ARTICLE FOR AGWAT

FARM LEVEL DECISION SUPPORT FOR SUGARCANE IRRIGATION MANAGEMENT DURING DROUGHT

A.Singels[1,2,3], A.L. Paraskevopoulos[1], M.L. Mashabela[1]

[1] South African Sugarcane Research Institute, Mount Edgecombe, South Africa.
[2] School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa
[3] Department of Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa

Corresponding author: abraham.singels@sugar.org.za

Highlights

- System developed for evaluating drought irrigation strategies for sugarcane
- Predicts irrigation impacts on crop survival, yield and gross margin at field and farm level
- Case studies show realistic predictions of crop response to deficit irrigation
- System aids strategic decision-making for irrigated sugarcane production during drought.
- Best spatial and temporal distribution of limited water for sugarcane production can be explored

Abstract

A large portion of global sugarcane is produced under irrigation, and this often occurs in areas where water supply is not abundant or reliable. Crop management decisions during limited water supply are complex and require information on the impacts of irrigation strategies on crops and profitability. This paper describes the development of a computerized system to support farm level management of limited irrigation water for sugarcane production. The system comprises a daily crop and water balance model, an irrigation module and a gross margin calculator. The model calculates crop yield and survival for the current (Y1) and the next season (Y2), for multiple fields on a farm, for a given irrigation strategy and water supply/climate scenario. Irrigation strategies that can be explored include: (1) scheduling irrigation using growth phase specific soil water thresholds (SWT), and (2) postponing replanting and/or abandoning low potential fields. Farm gross margin is calculated from simulated yields and production costs at field level and takes into account re-establishment costs when crops fail. The system was applied in a case study for a hypothetical farm of 18 fields near Komatipoort, South Africa. . Four possible restricted water allocation scenarios were investigated, namely, a mildly and severely restricted allocation (~50% and 25% of the full allocation)over a 24 month and 12 month period. Results from the case study show that under most circumstances a SWT of 60% of plant available soil water capacity applied during the germination and stalk growth phases produced the best outcome. Reducing SWT to 30% during the tillering phase makes more water available for use on other fields, resulting in higher crop survival under severe restrictions. Abandoning low potential fields under severe water restriction limited financial loss in Y2, but reduced future productive capacity thereafter.

Results suggest that the system produces realistic responses to irrigation applied and drought. It has the potential to aid strategic decision-making for irrigated sugarcane production during drought.

Keywords: sugarcane, water balance, irrigation, gross margin, crop model, water allocation

1. Introduction

Sugarcane is grown in more than a hundred countries around the world. In 2016, global sugarcane production amounted to 1 890 million tons valued at US$ 92 billion, harvested from 27 million ha at an average yield of 70 t/ha (FAO, 2018). The most important products from sugarcane are sugar, an important source of food energy, and renewable energy in the form of bio-ethanol and electricity. A large portion of global sugarcane is cultivated under irrigation. In many countries, water is a scarce resource, and increasing and competing demands often lead to restricted allocations for agricultural production. This is especially the case in Southern Africa and specifically in South Africa, where very low and erratic rainfall causes a strong demand for irrigation to stabilize crop yields. Concurrently surface water supplies for irrigation are limited and water allocation for irrigation is often restricted in times of drought.

It is estimated that 35% of sugarcane produced in South Africa is irrigated (Singels et al., 2015). A large portion of this is grown in the Nkomazi catchment in the Mpumalanga province. Rossler (2014) showed that the full water allocation for three of the four water sources in this region cannot meet the long term irrigation demand of sugarcane. Records show that since 2000, allocations were restricted below normal levels (full allocation of 960 to 1300 mm/annum depending on water source) in 2003/04, 2007/08, 2011 (Rossler, 2014), and in 2015/16 (Singels et al., 2017). Sugarcane growth was affected negatively by water deficit stress during these periods, leading to yield losses at harvest (Singels et al., 2017). Efficient irrigated sugarcane production requires guidance on the optimal use of irrigation water when demand for water exceeds supply.

Commercial sugarcane farms typically consist of several fields with varying agronomic conditions. The variation could arise from differences in the crop status (different varieties at different growth and ratoon stages), soil properties and irrigation systems. In South Africa the milling season typically stretches from April to December, and farmers are required to harvest and deliver cane to the mill throughout this period. Crops are therefore at various stages of development, covering the full growth cycle of about 12 months. In addition, sugarcane is ratooned after harvest, typically for seven or eight times, before the field will be re-planted after a short fallow period. This implies that crops are also at various ratoon stages at a given point in time. This variation may cause crops to respond differently to irrigation or the lack thereof. The consensus from studies by Ellis & Lankford (1990), Pene & Edi (1999), Robertson et al. (1999), Wiedenfeld (2000) and Rossler (2014), confirmed in a review by Carr & Knox (2011), is that cane yield is most sensitive during the stalk elongation phase, and less in the tillering and maturation phases. Numerous studies (Inman-Bamber & de Jager, 1988; Robertson & Donaldson, 1998; Singels & Inman-Bamber, 2002; Inman-Bamber, 2004; Inman-Bamber & Smith, 2005; Inman-Bamber et al., 2008; Inman-Bamber et al., 2009) have also shown that water stress during the maturation phase (i.e. the practice of drying-off) increases sucrose yields and has relatively little impact on cane yields.

Crop responses to water stress, which are growth stage and ratoon stage dependent, will impact profitability in the short and longer term, as drought effects could be carried over to subsequent seasons. There is therefore scope to explore different strategies of (1) scheduling irrigation at a field level, and of (2) spatially distributing the available water to the different fields, when water supply is limited.

Algorithms for optimizing the application of limited irrigation water for crop production have been developed. Rao et al. (1988) used a simple water balance (weekly time step) and empirical yield model (Doorenbos et al., 1979) with weather data to identify the optimal apportioning of limited water between the different growth phases within a growing season of a single crop, that would maximize crop yield. Inman-Bamber et al. (2005) used a sophisticated simulation model to explore different crop water status thresholds for triggering irrigations when supply was limited, to find the level that would maximize sugarcane yield. These two methods are not true optimization techniques – they find the best option from numerous possibilities and they apply to a single crop at a time. De Paly and Zell (2009) evaluated two types of evolutionary algorithms (genetic algorithm and particle swarm optimization), in combination with a simple soil water balance and yield response model of Doorenbos et al. (1979) to find optimal daily irrigation schedules for a single hypothetical field of maize. Lopez et al. (2017) included an automatic irrigation algorithm to the DSSAT crop modelling system, and then used three heuristic optimization algorithms to optimize irrigation (maximize single field maize and soybean yield) for various water supply scenarios. The irrigation algorithm schedules irrigation events according to growth phase specific soil water thresholds.

The MyCanesim sugarcane simulation system (Singels and Paraskevopoulos, 2017) has a sophisticated automatic irrigation algorithm that schedules irrigation events according to user specified soil water thresholds that may vary over the growing season, seasonal water supply, as well as irrigation system constraints (Paraskevopoulos, 2015).

Although these applications are able to optimize irrigation over the growing season, they all rely on a given water supply for a single field. Optimization across multiple fields (spatially and temporally) is therefore not possible. Ng Cheong and Teeluck (2018) developed software to assist sugarcane farmers in deciding how to distribute and schedule irrigation water on multiple fields. It uses a simple water balance model to calculate soil water status for the different fields. Priorities are assigned based on growth phase (germination, stalk growth, tillering and maturity), ratoon stage and system efficiency. The tool is designed for operational decision making regarding the next irrigation cycle. Although the tool was evaluated for user friendliness and usefulness, the quality of the advice has not been evaluated. Irrigation water is distributed assuming that prescribed priorities will optimize irrigation in terms of crop yield and survival.

Drought irrigation strategy decisions are complex, and are based primarily on expected profitability and sustainability of the farming enterprise, which will depend on crop responses on multiple fields. Ideally, reliable information is required on the impacts of a given strategy/decision on crop survival and financial profit at farm and field level. Although the systems reviewed here do provide some assistance for managing irrigation with limited water supply, they do not address these aspects adequately. The optimization goal seems to be yield maximization for one field at a time, and not maximization of farm production or profitability. In addition, some of these make use of simple (single soil layer , single crop evaporation coefficient) and untested soil water balance models and generic, empirical yield prediction models with low temporal resolution (e.g. growth phase total evapotranspiration deficit). Reliability of outputs depends on how realistic water balance and crop growth simulations are.

The aim of this work was to develop software to support farm level management of limited irrigation water for sugarcane production. The software should support strategic planning to provide general guidance for the medium term (3 to 21 months) rather than advice for short term operational management. The specific objectives were to (1) develop a system for evaluating the impacts of a chosen irrigation strategy on future crop growth and yield, and profitability at field and farm level for an assumed weather and water allocation scenario, and (2) to evaluate the system for credibility and usefulness, using South African case studies.

In summer rainfall areas in South Africa the water management year runs from April to March. Government storage dams normally get filled from December to March, the main rainfall period. By March prevailing dam levels will largely dictate how water will be allocated for the rest of the water year, assuming long term mean demand and supply for the next 12 months. Water allocations are updated on a weekly or monthly basis as the season progresses. When dam levels drop below certain thresholds, the water allocation for the next 12 months would be restricted.

There is therefore a need for South African sugarcane farmers and water managers to better understand the impact of the likely water allocation scenario on sugarcane production, when this is announced by water managers. A tool was needed to help managers work out a strategy for distributing available water on farms for the current and the following season, and to understand the short and medium term financial impacts. The impact of future rainfall also needed to be taken into account. Long lead forecasts of oceanic and atmospheric conditions such as El Nino Southern Oscillation (IRI, 2019; BOM, 2019, Everingham et al., 2008) that influence rainfall are becoming more reliable and could be used when exploring irrigation strategy impacts.

2. System description

2.1 Introduction

The system was designed and built in collaboration with sugarcane farmers, extension specialists and cane grower economists of the Pongola and Mpumalanga sugarcane producing areas in South Africa. Sugarcane crops are typically harvested at 11 to 14 months between the months of April and December.

The industry required a system that could provide guidance on irrigation strategy for the medium term (remainder of current season and possibly the following season), after the water allocation regime/outlook for the rest of the water year (April to May) is made known (normally early April, at the end of rainy season). The idea is that the system be applied during periods of current and future expected limited water supply. It can first be applied at the start of the milling season, and then on occasions, thereafter when the water allocation or rainfall outlook changes. The system should enable evaluation of different irrigation strategies on crop status and economics and field and farm level. Strategies should include reducing irrigation frequencies and/or amounts during specific growth phases, and prioritizing fields for irrigation according to current and future yield potential.

2.2 Overview of components and data flow

The system simulates crop growth for multiple fields under a given water allocation and weather scenario, distributes available irrigation water across competing fields, and schedules irrigation applications following a user-defined irrigation strategy. The system comprises a crop and water balance simulation model, an irrigation module and a gross margin calculator coded in Microsoft Excel using VBA. A process based daily crop growth and water balance simulation model calculates the impact of specified irrigation strategies on crop yield and survival for the current an next season (Y1 and Y2) under assumed future water supply (allocation) and climate scenarios. Available irrigation water is applied according to the specified irrigation strategy for each field, and following the specified survival priority for each field. Irrigation strategies that can be explored include: (1) scheduling rules based on growth phase specific soil water thresholds (SWT); (2) adjusting drying off periods, and (3) postponing replanting and/or abandoning low potential fields. Farm level gross margins are then calculated for Y1 and Y2 from simulated yields and production costs at field level, taking into account the feasibility of harvesting and the cost associated with replanting fields that failed.

