Increasing water use efficiency of irrigated sugarcane production in South Africa through better agronomic practices

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In South Africa (SA) approximately 30% of sugarcane is grown under irrigation and there is increasing pressure to demonstrate efficient use of limited water resources. Agronomic practices such as the use of a crop residue layer, changed row spacing, growing suitable varieties and accurate irrigation scheduling could potentially increase water use efficiency (WUE) by saving water and/or increasing yield. The aim of the study was to investigate to what extent WUE of irrigated sugarcane production in SA can be improved by better agronomic practices, and to gain a better understanding of the mechanisms involved in crop response to these factors.

An overhead irrigated field experiment was conducted near Komatipoort, South Africa on a shallow, well-drained, sandy clay loam over a four year period (one plant (P) and three ratoon crops (R1, R2 and R3)). Treatments consisted of factorial combinations of variety

(N14 and N26), row spacing (single rows spaced at 1.5 m and dual rows spaced at 1.8 m) and soil surface cover (bare soil and crop residue layer). Measurements included tiller population, interception of photosynthetically active radiation (FI_{PAR}), soil water content, and cane yield at harvest. Crop water use (CWU) was estimated using the water balance approach.

This study showed that significant reductions in water use and irrigation requirements, and increases in WUE, are possible by using a crop residue layer to cover the soil. Water savings were largest in P1 (26% in CWU and 32% in irrigation requirement) but substantial savings were also achieved in the R crops (about 15%). It is essential to practice accurate irrigation scheduling to realize these savings, taking into account soil cover and cultivar effects, especially during the period of partial canopy. Although the residue layer caused small reductions in yield in the P, R1 and R2 crops (on average 9%) these were not statistically significant. The combined effect of large CWU reductions and small changes in cane yield resulted in increased WUE (on average 18%).

These responses to a residue layer were achieved through a reduced rate of canopy development due to delayed emergence of tillers, causing less green canopy cover and reduced CWU, especially during the period of partial canopy cover when stalk growth has not yet commenced. CWU and FI_{PAR} were affected much less during the subsequent period of stalk growth, thus affecting cane yield minimally, provided irrigation scheduling was adjusted.

Variety N14 consistently developed a canopy more rapidly, intercepted more radiation and achieved a higher yield than N26. Row configuration had a significant impact on canopy development, seasonal FI_{PAR}, final stalk population but did not affect cane yield or WUE.

The study produced quantitative data for parameterizing crop models which will improve their reliability in irrigation management and yield prediction applications.

Keywords: crop residue layer; row spacing; variety; crop water use; cane yield

Introduction

In the South African sugar industry approximately 30% of the total annual sugarcane crop is produced in the northern irrigated areas of KwaZulu-Natal and Mpumalanga which represents 16% of the total area under sugar cane. There is continued pressure on the limited water resources available to the South African sugar industry. In addition, water use for South African agriculture is subject to increasing scrutiny from policy makers and environmentalists, as the industry has to demonstrate that water is used efficiently and effectively. The term water use efficiency (WUE) is widely accepted as measure of overall effectiveness of water use and can be defined as the fresh cane yield produced per unit of total crop water use (evapotranspiration). Of concern is the very low WUE values that are currently achieved in the irrigated regions of the industry. Previous research has indicated that WUE's of 12 to 18 kg m^{-3} are possible as compared to 6 kg m^{-3}, which was the average WUE in the Mpumalanga province of South Africa reported by Olivier and Singels (2003, 2004). In a more recent study by Jarmain et al. (2014) it was found through remote sensing techniques, that WUE in the same area ranged from 3 to 14 kg m^{-3}, with an average of about 8 kg m^{-3}.

Agronomic practices such as the use of a crop residue layer, reduced row spacing, growing suitable varieties and accurate irrigation scheduling could potentially be applied to increase WUE by saving water and/or increasing yield (Olivier et al., 2009).

Crop residue layer

Research work carried out in various sugarcane areas of the world has shown that the retention of a crop residue layer following green cane harvesting can have considerable yield responses in lower rainfall areas and little or negative responses in super-humid and low-temperature areas (de Beer et al., 1995; Kingston et al., 2005). Thompson (1966) reported average cane yield responses of 10 t ha^{-1} $annum^{-1}$ under rain fed conditions but under irrigation the response to crop residue retention was much lower. Such yield benefits can generally be attributed to better soil moisture retention. A crop residue layer could also have a negative effect on the crop by slowing down initial growth, tillering and radiation interception (Ridge and Dick, 1989; Kingston et al., 2005). Soil temperatures are affected by a residue layer. Hardman et al. (1985) reported reductions of 4 to 6°C, while Kingston et al. (2005) reported reductions of 1 to 3.4°C in winter and spring. Most researchers agree that the difference in temperature disappeared when the canopy started to shade the soil surface.

Crop residue layers have long-term beneficial effects on soil health (organic matter, micro-organism activity and nutrient status), (Wood, 1991; Graham et al., 2000; Robertson and Thorburn, 2000; Viator et al., 2005). Although residues contain 50-80 kg ha^{-1} of N depending on the mass of residue, improvement in soil N status often takes several years (Thorburn et al., 2005). There are, however, other possible fates for the additional N made available. Higher soil moisture conditions (lower soil water evaporation and run-off and higher deep percolation) under a crop residue system could promote de-nitrification and loss of nitrate through deep percolation below the root zone (Probert et al., 1995).

Negative responses to crop residue systems have been observed with regards to insect pests such as trash worm and Eldana (de Beer et al., 1995). These negative effects may vary according to the variety, season of harvest, amount of trash material present and the crop class (ratoon number).

Row spacing

Despite early claims of large yield increases from high plant population densities in narrow rows to achieve more rapid tiller and leaf area development (Bull and Bull, 1996, 2000), subsequent results of independent trials and commercial evaluations have been disappointing (Garside et al., 2002). Singels et al. (2005a) stated that increases in radiation interception of between 10% and 15% could be expected in theory if cultivar and planting density is adjusted to optimally match the crop starting date. There is, however, evidence that early differences in radiation interception (Robertson et al., 1996) and growth (Everson et al., 1997) does not necessarily lead to higher final cane yield. Increasing biomass production by increasing radiation interception has had limited impact in many higher yielding environments due to stalk death late in the season (Muchow et al., 1994). The advantage of increased interception and cane yield at high plant densities diminishes with crop age and not all of the additional radiation intercepted by the crop benefits cane yield (Singels et al., 2005a). Results from Swaziland and Zimbabwe under drip irrigation suggest that these gains also diminish as ratoon age increases. Singels et al. (2005a) supported these findings and concluded that the scope of increasing cane yield through increased radiation interception is somewhat limited in a sugarcane production system that is based on several ratoons and/or harvest ages of more than 12 months. Irvine and Benda (1980) emphasised the importance of varietal selection, as much greater differences in cane yield occurred amongst varieties in closer row spacing compared to wider row spacing.

