The effect of crop residue layers on evapotranspiration, growth and yield of irrigated sugarcane†

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Abstract

A layer of harvest residues from the previous crop can reduce wasteful evaporation from the soil surface and thereby increase the efficiency of use of limited water resources for agricultural production. The practice of harvesting sugarcane green and leaving crop residues in the field, as opposed to burning the residue, has been re-adopted in many sugarcane industries worldwide. However, a better understanding of the dynamic impacts of residue layers on various aspects of the cropping system is required to (1) enable the formulation of sets of best management practices for specific production scenarios, and (2) promote the use of residue layers in areas where it is desirable and has not been adopted, such as irrigated sugarcane production in South Africa. The objective of this study, therefore, was to quantify the effect of 2 different types of residue layers on crop growth, cane yield and evapotranspiration of fully irrigated sugarcane. A layer of cane tops and dead leaves (Trash) and a layer of green tops (Tops) were applied to the soil surface of sugarcane crops (plant crop and first ratoon crop of variety N14) grown on lysimeters at Pongola, South Africa. Observations of crop growth (stalk population, stalk height, canopy cover), cane yield and evapotranspiration for these treatments were compared to that of a bare soil treatment. The data were also used to derive values of crop evaporation coefficients for different development phases and these were compared to FAO56 recommendations. Initial stalk population in the plant crop and radiation capture in the plant and ratoon crop were affected negatively by crop residue layers, but without significantly reducing final stalk population and cane yield. Peak stalk population occurred later in crops grown in residue layers, but peak and final stalk populations were unaffected. Evapotranspiration was reduced by both residue layers, mainly due to a slower developing canopy (reduced transpiration) and reduced evaporation from the soil, during the pre-canopy phases. Increased drainage was observed under residue layers, emphasising the importance of accurate irrigation scheduling to avoid water logging. The FAO56 methodology for calculating crop evaporation coefficient values for the initial, development and late season phases are supported by the results obtained here. Crop evaporation coefficient values were significantly reduced by residue layers. It is important that irrigation scheduling practices be adjusted to realise the potential water savings of sugarcane production systems that make use of residue layers. This study provides the information required to do that. The information could also be used to improve the ability of the crop models to accurately simulate crop growth and evapotranspiration in a residue layer cropping system.

Keywords*:* water use, irrigation, stalk population, canopy development, lysimeter, crop evaporation coefficient, trash blanket

Introduction

Worldwide, irrigated agriculture is under pressure to demonstrate that limited water resources are being used efficiently. One way of achieving this is through the retention of a layer of harvest residues from the previous crop to reduce wasteful evaporation from the soil surface. The practice of harvesting sugarcane green and leaving crop residues in the field (also named green cane harvest and trash blanket system, GCHTB), as opposed to burning the residue, has been re-adopted in many sugarcane industries worldwide (Thorburn et al., 1999). However, a good understanding of the dynamic impacts of crop residue layers on various aspects of the cropping system is required to enable the formulation of sets of best management practices for specific production scenarios. It may also assist in promoting the GCHTB system of cane production in areas where this is desirable but has not been adopted yet. For example, in South Africa there is a reluctance to convert from burning sugarcane at harvest to GCHTB, due to a perceived lack of benefit, especially in irrigated scenarios.

Research work carried out in various sugarcane areas of the world has shown that the retention of a layer of crop residues following green cane harvesting can have considerable yield responses in low 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 $t \cdot ha^{-1}$ per annum 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 blanket could also have a negative effect on the crop by slowing down initial growth, tillering and radiation interception (Ridge and Dick, 1989). Hardman et al. (1985) has reported that soil temperatures under a crop residue blanket can be between 4°C and 6°C lower than under a bare soil surface. Most researchers (Page et al., 1986; Wood, 1991) agree that the difference in temperature disappeared when the canopy started to shade the soil surface.

A crop residue layer reduces evaporation from the soil and this is expected to reduce evapotranspiration, especially during the period of partial canopy. Denmead et al. (1997) concluded from micrometeorological measurements that evaporation

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from a residue covered soil was, at most, half of what could be expected from a bare soil. Thorburn et al. (1999) used the APSIM model to estimate soil evaporation from burnt and residue covered fields for the Herbert region in Australia and found that the average reduction due to the residue layer was about 30%. In another simulation study, Van Antwerpen et al. (2002) found a reduction in dryland water use under a residue layer for selected South African scenarios of 90 to 100 mm per annum. This is very similar to the average reduction reported by Thompson (1966). A review by Kingston et al. (2005) makes mention of 100 to 200 mm of additional water available to the crop in water-limited scenarios and yield responses of 7 to 10 $t{\cdot}ha^{-1}$. Gosnell and Lonsdale (1978) also reported reduced irrigation input due to a residue layer. These impacts may vary widely because of the dynamic nature of climatic and soil factors and their interaction with crop growth and development. Improved predictions of these impacts may be possible if existing methods of calculating sugarcane evapotranspiration are refined to better account for the effect of residue layers.

Evapotranspiration (ET) calculations mostly require some measure of atmospheric evaporative demand (reference evapotranspiration) and a crop evaporation coefficient (*Kc*) that reflects the effect of the crop/soil surface. An alternative, more fundamental, approach is to calculate ET directly from weather data and surface resistance (see Wallace, 1995). Farahani and Ahuja (1996) extended the resistance-based ET model of Shuttleworth and Wallace (1985) to account for surface residue effects, but acknowledge the difficulties associated with determining the parameters of the models. For this reason we selected the more practical 2-step approach.

