EFFICIENT USE OF WATER RESOURCES IN SUGAR PRODUCTION: A PHYSIOLOGICAL BASIS FOR CROP RESPONSE TO WATER SUPPLY

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SUMMARY

Efficient use of water (both rainfall and irrigation) is central to profitable and sustainable sugarcane production. To maximise profitability in fully irrigated systems, the application of water needs to be matched with crop water requirements for cane and sucrose production, as moderated by climate and management inputs. Under supplementary irrigation, the timing of water application in relation to growth stage and climatic conditions is critical to maximising the economic benefit from a limited water resource. In rainfed systems, profitability can be maximised by matching management inputs to the production potential and production risk as determined by rainfall variability in different climates. Efficient use of water will also minimise possible deleterious environmental impacts, by avoiding excess runoff, deep drainage and leaching of agricultural chemicals. Whilst useful advances have been made in irrigation technology under full irrigation, little information was available to determine the cane and sugar yield response to timing of rainfall and irrigation across locations and seasons particularly under supplementary irrigated and rainfed production systems.

Accordingly, this project aimed to conduct strategic research to develop quantitative information on the impact of water shortage at different growth stages on cane and sugar yield. This information was then used in simulation analysis in this project to assess the consequences of different irrigation strategies in relation to amount and timing of water application, cost of water and price of sugar.

This project has provided quantitative information on how the yield determining processes in terms of leaf area production, biomass accumulation and partitioning to stalk biomass and cane yield, and sucrose accumulation and sucrose concentration on a fresh and dry weight basis, are impacted by water supply. Enhanced response functions have been incorporated into the systems model APSIM-Sugarcane. Whilst all field experimentation in this project was conducted in the Burdekin, the on-flow result of enhancement of APSIM-Sugarcane will allow extrapolation to other regions in terms of the development of management strategies that best utilise the water resources available in fully irrigated, supplementary irrigated and rainfed farming systems to maximise profitability and minimise environmental impact.

A key finding of the project has been the comparative insensitivity of sugarcane yield at harvest to early season water deficit. The implication of this finding is that considerable water savings could be made through less frequent irrigation in the early stages of crop growth in fully irrigated areas such as the Burdekin.

In contrast to early season water deficit, water deficit imposed when the canopy is well established had a significant impact on yield. Not only was total biomass, stalk biomass and stalk sucrose decreased, but partitioning was also affected with reduced proportion of stalk biomass in total biomass and reduced sucrose concentration.

An APSIM-Sugarcane simulation analysis was conducted to assess the risks of yield loss resulting from saving water by withholding irrigation at different leaf appearance phases. The analysis indicates that there are possibilities for saving water in the Burdekin by using irrigation sparingly before 10 leaves appear on primary shoots provided the soil profile is filled after harvesting. This has implications not only for reducing water use and increasing water use efficiency, but also for reducing deep drainage during the early stages of crop development while nutrients are being rapidly taken up by roots.

This project has greatly increased understanding of the physiological basis of drying-off in sugarcane prior to harvest. Key findings are:

- Sucrose concentration changes within a few weeks of drying, whereas more prolonged drying is required to lower cane yield. While stalk desiccation under drying-off lowers cane yield, this is mitigated somewhat by a greater proportion of the stalk being millable.

- Increases in sucrose concentration can be attributed equally to increases in dry matter content and sucrose DM concentration. These changes are most noticeable at the base and near the top of the stalk.
- Interruption of drying-off by rain can reverse increases in sucrose concentration, due to resumption of stalk growth.

These findings on the physiological response to drying-off were used in an APSIM-Sugarcane analysis to determine the economically-optimum duration of drying-off for irrigated sugarcane at Ayr for a range of harvest dates and soil types. This duration varied with harvest date and soil type (range 29 to > 150 days). When drying-off for a given duration, there are some seasons when, due to climatic variability, drying-off is not long enough or for too long. Overall, it was shown that drying-off to achieve a 4% reduction in cane yield in 50% of seasons seems to minimise risk. The model output was also used to indicate a likely rule-of-thumb for drying-off management that could be applied across soil types and harvest times taking account of rainfall during the drying-off period.

This project has enhanced knowledge on sugarcane response to water supply through three publications in international journals and three publications in the Proceedings of the Australian Society of Sugar Cane Technologists.

This project has successfully achieved its aims by enhancing knowledge on the impact of water supply on the yield determining processes and by facilitating the development of management strategies that best utilise the water resources available to the Australian sugar industry.

BACKGROUND

Although sugar is produced in the some of the most humid regions of Australia, water remains a major limitation to production. Experience in other rainfed and irrigated production systems in Australia has shown that use of both surface and ground water resources can easily have long term impacts on future productivity of the system. There is no reason why the sugar industry should be exempt from the consequences of ignorance or mismanagement in regard to the hydrological cycle. At the outset of this project, it was clear that efficient use of water (both rainfall and irrigation) was central to profitable and sustainable sugarcane production. Maximum profitability in fully-irrigated systems required the application of water to match crop water requirements for cane and sucrose production, as moderated by climate and management inputs. Under supplementary-irrigation, the timing of water application in relation to growth stage and climatic conditions was thought to be critical for maximising the economic benefit from a limited water resource. In rainfed systems, profitability could be maximised, by matching management inputs to the production potential and production risk as determined by rainfall variability in different climates.

During the life of this project, there has been increased public awareness of water as a production factor and more importantly as a national resource and major component of a fragile environment. The National Agenda for Water Reform has moved in the direction of full recovery of water supply cost, separate water and property rights, specific water allocation to the environment and increased water use efficiency in agriculture. A new initiative on water use efficiency has been launched by DNR who have asked the sugar industry to make 60,000 Ml available for irrigation from existing water resources. The products of CTA016 are therefore highly pertinent for the current focus on water use in the Australian sugar industry.

Radiation and temperature as key sugarcane production factors were the subject of SDRC Projects CTA004 and CTA012. These projects have led to a better understanding of the processes of yield and CCS accumulation under conditions of high water and nutrient inputs. Limits to yield in terms of these climatic factors have been identified. Crop growth mechanisms driven by radiation and temperature have been established and captured in mathematical expressions which were necessary for the development of the Sugarcane module now in use within the APSIM modelling environment. In CTA016, the strategic research approach of the earlier projects was extended to water as production factor. Water has of course been extensively researched in the sugar industry largely from the perspective of irrigation requirements. CTA016 was designed to build on past research by going into more detail in order to improve our knowledge of the soil-plant-atmosphere continuum of water. Knowledge of the mechanisms identified as important have been formalised mathematically and incorporated into the APSIM-Sugarcane modelling environment. This project has thus augmented the output from the earlier projects by adding the water balance and crop response to water stress to modelling capability. This capability was then used extensively in developing practical guidelines for saving water during drying off and during early stages of development. This modelling capability was also tested and used in a later more applied project (CTA018) to facilitate more efficient use of limited water supplies under supplementary irrigation.

OBJECTIVES

This project was designed to augment outputs from CTA014 and CTA012 by accounting for the effects of variable water supply on yield, thus allowing the scope for yield improvement to be assessed for fully-irrigated, and supplementary-irrigated and rainfed production systems. Whilst useful advances have been made in irrigation technology under full irrigation, little information was hitherto available to determine the cane and sugar yield response to timing of rainfall and irrigation across locations and seasons, particularly under supplementary-irrigated and rainfed production systems.