Variety

Specific varietal characteristics may play a key role in determining the response to a crop residue layer and high planting density system. Low soil temperatures beneath a crop residue layer early in the new growing season represented a serious constraint on the speed of emergence and tillering of some Australian varieties (Hardman et al., 1985; Ridge and Dick, 1989). Research by Murombo et al. (1997) in Zimbabwe similarly found that germination and tillering of some cane varieties were very poor under a crop residue system and that as a consequence, the numbers of stalks and stools were reduced. Viator et al. (2005) concluded that most currently grown varieties in Louisiana do not tolerate the environmental conditions created by post-harvest residues. Survival of tillers until final harvest is strongly influenced by not only the variety but also the population density of established primary shoots and growing conditions during the latter part of the growing season (Bell and Garside, 2005). There is evidence that certain varieties have a low tiller production potential and therefore perform poorly in wider row spacing configurations (Singels and Smit, 2002; Khandagave et al., 2005). According to Singels et al. (2005b) there is some opportunity for increasing sugarcane productivity by correctly matching variety to the environment and managing them correctly. Very little is, however, known about the response of the major South African irrigated varieties to a crop residue and high density planting system.

Irrigation scheduling

Scheduling of irrigation could be defined as a planned programme of irrigation application specified by dates and amounts to achieve specific objectives. These objectives could be to avoid water wastage, avoid plant stress, achieve maximum yields, maximize profits or maximize water use efficiency (Singels and Smit, 2006). A large number of scheduling tools are available that range from relatively simple instruments to measure soil water content directly to sophisticated crop models (Olivier and Singels, 2004; Paraskevopoulos and Singels, 2014).

Seasonal WUE quoted in the literature for well-managed sugarcane varies from 6 to 12 kg m^{-3} (Thompson, 1976; Kingston, 1994; Keating et al., 1999; Inman-Bamber et al., 1999; Olivier and Singels, 2003; Ngxaliwe et al., 2014). WUE increases when cane is mildly stressed and can reach values of up to 14 kg m^{-3} (Olivier and Singels, 2003). Irrigation water use efficiency can be much greater than WUE based on CWU if irrigation is applied to match the soil water deficit when soil water evaporation is low, when stalk elongation has commenced and when relative humidity is high (Inman-Bamber et al., 1998). Recent experiments with limited irrigation have confirmed that large responses of 20 kg m^{-3} of irrigation are possible with well-timed applications of water. Field trials at Mount Edgecombe yielded irrigation responses varying from 3 to 48 kg m^{-3} depending on scheduling strategy and rainfall (Inman-Bamber et al., 1998).

The aim of this study was to determine to what extent WUE of irrigated sugarcane production in South Africa can be improved by using a residue layer and /or, increasing plant density. A better understanding of the effects of these factors over several ratoon cycles and for different varieties on crop development, crop water use, and yield will assist in the development of better agronomic practices for efficient use of irrigation water for sugarcane production in South Africa.

Materials and methods

Site details

A field experiment was conducted on the South African Sugarcane Research Institute‘s Research Station near Komatipoort (25° 37’S; 31° 52’E, altitude 187m a.s.l). The soil was a shallow (0.63 m), well-drained, red sandy clay loam (clay content of 30%), classified as a Shortlands (Soil Classification Working Group, 1991). The region is characterized by very hot summers and mild winters with a long-term mean annual rainfall of 550 mm. The trial was conducted over a four year period (one plant crop (P) and three ratoon crops (R1, R2 and R3). Experimental details are provided in Table 1.

The information in Table 1 shows that rainfall was unusually high in the plant crop, while radiation and evaporation data suggest that the P crop had the highest climatic potential for growth and yield, followed by the R1 crop. The R2 and R3 crops had similar climatic potential which was lower than the preceding crops. The thermal environments followed a similar trend, although the R2 crop experienced some unusually low minimum temperatures.

Table 1: Experimental details of the plant and ratoon crops including a climate summary (rainfall, radiation, maximum (Tmax) and minimum (Tmin) air temperature, reference cane evapotranspiration (ETref, McGlinchey and Inman-Bamber, 1996), FAO short grass evapotranspiration (ETo, Allen et al., 1998) and thermal time (TT). Growing season totals (Sum), averages (Ave), minimum (Min) and maximum (Max) are shown.

Crop		Season			
		P	R1	R2	R3
Start date		25 April 2005	25 April 2006	24 April 2007	20 May 2008
Harvest date		25 April 2006	24 April 2007	20 May 2008	26 May 2009
Growing period (days)		365	364	391	371
Dry off period (days)		40	20	21	35
Residue amount (t ha^{-1})		8.1	12.0	9.9	6.8
Weather variable					
Rainfall (mm)	Sum	839	568	573	599
Radiation (MJ m^{-2})	Sum	6576	6388	6566	6199
	Ave	18.0	17.6	16.7	16.7
Tmax (˚C)	Ave	30.9	31.2	30.5	30.9
	Min	18.8	20.0	19.1	19.2
	Max	42.9	43.1	42.6	40.9
Tmin (˚C)	Ave	16.1	15.3	14.4	14.7
	Min	3.3	0.5	-1.2	0.6
	Max	25.2	25.4	24.2	24.2
TT (^{o}Cd)	Sum	2737	2660	2579	2552
	Ave	7.5	7.3	6.6	6.9
ETref (mm)	Sum	2122	1979	1968	1809
	Ave	5.8	5.4	5.0	4.9
ETo(mm)	Sum	1720	1584	1584	1494
	Ave	4.7	4.4	4.0	4.0

Treatments

The experiment was conducted as a split plot design with irrigation level (Standard or Savings) as main plots (60 m x 90 m). Within each of the main plots, treatments consisted of factorial combinations of variety, row spacing arrangement and soil surface cover as sub-plots. Sub-plot treatments were completely randomised within each of the two main plots and replicated five times. Gross plot size was 8 m long and 11 m wide. Varieties were chosen to represent slow (N26) and quick (N14) canopy developmental conditions. A standard single row spacing of 1.5 m was compared against dual rows spaced 1.8 m apart (each row in the dual configuration was 0.6 m apart). Surface cover treatments were selected to represent burnt conditions (no plant residue material on the soil surface, named "Bare") and green cane harvested conditions (a thick layer of plant residue consisting of dry cane tops and dead leaf, named "Residue").

An overhead floppy irrigation system was used. Sprinkler were spaced 12 m x 14 m and delivered 4 mm h^{-1}. Two irrigation treatments were applied. The “Standard” treatment consisted of a schedule of irrigations aimed at replacing water extraction as measured in the bare soil, 1.5 m spaced N14 plot. The “Savings” treatment consisted of a schedule of irrigations aimed at replacing water extraction measured in the residue covered, 1.5 m spaced N14 plot. Irrigations (target of 30 mm gross) were applied whenever the relevant measured deficit reached 30 mm. This meant that all 40 sub-plots (two levels each for variety, row spacing and soil surface cover, replicated five times) within a given main plot received the same irrigation schedule. Irrigation was suspended before harvest according to dry off recommendations by Donaldson and Bezuidenhout (2000), Table 1

Based on annual soil analysis data, 22 kg N ha^{-1} and 44 kg P ha^{-1} was applied as Mono Ammonium Phosphate (33) at planting and a further 46 kg N ha^{-}1 as Urea (46) one month after planting. In the R1 crop 120 kg N ha^{-1} was applied as Limestone Ammonium Nitrate (28) and in R2 and R3 120 kg N ha^{-1} and 20 kg P ha^{-1} as Limestone Ammonium Nitrate (28) and Super Phosphate (10.5). Typical chemical properties of this soil over the experimental period were pH_{water} of 7.2, , and P , K , Ca , Mg , Na contents of 50, 235, 3400, 900 ppm respectively and organic matter content of 2.3%, all within the acceptable norms.

