REFEREED PAPER

ADAPTATION OF CANEGRO SUGARCANE MODEL TO THE 2D SOIL-WATER OPTION WITHIN THE DSSAT CROPPING SYSTEM MODEL VER. 4.5.2.002

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Abstract

A commonly used crop model for sugarcane production is the DSSAT-CaneGro, which is a modular software package that integrates principles from experts in various fields to provide a unified cropping system model. The DSSAT-CaneGro model has been used worldwide for addressing irrigation, making it a viable tool for improving efficiencies in crop production. However, despite previous applications of DSSAT to a wide range of cropping systems, the soil-water balance currently implemented in DSSAT simulates one-dimensional (1D), vertical flow on a daily time step approach. While such 1D modelling approaches adequately simulate water infiltration for rainfed, sprinkler or flood irrigation systems that apply water with high uniformity, such an approach may be insufficient for low volume irrigation systems (e.g. drip). Drip irrigation applies water non-uniformly with sharp soil-moisture gradients both radially and vertically from emitters and requires a two-dimensional (2D) approach. Further, a daily time step is inadequately coarse for capturing the temporal dynamics of the system under high frequency drip irrigation regimes, necessitating sub-daily time steps. The objective of this study was to compare outputs of the standard CaneGro model to those of a 2D version of DSSAT-CaneGro, as part of the calibration step described in Stage 1 of the Agricultural Model Intercomparison and improvement Project sugarcane model calibration and sensitivity analysis protocol. Comparisons of the DSSAT-CaneGro 1D and 2D models for three experiments are provided and indicate similar biomass, yield, water use and leaching between the two models.

Keywords: sugarcane, model, two-dimensional, drip irrigation, calibration, comparison

Introduction

Worldwide, fresh water is becoming an increasingly scarce resource, becoming the limiting factor for agricultural development in many regions and countries (Qureshi *et al*., 2001). Water management has to increase its efficiency, especially in the uppermost water consumer sectors, such as agriculture. This can only be achieved by generating appropriate scientific information to address water shortage and environmental contamination. For example, reconciling increasingly stringent Florida water quality regulations with the expected increase of sugarcane (*Saccharum* spp.) planted area in the state will require integrating irrigation systems commonly used for other crops in sandy soil into sugarcane irrigation management. Furthermore, since many soils are highly leachable, N must be managed well to ensure adequate nutrition for the crop and protection of groundwater from excessive leaching of nitrate. For these reasons, drip irrigation is an alternative worthy of consideration for sugarcane production with higher water use efficiency.

Sugarcane production has a high irrigation water requirement, particularly on sandy mineral soils with low water retention (Lang *et al*., 2006). Lack of water causes considerable delays in sugarcane development, reducing biomass accumulation and yield (Subirós, 2000). Subsurface or seepage irrigation of sugarcane in Florida requires 884 kg of water for the production of 1 kg of sugar in plant cane, and 1,115 kg of water in ratoon cane (Wright *et al*., 2011). Several studies of drip irrigation in sugarcane have demonstrated economic viability with yield increases of up to 60% in cane weight compared with rainfed production (Camp, 1998; Wiedenfeld, 2004). Drip irrigation systems have been broadly used for sugarcane in other countries (Australia, Brazil, South Africa) (Batchelor *et al*., 1990; Wiedenfeld, 2004; Subirós, 2000). Subsurface drip irrigation (SDI) offers many advantages over rainfed production: 1) increased sucrose yield; 2) improved water use efficiency; 3) reduced cost of cane production; 4) reduced labor inputs when automated; 5) increased crop nutrient uptake efficiency (NUE); and 6) improved application of water through an even distribution along the rows, but not between rows (Ndlovu, 2000). As noted by Skaggs *et al*. (2004), realising the full potential of subsurface drip technologies in sugarcane requires optimising the operational parameters that are available to irrigators, such as the frequency and duration of irrigation, emitter discharge rate, spacing, and the placement of the drip laterals. Thus, the proper design and management of SDI systems requires knowledge of the precise distribution of water around the emitters to determine an optimal distribution of water in the sugarcane root zone.