Accordingly, this project, conducted mainly in the Burdekin, was to develop quantitative information on the impact of water shortage at different growth stages on cane and sugar yield, using simple modelling technology to allow the responses to be extrapolated across locations and seasons. This information was to be used in simulation analysis to assess the consequences of different irrigation strategies in relation to amount and timing of water application, cost of water and price of sugar. It was possible in this project to investigate the feasibility and consequence of water savings during the early stages of crop development and during the maturation phase. Consequences for CCS and increased profitability were also assessed.

The project also aimed to provide information for interpreting and extending the results of other projects by the use of crop and soil models, particularly those concerned with movement and uptake of nitrogen in the soil profile (relevant to fertiliser management and nitrogen leaching).

RESEARCH METHODOLOGY

Early water stress - Field experiments (Burdekin)

Four field experiments were conducted at CSR Kalamia Estate, Ayr, Australia (19.57^{o}S, 147.4^{o}E) during the 1995/96 and 1996/97 sugarcane-growing seasons. Details of site, cultivar, crop management, experimental treatments, and dates of crop sampling are given in Table 1. Experiments 1 to 3 were replicated designs, which permitted statistical comparisons among the various treatments within an experiment. Experiment 4 was unreplicated. While the design of Experiment 4 did not allow statistical comparisons among treatments, the large number of treatments (9) allowed the establishment of trends in crop variables in response to an increasing water deficit.

Sites and soils

The soil at Field 11 (Experiments 1, 2 and 4) consisted of 30cm of clay loam overlying coarse sand (USDA soil taxonomy: Dystropept). This soil holds 73 mm of plant available water in the root zone (0-150 cm), determined as the difference between soil water content soon after irrigation, and after an extended drying cycle when the crop ceased growing (see pp.8-9 and Table 2). The soil type at field 62 (Experiment 3) was a silt loam (USDA soil taxonomy: Dystropept), with approximately 150 mm of plant available water (Table 3).

Crop management and treatments

Crops were grown according to accepted local practice for sugarcane culture (Anon, 1995). Inputs of fertiliser were high so as to prevent nutrient deficiency. Pests, diseases and weeds were controlled to negligible levels.

Water deficits were imposed by withholding irrigation. In well-watered treatments or in water deficit treatments during times when irrigation was not being withheld, irrigation was applied via surface flooding, whenever the soil matric potential at 30 cm depth, as determined by a ceramic-tip suction sampler, reached 60 kPa. The volume of water applied was always enough to bring the soil to the drained upper limit of plant available water capacity on both soil types.

Table 1. Details of site, crop cultural and experiment design details for the four water deficit experiments conducted at Ayr.

	EXPERIMENT 1	EXPERIMENT 2
Site	Field 11	Field 11
Land history	Fallow since 1990	Previous crop was Experiment 1
Date of crop start	Planted *12 April 95*	Ratooned *17 July 96*, first watering *29 July 96*
Cultivar	Q96	Q96
Fertiliser	*12 April 95* – diammonium phosphate 250kg/ha *1 Sept 95* – potassium sulphate 300kg/ha *6 Sept 95* – urea 300kg/ha	*29 July 98* - 494kg/ha of urea
Treatments	1. Well-watered. 2. Early-season stress: irrigation withheld *14 April 95* until 62 mm rain on *2 to 8 Aug 95*. 3. Mid-season stress: irrigation withheld *28 Sept to 15 Dec 95*.	1. Well-watered 2. Early-season stress: irrigation withheld *14 Aug to 26 Nov 96* 3. Mid-season stress: irrigation withheld *26 Nov 96 to 21 Jan 97*.
Replication	4	4
Plot size	6 rows x 50m	6 rows x 50 m
Pest, weed and disease control	*12 May 95* - weeds 2.25kg/ha atrazine (900g /kg) 0.6 kg/ha diuron (900g/kg) *1 Sept 95* – canegrubs chlorpyrifos 20 kg/ha. *26 Sept 95* - grass weeds 3.1kg/ha atrazine (900g /kg) 1.26 kg/ha diuron (900g/kg), 2.06 kg/ha pendimethalin (330g/kg)	*8 Oct 96* - weeds 2.0 kg/ha 24d-amine (800g/kg), 2.0 kg/ha diuron d.f. (900g/kg), 2.75kg/ha atrazine d.f. (900g/kg), 9kg/ha trifluralin (400g/l). *2 Dec 96* - 6.0 kg/ha ametryn (500 g/ka), 3.35 kg/ha atrazine.
Other field operations	*6 Sept 95* - hilling up	*30 Sept to 7 Oct 96* - hilling up
Drying-off before harvest	Irrigation withheld from *9 May 96* (68 days)	Irrigation withheld from *5 May* (97 days)
Mechanical crop harvest	*17 July 96*	*12 Aug 97*
Crop samplings	*20 June, 15 Aug, 15 Oct, 5 Dec 95, 7 Feb, 27 Mar, 4 June 96* (412 days crop duration)	*26 Nov 96, 21 Jan, 1 April, 10 July 97* (353 days crop duration)
	EXPERIMENT 3	EXPERIMENT 4
Site	Field 62	Field 11
Land history	Continuous sugarcane prior to 6 months fallow	Previous crop was Experiment 1
Date of crop start	Planted *21 April 95*	Ratooned *17 July 96*, first watering *29 July 96*
Cultivar	Q117	Q96
Fertiliser	*21 April 95* - 494kg/ha of urea	*29 July 96* - 494kg/ha of urea
Treatments	1. Well-watered throughout. 2. Well-watered until *22 Nov* then irrigated on *15 and 29 Dec, 26 April 96*. 3. Well-watered until *22 Nov* then irrigation withheld until harvest.	All plots irrigated after ratooning until *13 Aug 96*, then irrigation progressively withheld to achieve 70, 117, 126, 138, 146, 167, 182, 207, 239 days without irrigation, prior to irrigation on *7 April 97*.
Replication	2	None
Plot size	8 rows x 20 m	4 rows x 50 m
Pest, weed and disease control	*31 Aug 95* – canegrubs chlorpyrifos 20 kg/ha. *27 Oct 95* - weeds 2.22 kg/ha pendimethalin (330 g/ka), 1.35 kg/ha diuron d.f. (900g/kg), 3.4 kg/ha atrazine d.f. (900g/kg) *27 oct 95* - weeds 1.74 kg/ha ametryn (500 g/ka), 1.4 kg/ha 24d ester.	*8 oct 96* - weeds 2.0 kg/ha 24d-amine (800g/kg), 2.0 kg/ha diuron d.f. (900g/kg), 2.75kg/ha atrazine d.f. (900g/kg), 9kg/ha trifluralin (400g/l).
Other field operations	*1 Sept 95* - hilling up	*30 Sept To 7 Oct 96* - hilling up
Drying-off before harvest	Irrigation withheld from *30 April 96* until harvest (13 days)	Irrigation withheld from *5 May 97* before final harvest (97 days)
Mechanical crop harvest	*13 May 96*	*12 Aug 97*
Crop samplings	*16 Nov 95, 6 Feb, 23 April, 11 June 96* (410 days crop duration)	*10 July 97* (353 days crop duration)

Experiments 1 and 2 were conducted on the plant and ratoon cycles of the same crop at Field 11. Ratooning occurred following burning and mechanical harvesting. In Experiments 1 and 2, there was a well-watered control and two water deficit treatments. The early-season treatment was designed to impose stress during the tillering phase, while the mid-season treatment was intended to span the start of stalk elongation (Fig. 1). Carry-over effects of water deficit treatments from the plant crop to the first ratoon were considered negligible after measurements of stalk population density before (see Table 4) and after harvest of the plant crop showed no effects of the previously-imposed water deficit treatments. In Experiment 3, three levels of water deficit were imposed: well-watered, and two treatments with irrigation withheld mid-season to achieve an intermediate and severe level of yield reduction. In this experiment, cultivar Q117 was used, whereas cultivar Q96 was used in the other 3 experiments. Experiment 4 was unreplicated, with 9 treatments where irrigation was withheld starting at different stages of crop development. The 9th treatment was effectively well-watered, as substantial rain occurred soon after irrigation was withheld. Significant rainfall (67 mm) occurred on 31 January 97 (194 days after ratooning), which effectively ended all the deficit treatments. Thereafter all treatments were well-watered. In all experiments, consistent drying-off management was attempted, so that there would be no confounding effect of late-season irrigation management on yield and sucrose accumulation.