Measurements

For the determination of fractional interception (FI) of radiation, a model PAR-80 Ceptometer, (Decagon Devices, Pullman, WA, USA) was used to measure photosynthetic active radiation (PAR) biweekly in all plots. One reading was taken above the canopy and 10 readings below the canopy between the hours of 11h00 and 13h00. For single rows, below canopy readings were taken such that the instrument covered the area between the middle of the inter-row and the row and for dual rows, such that the instrument covered the area between the middle of the inter-row and the middle of the dual row.

Tiller population was determined by counting the number of tillers per fixed length of row (2 m) and expressing it as the number of tillers per m^2. At harvest cane yield was determined by weighing all cane (without the tops) on the nett plots (7 x 10 m) excluding the guard rows.

Volumetric soil water content (SWC in units of %) was measured in all the bare soil, 1.5 m spaced N14 treatment and residue covered, 1.5 m spaced N14 treatment plots (five replications each) of the Standard and Savings irrigation treatments. These measurements were conducted using a neutron water meter (Model 503DR CPN Hydro probe, Campbell Pacific Nuclear, CA, USA) calibrated for the soil using one aluminium access tube, inserted 0.6 m deep in the centre of each plot.

Measurements were taken at least three times a week making sure that readings were taken before and after an irrigation event. Soil water content measurements were taken at 0.25 m intervals between 0 and 0.25 m depth and 0.15 m intervals between 0.25 m and 0.55 m depth. Volumetric SWC measurements were converted to available soil water content in the profile (ASWC) by making use of a profile field capacity (FC) value of 182 mm/0.6 m and permanent wilting point (WP) of 115 mm/0.6 m. ASWC capacity ($ASWC_{capacity}$) of the profile was taken as 70 mm. The FC value was determined by a combination of in situ gravimetric soil samples and laboratory pressure plate determinations and the WP by pressure plate method. Twenty catch cans (at 2 m height) spread randomly throughout the trial were used to measure irrigation amounts.

Calculations

Fractional interception

Fractional interception (FI_{PAR} in %) was calculated according to equation 1:

$$FI_{PAR} = [1 - (R_b/R_a)] .100 \qquad (1)$$

where R_a represents the average radiation reading above and R_b the average radiation reading below the canopy. Polynomial regression lines were fit to the FI_{PAR} data in order to estimate FI_{PAR} for each day of the growing season. A polynomial equation was fitted to the observations, which was then used to calculated seasonal average FI_{PAR}.

Crop water use

Total crop water use (CWU) for the full growing season (GS) was estimated using the soil water balance equation:

$$\Sigma CWU_{daily} = \Delta S + \Sigma I_{eff} + \Sigma R_{eff} - \Sigma DR \qquad (2)$$

where ΔS is the change in storage (the difference in ASWC between consecutive measurements), ΣI_{eff} and ΣR_{eff} are effective irrigation and rainfall respectively and ΣDR is drainage (of water out of the root zone) plus runoff (runoff was assumed to be zero as the fields were flat). I_{eff} and R_{eff} were calculated by assuming an interception loss per event equal to 2 mm (Schulze et al., 2008). DR for individual events was calculated according to equation 3:

$$DR = (ASWC + I_{eff} + R_{eff} - ET_{FAO}) - ASWC_{capacity} \qquad (3)$$

with reference evapotranspiration ($ET_{FAO,}$ as defined by Allen et al., 1998). It should be noted that the treatment average ASWC values were used in the water balance calculations.

In addition, CWU was also calculated for the partial canopy (PC) and full canopy (FC) periods. The PC period was taken from the start of the crop (planting date or date of previous harvest) up to observed peak tiller population and the FC period as the period thereafter up to harvest. There was good correlation between the occurrence of peak tiller population and the onset of the stalk growth period ($R^2 = 0.61$) as well as with attainment of full canopy (FI_{PAR}>80%) ($R^2 = 0.63$). The Canesim crop model (Singels, 2007) was also used to confirm the water balance CWU calculations.

Water logged and water stress days

Water logged days were defined as days during the growing season when the daily calculated values of ASWC exceeded 75 mm (5 mm above the ASWC capacity value of 70 mm to exclude days where ASWC was at or close to capacity) . Water stressed days were defined as days during the active growing season (excluding the drying off period) when daily calculated profile SWC was less than 30 mm (5 mm below the estimated stress point of 35 mm (50% of ASWC capacity) to exclude days where ASWC was close to this threshold).

Water use efficiency (WUE) was defined as the ratio of fresh cane yield to seasonal total crop water use in units of kg m^{-3} (equivalent to t ha^{-1} 100 mm^{-1}).

Thermal time

Crop growth parameters (FI_{PAR} and stalk population) were related to thermal time (TT), which was calculated according to equation 4:

$$TT = \Sigma(T_{ave} - T_{base}) \, . \, \Delta t \qquad (4)$$

where T_{ave} is the average daily air temperature (^oC, calculated from the maximum and minimum air temperature), T_{base} is the base temperature (taken as 16^oC) and Δt the time interval. TT was accumulated up to 50% PAR interception (TT50) either from the date of planting (plant crop) or date of previous harvest (ratoon crops).

Data were analysed using analysis of variance (ANOVA) with GenStat Version 14 where possible (peak tiller population, final stalk population, annualised cane yield). The ANOVA for WUE was based on replicated cane yield data only, since replicated CWU data was not available. Statistical significance of main and interaction effects were calculated for the 5% ($P \leq 0.05$) and 1% ($P \leq 0.01$) confidence levels and least significant differences (LSD) determined for $P \leq 0.05$. ANOVA could not be conducted on TT50 and seasonal average FI_{PAR} data because the data were based on curves fitted to average values. In order to get some indication of the statistical significance of differences in seasonal average FI_{PAR}, an overall LSD value ($P \leq 0.05$) was calculated based on the average standard error of seasonal average FI_{PAR} values, which was calculated from the average number of samples taken over a growing season (n = 11), the average standard deviation of individual samples (consisting of 10 readings per sample) and treatment average standard deviation (consisting of 5 replicated plots).

Results and discussion

Water balance

ASWC was mostly maintained within the target range for the two irrigation treatments in P. A few large rainfall events towards the end of the season caused ASWC to exceed the drained capacity of 70 mm in both the Standard and Savings irrigation treatments (Table 2). The Savings, bare treatment had the most number of days where the lower level of ASWC was exceeded, a trend repeated in subsequent crops (Table 2). This was because irrigation scheduling of the Savings treatments was done according to crop water use of the residue covered plots.

In R1, R2 and R3 there were considerably more days than in the P crop where the ASWC was below the lower limit of the target range in both the Standard and Savings irrigation treatment (Table 2). The upper limit of ASWC was exceeded occasionally after rainfall and similar to the P crop (Table 2).