The user specifies the nearest weather station and chooses one of three rainfall categories (below, near and above normal) expected for the remainder of the current season. The system compiles weather data for simulations using historic data that correspond to the chosen category. For the period from April to the current date, recently recorded data are used. For the future period, a past weather data sequence is selected to represent the future. The selected sequence will fall in the same rainfall category for the relevant period in Y1, than that chosen by the user. Other user inputs include the past and expected future weekly water allocation for the farm, field inputs such as size, crop cycle dates, cultivar, ratoon stage, soil type, irrigation system type, the irrigation strategy for each field and financial information required for gross margin calculations. Outputs from the simulation include irrigation applied, crop status (alive, failed), yield and gross margin for each field for Y1 and Y2, as well as for the farm as a whole.

System components and data flow are illustrated in Figure 1 and data organization is explained in Table 1.

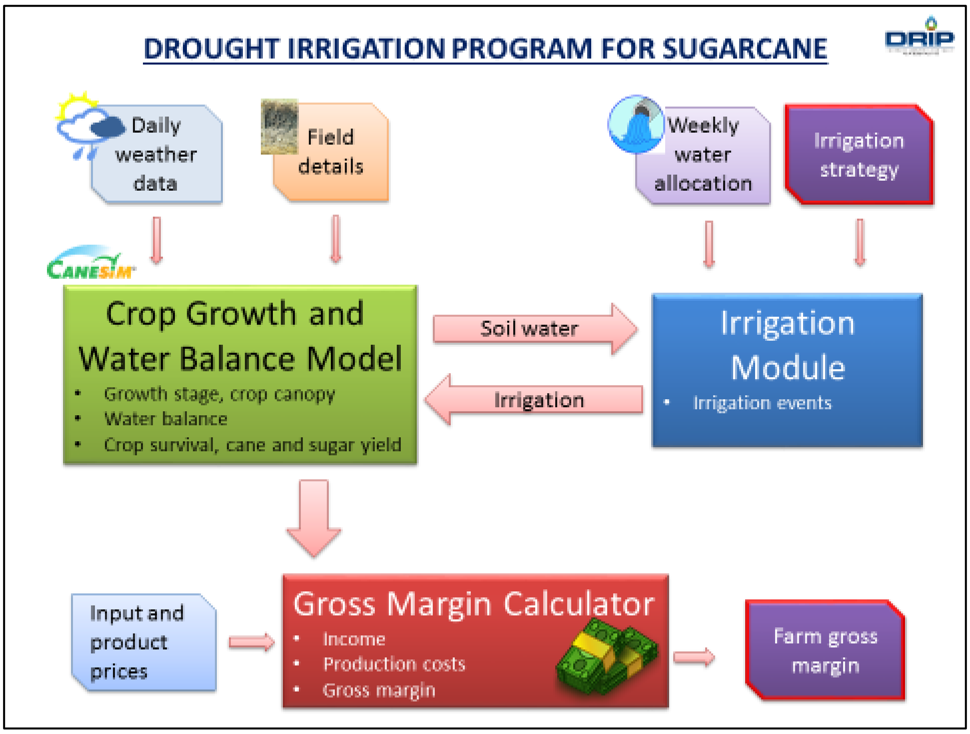


Figure 1. System components and data flow

2.3 Model

A balanced modelling approach in terms of complexity is required to achieve adequate prediction accuracy and operational practicality (rapid simulation of multiple fields and scenarios). Soil water balance simulation should have a daily time step to capture effects of large rainfall events, it should have a multi-layered soil representation to capture rooting distribution effects on crop water status, and it should distinguish between evaporation from the soil (in order to account for different wetting patterns and frequencies), and transpiration, a strong driver of crop yield.

Accuracy is also needed in simulating the formation and senescence of the crop canopy, which determines radiation interception, transpiration and photosynthesis. The strong relationship between yield formation and transpiration found for sugarcane provides a convenient way of calculating cane yield, while temperature and water status impacts on sucrose accumulation must be simulated to capture seasonal and irrigation effects on sucrose yields.

Crop and canopy development and water balance aspects of the model use here are based on the simulation approach used in the Canesim model (Singels and Paraskevopoulos, 2017). A precursor version of the Canesim model has been evaluated for simulation of the water balance and unstressed canopy development (Singels et al., 1998; Singels & Donaldson, 2000) and these aspects are considered a solid basis to work from

Three phenological phases are simulated namely (1) germination phase during which buds sprout and emerge as primary shoots, (2) the tillering phase during which the canopy and roots of the crop develop rapidly, and (3) the stalk growth phase when the canopy is relatively full and the roots have colonized the soil profile. The progression of these phases depends on thermal time and is calculated as in Canesim. A fourth phase is simulated during which irrigation is withheld to increase the sucrose content in cane stalks (named the drying off phase, see Robertson and Donaldson, 1998). This phase commences a user-specified number of days before the planned harvest date.

Green canopy cover (FI, defined as the fractional interception of photosynthetically active radiation by green leaves) is simulated as in Canesim, based on work by Smit and Singels (2006), but with three adjustments. Firstly, no canopy expansion takes place when profile available soil water content is below 30% of capacity. Secondly, the canopy expansion after water stress is relieved, occurs at twice the rate of the reduction in green canopy during water stress based on findings by Smit and Singels, 2006). This is to reflect the observed ability of sugarcane crops to accelerate leaf growth during recovery from water stress (Rossler, 2014). Thirdly, green canopy decline (senescence) during water stress is allowed to continue past the lower limit set in Canesim, if water stress conditions persist, and the crop is considered to have failed (no prospect of recovery to a viable crop stand) when the green canopy fraction declines below a value of 0.1. The following equations were used to simulate canopy senescence and recovery:

$FI = FIo\,(1 - FWavg)$	*Eq. 1*
$FWavg = (\Sigma\, FW) / FWperiod$	*Eq. 2*

FW = 1 when Gstress <0.5, and FW = -2 when Gstress >.5	*Eq. 3*

where FIo is the potential (unstressed) canopy cover (see Singels and Donaldson, 2000), FWavg is the reduction in fractional canopy cover due to the "net" cumulative water stress experienced by the crop, calculated by counting the number of days with water stress (FW=1) and number of days with no water stress (FW=-2). The value of FW is derived from the water stress index for expansive growth (Gstress) and is assigned a value of 1 for days that the crop experiences water stress (Gstress < 0.5), and a value of -2 when the crop is unstressed and in recovery (Gstress >=0.5). FWperiod is defined as the number of consecutive days with water stress required to reduce a full green canopy to zero (a value of 100 d assumed, based loosely on Smit and Singels, 2006).

A cascading water balance is maintained for a layered soil profile. The number of soil layers depends on the chosen maximum effective rooting depth (30, 60, 100, 140 cm). Layer thickness are 30, 30, 40 and 40 cm. Water flows and root development are calculated as in Canesim.

Table 1. Organization of input and output data.

Folder	Files	Sheet	Variables	Functionality
Input[1]	Farm input	Meta	• Name, number of fields, weather station name, forecasted rainfall category, annual water allocation for restricted and non-restricted period, current date and start and end dates of restrictions, weekly water allocation calculation option, comments for output	• Update weather data • Run program
		Field	• Field details: Size, soil water holding capacity, yield potential • Crop detail; Ratoon stage, crop start and harvest dates, harvesting method, cultivar, row spacing, crop health rating • Irrigation system details: Type, typical irrigation amount and cycle period • Irrigation strategy: Pro-rata option, irrigation triggers for each growth phase, dry off start date, survival priority, abandon option. • Observed crop status: Most recent observation date, canopy cover and soil water content	
		Economics	• Financial information: Production costs and product price (see Table 3 for more details)	
		Water allocation	• Weekly water allocation for the current and following season	
	Weather data	Weather	• The entire record of daily values of rainfall, maximum and minimum temperature and reference sugarcane evapotranspiration for the specified weather station.	
		Irrigation demand	• Long term mean weekly irrigation demand for the specified station	
Output[1]				
Farm	Farm output	Summary	• Monthly field and farm information re water balance, crop status, yields, production costs and gross margins.	
		Fields	• Seasonal information on irrigation applied, yields, production costs and gross margin	
Comparison	Comparison	Strategy	• Seasonal information on farm average irrigation applied, yields, crop survival, production costs and gross margin foe each farm irrigation strategy simulated	Run comparison
System[2]				
Common	*Global*		• *Crop model parameters*	
	Soil		• *Soil properties for a collection of generic soil types: Effective rooting depth, texture, water retention characteristics*	
	Crop		• *Cultivar parameters for crop model, cardinal temperature for phenology, parameters for yield potential as determined by cultivar, soil and crop health ratings*	
	Pro-rata		• *Daily time series for cumulative irrigation requirement for crops started in different months for the specified weather station. Used for pro-rata algorithm*	
			•	
Debug				
Template	*Results*		*Template for storing and displaying field results*	
	Debug		*Template for storing and displaying program debugging information*	
	Summary		*Template for storing and displaying farm summary results*	

[1]Accessible to users, [2]Only accessible to administrator.

It was decided to use a functional approach to calculating cane and sucrose yield focussing on water relations, rather than the sophisticated biomass accumulation and partitioning alorithms available in existing crop simulation models such as DSSAT-Canegro (Jones and Singels, 2018), APSIM-Sugar (Keating et al., 1999) and Canesim (Singels & Paraskevopoulos, 2017). It was important to simulate yield response to water accurately, and to also keep it relatively simple to minimize computing time. The cane yield calculation was therefore based on the algorithm used by Singels et al. (1999), which was derived from simulations from the Canegro model, a well tested model. It was also important that yield calculations also account for soil, cultivar and crop health differences between fields, as these factors will cause differential yield responses to irrigation.

The following equations were used to calculated cane yield (CY in t/ha):

$CY = TE\ (Transcum - Transb)$	*Eq. 4*
$TE = TEi - \delta\ (Transcum - Transb)$	*Eq. 5*

where *TE* is the average transpiration efficiency at harvest, defined as the cane yield produced per unit of transpiration during the stalk growth phase (in (t/ha)/mm), *Transcum* is the cumulative transpiration at harvest since the start of the crop (in mm) and *Transb* is the total transpiration from the crop emergence to the start of stalk growth (in mm). It has been shown that *TE* declines as the crop matures (Park et al., 2005 and van Heerden et al., 2010) and hence *TE* was calculated as function of the initial *TE* during early stalk growth (*TEi*), and cumulative transpiration since the start of stalk growth (see Figure 2). Parameter *δ* is the average decline in TE per unit transpiration during the stalk growth phase (in t/ha/mm). *TEi* is calculated as a function of maximum *TEi* for a given field as determined by its yield potential category (*TEo*), as well as ratoon stage (ratoon#):

$TEi = TEo\ [1 - \rho\ (ratoon\# - 1)]$	*(ratoon crops)*	*Eq. 6*
$TEi = .95\ TEo$	*(plant crops)*	*Eq. 7*

Parameter *ρ* is the fractional yield decline for each successive ratoon after the first ratoon. A fractional decline rate of 0.037/ratoon was assumed based on the finding by Ramburan et al. (2013) that average yield decline rate equalled about 9t/ha/ratoon for irrigated cane.

Model parameters are described given in Table 2.

