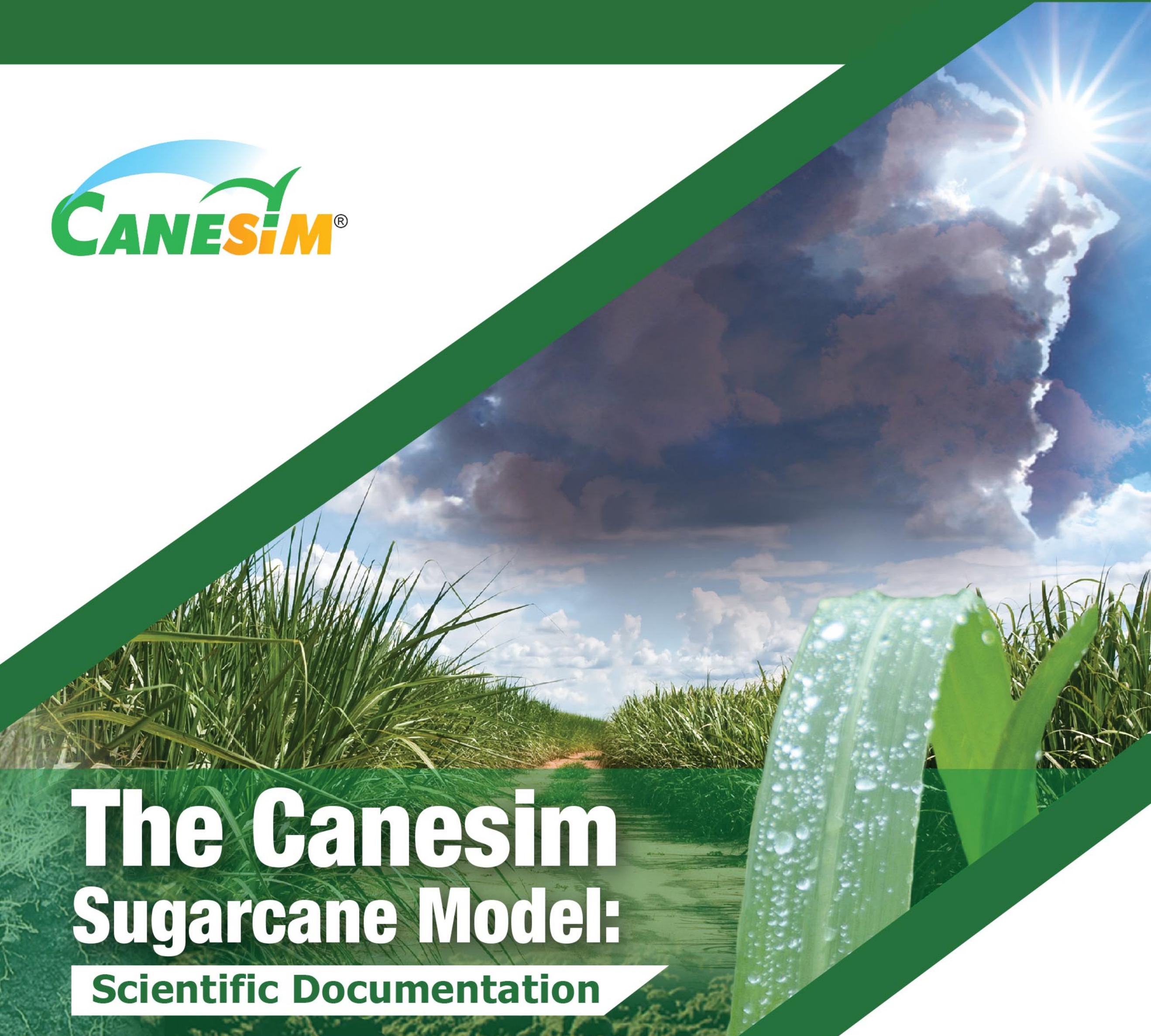

The Canesim Sugarcane Model:

Scientific Documentation

A. Singels & A.L. Paraskevopoulos

THE CANESIM® SUGARCANE MODEL: SCIENTIFIC DOCUMENTATION

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1. Introduction

Sugarcane is an important crop globally, grown in tropical and subtropical regions in over 100 countries. Globally 1.9 billion tons of cane were produced in 2013 from 27 million ha (FAO, 2016). The most important products from sugarcane are sugar and renewable energy in the form of bio-ethanol and electricity. Growth simulation models play an important role in supporting crop management and research to achieve efficient and sustainable production. Various processed based sugarcane models have been developed for this purpose. These include the well documented DSSAT-Canegro, APSIM-sugar and Mosicas (see Singels, 2014). The model was developed by the South African Sugarcane Research Institute (SASRI) and has been used widely to support the strategic planning and operational management of sugarcane production in South Africa (Singels and Bezuidenhout, 2005; Singels and Smith, 2006; van den Berg *et al*., 2013; Paraskevopoulos and Singels, 2014; Jones and Singels, 2015). Despite this, the scientific concepts represented in the simulation of soil and crop processes have not been documented well.

The purpose of this book is to provide a detailed documentation of the scientific concepts and their mathematical representation in the Canesim® sugarcane model (version 17.0 as implemented on 30 March 2017), to describe the evaluation of its simulation accuracy against experimental data, and to demonstrate its potential for supporting sugarcane production by presenting a few application examples.

1.1 Brief history of the Canesim® model

The precursor of Canesim®, namely Irricane, was developed in the late 1990s for operational irrigation scheduling (Singels *et al*., 1998). Irricane had a simple single layer soil water balance and a simple canopy development subroutine. Crop water use was calculated using a daily dual crop coefficient approach as described by Allen *et al*. (1998). The program was written in QuickBASIC4.5 (Microsoft) and used text format input and output files. The executable code ran on the DOS computer operating platform. Yield calculation was introduced later to the model, by adding equations describing the relations between transpiration and yield (Singels *et al*., 1999a). This version was further adapted and made available to the public on the internet (Singels *et al*., 1999b) under the name Canesim® following a trademark challenge by CIRAD.

SQR-Canesim was developed in collaboration with SQR-software (sqrsoftware.co.za) in the early 2000s, mainly to address the perceived lack of user friendliness of the original Canesim®. The focus was still to provide irrigation scheduling support to sugarcane growers and advisors. A graphical user interface was developed in Delphi (Borland) and data stored in a Paradox database (Corel Corporation). This allowed users to set up and simulate multiple crop scenarios. The interface enabled easy editing and viewing of data in tabular and graphical formats, while input and output data were stored in the database for future use. The program was distributed on CDROM for installation on desktop computers. This system was still being used operationally in 2015.

The MyCanesim® system was developed in 2004 to provide the full functionality of the Canesim® crop model via the Internet. The system (but not the underlying crop model) is described by Singels (2007). Early versions still had a one layer soil water balance and a simple thermal time driven canopy cover algorithm. The empirical yield equation was replaced with the source-sink based biomass accumulation and partitioning model of Canegro (Singels and Bezuidenhout, 2002). Other refinements included simulation of residue layer impacts on canopy development and the soil water balance and the response of crop canopy to water stress. The model code was written in PL/SQL, operates on an Oracle database (Oracle Corporation) and uses Oracle Portal to generate web pages that the user can interact with. The interface was designed to accommodate two types of users, namely ‘tactical users’ that require real-time irrigation advice and yield forecasts, and ‘strategic users’ that require modelling for research purposes.

2. Model structure

2.1 Overview

The Canesim® model is a daily time step, point-based simulation model driven by water, temperature and radiation. It requires data for soil water-holding capacity, crop management details, irrigation system properties, daily irrigation and weather data (temperature, rainfall and reference evaporative demand) as well as plant characteristics as inputs. The model simulates canopy development, interception of solar radiation, water uptake and evapotranspiration, biomass accumulation and its partitioning to root, leaf, stalk fibre and stalk sugar. The soil water balance is simulated using a multi-layered profile and keeping track of infiltration and redistribution of rainfall and irrigation and extraction by the plant. Model structure and information flow are shown in Figure 2.1. The different inputs and outputs indicated in Figure 2.1 are further elaborated in this chapter. A more detailed description of the biophysical processes addressed and how they interact in the model is given in chapters 3 (Phenology), 4 (Canopy development), 5 (Crop water use, soil water balance and root development), 6 (Biomass accumulation and partitioning) and 7 (Lodging).

2.2 Inputs

Soil

The soil parameters used by the model *per se* are:

- Maximum effective rooting depth (ERD, cm);
- The number of soil layers considered and the thickness (Z(l), cm) of each layer l;
- The plant available water capacity (AWC, mm) per layer and for the soil as a whole (TAM, mm);
- Volumetric soil water content at saturation (θsat, mm) of each layer;
- A drainage rate coefficient (day^{-1}) for each layer and for the root zone as a whole.

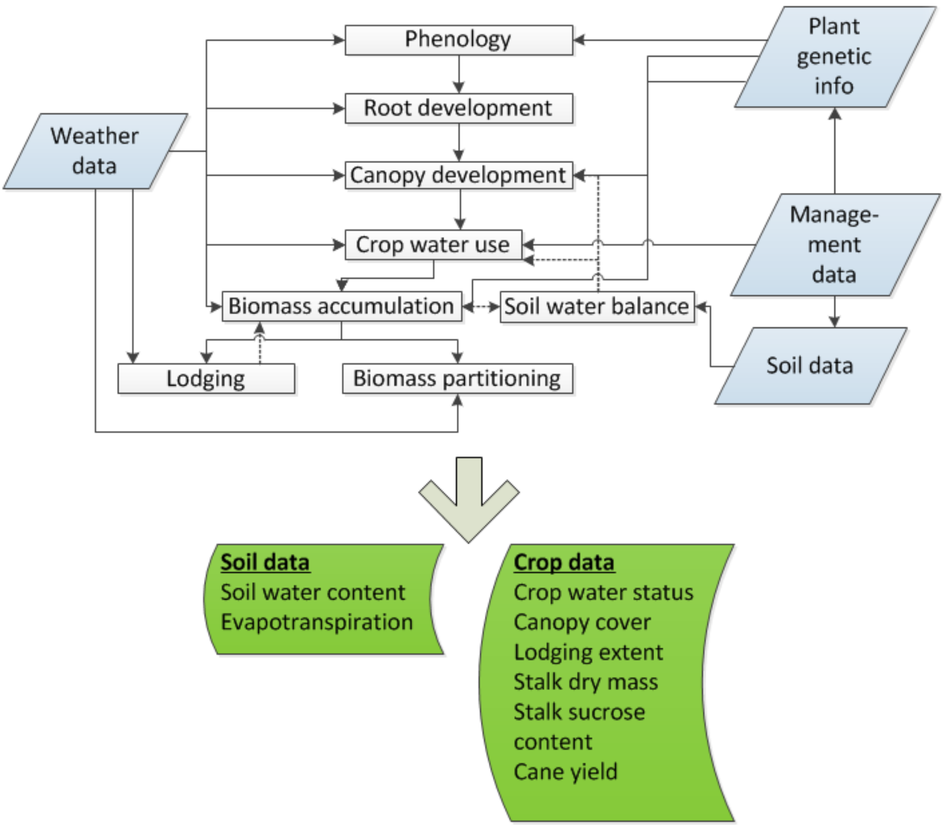


Figure 2.1. Diagrammatic presentation of the model structure and information flow of the Canesim® model. Inputs are indicated in blue blocks, processes in white blocks and outputs in green blocks.

The program allows for soil water retention parameters to be estimated from texture information (van Antwerpen *et al*., 1994).

$$AWC(l) = Z(l)\ (\theta dul(l) - \Theta ll(l))\ 10 \qquad \text{Eq. 2.1}$$

$$\Theta sat(l) = 0.95\ (1 - BD(l) / 2.65) \qquad \text{Eq. 2.2}$$

$$\Theta dul(l) = 54.7\ CLAY(l) / (24.53 + 100\ CLAY(l)) \qquad \text{Eq. 2.3}$$

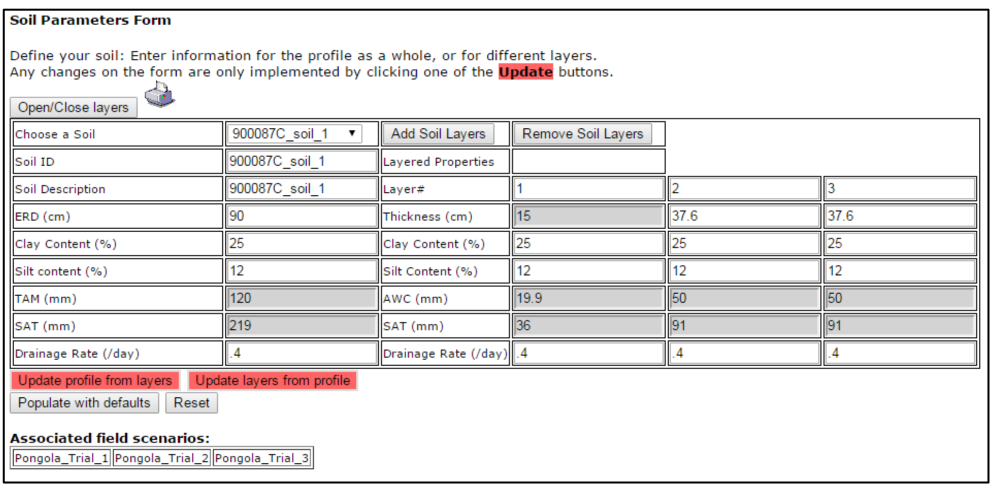
$$\Theta ll(l) = 91.94\ CLAY(l) / (135.54 + 100\ CLAY(l)) \qquad \text{Eq. 2.4}$$

where θdul(l) and θll(l) are the volumetric soil water contents at the drained upper limit and lower limit of plant available water for layer l, BD(l) is the soil bulk density (g/cm^3) for layer l, CLAY(l) is the clay content of the soil (fraction) for layer l. Moreover BD(l) is estimated from CLAY(l):

$$BD(l) = 1.8-1.5\ (CLAY(l) - 0.1) \text{ with } 1.2 <= BD(l) <= 1.9 \qquad \text{Eq. 2.5}$$

Through the graphical user interface of the model, the user can select a previously created set of soil parameters (see Figure 2.2), which can be adapted and saved as a new soil; or create a new set of parameters from scratch.

The number and thickness of soil layers must be determined within the following constraints and taking into account maximum rooting depth. The number of layers must be between three and ten inclusive, the top layer is always 15 cm thick, and the thickness of other layers should be between 15 and 50 cm. Maximum rooting depth (ERD) needs to be specified and the presence of a water table below the bottom layer can be indicated.



Soil Parameters Form

Define your soil: Enter information for the profile as a whole, or for different layers.
Any changes on the form are only implemented by clicking one of the **Update** buttons.

Open/Close layers

Choose a Soil	900087C_soil_1	Add Soil Layers	Remove Soil Layers		
Soil ID	900087C_soil_1	Layered Properties			
Soil Description	900087C_soil_1	Layer#	1	2	3
ERD (cm)	90	Thickness (cm)	15	37.6	37.6
Clay Content (%)	25	Clay Content (%)	25	25	25
Silt content (%)	12	Silt Content (%)	12	12	12
TAM (mm)	120	AWC (mm)	19.9	50	50
SAT (mm)	219	SAT (mm)	36	91	91
Drainage Rate (/day)	.4	Drainage Rate (/day)	.4	.4	.4

Update profile from layers | Update layers from profile
Populate with defaults | Reset

Associated field scenarios:
Pongola_Trial_1 | Pongola_Trial_2 | Pongola_Trial_3

Figure 2.2. Soil input form.

Weather

Daily rainfall (mm), shortwave radiation (Srad in MJ/m^2), maximum temperature (Tmax in °C), minimum temperature (Tmin in °C) and sugarcane reference evaporation (Eref in mm, McGlinchey and Inman-Bamber, 1996) are used as weather data input. In the MyCanesim® system the Canesim® model is linked to the SASRI weather database and any of 52 automatic and 56 manual weather stations situated in the sugarcane production areas of South Africa and Swaziland can be selected.

Historical data are used for the past while weather sequences from the past can be selected to represent the future when the model is applied for prediction purposes (yield forecasting or irrigation scheduling). Selection of weather sequences can be based on the expected three month rainfall categories (above-normal, normal, below-normal, long term median), or on expected El Niňo categories (strong, medium and weak El Niňo, neutral, or strong medium and weak La Nina).

The default atmospheric CO_2 concentration (in ppm) used in the simulation is determined from the cropping dates. The user can override the default by specifying the concentration to be used.

Plant

Row spacing, ratoon crop class (plant or ratoon) and residue cover are required as inputs. The user selects a cultivar from a dropdown list. Genetic characteristics are represented by crop parameters, which are divided into two types, namely generic ‘crop’ parameters that have common values for all sugarcane genotypes (Table 2.1), and ‘cultivar’ parameters that have genotype specific values (Table 2.2). Cultivar parameter values have been estimated using experimental observations and subjective expert ratings (South African Sugarcane Research Institute (SASRI) cultivar information sheets).

Table 2.1. Generic crop parameters.