Substantially more DR (67% or 118 mm) was recorded in the plant crop compared to the subsequent ratoon crops. The Standard and Savings irrigation treatments, had estimated DR values of 314 mm (accumulated over 13 drainage events) and 272 mm (12 drainage events), respectively (Table 2). This can be attributed to the plant crop receiving substantially more rainfall (approximately 45%) compared to the ratoon crops seasons (Table 1). Rainfall efficiency could have been increased significantly in the P and R crops had the soil profile not been filled to field capacity after each irrigation.

Seasonal CWU values in the Standard Bare irrigation treatment ranged from 1737 mm in P to 1340 mm in R3. CWU variation was caused by varying atmospheric demands (Table 1), and rainfall and irrigation amounts. Previous modelling studies by Singels (2007) have calculated CWU for sugarcane grown in Mpumalanga of approximately 1300 mm annum^{-1}. Rossler (2014) has determined CWU for cultivar N49 grown in the same region as 1308 mm and 1152 mm for a P and R crop respectively. In this study there was also good agreement between calculated and model derived CWU figures.

The presence of a residue layer had a marked effect on the total amount of irrigation applied to the crop (Table 2). In the P crop, a residue layer reduced irrigation requirement and CWU by 32% (453 mm) and 26% (460 mm) respectively. Although the addition of a residue blanket in the P crop is not normal practice, the primary aim of this study was to investigate residue layer effects and delaying treatment application to the R1 crop was considered too costly and time consuming. Similar, but slightly smaller savings in irrigation requirement (average of 15% or 183 mm) and CWU (average of 13% or 202 mm) was recorded in the ratoon crops. For the Savings Residue irrigation treatment, season CWU values ranged from 1277 mm in the P crop to between 1195 mm and 1484 mm in R1 and R2 respectively.

These findings are in agreement with the 23% (317 mm) and 10% (137 mm) saving in CWU reported by Olivier and Singels (2012) for a plant and ratoon crop of N14 grown on a weighing lysimeter. The reduction in CWU due to a residue layer is mainly as a result of reduced evaporation from the soil surface, especially in the period leading up to full canopy. In the current study this can clearly be demonstrated by comparing the reduction in CWU in the period before and after full canopy. In the P crop, CWU was reduced by 44% (326 mm) compared to 14% (135 mm) in pre-and-post full canopy respectively (Table 2). Similarly in the ratoon crops CWU was reduced by an average of 28% (116 mm) compared to 8% (87 mm) in pre-and-post full canopy respectively (Table 2).

Table 2: Crop water use (CWU), effective irrigation (Ieff) and rainfall (Reff), and drainage plus runoff (DR) of the different treatments for the partial canopy (PC), full canopy (FC) and full growing season (GS) periods. Number of water logged (soil water content > 75 mm) and stressed days (soil water content < 30 mm) are also shown.

Crop	**Irrigation treatment**	**Surface cover**	**Period**	**CWU (mm)**	**Ieff (mm)**	**Reff (mm)**	**DR (mm)**	**Water logged days**	**Water stressed days**
P	Standard	Bare	PC	742	763	15	30	3	4
			FC	996	674	644	284	10	4
			GS	1737	1437	659	314	13	8
		Residue	PC	689	763	15	64	5	1
			FC	853	674	644	460	20	0
			GS	1541	1437	659	524	25	1
	Savings	Bare	PC	448	479	15	15	2	116
			FC	966	505	644	187	5	35
			GS	1414	984	659	202	7	151
		Residue	PC	416	479	15	28	2	3
			FC	861	505	644	244	10	3
			GS	1277	984	659	272	12	6
R1	Standard	Bare	PC	322	310	40	22	1	6
			FC	1195	949	398	132	6	54
			GS	1517	1259	438	153	7	60
		Residue	PC	325	310	40	40	4	2
			FC	1169	949	398	146	5	57
			GS	1494	1259	438	186	9	59
	Savings	Bare	PC	227	192	40	0	0	50
			FC	1071	807	398	110	5	90
			GS	1298	999	438	110	5	140
		Residue	PC	194	192	40	5	0	10
			FC	1000	807	398	155	7	45
			GS	1195	999	438	160	7	55
R2	Standard	Bare	PC	448	410	67	45	3	11
			FC	1199	951	363	128	9	48
			GS	1646	1361	430	173	12	59
		Residue	PC	410	410	67	87	6	4
			FC	1201	951	363	102	7	86
			GS	1610	1361	430	189	13	90
	Savings	Bare	PC	319	270	67	20	1	67
			FC	1201	908	363	62	3	73
			GS	1520	1177	430	82	4	140
		Residue	PC	324	270	67	29	2	6
			FC	1160	908	363	126	8	42
			GS	1484	1177	430	155	10	48
R3	Standard	Bare	PC	456	476	17	42	4	18
			FC	884	548	446	152	9	48
			GS	1340	1024	464	194	13	66
		Residue	PC	441	476	17	64	4	28
			FC	799	548	446	165	8	71
			GS	1240	1024	464	229	12	99
	Savings	Bare	PC	384	356	17	1	0	82
			FC	819	565	446	142	7	77
			GS	1203	921	464	144	7	159
		Residue	PC	360	356	17	33	1	23
			FC	858	565	446	183	9	48
			GS	1218	921	464	216	10	71

Many similar advantages to the presence of a residue layer have been reported in the literature. Thompson (1965, 1966) found that a residue layer made an extra 90 mm of rainfall available for crop use. Murombo et al. (1997) found that a crop residue layer could reduce water loss by as much as 288 mm, the equivalent of 47% of the cane water consumption under burnt cane conditions. Similarly, Thorburn et al. (1999) indicated for Australian conditions that a residue layer could reduce soil water evaporation by an amount equal to 16% of annual rainfall. Van den Berg et al. (2006) calculated that a residue layer, on average, made an extra 140 mm available to dryland crops for a coastal site in South Africa.

Crop growth

Canopy development

Irrigation treatment had no impact on thermal time requirement for 50% canopy (TT50) and therefore results from only the Savings treatment will be discussed. Clear differences in speed of canopy development were observed between cultivars. Cultivar N26 took on average, 99 ^{o}Cd, 74 ^{o}Cd and 61 ^{o}Cd more to reach 50% canopy than N14 in the P, R1 and R2 crop respectively (Table 3). Results also seem to indicate that cultivar differences diminished with ratoon age. As a result, seasonal average FI_{PAR} of cultivar N14 was 4%, 4% and 2% higher than cultivar N26 in the P, R1 and R2 crops respectively (Table 4). These differences were statistically significant in the P and R1 crops when compared to the overall LSD value of 2.5%.

In the P crop, dual rows caused an average reduction in TT50 of 61 and 95 ^{o}Cd for N14 and N26 respectively. Similar trends were observed in R1, but the reduction in TT50 was much smaller, 23 ^{o}Cd and 46 ^{o}Cd for N14 and N26 respectively. Olivier and Singels (2003) similarly found that dual rows of N25 in a drip-irrigated crop required less thermal time (38 ^{o}Cd) to reach 80% canopy cover than 1.5 m single rows. When compared to the overall LSD value of 2.5%, seasonal average FI_{PAR} of dual rows was significantly (3%) higher for both the P and R1 crop for N14, and only for the P crop of N26 (Table 4).