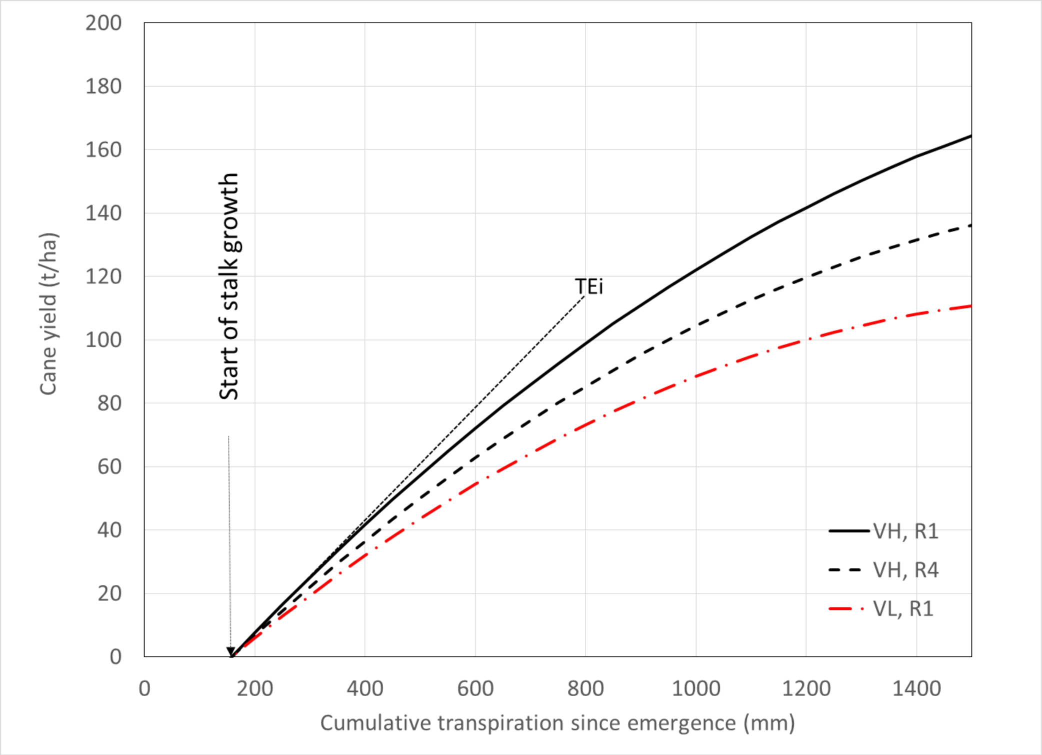


Figure 2. Cane yield at harvest calculated as a function of cumulative transpiration since crop emergence for a 1st (R1) and 4th ratoon (R4) crops with a very high (VH) yield potential; and a 1st ratoon crop with a very low (VL) yield potential. The start of stalk growth is indicated as well as the initial transpiration efficiency (TEi) for the VH R1 crop.

Sucrose yield (SY in t/ha) is the product of sucrose content (SC) and cane yield (CY in t/ha). SC is calculated as non-linear function of CY and a sucrose accumulation index (RVIavg):

$SC = \{SCmax / (1 + \exp(\gamma (CY - \beta)))\} \{1 + \sigma [(RVIavg - 0.6)/(0.75-0.6)\}$	*Eq. 8*

where *SCmax* is defined as the cultivar specific sucrose content of a 12 month crop at a reference maturity condition (*RVIavg* = 0.6), γ is an empirical parameter determining the shape of the SC vs. CY curve; β is the CY where a SC of half the maximum value is reached and σ is the relative increase in SC when *RVIavg* increases from 0.6 to 0.75. Eq. 8 is illustrated in Figure 3.

RVIavg represents the maturity condition of the crop as impacted by mild water stress and cool temperatures over the most recent 21 days and is calculated as the average daily *RVI* over this period:

$RVI = [(FT + FW)/2]$	*Eq. 9*

where

$FT = 1 / (1 + \exp(0.32 * (Tmean - 25)))$ *(from Singels & Bezuidenhout, 2002)*	*Eq. 10*

and

$FW = (1 - SWSI)^{.5}$ *(from Singels & Bezuidenhout, 2002)*	*Eq. 11*

where SWSI is the soil water satisfaction index which is determined by the availability of soil water in relation to the demand (value of 1 for ample water, zero for no water).

Eq. 8 attempts to capture the effect of thermal maturity of the crop and recent temperature and water status conditions on the sucrose accumulation process.

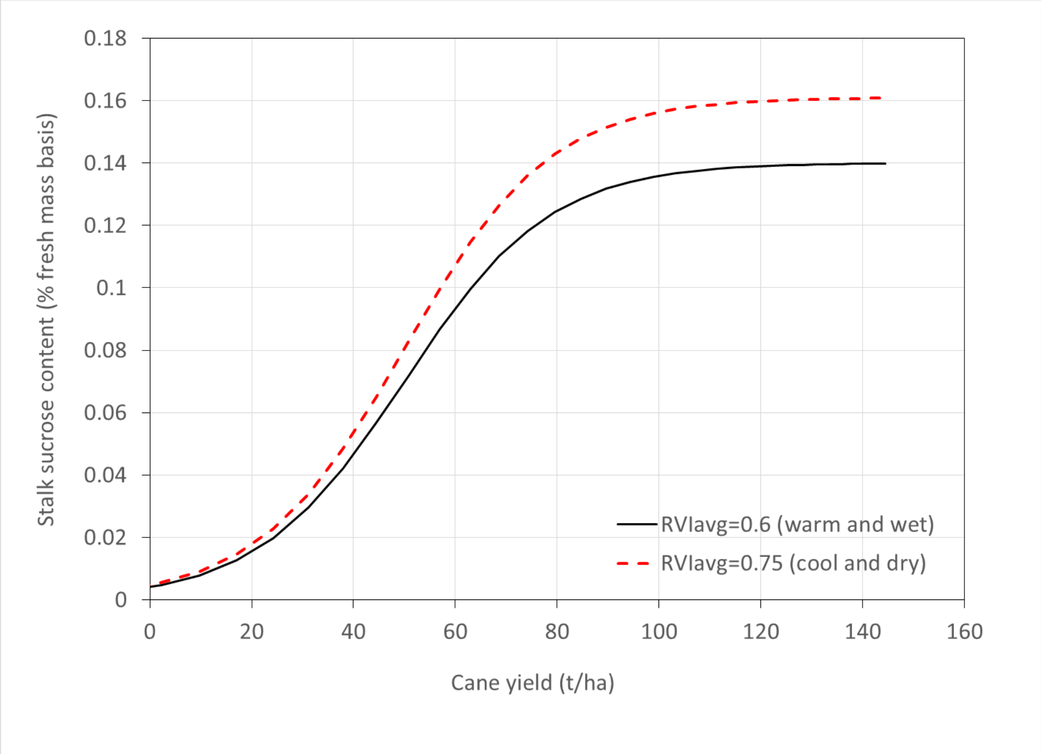


Figure 3. Stalk sucrose content calculated as a function of cane yield for a sucrose accumulation index (RVIavg) values of 0.6 (warm, wet conditions) and 0.75 (cool, dry conditions).

Table 2. Parameters for the yield model.

Parameter	Description	Value	Reference
Transb	Transpiration required from shoot emergence to start of stalk growth (Eq. 4 and 5)	158 mm	Reformulated from Singels et al. (1999)
TEo	Maximum transpiration efficiency during early stalk growth for the given category of yield potential (very high, high, medium, low and very low) (Eq. 6 and 7)	0.19, 0.18, 0.17, 0.16, 0.15 t/ha/mm	Reformulated from Singels et al. (1999)
δ	Decline in transpiration efficiency per unit of transpiration in the stalk growth phase (Eq. 5)	0.000045 t/ha/mm	Adapted from Singels et al. (1999)
ρ	Fractional yield decline for each successive ratoon crop (Eq. 6)	0.037	Ramburan et al. (2013)
γ	Empirical parameter determining the shape of the sucrose content vs. cane yield curve (Eq. 8)	-0.07	
β	Cane yield at which sucrose content reaches half its maximum value (Eq. 8)	50 t/ha	
σ	Relative increase in sucrose content when RVIavg increases from 0.6 to 0.75 (Eq. 8)	0.15	
SCmax	Cultivar specific sucrose content of a 12 month crop at a reference maturity condition (RVIavg=0.6) (Eq. 8)	0.14 to 0.18	Thompson et al. (1976)

Simulated yields were compared to yields measured for cultivar NCo376 in 26 diverse experiments conducted in South Africa that included water stressed and well-water scenarios (Singels and Bezuidenhout, 2002). Simulation accuracy of the new model was satisfactory, and as good as the standard Canesim model (Singels and Paraskevopoulos, 2017) for predicting cane yield ($R^2 = 0.88$, root mean square error (RMSE) = 16 t/ha, n = 137). Sucrose yields were not as accurate ($R^2=0.88$, RMSE= 4.1 t/ha, n=135 compared to $R^2=0.88$, RMSE= 3.9 t/ha for the standard Canesim model). Overall the model was considered sufficiently reliable for predicting crop response to irrigation, weather and soil factors to be included in the software package.

2.4 Irrigation Module

The irrigation module evaluates current simulated soil water content and crop status (growth phase and crop vigour) for a given field in the context of the irrigation strategy specified for that field, as well the remaining water availability for each week, to schedule an irrigation event for the given field. The algorithm logic is illustrated in Figure 4.

An irrigation strategy consists of four basic elements:

- Field level restriction: The first option is to apply, or not apply, the restricted water allocation during the drought period (period with restricted farm water allocation) for the given field (named the pro-rata option). When the pro-rata option is chosen, it will restrict cumulative irrigation applied since the start of the drought, from exceeding the cumulative water allocation at that point in time. The latter is calculated as the product of the annual water allocation for the drought period, expressed as a fraction of the normal (unrestricted) allocation, and the long term mean cumulative irrigation demand since the start of the drought period (see Paraskevopoulos, 2015 for details). Generally, when the pro-rata option is chosen, limited water will be used to irrigated more fields, compared to when the option is not chosen.

- Field specific irrigation scheduling triggers: Irrigations are scheduled, assuming adequate water supply, using user-specified soil water thresholds (SWT) defined for each of the germination (G), tillering (T) and stalk growth (S) phases. Irrigations can be scheduled when available soil water content reaches the specified threshold (typically 60, 30 or 20% of capacity). Irrigations are withheld during the maturation (drying-off) phase. The start and end of the maturation phase is specified by the user, and the duration can thus be varied in order to manipulate water distribution between fields.
- Survival priority: All fields on the farm need to be assigned a priority ranking, which will determine the order in which fields will queue for water in a given week. Normally high potential fields with efficient irrigation system will be assigned higher priorities compared to low potential fields with less efficient irrigation systems.
- Abandonment: Specifies whether a given field should be abandoned, that is not receive any irrigation or other inputs after the harvest of the previous crop. This may be a feasible option for fields that seem due to die or that are likely to fail or make a financial loss.

