizer types and rates) are summarized in Table 2. Corn was harvested on November 15, 2000, November 7, 2001 and December 16, 2003; Soybean was harvested on October 16, 2002 and November 15, 2004. The grain yields were expressed as grain dry weight. No-tillage was used for both corn and soybean crops.

As the water management component of the experiment has been described elsewhere (Tan et al., 2007), only the salient features will be repeated here. The treatments included an single controlled tile drainage-subsurface irrigation (CDS) plot and a single traditional free tile drainage (TD) plot, each 25 m by 131 m. Both plots contained six 104 mm diameter tile lines (4.6 m spacing, 60 cm average depth) for soil water drainage, and a single catch basin for drainage of surface runoff water. The volumes of surface runoff water and tile drainage water were recorded automatically using flow meters and data loggers (Campbell Scientific CR21X); then routed into a wetland-reservoir for optional subsurface irrigation of the CDS plot during water deficit periods. Samples of surface runoff and tile drainage were collected from both plots periodically using auto-samplers (ISCO) and analyzed for nitrate concentration (Tan et al., 2007). Controlled drainage in the CDS treatment was accomplished by attaching a "riser" to the tile outlet which effectively raised the tile elevation and thereby increases water storage within the soil profile. Sub-irrigation under CDS was achieved by pumping water from the wetland-reservoir back up the tile lines and into the crop root zone. The CDS outlet riser was set at 40 cm below soil surface, and sub-irrigation was initiated when the water table fell below 40 cm. Sub-irrigation was applied to the CDS treatment to maintain maximum crop water requirement (i.e., close to 100% of crop water requirement). The CDS treatment received 287 mm of sub-irrigation water in 2001 and 203 mm of sub-irrigation water in 2002 because of generally dry weather; it also received 153 mm of sub-irrigation water in 2003 because of low rainfall in June and July and apparently high crop water demand and low rainfall in June and July (Tan et al., 2007). No sub-irrigation water was applied to CDS in 2000 and 2004 because growing season rainfall was sufficient to meet for crop demand (Tan et al., 2007).

Soil physical and hydraulic properties (i.e. texture, organic carbon content, bulk density, porosity, field capacity, wilting point, saturated hydraulic conductivity) were obtained using two types of undisturbed soil core samples (aluminum cylinder: 7.6 cm diameter and 7.6 cm long; stainless steel cylinder: 10 cm diameter and 10 cm long) and grab samples collected from the 0–10, 20–30 and 40–50 cm depths. Daily measurements of volumetric soil water content in the crop root zone (0–30 cm depth) were collected from July 8 to October 13 in 2000, and from July 4 to September 7 in 2001 using in situ TDR probes (Campbell Scientific Water Content Reflectometer, CS615). Soil water contents in 2003, 2004 and 2005 were not measured.

2.2. Model description

DSSAT v4.5 includes CSM (Crop System Model) modules to simulate more than 20 crops and fallow systems (Hoogenboom et al., 2003; Jones et al., 2003) using one soil water model and two soil C/N models; i.e. the CERES-based soil model and the Century-based soil model (Gijsman et al., 2002; Porter et al., 2009). The DSSAT model has been widely and successfully used for crop yield simulation under different management strategies; for optimizing resource use; for yield trend simulation under different soil and climate scenarios; and for crop risk analysis (Jeffrey et al., 2010; Jones et al., 2003; Sarkar, 2009). Hence, DSSAT is particularly useful for predicting the short-, medium- and long-term impacts of specific land management practices on crop yield, soil water storage, nitrate-N leaching losses, etc. (Boote et al., 2010; Bowen, 1998; Gheysari et al., 2009; Mullen et al., 2009). In this study, the DSSAT v4.5 (Hoogenboom et al., 2009) sequence simulation using CERES-Maize, CROPGRO-Soybean, updated soil water model (Ritchie et al., 2009) and Century-based soil models were used to simulate crop yields and soil water–nitrogen dynamics on the CDS and TD treatments at the field site.

2.3. Model inputs

DSSAT inputs include crop management data, soil profile data, daily weather data and cultivar/genotype coefficients. If the database is complete, DSSAT can accurately simulate crop growth and soil water-nutrient dynamics (uptake and cycling) in the plant-soil system. Incorporation of cultivar/genotype coefficients allows DSSAT to account for differences in genotype among crop cultivars, which is a distinct advantage of DSSAT relative to many other process-based cropping system models.