Table 3: Thermal time to 50% canopy (TT50 in ^{o}Cd) for the different treatments and the average TT50 for treatments groupings.

Plant crop								
		Standard			**Savings**			**Ave**
Variety	**Row spacing**	**Bare**	**Residue**	**Ave**	**Bare**	**Residue**	**Ave**	
N14	Single	485	748	603	534	662	598	601
	Dual	431	557	494	473	601	537	516
	Ave	458	653	556	504	632	568	562
N26	Single	601	941	771	557	871	714	743
	Dual	495	797	646	520	717	619	633
	Ave	548	869	709	539	794	667	688
Ave		503	761	633	522	713	618	625
Ratoon 1								
N14	Single	311	401	356	319	393	356	356
	Dual	332	373	353	298	368	333	343
	Ave	322	387	355	309	381	345	350
N26	Single	409	498	454	368	516	442	448
	Dual	393	473	433	326	465	396	415
	Ave	401	486	444	347	491	419	432
Ave		362	437	400	328	436	382	391
Ratoon 2								
N14	Single	318	415	367	310	415	363	365
	Dual	334	421	378	334	438	386	382
	Ave	326	418	373	322	427	375	374
N26	Single	318	503	411	382	456	419	415
	Dual	401	487	444	391	511	451	448
	Ave	360	495	428	387	484	436	432
Ave		343	457	400	355	456	406	403

In the R2 crop dual rows required slightly more thermal time to reach 50% cover 50 than single rows (23 ^{o}Cd more or 3 days later, and 32 ^{o}Cd more or 4 days later for N14 and N26 respectively). The reason for this could be that dual rows had merged into a single, wide row, while single rows widened considerably. Results from Swaziland and Zimbabwe suggest that advantages of increased interception and cane yield of high density narrow rows diminishes with crop age and also as ratoon number increases. Seasonal average FI_{PAR} of dual rows was 2% and 1% lower than single rows in R2for N14 and N26 respectively. These differences were not statistically significant.

Residue layers had a negative effect on the rate of canopy development in all years. Increases in TT50 of 128 ^{o}Cd, 72 ^{o}Cd and 105 ^{o}Cd and 255 ^{o}Cd , 144 ^{o}Cd and 97 ^{o}Cd in the P, R1 and R2 crops were measured for N14 and N26 respectively (Table 3). Cultivar N14 seemed to be less sensitive to a residue layer from the first ratoon onwards, which was not the case for cultivar N26. Olivier and Singels (2006) found that the TT50 for N14 plant crop covered by either cane tops or a full residue layer was increased by 214 and 355 ^{o}Cd respectively. Ridge and Dick (1989) and Wood (1991) have shown that a crop residue layer could have a negative effect on the crop by slowing down initial growth, tillering and radiation interception. Hardman et al. (1985) reported that lower soil temperatures under a residue layer (between 4°C and 6°C lower than under a bare soil surface) could result in reduced development rate. A residue layer caused a reduction of about 5% in FI_{PAR} which was significant when compared to the overall LSD value of 2.5%.

Results suggest strongly that a residue layer will have a marked effect on canopy development and therefore crop water demand and that this effect is variety specific. This should be taken into account when developing irrigation scheduling strategies for the different production systems.

Table 4: Seasonal average fractional interception of photosynthetic active radiation (FI_{PAR}, %) values for the different treatments and the average for treatments groupings. For

Plant crop								
		Standard			**Savings**			**Ave**
Variety	**Row spacing**	**Bare**	**Residue**	**Ave**	**Bare**	**Residue**	**Ave**	
N14	Single	70	61	66	68	65	67	67
	Dual	73	68	71	72	68	70	71
	Ave	72	65	69	70	67	69	69
N26	Single	65	55	60	66	58	62	61
	Dual	68	60	64	69	63	66	65
	Ave	67	58	63	68	61	65	64
Ave		70	62	66	69	64	67	67
Ratoon 1								
N14	Single	70	63	67	69	65	67	67
	Dual	69	66	68	72	67	70	69
	Ave	70	65	68	71	66	69	69
N26	Single	64	60	62	66	60	63	63
	Dual	65	61	63	69	61	65	64
	Ave	65	61	63	68	61	65	64
Ave		68	63	66	70	64	67	67
Ratoon 2								
N14	Single	72	67	70	73	67	70	70
	Dual	68	65	67	70	65	68	68
	Ave	70	66	68	72	66	69	69
N26	Single	70	64	67	68	66	67	67
	Dual	67	65	66	67	64	66	66
	Ave	69	65	67	68	65	67	67
Ave		70	66	68	70	66	68	68

* Average sampling error for an individual observation = 10.3%. Overall least significant difference = 2.5% ($P \leq 0.05$).

Crop models are often used as tools to support irrigation scheduling and management and should adequately reflect responses to the factors investigated here. In the Canesim sugarcane model values of TT50 = 550 ^{o}Cd and 350 ^{o}Cd are used to simulate canopy development for plant and ratoon crops of cultivar NCo376 on bare soil at a row spacing of 1.4 m (Singels and Donaldson, 2000). The effect of row spacing is simulated by assuming a reduction of TT50 = 125 ^{o}Cd per meter reduction in row spacing. In the context of this experiment the Canesim values for NCo376 in a plant crop would be 563 ^{o}Cd for the single row treatments (compared to the average measured value for N14 of 510 ^{o}Cd) and 487 ^{o}Cd for dual row treatments (compared to the average measured value for N14 of 452 ^{o}Cd). Similarly for a ratoon crop, Canesim values would be 363 ^{o}Cd for the single row treatments (compared to the average measured value for N14 of 315 (R1) and 314 ^{o}Cd (R2)) and 287 ^{o}Cd for dual row treatments (compared to the average measured value for N14 of 315 (R1) and 334 ^{o}Cd (R2)).

The information obtained in this study is valuable to refine the model to simulate the impact of a residue layer on canopy development. It also provides the cultivar specific information required by the model for N14 and N26. These adjustments are essential to improve the performance of models to be applied as irrigation scheduling tools.

Tiller and stalk population

Irrigation treatment did not have any impact on tiller population and therefore results from only the Savings treatment will be discussed. Peak tiller population ($Tpop_{peak}$) was significantly lower ($P \leq 0.01$) for N26 (9%, 20%, 15% and 32% in the P, R1, R2 and R3 crops, respectively) than for N14 (Table 5). At harvest cultivar N14 still had an average of 14% more stalks (1.5 stalks m^{-2}) than cultivar N26 (Table 5) which was highly significant ($P \leq 0.01$) for the P, R1 and R2 crops. For cultivar N26, $Tpop_{peak}$ was also reached slightly later (it required an extra 84 ^{o}Cd, 57 ^{o}Cd, 113 ^{o}Cd and 127 ^{o}Cd in the P, R1, R2 and R3 crops respectively) than in cultivar N14 (Table 6). Tiller population differences can help to explain the slower canopy development and lower average seasonal FI that was observed for N26.