In the South African sugar industry, the Penman-Monteith equation has been used as the basis for estimating potential evapotranspiration (ET_{ref}) for a reference sugarcane crop (3 m tall, fully canopied and well watered) (McGlinchey and Inman-Bamber, 1996). This formulation of the Penman-Monteith equation has become widely accepted as a standard for the estimation of ET_{ref} for sugarcane in South Africa (Singels et al., 1998; Singels et al., 1999).

Internationally the Penman-Monteith-based 'short grass' reference evaporation (ET_0) defined in the Food and Agricultural Organisation (FAO) Report No. 56 (Allen et al., 1998), used together with a crop evaporation coefficient of 1.25, is the proposed standard for the estimation of ET_{ref} for a stress-free, fully canopied sugarcane crop. This approach has been verified against Bowen ratio estimates of potential sugarcane evapotranspiration in both Australia and Swaziland (Inman-Bamber and McGlinchey, 2003).

A single (where the effect of soil and vegetative surfaces are combined) or dual crop evaporation coefficient (where the effect of the 2 surfaces are separately calculated) can be used. *Kcb* represents the effect of canopy cover while *Ke* represents the effect of the area of exposed soil and the degree of wetness of the soil surface. Allen et al. (1998) proposed a reduction in *Ke* of 5% for each 10% of soil surface that is covered by organic mulch. The authors warn that this is just an approximation and that the controlling factors, such as the partial reflection of radiation from the residue layer, micro-advection of heat from the residue layer into the soil and the insulating effect of residue layer, vary widely. They recommend that measurements be taken to obtain more precise estimates.

Crop models are often used to assist in analysing new production strategies as well as to support tactical crop management such as irrigation scheduling. APSIM-sugarcane (Keating et al., 1999), CANEGRO (Inman-Bamber, 1991) and CANESIM (Singels et al., 1998) are 3 prominent sugarcane models that are used as research and management tools. The latter two do not accommodate a residue layer. While APSIM-sugarcane accounts for the reduction in evaporation due to a residue layer, it does not account for the impact on growth and development apart from the indirect impacts through changed water and nutrient status of the soil. More recently a standalone model was developed by Jones and van den Berg (2006) to simulate the effect of a residue layer on sugarcane water use. It simulates daily evaporation from the soil and 2 sub-layers of residue as a function of evaporative demand, the amount of residue and the time after a wetting event. It does not simulate the impact of residue layers on canopy development and also does not simulate stalk and sucrose yields. Quantitative information is required to refine these models to adequately account for the impact of residue layers.

The objective of this study therefore was to quantify the effect of 2 different types of residue layers on (1) crop growth (stalk population, stalk height, canopy cover), (2) cane yield and (3) evapotranspiration of fully irrigated sugarcane. This could point the way to the changes required in crop models and ET algorithms. It is also essential for formulating best irrigation management practices for more efficient sugarcane production.

Methods

A field experiment was conducted on a trial site at the South African Sugarcane Research Institute (SASRI) research station at Pongola (27° 24' S, 31° 35' E, altitude: 308 m) that contained 3 weighing lysimeters, each 2.44 m long, 1.52 m wide and 1.22 m deep. Experimental details are given in Table 1.

Table 1
Experimental details for the plant and ratoon crop

	Plant crop	Ratoon crop
Cultivar	N14	N14
Row spacing (m)	1.4	1.4
Start date	2 Apr '04 (first irrigation)	11 Apr '05
Harvest date	11 Apr '05	16 May '06
Residue amount ($t{\cdot}ha^{-1}$)		
Trash treatment	8.3	12.4
Tops treatment	1.8	1.7

The soil surrounding the lysimeters was a deep (1.8 m), well-drained, red sandy clay loam (clay content of 40%), classified as a Hutton form (Soil Classification Working Group, 1991), a Ferric Ferrasol (according to the ISSS Working Group RB., 1998). When originally constructed, lysimeter tanks were back-filled with soil monoliths of the same soil. The soil has a field capacity of 312 $mm{\cdot}m^{-1}$ and permanent wilting point of 111 $mm{\cdot}m^{-1}$, (Thompson and Boyce, 1968) resulting in available water capacity of 242 mm assuming that the crop will utilise the full lysimeter depth of 1.22 m.

Lysimeters, as well as the area surrounding each lysimeter, either had:

- No residue cover (Bare)
- Soil covered by a light layer of cane tops (Tops)
- Soil covered by a heavy layer of tops and dead leaves (Trash)

Cane tops provided a soil surface cover of approximately 50-60% and the trash approximately 95-100% (determined by

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visual estimate). This material was collected in an adjacent field that had been harvested green and applied 3 weeks after planting at the rates given in Table 1. GCHTB is normally only practised from the first ratoon onwards, but was also applied in the plant crop in this experiment.

Hourly changes in weight of individual lysimeters were detected electronically (calibration error of 0.22 mm; $r^2 = 0.97$, $n = 98$) via load cells (Route Calibration Services, Pretoria, RSA) connected to a CR10X (Campbell Scientific Inc., Logan UT, USA) data logger. Electronic tipping-bucket rain gauges (model TR-525, Texas Electronics Inc., Dallas, Texas, USA) measured deep drainage under each lysimeter. Manual readings were taken whenever electronic gauges failed.