Name	Category	Description	Value
Tbgro	Phenology	Base temperature for shoot emergence and start of stalk growth (°C)	10
Tbphoto	Phenology	Base temperature for photosynthesis (°C)	10
To1photo	Phenology	Lower optimal temperature for photosynthesis (°C)	20
To2photo	Phenology	Upper optimal temperature for photosynthesis (°C)	40
Tocan	Phenology	Optimal temperature for canopy development (°C)	35
Togro	Phenology	Optimal temperature for phenological development and root growth (°C)	30
Tucan	Phenology	Upper temperature threshold for canopy development (°C)	48
Tugro	Phenology	Upper temperature threshold for phenological development and root growth (°C)	43
Tuphoto	Phenology	Upper temperature threshold for canopy development (°C)	47
Tosuc	Phenology	Optimal temperature for maintenance respiration (°Cd)	40
Tusuc	Phenology	Upper temperature threshold for maintenance respiration (°C)	47
dTT50res10	Canopy	Change in thermal time required to reach 50% canopy cover due to the presence of a residue layer (°Cd)	-30
dTT50row	Canopy	Thermal time adjustment a row spacing change from the reference of 1.4 m (°Cd)	125
k	Canopy	Empirical shape factor for the relationship between canopy cover and thermal time	2.453
Respcf	Biomass	Fraction of daily biomass increments consumed through growth respiration	0.25

Name	Category	Description	Value
RespQ10	Biomass	The Q10 coefficient for the response of maintenance respiration rate to temperature	1.68
Rgro	Biomass	Root penetration rate per unit thermal time (m/(°Cd))	0.0017
Respcons	Biomass	Daily biomass increments consumed to maintain the stored sucrose pool, expressed as a fraction of the sucrose stored in stalks	0.00121
Δmax	Partitioning	Maximum gradient in sucrose content in the immature section of the stalk ((g/g)/(t/ha))	0.07
Δamin	Partitioning	Minimum gradient in sucrose content in the immature section of the stalk ((g/g)/(t/ha))	0.01
FWCON	Partitioning	Coefficient for the sensitivity of sucrose accumulation to water deficit	1
AMrange	Lodging	The range in aerial mass (fresh biomass plus any water attached to it) from the point where lodging commences up to the point where lodging is complete (t/ha)	30
ΔFI	Lodging	The fractional reduction in radiation interception for a fully lodged crop	0.13
ΔRUE	Lodging	The fractional reduction in radiation conversion efficiency for a fully lodged crop	0.23
GSTRESS	Drought sensitivity	The available soil water threshold below which expansive growth is reduced below its potential value at a reference atmospheric demand of 5 mm/d	0.8
FIred	Drought sensitivity	Maximum reduction if fractional canopy cover due to water deficit	0.3
FIduro	Drought sensitivity	Water stress period required to effect the maximum reduction in canopy cover (d)	21
FLODGEswco	Lodging	Maximum increase in the lodged fraction due to saturated soil	0.25

Name	Category	Description	Value
Ux	Lodging	Daily wind run above which lodging susceptibility is increased (km/d)	200
FLODGEuo	Lodging	Maximum increase in the lodged fraction due to strong wind	0.25

Table 2.2. Cultivar parameters.

Name	Category	Description	NCo 376 value	Value Range
Tbcan	Phenology	Base temperature for canopy development (^oC)	16	12-18
TTEMpo	Phenology	Thermal time required from planting to shoot emergence on a bare soil (^oCd)	100	50-350
TTEMro	Phenology	Thermal time required from cutback to shoot emergence on a bare soil (^oCd)	300	250-550
TTsg	Phenology	Thermal time required from shoot emergence to start of stalk growth (^oCd)	1000	900-1230
TT50ref	Canopy	Thermal time required from shoot emergence to 50% canopy cover for a reference crop (unstressed, bare soil and row spacing of 4 m)	250	190-370
RUEo	Biomass	Radiation conversion efficiency for reference condition, defined as the total gross (pre-respiration) photosynthate produced per unit of short wave radiation intercepted, for a crop growing at optimal temperature and water status.	2.25	1.63-2.25

Name	Category	Description	NCo 376 value	Value Range
ADMPFmax	Partitioning	Maximum partition fraction of daily biomass increments to aboveground plant parts	0.88	0.75-0.90
SPFmax	Partitioning	Partition fraction of daily aboveground biomass increments to stalk material during the stalk growth phase	0.65	0.65-0.80
SUCmax	Partitioning	Maximum sucrose content in the mature section of the stalk	0.58	0.53-0.67*
T50	Partitioning	Temperature threshold where daily stalk mass increments are partitioned 50:50 to fibre and sucrose (^oC)	25	23-29
ESTRESS	Drought sensitivity	The relative available soil water content threshold below which transpiration and photosynthesis rates are reduced below their potential values	0.45	0.3-0.6
AMbase	Lodging	Aerial mass (fresh mass plus attached water) at which lodging commences when other lodging factors such as water and wind are absent (t/ha)	260	260-190

*Sucrose cultivars only, excludes high fibre cultivars

Parameter values for the main reference cultivar NCo376 were determined through direct and indirect calibration on growth analysis (canopy cover, biomass and stalk yield) data from 26 field trials. Selected cultivar parameter values for other cultivars were estimated from experimental data and subjective observations (expert ratings in SASRI information sheets). Parameter values are given in the Appendix. The procedure involved assigning seven classes to expert ratings for the different traits, ranging from very low (1) to very high (7). Parameter values for the different classes were estimated by associating values for a determined through direct or indirect calibration on experimental data for a given cultivar to the class assigned to that cultivar.

TTEMpo and TTEMro were estimated from germination ratings, TT50 from canopy formation ratings and fractional interception measurements, TTsg from canopy formation ratings and leaf appearance measurements, RUEo from average relative cane yields (cane yields expressed as percentage of the reference cultivar NCo376) from the cultivar evaluation trial database and leaf level gas exchange measurements, ESTRESS values from drought tolerance ratings and crop water use data, SUCmax values from average relative sucrose content from the cultivar evaluation trial database, T50 values from earliness (optimal month of harvest) ratings, and AMbase from lodging susceptibility ratings and lodging observations.

Management

The model requires crop start and harvest dates, row spacing, crop class (plant or ratoon crop), and the amount of crop residue from previous crop. Identifiers for weather station, rain gauge (optional), soil water meter (optional), irrigation data (optional), cultivar and soil are also needed. Rainfall data from a specified rain gauge will override data from the weather station for the period for which rain gauge data is available. Root zone soil water status observations can be used to reset model simulations (see Paraskevopoulos and Singels, 2014), if this option is selected.

For irrigated scenarios the type of irrigation system needs to be specified, and for drip systems emitter depth and spacing are also required. This will determine how canopy interception losses from overhead systems will be calculated, as well as evaporation from partially (drip) or fully (overhead) wetted soil surfaces.

Irrigation dates and amounts can be entered by the user, or can be automatically uploaded from user specified gauges and flowmeters, once the necessary data linkage and conversion algorithms are put in place. Irrigation can also be simulated be specifying further irrigation system properties (target application amount, minimum cycle period) and scheduling rules (allowable depletion and refill levels, growing season allocation) (see Figure 2.3). Different sets of irrigation settings can be specified for up to four periods of the growing season.

The MyCanesim® system has a data upload option to enable easier setting up of a batch of fields or cropping scenarios for simulations. The function imports data from the specified CSV file, uploads the data to the relevant MyCanesim® database tables and creates the fields/scenarios under the specified user. Missing data are infilled with default vales. At present, the Plan-A-Head farm management software (www.planahead.co.za) can export the data in the required format.

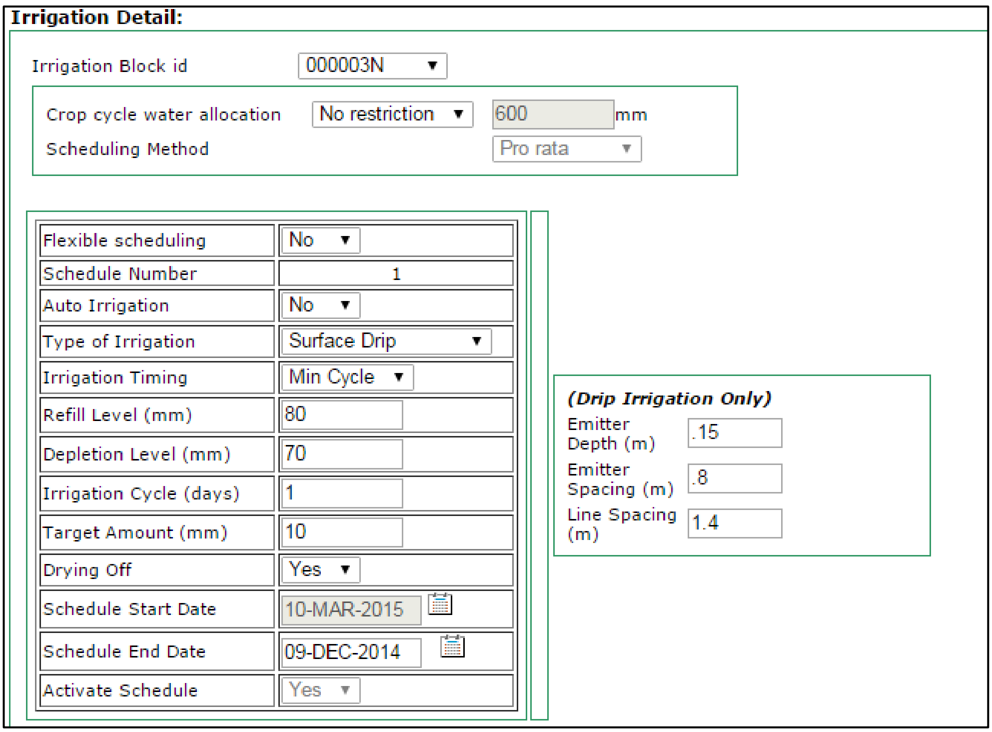


Figure 2.3. Irrigation input form.

2.3 Outputs

MyCanesim® simulation results are recorded in various reports, depending on the type of user. For 'strategic' (research) users the **Project** report summarises all cropping scenarios in a project in terms of the water balance (seasonal totals of evapotranspiration, rainfall and irrigation) and cane and sucrose yield at harvest.

Scenario reports provide a summary of field inputs used in the simulation as well as simulated cane and sucrose yield, stalk dry matter and sucrose content, soil water content, extent of lodging, seasonal totals of rainfall, irrigation and crop water use, canopy cover at harvest and the extent of missing weather data. It also provides a link to daily output that consists of cumulative values of rainfall, irrigation and evapotranspiration (mm); the sum of intercepted rainfall and irrigation (mm), deep drainage plus runoff (mm), root zone available soil water (mm), crop water status, canopy cover (%), cane yield (t/ha), stalk dry mass (t/ha), sucrose yield (t/ha), stalk sucrose (t/ha) and dry matter content (%), and the extent of lodging (rating from 1 to 9). The Scenario report also provides a link to graphical results. The Soil water graph shows daily values of simulated and measured available soil water content, irrigation and rainfall (Figure 2.4).

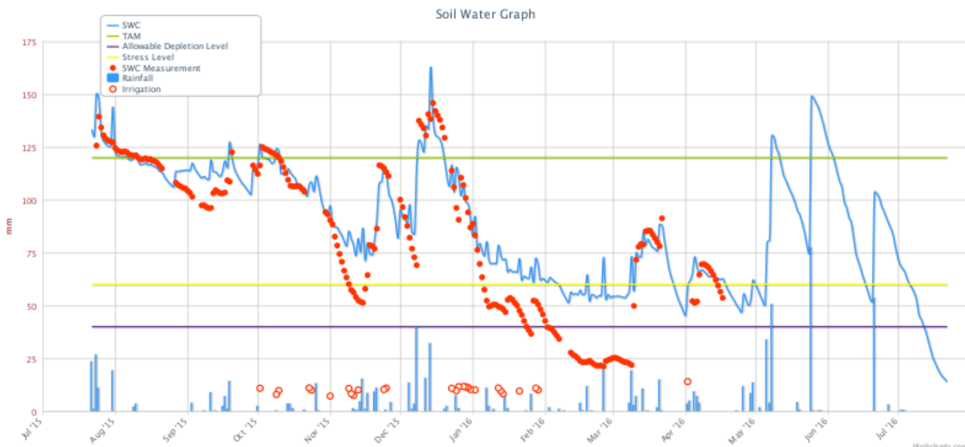


Figure 2.4. An example of the soil water graph displayed on the MyCanesim® website. The seasonal progression of simulated (blue line) and measured available soil water content (red circles), measured irrigation amounts (red circles), measured rainfall (blue bars) are shown, together with full capacity (green line), stress level (yellow line) and allowable depletion level (purple line). The specific situation for this crop was that limited irrigation water necessitated a deficit irrigation approach – hence the relative low depletion level. (Download date 31 May 2016).

The Crop status graph show daily values of crop water status, canopy cover, cane yield and sucrose yield. The Water budget graph shows daily cumulative values of ET, irrigation and rainfall.

For ‘tactical’ (operational) users, the Farm report consists of seasonal totals of evapotranspiration (ET), rainfall and irrigation, as well as cane yield, stalk sucrose and dry matter content at harvest. The Field report consists of the same content as the Scenario report for ‘strategic’ users. Tactical users often use the system for forecasting and the field report therefore gives a summary of the simulated crop and soil water status for the current date, as well as for the projected harvest date. The Irrigation advice report consists of the suggested current irrigation action, the date of the next action (to stop or start irrigation), the projected start date of the drying-off period, the to-date totals of rainfall and irrigation, the estimated current yield and available soil water expressed as a percentage of the capacity for each field on the farm. The Final estimates report consist of projected totals of rainfall and irrigation as well as cane yield at harvest for each field of the farm.

Tactical users can also view field images and simulation results on a Google map (Figure 2.5). Field boundaries can be demarcated and the resulting polygon linked to a Canesim® simulation. Simulation outputs that can be viewed on the maps include crop parameters such as simulated current and final canopy cover, cane yield and sucrose content; field properties such as start and harvest dates, cultivar, soil water holding capacity; and irrigation scheduling information such as rainfall and irrigation amounts, soil water status and date of next irrigation action.

Figure 2.5. A Google map showing sugarcane fields near Pongola with the simulated current available soil water content expressed as a percentage of capacity for three demarcated fields.

Both user types can also view rainfall, irrigation and soil water records in the relevant reports. Apart from web reports, model output and advice could also be automatically disseminated through e-mail, fax and sms (Singels and Smith, 2006; Singels, 2007).

3. PHENOLOGY AND THERMAL TIME

Three phenological phases are considered in Canesim®, namely germination (from planting to shoot emergence or from cutback to shoot emergence), tillering (from shoot emergence to the start of stalk elongation) and stalk elongation (from the start of stalk elongation to harvest). Phenological development is governed by thermal time (TT) which is the time integration, at a daily basis of effective temperature (Teff). For this version of Canesim®, TT calculations were revised to follow those used in Canegro v4.6.0, as given in *Eq. 3.1* to *Eq. 3.5*.

$$Tmean = (Tmax + Tmin) / 2 \qquad \textit{Eq. 3.1}$$

$$Teff = 0 \text{ when } Tmean < Tb \text{ or } Tmean > Tu \qquad \textit{Eq. 3.2}$$

$$Teff = Tmean - Tb \text{ when } Tb < Tmean < To \qquad \textit{Eq. 3.3}$$

$$Teff = (Tmean - Tb)(1 - (Tmean - To) / (Tu - To)) \text{ when } To < Tmean < Tu \qquad \textit{Eq. 3.4}$$

$$TT = \Sigma\, Teff \qquad \textit{Eq. 3.5}$$

where Tmax is the daily maximum temperature, Tmin is daily minimum temperature, Tb is base temperature below which process rates equal zero, To is the optimal temperature at which process rates are maximum, and Tu is the upper limit temperature, above which process rates equal zero.

Apart from phenological phases and events (shoot emergence and start of stalk growth), several crop processes are also governed by Teff, such as expansive growth processes (canopy cover expansion and root penetration rate) and photosynthesis. Cardinal temperatures and thermal time requirements for these are given in Table 3.1, and were derived from Smit (2010), Liu *et al*. (1998), Inman-Bamber (1994), Singels *et al*. (2008), van Dillewijn (1952) and Ebrahim *et al*. (1998). Example relationships between Teff and Tmean are shown in Figure 3.1.

Table 3.1. Base (Tb), optimal (To) and upper-limit (Tu) temperatures (°C) for calculating thermal time for different plant processes for cultivar NCo376.

Process	**Tb**	**To**	**Tu**	**TT requirement**
Germination	16	30	43	TTEMpo[1] = 300ºCd TTEMro[2] = 100ºCd
Tillering	10	30	43	TTsg[3] = 1000ºCd
Canopy cover development	16	35	48	
Root penetration	10	30	43	
Photosynthesis	10	20, 40	47	

[1] TTEMpo is the thermal time requirement for shoot emergence of a plant crop growing on a bare soil.
[2] TTEMro is the thermal time requirement for shoot emergence of a ratoon crop growing on a bare soil.
[3] TTsg is the thermal time required since shoot emergence for stalks to start growing.

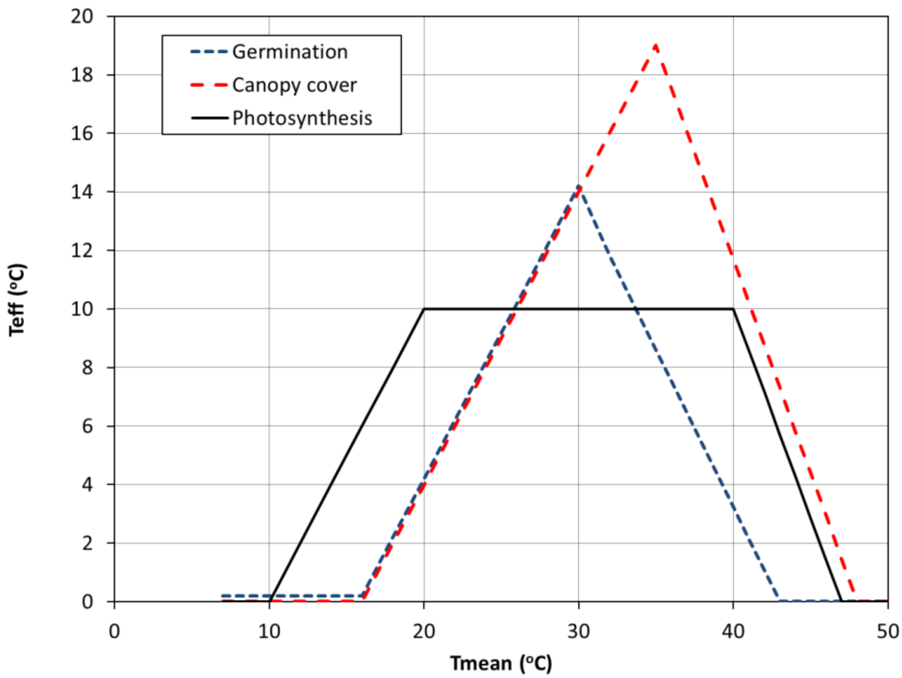


Figure 3.1. Effective temperature (Teff) as a function of mean daily temperature (Tmean) for the processes of germination, canopy development and photosynthesis, as used in Canesim®.