Dual rows caused a highly significant increase ($P \leq 0.01$) in $Tpop_{peak}$ of 10 and 13 tillers m^{-2} for N14 and N26 respectively in the P crop (Table 5). Similar increases of 10, 5 and 5 tillers m^{-2} for N14 and 9, 11 and 8 tillers m^{-2} for N26 were observed in the R1, R2 and R3 crops respectively. At harvest the final stalk population of dual rows were significantly higher ($P \leq 0.01$) than that of single rows (Table 5). Tillers compete for radiation, nutrients and water which lead to tiller death late in the growing season. For statistical significance, see footnote *.

Table 5: Peak tiller population (tillers per m^2) for the different treatments and the average for treatments groupings. Final stalk population is shown in brackets. **Plant crop**

		Standard			**Savings**			**Ave**
Variety	**Row spacing**	**Bare**	**Residue**	**Ave**	**Bare**	**Residue**	**Ave**	
N14	Single	31.5 (11.8)	29.8 (11.1)	30.6 (11.5)	32.5 (9.7)	27.7 (10.9)	30.1 (10.3)	30.4 (10.9)
	Dual	46.8 (13.2)	39.0 (13.2)	42.9 (13.2)	44.9 (9.8)	34.6 (11.7)	39.8 (10.8)	41.3 (12.0)
	Ave	39.1 (12.5)	34.4 (12.2)	36.8 (12.3)	38.7 (9.8)	31.2 (11.3)	34.9 (10.5)	35.8 (11.4)
N26	Single	30.9 (9.3)	22.5 (9.7)	26.7 (9.5)	27.9 (9.6)	23.0 (10.7)	25.5 (10.2)	26.1 (9.8)
	Dual	48.8 (10.9)	31.0 (10.7)	40.2 (10.3)	42.0 (10.6)	34.6 (10.6)	38.3 (10.6)	39.2 (10.5)
	Ave	39.9 (10.1)	27.0 (9.7)	33.4 (9.9)	35.0 (10.1)	28.8 (10.7)	31.9 (10.4)	32.7 (10.1)
Ave		39.5 (11.3)	30.7 (10.9)	35.1 (11.1)	36.8 (9.9)	30.0 (11.0)	33.4 (10.5)	34.2 (10.8)
Ratoon 1								
N14	Single	41.7 (11.5)	26.9 (10.7)	34.3 (11.1)	41.1 (11.5)	29.6 (11.5)	35.4 (11.5)	34.8 (11.3)
	Dual	54.2 (12.2)	31.7 (11.9)	43.0 (12.1)	54.8 (13.1)	36.3 (12.1)	45.6 (12.6)	44.3 (12.3)
	Ave	48.0 (11.9)	39.3 (11.3)	38.6 (11.6)	48.0 (12.3)	33.0 (11.8)	40.5 (12.1)	39.5 (11.8)
N26	Single	32.5 (7.5)	22.1 (8.1)	27.3 (7.8)	33.4 (10.3)	22.1 (9.5)	27.8 (9.9)	27.5 (8.9)
	Dual	44.1 (8.6)	23.2 (9.9)	33.7 (9.3)	45.2 (9.3)	28.8 (10.7)	37.0 (10.0)	35.3 (9.6)
	Ave	38.3 (8.1)	22.7 (9.0)	30.5 (8.5)	39.3 (9.8)	25.5 (10.1)	32.4 (10.0)	31.4 (9.2)
Ave		43.1 (10.0)	26.0 (10.2)	34.5 (10.1)	43.6 (11.1)	29.2 (11.0)	36.4 (11.0)	35.5 (10.5)
Ratoon 2								
N14	Single	41.4 (9.6)	35.1 (9.9)	38.3 (9.8)	43.2 (9.7)	34.5 (9.1)	38.9 (9.4)	38.6 (9.6)
	Dual	57.8 (9.3)	33.2 (9.6)	45.5 (9.5)	51.9 (9.4)	36.3 (8.1)	44.1 (8.8)	44.8 (9.3)
	Ave	49.6 (9.5)	34.2 (9.8)	41.9 (9.7)	43.1 (9.6)	35.4 (8.6)	41.5 (9.1)	41.7 (9.5)
N26	Single	30.9 (8.1)	26.9 (7.3)	28.9 (7.7)	30.8 (7.8)	28.0 (9.6)	29.4 (8.7)	29.2 (8.2)
	Dual	36.4 (8.3)	32.8 (6.2)	34.6 (7.3)	44.3 (7.6)	37.1 (8.3)	40.7 (8.0)	37.7 (7.7)
	Ave	33.7 (8.2)	29.9 (6.8)	31.8 (7.5)	37.6 (7.7)	32.6 (9.0)	35.1 (8.4)	33.5 (8.0)
Ave		41.7 (8.9)	32.1 (8.3)	36.9 (8.6)	40.4 (8.7)	34.0 (8.8)	38.3 (8.8)	37.6 (8.7)
Ratoon 3								
N14	Single	56.1 (8.8)	44.8 (8.1)	50.5 (8.5)	44.9 (9.2)	41.8 (9.4)	43.4 (9.4)	47.0 (9.0)

	Dual	55.8 (9.3)	47.7 (10.0)	51.8 (9.7)	63.3 (11.2)	32.8 (10.9)	48.1 (11.1)	50.0 (10.4)
	Ave	56.0 (9.1)	46.3 (9.1)	51.2 (9.1)	54.1 (10.1)	37.3 (10.2)	45.7 (10.3)	48.5 (9.7)
N26	Single	25.9 (8.5)	29.2 (8.1)	27.6 (8.3)	29.7 (8.9)	24.0 (9.9)	26.9 (9.4)	27.3 (8.9)
	Dual	32.1 (7.4)	27.2 (8.5)	29.7 (8.0)	39.8 (10.2)	29.8 (10.3)	34.8 (10.3)	32.3 (9.2)
	Ave	29.0 (8.0)	28.2 (8.3)	28.6 (8.2)	34.8 (9.6)	26.9 (10.1)	30.9 (9.9)	29.8 (9.1)
Ave		42.5 (8.6)	37.3 (8.7)	39.9 (8.7)	44.5 (9.9)	32.1 (10.2)	38.3 (10.1)	39.1 (9.4)

*Peak tiller population: Season, row spacing, surface cover and variety effects were highly significant ($P \leq 0.01$) with least significant difference (LSD) values of 1.8,1,3, 1.3 and 1.3 m^{-2} respectively.
*Final stalk population: Season, row spacing and variety effects were highly significant ($P \leq 0.01$) with LSD values of 0.6, 0.4 and 0.4 m^{-2} respectively

A residue layer caused a highly significant decrease ($P \leq 0.01$) in $Tpop_{peak}$ of 8 tillers m^{-2} (21%) and 6 tillers m^{-2} (17%) for N14 and N26 respectively (Table 5). Averaged over the three ratoon crops, $Tpop_{peak}$ of N14 was reduced by 13 tillers m^{-2} (27%) and N26 by 9 tillers m^{-2} (24%). Olivier and Singels (2006) found that a residue layer reduced $Tpop_{peak}$ of N14 by as much as 38% compared to bare soil. No significant differences in the final stalk population were observed between residue covered and bare soil plots (Table 5) or final stalk length (data not presented).