Lysimeters were irrigated individually according to demand on reaching a deficit of 20 mm as indicated by lysimeter readings. A watering can was used to apply exact irrigation amounts and to mimic an overhead irrigation system. The cane fields surrounding the lysimeters were irrigated with an aboveground drip irrigation system according to the Canesim program (Singels et al., 1998) and weather data obtained from an onsite automatic weather station. Surrounding fields were irrigated whenever a deficit of 20 mm was reached and received a total of 1 113 mm in the plant crop and 1 100 mm in the ratoon crop. Thermal time (also known as growing degree days), with units of °Cd, was calculated using a base temperature of 10°C for the period between germination and emergence and 16°C for the post-emergence period (Inman-Bamber, 1994). Emergence was assumed to have occurred in the plant crop when 200°Cd had accumulated since the start of germination (date of first irrigation). In the ratoon crop emergence was assumed to have occurred when 100°Cd had accumulated after cut back of the plant crop.

Stalk population, stalk height and fractional interception of photosynthetic active radiation (*Fi*, measured with a model PAR-80 Ceptometer, Decagon Devices, Pullman, WA, USA) were determined biweekly. In the plant crop, 3 replications of these measurements were made in each treatment, 1 on the lysimeter and 2 in the surrounding area. The same fixed length of row (2 m in surrounding cane and 2.44 m on the lysimeter) was used to determine stalk population and the height of 20 marked stalks for each sampling date and replication. For each *Fi* sampling, 10 *Fi* readings were taken per measurement replication. In the ratoon crop, stalk population, stalk height and *Fi* were measured in only 2 replications per treatment, 1 on the lysimeter, and 1 in the surrounding area.

Fi values for each day were estimated from 2 linear regressions fitted to pre- and post- 80% canopy data points. The average *Fi* was then calculated from the daily *Fi* values within each development phase as defined by FAO56 (Allen et al., 1998), namely the Initial phase (where *Fi* values increase very slowly and are at their lowest), the Development phase (where *Fi* increase progressively), the Mid-Season phase (where *Fi* reaches and remains at a maximum) and Late Season phase (where *Fi* starts to decrease at the end of the growing season). The start and end of each phase were estimated by evaluating a smoothed trend line of *Fi* time series.

At harvest (12 months of age) cane yield was determined by weighing all millable (from base up to natural breaking point) stalks on the lysimeter. Samples of equivalent size (2.44 m row) were harvested from the cane surrounding each lysimeter (3 samples were taken in the plant crop and 2 samples in the ratoon crop).

Crop evapotranspiration (ET_{crop}) was calculated as the daily change in lysimeter mass (converted to mm water) plus irrigation or rainfall (mm) minus deep drainage (mm). Suspect data, such as negative ET_{crop} values were replaced by values calculated as the products of estimated *Fi* and reference cane evaporation (ET_{3m}, McGlinchey and Inman-Bamber, 1996). A similar procedure was followed on irrigation or rainfall days when the difference between ET_{3m} and ET_{crop} was expected to be minimal but was greater than an arbitrarily chosen 3 mm. In the plant crop 13%, 14% and 17% of the respective ET_{crop} values in the Tops, Trash and Bare treatments were replaced. In the ratoon crop, 23% of ET_{crop} values in the Tops, 24% in the Trash and 20% in the Bare treatment were replaced.

To account for the effect of crop characteristics on crop water requirements, crop evaporation coefficients (Kc_{FAO}) were calculated to relate reference grass evapotranspiration (ET_0) to ET_{crop} according to FAO 56 guidelines (Allen et al., 1998). Crop evaporation coefficients (Kc_{3m}) were also calculated to relate Penman-Monteith derived potential evapotranspiration of a reference sugarcane crop (3 m tall, fully canopied and well-watered), (ET_{3m}) to ET_{crop}. Monthly average *Kc* values were calculated from monthly average ET_0, ET_{3m} and ET_{crop} values for each of the 3 treatments:

$$Kc_{FAO} = ET_{crop}/ET_0 \tag{1}$$

$$Kc_{3m} = ET_{crop}/ET_{3m} \tag{2}$$

Average *Kc* values were then calculated for each development phase from the monthly averages.

In this paper, water use efficiency (WUE) was calculated as the ratio of cane yield to total seasonal ET_{crop} in units of kg·m^{-3} (numerically equivalent to t·100 mm^{-1}).

Statistical analyses were conducted using a standard t-test ($P = 0.05$). For these tests measured data of stalk population, stalk height, *Fi*, and sugarcane yield taken on the lysimeter were grouped with data measured on the cane surrounding each lysimeter.

Results and discussion

Stalk growth and development

No significant differences in stalk height were observed amongst treatments in the plant crop through the season (Fig. 1) and at harvest (Table 2). In the ratoon crop, there were also no differences up to a thermal time of about 1 300°Cd, whereafter stalks in the Trash treatment elongated quicker than the other 2 treatments (Fig. 1), resulting in longer stalks at the final harvest (Table 2). Stalk elongation is highly sensitive to water stress and a slightly more favourable water balance in the Trash treatment may have reduced minor stress between irrigations experienced in the other treatments.