Emergence of primary shoots (and the start of canopy development) is simulated after the accumulation of a given amount of thermal time since planting (TTEMp) or cutback (TTEMr). These thermal time requirements depend on the amount of residue cover of the soil at the start of the crop (RES, t/ha). The following equations are used to simulate shoot emergence:

$$TTEMp = TTEMpo + dTTEMres \qquad \text{Eq. 3.6}$$

$$TTEMr = TTEMro + dTTEMres \qquad \text{Eq. 3.7}$$

$$dTTEMres = dTTEMpres10 \, . \, RES / 10 \qquad \text{Eq. 3.8}$$

where TTEMpo and TTEMro are thermal times (with a base temperature of 16°C) required for shoots to emerge after planting or cutback of the previous crop respectively, for a bare soil with no residue cover; dTTEMres is the additional thermal time required for shoots to penetrate the residue layer; and dTTEMpres10 is the additional thermal time required to penetrate a residue layer of 10 t/ha.

4. CANOPY DEVELOPMENT

Canopy cover is defined as the fraction of incident photosynthetically-active radiation (PAR) that can be used for photosynthesis. The terms ‘canopy cover’ and ‘fractional interception of PAR’ are used interchangeably here. Canopy development starts after shoots have emerged, which requires a crop and cultivar specific thermal time since planting or cutback (TTEMp and TTEMr).

The Canesim® canopy model for unstressed crops is fully described by Singels and Donaldson (2000). The model calculates the fractional interception of radiation for unstressed crops (FIo) as a function of thermal time since emergence (TTcan) and row spacing (RS):

$$FIo = TTI^k / (0.5^k + TTI^k) \qquad \textit{Eq. 4.1}$$

$$TTI = TTcan / TT50 \qquad \textit{Eq. 4.2}$$

where parameter k determines the shape of the canopy curve (k=2.453), TTI is a thermal time index, TTcan is the thermal time accumulated since shoot emergence, and TT50 is the thermal time required to reach 50 % canopy cover. TTcan is calculated using Eq. 3.1 to Eq. 3.5. TT50 is calculated as:

$$TT50 = TT50ref – dTT50row\ (1.4 – RS) + dTT50res \qquad \textit{Eq. 4.3}$$

where TT50ref is TT50 at a reference row spacing (RS) of 1.4 m for a bare soil (NCo376 value = 250°Cd), dTT50row is the response of TT50 to a change in RS from the reference value of 1.4 m (125 °Cd/m), and dTT50res is the change in TT50 caused by a residue layer (-30°Cd). Olivier *et al*. (2016) found that a residue layer causes a shift in partitioning of the available energy at the crop surface, leading to higher temperatures and accelerated canopy development, implying that dTT50res has a negative value.

The relationship between FIo and TTcan is illustrated in Figure 4.1.

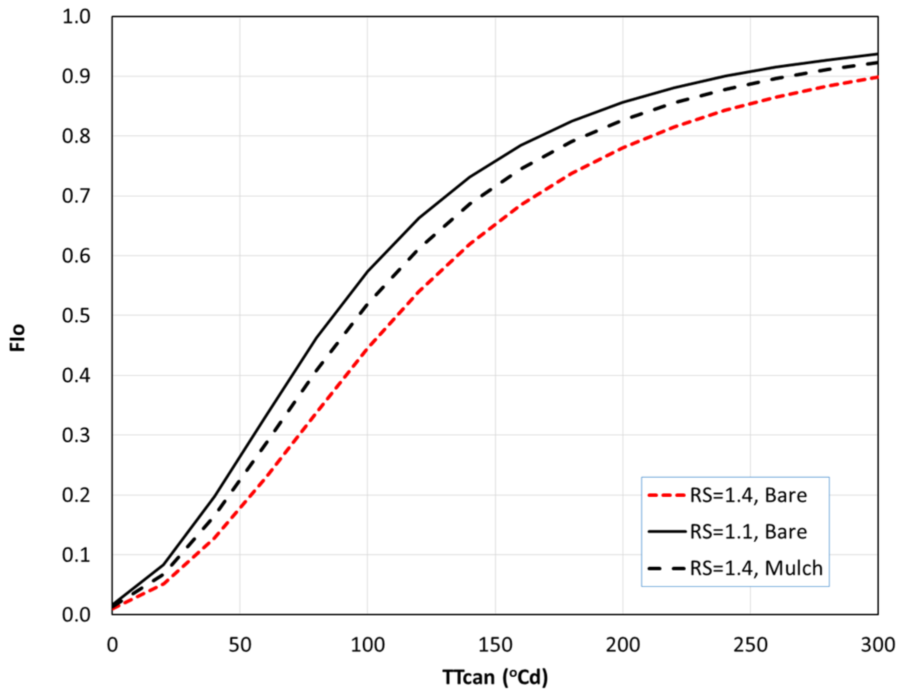


Figure 4.1. Potential canopy cover (FIo) as a function of thermal time after shoot emergence (TTcan) for different row spacings (RS in m) and soil covers.

In the case of water stress, canopy cover is reduced as a function of the duration of severe stress (net relative stress duration, FWcan) and the maximum reduction possible (FIred=0.3). Net relative stress duration (FWcan) is the stress duration (FWdur, d) expressed as fraction of the period required to effect the maximum reduction (FWduro=21 d).

$$FI = FIo\ (1 - FIred\ .\ FWcan) \qquad \text{Eq. 4.4}$$

$$FWcan = (FWdur\ /\ FWdur_0) \qquad \text{Eq. 4.5}$$

Stress duration (FWdur) is calculated as the number of days over the last FWduro days that the growth stress factor (GSTRESS) has been below 0.5 (indicating severe stress), minus the number of days that the growth stress factor exceeded 0.5 (indicating conditions favourable for recovery). Canopy cover is reduced when

FWcan is increasing from one day to the next and the canopy recovers when the net relative stress duration decreases from one day to the next. The model is partially based on the findings of Smit and Singels (2006).

5. SOIL AND CROP WATER BALANCE

Canesim® presents a multi-layered, cascading type soil water balance that accounts for drainage of free water, redistribution of water in the unsaturated phase (Jones and Kiniry, 1986), capillary movement of water from a water table if present (Singels and Manley, 1991), extraction of water by evaporation from the top soil layer (always 15 cm deep), and extraction of water through transpiration from layers (minimum of three and maximum of ten) in proportion to the rooting density and relative water content. Flows of the simulated water balance are illustrated in Figure 5.1.

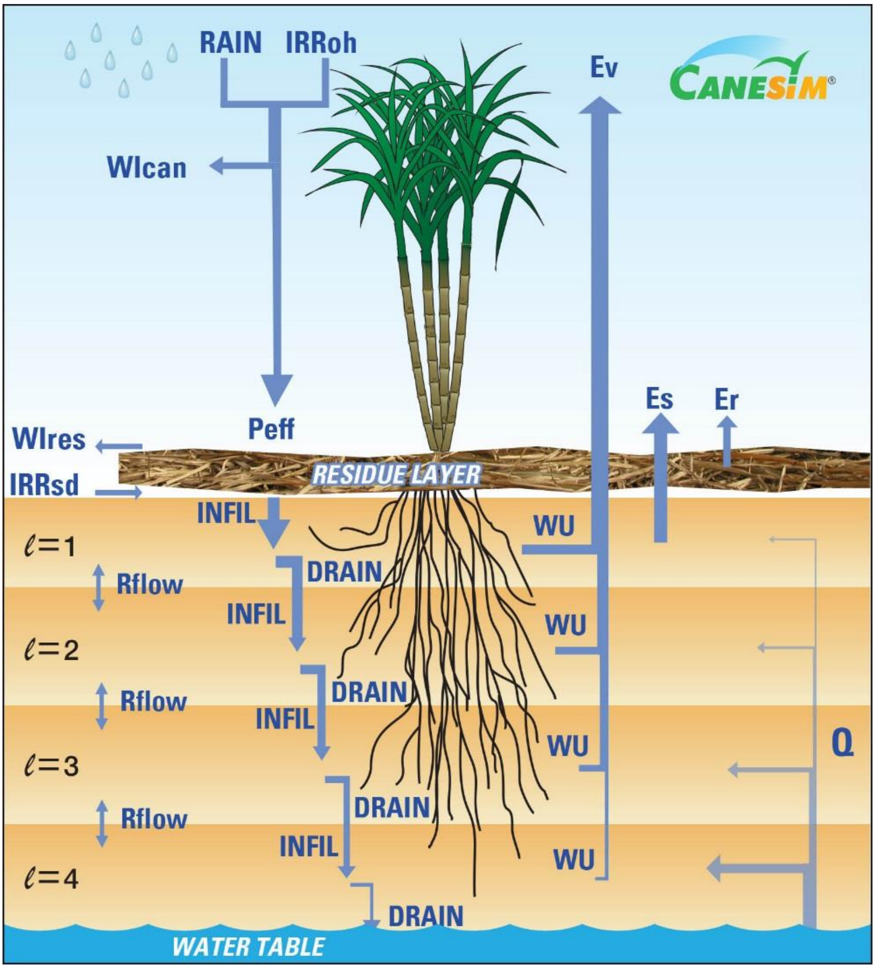


Figure 5.1. Diagram showing the flows in the Canesim® simulated water balance.

Interception of daily rainfall (RAIN) and overhead irrigation (IRR_{OH}) by the crop canopy (WIcan) is calculated as a function of the maximum amount that can be intercepted (WIcano), which is a function of canopy cover (FI) and the maximum amount that can be intercepted by a full canopy (WImax = 2 mm/d following Schulze *et al*., 2008). WIcan may not exceed evaporative demand (Eref) for the given day. It should be noted that although WIcan is assumed to eventually evaporate during the day, the calculation of crop evapotranspiration is not affected by it. The water available for infiltration into the soil or residue cover (Peff) is calculated as the balance:

$$WIcan = \min [WIcano, (RAIN + IRR_{OH}), Eref] \qquad Eq.\ 5.1$$
$$WIcano = WImax \cdot FI \qquad Eq.\ 5.2$$
$$Peff = Wcan - WIcan \qquad Eq.\ 5.3$$

Water can also be intercepted by a residue layer covering the soil. The capacity for interception (Wires) is calculated as the difference between the maximum amount of water that the residue layer can hold (Wresmax, calculated as a function of the amount of residue RES) and the antecedent amount of water present in the residue layer (Wres). Water available for infiltration into the top soil layer (Peff) is then updated from the previous day's value:

$$Wires = \min (Peff, Wresmax - Wres) \qquad Eq.\ 5.4$$
$$Wresmax = RES\,[0.308 \exp(-0.026\, RES) + 0.02] \text{ (from Jones and van den Berg, 2006)} \qquad Eq.\ 5.5$$
$$Peff = Peff - Wires \qquad Eq.\ 5.6$$

In addition to Peff, irrigation water from drip irrigation systems (IRR_{SD}) is directly allocated to the top soil layer, and SWC value updated from the previous day's value:

$$INFIL(1) = Peff + IRR_{SD} \qquad Eq.\ 5.7$$
$$SWC(l) = SWC(l) + INFIL(1) \qquad Eq.\ 5.8$$

Free water (water above the saturated level (SAT)) is immediately passed from the top layer (Drainfree (l=1)) onto the second layer (INFIL(l=2)). The same procedure is applied to subsequent layers to determine drainage of free water from a given layer to the layer below it, and so on. The SWC value for each layer is then updated from the previous day's value:

$$DRAINfree(l) = \max(0, SWC(l) - SAT(l)) \quad \text{Eq. 5.9}$$

$$INFIL(l+1) = DRAINfree(l) \quad \text{Eq. 5.10}$$

$$SWC(l) = SWC(l) - DRAINfree(l) + INFIL(I) \quad \text{Eq. 5.11}$$

Thereafter water in the saturated phase is drained out of the given layer (DRAINsat(l)) and infiltrated into the layer below, whereafter the SWC for the given layer is updated from the previous day's value:

$$DRAINsat(l) = \max[0, Dcon(l) \,.\, (SWC(l) - AWC(l))] \quad \text{Eq. 5.12}$$

$$INFIL(l+1) = DRAINsat(l) \quad \text{Eq. 5.13}$$

$$SWC(l) = SWC(l) - DRAINsat(l) + INFIL(l) \quad \text{Eq. 5.14}$$

where parameter Dcon is a user-specified drainage constant (defined as the fraction of water above the available capacity that is drained per day) for a given layer, and AWC(l) is the available water capacity for the given layer.

Water in the unsaturated phase is redistributed among layers as a function of the difference in available soil water content (θ, expressed as a fraction) and a soil water diffusivity coefficient (Dif, cm^2) (following Jones and Kiniry, 1986):

$$RFLOW(l) = 10 \,.\, Dif\,[\theta(l) - \theta(l\text{-}1)] \quad \text{Eq. 5.15}$$

$$Dif = 0.88 \exp(35.4\,[\theta(l) - \theta(l\text{-}1)] / [(Z(l) + Z(l\text{-}1)) / 2] \quad \text{Eq. 5.16}$$

$$SWC(l\text{-}1) = SWC(l\text{-}1) + RFLOW(l) \quad \text{Eq. 5.17}$$

$$SWC(l) = SWC(l) - RFLOW(l) \quad \text{Eq. 5.18}$$

where RFLOW(l) is flow of unsaturated water from layer l into layer l-1 (mm), and Z is layer thickness (cm).

When the presence of perched water table is specified in the soil inputs (assumed to be at a constant depth immediately below the bottom soil layer), the contribution of groundwater to transpiration (Qv in mm) and soil evaporation (Qs in mm) is calculated from effective rooting depth (ERD in cm):

$$Qv = min\ ((4.216*10^5/(0.826\ ERD)^3, Ev) \qquad Eq.\ 5.19$$

$$Qs = min\ ((4.216*10^5/(ERD\ -7.5)^3, Es) \qquad Eq.\ 5.20$$

$$Q = Qv + Qs \qquad Eq.\ 5.21$$

Q is added to soil layers stepping from the bottom layer (lend) up, with the proviso that the resultant SWC may not exceed AWC.

$$SWDEF(l) = AWC(l) – SWC(l) \qquad Eq.\ 5.22$$

$$SWC(l) = min\ [SWC(l) + Q, AWC(l)]; \qquad Eq.\ 5.23$$

$$Q = Q – min\ [Q, SWDEF(l)] \qquad Eq.\ 5.24$$

where SWDEF is the soil water deficit (mm).

Evaporation from the soil (Es) and residue layer (Er) is calculated as the function of the soil evaporation coefficient Ks, sugarcane reference evaporation (Eref) and a residue impact factor (Fesr). The evaporated water is taken first from the residue layer if it is present, and the remainder from the soil layer beneath the residue layer.

$$Er = min\ [(Ks\ .\ Eref\ .\ Fesr)\ .\ Wres] \qquad Eq.\ 5.25$$

$$Es = min\ [(Ks\ .\ Eref\ .\ Fesr – Er), (0.9\ Epool)] \qquad Eq.\ 5.26$$

Es is not allowed to exceed 90% of the pool of evaporable water (Epool). Epool is calculated by maintaining a balance of water infiltrated into the top soil layer and water evaporated from it. Epool is not allowed to exceed 10 mm (Epoolmax = 10) or drop below zero.

$$Epool = \min (10, \{\max [0, (Epool + Peff - Es)]\}) \qquad \text{Eq. 5.27}$$

The evaporation coefficient, Ks, is calculated from factors representing the impacts of soil surface wetness (Fs) and canopy cover (FI):

$$Ks = Fs\ (1 - FI) \qquad \text{Eq. 5.28}$$

$$Fs = Fsr1 + Fsr2 \qquad \text{Eq. 5.29}$$

Fsr1 represents the wetness of exposed soil surface not wetted by irrigation, while Fsr2 represents the wetness of the exposed soil wetted by irrigation:

$$Fsr1 = \exp (-0.4.\ Tes)\ (1\text{-}Awet) \qquad \text{Eq. 5.30}$$

$$Fsr2 = \max \{[\exp (-0.4\ Tes)\ Awet]\ ,\ [\exp (-0.4\ Ti)\ Awet]\} \qquad \text{Eq. 5.31}$$

where Tes is the number of days since the last rainfall event, Ti is the number of days since the last irrigation event, and Awet is the soil surface area (m^2/m^2) wetted by irrigation, Awet values of 1.0, 0.5 and 0.0 are assumed for overhead, surface drip and sub-surface drip irrigation systems respectively.

$$Fesr = [\exp (-0.16\ RES)] \qquad \text{Eq. 5.32}$$

The water content of the residue layer is then updated:

$$Wres = Wres + WIres - Er \qquad \text{Eq. 5.33}$$

Transpiration

Transpiration rate (Ev) is determined by evaporative demand and soil water supply. Evaporative demand is determined by the extent of green canopy cover (FI) and atmospheric conditions, as represented by sugarcane reference evapotranspiration

(Eref following McGlinchey and Inman-Bamber, 1996) and atmospheric CO_2 concentration effect on stomatal conductance (Tratio). Soil water status is determined by soil water supply, rooting density and evaporative demand (Eref). Water uptake from each soil layer (WU(l)) is calculated as:

$$WU(l) = Eref \,.\, FI \,.\, Tratio \,.\, RDF(l) \,.\, FW(l) \qquad \textit{Eq. 5.34}$$

where RDF(l) is the length of roots in layer l, expressed as a fraction of total length of roots in the soil profile as a whole, FW(l) is the soil water status factor (FW) for layer l, and Tratio is the ratio of potential transpiration rate at a given CO_2 concentration to that at the reference CO_2 concentration of 330 ppm (following Boote *et al*., 2010). WU(l) is then summed over all layers in the profile to determine the total crop transpiration (Ev).

The simulation of water stress follows the Aquacrop (Steduto *et al*., 2009, see Figure 5.2) approach of using atmospheric demand dependent, process specific relative available soil water thresholds to simulate the impacts on transpiration, photosynthesis and expansive growth. The water status factor (FW) for soil layer l is calculated as:

$$FW(l) = 1 - [\exp(Drel(l)\, Fshape) - 1] / [\exp(Fshape) - 1] \qquad \textit{Eq. 5.35}$$

$$Drel(l) = (RSWD(l) - Pup) / (Plo - Pup) \quad \text{with } 0 <= Drel <= 1 \qquad \textit{Eq. 5.36}$$

$$RSWD(l) = 1 - (SWC)(l) / AWC(l) \qquad \textit{Eq. 5.37}$$

where Drel(l) is the soil water depletion for layer l normalised with respect to the upper (Pup) and lower thresholds (Plo) of relative soil water depletion (RSWD). RSWD is calculated from available soil water content (SWC) and available soil water capacity (AWC) for each layer. Parameter Fshape determines the shape of the curve describing the relationship between FW and Drel and is assumed to have a value of two to reflect a slightly convex (slow initial decline followed by a more rapid decline) shape.