2.3.1. Experimental treatments

Two separate crop management files were created in DSSAT for the TD and CDS treatments. The water table depth was not controlled for TD, while for CDS, the water table was fixed at 40 cm for a 6-week period after planting and for a 2 to 3 week period before harvest. Irrigation can be applied on specific dates with specified irrigation amount, or it can be controlled using the plant available soil water. For example, if plant available water drops

Table 1
Measured, calibrated and assumed soil profile data under the free tile drainage (TD) and controlled tile drainage with sub-irrigation (CDS) treatments. Details are given in the text.

Soil depth (cm)	Bulk density ($g\,cm^{-3}$)	Field capacity ($cm^3\,cm^{-3}$)	Wilting point ($cm^3\,cm^{-3}$)	Sat. water content ($cm^3\,cm^{-3}$)	Organic carbon (%)	Silt (%)	Clay (%)	pH	Root growth factor
Free tile drainage (TD)									
0–10	1.27	0.346	0.201	0.433	1.66	48.8	29.1	5.4	1.00
10–20	1.44	0.374	0.249	0.472	1.57	43.7	38.9	5.4	1.00
20–40	1.44	0.374	0.249	0.472	1.00	43.7	38.9	5.4	0.55
40–60	1.49	0.390	0.238	0.472	0.20	43.7	38.9	5.4	0.37
60–150	1.49	0.390	0.238	0.472	0.10	43.7	38.9	5.4	0.12
Controlled tile drainage with sub-irrigation (CDS)									
0–10	1.27	0.358	0.225	0.433	1.66	48.1	28.8	5.4	1.00
10–20	1.44	0.390	0.249	0.472	1.57	47.3	33.2	5.4	1.00
20–40	1.44	0.390	0.249	0.472	1.00	47.3	33.2	5.4	0.55
40–60	1.49	0.390	0.249	0.472	0.20	47.3	33.2	5.4	0.37
60–150	1.49	0.390	0.249	0.472	0.10	47.3	33.2	5.4	0.12

below the specified water holding capacity in an irrigation management depth, an irrigation event is triggered. The irrigation amount applied can be either a specified (fixed) amount, or the amount required to refill the management depth to the water holding capacity (Jones et al., 2003; Thorp et al., 2008). This flexibility allows DSSAT to simulate sub-irrigation in CDS by setting: (1) irrigation management to automatic applications; (2) irrigation method to drip or trickle irrigation; and (3) irrigation management depth to 40 cm.

2.3.2. *Soil profile data*

The DSSAT soil profiles were represented as five layers (0–10, 10–20, 20–40, 40–60, 60–150 cm), and the measured soil physical-hydraulic properties were distributed among the layers. Measured soil physical properties were available only to the 60 cm depth, and therefore the soil physical data at the 40–60 cm layer (C horizon) were also used for the 60–150 cm layer. The root growth factor (*RGF*) was determined using the calibrated relationship: $RGF = 1.0 \times \exp(-0.02 \times DLC)$, where *DLC* is the depth to the centre of each soil layer for layers deeper than 20 cm ($RGF = 1$ for layers shallower than 20 cm) (Uryasev et al., 2004).

Using the measured soil physical properties data for 0–60 cm, initial DSSAT runs for the corn–corn–soybean–corn–soybean cropping sequence at the field site produced simulated soil water contents in the 0–30 cm depth range that were significantly lower than the measured water contents. Therefore, the soil water content at field capacity was "calibrated" by systematically increasing it (by 1–10%) until the simulated and measured water content (0–30 cm) in 2000 under TD and CDS achieved "acceptable" *n-RMSE* values of <15.0%. Other soil and crop parameters (albedo, evaporation limit, drainage rate and runoff curve number) were set according to the recommendations of Gijsman et al. (2007).

The soil organic carbon (C) content in the 0–10 and 10–20 cm layers was set to the measured values at the field site (i.e. 1.66 and 1.57%, respectively, Table 1). Below 20 cm, the C content was calibrated (since no measurements were available) by initially assuming a linear decrease from 1% at 20 cm to 0.5% at 150 cm based on data in Liu et al. (2010), and then adjusting the values in each soil layer until a minimum *n-RMSE* value was achieved between simulated and measured soil nitrate-N loss for the 2002 and 2003 calibration years in the TD and CDS treatments. The resulting C distribution (Table 1) is comparable to measured and simulated distributions in the literature (e.g. Gregorich et al., 2009; Meersmans et al., 2009).