To improve crop water and nutrient use efficiency, the impact of drip irrigation systems on sugarcane biomass accumulation, nutrient use and yield must be understood and compared with the same growth parameters of other irrigation methods. Drip irrigation is a promising technology that offers high water use efficiency (>85%) and is often specified as a best management irrigation practice for reducing groundwater contamination (Evans *et al*., 2007). The objective of this paper is to: (i) describe changes made in DSSAT code to define a 2 dimensional soil water movement, (ii) compare the biomass, yield transpiration and drainage output from the original 1D DSSAT with similar output from the 2D soil-water model, and (iii) evaluate the use of DSSAT-CaneGro with a 2D soil water in determining water use patterns. Datasets from the AgMIP project were used to develop comparison data and model evaluations.

Description of CaneGro with 2D soil module

In this research, the Decision Support System for Agrotechnology Transfer Cropping Systems Model (DSSAT-CSM) was amended to allow for water-limited simulation under cultural practices common for intensive agricultural production, including drip irrigation. A 2D water balance model was developed with an emphasis on creating a practical model with flexible input requirements and reasonable computation time. Model parameter estimation methodology designed to utilise the standard DSSAT soil inputs are described below. Soil moisture measurements during a field experiment with and without plant uptake were compared to model output (Jones, 2013). Evaluation of the parameter estimation methodology indicated the methodology provided unbiased characterisation of soil water retention curves (SWRC), with an overall root mean square error (RMSE) of 0.0458 cm^3/cm^3. However, SWRCs were more accurately characterised when estimated from soil water measurements from a wider range of soil water potentials, with an overall RMSE of 0.0277 cm^3/cm^3. These results are now in review for publication.

The 2D soil-water balance model added to the DSSAT-CSM (DSSAT-2D) assumes 2D vertical plane flow, with uniformity assumed along the crop row. Water flow under drip irrigation systems is truly a transient, 3D process (Cote *et al*., 2003). However, 2D approximations are reasonable for drip-irrigated systems when emitters are closely spaced (Bresler, 1977; Warrick, 1985). Schwartzman and Zur (1986) found emitter spacings tend to be sufficiently close under row crop production, with emitters typically spaced such that a nearly continuous wetted soil strip is created along the crop row. This 2D simplification is commonly used for modeling drip-irrigated systems (Elmaloglou and Malamos, 2003; Roberts *et al*., 2009; Rubin, 1968; Skaggs *et al*., 2004).

Richards equation

Water flow within DSSAT-2D is computed using the Richards equation (Richards, 1931), which is the most widely used (Pachepsky et al., 2003) and accurate model for unsaturated soil-water flow (Gowdish and Muñoz-Carpena, 2009). The potential-based form is the most commonly used and is applicable for variably saturated and heterogeneous soils (Hillel, 1998). However, numerical solutions of this form require short time steps and small spatial intervals (Hillel, 1998). Due to the challenges in numerically solving the potential-based form of the Richards equation, Childs and Collis-George (1950) made mathematical manipulations in order to create an alternate water-content-based form, which circumvents some of these issues. The water-content-based form of Richards equation introduces the hydraulic diffusivity term (D), which improves the efficiency of numerical solutions. This form is less sensitive to the non-linear relationship of the soil hydraulic conductivity (K) and potential (ψ) and can tolerate much larger time and space intervals (Hillel, 1998).

Parameterisation of the soil water retention curve

To utilise the Richards equation, it is necessary to parameterise the model, providing the soil water retention curve (SWRC) as well as the K and D functions. There are many methodologies that can be used to relate soil water potential (θ_ψ), non-saturated hydraulic conductivity (K_θ) and diffusivity (D_θ) (Gardner and Mayhugh, 1958; Gupta *et al*., 1974; Mualem, 1976; Saxton and Rawls, 2006; Van Genuchten, 1980). Considering the strengths and weaknesses of these models, the Van Genuchten (1980) SWRC model and the Mualem (1976) pore-size distribution model were selected. These models were selected due to their wide use (Schaap and Leij, 2000; Tuller and Or, 2001; Kosugi *et al*., 2002; Ippisch et al., 2006), applicability to a wide range of soils (Van Genuchten and Nielsen, 1985), and flexibility for characterising many soil types and scenarios (Mace *et al*., 1998). Importantly, the Van Genuchten model can be used to compute the necessary θ_ψ, K_θ and D_θ functions.