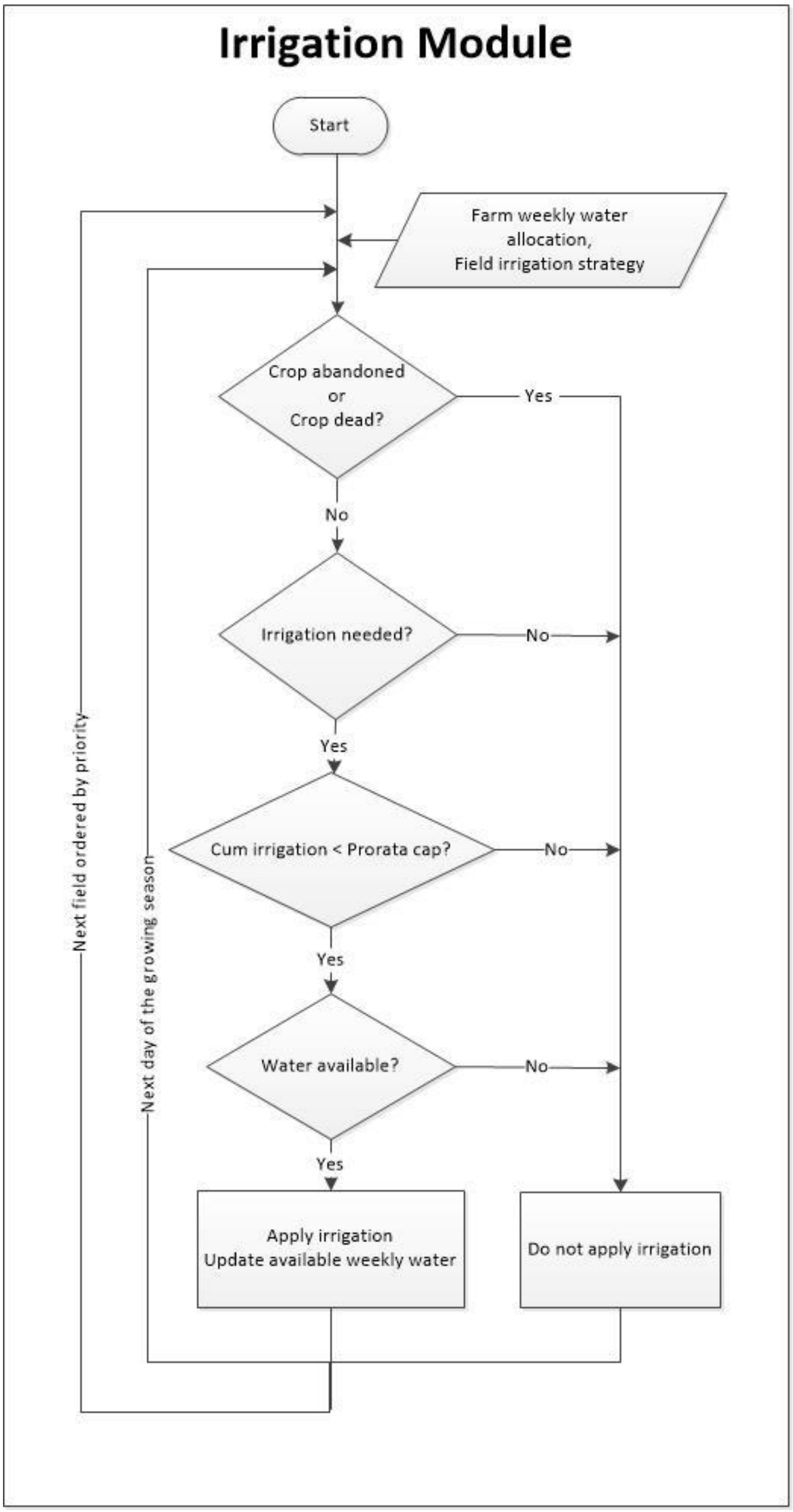


Figure 4. Flow chart for the logic of the Irrigation Module

Options also exist for varying irrigation amounts and/or cycle periods (minimum duration between consecutive irrigations) in an attempt to alter water distribution across different fields on the farm.

2.5 Gross Margin Module

The gross margin (GM) for each field for the current (Y1) and the next season (Y2), is calculated by subtracting the crop establishment costs (Cbase), irrigation costs (Cirr), harvest costs (Char) and transport costs (Ctrans) from the income derived from delivered cane. Costs and income vary depending on the status of the crop and how it was treated (Figure 5).

When harvesting (Char in R/ha) plus transport (Ctrans in R/ha) costs exceeds potential income, or when cane yield is less than 35 t/ha, then harvesting will not take place. The GM is then taken as the negative sum of Cirr and Cbase and the cost of slashing back the living crop (Eq. 13). The cost of slashing back is taken as the product of cane yield (CY in t/ha) and the unit cost of cutting cane (Ccut in R/t). When the crop is dead the gross margin is taken as the negative sum of Cirr and Cbase only (Eq. 14):

$$GM = Income - Cbase - Cirr - Char - Ctrans \quad \text{(when } Income => Char + Ctrans\text{, or with } CY>35 \text{ t/ha)} \qquad \text{Eq. 12}$$

$$GM = -(Cbase + Cirr + CY.Ccut) \quad \text{(for living crops with } Income<Char + Ctrans\text{, or with } CY<35 \text{ t/ha)} \qquad \text{Eq. 13}$$

$$GM = -(Cbase + Cirr) \quad \text{(for dead crops)} \qquad \text{Eq. 14}$$

Income is calculated as the product of the Recoverable Value (RV, the cane payment measure used in South Africa - see Groom (1999) for definition) price (RVprice in R/t) and the RV yield (RVY in t/ha).

$$Income = RVprice \, . \, RVY \qquad \text{Eq. 15}$$

RV yield is calculated by assuming that RV content (RVC in %) is 2 units below the sucrose content of cane (SUC in %):

$$RVY = RVC \, . \, CY \qquad \text{Eq. 16}$$

$$RVC = SUC - 2 \qquad \text{Eq. 17}$$

Irrigation costs (Cirr in R/ha) are taken as the sum of cost of capital investment and operational costs (water, electricity and labour associated with irrigation application):

$$Cirr = Ccap/100. \, Gperiod/365. \, Cinv + Cwefix. \, Gperiod/365 + Irr \, . \, Cwevar + Clabour. \, Gperiod/365 \qquad \text{Eq. 18}$$

where Ccap is the unit cost of capital (%/annum), Gperiod is the growing period duration in d, Cinv is the initial capital investment required to establish the irrigation system (R/ha), Irr is the amount of irrigation applied per crop (mm), Cwefix and Cwevar are fixed and variable water plus electricity costs (R/ha/annum and R/mm respectively), and Clabour is labour costs (R/ha/annum).

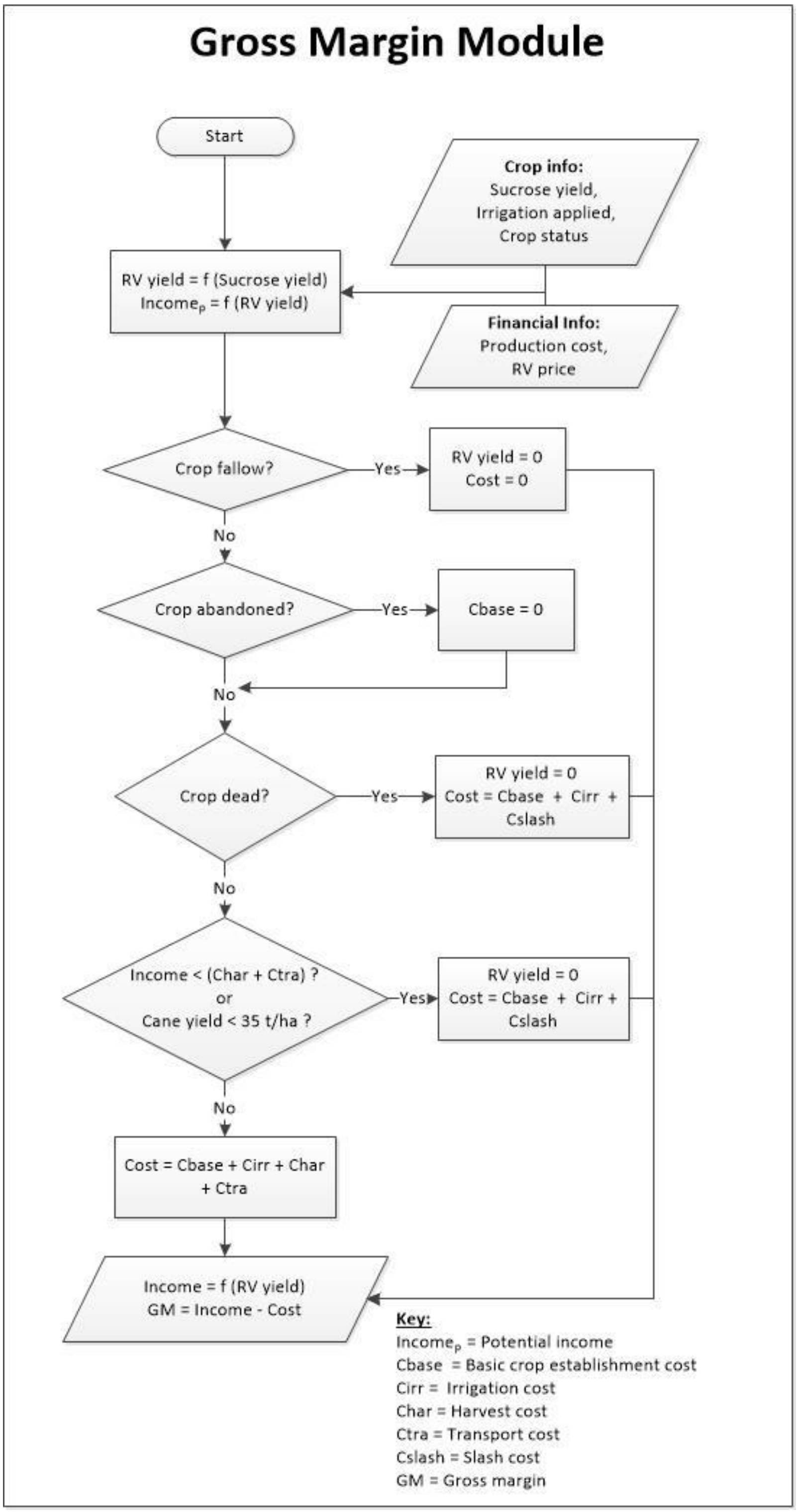


Figure 5. Programming logic of the Gross Margin Calculator. Please note that ***Income*** *is recalculated after testing potential income (*$\textbf{Income}_p$*) against harvest conditions (Eq. 12)*

Harvesting costs (Char) is calculated as:

$$Char = Cburn + Cspread + CY.\,(Ccut + Cload) \qquad \text{Eq. 19}$$

where Ccut and Cload is the unit cost of cutting and loading (R/t), , Cburn, and Cspread is the unit area cost of burning, and spreading green tops (R/ha), respectively.