An exponential decline in soil water depletion thresholds as atmospheric evaporative demand (represented by sugarcane reference evapotranspiration – Eref in mm/d) increases, is considered more appropriate than a linear decline used in Aquacrop. Non-linear relationships between soil water threshold levels and evaporative demand are also used by Slabbers (1979), Doorenbos and Kassam (1986) and in Wofost (Supit *et al*., 1994). Hence, the upper and lower fractional depletion thresholds where a reduction in process rates starts (Pup), and where the process rate declines to zero (Plo), were calculated using *Eq. 5.38* to *Eq. 5.41*:

$$Pup = Cup / (Eref + Cup) \qquad \text{Eq. 5.38}$$

$$Plo = Clo / (Eref + Clo) \qquad \text{Eq. 5.39}$$

$$Cup = m \cdot \exp(n.Pup5) \qquad \text{Eq. 5.40}$$

$$Clo = m \cdot \exp(n.Plo5) \qquad \text{Eq. 5.41}$$

where Pup5 and Plo5 are soil water depletion thresholds at a reference Eref of 5 mm/d, Cup and Clo are intermediate variables and m and n are empirical constants.

Different Pup5 and Plo5 values apply to expansive growth on one hand, and transpiration and photosynthesis on the other hand, as calculated from crop and cultivar parameters using *Eq. 5.42* to *Eq. 5.45*:

$$Pup5 = 1 - ESTRESS \text{ for transpiration and photosynthesis} \qquad \text{Eq. 5.42}$$

$$Plo5 = Pup5 + 0.35 \text{ for transpiration and photosynthesis} \qquad \text{Eq. 5.43}$$

$$Pup5 = 1 - GSTRESS \text{ for expansive growth} \qquad \text{Eq. 5.44}$$

$$Plo5 = Pup5 + 0.5 \text{ for expansive growth} \qquad \text{Eq. 5.45}$$

where ESTRESS is a cultivar specific drought sensitivity parameter, defined as the available soil water threshold below which transpiration and photosynthesis rates are reduced below their potential value due to stomatal closure at reference Eref of 5 mm/d (ESTRESS=0.45 for NCo376). GSTRESS is the drought sensitivity parameter that applies to expansive growth and a generic value of 0.8 is assumed for all cultivars.

FW values for individual layers are then aggregated to a process specific crop water status factor, named the water satisfaction index (WSI), that controls photosynthesis and transpiration (WSI_P), and expansive growth (WSI_G). This upscaling takes into account the fractional rooting length of the different layers (RDF(l)):

$$WSI = \Sigma \, FW\,(l)\,.\,RDF\,(l) \qquad \textit{Eq. 5.46}$$

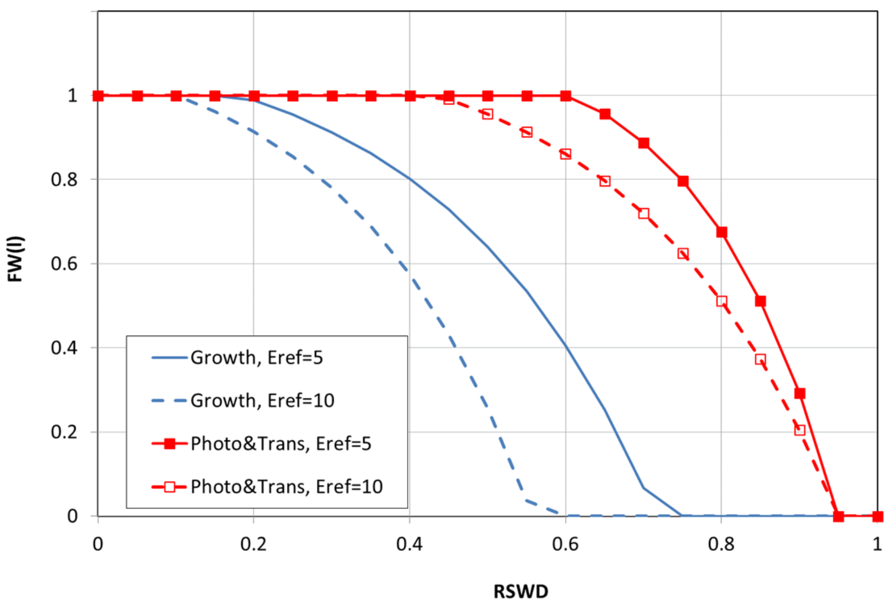


Figure 5.2. The Aquacrop soil water status factor (FW(l)) that regulates expansive growth (blue lines) and photosynthesis and transpiration (red lines), as a function of relative soil water depletion (RSWD) and atmospheric evaporative demand (Eref).

Rooting depth (Rdepth in m) is calculated as a function or thermal time since the crop start (CumTT10 in °Cd with Tbase=10°C) and bud depth (assumed to be 0.1m)

$$Rdepth = Rgro \,.\, CumTT10 + 0.1 \text{ with } Rdepth >= 0.5 \text{ for ratoon crops} \qquad \text{Eq. 5.47}$$

where Rgro is the root penetration rate per unit thermal time (a crop parameter). For a ratoon crop a lower limit of 0.5 m applies to represent roots that remain alive after the harvest of the previous crop.

The rooting density for each layer (RDF(l)) with roots, expressed as the length of roots present in the layer as a fraction of the total length of roots in the soil profile, is calculated as:

$$CumRDF(l) = 1 - \exp\,(\alpha / Rdepth \,.\, Z(l)) / \beta \qquad \text{Eq. 5.48}$$

$$RDF(1) = CumDRF(1) \qquad \text{Eq. 5.49}$$

$$RDF(l) = CumRDF(l) - CumRDF(l\text{-}1) \qquad \text{Eq. 5.50}$$

where CumRDF is RDF accumulated over soil layers from the top to the bottom, Z (l) is the depth of the bottom of soil layer l (m). Values for parameters α and β were determined by calibration of *Eq. 5.48* to data presented by van Antwerpen (1998, p 55) (α = -3.1 and β = 0.955).

Crop evapotranspiration (ET) is taken as the sum of transpiration (Ev), evaporation from the soil (Es) and evaporation from the residue layer (Er).

6. BIOMASS ACCUMULATION AND PARTITIONING

The photosynthesis algorithm of Canegro 4.6.0 was incorporated into Canesim®. Radiation conversion efficiency (RUE in g/MJ, defined as the gross photosynthate produced per unit intercepted solar radiation) is calculated as a function of maximum RUE under ideal conditions (RUEo), the crop water status factor (WSI, *Eq. 5.46*), a temperature control factor (FT) and an atmospheric CO_2 concentration control factor (FCO2):

RUE = RUEo . FT. WSI . FCO2 (1 − Flodge . ∆RUE)	*Eq. 6.1*
FT = 1 for To1photo < Tmean < To2photo	*Eq. 6.2*
FT = 1 − (Tmean − To2photo) / (Tuphoto − To2photo) for Tmean>To2photo	*Eq. 6.3*
FT = 1 − (To1photo − Tmean) / (To1 photo − Tbphoto) for Tmean<To1photo	*Eq. 6.4*

where To1photo and To2photo are the lower and upper values of the optimal temperature range and Tbphoto and Tuphoto are the temperature values below and above which the photosynthesis rate is zero (°C), Flodge is the extent of lodging (see Chapter 10) and ∆RUE is the fractional reduction in RUEo for a fully lodged crop. Based on the findings of Stokes *et al*. (2016) zero CO_2 fertilizer effect is assumed, and therefore FCO2=1.

The rate of gross photosynthesis (Pgross, t/ha/d) is then calculated from RUE and intercepted solar radiation, calculated as the product of fractional interception (FI) and incoming solar radiation (Srad, MJ/m^2/d):

Pgross = RUE . FI . Srad / 100	*Eq. 6.5*

where division by 100 is required for unit conversion.

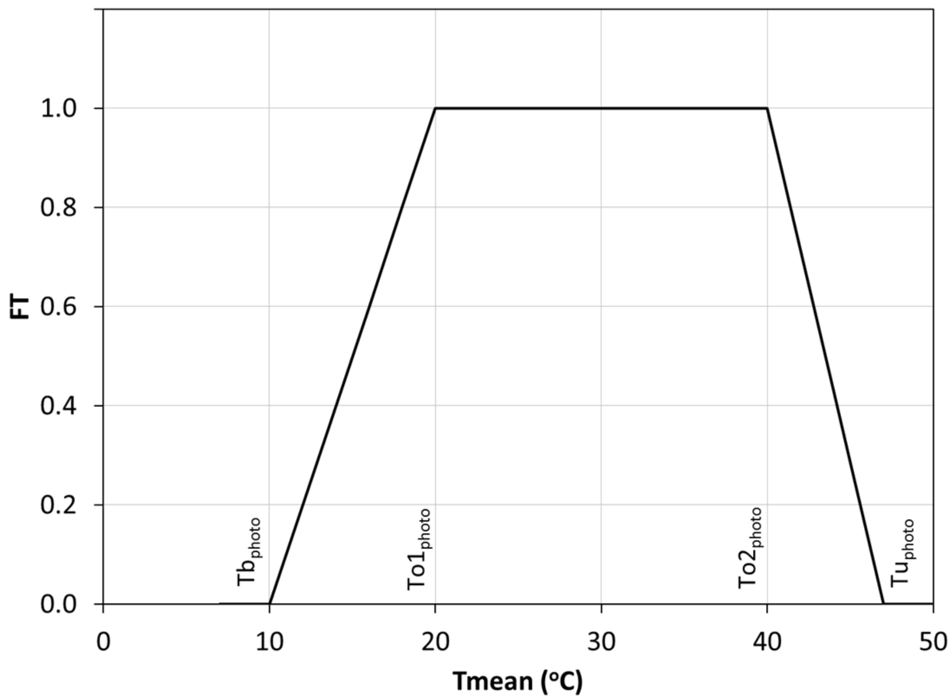


Figure 6.1. The temperature factor (FT) that regulates efficiency of conversion of intercepted radiation to biomass as a function of mean daily temperature (Tmean). The various cardinal temperatures are indicated (Eq. 6.2 to Eq. 6.4).

Growth respiration (Rg in t/ha/d) is calculated as a function of daily gross photosynthesis (Pgross, t/ha/d):

$$Rg = Respcf \cdot Pgross \qquad \text{Eq. 6.6}$$

where Respcf (generic crop parameter, see Table 2.1) is the fraction of Pgross lost through respiration.

Maintenance respiration (Rm in t/ha/d) is only calculated for the pool of stored sucrose (SUCM, t/ha). Although maintenance of live leaf, meristem and root tissue also requires energy from respiration, this is ignored mainly because Canesim® does not simulate a leaf and root mass balance.

The fraction of biomass lost through maintenance respiration is calculated as a function of daily mean temperature (Tmean, °C):

$$Rm = SUCM \cdot Respcons \cdot RespQ10 \wedge [(Tmean-10)/10)] \text{ when } Tmean < Tosuc \qquad \text{Eq. 6.7}$$

$$Rm = SUCM \cdot Respcons \cdot RespQ10 \wedge [(Tosuc - 10)/10)] \cdot [1-(Tmean - Tosuc) / (Tusuc - Tosuc)] \qquad \text{Eq. 6.8}$$

where Respcons is fractional respiration rate at a reference temperature of 10°C (0.00121g/g/d), and RespQ10 determines the steepness of the exponential increase with temperature and had a value of 1.68 (derived from Liu and Bull, 2001), and Tosuc and Tusuc is optimal and upper limit temperature (°C).

Daily biomass accumulation (dTOT in t/ha/d) is then calculated as the difference between gross photosynthate (Pgross in t/ha/d) and the sum of growth (Rg) and maintenance respiration (Rm):

$$dTOT = Pgross - (Rg + Rm) \text{ with } dTOT>=0 \qquad \text{Eq. 6.9}$$

dTOT is partitioned first to aerial dry mass (dADM in t/ha/d) and roots (dRT in t/ha/d), after which dADM is partitioned to stalk (dSK in t/ha/d) and leaf material (dLF in t/ha/d) following the Canegro 4.5.1 method described in Singels and Bezuidenhout (2002).

$$ADMPF = ADMPFmax\ [1 - exp^{(-b.\ TOT)}] \qquad \text{Eq. 6.10}$$

$$RTPF = 1 - ADMPF \qquad \text{Eq. 6.11}$$

$$dADM = dTOT \cdot ADMPF \qquad \text{Eq. 6.12}$$

$$dRT = dTOT \cdot RTPF \qquad \text{Eq. 6.13}$$

$$dSK = dADM \cdot SKPF \qquad \text{Eq. 6.14}$$

$$dLF = dADM \cdot (1 - SKPF) \qquad \text{Eq. 6.15}$$

where ADMPFmax is the maximum partition fraction of daily biomass increments to aerial dry mass (see Table 2.2), ADMPF, RTPF and SKPF are the partitioning coefficients for aerial dry mass, root mass and stalk mass respectively on any given day, TOT is total dry biomass of the crop on the given day (t/ha), and b is an empirical parameter that determines the rate of increase in ADMPF with increasing TOT.

Stalk mass increments are partitioned to stalk sucrose (dSUC in t/ha/d) and the rest (stalk fibre plus non-sucrose, dFNS in t/ha/d) following the Canegro 4.5.1 method (Singels and Bezuidenhout, 2002). In essence:

$$dSUC = \min(SUCcap, dSK) \qquad \text{Eq. 6.16}$$

$$SUCcap = SUCeq - SUC \qquad \text{Eq. 6.17}$$

$$SUCeq = SCmax \,.\, SK - 0.5\,(SCmax)^2 / \Delta \qquad \text{Eq. 6.18}$$

$$\Delta = \Delta max\,(FWs + FTs - FWs.FTs) \text{ with } \Delta >= \Delta min \qquad \text{Eq. 6.19}$$

$$dFNS = dSK - dSuc \qquad \text{Eq. 6.20}$$

where SUCcap is the capacity of the crop to store sucrose, defined as the difference between the current sucrose mass (SUCM in t/ha) and the theoretical sucrose mass (sink size, SUCeq in t/ha) that would have been achieved had the crop experienced uniform temperature (FTs) and water status (FWs) conditions equal to current conditions, given the source history of the crop as reflected by the current stalk dry mass (SK in t/ha). Δ is the ripening gradient which is defined as gradient in sucrose content in the immature section of the stalk, expressed as the increase in sucrose content per unit increase in stalk mass commencing from the top of the stalk, and varies between Δmax, the maximum gradient achieved under dry and cool conditions and Δmin, the minimum gradient achieved under warm and well-watered conditions. SUCeq is also determined by the genetically determined maximum sucrose content in the base of a mature section of the stalk (SCmax). The theoretical framework for the concepts in Eq. 6.16 to Eq. 6.20 is illustrated in Figure 6.2.

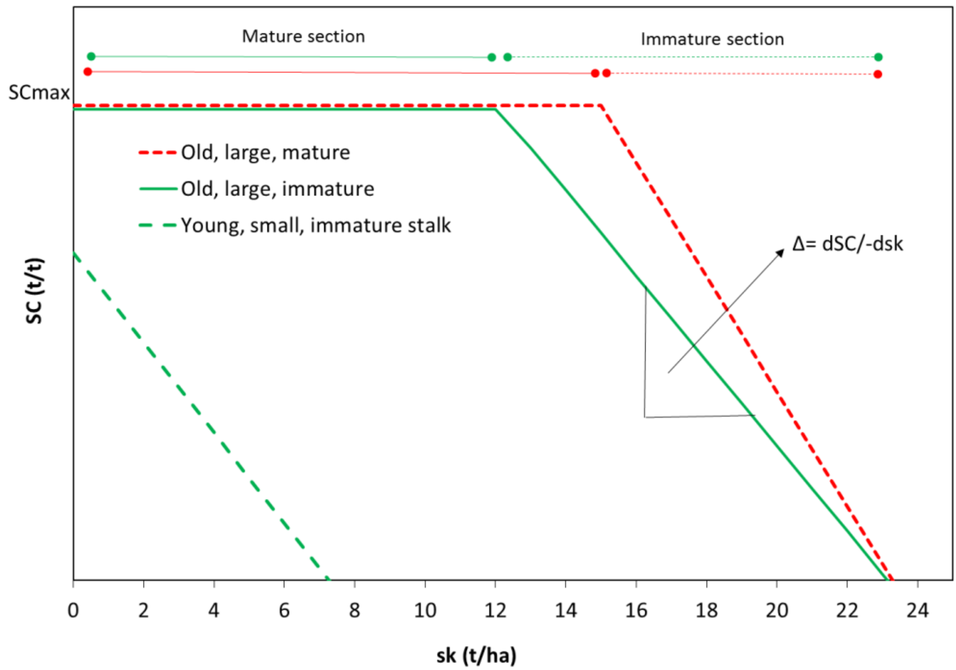


Figure 6.2. A schematic diagram of the distribution of sucrose within a single "big" stalk (SC - sucrose content as a function of sk - cumulative stalk mass measured from the base) for three hypothetical instances namely (1) a young, small immature stalk with a dry mass of 7 t/ha, (2) an older, larger stalk with a dry mass of 23 t/ha, with a relatively long immature section and (3) an older, larger stalk also with a dry mass of 23 t/ha with a relatively short immature section. The maximum sucrose content in the mature section of stalk (SCmax) and the ripening gradient (Δ) in the immature section of the stalk is also indicated. (Adapted from Singels *et al*., 2002)

One difference in the sucrose accumulation algorithm between Canesim® and Canegro is in the calculation of the crop water stress factor that controls sucrose accumulation in the stalk, FWs:

$$FWs = (1 - WSI_G)^{FWCON} \qquad \text{Eq. 6.21}$$

where WSI_G is the soil water deficit factor controlling expansive growth (Eq. 5.46). During model calibration it was found that FWCON=1 produced more accurate predictions of sucrose content than FWCON=0.5 used in Canegro 4.5.1.