2.3.3. *Weather data*

The required minimum weather data (daily maximum and minimum temperature, precipitation, solar radiation) for 2000–2004 were obtained from a weather station located approximately 10 km from the field site, and they were input into DSSAT using the *WeatherMan* software (Pickering et al., 1994; Wilkens, 2004). The monthly precipitation and monthly average air temperature at the field site for 2000–2004 were reported in Tan et al. (2007). Total annual precipitation was greater in 2000 (743 mm), 2003 (910 mm) and 2004 (858 mm) than in 2001 (675 mm) and 2002 (644 mm).

2.3.4. *Crop growth*

Cultivar coefficients should be calibrated to achieve the observed yield or biomass under a no stress growing condition, i.e. no water, heat or nutrient deficiencies (Boote, 1999; Liu et al., 2010). In this study, the CDS treatment was selected for calibration of cultivar coefficients because it ensured sufficient soil water via sub-irrigation during the growing season. Soybean growth in 2002 and corn growth in 2003 under CDS were used as the calibration years because 2000 and 2001 were

Table 2
Cropping practice and crop yield data at the field site during 2000–2004.

Year	Crop	Cultivar	Planting date	Planting density (seed ha^{-1})	Harvest date	Fertilizer application ($kg\,ha^{-1}$)			
						Starter[a]			Side dress[b]
						N	P_2O_5	K_2O	N
2000	Corn	Pioneer 34G81	May 26	74,000	November 15	17.7	76.8	17.7	150
2001	Corn	Pioneer 34G81	May 20	74,000	November 7	17.7	76.8	17.7	150
2002	Soybean	Pioneer 93B01	June 1	580,000	October 16	0	0	0	0
2003	Corn	Pioneer 34G81	May 15	74,000	December 16	17.7	76.8	17.7	150
2004	Soybean	Pioneer 93B01	June 15	580,000	November 15	0	0	0	0

[a] The starter fertilizer was applied prior to planting.
[b] Side-dress fertilizer in the form of urea–ammonium nitrate (UAN 28% liquid) was applied at the six leaf stage in June.

Table 3
The default and calibrated cultivar coefficients, controlled tile drainage with sub-irrigation (CDS) treatment.

Corn cultivar, 2003 calibration year	Default PIO33y09	Calibrated CDS001
P1: time from seedling emergence to the end of juvenile (degree days >8 °C)	245	275
P2: extent to which development (expressed as days) is delayed for each hour (hour increase in photoperiod > the longest photoperiod 12.5 h)	0.50	0.20
P5: thermal time from silking to physiological maturity	905	650
G2: maximum possible number of kernels per plant	780	760
G3: Kernel optimum filling rate during the linear grain filling stage (mg day^{-1})	6.00	5.20
PHINE: phylochron interval between leaf tip to emerge (degree days)	48.0	39.0
Simulated dry yield (kg ha^{-1})	9921	6204
Growth period (days)	184	151
Soybean cultivar, 2002 calibration year	**Default Kenwood**	**Calibrated CDS113**
PPSEN: slope of the relative response of development to photoperiod with time (positive for short day plants) (1/h)	0.249	0.200
EM-FL: Time between plant emergence and flower appearance (R1) (photothermal days)	17.0	16.2
FL-SH: time between first flower and first pod (R3) (photothermal days)	6.5	11.0
FL-SD: time between first flower and first seed (R5) (photothermal days)	13.5	11.0
SD-PM: time between first seed (R5) and physiological maturity (R7) (photothermal days)	33.5	38.70
FL-LF: time between first flower (R1) and end of leaf expansion (photothermal days)	26.0	19.50
LFMAX: maximum leaf photosynthesis rate at an air temperature of 30 °C, 350 vpm CO_2, and high light condition (mg CO_2 m^{-2} s^{-1})	1.050	1.420
SLAVR: specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	375.0	300.0
SIZLF: maximum size of full leaf (three leaflets) (cm^2)	180.0	140.0
WTPSD: maximum weight per seed (g)	0.190	0.150
SFDUR: seed filling duration for pod cohort at standard growth conditions (photothermal days)	22.0	19.2
THRSH: threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity	77.0	79.0
Simulated dry yield (kg ha^{-1})	3680	2786
Growth period (days)	107	114