Transport costs are the product of the unit cost and cane yield:

$$Ctrans = Ctru\,.\,CY \qquad \text{Eq. 20}$$

Cbase is calculated as the cost of establishment of the plant (Cestp) or ratoon crop (Cestr), plus the investment required for re-establishment of a plant crop after the ratoon cycle of eight crops has been completed (Crest).

$$Cbase = Cestp + Crest \text{ (for plant crops)} \quad Cbase = Cestr + Cre\text{-}est \text{ (for ratoon crops)} \qquad \text{Eq. 21}$$

The investment required for crop re-establishment is taken as the difference in cost between establishment of a plant and ratoon crop, divided in eight equal instalments over the length of the ratoon cycle. When the crop fails, the instalment is ramped up in proportion to the relative number of ratoon crops that were lost (Eq. 22).

$$Crest = (Cestp - Cestr).(1 - Rat\#/8) \qquad \text{(for crop failure)} \qquad \text{Eq. 22}$$

where *Rat# refers the ratoon crop number where 0 is the plant crop.*

Table 3. Input data for gross margin calculation (typical ZAR values for 2016 are shown, 1 US$~13.5 ZAR)

Cost item	Acronym	Quantum
Crop establishment costs (R/ha)	Cestp Cestr	Plant crop: 29 200 Ratoon crop: 12 000
Irrigation costs Capital layout (R/ha)	Cinv	Drip:52 000 Centre pivot: 21 000 Portable overhead: 14 000
Cost of capital (%/annum)	Ccap	8%
Fixed water and electricity (R/ha/annum)	Cwefix	2100
Variable water and electricity costs (R/mm)	Cwevar	2
Labour (R/ha/annum)	Clabour	Drip: 210 Overhead: 400
Harvesting costs	Char	
Burning (R/ha)	Cburn	73
Cutting (R/t)	Ccut	22 (windrow), 38 (stacking)
Spreading tops (R/ha)	Cspread	120
Loading and infield transport (R/t)	Cload	22
Transport cost (R/t)	Ctru	71
RV price (R/t)	RVprice	4250

GM calculations for season three (Y3) are not based on model simulations, and are merely broad indications of the impact of crop failure in Y1 and Y2 on potential future income. It is based on assumptions regarding RV yield (CY=120 t/ha, RVC=0.12) crop age at harvest (12 months) and irrigation amounts (long term mean irrigation requirement for all surviving fields. Y3 GM for fields with no crops was taken as zero.

Farm average gross margin for each season is calculated by summing cane production (t) that was delivered to the mill and dividing it by the area of fields that was harvested for the given season.

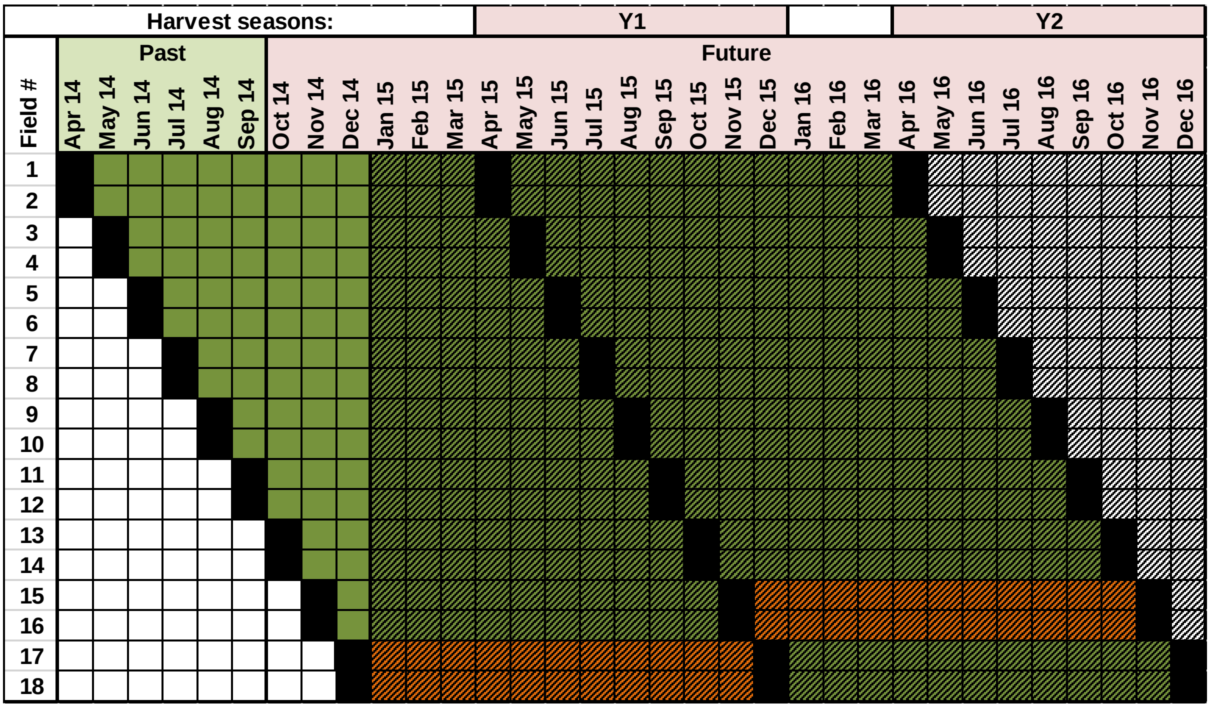
3. Case studies

3.1 Farm set up

The hypothetical farm consisted of 18 fields of 1 ha each, near Komatipoort. Sixteen of these fields had cane growing on them, with ratoon stages varying from a plant crop through to ratoon stage 7. Crops were harvested (and started) on the 15th of each month of the milling season (April to December). For the base case two fields were fallowed in year 1 and got planted in year 2, while two fields with ratoon stage 7 in year 1 were fallowed in year 2. Fields had identical soils with available water capacity of 100 mm. Overhead irrigation with a normal application of 35 mm and a minimum cycle period of 5 days were assumed.

Daily weather data from the Ten Bosch weather station near Komatipoort (25°33' S, 31°57' E, 170 masl) for the period April 2014 to December 2016 were used as weather input. The current date was taken as 1 October 2014, and the farmer “learnt” that, given current water supply levels, there was a strong probability that water restrictions will be imposed from January 2015, if dam inflows remain below normal. Water supply may be restricted for 12 months or longer, depending on when good rainfall in the catchment will restore dam levels to the required thresholds. In real world applications the system will select a past weather data sequence that most closely matches expected future weather as indicated by long term rainfall forecasts. For the hypothetical case here a perfect forecast was assumed (weather data for 2014/15/16 were used for simulations).

Farm set up and time lines of crop growing periods, harvesting periods and water restrictions are illustrated in Figure 6.



Harvest seasons:													Y1												Y2								
	Past						Future																										
Field #	Apr 14	May 14	Jun 14	Jul 14	Aug 14	Sep 14	Oct 14	Nov 14	Dec 14	Jan 15	Feb 15	Mar 15	Apr 15	May 15	Jun 15	Jul 15	Aug 15	Sep 15	Oct 15	Nov 15	Dec 15	Jan 16	Feb 16	Mar 16	Apr 16	May 16	Jun 16	Jul 16	Aug 16	Sep 16	Oct 16	Nov 16	Dec 16
1	■	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧	▧	▧
2	■	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧	▧	▧
3		■	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧	▧
4		■	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧	▧
5			■	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧
6			■	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧	▧
7				■	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧
8				■	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧	▧
9					■	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧
10					■	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧	▧
11						■	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧
12						■	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧	▧
13							■	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧
14							■	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	▧	▧
15								■	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	■	▧
16								■	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	■	▧
17									■	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■
18									■	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	■	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■

Figure 6. A diagram showing the crop growing period for different fields on a hypothetical farm. The current date is 1 October 2014 and the system is being applied to estimate irrigation impact for crops to be harvested in season Y1 and the following season Y2. Black cells indicate start and harvest months, green cells indicate growing crops that are simulated, while brown cells indicate fallow fields. Cells with a hash pattern indicate the period with restricted water supply (24 month scenario). White cells indicate fields that are not simulated and which receive a part of the farm water allocation that is proportional to the field size.

3.2 Water allocations

Four restricted water allocation scenarios were investigated, namely, a mildly and severely restricted allocation (600 and 300 mm/annum, respectively), applied over a long (January 2015 to December 2016) and short (January 2016 to December 2016) period. The full (non-restricted) allocation for this area is 1300 mm/annum. It should be noted that for this case study the allocation applied to area under cane (16 ha), and not total cultivated area (18ha).

The annual allocation (Alloc in mm) was distributed between the 52 weeks of the water year (April to May) based on ratio of the long term mean estimated irrigation demand for a given week (Irrdem(w) in mm) to the long term mean annual irrigation demand (Irrdem in mm):

$$Alloc(w) = Irrdem(w) / Irrdem \, . \, Alloc \qquad \text{Eq. 20}$$

where Alloc (w) is the weekly allocation. Irrdem(w) was taken as difference between long term mean weekly reference sugarcane evapotranspiration (Ecref(w) as defined by McGlinchey & Inman-Bamber (1996)) and 70% of long term mean weekly rainfall (R(w)) (only positive values), for each week of the year averaged over the period 2001 to 2016.

Irrdem(w) = 1/16 Σ Ecref(w) – 1/16 Σ 0.7 R(w) and Ecref(w) >= 0.7 R(w)	*Eq. 24*

Monthly rainfall, water allocation and long term mean irrigation demand for selected scenarios are shown in Figure 7.

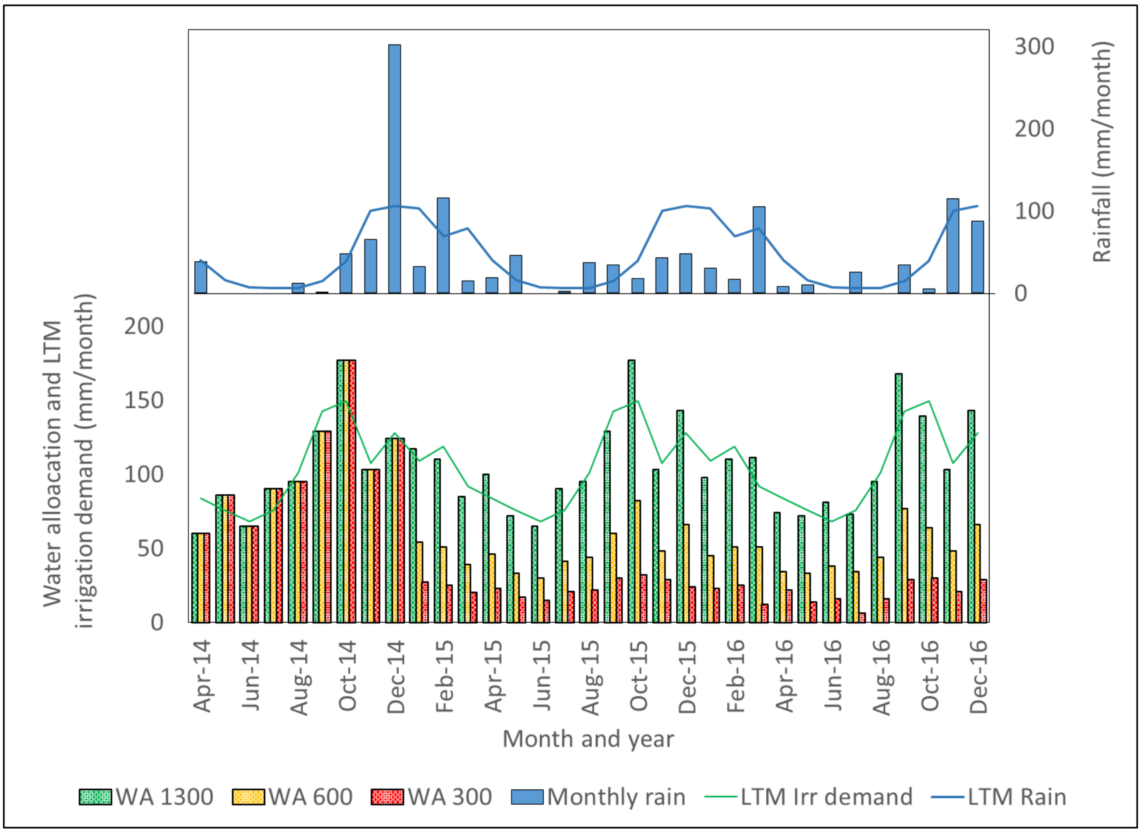


Figure 7. Monthly distribution of rainfall and water allocation (WA) for three water allocation scenarios (see text for explanation) used in the simulations for the long drought scenario. Long term mean (LTM) rainfall and irrigation (Irr) demand for the study site are shown for comparison.