Daily increments in each stalk biomass component are accumulated over time to yield the mass of each component on a given day. Cane yield and sucrose content (fresh mass basis) is calculated from dry mass basis values and the estimated amount of moisture in stalks (SKWATER in t/ha):

$$SKWATER = SKWa.SK - SKWb.SUCM \qquad \textit{Eq. 6.22}$$

where SK is stalk dry mass (t/ha) and SUCM is stalk sucrose mass (t/ha), and SKWa and SKWb are empirical parameters determined from data from the SASRI Released Cultivar Database (SKWa=3.607 and SKWb=2.078). *Eq. 6.22* is based on the model proposed by Martiné and Lebret (2001).

7. LODGING

The lodging algorithm described by Van Heerden *et al*. (2015) and previously implemented in DSSAT-CanegroV4.5 and in Canesim® models (Singels *et al*., 2008; Singels, 2007) was also implemented in this version of Canesim®. It acknowledges two basic factors that exert force on upright cane that can cause it to fall over. These are (1) the mass of the cane stalks and associated leaf material, plus the water retained on the leaves, and (2) wind. Cane stalks are anchored in the ground and their ability to withstand these forces are dependent on cultivar characteristics as well as the wetness of the soil around the roots. The ability to withstand these forces also varies somewhat between stalks of the same crop, hence causing partial and incremental lodging as the crop increases mass and becomes progressively more susceptible to lodging. The modelling approach effectively reduces the mass threshold above which lodging occurs, on days when wind and wet soil are conducive to lodging.

Partial or full lodging of cane stalks is simulated when the fresh mass of above-ground plant parts (AFM in t/ha) plus the rainfall and irrigation water retained on them (WM in t/ha), that is the aerial mass (AM in t/ha), exceeds a cultivar-specific threshold (AMbase in t/ha, the aerial mass at which lodging commences when other lodging factors such as water and wind are absent). The extent of lodging is proportional to the magnitude of the extent to which the threshold is exceeded. Full lodging is simulated when AM equals or exceeds an upper threshold (see Figure 7.1). This attempts to represent the variation in the ability of stalks and/or stools to withstand lodging that often results in partial lodging.

The mathematical representations of these simulations are described below:

$$Flodge_{AM} = (AM - AMbase) / (AMrange) \qquad \text{Eq. 7.1}$$

$$AM = AFM + WM \qquad \text{Eq. 7.2}$$

$$AFM = ADM / DMC \qquad \text{Eq. 7.3}$$

$$WM = WIcan.\rho \qquad \text{Eq. 7.4}$$

where $Flodge_{AM}$ is the fraction of cane stalks that can potentially lodge due to excessive aerial mass on a given day, AMrange is the range in AM from the point where lodging commences up to the point where lodging is complete (recognising the variability in stalks/stools to withstand lodging forces), ADM is the aerial dry mass on the given day, DMC is the dry matter content of aerial dry mass (assumed to be 0.27), WIcan is rainfall and overhead irrigation intercepted by the canopy on the given day (Eq. 5.1), and ρ is a coefficient for converting the units of intercepted water from mm (kg/m^2) to t/ha.

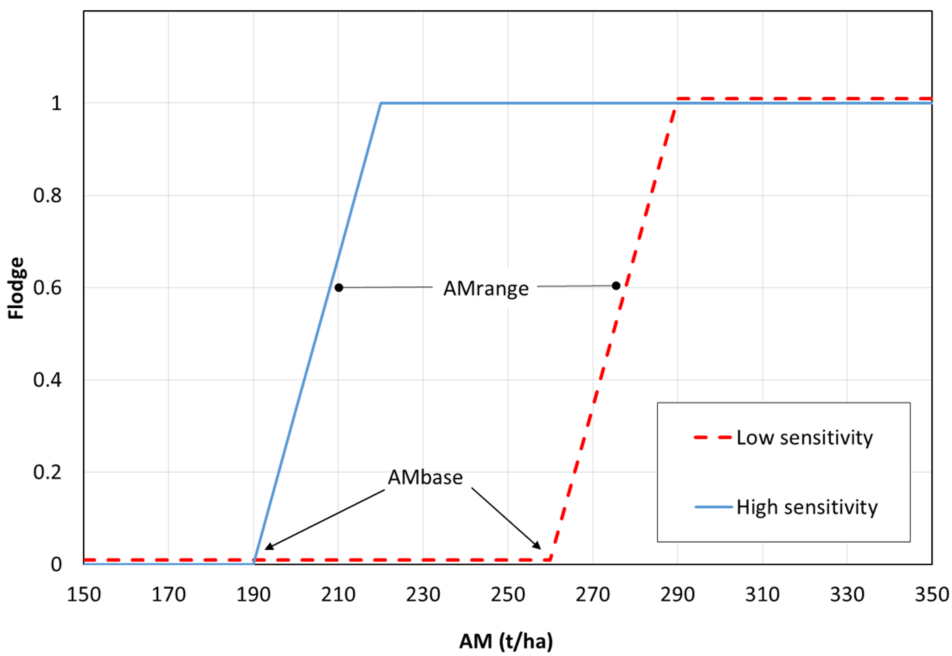


Figure 7.1. The fraction of lodged stalks (Flodge) as a function of the aerial mass of fresh cane plus the mass of any water attached to it (AM), for two hypothetical cultivars with low and high sensitivity to lodging. Model parameters AMbase and AMrange (Eq. 7.1) are also shown.

Rint and Iint is calculated by the Canesim® model as a function of canopy cover, rainfall and/or overhead irrigation amount. A fully canopied crop (such as crops prone to lodging) will intercept all rainfall and/or overhead irrigation up to a maximum value of 2 mm per day (Schulze *et al*., 2008).

Lodging can be exacerbated by a water saturated top soil and by strong wind. The saturated soil effect is simulated by adding 0.25 to the lodged fraction ($Flodge_{SWC} = 0.25$) when the available soil water content of the profile is at or above field capacity (AWC).

The lodged fraction also increases by 0.25 ($Flodge_U = 0.25$) when daily windrun (U in km/d) exceeds a threshold (Ux) of 200 km/d.

The combined extent of lodging due to all three factors is then calculated:

$$Flodge_P = Flodge_{AM} + Flodge_{SWC} + Flodge_U \text{ with } 0 <= Flodge_P <= 1 \qquad \text{Eq. 7.5}$$

where $Flodge_P$ is the potential extent of lodging on a given day, expressed as a fraction of the stalks per unit area. Lodging is only simulated when the value of $Flodge_P$ exceeds the actual lodged fraction of the previous day ($Flodge_{i-1}$) (*Eq. 7.6*). The lodged fraction on the given day ($Flodge_i$) is then set equal to $Flodge_P$ and the actual extent of lodging on the give day equals the difference between $Flodge_P$ and $Flodge_{i-1}$.

$$Flodge_i = Max\,(Flodge_P, Flodge_{i-1}) \qquad \text{Eq. 7.6}$$

This enables the simulation of incremental lodging, as is often observed, with stronger forces required to lodge stalks that have remained upright during previous lodging events. Eq. 7.5 also implies that wind and a saturated top soil will only contribute to lodging (a maximum effect of 25% each) when the aerial mass is high enough to push the current value of Flodge over its previous highest value.

The model simulates the impact of lodged cane on the interception of radiation (FI) and on radiation use efficiency (RUEo, here defined as the dry biomass assimilated through gross photosynthesis (before respiration), per unit intercepted shortwave radiation) as indicated in *Eq. 7.7* and *Eq. 7.8*. Although the work by Singh *et al*. (2002) shows that different mechanisms are involved in yield reduction, ultimately biomass growth per unit intercepted radiation is reduced, as well as the amount of radiation intercepted. These two processes are the main drivers of simulated biomass accumulation and are reduced by 13 and 23% respectively for fully lodged cane based on results of two experiments conducted in Ayr (1998/99) and Feluga (1997/98) in Australia, and reported by Singh *et al*. (2002). Partially lodged cane has a proportional impact.

$$RUE = RUEo\ (1 - Flodge\ .\ \Delta RUE) \qquad \text{Eq. 7.7}$$

$$FI = FIo\ (1 - Flodge\ .\ \Delta FI) \qquad \text{Eq. 7.8}$$

where RUEo is the unadjusted RUE of an erect crop, ∆RUE is the fractional reduction in RUE for a fully lodged crop, FIo is the unadjusted fractional interception of radiation for an erect crop and ∆FI is the reduction in FI for a fully lodged crop.

The simulated extent of lodging (LE) was calculated from the lodged fraction (Flodge) as follows (*Eq. 7.9*):

$$LE = 8\ Flodge + 1 \qquad \text{Eq. 7.9}$$

This implies a range from 1 to 9 for LE, which corresponds to the scale of visual ratings of lodging used at SASRI (van Heerden *et al*., 2015).

The model was calibrated and evaluated on three data sets from Pongola and Komatipoort (van Heerden *et al*., 2015). Model parameters are described in Table 7.1.

Table 7.1. Description of lodging parameters.

Parameter	Description	Default value
AMbase	Aerial mass at which lodging commences when other lodging factors such as water and wind are absent	220 t/ha
AMrange	Range in aerial mass required for complete lodging	30 t/ha
$Flodge_{SWCo}$	Maximum increase in lodging fraction due to a saturated soil	0.25
$Flodge_{Uo}$	Maximum increase in lodging fraction due to wind	0.25
Ux	Daily wind run above which lodging susceptibility is increased	200 km/d
ΔRUE	Fractional reduction in radiation use efficiency for a fully lodged crop	0.23
ΔFI	Reduction in fractional interception of radiation for a fully lodged crop	0.13

The study by van Heerden *et al*. (2015) showed that the onset, progression and final extent of lodging was simulated realistically for a number of soil/crop/atmospheric conditions when crop biomass simulations were forced to reflect actual values. Very little parameter calibration was required; the threshold for the commencement of lodging was increased for cultivar N25 (AMbase = 230t/ha) and reduced for N49 (AMbase = 200t/ha), suggesting that the latter was more prone to lodging than the former. In this study, simulated lodging was primarily driven by crop size and lodging events were triggered by rainfall that added weight to the aerial mass of the crop, and reduced the anchoring ability of the soil through saturation of the top soil. The contribution of wind and a wet top soil to crop lodging could not be tested directly and future testing with appropriate data is advised.

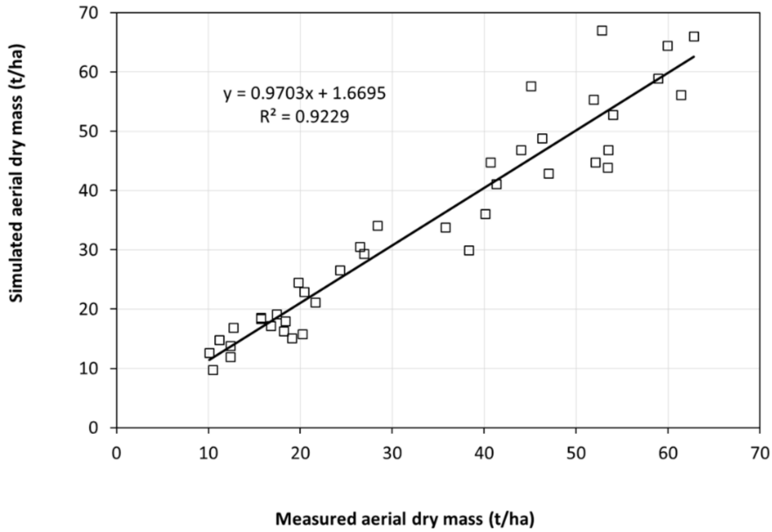
8. MODEL EVALUATION

The model was evaluated by comparing simulated yields values to measured values for two data sets namely, an extensive set of experimental data for cultivar NCo376 collected in diverse field trials, and a smaller multi-cultivar dataset collected in two contrasting environments.

8.1 NCo376 validation

Aerial dry mass (ADM), stalk dry mass (SDM), sucrose mass (SUCM) and sucrose content (SC) observations for cultivar NCo376 from 26 experiments (see Singels and Bezuidenhout, 2002 for a description) were used to validate the Canesim® model. Only two of the parameters listed in Table 2.2 were adjusted after implementing the changes from the version used by Singels (2007). The best fit of simulated values to observed values of ADM was found when radiation use efficiency (RUEo) was set to 2.25g/MJ. A secondary adjustment was made to the aerial mass threshold for lodging (AMbase), increasing it from 220 to 260 t/ha to reflect this cultivar's resistance to lodging.

Results are shown in Figure 8.1 and Figure 8.2 and summarized in Table 8.1. It is concluded that simulation accuracy for cultivar NCo376 is highly acceptable for aerial dry mass and stalk dry mass, and reasonable for sucrose yield and content.



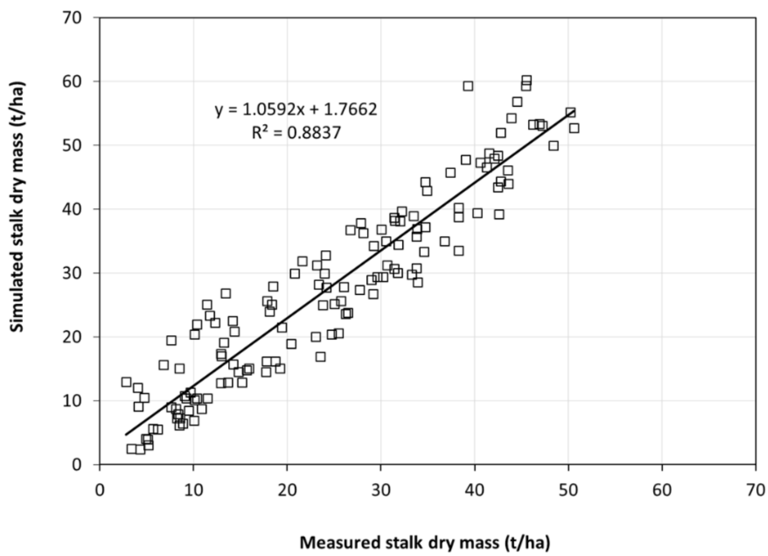


Figure 8.1. Scatterplot of simulated and measured aerial and stalk dry mass for the NCo376 dataset.

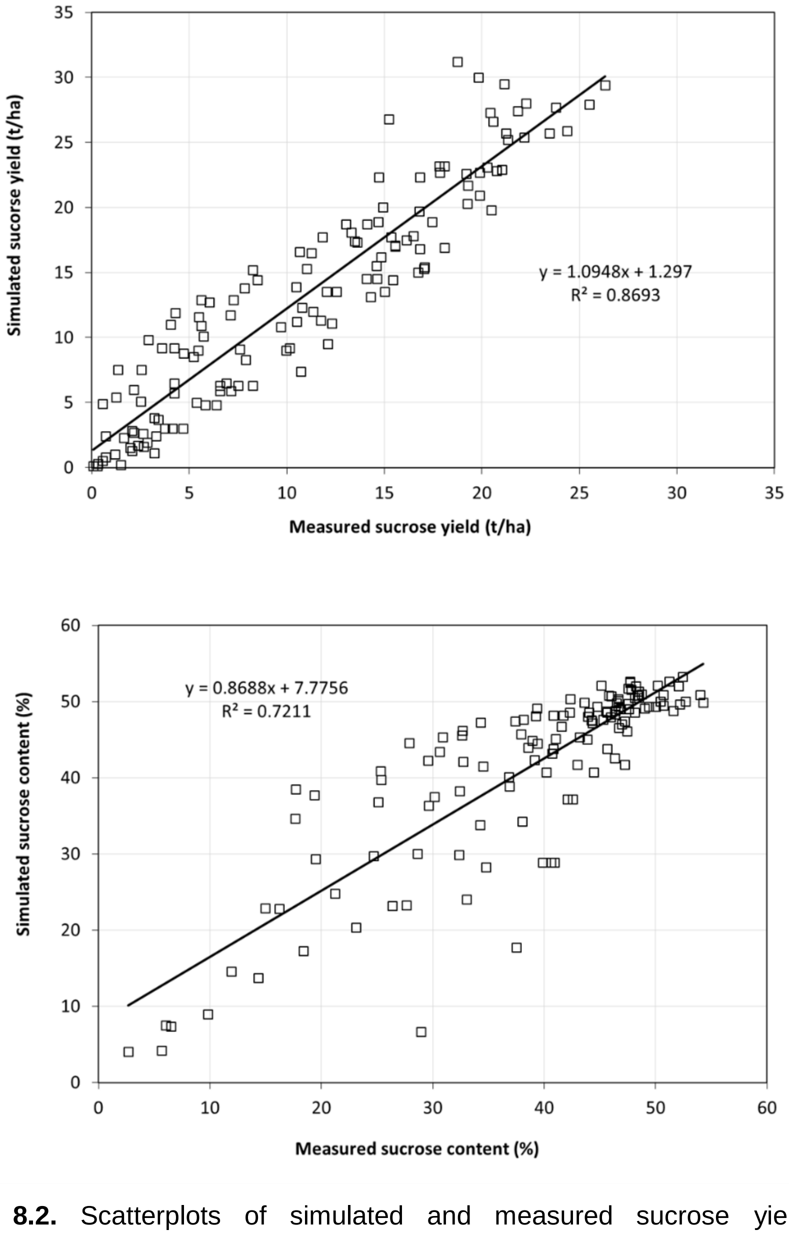


Figure 8.2. Scatterplots of simulated and measured sucrose yield and content (dry mass basis) for the NCo376 dataset.

Table 8.1. Validation statistics of aerial dry mass (ADM), stalk dry mass (SDM), sucrose mass (SUCM) and sucrose content (SC) predictions for the NCo376 data set. The slope and intercept of the linear regression between simulated and observed values, coefficient of determination (R^2), root mean squared difference between simulated and observed values (RMSE) and mean absolute difference between simulated and observed values, expressed as fraction of the observed values and the number of data pairs used in the test are given.