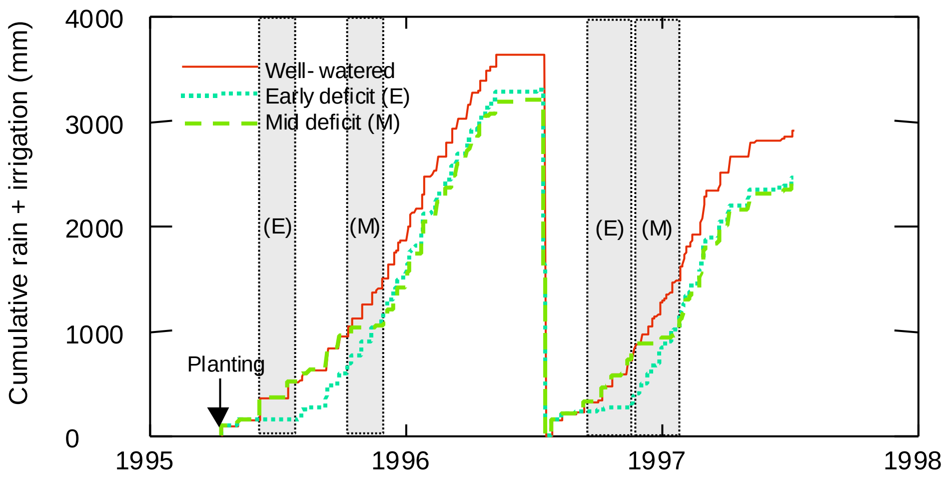

Figure 1. Cumulative rain plus irrigation for well-watered, early and mid season deficit treatments for a plant and ratoon crop of Q96 in Experiments 1 and 2 at Kalamia

Measurements

The number of live stalks per m^2, green leaf area index, aboveground biomass and components were determined following the procedure described by Muchow *et al.* (1993). At each sampling, four inner rows each 2.5 m in length (15 m^2) were cut at ground level from each plot. Load cells were used to determine the total fresh weight (± 0.1 kg) in the field. A 15 stalk sub-sample, was taken and partitioned into green leaf blades, dead leaf and dead sheaths (defined as trash), millable stalks, and cabbage (defined as the immature top of the stalk plus all green leaf sheaths). The fresh weight of each component was determined. Fresh millable stalk (cane) yield was calculated as the product of the field quadrat total fresh weight and the proportion of millable stalks on a fresh weight basis. Then the material from the leaf blades, cabbage and millable stalk components was fibrated (finely-chopped) using a cutter-grinder, and two representative subsamples were placed in 850 ml aluminium foil trays for drying at 80°C. After the dry matter content was determined, the green leaf, trash, millable stalk, and cabbage dry matter yields on a dry weight basis were determined per unit land area from the total fresh weight from the 10 m length of row, the component proportion of the total above-ground material on a fresh weight basis, and the component dry matter content. The net aboveground biomass was calculated as the sum of the individual components. In addition, the number of visible nodes was counted with and without green fully-expanded leaves, on sub-samples taken from field quadrats, A green leaf was defined as that with at least 50% green area.

Two 500g samples were taken for sucrose analysis from the fresh fibrated material of millable stalk. The fibrated material was placed into a steel cylinder cage, and juice was expressed by applying 15.7 MPa for 60 seconds using a Carver Press (Model M, F.S. Carver Inc., Wabash, Indiana, USA). The fresh and dry weight of the remaining fibrated material (biscuit) was determined for calculation of fibre content. Brix was determined on the juice using an automatic temperature compensated (20^{o}C) Brix meter (Model PR-1, Atago Pty Ltd, Tokyo, Japan). For the determination of pol on the juice, 2.5g of lead acetate was thoroughly mixed with the juice, the juice was filtered through a Whatman No. 91 filter paper, and the filtrate was passed through a Polarimeter (Polartronic, Schmidt and Halasch, Berlin, Germany). Sucrose concentration in the juice was calculated from the pol reading using the following polynomial equation, developed on a wide range of samples in other experiments (projects CTA014 and CTA012).

$$S = (-6.517+ 25.3*P -0.011*P^2 + 2.937* B -0.207* B^2),$$

Where S is the sucrose percentage in juice, P and B are the pol and brix in expressed juice, respectively. Sucrose DM concentration was calculated from the sucrose concentration in the juice and the stalk dry matter content, ignoring the insignificant amount of sucrose remaining in the pressed fibre biscuit.

In order to follow the dynamics of tillering in detail, the number of stalks with at least one fully-expanded leaf was measured in Experiment 1 from a 20 m row length, at weekly intervals.

In Experiments 1 and 2, radiation interception was measured using tube solarimeters. On 12 July 1995 (90 DAP) in Experiment 1, and 2 October 1996 (77 DAP in Experiment 2), two pairs of two tube solarimeters (Type TSL, Delta-T Devices, Cambridge, Great Britain) were placed diagonally across the 1.5 m inter-row in each replicate at ground level. A reference tube solarimeter was placed above the crop. The tubes were raised over time to be below the last green leaf, so that radiation interception by green leaf only was measured, and not that additionally intercepted by stalk and trash. The tube solarimeters were used to record the incident and transmitted short-wave radiation (0.35-2.5 μm), respectively, at 2 min intervals. Daily totals and individual tube-calibration factors were used to calculate the fraction of the incident radiation intercepted by the crop. The amount of radiation intercepted was calculated as the product of the daily fraction intercepted and incident radiation. Seasonal radiation use efficiency was calculated as the biomass produced at final harvest divided by the total amount of radiation intercepted over the season. In Experiment 1, the solarimeters were removed temporarily from the crop between 31 August and 7 September 1995 to allow for hilling up, and then removed permanently on 16 January 1996 (274 DAP) in Experiment 1 and 1 April 1997 (258 DAP) in Experiment 2, so as to avoid damage to the instruments by lodging. After removing the tube solarimeters, only incident radiation was measured with the reference solarimeter. Intercepted radiation was estimated until final crop sampling using linearly interpolated values of LAI between crop samplings, and an assumed extinction coefficient of 0.4, which was determined from measurements made before the solarimeters were removed. The radiation extinction coefficient was calculated from the value of fractional interception measured in each plot on the date that LAI was measured.

Soil water content from 20 to 150 cm was measured by neutron probe, with the 0-20 cm layer determined gravimetrically. Two access tubes were measured in each plot, one at the mid-point of the 1.5 m inter-row space, and the other situated within the crop row. The probe was calibrated with soil samples taken at the time of installation of the neutron probe access tubes. Gravimetric water content was converted to a volumetric basis with bulk density samples taken from cores where soil volume was considered accurate.