Soil characterisation

The DSSAT model represents the soil of a production unit one-dimensionally, splitting the soil profile into homogenous layers spanning various depths. Each soil layer is characterised by a range of properties needed to operate the DSSAT-CSM. Among the standard soil property inputs are the soil lower limit of plant extractable water (θ_{LL}), drained upper limit (θ_{DUL}), and saturation (θ_s) volumetric water contents (VWC), which constitute three points of the SWRC. Additionally, DSSAT soil property inputs include soil texture and soil fractions. In order to estimate the necessary parameters for the Richards equation using the standard DSSAT model inputs, several steps were necessary for each soil layer. First, the SWRC was derived using relationships reported by Saxton and Rawls (2006). Many equations have been proposed that relate soil water retention, soil texture, soil hydraulic properties, and other soil properties (Hillel, 1998; Rawls *et al.*, 1992; Schaap and Leij, 2000). The Saxton and Rawls (2006) relationships were chosen due to their applicability to the DSSAT inputs, previous applications in agricultural hydrology (Caruso *et al*., 2013; Looper and Baxter, 2011; Shrestha *et al*., 2010), and reports of good performance compared to other methods (Gijsman *et al*., 2002). However, instead of estimating the soil hydraulic parameters from the soil textural information alone, the DSSAT input data were used to improve the estimations. To operate the 2D water balance, users have the option of entering the Van Genuchten parameters directly for each soil layer. If the Van Genuchten parameters are estimated from expert information such as fitting to SWRC data, this is preferred for improving the accuracy of simulations of soil-water dynamics and eliminating the Saxton and Rawls calculations. However, to ensure that users with knowledge of only the standard soil properties for each soil layer can utilise the model, a methodology was developed to estimate the Van Genuchten parameters from the standard DSSAT soil property inputs. This also allows the 2D model to be used for existing DSSAT experimental data, for which Van Genuchten parameters have not been estimated.

Two-dimensional cell structure

In order to implement the model within the DSSAT-CSM, the modelling space was discretised into a 2D grid (Figure 1). Half of the modeling space is simulated, with symmetry assumed across the row centre in order to reduce computational time. The model allows for the creation of a rectangular raised bed with user specified dimensions, and delineates grid cells as either within the raised bed, beneath the raised bed, within the furrow, or beneath the furrow. Sugarcane is not typically grown on raised beds, thus the cells within the raised bed are eliminated and simulation is provided for a continuous row of cells approximating production on level soil. Drip irrigation is simulated as a line source to apply water as specified at the row center, or twin lines can apply water if aligned equidistant from the row center. This irrigation water enters the cell beneath the line source, which stores all the applied irrigation until it flows vertically or horizontally from the cell.

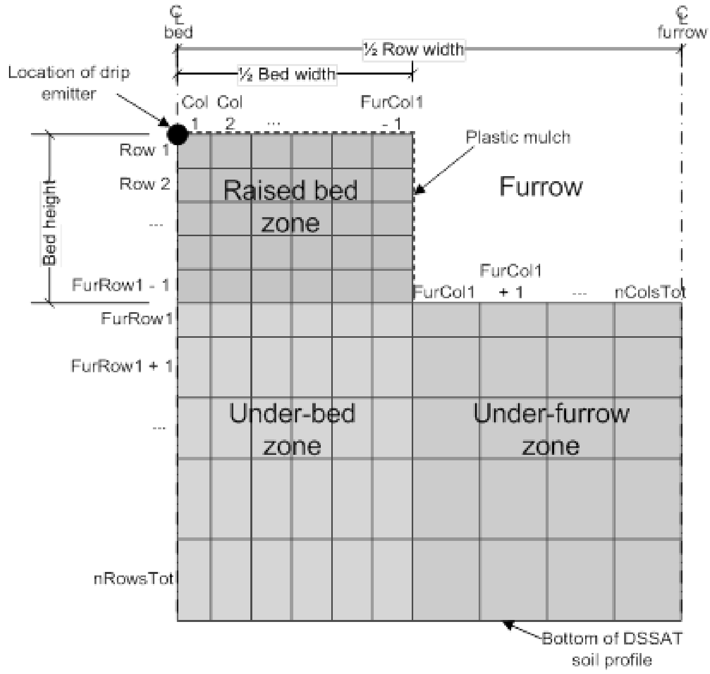

Figure 1. Cross-section of half of a raised bed system as modelled by DSSAT-2D.