	Slope	**Intercept**	**R^2**	**RMSE**	**RMAE**	**n**
ADM	0.970	1.67	0.923	9.51	0.18	40
SDM	1.059	1.76	0.884	6.08	0.29	133
SUCM	1.095	1.297	0.869	3.86	0.29	135
SC	0.869	7.776	0.721	7.07	0.17	128

8.2 Multi-cultivar validation

The second dataset against which the model was evaluated consists of yield data at harvest for eight cultivars in an irrigated field trial in Pongola and a dryland field trial in Gingindlovu (Ngobese, 2015). The study was reported by Singels *et al*. (2016).

Parameter values for cultivars other than NCo376 (see Table A1 in the Appendix) were estimated independently from these trials from experimental data and/or subjective expert ratings (SASRI cultivar information sheets) relative to that of NCo376. TT50 was determined from expert ratings of canopy formation. TTsg was determined on the assumption that stalks start growing when primary tillers carry ten fully expanded leaves, and was estimated from reference leaf appearance rate (LARo, defined as leaf appearance rate per unit thermal time) measured in a pot experiment at Mount Edgecombe (Hoffman, 2017). RUEo values were derived from leaf photosynthesis measurements (Licor 6400) in the same pot experiment. Pup5 values were derived from expert ratings of drought sensitivity. Values for the remaining cultivar parameters (Table 2.2) were kept the same as NCo376 values.

Table 8.2. Estimated parameter values and simulated and observed stalk dry mass for eight sugarcane cultivars grown at Pongola and Gingindlovu. Parameter acronyms are explained in Table 2.2.

Cultivar	**NCo376**	**N12**	**N19**	**N25**	**N31**	**N36**	**N41**	**N52**
TT50 (°Cd)	250	340	220	250	220	220	280	220
TTsg (°Cd)	1000	1230	1050	950	1100	1050	950	1000
RUEo (g/MJ)	2.25	1.63	1.74	2.20	1.97	1.85	1.97	2.20
ESTRESS	0.45	0.45	0.55	0.5	0.35	0.5	0.35	0.5

Results are shown in Figure 8.3 and Table 8.3 (from Singels *et al*., 2016). Although the model systematically underestimated SDM (on average by 7%) for Pongola, the simulated ranking of cultivars correlated excellently with the observed ranking (r=0.74*). The simulated cultivar range in SDM of 14 t/ha also compared well with the observed range of 10 t/ha ($LSD_{0.05}$ of observed SDM 6.0 t/ha). Observed and simulated SDM were best correlated with parameter RUEo (0.81* and 0.99*), followed by TTsg (-0.60 and -0.84*).

The model also underestimated yields for Gingindlovu (on average by 22%) and the simulated cultivar ranking was not correlated to the observed ranking. It should be noted that these crops experienced severe drought conditions for eight out of 12 months and that observed yield differences were statistically insignificant ($LSD_{0.05}$=4.9 t/ha).

Simulated yields for Gingindlovu were strongly correlated with RUEo (0.99*) and TTsg (-0.79*), while observed yields were best correlated with TT50 (-0.73*). This suggests that the model probably over-emphasizes the impact of RUEo and TTsg on cane yield, at the expense of TT50.

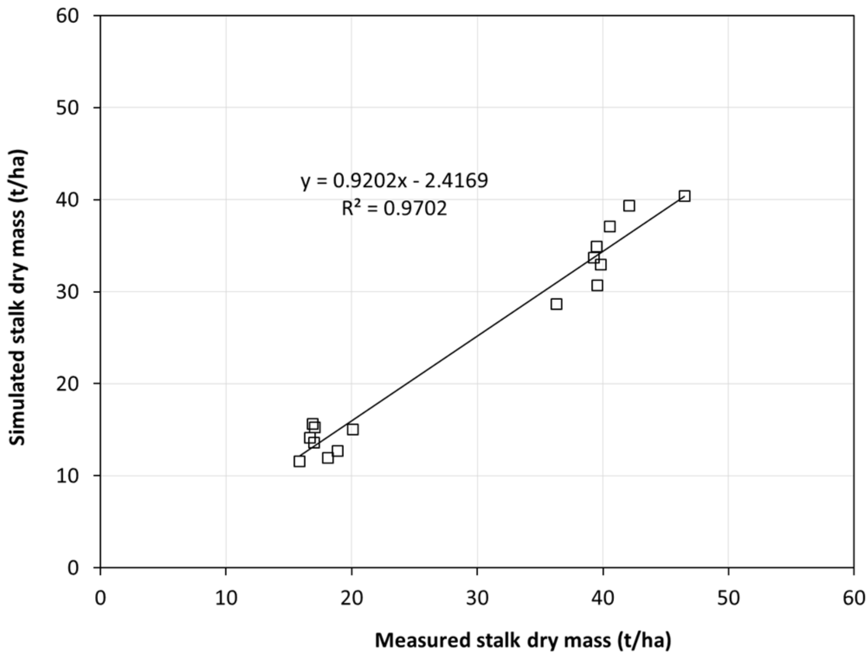


Figure 8.3. Scatterplot of simulated and measured stalk dry mass at harvest for eight cultivars grown in Pongola and Gingindlovu.

Table 8.3. Validation statistics for stalk dry mass predictions for the multiple cultivar dataset for different experiments and for the data combined. The slope and intercept of the linear regression between simulated and observed values, coefficient of determination (R^2), root mean squared difference between simulated and observed values (RMSE) and mean absolute difference between simulated and observed values, expressed as fraction of the observed values, and the number of data pairs used in the test are given.

	Slope	**Intercept**	**R^2**	**RMSE**	**RMAE**	**n**
Pongola	1.218	14.51	0.765	6.01	0.14	8
Gingindlovu	0.364	8.28	0.0576	3.54	0.16	8
Combined	0.884	0.92	0.962	4.93	0.15	16

These preliminary results suggest that the model was able to simulate differences in cultivar performance in irrigated field trials through trait parameter estimations from independent experimental data and expert ratings. The validity or not of possible drought coping traits could not be assessed reliably.

8.3 Conclusion

Model evaluation suggests that stalk dry mass can be simulated accurately for the reference cultivar NCo376 for a wide range of conditions. A preliminary test also indicates that the model is able to simulate genetic differences under well-watered conditions.

9. IMPLEMENTATION

The Canesim® model is coded in Oracle's Procedural Language/Structured Query Language (PL/SQL). Canesim® was written using a non-object oriented programming (OOP) package and package body with about 56 procedures and functions. Input and output data are currently stored in around 100 key data tables in an Oracle 12c edition database.

The web interface to Canesim®, called MyCanesim®, for manipulating input data and viewing outputs, was programmed in PL/SQL and housed under the Oracle Portal application. This website allows users to create custom profiles where they can run many simulations over many years and to save their results (and inputs) for viewing at a later stage. The PL/SQL for the website outputs HTML, Javascript and jQuery calls, but it is planned to upgrade the site using Oracle application development framework (ADF). The system can be accessed at http://portal.sasa.org.za.

A simplified version of the system (MyCanesim® Lite) is also available at http://sasri.sasa.org.za/MyCanesim_Lite/index.php. The web interface is written in the PHP programming language and interacts with MyCanesim® database tables and the Canesim® model with full functionality to execute simulations and display results. MyCanesim® Lite allows the user to specify the weather station, crop start and harvest dates, crop class, residue layer type, soil water holding capacity and irrigation type (Figure 9.1). Other inputs are derived from these basic inputs, or default values are used (see Table 9.1). The system outputs seasonal water balance totals, canopy cover and cane yield at harvest (Figure 9.1) for a single season or for multiple seasons. Daily data for more variables can be downloaded or viewed in graphs.

Table 9.1. Assumptions for MyCanesim® Lite inputs.

	Input variable	Value/calculation
Soil	Clay and silt content	25% and 12%, respectively. Used to calculate soil water retention properties (Θsat, Θdul, Θll and AWC*) (*Eq. 2.2 to Eq. 2.4)*
	Soil layering and maximum rooting depth	AWC / (Θdul – Θll)*
	Initial soil water content	50% of AWC*
Crop	Cultivar	NCo376
	Row configuration	Single rows spaced at 1.2 m
Weather	Climate forecast option	Weather data sequence from the past with long term median rainfall for the next three months.
	Atmospheric CO_2 option	CO_2 concentration for the relevant period (historical data)
Irrigation	Irrigation system type	Overhead
	Application amount and cycle period Full irrigation: Supplementary irrigation:	 35 mm x 7 days 35 mm x 14 days
	Depletion level	50% of AWC
	Refill level	Depletion level + 35mm, or AWC – 10mm
	Drying off option	Off
	Water allocation	Unrestricted

* AWC- available soil water capacity (mm); Θsat, Θdul, Θll – soil water content at saturation, field capacity and wilting point, respectively.

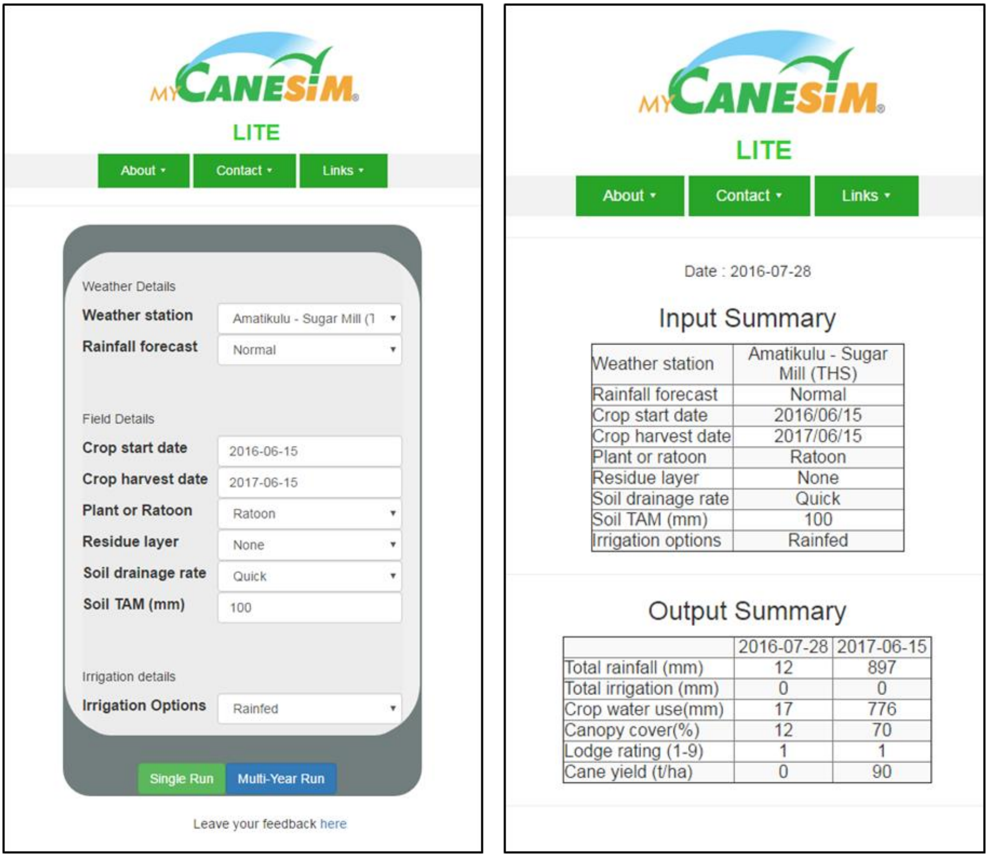


Figure 9.1. Examples of the input and output pages of the MyCanesim® Lite application.

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10. APPLICATION EXAMPLES

Three examples are now described of how Canesim® simulations conducted within the MyCanesim® system, are applied to support decision making for efficient and sustainable production of sugarcane.

10.1 Irrigation scheduling advice

Initially MyCanesim® was used to provide operational irrigation scheduling advice to a group of small-scale farmers in Pongola. This service was initiated in May 2005 (Singels and Smith, 2006) and was extended to 50 farmers by 2008 (Paraskevopoulos, 2016). Subscription numbers have declined since then due to the cessation of unviable farming operations. The number of growers registered for the service in 2016 was 24 small-scale growers in Pongola and Makhathini and two commercial growers in Heatonville.

To support these farmers, a MyCanesim® procedure, called IrrigationSMS, generates irrigation scheduling advice for subscribed fields on a daily basis using data output from Canesim® simulations. MyCanesim® integrates measured soil water and irrigation data into Canesim® simulations for improved simulation and forecasting accuracy. Ideally the data integration is automated (electronic soil water sensors, irrigation gauges and flow meters) so that minimal intervention is required from users. The procedure also accounts for spatial variation in soil water status in fields irrigated with portable sprinkler and centre pivot irrigation systems (see Singels and Smith, 2006).

Essentially, the advice consists of a forecasted date of next irrigation action, and the type of irrigation action (stop or start) required. The next date of irrigation action is determined by assessing forecasted soil water status against the chosen depletion threshold and taking into account irrigation system constraints (minimum cycle period and typical application amounts). The estimated best date to start drying off the crop is also provided. Advice is provided in several forms and formats (see Figure 10.3 and Figure 2.5).

Typically, commercial farmers and extension staff receive irrigation advice by e-mail, fax or web downloads, while small-scale farmers receive the advice by *SMS* (Singels, 2007). Scheduling decisions can also be based on simulated soil water status in relation to the chosen depletion level, which can be viewed in graphical form in MyCanesim® (Figure 10.2).

28-Jul-16 08:06

***MyCanesim* Irrigation Advice and Current Estimates**

The "My Canesim" system calculates current and future estimates of the crop water budget and crop yield based on weather data and field information. The system uses this information to suggest best irrigation schedules for individual fields.

Grower Code: 900003 / A **Date:** 28/JUL/16

Field / Grower	Current Action	Next Action	Start Date	Harvest Date	Dry Off Start Date	Active / Inactive	Rain Now (mm)	Irrigation Now (mm)	Yield Now (t/ha)	Current SWC/TAM (%)
Mthembu D	Irrigating since 2016/07/27	18/AUG/16 - Stop	15/JUN/16	15/JUN/17	2017/05/28		11.9	0	0	49
Simelane NM	Irrigating since 2016/07/27	23/OCT/16 - Stop	15/DEC/15	15/DEC/16	2016/11/30		190.4	126	25.02	11.3
Mathe CE	Irrigating since 2016/07/27	07/SEP/16 - Stop	15/OCT/15	15/OCT/16	2016/09/27		307.8	168	41.63	5.2
Ntshangase MA	Irrigating since 2016/07/27	01/SEP/16 - Drying Off	15/SEP/15	15/SEP/16	2016/09/01		328.6	210	43.71	3.5
Siyaya B	Irrigating since 2016/07/27	30/SEP/16 - Stop	25/NOV/15	25/NOV/16	2016/11/02		263.2	126	36	4.8
Dlomo SR	Irrigating since 2016/07/27	12/AUG/16 - Stop	02/JUL/16	02/JUL/17	2017/06/18		10.9	0	0	64.2
Magagula VS Plot 485	Not irrigating since 2016/05/31	10/JUL/16 - Drying Off	10/JUL/15	30/JUL/16	2016/07/10		373.5	336	54.35	3.5
Magagula VS Plot 516	Not irrigating since 2016/05/31	16/JUL/16 - Drying Off	10/JUL/15	30/JUL/16	2016/07/16		373.5	294	49.8	2.8
Phakathi FD	Irrigating since 2016/07/27	28/SEP/16 - Stop	15/NOV/15	15/NOV/16	2016/10/20		286.7	126	36.47	3.8
Thabethe BE	Irrigating since 2016/07/27	17/AUG/16 - Stop	16/JUN/16	16/JUN/17	2017/05/27		11.8	0	0	83.8
Malinga RT	Irrigating since 2016/07/27	23/SEP/16 - Stop	15/DEC/15	15/DEC/16	2016/11/22		190.4	168	43.89	10.5
Khumalo MH	Irrigating since 2016/07/27	28/AUG/16 - Stop	15/SEP/15	15/SEP/16	2016/09/01		328.6	294	39.35	6.7
Mbokazi A	Irrigating since 2016/07/27	03/OCT/16 - Drying Off	19/OCT/15	19/OCT/16	2016/10/03		295.8	252	50.28	4.8
Dlamini LZ	Irrigating since 2016/07/27	01/OCT/16 - Drying Off	19/OCT/15	17/OCT/16	2016/10/01		295.8	210	41	5
Xaba G.S	Irrigating since 2016/07/27	31/JUL/16 - Drying Off	24/AUG/15	22/AUG/16	2016/07/31		352.4	294	48.45	4.4

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Figure 10.1. Example of the MyCanesim® report for irrigation scheduling advice.

Figure 10.2. An example of a MyCanesim® soil water balance graph showing simulated and measured available soil water content (SWC) (courtesy Aquacheck), irrigation amounts as determined from flowmeter data (courtesy Omnisense) and rainfall. The projected SWC is assessed in relation to the allowable depletion level to indicate the timing of the next irrigation. The download (current) date was 31 September 2016. See Figure 2.4 for a full explanation of variables.

10.2 Benchmarking agronomic management

Paraskevopoulos and Singels (2014) demonstrated the potential value of integrating soil water monitoring data with weather-based simulations in the MyCanesim® system. Agronomic performance, including the quality of irrigation management, was inferred from simulated and observed data for a number of irrigated sugarcane fields in Mpumalanga for the 2011/12 growing season. Simulated yields using optimal irrigation (Y_{opt}) were compared to yields from simulations that were corrected with measured soil water data (Y_{swc}) and actual yields (Y_{obs}). Criteria for inferring agronomic performance are given in Table 10.1 (from Paraskevopoulos and Singels 2014).

Table 10.1. Crop management performance criteria. Y_{opt} is the simulated yield using an optimal irrigation schedule; Y_{swc} is the yield from a simulation based on observed soil water records; and Y_{obs} is the actual yield achieved.

Comparison	Deduction
$Y_{obs} > 0.85\ Y_{opt}$	Good irrigation[1], good crop husbandry
$Y_{obs} < 0.85\ Y_{opt}$	Crop underperformance due to one or more limiting factors
$Y_{swc} > 0.85\ Y_{opt}$	Good irrigation[1]
$Y_{swc} < 0.85\ Y_{opt}$	Under irrigation caused preventable drought stress
$Y_{obs} > 0.85\ Y_{swc}$	Good crop husbandry
$Y_{obs} < 0.85\ Y_{swc}$	Suboptimal crop husbandry

[1] Irrigation practices were evaluated given the limitations of the existing irrigation system

The extent of water stress (drought stress and waterlogging) experienced is also an indication of the appropriateness of irrigation practices. Drought stress days were defined as days when available soil water content of the root zone (SWC) was less than 40% of capacity (AWC), excluding the last 30 days of the season (when irrigations are typically intentionally withheld to promote sucrose accumulation). Waterlogged days were defined as days when SWC exceeded 110% of AWC.