used for soil water content calibration and evaluation, respectively. Cultivar coefficients for corn (PIO 33Y09, grown in Berks County, USA at 40° 41′N, 96° 52′W) and soybean (ISU113 KENWOOD TEMPPAP) in the DSSAT Genotype file were chosen as the default cultivars based on southwestern Ontario Crop Heat Units of 3000–3300. However, using these default cultivars, the simulated yields for both soybean and corn were higher than the measured yield. At the same time, the default corn cultivars coefficients caused a simulated corn growing period of 184 days, which was substantially longer than the actual southwestern Ontario growing period of 130–155 days (Table 3). The cultivars were therefore calibrated using the Boote (1999) method and the "Genotype Coefficient Calculator" (*GenCalc v2.0*) in DSSAT (Anothai et al., 2008; Hunt et al., 1993) to achieve more realistic simulated growing periods of 151 days for corn and 114 days for soybean (Table 3).

2.4. Model performance indicators

Model accuracy was assessed using root mean square error (*RMSE*), normalized *RMSE* (*n-RMSE*), index of agreement (*d*), and linear regression with the coefficient of determination (R^2). The generalized equations for *RMSE* and *n-RMSE* are based on Loague and Green (1991). Model performance is considered excellent when *n-RMSE* < 10%; good if 10% ≤ *n-RMSE* < 20%; fair if 20% ≤ *n-RMSE* < 30%; and poor if *n-RMSE* ≥ 30% (Jamieson et al., 1991). The index, *d* (0–1), is both a relative and bounded measure, which provides a single index of model performance that encompasses bias and variability (Anothai et al., 2008; Willmott, 1982). The model simulates well when *d* approaches 1.

3. Results and discussion

3.1. Soil water content

The patterns and magnitudes of the root zone soil water content measurements in 2000 and 2001 reflect the weather and water management system, given that corn was grown both years. In the wet growing season of 2000 (511.8 mm precipitation, see also Table 1 of Tan et al., 2007), the root zone water content distributions in TD and CDS had many coinciding "spikes" due to frequent rainfall events, and the average water contents were not much different from the average field capacity values for the root zones of the two plots (i.e. ≈0.36 m^3 m^{-3} for TD; ≈0.38 m^3 m^{-3} for CDS) (Table 1). As expected, the average root zone soil water content under CDS in 2000 (≈0.37 m^3 m^{-3}) was greater than under TD (≈0.30 m^3 m^{-3}), because tile drainage was controlled with the CDS system. In the dry growing season of 2001 (405.8 mm precipitation, see also Table 1 of Tan et al., 2007), the root zone soil water content in TD had no significant spikes as a result of few rainfall events, and the water content declined steadily from about 0.3 m^3 m^{-3} in July to about 0.18 m^3 m^{-3} in September, as the corn crop continued to extract soil moisture. The root zone water content in TD was below the wilting point (≈0.23 m^3 m^{-3}) (Table 1) from about August 2001 onward, and this was reflected in the low corn grain yield (3132 kg ha^{-1}) for that year and treatment (Fig. 1a). The root zone water content in CDS also had no spikes in 2001 due to lack of rainfall, but sub-irrigation maintained the water content close to the average root zone field capacity (≈0.38 m^3 m^{-3}) until August, and above the average root zone wilting point (≈0.24 m^3 m^{-3}; Table 1) until September. As a result, the 2001 corn grain yield for CDS (6046 kg ha^{-1}) was almost double that for TD (Fig. 1).

Although the slopes of simulated soil water content in the 0–30 cm depth versus measured water content were different from unity, the model could nonetheless explain 61–79% of the linear relationship between simulated and measured values (Fig. 1). In particular, R^2 = 0.79 and 0.61 for both TD and CDS, respectively, in calibration year 2000, and R^2 = 0.68 and 0.77 for TD and CDS, respectively, in evaluation year 2001. Furthermore, the model-data fits were consistently within the "good" category, as indicated by *n-RMSE* values of 14.8 and 13.7% for TD and CDS, respectively, in calibration year 2000; and 11.6 and 9.9% for TD and CDS, respectively, in evaluation year 2001, as well as moderately high *d*, ranging from 0.724 to 0.831 (Table 4).