Early water stress – Growth Model validation and application

The APSIM-Sugarcane model (Keating *et al.*, 1999) simulates leaf area development, transpiration and soil evaporation as well as cane yield development. Published data from a 3-year lysimeter experiment (Thompson, 1968) was used to test the validity of APSIM-Sugarcane for estimating crop water demand during early growth stages. We then established the capability of the APSIM-Sugarcane model for assessing the effect of various stress treatments applied during the early stages of crop growth in Experiments 1 and 2. Finally the model was used determine long term risks associated with saving water at various growth stages as defined by number of fully expanded leaves on primary stalks. Leaf number per stalk is a convenient way of determining the growth stage of determinant crops and is less ambiguous than qualitative definitions such as ‘tillering’, ‘rapid growth’ and ‘maturation’ phases that have been used previously (Ellis and Lankford, 1990).

Model parameterisation - phenology

Simulation of phenology was based on thermal time and was identical to that described by Keating *et al.* (1999) when APSIM-Sugarcane was validated for a large number of sugarcane crops. Lateral buds were assumed to be 150 mm deep and these sprouted after 350 °C days for the plant crop and 100 °C days for ratoons crops. Shoots reached the soil surface and produced the first leaf after 190 °C days. Thermal time (TT) required for appearance of the leaf collar of subsequent leaves was based on data from Robertson *et al.* (1998). TT required for leaf 2 to 20 varied linearly from 80 to 105 °C days and TT required for leaf 30 and 40 was 125 and 150 °C days respectively. The model interpolated linearly for the intervening leaves.

Model parameterisation - leaf area

Mean measured stalk populations at harvest were used in the simulations and these were 7.3 stalks m^{-2} for the plant crop (Experiment 1) and 7.8 stalks m^{-2} for the ratoon crop (Experiment 2). APSIM-Sugarcane computes leaf area development on individual cane stalks by considering leaf emergence, area of expanded leaf blades and the proportion of expanding to expanded leaf area. For Q96, leaf area increased linearly from leaf 1 (15 cm^2) to leaf 14 (550 cm^2) and then remained at 550 cm^2 for subsequent leaves. Tillers were assumed to boost LAI by 50% between the appearance of leaf 4 and 10 and then this contribution was deducted as superfluous tillers died. Number of green leaves per stalk was allowed to reach a maximum of 13 and was reduced by simulated water stress and reduced light penetration as described by Keating *et al.* (1999).

Model parameterisation - cane yield

Only dry cane yield was simulated but it is reasonable to assume a water content of about 70 % for mature cane based on the analysis of samples taken at harvest in Experiments 1, 2 and 3 (see Tables 4 and 5). Dry matter allocation to cane stalks started after 1900 °C days from emergence and then 0.7 of daily dry matter was allocated to the stalk.

Determination of plant available soil water content (PAWC)

The most severe stress treatment in the experiments in Field 11 was the mid-season stress of Experiment 2. At the end of this stress period, all except about four mature green leaves per stalk had senesced. Cane stalks cannot endure water stress much greater than this (Inman-Bamber, 1994) and it is unlikely that much water would have been extracted after this stage. Nine days before the end of the late stress period, soil water content (SWC) was as low as had been measured since the trial began (two years before) and this was taken to be the lower limit (LL) of water extraction (see Fig. 4). SWC measured 8 days after 98 mm irrigation had been applied was taken as the drained upper limit. Profile available water content was 73 mm (Table 2). Saturated soil water content (SAT) was determined as 0.5((1-BD/2.65)-DUL) +DUL from Jones and Kiniry (1986).

Table 2. Water content at lower limit (LL) and drained upper limit (DUL) and saturation (SAT). Bulk density (BD) and soil water conductivity coefficient (SWCON) for a clay over sand duplex soil of the Ayr experiment.

Depth interval (mm)	LL ($m\ m^{-1}$)	DUL ($m\ m^{-1}$)	SAT ($m\ m^{-1}$)	BD ($g\ ml^{-1}$)	SWCON	Clay (%)
0 - 200.	0.220	0.329	0.405	1.37	0.5	35.4
200 - 400.	0.160	0.232	0.354	1.38	0.5	37.4
400 - 600.	0.126	0.198	0.319	1.48	0.9	9.4
600 - 900.	0.126	0.174	0.288	1.58	0.9	11.4
900 - 1200.	0.106	0.116	0.235	1.71	0.9	10.8
1200 - 1500.	0.100	0.107	0.200	1.70	0.9	4.8
1500 - 1800.	0.107	0.118	0.200	1.70	0.9	5.8

Root water extraction

The maximum fraction of available soil water that can be extracted in a day (*kl*) was determined by fitting SWC to an exponential decay function of time.

$$SWC = LL + (DUL - LL)\ \exp(-kl(t - t_o))$$

Where t-t_o is the duration (days) of the exponential decay.

Changes in SWC during the severe mid-season stress applied in Experiment 2 were taken as root water extraction and kl (Table 2) was determined from non-linear regression of SWC on t-to (SYSTAT®, Chicago, Il, USA).

Soil water conductivity coefficient (SWCON)

In the APSIM and CERES models, SWCON is the proportion of water above DUL that drains from a layer in a day (Jones and Kiniry, 1986). SWCON was not measured directly but we can assume that the profile drained very rapidly judging by the amount of irrigation requited to get water to the end of the 50 m furrows. During the time taken to apply furrow irrigation, infiltration occurred at a rate equivalent to 456 ± 31 mm/d which is why such large amounts of water were applied with each irrigation (Fig. 1). SWCON was set at 0.5 for the clay horizon and 0.9 for the underlying sand horizon (Table 2).

Long-term simulations

The duplex soil of Experiments 1, 2 and 4 with 73 mm PAWC represents the poorer soils of the Burdekin irrigation region and the soil of Experiment 3 with PAWC = 150 mm represents a reasonably good soil in this area (Holden, 1988). Soil parameters developed for simulations of Experiments 1, 2 and 4 were used for long-term simulations of crops in the duplex soil. Parameters for the silty loam (Table 3) of Experiment 3 (Ybarlucea) were determined less rigorously but were reasonable assumptions for the purpose of determining risks associated with water savings in early to mid stages of crop development.

Table 3. Water content at lower limit (LL) and drained upper limit (DUL) and saturation (SAT). Bulk density (BD) and soil water conductivity coefficient (SWCON) for a silty loam in Ayr.

Depth interval (mm)	LL (m m-1)	DUL (m m-1)	SAT (m m-1)	BD (g ml-1)	SWCON	Clay (%)
0 - 200.	0.14	0.28	0.38	1.43	0.6	24
200 - 400.	0.18	0.27	0.38	1.56	0.6	32
400 - 600.	0.19	0.26	0.38	1.6	0.6	32
600 - 900.	0.16	0.25	0.38	1.6	0.6	26
900 - 1200.	0.12	0.23	0.38	1.6	0.6	20
1200 - 1500.	0.07	0.12	0.38	1.6	0.6	-

Two cropping cycles were simulated. Autumn cycle crops were 'planted' in early May 1960 and ratooned repetitively in early June each year until 1998. Successive ratoons without replanting is not possible in practice but the simulations were designed to consider risks applicable in any one crop in any year without complications associated with variations in harvest date and crop age. Spring cycle crops were also 'planted' in early May 1960 and were then harvested in early October each year. Plant crop simulations were discarded in the analysis. Sufficient N fertiliser was 'applied' in the simulations to eliminate N supply as a cause of N stress. Irrigation was applied (200 mm) to fill the soil profile immediately after each harvest. Thereafter 35 mm was applied to the duplex soil and 70 mm to the loam on a 7-d minimum cycle when soil water deficit exceeded 35 and 70 mm respectively. Drying-off was simulated by withholding water 60-d before harvest. Water stress treatments were applied by withholding water during 5 and 10 leaf appearance phases. The 5-leaf stress treatments were: leaf 1 up to and including leaf 5, leaf 5 to 10, leaf 10 to 15, leaf 15 to 20, leaf 20 to 25 and leaf 25 to 30. The three 10-leaf stress treatments were from leaf 1 to leaf 10, leaf 10 to 20 and leaf 20 to 30.