3.3 Irrigation strategies

Preliminary runs showed that the pro-rata option produced the best outcomes for restricted water allocation scenarios because it distributed the water across fields in a better way.

SWT values of 60, 30 and 20% of plant available soil water capacity were used for the tillering (T) and stalk growth (S) phases. Preliminary runs indicated that using SWT of less than 60% in the germination (G) phase were irrational as this led to underutilization of available water and excessive crop death.

The standard drying off period varied from 28 days to 50 days depending on harvest month (Pers. comm. F.C.Olivier, 2017, SASRI, Mount Edgecombe). An extended drying off period for periods (D2) with restricted water supply was also investigated, by bringing forward the start of the drying off period by one week.

Fields were assigned priorities for survival according to the ratoon class, with plant crop fields having the highest priority and 7th ratoon fields the lowest priority. Field management strategies consisted of (1) not replanting the two fields that were due for replanting in Y2 , and (2) abandoning low potential fields or fields that are due to fail.

Irrigation strategies were therefore defined in terms of number of fields to be abandoned (A), SWTs used to trigger irrigations in the germination (G), tillering (T) and stalk growth (S) phases, and the duration of the drying period (D1 – normal, D2 - extended). For example, the strategy code A5_G60_T30_S60_D1, refers a strategy where five fields were abandoned, SWT of 60, 30 and 60% were used for the germination, tillering and stalk growth phases respectively, and crops underwent the standard drying off period.

4. Results

Results for the baseline irrigation strategy (A0_G60_T60_S60_D1) under the long and severe water restriction scenario are shown in Figure 8. Water restrictions started in January 2015, and fields with lower priorities (fields # 8-16) got little or no water from January to April 2015. When harvesting commenced in April 2015, this allowed the saving of water on young ratooning fields (fields # 1 to 7), which could be applied on maturing crops (fields # 9-16). This enabled the survival of all fields in 2015, although yields were depressed on some of the fields to the point where a financial loss were made (fields # 13-16). From October 2015 to October 2016 water allocation was only adequate to irrigated fields # 1-11, and two replanted fields (field # 17 and 18), with the result that three fields failed (field # 12-14). Yields and GMs for surviving fields were mostly lower in 2016 than in 2015, due to the longer period of restricted water supply. Farm average GM was also much lower.

The results from this simulation suggest possible adjustments to the irrigation strategy could be explored to mitigate negative impacts. These include (1) not planting in Y2 in an attempt to save some of the older ratoons, (2) abandoning fields that were due to die to save irrigation water and costs, (3) using a lower SWT for selected phases to see whether available water could be used on more fields without affecting farm profitability, and (4) extending the drying off period to use available water on more fields without affecting farm profitability.

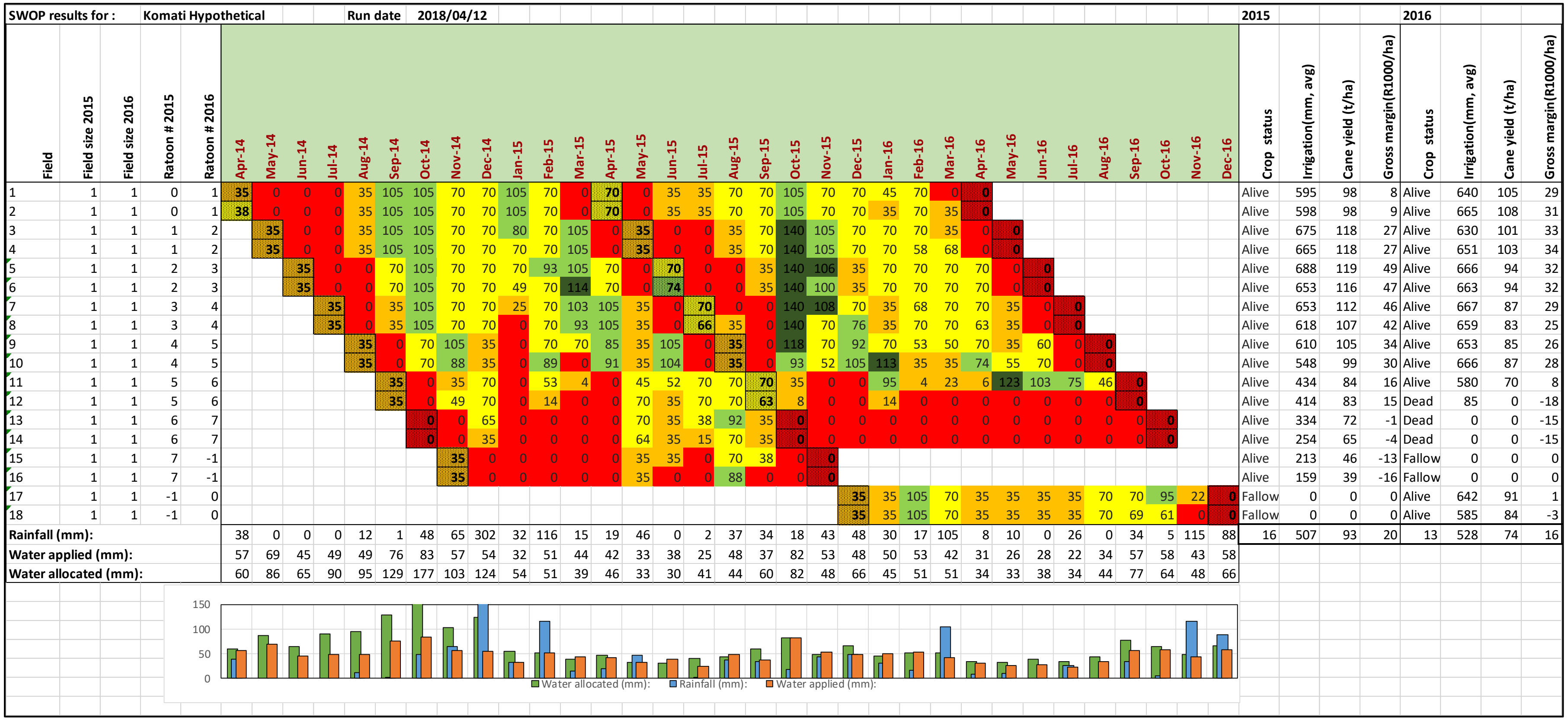
The next section deals with exploring different irrigation strategies for the different water allocation scenarios. Simulation results are summarized in Table *4*. Gross margin results for these are shown Figure 9.

The main findings emerging from these are:

- Long, mild water restriction (24mo x 600 mm/annum): Not planting in Y2 increased Y2 GM but also led to crop failure in one additional field, compared to the base line strategy (A0_G60_T60_S60_D1). Y2 GM was increased further by abandoning two additional low potential fields. Using SWT= G60_T30_S60 caused one more field to fail, and reducing Y2 GM marginally, compared to the baseline strategy. An extended drying off period had little effect, and reduced Y2 GM slightly compared to the corresponding standard drying off strategies.
- Long, severe water restriction (24mo x 300 mm/annum): A similar response to abandoning fields was achieved for the 300 mm water allocation, increasing Y2 GM

but causing a drop in projected Y3 GM due to fewer fields having viable crops. Using SWT= G60_T30_S60 caused crops on two more fields to fail, compared to the baseline strategy, while GM in Y1 and Y2 were similar to that of the baseline strategies. Using SWT= G60_T30_S30 performed worse than the baseline strategies in terms of GM and crop survival, and was therefore not a good option to take.

- Short, mild restriction (12mo x 600 mm/annum): Using SWT= G60_T30_S60 produced similar results to the baseline strategy. Not planting in Y2 increased GM. Extending the drying off period in Y2 saved one additional field, compared to the baseline strategy. Using SWT= G60_T30_S30 succeeded in saving all fields (including newly planted fields in Y2), with only a small reduction in Y2 GM, compared to the baseline. This suggest that deficit irrigation applied throughout the growing period could be a feasible option when the restrictions are not that severe and for a relatively short period.
- Short, severe restriction (12mo x 300 mm/annum): Using SWT= G60_S30_T60 performed similarly or slightly worse than the baseline strategy. Extending the drying off period succeeded in saving one additional field. Using SWT= G60_T30_S30 also saved one additional field compared to corresponding baseline strategies.
- Overall, using a SWT= G60_T20_S20 caused increased crop failure and large yield and GM reductions for all water allocation scenarios, compared to the baseline strategies.



SWOP results for :		Komati Hypothetical							Run date		2018/04/12																												2015				2016			
Field	Field size 2015	Field size 2016	Ratoon # 2015	Ratoon # 2016	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Crop status	Irrigation(mm, avg)	Cane yield (t/ha)	Gross margin(R1000/ha)	Crop status	Irrigation(mm, avg)	Cane yield (t/ha)	Gross margin(R1000/ha)
1	1	1	0	1	35	0	0	0	35	105	105	70	70	105	70	0	70	0	35	35	70	70	105	70	70	45	70	0	0									Alive	595	98	8	Alive	640	105	29
2	1	1	0	1	38	0	0	0	35	105	105	70	70	105	70	0	70	0	35	35	70	70	105	70	70	35	70	35	0									Alive	598	98	9	Alive	665	108	31
3	1	1	1	2		35	0	0	35	105	105	70	70	80	70	105	0	35	0	0	35	70	140	105	70	70	70	35	0	0								Alive	675	118	27	Alive	630	101	33
4	1	1	1	2		35	0	0	35	105	105	70	70	70	70	105	0	35	0	0	35	70	140	105	70	70	58	68	0	0								Alive	665	118	27	Alive	651	103	34
5	1	1	2	3			35	0	0	70	105	70	70	70	93	105	70	0	70	0	0	35	140	106	35	70	70	70	70	0	0							Alive	688	119	49	Alive	666	94	32
6	1	1	2	3			35	0	0	70	105	70	70	49	70	114	70	0	74	0	0	35	140	100	35	70	70	70	70	0	0							Alive	653	116	47	Alive	663	94	32
7	1	1	3	4				35	0	35	105	70	70	25	70	103	105	35	0	70	0	0	140	108	70	35	68	70	70	35	0	0						Alive	653	112	46	Alive	667	87	29
8	1	1	3	4				35	0	35	105	70	70	0	70	93	105	35	0	66	35	0	140	70	76	35	70	70	63	35	0	0						Alive	618	107	42	Alive	659	83	25
9	1	1	4	5					35	0	70	105	35	0	70	70	85	35	105	0	35	0	118	70	92	70	53	50	70	35	60	0	0					Alive	610	105	34	Alive	653	85	26
10	1	1	4	5					35	0	70	88	35	0	89	0	91	35	104	0	35	0	93	52	105	113	35	35	74	55	70	0	0					Alive	548	99	30	Alive	666	87	28
11	1	1	5	6						35	0	35	70	0	53	4	0	45	52	70	70	70	35	0	0	95	4	23	6	123	103	75	46	0				Alive	434	84	16	Alive	580	70	8
12	1	1	5	6						35	0	49	70	0	14	0	0	70	35	70	70	63	8	0	0	14	0	0	0	0	0	0	0	0				Alive	414	83	15	Dead	85	0	-18
13	1	1	6	7							0	0	65	0	0	0	0	70	35	38	92	35	0	0	0	0	0	0	0	0	0	0	0	0	0			Alive	334	72	-1	Dead	0	0	-15
14	1	1	6	7							0	0	35	0	0	0	0	64	35	15	70	35	0	0	0	0	0	0	0	0	0	0	0	0	0			Alive	254	65	-4	Dead	0	0	-15
15	1	1	7	-1								35	0	0	0	0	0	35	35	0	70	38	0	0														Alive	213	46	-13	Fallow	0	0	0
16	1	1	7	-1								35	0	0	0	0	0	35	0	0	88	0	0	0														Alive	159	39	-16	Fallow	0	0	0
17	1	1	-1	0																					35	35	105	70	35	35	35	35	70	70	95	22	0	Fallow	0	0	0	Alive	642	91	1
18	1	1	-1	0																					35	35	105	70	35	35	35	35	70	69	61	0	0	Fallow	0	0	0	Alive	585	84	-3
Rainfall (mm):					38	0	0	0	12	1	48	65	302	32	116	15	19	46	0	2	37	34	18	43	48	30	17	105	8	10	0	26	0	34	5	115	88	16	507	93	20	13	528	74	16
Water applied (mm):					57	69	45	49	49	76	83	57	54	32	51	44	42	33	38	25	48	37	82	53	48	50	53	42	31	26	28	22	34	57	58	43	58								
Water allocated (mm):					60	86	65	90	95	129	177	103	124	54	51	39	46	33	30	41	44	60	82	48	66	45	51	51	34	33	38	34	44	77	64	48	66								