Stalk population of the Tops and Trash treatments was lower than that of the Bare treatment during the first part of the season (Fig. 2). Peak stalk population of the residue treatments were lower than that of the Bare treatment (by 23% and 15% for the Tops and Trash treatments, respectively) but this was not significant (Table 2). Peak stalk population occurred 500°Cd later in the residue treatment compared to that in the Bare treatment (Fig. 2).

In the ratoon crop none of the observed differences in stalk population were statistically significant (Fig. 2). The seemingly large differences between treatments during the middle of the season suggest that sampling size and number of repetitions were insufficient. Peak stalk population for all treatments

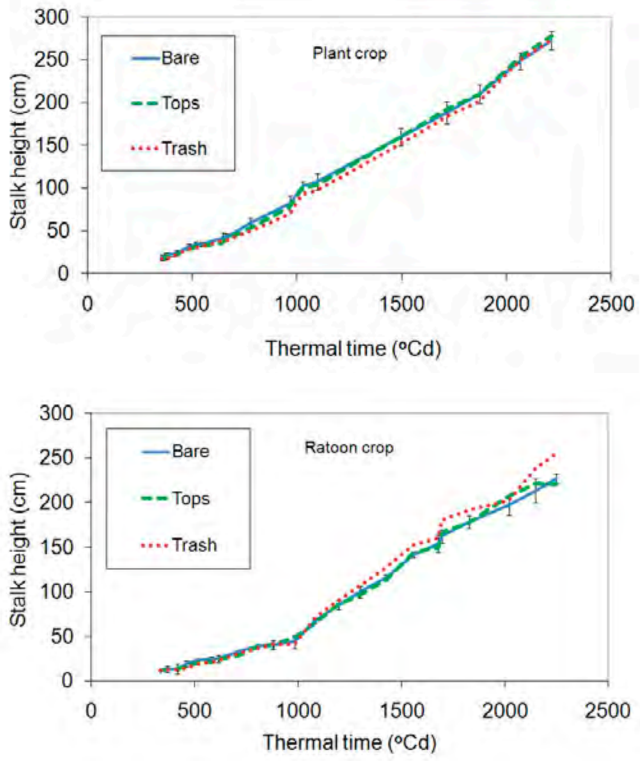

Figure 1
Stalk height as a function of thermal time for the different treatments for the plant and first ratoon crops. The sampling error is indicated by the standard error for the Bare treatment.

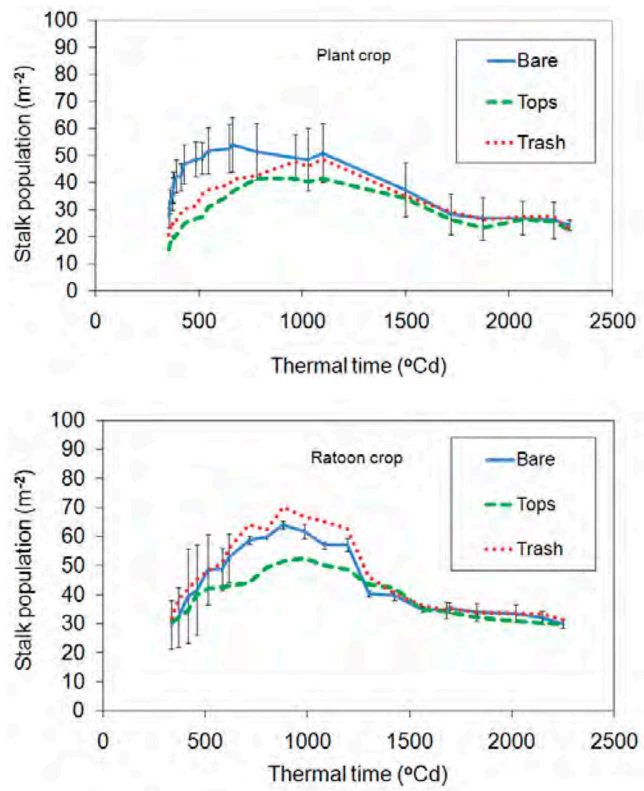

Figure 2
Stalk population as a function of thermal time for the different treatments for the plant and first ratoon crops. The sampling error is indicated by the standard error for the Bare treatment.

Table 2
Final stalk length and peak and final stalk population for the plant and ratoon crops (average values for lysimeters and surrounding crop). Values with common superscripts are not significantly different (t-test, *P*=0.05)

Surface cover	Final stalk length (cm)	Peak stalk population (stalks·m^{-2})	Final stalk population (stalks·m^{-2})
Plant crop			
Bare	273^{a}	53^{a}	24^{a}
Tops	279^{a}	41^{a}	24^{a}
Trash	273^{a}	46^{a}	23^{a}
Ratoon crop			
Bare	231^{b}	62^{b}	30^{b}
Tops	229^{b}	53^{c}	30^{b}
Trash	254^{c}	67^{b}	31^{b}

was reached at the same time, but was 5% higher in the Trash treatment and 14% lower in the Tops treatment compared to the Bare treatment (not significant). Final stalk population was similar for all 3 treatments in both plant and first ratoon crops (Fig. 2 and Table 2).

Residue layers can have a negative effect on the crop in winter months by slowing down initial growth and tillering and can be ascribed to lower soil temperatures under the residue layer (Beater and Maud, 1962; Wood, 1991; Morandini et al., 2005 and Viator et al., 2005). Morandini et al. (2005) reported that the soil temperature was 1.5°C higher at emergence and tillering where residues were burnt as compared to an unburned field. Another reason for a reduction in tillering is the bigger effort required by the crop to penetrate the residue layer. These 2 aspects were unfortunately not monitored in this study.