Late water stress (drying-off) - field experiments

Two experiments were conducted on consecutive ratoon crops of the same cycle on a silty river loam overlying sand (USDA Soil Taxonomy: Dystropept) in Block 8 of J. Ybarlucea's farm at Ayr, Queensland (19.5^{o}S), under furrow irrigation. Variety Q117 was grown for the first and second ratoon from 1994 (harvested 3 July, 1995) to 1996 (harvested 17 June, 1996). Irrigation was withheld from treatments for varying lengths prior to harvest. In the commercial setting of the experiments, it was not possible to have a control treatment that was irrigated until harvest. Instead, a treatment of minimal drying-off was imposed, which comprised of 4 and 5 weeks without irrigation in 1994/95 and 1995/96, respectively.

In the first ratoon (first experiment), the crop was subjected to 3 irrigation treatments:

Treatment 1: minimal drying-off, where irrigation was applied until 4 weeks before harvest (31 May 1995).

Treatment 2: moderate drying-off, where irrigation was applied until 9 weeks before harvest (5 May 1995).

Treatment 3: severe drying-off, where irrigation was applied until 13 weeks before harvest (5 April 1995).

Drying-off in Treatment 2 and 3 was interrupted on 8 May 1995 with a rainfall event of 41mm, otherwise negligible rain fell during the drying-off periods.

In the second ratoon (second experiment), the plots were re-randomised on the same field, as measurements of tiller population regrowth indicated that the previous treatments in the first ratoon had not produced any carry-over effects. The treatments in the second ratoon were:

Treatment 1: minimal drying-off, where irrigation was applied until 4 weeks before harvest (21 May 1996).

Treatment 2: interrupted drying-off, where irrigation was applied until 13 weeks before harvest (20 March 1996); followed by periods of 9 weeks without irrigation, followed by one irrigation that re-filled the profile on 21 May 1996, and then 4 weeks of further drying-off.

Treatment 3: severe drying-off, where irrigation was applied until 13 weeks before harvest (20 March 1996).

Drying-off in Treatments 2 and 3 was interrupted on 13-14 April 1996 and 1 May 1996 with a rainfall event of 29mm and 23mm, respectively. Otherwise, negligible rain fell during the drying-off periods.

Samplings were conducted in each treatment at various intervals prior to final harvest as described above. Measurements were made of cane yield and tops (fresh and dry weight basis), sucrose concentration and CCS of millable stalk, leaf area index, number of fully-expanded live and senesced leaves per stalk, and daily stalk elongation rate. As drying-off treatments were expected to generate different rates of leaf senescence and it is not possible to recover all senesced leaf during field sampling, a method was developed to estimate unrecovered trash. To calculate the weight of unrecovered trash, a count was made on a 15 stalk subsample of the number of nodes without a leaf attached, this was multiplied by the average weight of a senesced leaf determined on 30 leaves taken from neighbouring stalks.

Soil water content from 0.2 to 1.5 m depth was measured with a neutron probe, the 0-0.2 m layer was determined gravimetrically. From these measurements the plant available water capacity of the soil was determined as the difference in profile soil water between the wettest and driest profiles. Daily rainfall was recorded by the farmer 200m from the block.

Late water stress (drying-off)-Growth model application

Targets for drying-off

Design of recommendations for drying-off needs to account for the trade-off between cane yield reduction and increase in CCS. Robertson and Donaldson (1998) attempted to do this by showing that CCS is increased on average by 8% by drying-off, for reductions in cane biomass up to 50%. It can be shown that because CCS is less sensitive than sucrose yield to drying-off, and the Australian cane payment system rewards high CCS, then the return per hectare to the grower in the Australian situation will not be reduced until cane biomass is reduced by more than 8% (Robertson *et al*., 1998). A reduction of cane yield in the vicinity of 4% would provide highest return per hectare, and this also coincides with the level of water stress where sucrose yield either does not change or increases in response to drying-off. It should be noted here that reduction in cane biomass is used in defining the targets, because reduction in the weight of fresh cane is complicated by the variable degree of moisture loss that occurs under drying-off (Robertson and Donaldson, 1998). The 4 and 8% targets are conservative because they do not take account of the money saved through withholding irrigation during the drying-off period, nor the reduced harvesting costs gained by the smaller cane yield. It also ignores any possible benefits gained by the prevention of lodging.

Model simulations

The ability of the APSIM-Sugarcane model to simulate reduction in cane biomass under drying-off has been tested using results of drying-off experiments conducted in Australia and Southern Africa (Robertson *et al*., 1998). Simulation output from APSIM-Sugarcane was used to determine the duration of drying-off required to reduce cane biomass by either 4 or 8% at Ayr for harvest dates on the 15th of each month from May to November, inclusive.

Details of the simulation set-up and analysis of output data has been described by Robertson *et al*. (1998). Three soil types were simulated, having high (210 mm), medium (162 mm) and low (114 mm) amounts of total plant available water in a 150 cm root zone, and span the range in PAWC for Australian sugar-growing soils (Anon, 1991). These PAWC values would correspond to readily-available soil water amounts (Shannon *et al*., 1996) of approximately 80, 60 and 30 mm. A fully-irrigated production system was assumed. For each harvest date, irrigation was then withheld for 0, 30, 60, 90 and 120 days before harvest. Simulations were conducted for 12 month crops of Q117 for the years 1961-1985 for the historical climatic record described by Muchow *et al*. (1997). At Ayr, the months of the traditional harvesting season (June to November) have the lowest monthly rainfall amounts and variability. Rainfall amount and variability is greatest leading up to the May harvest date, and least leading up to the August harvest date.

The cane biomass simulated at harvest for each drying-off regime was divided by that simulated for the corresponding crop that had not been dried-off to calculate the reduction in cane biomass. Values of relative cane biomass were classified in terms of whether they fell into one of 4 classes: (1) 1.0. *i.e.* no reduction; (2) 1.0 - 0.96, *i.e.* < 4% reduction; (3) 0.96 - 0.92, *i.e.* between a 4 and 8% reduction; and (4) < 0.92, *i.e.* > 8% reduction. The duration of drying-off required to reduce cane biomass by 4 or 8% for each soil type will depend upon the crop water demand and the effective rainfall during the drying-off period. Hence, the model was also configured to output for the drying-off period, effective rainfall (rainfall minus deep drainage and runoff) and crop evapotranspiration used by the well-watered control.