A summary of the results of the analysis is given in Table 10.2. Fields 8A, 8C, 17, 3B, 7, 1 and 14 are underperforming because Y_{obs} is less than 85% of Y_{opt}. Insufficient irrigation and preventable drought stress are inferred for fields 8C and 17. Subsequent analysis showed that this was due to excessive drying off (in the case of field 8C) and irrigation system failures (in field 17).

For fields where Y_{obs} was less than 85% of Y_{swc}, this was taken as an indication of yield limiting factors other than insufficient irrigation, for example poor crop stand, weed competition, nutrient deficiency or pest and disease damage. This seemed to be the case for fields 8A, 8C, 3B, 7 (poor crop stand was observed in this field), 1 and 14. Water logging may have been a problem on fields G1, 7 and 81 as indicated by the high numbers of water logged days.

Table 10.2. Simulated yields using optimal irrigation (Y_{opt}), observed yields (Y_{obs}) and yields using soil water corrected simulations (Y_{swc}) expressed as percentages of the Y_{opt}, the number of drought stress days (ASWC<40%AWC, excluding the last 30 days when crops are typically intentionally stressed to prepare the field for harvesting), the number of water logged stress days (ASWC>110%AWC) and the percentage of days of the growing season for which soil water status data was available (SWI data) for the different fields.

Farm code	Field Name	Y_{Opt} (t/ha)	Y_{obs} / Y_{opt} (%)	Y_{swc} / Y_{opt} (%)	Y_{obs} / Y_{swc} (%)	Stress days (drought)	Stress days (waterlogged)	SWI data availability (%)	Main conclusion from analysis[1]
A	8A	116	76	94	81	33	8	59	Good irrigation, suboptimal husbandry, short periods of drought stress.
A	8C	116	71	86	82	81	6	69	Good irrigation, suboptimal husbandry. Excessive drying off.
B	17	89	78	63	124	187	12	73	Under irrigation, good husbandry, prolonged drought stress.
C	G7	113	92	97	95	92	8	33	Good irrigation, drought stress due to system limitations.
C	G1	125	86	96	89	4	38	57	Good irrigation, good husbandry, some waterlogging.
C	G4	121	103	98	105	4	23	25	Good irrigation, good husbandry, some waterlogging.
D	3B	135	59	93	64	13	11	55	Good irrigation, suboptimal husbandry.
D	7	115	68	93	73	4	46	63	Good irrigation, suboptimal husbandry, some waterlogging.
E	12	101	101	97	104	43	5	61	Good irrigation, good husbandry, some drought stress.
F	72	154	92	99	93	3	24	83	Good irrigation, good husbandry.
F	81	130	86	93	92	24	69	88	Good irrigation, good husbandry, some waterlogging.
G	1	97	84	99	84	1	4	64	Good irrigation, suboptimal husbandry.
G	14	90	74	92	81	12	4	86	Good irrigation, suboptimal husbandry.

[1] ‘Good irrigation’ means good scheduling given the limitations of the existing irrigation system.

The information derived from comparing the yields from various simulations with observed yields are useful for identifying underperforming fields and indicating likely causes of the underperformance. This could be used to work out remedial actions.

10.3 Researching lodging impacts

Lodging typically occurs in high-yielding crops under conditions of wet soil, wet leaf canopy and strong wind. Lodging is known to reduce the productivity of sugarcane. This is caused by a reduction in radiation interception, radiation use efficiency and stalk damage in lodged crops. More labour input is also required to harvest lodged cane, and payloads are reduced.

Paraskevopoulos *et al*. (2016) used the Canesim® model to study the impact of lodging on yields and profitability, as effected by genotype, crop cycle and climate. In the first study, simulations were conducted for Pongola and Malelane using daily weather data for the period 1970 to 2014. Twelve-month ratoon crops started at six different times of the year were simulated for varieties N14, N25, and N41.

Long-term average simulated yields and lodging extent (LE*)* increased as crops started later in the season, and were higher for Malelane than for Pongola. Yields were highest for N25, whereas LE was highest for N41. Lodging had negligible impacts on simulated cane yields (a maximum reduction of 1.5 t/ha), but substantial impacts on harvest and transport costs and hence on gross margins, with a maximum loss of R2800/ha (≈US$215/ha in 2017). Lodged N25 (high yield, medium lodging tolerance) had higher gross margins than unlodged N14 (medium yield, high lodging tolerance), even though N25 was less tolerant to lodging. These results suggest that, overall, it is more profitable to farmers to target high yields and accept a high risk of lodging than to avoid lodging at yield levels of around 120 t/ha.

In a second study the potential financial benefit of breeding for high lodging tolerance in high yielding varieties was explored. Simulations were conducted for two hypothetical very high yielding ‘N25-type’ varieties, with medium (N25S_M) and high (N25S_H) tolerance to lodging, grown in Malelane. Genetic parameters were based on those of variety N25, but with a maximum radiation use efficiency of 2.65

g/MJ as opposed to 2.2 g/MJ (a 20% increase). Variety N25S_M produced higher average simulated yields and gross margins than N25 (about R5300 and R3000/ha for April and December respectively) despite higher LE. Increased lodging tolerance (N25S_H) led to decreased LE and further increases in average yield, but a substantial increase in average gross margins (about R3000 and R3800/ha for April and December respectively) compared to N25S_M (Figure 10.3)

Results suggest that breeding for lodging tolerance is important, and that significant gains in profitability can be made, especially when yields are already high. The study puts forward a new simulation framework for analysing the impact of lodging on sugarcane production profitability that can be used for other scenarios.

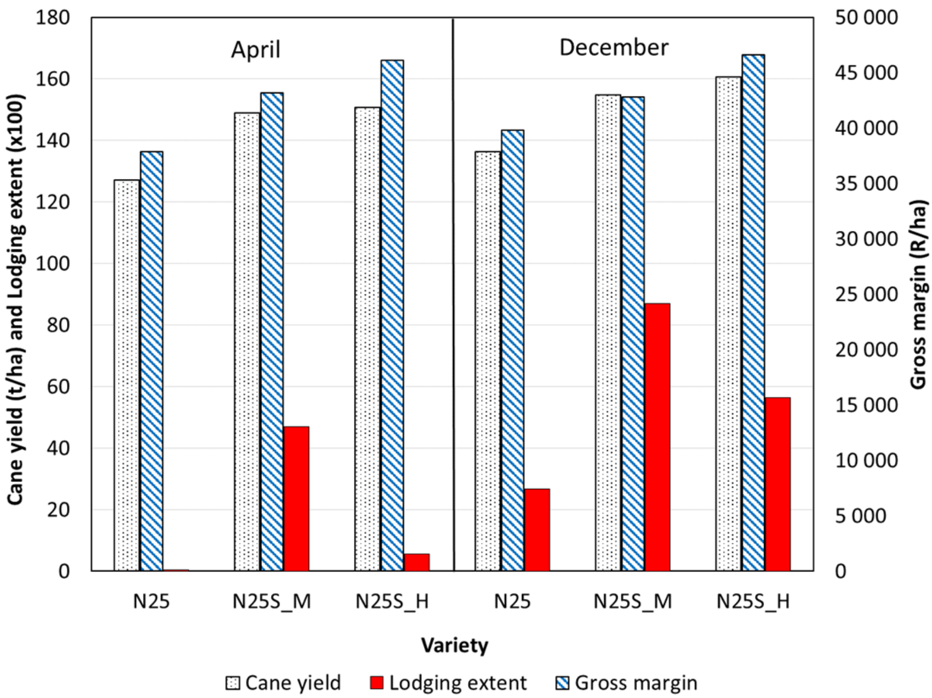

Figure 10.3. Long term average cane yield, lodging extent and gross margin for the standard N25 (high yielding, medium lodging tolerance) and very high yielding cultivars (N25S) that have medium (M) and high (H) tolerance to lodging for the April and December crop cycles for Malelane (from Paraskevopoulos *et al*., 2016).

11. SUMMARY

The Canesim® model simulates crop canopy development, root growth, evapotranspiration, biomass accumulation and partitioning using daily weather data, soil property and crop management information, as well as cultivar characteristics. The model is managed within the web-based MyCanesim® system and outputs daily and seasonal values of soil water and crop status, such as available soil water content, evapotranspiration, crop canopy cover, crop water status, lodging extent, aboveground biomass, stalk dry mass and sucrose mass. Simulation accuracy has been determined for aboveground biomass, and stalk dry mass and sucrose yields and found to be acceptable. MyCanesim® can be applied for strategic evaluations (e.g. for researching climate change and genetic trait impacts) and for operational support (e.g. crop forecasting and irrigation scheduling).

12. ACKNOWLEDGEMENTS

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- Rextin (now Saryx) built the Oracle Interface.
- SASRI and the Water Research Commission provided funding.
- Maurits van den Berg reviewed the manuscript and made valuable suggestions.

13. REFERENCES

Allen RG, Pereira LS, Raes D and Smith M (1998). Crop evapotranspiration: guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Boote KJ, Allen LH Jr, Prasad PVV and Jones JW (2010). Testing effects of climate change in crop models. In: Hillel D and Rosenzweig C (Eds). *Handbook of climate change and agro-ecosystems: Impacts, adaptation and mitigation*. ICP series on climate change impacts, adaptation and mitigation Vol. 1. Imperial College Press pp 109-129.

Campbell GS (1985). Soil physics with Basic: Transport models for soil-plant systems. Elsevier.

Doorenbos J and Kassam AH (1979). Yield Response to Water. Food and Agriculture Organization of the United Nations, Rome, FAO Irrigation and Drainage Paper 33, p. 193.

Ebrahim MK, Vogg G, Osman MNEH and Komor E (1998). Photosynthetic performance and adaptation of sugarcane at suboptimal temperatures. *J Plant Physiology:* 153: 587-592.

FAO, 2016. FAOSTAT beta. Food and Agriculture Organization of the United Nations. http://fenix.fao.org/faostat/beta/en/#data/QD.

Hoffman, N. 2017. Pot trial phenotyping to predict sugarcane genotype field performance with the Canegro Model. M.Sc. thesis, University of KwaZulu-Natal.

Inman-Bamber NG (1994). Temperature and seasonal effects on canopy development and light interception of sugarcane. *Field Crops Res* 36:41-51

Jones CA and Kiniry JR (1986). CERES-Maize: A simulation model of maize growth and development. Texas A&M University Press, College Station, Texas, USA.

Jones MR and Singels A (2015). Analysing yield trends in the South African sugar industry. *Agric. Systems* 141: 24-35.

Jones MR and van den Berg M (2006). Modelling trash management and its impacts: Methodology. *Proc S Afr Sug Technol Ass* 80: 190-194.

Liu DL and Bull TA (2001). Simulation of biomass and sugar accumulation in sugarcane using a process-based model. *Ecological Modeling* 144: 181–211.

Liu DL, Kingston G and Bull TA (1998). A new technique for determining the thermal parameters of phenological development in sugarcane, including suboptimum and supra-optimum temperature regimes. *Agricultural and Forest Meteorology* 90:119-139.

Martiné JF and Lebret P (2001). Modelling the water content of the sugarcane stalk. *Proc S Afr Sug Technol Ass* 75: 211-214.

McGlinchey MG and Inman-Bamber NG (1996). Effect of irrigation scheduling on water use efficiency and yield. *Proc S Afr Sug Technol Ass* 70: 55-56.

Ngobese I (2015). Genetic coefficients of sugarcane phenology traits for crop model refinement. M.Sc. dissertation. University of the Free State, Bloemfontein, South Africa.

Olivier FC, Singels A and Savage MJ (2016). Driving factors of crop residue layer effects on sugarcane development and water use. *Proc S Afr Sug Technol Ass* 89: 144-148.

Paraskevopoulos AL and Singels A (2014). Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. *Computers and Electronics in Agriculture* 105: 44-53.

Paraskevopoulos AL, Singels A, Tweddle PB and van Heerden PDR (2016). Quantifying the negative impact of lodging on irrigated sugarcane productivity: A crop modelling assessment. *Proc S Afr Sug Technol Ass* 89: 154-158

Schulze RE, Hull PJ and Maharaj M (2008). Soil Water. In: Schulze RE, Hull PJ and Bezuidenhout CN (2008). *South African Sugarcane Atlas*. University of KwaZulu-Natal, School of Bioresources Engineering and Environmental Hydrology, Pietermaritzburg, RSA, ACRUcons Report, 57, Section 6.1, 103-112

Singels A (2007). A new approach to implementing computer-based decision support for sugarcane farmers and extension staff. The case of My Canesim®. *Proc Int Soc Sug Cane Technol* 26: 211-219 (also published in *Sugar Cane International* 26: 22-25).

Singels A (2014). Crop Models. In: Physiology, biochemistry and functional biology of sugarcane. (Ed: P.H. Moore and F. C. Botha). 541-571. World in Agriculture Series. Wiley-Blackwell. ISBN 978-1-118-77138-9

Singels A and Bezuidenhout CN (2002). A new method of simulating dry matter partitioning in the Canegro sugarcane model. *Field Crops Res* 78: 151-164.

Singels A and Bezuidenhout CN (2005) Forecasting South Africa's sugarcane crop with the Canesim® crop model. Proc. of the XXV Congress of the Int. Soc. Sugar Cane Tech., 2: 184 - 190. This article also appeared in *Sugar Cane International* 24(1): 26-30 (2006).

Singels A and Donaldson RA (2000). A simple model of unstressed sugarcane canopy development. *Proc S Afr Sug Technol Ass* 74: 151-154.

Singels A and Manley CR (1991). Die PUTU koringgroeimodel: Verdere verfyning en aanwending. Final research report to the Department of Agricultural Development by the University of the Free State, Bloemfontein. 73 pp.

Singels A and Paraskevopoulos AL (2010) . Optimizing irrigation scheduling of portable overhead systems: a simulation study. *Proc S Afr Sug Technol Ass* 83: 174-178.

Singels A and Smith MT (2006). Provision of irrigation scheduling advice to small-scale sugarcane farmers using a web based crop model and cellular technology: A South African case study. *Irrig Drain* 55: 363-372.

Singels A, Bezuidenhout CN and Schmidt EJ (1999). Evaluating strategies for scheduling supplementary irrigation of sugarcane in South Africa. *Proc Aust Soc Sug Cane Technol* 21: 219-226.

Singels A, Hoffman N, Paraskevopoulos A and Ramburan S (2016). Sugarcane genetic trait parameter estimation. iCROPM2016 International Crop Modelling Symposium, held from 15 to 17 March 2016 in Berlin, Germany.

Singels A, Kennedy AJ and Bezuidenhout CN (1998). IRRICANE: A simple computerized irrigation scheduling method for sugarcane. *Proc S Afr Sug Technol Ass* 72: 117-122.

Singels A, Kennedy AJ and Bezuidenhout CN (1999). Weather based decision support through the Internet for the agronomic management of sugarcane. *Proc S Afr Sug Technol Ass* 73: 30-32.

Singels A, Jones M and van den Berg, M (2008). DSSAT v4.5 Canegro Sugarcane Plant Module: Scientific documentation. SASRI, Mount Edgecombe, South Africa. pp 34.

Singh G, Chapman SC, Jackson PA and Lawn RJ (2002). Lodging reduces sucrose accumulation of sugarcane in the wet and dry tropics. *Austr J Agric Res* 53: 1183-1194.

Slabbers PJ (1979) Practical prediction of actual evapotranspiration. *Irrig. Sci*. 1980, 185–196.

Smit MA (2010). Characterising the factors that affect germination and emergence in sugarcane. *Proc S Afr Sug Technol Ass* 83: 230 – 234

Smit MA and Singels A (2006). The response of sugarcane canopy development to water stress. *Field Crops Res* 98: 91-97.

Steduto P, Hsiao TC and Raes D (2009). AquaCrop: The FAO crop model to simulate yield response to water: I: Concepts and underlying principles. *Agronomy Journal* 101: 426-437.

Supit I, Hooijer AA and van Diepen CA. (Eds.) (1994). System Description of the WOFOST 6.0 Crop Simulation Model Implemented in CGMS. Volume 1: Theory and Algorithms. Joint Research Centre of the European Commission, Luxembourg, Office for Official Publications of the European Communities, EUR 15956, p. 146.

van Antwerpen RV, Meyer JH and Johnston MA (1994). Estimating water retention of some Natal sugar belt soils in relation to clay content. *Proc S Afr Sug Technol Ass* 68: 75-79.

van Antwerpen RV (1998). Modelling root growth and water uptake of sugarcane cultivar NCo 376. PhD thesis, University of the Orange Free State, Bloemfontein, South Africa.

Van den Berg M and Singels A (2013) Modelling and monitoring for strategic yield gap diagnosis in the South African sugar belt. *Field Crops Res* 143: 143–150.

Van Dillewijn C (1952). Botany of sugarcane. Chronica Botanics Co., Waltham, M.A. USA, p.: 371.

van Heerden PDR, Singels A, Paraskevopoulos A and Rossler R (2015). Negative effects of lodging on irrigated sugarcane productivity – An experimental and crop modelling assessment. *Field Crops Res* 180: 135-142.

14. APPENDIX

Table A1. Trait parameter values for different sugarcane cultivars estimated from experimental data and expert ratings.