The results clearly show that the response of tiller development to a residue layer is strongly dependant on variety and row spacing. Results also show that soil cover had a stronger effect on tiller development than row spacing. Research by Murombo et al. (1997) in Zimbabwe found that germination and tillering of some cane varieties were very poor under a crop residue layer system and that as a consequence, the numbers of tillers were reduced. Donaldson et al. (2003) and Zhou (2003) have shown that there is a clear difference in the shoot appearance rate for the two varieties NCo376 and N14, confirming the strong genetic influence on tiller development. Tiller appearance rate and peak tiller population for a given variety is highly dependent on initial bud density (Singels and Smit, 2002). There is evidence that certain varieties have a low tiller production potential and therefore perform poorly in wider row spacing configurations (Singels and Smit, 2002; Khandagave et al., 2005).

Cane Yield

Final cane yield (annualised to allow for comparison between crops) of N26 was significantly lower ($P \leq 0.01$) than N14 in all crop years (Table 6). In R3 the difference had however declined to 12% (12 t ha^{-1}) from an initial difference of 17% (26 t ha^{-1}) in P. The higher cane yield of cultivar N14 could be explained by a faster canopy development and greater interception of radiation compared to N26 (Table 3 and 4).

Dual rows did not cause any significant increase in cane yield (Table 6) in spite of having slightly faster canopy development and higher average seasonal FI_{PAR}. Lack of significant yield advantage can be explained by the fact that FI_{PAR} during the stalk growth period of dual rows were similar to that of the single rows (Table 4).

Table 6: Annualised cane yield (t ha^{-1} annum^{-1}) for the different treatments and the average cane yield for treatment groupings. For statistical significance, see footnote *.

Plant crop								
		Standard			**Savings**			**Ave**
Variety	**Row spacing**	**Bare**	**Residue**	**Ave**	**Bare**	**Residue**	**Ave**	
N14	Single	167	149	158	147	165	156	157
	Dual	155	153	154	147	148	147	151
	Ave	161	151	156	147	156	151	154
N26	Single	125	118	121	135	128	131	126
	Dual	132	120	126	128	130	129	127
	Ave	128	119	124	131	129	130	127
Ave		145	135	140	139	143	141	140
Ratoon 1								
N14	Single	172	153	162	165	165	165	164
	Dual	174	153	163	172	157	164	164
	Ave	173	153	163	168	161	165	164
N26	Single	131	124	128	133	120	126	127
	Dual	141	138	140	140	122	131	135
	Ave	136	131	134	136	121	129	131
Ave		154	142	148	152	141	147	147
Ratoon 2								
N14	Single	141	135	138	132	129	131	134
	Dual	132	145	139	135	115	125	132
	Ave	137	140	138	134	122	128	133
N26	Single	128	106	117	110	128	119	118
	Dual	119	112	116	117	108	112	114
	Ave	124	109	117	113	118	116	116
Ave		130	125	127	124	120	122	125
Ratoon 3								
N14	Single	107	87	97	100	114	107	102
	Dual	92	95	93	105	113	109	101
	Ave	100	91	95	103	114	108	102
N26	Single	75	91	83	93	88	90	87
	Dual	82	89	86	102	94	98	92
	Ave	79	90	84	97	91	94	89
Ave		89	91	90	100	103	101	95

*Season and variety effects were highly significant ($P \leq 0.01$) and surface cover significant ($P \leq 0.05$) with least significant difference (LSD) values of 5.0, 4.0 and 4.0 t ha^{-1} respectively.

Our study confirms the findings from other studies that row spacing has limited impact on radiation interception and yield (Garside et al., 2002; Singels et al., 2005a) and that increased early development rate does not necessarily lead to higher yields (Robertson et al., 1996; Everson et al., 1997).

In the Standard irrigation treatment the residue layer reduced cane yield significantly ($P \leq 0.05$) in the single row treatment of the P and R2 crops and both single and dual row treatment for the R1 crop (Table 6). The average loss compared to the bare soil equated to approximately 9% (13 t ha^{-1}). Smaller (2%, 2 t ha^{-1}) reductions were observed in the R3 crop. These reductions in cane yield could be due to reduced rates of tillering and reduction in FI_{PAR} in the presence of a residue layer (Tables 3 and 4). Increased DR (62% or 138 mm and 33% or 37 mm in the P and R1 crops respectively) as well as more water stressed days (9, 37 and 40 days in R1, R2 and R3 respectively) could have further contributed to lower cane yields of the residue treatments (Table 2).

In the Savings irrigation treatment there was no significant reduction in cane yield due to the presence of a residue layer except for the dual row treatment of the R1 and R2 crops. Cane yields were not significantly different to that of bare soil in the Standard irrigation treatment (Table 6). Averaged over season, about 36% (81 mm) less DR was recorded compared to residue covered soil in the Standard irrigation treatment. This emphasizes the importance of adjusting irrigation scheduling to avoid water logging and its negative impact on cane yield under a crop residue system. The average cane yield achieved over the four crops for the residue layer receiving the Savings irrigation was only 5 and 2 t ha^{-1} lower than that of the bare soil receiving the Standard irrigation for N14 and N26 respectively (Table 6).

Published reports of yield response to a residue layer are inconclusive. Retention of a residue layer following dryland green cane harvesting can have considerable yield responses in lower rainfall areas and little or negative responses in super-humid and low-temperature areas (de Beer et al., 1995). Thompson (1966) reported average cane yield responses of 10 t ha^{-1} per annum in a green cane harvesting system under rain fed conditions. Wood (1991) pointed out that cane yields were 1.6 t ha^{-1} higher in burnt cane than in a green cane harvested system in poorly drained soils. Prove et al. (1989) did not find any differences in cane yield between burnt cane and green cane systems in the wet tropics of Australia. Thompson (1966) reported that, under irrigation, the yield response to residue retention was much less than the 10 t ha^{-1} per annum achieved under dry land conditions. Gosnell and Lonsdale (1978) came to similar conclusions with low levels of irrigation in Zimbabwe, but showed a substantial yield depression with crop residue retention when irrigation and fertiliser practices were not adjusted relative to burnt field plots. Olivier and Singels (2006) reported that although residue treatments reduced final cane yield by an average of 14% under irrigated conditions, yields were not statistically different from that of the bare soil treatment.

We conclude that a residue layer has minimal impacts on cane yield at 12 months when irrigation scheduling accounts for its CWU reducing effect.

Over the four year period (one plant and 3 ratoon crops) cane yield had declined by an average of 32% (50 t ha^{-1} or 12.5 t ha^{-1} annum^{-1}) and 28% (35 t ha^{-1} or 8.8 t ha^{-1} annum^{-1}) for N14 and N26 respectively which was significant at the $P \leq 0.01$ level. This decline is partially ascribed to a reduction in the climatic potential over time. Climate data (Table 1) show that evaporative demand (closely associated with biomass growth and yield) was 7% lower in the R1 crop and 15% lower in the R2 and R3 crops, compared to the P crop. Water stress may have also contributed to this trend, as the extent of stress experienced in the P crop was less than the ratoon crops (Table 2). Other factors that cause yield decline over ratoon cycles, such as a decline in stalk population may have also contributed. Ramburan et al. (2013) reported for irrigated conditions in South Africa that the average yield decline varied between 10.8 and 7.3 t ha^{-1} $annum^{-1}$ for N25 and N32 respectively and a result of genetic, environmental and management effects.