RESULTS AND DISCUSSION

Early water deficits – field experiments

Yield components at final harvest

In Experiment 1, no crop variables at final crop sampling were reduced by early-season stress (Table 4). However, the mid-season stress reduced total biomass, stalk biomass, the proportion of stalk in biomass, fresh millable stalk and sucrose yield, and stalk dry matter content (Table 4). The 26% reduction in total biomass was due to a 5% reduction in the seasonal fraction of radiation intercepted and a 21% reduction in the seasonal radiation use efficiency. In Experiment 2, the early-season deficit treatment was more severe than that in Experiment 1, and reduced final total biomass by 20% (Table 5). The impact on the seasonal fraction of radiation intercepted and seasonal radiation use efficiency was only able to be determined with confidence until April at which time the seasonal fraction of radiation intercepted was 0.77 in the well-watered and 0.60 in the early-season treatment (data not shown). In addition, stalk biomass, fresh millable stalk and sucrose yield, sucrose FM concentration were also reduced (Table 5). The mid-season deficit in Experiment 2 reduced all variates shown in Table 5, except stalk dry matter content and stalk number. In Experiment 3, the mild deficit reduced biomass, and fresh millable stalk (but not stalk biomass). The severe deficit reduced all crop variables except stalk sucrose DM concentration and dry matter contents, and stalk number.

Total leaf number per stalk, millable stalk biomass, stalk sucrose yield, and fresh millable stalk yield declined significantly with the length of the deficit period in Experiment 4 (Fig. 2). There was a trend for stalk dry matter content to increase with the length of the deficit period. Stalk number, number of green leaves and LAI all showed no significant change. Sucrose DM concentration in the millable stalk also did not change significantly due to the value for the longest deficit treatment, which went against the trend of declining sucrose DM concentration with increasing length of deficit. We cannot find any plausible reason to explain this departure from the trend.

This series of field studies has shown that the timing and severity of early and mid-season water deficit has important implications for crop yield at final harvest.

Table 4. Components of stalk and sucrose yield at final harvest from Experiment 1. For each variate, values followed by a common letter are not significantly difference at P<0.05.

Variate		Well-watered	Early-season deficit	Mid-season deficit
Total biomass	t ha^{-1}	56.8 a	58.3 a	42.2 b
Stalk biomass	t ha^{-1}	46.7 a	48.2 a	33.3 b
Proportion stalk in biomass		0.82 a	0.83 a	0.79 b
Cane FW yield	t ha^{-1}	149 a	156 a	113 b
Stalk DM content	g gFW^{-1}	0.31 a	0.31 a	0.29 b
Stalk sucrose DM concentration	g gDW^{-1}	0.47 ab	0.48 a	0.46 b
Stalk sucrose FM concentration	g gFW^{-1}	0.15 a	0.15 a	0.14 a
Stalk sucrose yield	t ha^{-1}	24.2 a	23.3 a	15.3 b
Number of stalks	m^{-2}	7.33 a	7.28 a	7.23 a
Fully-expanded green + dead leaves		28.4 a	27.2 a	26.4 a
Individual stalk weight	g	773 a	812 a	585 b
Seasonal fraction of radiation intercepted		0.75 a	0.73 ab	0.71 b
Seasonal radiation use efficiency	g MJ^{-1}	1.16 a	1.23 a	0.92 b

Table 5. Components of stalk and sucrose yield at final harvest from Experiment 2. For each variate, values followed by a common letter are not significantly difference at p<0.05

Variate		Well-watered	Early-season deficit	Mid-season deficit
Total biomass	t ha-1	47.6 a	38.1 b	32.4 c
Stalk biomass	t ha-1	36.8 a	28.5 b	22.4 b
Proportion stalk in biomass		0.77 a	0.75 a	0.69 b
Cane FW yield	t ha-1	120 a	95.4 b	72.6 c
Stalk DM content	g gFW-1	0.31 a	0.30 a	0.31 a
Stalk sucrose DM concentration	g gDW-1	0.53 a	0.54 a	0.50 b
Stalk sucrose FM concentration	g gFW-1	0.16 a	0.16 ab	0.15 b
Stalk sucrose yield	t ha-1	19.6 a	15.3 b	11.2 c
Number of stalks	m-2	7.73 a	7.70 a	7.87 a
Fully-expanded green + dead leaves		24.4 a	21.7 b	21.4 b
Individual stalk weight	g	621 a	500 ab	412 b

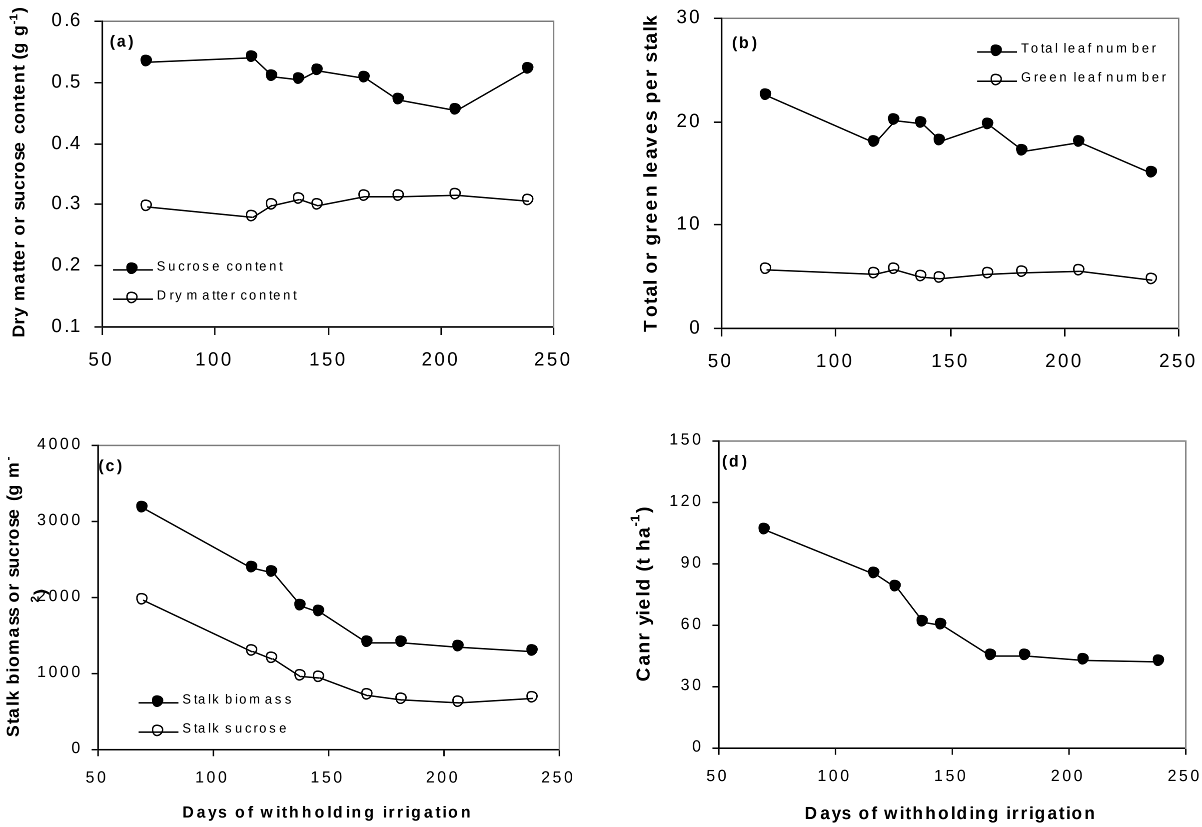

Figure 2. Trends at final harvest with length of water deficit period in Experiment 4 of (a) stalk dry matter content and sucrose concentration (b) total and green leaf number, (c) millable stalk biomass and stalk sucrose, (d) cane yield.