Soil water movement and root water uptake

With the grid cell constructed and boundary conditions set, soil-water flows are simulated in order to update the cell water contents at a new time step. The model operates on a variable time step that is calculated based on the dynamics within the system to assure numerical stability and convergence (Gerald, 1978). The global minimum time step is applied. Flows between cells are calculated assuming D and K values that are the geometric average of the respective values from the two cells (Figure 2).

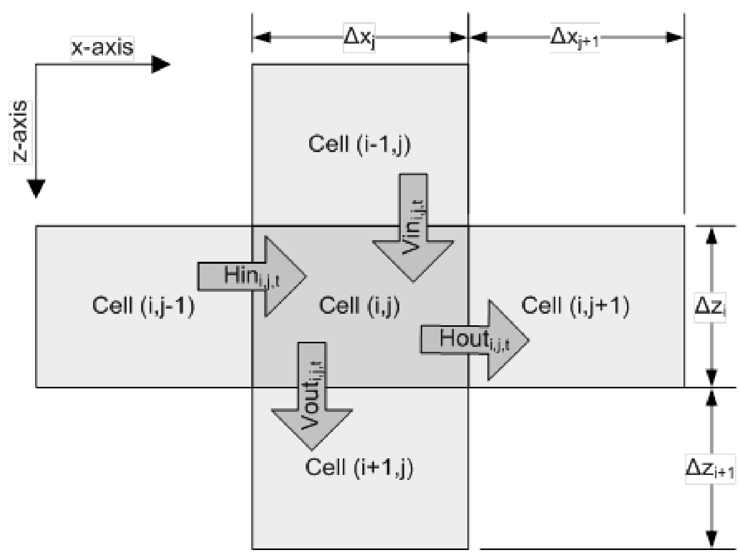

Figure 2. Definitions of the DSSAT-2D grid cell dimensions and layout.

While the previously described soil-water flow calculations are implemented on a variable time step, other flows are computed on a daily basis, but partitioned on a sub-daily time step. Potential evaporation and transpiration demand are computed using the original DSSAT methodologies (Hoogenboom et al., 2009), with the daily demand distributed across the day according to the daily distribution of solar radiation. Actual evaporation can be limited based on the soil surface cover and water content. Actual root water uptake is limited by θ, root density, root distribution, and soil properties. Root growth is also computed on a daily basis according to standard DSSAT methodologies, with uniform lateral root distribution. Daily rainfall infiltration is computed using the Soil Conservation Service runoff curve number method (USDA, Soil Conservation Service, 1972). The daily infiltration is distributed across the day and evenly applied to non-mulched surface cells, with rainfall on mulched areas being routed to the furrowed area. At the end of each time step, the θ in each cell is updated considering infiltration, and root water uptake.

Description of AgMIP-Sugarcane Pilot Stage 1 simulations

Changes to CaneGro Ver. 4.5 were mainly restricted to Fortran code files SC_CNGRO.FOR and SC_ROOTG.FOR, with some modifications in SC_Poplt3.FOR and SC_Canop3.FOR. A single parameter was added to the CaneGro 'Species' file to adjust root length density to the 2D soil and root model.[1] No changes were made to the other two CaneGro 'genotype' files, or to the parameter values in those files. Neither the weather nor soil input files were modified. Some changes were made to the 2D version of the DSSAT experiment control files, *.SCX. The '*FIELDS' section requires addition of three parameters for the 2D version: Bed width (BDWD), Bed height (BDHT) and Plastic mulch albido (PMALB). In these experiments, the bed width is set equal to row spacing, bed height is zero and -99 is placed under the plastic mulch switch. Also in the *.SCX experiment control file the switch corresponding to hydrology method 'HYDRO' (in METHODS line of the SIMULATION CONTROLS section), must be changed from R (default Richie water balance method) to G (modified Green-Ampt drip irrigation model).