Garrison et al. (1999) also reported reasonable soil water content simulations using CERES-Maize for a tile-drained field in Iowa. On the other hand, Asadi and Clement (2003) found that DSSAT 3.5 consistently underestimated soil water content, although the simulations were still generally within the 95% confidence limits. In this study, DSSAT v.4.5 tended

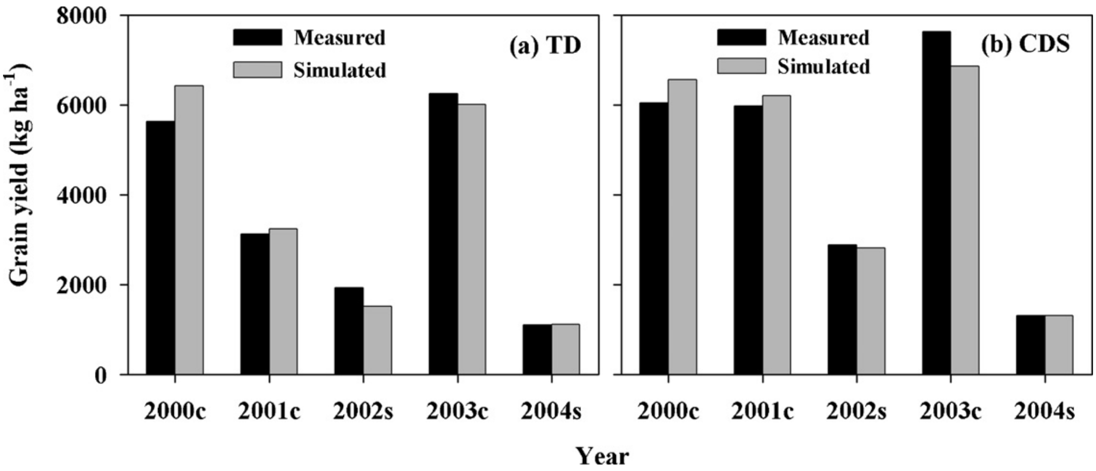

Fig. 1. Comparison of measured and simulated dry grain yield for 2000–2004 under: (a) free tile drainage (TD); and (b) controlled tile drainage with sub-irrigation (CDS). Letters after the year, “c” and “s”, refer to corn and soybean, respectively.

to overestimate the measured soil water content for TD in 2000 and CDS in 2001, and underestimate the measured water content for CDS in 2000 and TD in 2001 (Fig. 2). Using DSSAT 4.0, (Wang et al., 2010) found that soil water contents could be overestimated by the model when root water uptake occurs from deeper soil layers. Another factor affecting the accuracy of both simulated and measured soil water contents is field scale variability (Lu et al., 2009).

3.2. Crop yields

The measured and simulated corn and soybean yields are compared (Fig. 1) and statistical analyses for the calibration and evaluation years are made (Table 4). For TD, the model overestimated crop yield by 12.3% and underestimated it by 26.8% in 2000 and 2002, respectively, but predicted the measured yields within ±4.0% in other years. For CDS, the predicted and measured yields were within ±10% (Fig. 1). The *n-RMSE* values for TD and CDS were 8.2 and 10.4%, respectively, in the calibration years, and 14.0 and 4.3%, respectively, in the evaluation years; also the *d* values were very high ranging from 0.985 to 0.998 for calibration and evaluation years (Table 4), indicating consistently good or excellent model-data fits. Hence, the CERES-Maize and CROPGRO-Soybean CSM models performed well under both TD and CDS managements.

3.3. Cumulative nitrate-N loss in tile drainage

Measured and simulated cumulative tile nitrate-N losses are compared in Fig. 3, and statistical analyses for the calibration and evaluation years are given in Table 4. It is seen that the overall nitrate-N loss patterns are similar between TD and CDS, which may reflect a weather effect, given that cumulative nitrate-N loss is directly related to cumulative volume of tile outflow. Note, however, that the simulated and measured rate of nitrate-N loss from CDS was consistently lower than from TD, such that by the end of the 5-year period the cumulative loss from CDS (65.3 kg N ha^{-1}) was 30% less than from TD (92.8 kg N ha^{-1}). The reduced loss from CDS was due primarily to the controlled/restricted tile drainage for that treatment (Tan et al., 2007), and this was also recently shown in a DRAINMOD-NII modeling study (Luo et al., 2010).