Canopy development and biomass production

In Experiment 1, biomass was reduced by 46 % or 1.3 t ha^{-1} at the end of the early deficit treatment. Although this effect was highly significant at the time (124 DAP) the 1.3 t ha^{-1} treatment difference was similar to the standard error of biomass measured at final harvest. thus even if the treatment difference lasted from dap 125 to harvest, it could not be detected at harvest. If water deficit occurs early and is relieved, the crop can respond through increased tillering and leaf appearance to re-establish a canopy so that lost biomass production can be minimised. Inman-Bamber (1986) showed that when potted sugarcane plants were watered after experiencing two levels of water stress, plant extension rate increased up to 1.6 times the rate for unstressed plants. Roberts *et al.* (1990) showed that "the activity of water stressed plants after re-wetting has often shown higher rates than treatments remaining fully-irrigated throughout and may contribute to compensatory growth between treatments". Inman-Bamber and de Jager (1986) found that leaf extension rates took about 3 to 4 days to recover to rates exceeding those of unstressed plants. Hence, while some compensatory growth is possible after water stress, the effect of an early water deficit is not likely to be detectable in yield at harvest. These studies confirm the observation that final yield of sugarcane is relatively insensitive to withholding of irrigation during the tillering phase (Ellis and Lankford, 1990). Moreover these results provide some physiological insight as to the mechanisms for crop response.

In contrast to the short-lived effect of water deficit when the canopy is small (LAI<2), water deficits applied when the canopy is more developed (LAI>2, see Fig. 5) reduced biomass production severely (Table 4). The reduction is primarily due to reduced photosynthetic rate of leaves, estimated by RUE, which decreased sharply in deficit treatments (Table 4). Radiation interception was little affected by the early or mid-season stress, indicating that reduced leaf expansion was not sufficient to reduce biomass. The impact on RUE occurs through rapid onset of water stress in the deficit treatment, which has an already well-established canopy, and the fact that with full crop cover impacts on radiation interception are less important. Moreover, upon relief of mid-season water deficit, there appears to be a more limited ability for the crop canopy to re-establish compared to earlier stressed crops. After the recovery period in the mid-season deficit treatments, the number of green leaves had returned to be similar to that in the well-watered treatment. However, LAI was still significantly lower (see Fig. 5), implying that leaf size was smaller in the previously stressed crops. For example, calculations for Experiment 2 indicate that mean size of green leaves in the mid-season treatment after 80 days of recovery was 630 cm^2 in the well-watered crop vs 436 cm^2 in the mid-season deficit crop. The combined effect of these processes in mid-season deficit crops is that the initial difference in biomass production at the end of the deficit period is compounded by final harvest. For example, in Experiment 2, a 4.5 t ha^{-1} difference between well-watered and mid-season deficit crops at the end of the stress at 187 DAP compounded to result in a difference of 9.5 t ha^{-1} at final harvest at 357 DAP. Muchow (1989) showed a larger effect of later-imposed water deficit than early water deficit, in sorghum and maize. In their study, RUE was also affected more than seasonal radiation interception when stresses were imposed after full canopy cover was reached.

It must be emphasised that the early-season deficit treatments in these experiments consisted of withholding irrigation after one establishment irrigation. Such a regime will remove any possible confounding effect of water deficit on the sprouting of leaf and tiller buds. Early water deficit imposed without the establishment irrigation will possibly have more serious consequences for crop production than those described in this study. Ferraris and Chapman (1991) showed that the rate of bud emergence from stubble setts was affected by level of soil water, and found a relationship between tiller production and the rapidity of bud emergence.

Millable stalk and biomass yield

Despite the complexity of timing and severity of water deficit on biomass accumulation, the impact of water deficit on millable stalk biomass could be explained to a high degree through variation in biomass accumulation. The relationship in Fig. 3 is similar to that reported by Robertson *et al.* (1996) for two other Australian varieties (Q117 and Q138) under well-watered high-input conditions. Muchow *et al*. (1996) showed that the impact of nitrogen deficit on millable stalk biomass could be explained through a common regression relationship with total biomass. The current study shows that reductions in biomass accumulation due to water deficit reduce millable stalk not only through less biomass available for partitioning but also the fraction partitioned to stalk is less at lower biomass levels. This also indicates that sugarcane has fairly conservative allometry between stalk and non-stalk plant parts under widely varying conditions.

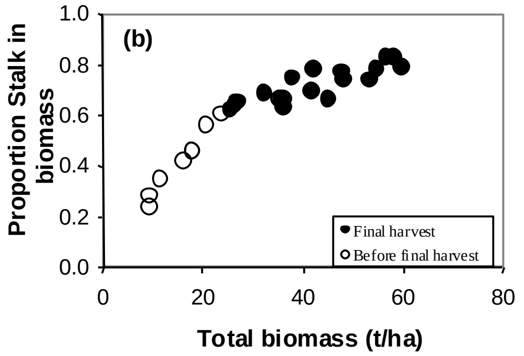

Figure 3. Relationship between the proportion of total biomass present as millable stalk biomass and total biomass). Points are replicate means of individual treatments in Experiment 1-4.

Early water deficits – Growth Model validation and application

Plant available water (PAW)

Simulated PAW was a reasonable reflection of PAW measured in the stress treatments (Fig. 4) and well water treatment (not shown). The variance in measured PAW between plots probably arises from the use of data from only one treatment (mid stress) to determine LL. Varying clay content (not measured) would have given rise to variation in LL and hence PAW. Soil water extraction during the stress periods is of particular interest since we are concerned about the validity of water uptake predictions by the model. PAW during the two stress periods in the mid-season water deficit treatment was simulated mostly within the standard error of the measurements. Simulated water extraction in the early-season water deficit treatment was a little too mild for the plant crop and too severe for the ratoon crop (Fig 4). Given the limitation of measuring PAW accurately, the data support validity of water uptake rates by the model

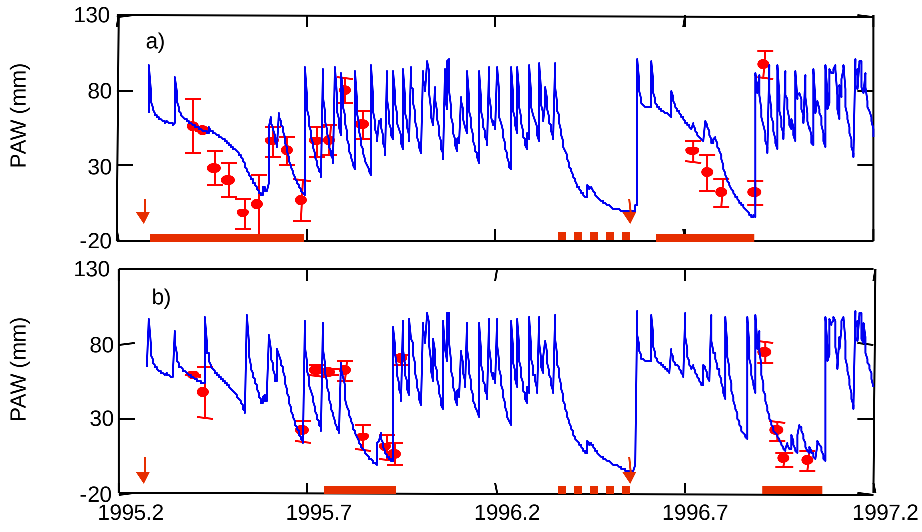

Figure 4. Measured (dots) and simulated (lines) plant available water (PAW) during a plant and ratoon crop of Q96 which was denied irrigation during early (a) or the middle (b) of the growth cycle. X-axis thickened to show stress periods (solid) and drying off period (broken). Bars show standard errors of PAW measurements and arrows show planting and ratoon dates respectively.