Torres and Villegas (1995) found that a residue layer reduced shoot growth after harvest in a ratoon crop, but there were no differences between systems 6 months later. The latter was confirmed by Chapman et al. (2001) who showed that growth differences between burnt and unburned fields harvested early and at the end of the season, were no longer noticeable after 100 days and 40 days, respectively. The general trends from our study support these findings.

Radiation interception

Residue layers had a negative effect on rate of canopy development of the plant crop. The Bare treatment reached 80% radiation interception 20 days before the Tops treatment and 45 days before the Trash treatment (Fig. 3). Thermal time required (since emergence) to reach 50% and 80% radiation interception for the Bare, Tops and Trash treatments were 300, 375 and 450°Cd and 700, 750 and 850°Cd, respectively. All treatments intercepted close to 100% of incoming radiation flux towards the end of the growing season. The value of 300°Cd to reach 50% canopy for the Bare treatment is very close to the value of 250°Cd that is normally used in the Canesim simulation model to simulate canopy development of Cultivar NCo376 on bare soil (Singels and Donaldson, 2000).

In the ratoon crop, thermal time required to reached 50% and 80% radiation interception for the Bare, Tops and Trash treatments were 450, 550 and 600°Cd and 750, 800 and 800°Cd, respectively (Fig. 3). The delay in application of residue material in the plant crop could explain why thermal

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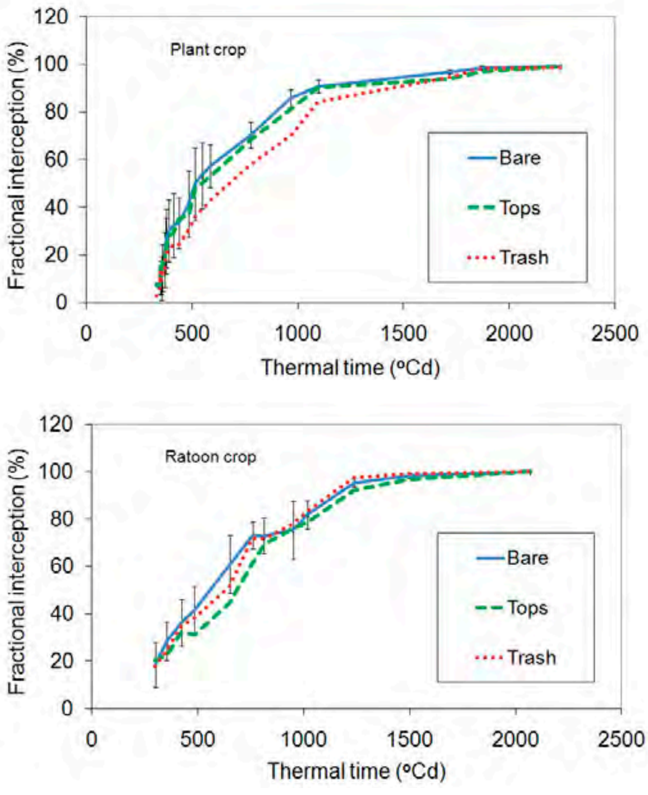

Figure 3
Fractional interception of photosynthetically active radiation as a function of thermal time for the different treatments for the plant and first ratoon crops. The sampling error is indicated by the standard error for the Bare treatment.

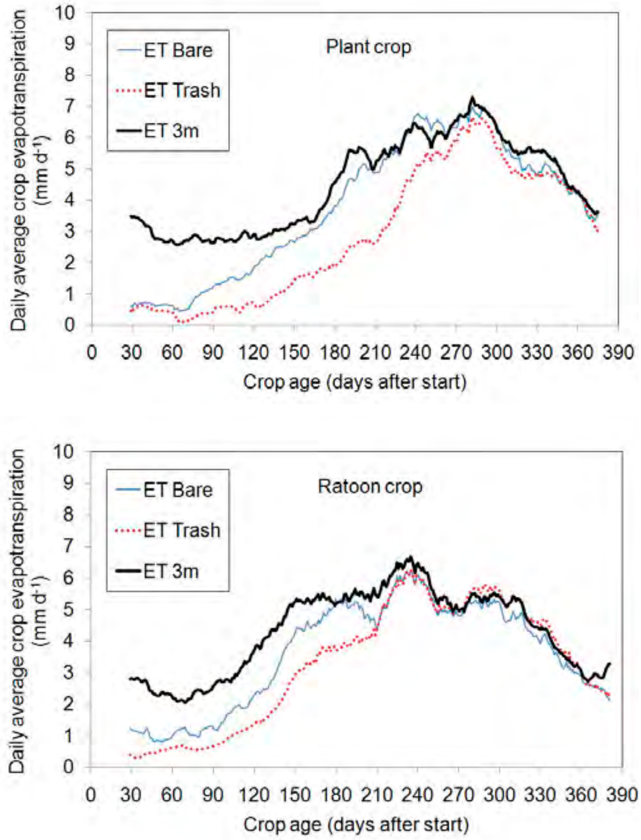

Figure 4
Daily average crop evapotranspiration (ET_{crop} - 30 day moving average to demonstrate treatment differences clearly) for the plant and first ratoon crops for the Bare and Trash treatments. Reference cane evapotranspiration (ET_{3m}) is also shown.

time requirements (to reach 50 and 80% radiation interception) of the ratoon crop were larger than that of the plant crop. One would normally expect plant crop thermal time values to be larger than that of the subsequent ratoon crop.