Figure 8. Results for the 24 month 600 mm water allocation and the A0_G60_T60_S60_D1 irrigation strategy. Field details are given on the left. The "heat map" shows monthly simulated irrigation amounts applied by the program on each field. The water balance graph at the bottom shows monthly rainfall, water allocation and irrigation applied for the farm as whole. On the right the simulated crop status, cane yield, and gross margin at field and farm level for the different seasons are shown.

Table 4. Number of fields that survived, seasonal irrigation applied averaged over irrigated fields (mm), cane yield (t/ha) averaged over fields that were harvested for years one and two, and farm average gross margin (ZAR/ha, 1ZAR~13.5US$) for years one, two and three (Y1, Y2, Y3) for different water allocation scenarios and irrigation strategies.

Period with restricted supply (months)	Restricted water allocation (mm/aunnum)	Irrigation strategy code[1]	Fields survived Y1	Fields survived Y2	Irrigation Y1	Irrigation Y2	Cane yield Y1	Cane yield Y2	Gross Margin Y1	Gross Margin Y2	Gross margin Y3[2]
0	1300	A0_G60_T60_S60_D1	16	16	687	982	111	121	32	43	33
24	600	A0_G60_T60_S60_D1	16	13	507	604	93	92	20	17	27
		A0_G60_T60_S60_D2	16	13	499	600	92	91	20	16	27
		A2_G60_T60_S60_D1	16	12	507	655	93	92	20	19	25
		A4_G60_T60_S60_D1	16	12	507	655	93	92	20	21	25
		A0_G60_T30_S60_D1	16	13	528	581	95	89	22	15	27
		A2_G60_T30_S60_D1	16	11	528	603	95	93	22	17	23
		A5_G60_T30_S60_D1	16	11	528	651	95	93	22	20	23
		A0_G60_T30_S30_D1	16	12	404	440	82	65	14	2	33
		A0_G60_T30_S30_D2	16	16	400	438	82	66	14	2	33
		A0_G60_T20_S20_D1	16	8	299	179	69	43	5	-22	17
	300	A0_G60_T60_S60_D1	16	13	366	323	83	52	10	-11	27
		A0_G60_T60_S60_D2	16	13	366	344	83	52	10	-11	27
		A2_G60_T60_S60_D1	16	11	366	332	83	53	11	-8	23
		A5_G60_T60_S60_D1	16	11	366	352	83	53	10	-5	23
		A0_G60_T30_S60_D1	16	11	374	305	81	54	11	-11	23
		A2_G60_T30_S60_D1	16	11	374	325	81	53	11	-7	23
		A5_G60_T30_S60_D1	16	11	376	352	82	53	11	-4	23
		A0_G60_T30_S30_D1	16	12	317	264	78	53	7	-12	23
		A0_G60_T30_S30_D2	16	12	320	262	78	54	8	-12	25
		A2_G60_T30_S30_D1	16	11	317	283	78	53	7	-8	23
		A5_G60_T30_S30_D1	16	11	317	346	78	53	7	-4	23
		A0_G60_T20_S20_D1	16	8	278	175	71	41	3	-23	17
12	600	A0_G60_T60_S60_D1	16	13	687	672	111	106	32	24	27
		A0_G60_T60_S60_D2	16	14	687	673	111	101	32	24	29
		A2_G60_T60_S60_D1	16	13	687	758	111	105	28	27	27
		A0_G60_T30_S60_D1	16	13	687	672	111	106	32	24	27
		A0_G60_T30_S60_D2	16	14	687	678	111	102	32	24	29
		A2_G60_T30_S60_D1	16	13	687	758	111	105	32	28	27
		A3_G60_T30_S60_D1	16	13	687	803	111	105	32	29	27
		A0_G60_T30_S30_D1	16	16	687	636	111	88	32	21	33
		A0_G60_T30_S30_D2	16	16	687	637	111	88	32	21	33
		A2_G60_T30_S30_D1	16	14	687	690	111	93	32	24	29
		A0_G60_T20_S20_D1	16	15	687	511	111	78	32	9	31
	300	A0_G60_T60_S60_D1	16	12	687	539	111	88	32	12	25
		A0_G60_T60_S60_D2	16	13	687	542	111	88	32	13	27
		A2_G60_T60_S60_D1	16	10	687	594	111	98	32	17	21
		A6_G60_T60_S60_D1	16	10	687	744	111	103	32	22	21
		A0_G60_T30_S60_D1	16	11	687	535	111	87	32	11	23
		A0_G60_T30_S60_D2	16	12	687	536	111	88	32	13	27
		A2_G60_T30_S60_D1	16	10	687	594	111	98	32	17	21
		A6_G60_T30_S60_D1	16	10	687	744	111	103	32	22	21
		A0_G60_T30_S30_D1	16	13	687	525	111	86	32	12	27
		A0_G60_T30_S30_D2	16	14	687	524	111	86	32	12	29
		A2_G60_T30_S30_D1	16	11	687	582	111	91	32	17	23
		A5_G60_T30_S30_D1	16	11	687	675	111	95	32	20	23
		A0_G60_T20_S20_D1	16	11	687	491	111	81	32	2	23

[1] ***A*** refers to the number of fields that were abandoned (irrigation ceased at the start of the crop; ***G***, ***T*** and ***S*** refers to the soil water thresholds for irrigation for the germination phase, tillering and stalk growth phases, ***D*** refers to standard (***1***) or extended drying off period (***2***).

[2] General indications of potential income in Y3 as affected by crop failure in Y1 and Y2.

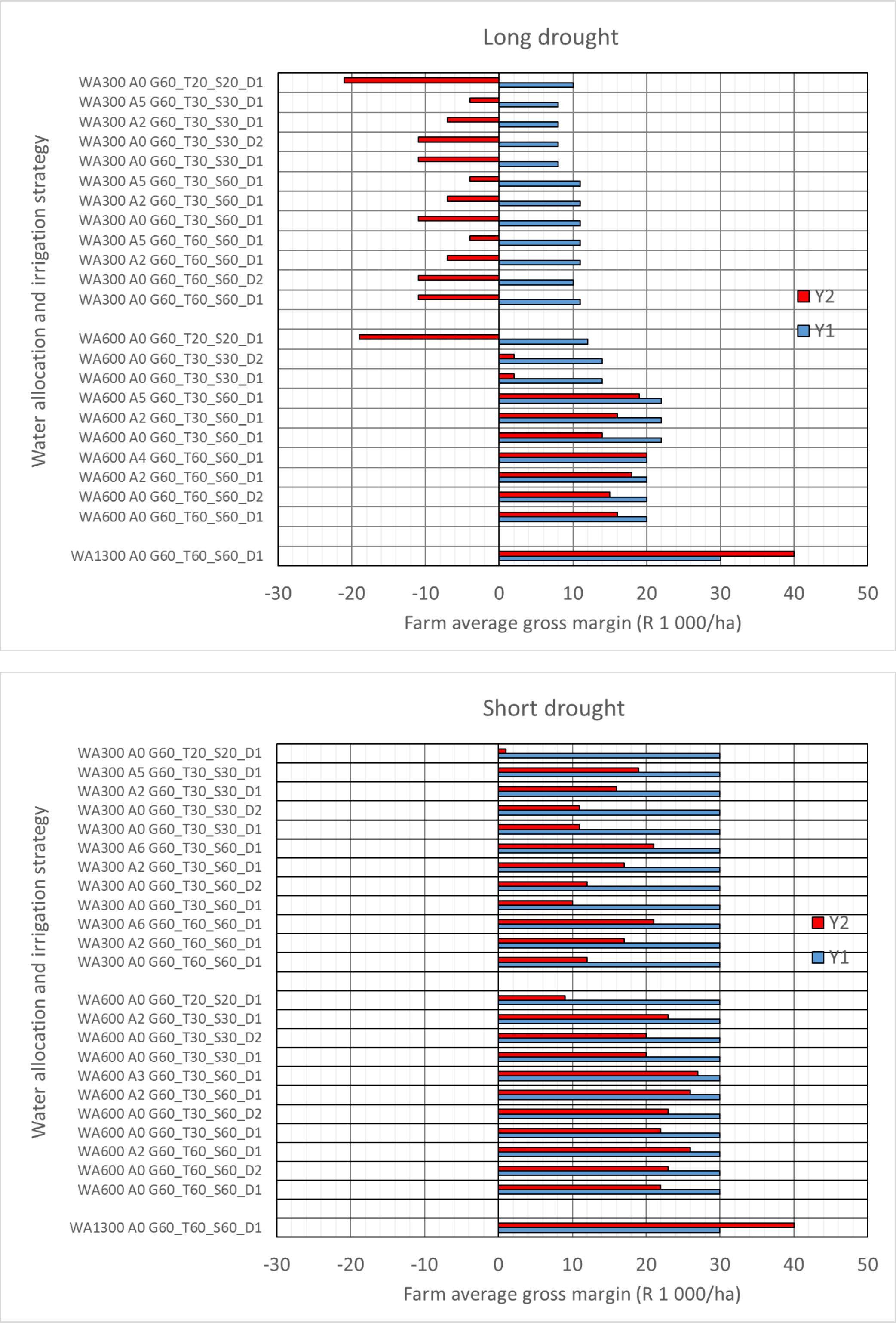


Figure 9. Calculated farm average gross margin (ZAR 1000/ha) for year 1 and 2 (Y1, Y2) for different water allocation scenarios (WA) and irrigation strategies. Irrigation strategies are formulated in terms number of fields abandoned (A), and the soil water thresholds (% of full capacity) used for the germination (G), tillering (T) and stalk growth (S) phases. The top graph shows results for the 24 month water restriction and the bottom graphs for the 12 month restriction.

5. Concluding discussion

A system was developed for assessing sugarcane farm irrigation strategies during drought periods when current and future water supply are expected to be insufficient. It is designed to be applied on multiple fields with a shared water allocation, to explore best ways of distributing the available supply spatially and temporally over two seasons. Previous work reported in the literature dealt with single fields and seasons only, and spatial optimization has not been addressed.