Outputs of the standard CaneGro model are compared to those of the 2D version as part of the calibration steps as described in Phase 1, Stage 1 of the 'AgMIP sugarcane model calibration and sensitivity analysis protocol'. This requires both models to be run using input files that are entirely identical, except for the changes in the FileX mentioned above. At this stage in the AgMIP calibration process, only management and weather data are available, and the models will be run with generic genotype parameters. To date three sites have been completed, and it is planned to test both the standard and 2D versions of the CaneGro model at the 11 sites for which data are available.

Stage 1 simulation results

Analysis here focuses on very broad, mostly 'end of season' results of the simulations in order to understand where the 1D and 2D rainfed, sprinkler and drip irrigation versions of the same experiment are similar, and where important differences may lie. Detailed comparisons of root growth and soil water status will be guided by these broader results (Tables 1, 2 and 3).

[1] The parameter, RtcmpgCoef, is used to adjust the existing RTCMPG parameter (root cm/g), and does not affect the 1D model in any way.

Table 1: Model output for La Mercy, South Africa, planting date experiment using DSSAT 1D and 2D models.

Output parameter	1D planting, year-day of year				2D planting, year-day of year			
	89-213	89-335	90-091	90-213	89-213	89-335	90-091	90-213
Precipitation (mm)	1506	1895	1310	1448	1506	1895	1310	1448
Max leaf area index	5.1	6.6	6.6	4.9	4.6	5.0	5.4	4.3
Above-ground biomass (kg/ha dry matter)	56686	65597	55173	57950	57498	63487	51375	55499
Sucrose (kg/ha)	13889	16553	15811	14555	14825	16156	15974	13756
Soil evaporation (mm)	179	206	200	197	239	375	337	342
Transpiration (mm)	906	1085	880	923	1018	1145	856	969
Drainage (mm)	130	182	54	126	0	0	0	0

The 1D and 2D above-ground biomass dry yields show similar amounts (avg <4% difference) and trends across the planting dates. The simulated sucrose amounts vary slightly (avg <4% difference), with the 2D model simulating a very slightly higher proportion of sucrose in the above ground dry matter (27% vs 26%). The 2D version does appear to respond somewhat differently to seasonal rain patterns, with its lowest-yielding and next-lowest-yielding planting dates switched compared to the 1D version. LAI values show the most variation between 1D and 2D results in this experiment, with 2D LAI ranging from 10% to 24% smaller than the 1D values. This consistency (all smaller) was not found in other experiments. The 2D version generally registered slightly higher transpiration values. However, the major difference between the models is in the soil-water movement. The 2D model has much higher soil evaporation, which largely accounts for the absence of drainage. More data are needed to evaluate whether the 2D soil evaporation rates are an improvement or not with respect to the 1D model.

Table 2. Model output for Brazil Piracicaba, Sao Paolo rainfed vs irrigation experiment using DSSAT 1D and 2D models.

Output parameter	1D		2D	
	Rainfed	Irrigated	Rainfed	Irrigated
Precipitation (mm)	1023	1023	1023	1023
Irrigation (mm)	0	705	0	705
Max leaf area index	4.1	5.0	4.0	5.3
Above-ground biomass (kg/ha dry matter)	33490	45354	35867	48096
Sucrose (kg/ha)	6371	10762	7554	11459
Soil evaporation (mm)	326	312	459	436
Transpiration (mm)	546	899	520	834
Drainage (mm)	60	101	0	4

The tendencies observed in the La Mercy, South Africa, simulations are also apparent in this Brazilian experiment. Soil evaporation is much higher and drainage is much lower in 2D. However, here there is an irrigated treatment to compare with rainfed production. In this case, 2D biomass and sucrose outputs are consistently higher than 1D outputs. Somewhat in contrast to the La Mercy results, 1D and 2D give very similar LAI results, only 2% difference in rainfed and 6% difference in irrigated LAI. Soil drainage is again almost non-existent in the 2D version.

Table 3. Model output for the Komatipoort, South Africa, irrigation rate experiment for DSSAT 1D and 2D models for sprinkler irrigation and DSSAT 2D model for drip irrigation.