We recommended that the thermal time requirement for reaching 50% canopy cover (a parameter in the Canesim model) be increased by 2°Cd per % residue cover for ratoon crops. This translates to a delay of 100 and 190°Cd for the Tops and Trash treatment, assuming a cover of 50% and 95%, respectively, compared to observed delays of 100 and 150°Cd.

Evapotranspiration

Daily average ET_{crop} trends are presented in Fig. 4 and seasonal totals of ET_{crop} and water balance components (irrigation, drainage and rainfall) in Table 3.

In the plant crop, the presence of residue layers had a marked effect on daily ET_{crop}. During the period leading up to full canopy closure, daily ET_{crop} in the Tops treatment was reduced by an average of 16% (196 mm), and that of the Trash treatment by 17% (215 mm), compared with the Bare treatment (Fig. 4). After full canopy closure, daily ET_{crop} of all treatments was fairly similar. As a result, seasonal ET_{crop} was reduced by 19% and 23% for the Tops and Trash treatments, respectively (Table 3). A significant amount of drainage was measured in the Trash treatment. This was partly due to frequent irrigation during early establishment to ensure good germination. In the Trash treatment rainfall also frequently fell on the same day as the irrigation or shortly after.

In the first ratoon crop, residue layers also had a marked effect on ET_{crop} in the pre-canopy phase, although to a lesser extent than in the plant crop. Daily average ET_{crop} of the Tops treatment was reduced by an average of 15% (155 mm) and that of the Trash treatment by 17% (177 mm) compared to the Bare treatment (Fig. 4). After full canopy closure, daily ET_{crop} of all treatments was fairly similar. As a result, seasonal ET_{crop} was reduced by 14% and 10%, respectively, for the Tops and Trash treatments (Table 3). Some of the drainage in the Tops and Trash treatments could have been prevented by more accurate scheduling of irrigation.

In the plant crop, ET_{crop} (as determined from lysimeter recording) was substantially lower than the sum of irrigation plus rainfall minus drainage (Table 3). This is ascribed to the fact that the season started with dry soil profiles and ended with soils being at field capacity, implying that the change in soil water content over the season (not measured) was large and positive. Evidence for high soil water contents at harvest is the drainage that was observed up to 11 days before harvest in all treatments. In addition a very short drying off period of 21 days was applied, compared to 62 days in the ratoon crop. In the ratoon crop, ET_{crop} matched the seasonal water balance more closely.

FAO56 (Allen et al., 1998) and Penman-Monteith (McGlinchey and Inman-Bamber, 1996) crop evaporation coefficients for the period of partial canopy differed significantly between treatments (Fig. 5 and Table 4). This is due to (1) a decreased transpiration due to a reduction in the

Table 3
Seasonal totals of the different water balance components (*I* - irrigation, *R* - rainfall, *D* - deep drainage) and lysimeter-recorded crop evapotranspiration (ET_{crop}) for the different treatments and crops

Crop	Treatment	ET_{crop} (mm)	$I+R-D$	*I* (mm)	*R* (mm)	*D* (mm)
Plant	Bare	1 378	1 605	1 062	623	79
	Tops	1 110	1 341	897	623	179
	Trash	1 061	1 211	976	623	388
Ratoon	Bare	1 341	1 375	901	535	61
	Tops	1 153	1 210	773	535	98
	Trash	1 204	1 183	731	535	84

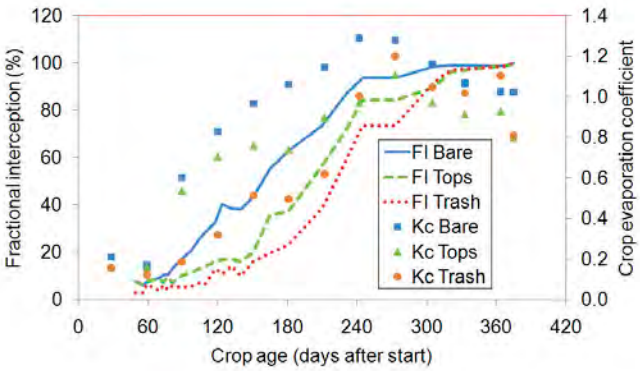

Figure 5
Measured fractional interception of photosynthetic active radiation as affected by different residue layers in the plant crop. Corresponding monthly average FAO crop evaporation coefficients ($Kc_{FAO} = ET_0/E_{crop}$) are presented by the symbols.

interception of radiation in residue treatments, as is evident from *Fi* observations (for the plant crop), and (2) reduced evaporation from the soil in the residue treatments. The average (for the plant and ratoon crop) reduction in Kc_{FAO} values for the Tops and Trash treatments were 19 and 43% for Initial phase, and 23 and 38% for the Development phase, respectively (Fig. 5 and Table 4). Kc_{FAO} values for the late season phase were on average 26 and 28% lower in the Tops and Trash treatments, respectively, compared to the Bare treatment. Reductions in Kc_{3m} due to residue layers were very similar to that in Kc_{FAO}. These results emphasise the need for adjustments to *Kc* to account for residue layers for the accurate calculation of ET_{crop}.