CULTIVAR	TTEMpo (ºCd)	TTEMro (ºCd)	TTsg (ºCd)	TT50ref (ºCd)	RUEo (g/MJ)	ADMPFmax	SPFmax	SUCmax	T50 (ºC)	ESTRESS	AMbase (t/ha)
NCo376	300	100	1000	250	2.25	0.88	0.65	0.58	25	0.45	260
N12	300	100	1230	340	1.63	0.88	0.65	0.58	25	0.45	260
N14	300	100	1000	220	2.08	0.88	0.65	0.603	25	0.55	260
N16	300	100	950	220	2.2	0.88	0.65	0.58	25	0.5	230
N17	300	100	1000	250	1.7	0.88	0.65	0.58	25	0.5	220
N19	300	100	1050	220	1.74	0.88	0.65	0.626	25	0.55	200
N21	300	100	950	220	2.2	0.88	0.65	0.557	25	0.35	200
N22	300	100	950	220	2.25	0.88	0.65	0.626	25	0.55	260
N23	400	200	950	220	1.97	0.88	0.65	0.58	25	0.5	250
N24	400	200	1150	340	1.63	0.88	0.65	0.67	25	0.55	200
N25	300	100	950	250	2.2	0.88	0.65	0.557	25	0.5	230
N26	300	100	1150	340	1.63	0.88	0.65	0.65	25	0.55	200
N27	500	300	1150	340	2.2	0.88	0.65	0.603	25	0.35	250
N28	300	100	1050	280	1.97	0.88	0.65	0.626	25	0.55	260
N29	300	100	950	220	1.63	0.88	0.65	0.626	25	0.5	230
N30	400	200	950	220	1.63	0.88	0.65	0.67	25	0.55	230
N31	300	100	1100	220	1.97	0.88	0.65	0.534	25	0.35	200
N32	400	200	950	220	1.97	0.88	0.65	0.626	25	0.55	260
N33	300	100	950	220	2.2	0.88	0.65	0.557	25	0.35	260
N35	300	100	950	220	1.63	0.88	0.65	0.626	25	0.55	260
N36	300	100	1050	220	1.86	0.88	0.65	0.626	25	0.5	230
N37	300	100	950	220	1.97	0.88	0.65	0.58	25	0.55	230
N39	300	100	1050	280	2.2	0.88	0.65	0.58	25	0.35	230
N40	300	100	950	220	1.63	0.88	0.65	0.65	25	0.5	230

CULTIVAR	TTEMpo	TTEMro	TTsg	TT50ref	RUEo	ADMPFmax	SPFmax	SUCmax	T50	ESTRESS	AMbase
N41	300	100	950	280	1.97	0.88	0.65	0.603	25	0.35	200
N42	300	100	900	220	2.2	0.88	0.65	0.58	25	0.5	260
N43	300	100	950	220	2.2	0.88	0.65	0.626	25	0.5	230
N44	400	200	950	220	2.2	0.88	0.65	0.557	25	0.5	200
N45	300	100	950	220	2.2	0.88	0.65	0.58	25	0.5	230
N46	300	100	950	220	1.97	0.88	0.65	0.65	25	0.5	230
N47	500	300	1050	280	1.97	0.88	0.65	0.603	25	0.5	230
N48	400	200	1100	220	2.08	0.88	0.65	0.603	25	0.5	230
N49	300	100	1000	250	1.97	0.88	0.65	0.67	25	0.5	200
N50	300	100	1000	250	1.7	0.88	0.65	0.58	25	0.5	220
N51	300	100	1000	250	1.86	0.88	0.65	0.58	25	0.5	220
N52	300	100	950	220	2.2	0.88	0.65	0.537	25	0.5	190
N53	300	100	1000	250	1.7	0.88	0.65	0.58	25	0.5	220

15. LIST OF ABBREVIATIONS

Abbreviation	Definition and units
ADMPF	Partitioning coefficient for aerial dry mass, defined as the fraction of daily dry biomass gain partitioned to aerial plant components
ADMPFmax	Maximum partition fraction of daily biomass increments to aboveground plant parts
AFM	Fresh mass of aerial plant parts (t/ha)
AMbase	Aerial mass (fresh mass plus attached water) at which lodging commences when other lodging factors such as water and wind are absent (t/ha)
AMbase	Aerial mass (fresh mass plus any intercepted water attached to it) threshold, at which lodging commences when other lodging factors such as water and wind are absent (t/ha)
AM	Fresh mass of aerial parts plus intercepted rainfall and irrigation water retained on it (t/ha)
AMrange	The range in aerial mass (fresh biomass plus any water attached to it) from the point where lodging commences up to the point where lodging is complete (t/ha)
AWC(l)	Plant available water capacity, defined as the water content at field capacity, for layer l (mm)
Awet	soil surface area wetted by irrigation (m^2/m^2)
b	Empirical parameter for calculating ADMPF from TOT
BD(l)	Soil bulk density (g/cm^3) for layer l
CLAY(l)	clay content of the soil (fraction) for layer l
Clo	Intermediate variable to determine water stress thresholds
CO_2	Carbon dioxide
CumRDF(l)	Root length fraction accumulated from the top soil layer to layer l
CumTT10	Cumulative thermal time (base 10) from planting or cut back
Cup	Intermediate variable to calculate soil water depletion thresholds
dADM	Daily gain in aerial dry mass (t/ha/d)
Dcon(l)	Drainage constant defined as the fraction of water above field capacity that is drained (/d)
ΔFI	The fractional reduction in radiation interception for a fully lodged crop
ΔRUE	The fractional reduction in radiation conversion efficiency for a fully lodged crop
Δmax	Maximum gradient in sucrose content in the immature section of the stalk ((g/g) / (t/ha))
dFNS	Partitioning coefficient for stalk fibre and hexoses, defined as the fraction of daily stalk dry mass gain partitioned to the stalk fibre and hexoses pool
Dif	Soil water diffusivity coefficient for water flow
dLF	Daily gain in leaf dry mass (t/ha/d)

Abbreviation	Definition and units
DRAINfree(l)	Daily drainage of free water (above the saturated level) from soil layer l (mm)
DRAINsat(l)	Daily drainage of water held between field capacity and the saturated level in soil layer l (mm)
Drel(l)	Relative soil water depletion below field capacity for layer l
dRT	Daily gain in root dry mass (t/ha/d)
dSK	Daily gain in stalk dry mass (t/ha/d)
dSUC	Partitioning coefficient for stalk sucrose, defined as the fraction of daily stalk dry mass gain partitioned to the sucrose pool
dTOT	Daily dry biomass accumulation (t/ha/d)
dTT50res10	Change in thermal time required to reach 50% canopy cover due to the presence of a residue layer (°Cd)
dTT50row	Response of TT50 to a change in RS from the reference value of 1.4 m ((°Cd)/m)
dTTEMpres10	Additional thermal time required for the shoots to penetrate a residue layer of 10 t/ha
dTTEMres	Additional thermal time required for shoots to penetrate the residue layer (°Cd)
Epool	Amount of water that can evaporate from the soil at any given time(mm)
Epoolmax	The maximum amount of water that can potentially evaporate from the soil after a wetting event (mm)
Er	Daily evaporation from the residue layer (mm/d)
ERD	Effective rooting depth defined as the maximum depth that roots can penetrate to (cm)
Eref	Sugarcane reference evaporation (mm), defined as evapotranspiration from a fully canopied and well-watered sugarcane crop with leaf area index of 3.5 and a crop height of 3 m (McGlinchey and Inman-Bamber, 1996)
ESTRESS	The relative available soil water content threshold below which transpiration and photosynthesis rates are reduced below their potential values
ET	Evapotranspiration, i.e. the sum of evaporation from the crop canopy (any given crop canopy cover, crop water status) and evaporation from the exposed soil surface (wet or dry) (mm)
Ev	Daily transpiration (mm/d)
FCO2	Atmospheric CO_2 concentration control factor for photosynthesis
Fesr	Residue control factor for evaporation from the residue layer
FI	Fractional interception of photosynthetic active radiation by the green canopy, numerically equal to green canopy cover
FIduro	Water stress period required to effect the maximum reduction in canopy cover (d)
FIo	Fractional interception of the green canopy of an erect crop
FIred	Maximum reduction in fractional canopy cover due to water deficit
Flodge	The lodging extent on a given day (fraction of stalks lodged)

Abbreviation	Definition and units
$Flodge_{AM,}$	Potential extent of lodging on a given due to heavy aerial mass
$Flodge_{P}$	Potential extent of lodging on a given day due to the combined effect of all causal factors
$Flodge_{SWC}$	Potential extent of lodging due to saturated soil (fraction)
Flodgeswco	Maximum increase in the lodged fraction due to saturated soil
$Flodge_{U}$	Potential extent of lodging due to high wind speeds (fraction)
Flodgeuo	Maximum increase in the lodged fraction due to strong wind
Fs	Soil surface wetness control factor for soil evaporation
Fshape	Parameter to determine the shape of curve describing the relationship between FW and Drel
Fsr1	Factor to represent surface wetness of exposed soil not wetted by irrigation
Fsr2	Factor to represent surface wetness of exposed soil wetted by irrigation
FT	Temperature control factor for photosynthesis
WSI_{P}	Water satisfaction index, a crop water status factor calculated from layered soil water status and root density information and affecting gross photosynthesis and transpiration
WSI_{G}	Water satisfaction index, a crop water status factor calculated from layered soil water status and root density information and affecting expansive growth and sucrose accumulation
FW(l)	Soil water status factor for layer l
FWcan	Net relative stress duration
FWCON	Coefficient for the sensitivity of sucrose accumulation to water deficit (relates FWs to WSI_{G})
FWdur	Net duration of severe water stress, calculated as the difference in the number of stress days and number of recovery days in the last FWduro days (d)
FWduro	Duration of severe water stress required to effect the maximum reduction in green canopy cover (d)
FWs, FTs	Crop water and temperature status control factors for sucrose accumulation
GSTRESS	The available soil water threshold below which expansive growth is reduced below its potential value at a reference atmospheric demand of 5 mm/d
Iint	Irrigation intercepted by the canopy (mm)
INFIL(1)	Water infiltration into the top soil layer (mm)
IRR_{OH}	Daily overhead irrigation applied (measured above the crop canopy) (mm/d)
IRR_{SD}	Daily irrigation amount from drip irrigation systems (mm)
k	Empirical shape factor for the relationship between canopy cover and thermal time
Ks	FAO crop evaporation coefficient, defined as the ration of evapotranspiration to FAO reference grass evaporation
LARo	Leaf appearance rate per unit thermal time (/(°Cd))

Abbreviation	Definition and units
LE	Lodging extent expressed as an index from 1 (zero lodging) to 9 (fully lodged)
Peff	Water from rainfall plus overhead irrigation that penetrated through the crop canopy and is available for infiltration into the soil
Pgross	Daily gross (before respiration) photosynthetic rate (t/ha/d)
Plo	Lower threshold of soil water depletion for layer l for a given set of conditions, defined as the relative soil water depletion below which the rate of a given process equals zero
Plo5	Plo at the reference Eref of 5 mm/d
Pup	Upper threshold of soil water depletion for layer l for given set of conditions, defined as the relative soil water depletion below which the rate of given process declines below the maximum rate
Pup5	Pup at the reference Eref of 5 mm/d
Qs	Daily water table contribution to evaporation from the soil (mm/d)
Qv	Daily water table contribution to transpiration (mm/d)
RAIN	Daily rainfall (mm/d)
Rdepth	Depth of the rooting front at any given time (m)
RDF(l)	Root length fraction of layer l
RES	Amount of residue cover of the soil at the start of the crop (t/ha)
Respcf	Fraction of daily gross photosynthate consumed through growth respiration(g/g/d)
Respcons	Fraction of biomass consumed to maintain the stored sucrose pool at the reference temperature of 10°C, expressed as a fraction of the sucrose stored in stalks (g/g/d)
RespQ10	The Q10 coefficient for the response of maintenance respiration rate to temperature
RFLOW(l)	Daily flow of unsaturated water from layer l-1 into layer l (mm)
Rg	Daily growth respiration rate (t/ha/d)
Rgro	Root penetration rate per unit thermal time (m/(°Cd))
Rint	Rainfall intercepted by the canopy (mm)
Rm	Daily maintenance respiration rate (t/ha/d)
RS	Row spacing, taken as the distance between adjacent single cane rows, or the distance between dual row centres divided by two (m)
RSWD (l)	Relative soil water depletion for layer l
RTPF	Partitioning coefficient for roots, defined as the fraction of daily dry biomass gain partitioned to roots
RUE	Radiation conversion efficiency defined as the gross photosynthate produced per unit of intercepted shortwave radiation (g/MJ)
RUEo	Maximum radiation conversion efficiency defined as the gross photosynthate produced per unit of shortwave radiation intercepted by a crop growing under reference conditions (ideal water, temperature and atmospheric CO_2 status) (g/MJ)
SAT(l)	Available water content held at saturation in soil layer l (mm)

Abbreviation	Definition and units
SC	Sucrose content of millable stalks on a dry mass basis
sk	Cumulative stalk dry mass measured from the base of stalks up (t/ha)
SK	Total stalk dry mass of the crop at any given time (t/ha)
SKPF	Partitioning coefficient for stalks, defined as the fraction of daily aerial dry mass gain partitioned to stalks
SKWa	Empirical parameter to calculate SKWATER from stalk dry mass
SKWATER	Amount of water in stalks (t/ha)
SKWb	Empirical parameter to calculate SKWATER from sucrose mass
SPFmax	Partition fraction of daily aboveground biomass increments to stalk material during the stalk growth phase
Srad	Solar shortwave radiation (MJ/m^2)
SUCcap	Capacity of the crop to store sucrose, defined as the difference between the current sucrose mass and the theoretical sink for sucrose
SUCeq	Theoretical sucrose mass (sink size) that would have been achieved had the crop experienced current temperature and water status conditions throughout its life cycle, given the source history of the crop
SUCM	Stalk sucrose mass at any given time (t/ha)
SUCmax	Maximum sucrose content in the mature section of the stalk
SWC(l)	Available soil water content of soil layer l (mm)
SWDEF(l)	Soil water deficit of layer l, calculated as the difference between AWC and SWC
TAM	Plant available water capacity of the exploitable soil profile (mm)
T50	Temperature threshold where daily stalk mass increments are partitioned 50:50 to fibre and sucrose (°C)
Tb	Base temperature below which process rates equal zero (°C)
Tbcan	Base temperature for canopy development (°C)
Tbgro	Base temperature for phenological development and root growth (°C)
Tbphoto	Base temperature for photosynthesis (°C)
Teff	Effective temperature, defined as the temperature responsible for driving a given process. It is calculated as a function of ambient temperature and specified cardinal temperatures.
Tes	The number of days since the last rainfall event
Ti	The number of day since the last irrigation event
Tmax	Daily maximum temperature (°C)
Tmean	Daily mean temperature calculated as the average of the daily minimum and maximum temperature (°C)
Tmin	Daily minimum temperature (°C)
To	Optimal temperature at which process rates are maximum (°C)
To1	Lower optimal temperature for photosynthesis. Below this temperature photosynthesis rate declines (°C)
To1photo	Lower optimal temperature for photosynthesis (°C)

Abbreviation	Definition and units
To2	Upper optimal temperature for photosynthesis. Above this temperature photosynthesis rate declines (°C)
To2photo	Upper optimal temperature for photosynthesis (°C)
Tocan	Optimal temperature for canopy development (°C)
Togro	Optimal temperature for phenological development and root growth (°C)
Tosuc	Optimal temperature for maintenance respiration (°Cd)
TOT	Dry biomass on a given day (t/ha)
Tratio	Potential transpiration rate at a given atmospheric CO_2 concentration, expressed as ratio to the rate at the reference concentration of 330 ppm
TT	Thermal time, defined as effective temperature integrated over time (°C.d)
TT50	Thermal time requirement to reach 50 % canopy cover (°Cd)
TT50ref	Thermal time required from shoot emergence to 50% canopy cover for a reference crop (unstressed, bare soil and row spacing of 1.4 m) (°C.d)
TTcan	Thermal time accumulated since shoot emergence (°Cd)
TTEMpo	Thermal time required from planting to shoot emergence of a plant crop growing on a bare soil (°Cd)
TTEMro	Thermal time required from cutback to shoot emergence of a ratoon crop growing on a bare soil (°Cd)
TTI	Thermal time index
TTsg	Thermal time required from shoot emergence to the start of stalk growth (°Cd)
Tu	Upper limit temperature above which process rates equal zero (°C)
Tucan	Upper temperature threshold for canopy development (°C)
Tugro	Upper temperature threshold for phenological development and root growth (°C)
Tuphoto	Upper temperature threshold for photosynthesis (°C)
Tusuc	Upper temperature threshold for maintenance respiration (°C)
Ux	Daily wind run above which lodging susceptibility is increased (km/d)
WIcan	Canopy interaction of rainfall and overhead irrigation
WIcano	Maximum amount of water that can be intercepted by a crop with a given canopy cover (mm)
WImax	Maximum amount of daily rainfall and/or overhead irrigation that can possibly be intercepted by a fully canopied crop (mm/d)
WM	The mass of rainfall and overhead irrigation water intercepted by and retained in the canopy (t/ha)
Wres	Antecedent amount of water present in the residue layer (mm)
Wresmax	Maximum amount of water that the residue layer can hold (mm)
WU(l)	Daily water uptake from layer l
Y_{obs}	Observed cane yield (t/ha)
Y_{opt}	Simulated cane yield using an optimal irrigation schedule (t/ha)

Abbreviation	Definition and units
Y_{swc}	Simulated cane yield using measured soil water data (t/ha)
Z(l)	thickness of layer l (cm)
α	Empirical parameter to calculate root distribution with depth ((t/t)/(t/ha))
β	Empirical parameter to calculate root distribution with depth
Δ	Ripening gradient on a given day, defined as the rate of decline in sucrose content per unit additional stalk mass in the immature section of stalk ((t/t)/(t/ha))
Δmax	Maximum ripening gradient, defined as rate of decline in sucrose content per unit additional stalk mass in the immature section of stalks of a crop growing under ideal (cool, dry) conditions for sucrose accumulation ((t/t)/(t/ha))
Δmin	Maximum ripening gradient, defined as rate of decline in sucrose content per unit additional stalk mass in the immature section of stalks of a crop growing under conditions that are very unfavourable for sucrose accumulation and ideal for expansive growth (warm, well-watered) ((t/t)/(t/ha))
∆FI	Fractional reduction in FI for a fully lodged crop
∆RUE	Fractional reduction in RUE for a fully lodged crop
θ(l)	Soil water content of layer l (fraction)
θdul(l)	soil water content at drained upper limit for layer l
Θll(l)	Soil water content at the lower limit for layer l
θsat(l)	soil water content at saturation for layer l
ρ	Coefficient for converting the units of canopy intercepted water from mm (kg/m^2) to t/ha

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