Water Use Efficiency

Average values of WUE for cultivar N14 ranged from 10.4 kg m^{-3} in the P crop and 8.1 kg m^{-3} in the R3 crop respectively (Table 7). Reduction in cane yield over time was the main reason for the decline in WUE. Cane yield and WUE can differ significantly between different varieties. Olivier and Singels (2003) have for example reported that under well-watered conditions, N14 had higher yield and WUE than N22 and N25. This emphasizes the importance of correct variety choice as it could lead to more efficient use of water and improved productivity.

Row spacing had no effect on WUE mainly due to the lack of any yield advantage in dual rows (Table 6 and 7). Olivier and Singels (2003) reported for a drip irrigated crop of N25 that yield obtained with dual rows at 1.8 m, was 23% higher than that obtained in single rows at 1.5 m. These results however only represent one season.

Table 7: Water use efficiency (WUE in kg m^{-3}) for the different treatments and the average WUE for treatment groupings. For statistical significance, see footnote *.

Plant crop								
		Standard			**Savings**			**Ave**
Variety	**Row spacing**	**Bare**	**Residue**	**Ave**	**Bare**	**Residue**	**Ave**	
N14	Single	9.6	9.7	9.6	10.4	12.9	11.6	10.6
	Dual	8.9	9.9	9.4	10.4	11.6	11.0	10.2
	Ave	9.2	9.8	9.5	10.4	12.2	11.3	10.4
Ratoon 1								
N14	Single	11.3	10.2	10.7	12.7	13.8	13.2	11.9

	Dual	11.5	10.2	10.8	13.3	13.1	13.2	12.0
	Ave	11.4	10.2	10.8	13.0	13.4	13.2	12.0
Ratoon 2								
N14	Single	8.6	8.4	8.5	8.7	8.7	8.7	8.6
	Dual	8.0	9.0	8.5	8.9	7.7	8.3	8.4
	Ave	8.3	8.7	8.5	8.8	8.2	8.5	8.5
Ratoon 3								
N14	Single	8.0	7.0	7.5	8.3	9.4	8.8	8.1
	Dual	6.9	7.7	7.3	8.7	9.3	9.0	8.1
	Ave	7.4	7.3	7.3	8.5	9.3	8.9	8.1

*Season and irrigation effects were highly significant ($P \leq 0.01$) with least significant difference (LSD) values of 0.6 and 0.4 kg m^{-3} respectively.

There was a significant interaction ($P \leq 0.01$) between season and irrigation treatment. The Savings irrigation treatment had significantly higher WUE values in the P, R1 and R3 crops compared to the Standard irrigation treatment (Table 7), which was the result of smaller amounts of irrigation applied in the Savings irrigation treatment.

The presence of a residue layer had a marked effect on WUE. In the P, R1 and R3 crops WUE of the “Residue Savings” irrigation treatment was significantly higher ($P \leq 0.01$) than that of the “Bare Standard” treatment for both single and dual row configurations. . The response varied between years with the highest response recorded in the P and R3 crops (average increase of 29%) and lowest response in the R1 (average increase of 18%).

The WUE values quoted in Table 7 compare well with that reported by other authors in the literature. Thompson, (1976) reviewed a number of lysimeter studies and found that for South Africa the WUE was 9.7 kg m^{-3}. Similarly Kingston (1994) reviewed published data and established that the relationship between yield and ET was closer to 12.2 kg m^{-3} for Australian conditions. Robertson et al. (1997) used APSIM-Sugar to show that WUE for irrigated conditions differed between sites in Australia and South Africa (15.4 and 10.1 kg m^{-3} respectively) and also differed from rainfed crops (12.8 and 5.3 kg m^{-3} respectively). WUE from irrigation can be much greater than from rainfall if irrigation is applied to match soil water deficit when soil water evaporation is low, when stalk elongation has commenced and when relative humidity is high. Irrigation responses as high as 22 to 48 kg m^{-3} have been reported depending on irrigation scheduling strategy and rainfall (Robertson and Muchow, 1994; Robertson et al., 1997; Inman-Bamber et al., 1999). Had a different irrigation strategy been followed that made more efficient use of rainfall, WUE of the Savings irrigation treatment could have been increased up to 18.3 kg m^{-3} for N14.

Conclusions

This study demonstrated that substantial reductions in water use and irrigation requirements, and increases in WUE, are possible by making use of a crop residue layer. Water savings were largest in plant crop (26% in CWU and 32% in irrigation requirement) but significant savings were also achieved in the subsequent ratoon crops (about 15%). To realize these savings it is essential to practice accurate scheduling of irrigation, taking into account soil cover and variety effect, especially during the period of partial canopy.

Although the residue layer caused reductions in yield in the R1 and R2 crops of about 9% these were not statistically significant. The combined effect of reduced seasonal CWU and insignificant changes in cane yield increased WUE on average from 9.1 to 10.8 kg m^{-3} when irrigation scheduling was adjusted to account for the residue layer.

The study provided a better understanding of the mechanisms underlying the response of sugarcane growth, development and water use to a residue layer. The residue layer slowed canopy development through delayed emergence of tillers, causing less green canopy cover, than crops grown on bare soil. CWU was reduced as a result, presumably by reducing evaporation from the soil and by reducing transpiration from the lower canopy cover. Most of the CWU reduction occurred during the period of partial canopy when little or no stalk growth occurred. Interception of radiation during the stalk growth phase was largely unaffected, providing the energy for structural growth and sucrose storage in the stalk. CWU during the stalk growth period was not reduced markedly, suggesting limited impact on carbon fixation rates. Stalk populations were similar for the different treatments, providing a similar sink size for cane yield.

Dual rows significantly increased peak tiller population and final stalk population, especially in the P and R1 crops. Canopy development, interception of radiation and cane yield were very similar for the two row configurations, especially for the ratoon crops.

The consistently higher yield of variety N14 was associated with more rapid tiller production and canopy formation, leading to greater interception of radiation, than N26. N14 also had higher final stalk population (larger sink size), than N26. Yields for both cultivars peaked in R1, declining sharply thereafter due to reduced climatic potential, increased water stress and decreased stalk population.

The study produced valuable information for the parameterization of models such as APSIM-sugar (Keating et al., 1999), DSSAT-Canegro (Singels, 2008) and MyCanesim (Singels, 2007). Parameters include thermal time requirements for canopy development, delays in canopy development due to residue layer, tillering traits and row spacing impacts. This will enable more accurate simulation of crop growth and water use for these varieties and will improve the reliability of models to be used for irrigation management and yield prediction.

It is important to note that the extent of benefit observed in this study were for crops started in April with a relatively long period of partial canopy cover. Crops started in spring would have shorter periods of partial canopy cover with presumed smaller amounts of reduced water use. It is also important to test cultivars’ response to a residue layer as these may differ markedly. It is likely that similar effects from a residue layer and row spacing can be expected in locations with similar climate, such as the Malelane and Pongola regions in South Africa, as well as possibly sugarcane producing areas in Zimbabwe.

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