Allen et al. (1998) proposed a 5% reduction in evaporation component (*Ke*) for each 10% of the surface that is covered with organic mulch. Assuming a 50% and 95% cover for the Tops and Trash treatments, respectively, this amounts to reduction of 25% and 47.5%, which agrees well with observed reductions in *Kc* for the Initial and Development phases mentioned in the preceding paragraph. It also agrees well with the observed reduction in *Ke* for the Late phase in the Tops treatment (26%). The observed reduction in the Trash treatment for the Late phase was much less than expected (28%). The reason for this discrepancy is not known, although the observed rapid reduction in residue layer thickness prior to full canopy (data not presented) could have led to soil coverages below the assumed 50% and 95% for Tops and Trash treatments. We conclude that these results confirm the rule proposed by Allen et al. (1998) and it is recommended that crop growth and irrigation models use it for calculating evapotranspiration of crops grown on residue-covered soils.

Another observation is that observed *Kc* values for the Initial phase were lower for the plant crop than those for the ratoon crop. For example, $Kc_{FAO} = 0.16$ (averaged over the 3 treatments) for the plant crop, compared to $Kc_{FAO} = 0.34$ for the ratoon crop. It may be necessary to refine FAO56 tables (Allen et al., 1998) for this phase to acknowledge the difference between crop classes and we recommend that the value for plant crops be set equal to half that of the ratoon crop. This adjustment should save practitioners water when irrigating plant crops.

Kc values for the Mid-Season phase for the different treatments did not differ substantially between treatments. The average Kc_{FAO} values were 1.12, 1.01 and 1.13 for the Bare, Tops and Trash treatments, respectively, which are lower than the adjusted Kc_{FAO} value of 1.18 and 1.19 that was calculated for the climatic conditions in the plant and ratoon crops, respectively, according to the FAO56 methodology:

$$Kc_{FAO}\,(\text{adjusted}) = Kc_{FAO}\,(\text{table}) + (0.04\,(U_2 - 2) - (0.004\,(RH_{min} - 45)))*(h/3)^3 \qquad (3)$$

where:

RH_{min} is the phase average (i.e. the average calculated over the duration of each crop development phase as defined in Table 4) minimum relative humidity (52.6% in the plant crop and 53.6% in the ratoon crop)

Table 4
Evaporation coefficients for ET_0 (Kc_{FAO}) and ET_{3m} (Kc_{3m}), as determined in this study, compared to *Kc* and *Kcb* values reported by Allen et al. (1998). Average interception of radiation (*Fi*) for different developmental phases are also provided

					Bare			Tops			Trash		
Phase	FAO56 Duration (d)	Duration this study (d)	FAO *Kc*	FAO *Kcb*	Kc_{FAO}	Kc_{3m}	*Fi*	Kc_{FAO}	Kc_{3m}	*Fi*	Kc_{FAO}	Kc_{3m}	*Fi*
Initial	P 50	70	0.4	0.15	0.20	0.17	0.14	0.15	0.13	0.04	0.12	0.10	0.01
	R 30	55			0.43	0.44	0.15	0.36	0.43	0.08	0.24	0.21	0.11
Develop	P 170	173	-	-	1.03	0.88	0.45	0.81	0.69	0.32	0.56	0.47	0.24
	R 150	153	-	-	0.94	0.81	0.48	0.71	0.61	0.43	0.66	0.57	0.45
Mid	P 180	121	1.25	1.2	1.14	0.99	0.97	0.98	0.86	0.91	1.09	0.95	0.89
	R 220	151			1.10	0.97	0.96	1.04	0.90	0.96	1.17	1.01	0.97
Late	P140	11	0.75	0.7	1.18	1.10	1.00	0.79	0.76	1.00	0.60	0.57	1.00
	R 60	16			0.97	0.82	1.00	0.81	0.67	1.00	0.95	0.79	1.00

P - plant crop; R - ratoon crops

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U_2 is the phase average wind speed at 2 m height (1.19 m·s^{-1} in the plant crop and 1.28 m·s^{-1} in the ratoon crop)
h is phase average crop height (3.07 m in the plant crop and 2.84 m in the ratoon crop) and Kc_{FAO} (table) is the Kc_{FAO} value from the FAO56 tables (1.25).

Inman-Bamber and McGlinchey (2003) confirmed the suitability of using a Kc_{FAO} value of 1.25 but also pointed out that the value was reduced at times to 1.1, due to high humidity and low wind speed. These results (for the Mid-Season phase) are all in general agreement.

The Kc_{3m} values for the Mid-Season phase are close to unity for the Bare and Trash treatments, supporting the validity of the methodology developed by McGlinchey and Inman-Bamber (1996) to determine sugarcane evapotranspiration. The Kc_{3m} values of the Tops treatment was slightly lower than one.

The Kc_{FAO} values for the Late Season phase for the Bare treatment were substantially higher than the FAO56 recommendation (Table 4), confirming a similar result from Inman-Bamber and McGlinchey (2003). The duration of this phase was also substantially shorter than suggested by FAO56. We believe that this phase only starts when the 'drying-off' process is initiated, after the last irrigation.

It could be useful to derive relationships between *Kcb* (*Kc* for dry surface conditions) and *Ke* (the soil evaporation coefficient) on one hand, and *Fi* on the other hand. Crop models that routinely calculate *Fi* and hence using it to derive accurate daily estimates of *Ke* and *Kcb* could improve the accuracy of ET_{crop} estimates. However, day-to-day changes in *Kc* values were unfortunately too variable to allow meaningful derivation of *Kcb* (*Kc* for dry surface conditions) or *Ke* values.