For the most part, the simulated nitrate-N losses underestimated the measured losses, with the underestimate being somewhat greater for TD than CDS (Fig. 3). Nevertheless, the DSSAT predictions were good to fair, as indicated by the *n-RMSE* and *d* values (Table 4). Specifically, the cumulative nitrate-N losses were good for TD (*n-RMSE* = 17.8%, *d* = 0.678), but fair for CDS (*n-RMSE* = 21.6%, *d* = 0.529) in the calibration years, and fair for TD (*n-RMSE* = 20.6%, *d* = 0.979) and CDS (*n-RMSE* = 25.2%, *d* = 0.970) in the evaluation years (Table 4). This is consistent with Ng et al. (2000), who found that the LEACHM model also simulated nitrate-N leaching from CDS somewhat more accurately than from TD.

Table 4
DSSAT v4.5 performance for simulating grain yield, soil water content and nitrate-N loss under free tile drainage (TD) and controlled tile drainage with sub-irrigation (CDS).

Statistics	Grain yield (kg ha^{-1})		Water content (0–30 cm) (cm^3 cm^{-3})		Nitrate-N loss (kg N ha^{-1})	
	TD	CDS	TD	CDS	TD	CDS
Calibration years	2002 2003	2002 2003	2000	2000	2002 2003	2002 3003
RMSE	337	547	0.042	0.048	11.6	8.9
n-RMSE(%)	8.2	10.4	14.8	13.7	17.8	21.6
d	0.994	0.985	0.724	0.742	0.678	0.529
Sample no	2	2	98	98	12	12
Evaluation years	2000 2001 2004	2000 2001 2004	2001	2001	2000 2001 2004	2000 2001 2004
RMSE	460	200	0.026	0.037	9.1	7.6
n-RMSE(%)	14.0	4.3	11.6	9.9	20.6	25.2
d	0.987	0.998	0.737	0.831	0.979	0.970
Sample no	3	3	66	66	17	17