Output parameter	1D sprinkler			2D sprinkler			2D drip		
	low	med	high	low	med	high	low	med	high
Precipitation (mm)	403	403	403	403	403	403	403	403	403
Irrigation (mm)	543	679	1323	543	679	1323	542	674	1323
Max leaf area index	4.5	4.7	9.6	4.6	5.0	8.6	4.9	5.0	8.0
Above-ground biomass (kg/ha dry matter)	42209	49658	61040	42461	52066	60599	46743	53929	61354
Sucrose (kg/ha)	11321	13090	12017	10260	12906	11843	10734	12043	11211
Soil evaporation (mm)	239	204	150	313	275	218	217	222	194
Transpiration (mm)	579	743	990	534	705	978	626	749	1001
Drainage (mm)	79	79	476	19	14	366	19	18	376

The Komatipoort, South Africa, irrigation rate experiment (Table 3) is particularly interesting for the development of the 2D model since it includes data from a drip irrigation field experiment. As explained in the previous portion of this paper, the ability to simulate drip irrigation is a fundamental reason for developing the 2D versions of crop simulation models, including CaneGro. To better understand the drip irrigation implementation, it was compared to both 1D and 2D simulations using the same irrigation amount, applied from sprinklers.

First comparing the sprinkler-irrigated simulations, the 1D and 2D results are the closest for this experiment. Even so, some of the same tendencies seen in the previous South African and Brazilian experiments emerge: very similar biomass and sucrose yields, without either 1D or 2D versions showing consistently higher values. The range of above ground biomass yield values is slightly greater in 1D, but the same comparison for sucrose is greater in the 2D version. Plant transpiration is slightly lower in the 2D version. As in the Piracicaba case, LAI is proportionally closer in treatments with lower water availability, ranging from 2% difference with low irrigation, to 10% difference with high irrigation. This tendency was not as clear in the La Mercy simulation, however. Only in this experiment does the 2D model show substantial drainage. That is probably due to the relatively shallow soil profile: 85 cm as opposed to 165 cm for the La Mercy and Piracicaba experiments.

The irrigation water amounts in the drip section vary slightly from the sprinkler simulations; this is due to the difficulty in adjusting the drip setup to precisely match application depths. Comparing 2D sprinkler and the 2D drip simulation outputs, drainage is very similar in these, with both different from the 1D version. Soil evaporation is lower in the drip than the sprinkler version, although since the applicators are simulated to be 5 cm below the soil surface, evaporation directly from the soil should probably be considerably lower than shown. Other percentage differences between 2D sprinkler and drip versions are generally of a similar magnitude to differences between 1D vs 2D sprinkler outputs. However, there is a different pattern: in all cases, the 2D drip outputs show less range of variation from stress to non-stress conditions, as compared to the 2D sprinkler outputs. For example, taking the highest irrigation rate as the baseline, the lowest irrigation treatment causes the following reductions for sprinkler vs drip 2D versions, respectively: LAI 47% vs 39%; above-ground biomass 30% vs 24%; sucrose 13% vs 4% and transpiration 45% vs 37%. This consistency is likely due to the reduced soil evaporation with drip irrigation, which provides significantly more water to the plant. This is particularly noticeable under low irrigation, where soil evaporation decreases by 96 mm, and transpiration increases by 92 mm when drip replaces sprinkler irrigation. Note that these comparisons understate the relative efficiency of drip irrigation in one important way: the irrigation efficiency was set at 95% for all applications. The reason for this was to be able to compare the same amount of water in the soil across the three modelling alternatives. If the objective were to accurately model sprinkler irrigation, sprinkler efficiency would have to be set lower, at around 75% to account for irregular distribution and evaporation of water before it enters the soil.

Conclusions

An objective through this point in the development of the 2D version of CaneGro has been to reasonably simulate the above-ground outputs of the current 1D version of CaneGro. The 2D version of CaneGro is now functional, and does appear to reasonably simulate CaneGro 1D. Compared to 1D, the 2D end-of-season crop results did not show any troubling tendencies such as consistently higher or lower yields within the three experiments simulated so far. Going beyond crop outputs, however, the 2D version does show high soil moisture loss through direct evaporation ('soil evaporation'). This is particularly noticeable under rainfed conditions or when using sprinkler irrigation.

CaneGro 2D showed a tendency toward higher biomass and transpiration when using drip instead of sprinkler irrigation. This appears to reflect drip irrigation's reduced soil evaporation. However, even the 2D drip option leads to more soil evaporation than seems intuitively correct, so this will probably need to be adjusted once suitable soil-water content data are available.

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