Yield and water use efficiency

In both the plant and ratoon crop, cane yields of the residue treatments were lower than the Bare treatment (between 4% and 15%), although this was not statistically significant (see Table 5).

Published reports of yield responses to a residue layer are inconclusive (Morandini et al., 2005). Research work carried out in various sugarcane areas of the world has shown that the retention of a layer of crop residues following green cane harvesting can have considerable yield responses in low rainfall areas and little or negative responses in super-humid and low-temperature areas (De Beer et al., 1995). 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 dryland conditions. Gosnell and Lonsdale (1978) came to similar conclusions with low levels of irrigation in Zimbabwe, but showed a substantial yield depression with residue retention when irrigation and fertiliser practices were not adjusted relative to burnt field plots.

In both the plant and ratoon crops the WUE values of residue treatments were similar to that of the Bare treatments in spite of achieving lower cane yields (Table 5). Seasonal ET_{crop} values of residue treatments in the plant and ratoon crop were on average 21% and 12% lower, as compared to the Bare treatment (Table 3). All treatments had slightly higher WUE values in the ratoon crop, mainly due to the higher cane yields as compared to the plant crop.

The WUE values reported in Table 5 compare well with that reported in the literature. Many published responses are in the 6 to 12 kg·m^{-3} range (Thompson, 1976; Kingston, 1994; Inman-Bamber et al., 1999), but higher values of 22 to 48 kg·m^{-3} are also reported (Robertson and Muchow, 1994; Robertson et al., 1997; Inman-Bamber et al., 1999) depending on the irrigation scheduling strategy, seasonal rainfall and stage of development.

Table 5
Final cane yield as well as water use efficiency (cane yield/crop evapotranspiration, WUE) for the different treatments of the plant and ratoon crop. Values with common superscripts are not significantly different (t-test, *P*=0.05)

Crop	Treatment	Yield (t·ha^{-1})	WUE (kg·m^{-3})
Plant	Bare	126^a	9.1
	Tops	120^a	10.8
	Trash	121^a	11.4
Ratoon	Bare	171^b	12.8
	Tops	145^b	12.6
	Trash	159^b	13.2

Cautionary notes

Canopy development and yield data suggest that cane growth on the lysimeters was different from that of the surrounding cane. This may have been caused by:

- The different irrigation scheduling methods followed to irrigate the surrounding cane (drip irrigated according to the calculated demand of the Bare treatment) vs. the lysimeter area (sprinkler irrigated from a watering can according to the calculated demand for each treatment).
- Differences in rooting depth and density. Howel et al. (1985) pointed out that crop rooting pattern in lysimeter tanks, as influenced by irrigation regime, lysimeter depth and drainage system, may not reflect the field situation and as a result cause crop growth and water use to be different from that of the field.
- The lysimeter design. Metal sides of the lysimeter may have impacted on the thermal regime of the soil and the vegetation within the lysimeter (Grimmond et al., 1992).

Conclusions

We acknowledge that the replication in this experiment was not ideal. Residue depth and crop growth parameter measurements were only replicated 3 times in the plant crop and twice in the ratoon crop, while water use estimates could not be replicated because only 3 lysimeters were available. The non-significance of some treatment differences therefore needs to be interpreted with caution.

It should also be noted that the results obtained here are for cultivar N14. This cultivar is known to be more tolerant than many others to a residue layer in terms of germination, tillering and early growth. Adjustments to canopy development and crop water use algorithms should take this cultivar impact into account. Notwithstanding these limitations, we believe that the study produced useful information. The main findings were:

- Initial stalk population in the plant crop, and radiation capture in the plant and ratoon crop, were affected negatively by crop residue layers, but without reducing final stalk population and cane yield significantly. Peak stalk population occurred later in crops grown in residue layers, but peak and final stalk populations seem unaffected.

- ET_{crop} was reduced by both residue layers, mainly through reduced evapotranspiration during the pre-canopy phase. A full trash layer reduced ET_{crop} more than a layer of cane tops and the impacts were greater in the plant than in the ratoon crop.
- Decreased cane yields were observed in residue treatments but these were not statistically significant.
- Increased drainage was observed under residue layers, emphasising the importance of accurate irrigation scheduling to avoid water logging.
- The FAO56 methodology for calculating *Kc* values for the Initial, Development and Mid-Season phases was supported by the results obtained here. *Kc* values were significantly reduced by residue layers. The results from this study support the suggestions by Allen et al. (1998) to account for this. The *Kc* values obtained for the Late Season phase were higher than that proposed by FAO56.
- The methodology of McGlinchey and Inman-Bamber (1996) for calculating Mid-Season sugarcane evapotranspiration were also validated by the results of this study.

It is important that irrigation scheduling practices be adjusted to realise the potential water savings of sugarcane production systems that make use of residue layers. This study provides the information required to do that. Evaporation coefficients used in irrigation planning and management should be adjusted according to the rule proposed by Allen et al. (1998), by assuming a 50% and 95% soil cover for tops and full trash residue layers. The information could also be used to improve the ability of the crop models to simulate crop growth in a residue layer cropping system. Thermal time requirements for canopy development and tiller production need to be adjusted particularly for plant crops.

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