Sophisticated field and growth phase specific irrigation scheduling and field prioritization rules can be iteratively evaluated for assumed likely future weather and water supply scenarios, as suggested by long term forecasts. Irrigation strategies can be re-evaluated, when new water supply and climate information becomes available. The information generated by the system serves as a guide to support strategic irrigation and other crop management decisions during prolonged drought periods.

Some features can be considered advancements on what have been used in limited irrigation management support systems reported in the literature. The crop growth and water balance model is relatively sophisticated with high temporal resolution. It makes use of a daily time step (as opposed to weekly or growth phase time steps), multi-layer (as opposed to single) soil water balance with separation (as opposed to combined) simulation of soil evaporation (E) and transpiration (T). These features are important for realistic simulation of water balance as affected by large rainfall events, different soil wetting patterns caused by different irrigation systems, and rooting distribution with depth. Simulation of crop canopy responds dynamically to crop water status, in addition to temperature and row spacing. Cane yield is driven by T (and not ET) during the stalk growth phase and was shown to be accurate, while sucrose yield is driven by crop water status and temperature. These aspects enables more realistic simulations of crop response to water than simpler, empirical models that have been used for sugarcane irrigation optimization.

Some aspects of the program need further testing and possible refinement. These include the simulation of canopy senescence and crop failure due to prolonged water deficit, and the simulation of sucrose content.

Management decision need to be based on financial information. The system developed here combines biophysical and financial information through the calculation of gross margins. These account for crop establishment costs and focus on fixed and variable irrigation costs, as well as harvesting and transport costs. Estimated yields are used to determine feasibility of harvesting. The cost of re-establishing failed crops are calculated based on the ratoon stage of the failed crop.

The hypothetical case studies presented here suggest that the program produced realistic responses to irrigation applied and drought. It has enough flexibility to accommodate site specific conditions and preferences. Typically, the program will be run when a drought is looming or irrigation water supply is under threat. The program will be set up to simulate the completion of the current season (Y1), as well as the next season (Y2) by assuming the most likely rainfall and water supply scenario based on long term forecasts. The program can be used to provide broad guidelines for minimising the short and medium term impacts of protracted limited water supply on irrigated sugarcane production. It can also be used to estimate impacts of a given water supply scenario on farm production and profitability. It has the potential to be used for optimizing water distribution between farms, as well as between regions, by setting up and simulating virtual but representative cropping scenarios. It also has the potential for supporting strategic agronomic decisions such as optimizing field deployment of cultivars and irrigation systems, optimizing harvesting and planting schedules, and assessing economic consequences of applying different harvesting and irrigation systems.

Potential users include managers of large sugarcane farms and regional water use managers. The latter can set up representative simulations to represent important agro-climatic zones in a given water use district to explore impacts of spatial and temporal variation in water allocations over large areas.

Work is underway to develop an algorithm to automate the iterative formulation of irrigation strategies for a given set of condition, and subsequent evaluation of their impacts on crop status and profitability. A simple queueing of fields for weekly water could also be upgraded to evaluate the impact of weekly distribution and refine it if needed, but this will require a new simulation approach using object oriented programming.

6. Acknowledgements

We gratefully acknowledge valuable inputs from sugarcane farmers, SASRI extension specialists, and S.A. Canegrowers' Association economists during the development and testing of the software. We also acknowledge financial support from SA sugarcane farmers and millers' through the SA Sugar Association.

7. References

1. BOM, 2019. Long range sea surface temperature outlooks. Australia Government Bureau of Meteorology. http://www.bom.gov.au/climate/ocean/outlooks/#region=NINO34
2. Carr, M.K. and Knox, W., 2011. The water relations and irrigation requirements of sugar cane (Sacchrum officinarum): A review. Exp. Agric. 47: 1-25.
3. De Paly, M. and Zell, A. 2009. Optimal irrigation scheduling with evolutionary algorithms. In: Eds. Giacobini, M, Brabazon, A, Cagnoni, S, Di Caro, GA, Ekárt, A, Isabel, A, Esparcia-Alcázar, Farooq, M, Fink, A and Machado, P. Applications of Evolutionary Computing, Lecture Notes in Computer Science 5484:142-151. Springer Berlin Heidelberg, New York, USA.
4. Doorenbos, J., Kassam, A.H. and Bentvelsen, C.L.M. 1979. Yield response to water. In: FAO Irrigation and Drainage Paper No. 33, p. 200. FAO, Land and Water Development Division, Rome, Italy.
5. Ellis, R.D. & Lankford, B.A. 1990. The tolerance of sugarcane to water stress during its main development phases. Agric. Water Manage. 17: 117-128
6. Everingham, Y.L., Clarke, A.J. and van Gorder, S. 2008. Long lead rainfall forecasts for the Australian sugar industry. International Journal of Climatology 28: 111-117
7. FAO, 2018. FAOSTAT database of the Food and Agriculture Organization of the United Nations. Available at www.fao.org/faostat/
8. Groom G.M. 1999. An analysis of the 1998-99 Recoverable Value (RV) cane quality scheme to determine the varying effects of growing conditions and management practices on cane quality. Proc. S. Afr. Sug. Technol. Ass. 73: lii-lvii.
9. Inman-Bamber, N.G. & De Jager, J.M. 1988. Effect if water stress on sugarcane stalk growth and quality. Proc. S. Afr. Sug. Technol. Ass.52: 140-144.
10. Inman-Bamber, N.G. & Smith, D.M., 2005. Water relations in sugarcane and response to water deficits. Field Crops Res. 92: 185-202.

11. Inman-Bamber, N.G., 2004. Sugarcane water stress criteria for irrigation and drying off. Field Crops Res. 89: 107–122.
12. Inman-Bamber, N.G., Attard, S.J., Baillie, C., Lawson, D. and Simpson, L. 2005. A web-based system for planning use of limited irrigation water in sugarcane. Proceeding of the International Society of Sugar Cane Technologists Association 27:170-181.
13. Inman-Bamber, G., Bonnett, G.D., Spillman, M.F., Hewitt, M.L.and Jackson, J., 2008. Increasing sucrose accumulation in sugarcane by manipulating leaf extension and photosynthesis with irrigation. Aust. J Agri. Res. 59: 13-26.
14. Inman-Bamber, G., Bonnett, G.D., Spillman, M.F., Hewitt, M.L and Xu, J., 2009. Source-sink differences in genotypes and water regimes influencing sucrose accumulation in sugarcane stalks. Crop Pasture Sci. 60: 316-327.
15. IRI, 2019. IRI ENSO Forecast. International Research Institute for Climate and Society. Columbia University. https://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/
16. Jones, M.R., and Singels, A. 2018. Refining the Canegro model for improved simulation of climate change impacts on sugarcane. Eur. J. Agron. 100: 76-86
17. Keating, B.A., Robertson, M.J., & Muchow, R.C. 1999. Modeling sugarcane production systems I. Development and performance of the sugarcane module. Field Crops Res. 61: 253-271.
18. Lopez, J. R., Winter, J. M., Elliott, J., Ruane, A. C., Porter, C. and Hoogenboom, G. 2017. Integrating growth stage deficit irrigation into a process based crop model. Agricultural and Forest Meteorology *243: 84-92*
19. McGlinchey, M.G. and Inman-Bamber, N.G. 1996. Predicting sugarcane water use with the Penman-Monteith equation. In: Evapotranspiration and Irrigation scheduling (eds. C.R. Champ, C.R.E.J. Sadler and R.E.J. Yoder), pp. 592-598. Proceedings International Conference, 3-6 November 1996, San Antonio, Texas, USA.
20. Ng Cheong L.R. and Teeluck M. 2018. Development of an irrigation scheduling software for sugarcane. Sugar Tech 20: 36-39.
21. Paraskevopoulos, A.L., 2015. Improvements to the functionality of the MyCanesim® irrigation scheduling advice system for sugarcane. M.Sc. dissertation, University of Kwazulu-Natal, Pietermaritzburg. p107.
22. Park, S.E., Robertson, M., & Inman-Bamber, N.G. 2005. Decline in the growth of a sugarcane crop with age under high input conditions. Field Crops Res. 92: 305-320.
23. Pene, C.B.G. and Edi, G.K. 1999. Sugarcane yield response to deficit irrigation at two growth stages. In: Crop Yield Response to Deficit Irrigation (Kirda, C., Moutonette, P., Hera, C. & D.R. Nielsen (Eds) . Kluwer Academic Publishers, London.
24. Ramburan, S., Wettergreen, T., Berry, S.D. and Shongwe, B. 2013. Genetic, environmental and management contributions to ratoon decline in sugarcane. Field Crop Res. 146:105-112
25. Rao, N.H., Sarma, P.B.S., and Chander, S. 1988b. Irrigation scheduling under a limited water supply. Agricultural Water Management 15:165-175.
26. Rossler, R. 2014 Water stress effects on the growth, development and yield of sugarcane. M.Sc. Agric. dissertation, University of Pretoria.
27. Robertson, M. J. and Donaldson, R. A. 1998. Changes in the components of cane and sucrose yield in response to drying-off of sugarcane before harvest. Field Crops Res. 55: 201-208Robertson, M.J., Inman-Bamber, N.G., Muchow, R.C. & Wood, A.W., 1999. Physiology and productivity of sugarcane with early and mid-season water deficit. Field Crop Res. 64: 211-227.
28. Singels A, Leslie GW, McFarlane SA, Miles N, Gabriel A, Nicholson R. 2015. South African sugarcane production in 2014/15 from an agricultural perspective. Proc. S. Afr. Sug. Technol. Ass. 88:1-22

29. Singels A., McFarlane, S.A., Nicholson, R., Way, M. and Sithole, P. 2017. Review of South African sugarcane production In The 2016/2017 Season: Light at the end of the tunnel? Proc. S. Afr. Sug. Technol. Ass. 90: 1-19
30. Singels, A. and Donaldson, R.A. 2000. A simple model of unstressed sugarcane canopy development. Proc. S. Afr. Sug. Technol. Ass. 74: 151-154
31. Singels, A., Bezuidenhout, C.N. and Schmidt, E.J. 1999. Evaluating strategies for scheduling supplementary irrigation of sugarcane in South Africa. Proc. of Aust. Soc. Sugar Cane Technol. 21: 219 – 226
32. Singels, A. & Bezuidenhout, C.N., 2002. A new method of simulating dry matter partitioning in the Canegro sugarcane model. Field Crops Res. 78: 151 – 164.
33. Singels, A. and Paraskevopoulos A.L., 2017. The Canesim® sugarcane model: Scientific documentation. Published by the South African Sugarcane Research Institute, Mount Edgecombe. ISBN 978-0-6399083-0-4
34. Singels, A., Jones, M., van den Berg, M., 2008. DSSAT v4.5 Canegro Sugarcane Plant Module: Scientific documentation. SASRI, Mount Edgecombe, South Africa. pp 34.
35. Smit, M.A. & Singels, A., 2006. The response of sugarcane canopy development to water stress. Field Crops Res. 98:91-97.
36. Thompson, G.D. 1976. Water use by sugarcane. South African Sugar Journal 60: 593-600 and 627-635.
37. van Heerden, P.D.R., Donaldson R.A., and Watt, D.A. 2010. Biomass accumulation in sugarcane: Unravelling the factors underpinning reduced growth phenomena. Journal of Experimental Botany 61: 2877-2887
38. Wiedenfeld, R.P., 2000. Water stress during different sugarcane growth periods on yield and response to N fertilization. Agric. Water Manage. 43: 173-182.