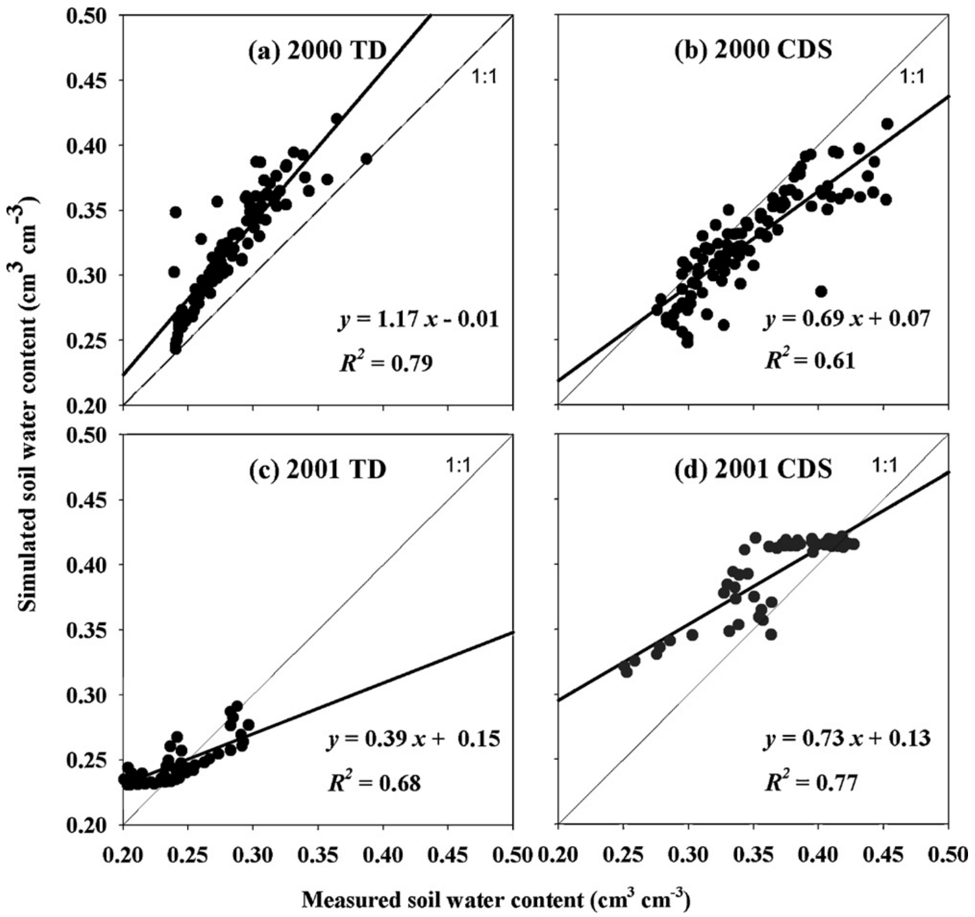

Fig. 2. Comparison of simulated and measured soil water content (0–30 cm) in calibration year 2000 for: (a) free tile drainage (TD) and (b) controlled tile drainage with sub-irrigation (CDS); and in validation year 2001 for: (c) TD and (d) CDS. The straight lines are linear regressions, with equation coefficients and R^2 values given.

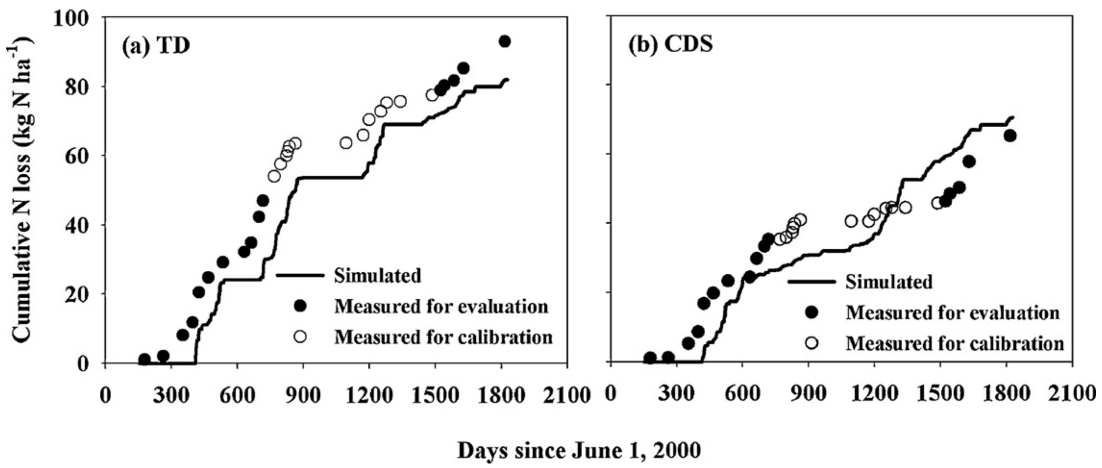

Fig. 3. Simulated and measured cumulative tile nitrate-N loss from June 1, 2000 to December 31, 2004 under: (a) free tile drainage (TD); and (b) controlled tile drainage with sub-irrigation (CDS).

4. Conclusion

For a 5-year side-by-side comparison of CDS and TD on a fine-textured soil in southwestern Ontario, DSSAT v.4.5 provided excellent simulations of corn and soybean grain yields, good simulations of root zone soil water content, and reasonable simulations of cumulative nitrate-N loss in tile outflow. Hence, DSSAT v.4.5 appears useful for simulating/predicting the short term (5–8 years) impacts of CDS and TD on environmental quality, crop productivity, and soil profile processes, at least on fine-textured soils in southwestern Ontario. The fact that others have also used DSSAT or its component submodels to successfully simulate crop yields and nitrate-N balance in a variety of soils under TD (e.g. Asadi and Clement, 2003; Garrison et al., 1999; DeJonge et al., 2007; Liu et al., 2010) implies that the DSSAT system is widely applicable. Nevertheless, further study is needed to confirm that the model can be usefully applied to a wide range of crop rotations (e.g. corn–alfalfa and wheat–corn), to other soil types, regions and climates, and to the prediction of the medium- and long-term impacts of water management using CDS and/or TD.

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