Leaf area index (LAI)

LAI of the well-watered treatment was simulated accurately for the first four samplings of the plant crop (Fig. 5a). In the ratoon crop, measured and simulated LAI reached a value of 3 at about the same time, but the simulation tended to overestimate LAI thereafter. Simulations failed to account fully for the decline in LAI in the final months of growth in all crops and treatments.

LAI measured at the end of the early-season water deficit treatment in the plant crop was reduced by 51% in relation to the control but this was only partly captured by the simulation which resulted in a 12% reduction in LAI. Seven weeks later, the effect of early-season water deficit on measured and simulated LAI was small (13 and 6% respectively). At the end of the early-season water deficit treatment in the ratoon crop, measured LAI was reduced by 64% and simulated LAI by 41 % in relation to control LAI. Eight weeks later when the measured effect of early-season water deficit on LAI was zero, the simulated LAI was still lower (15%) than the control simulated LAI. Control LAI was overestimated and early-season water deficit LAI was correctly simulated at this point.

The loss of LAI during the mid-season water deficit treatment in both plant and ratoon crops was captured well by the model (Fig. 5c). LAI at the end of the mid-season water deficit treatment in the plant crop was 46% lower than control for measured, and 41% lower for simulated LAI. At the end of the mid-season water deficit treatment in the ratoon crop, measured LAI was 42% lower than measured control LAI and simulated mid-season water deficit LAI was 48% lower than simulated control LAI.

Recovery from mid-season water deficit stress in the plant and ratoon crops was simulated with reasonable accuracy.

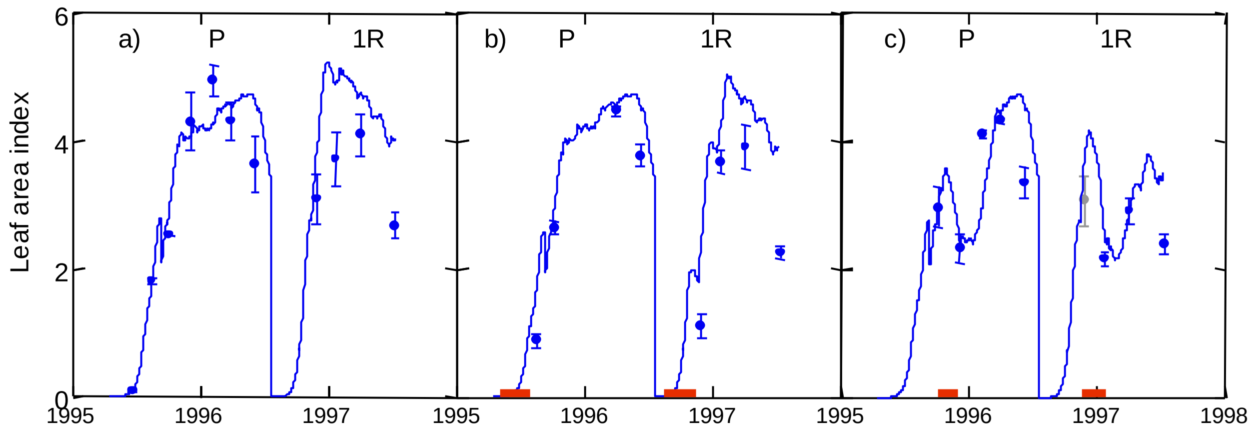

Figure 5. Measured (dots) and simulated (lines) leaf area index in well-watered (a), early stress (b) and mid-season water deficit (c) treatments applied to a plant (P) and first ratoon crop (1R). X-axis is thickened to show periods when irrigation was denied to impose water stress treatments. Bars show standard errors of LAI measurements.

The simulation of the effects of stress on LAI was regarded as satisfactory. Simulation of the loss of leaf area in the later stages of the crop was not accurate but this affected all treatments in like manner. Lodging occurred to some extent prior to harvesting in both plant and ratoon crops and this may have reduced LAI in a way that is not yet included in the model. In addition the model does not account for the observed reduction in area per leaf as a consequence of water stress. The model could be improved by taking this effect of water stress into account.

Stalk DM yield

Simulated stalk DM yield for the well-watered treatment in Experiment 1 was close to mean measured stalk yield (Fig. 6a). The simulation slightly under estimated stalk yield in the plant crop of the early-season water deficit treatments and slightly over estimated stalk yield of the ratoon crop (Fig. 6b). Stalk yield was over estimated in both crops of the mid-season water deficit treatment. The errors were more pronounced for the early samplings than for later samplings (Fig. 6c). This was partly because the model generally predicted some stalk mass before any stalk mass was measured in all treatments. An important component of the validation process of the model for the purpose of risk assessment for saving water was the accurate simulation of yield loss due to withholding irrigation at various growth stages. The simulations accounted for 89% of the variation in yield loss measured at various times in Experiment 1 but the model generally underestimated yield loss by about 30% (Fig. 7). The intercept was not significantly different from zero (p=0.05) but the slope (0.67) differed significantly from 1.00.

In Experiment 4 yield losses were incurred by withholding irrigation for various periods after an initial irrigation at ratooning. In this case, simulation reflected the losses very well. The simulation accounted for 98% of the variation in measured yield loss. The intercept and regression coefficients did not differ significantly (p=0.05) from zero and 1.00 respectively (Fig. 7).

Despite good performance of the model in accounting for the yield losses measured in the experiments, it would be wise to assess risks of withholding water under a range of yield loss estimates corresponding to uncertainty both in the model and with random errors in experimental measurements in the field.

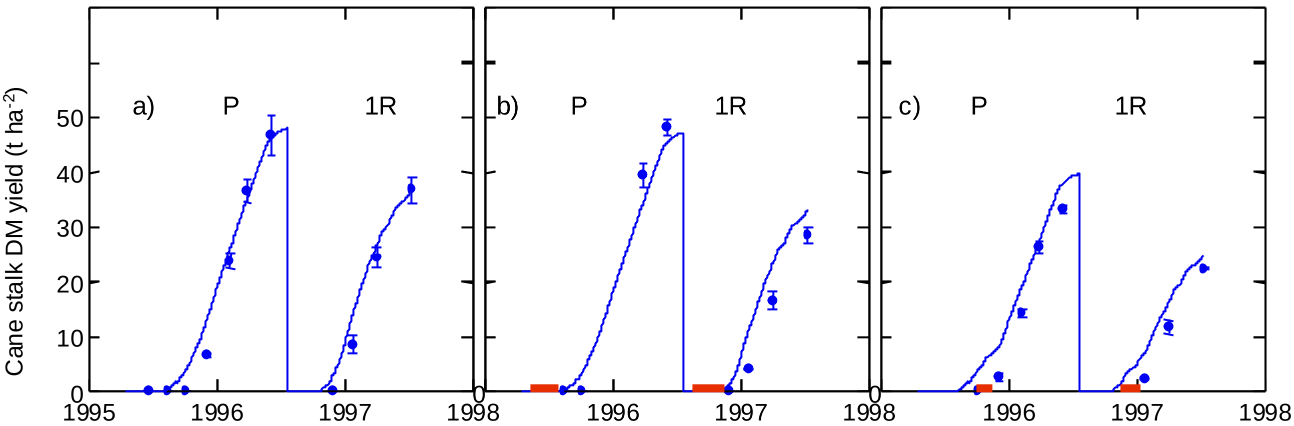

Figure 6. Measured (dots) and simulated (lines) cane stalk dry matter (DM) yield in well-watered (a), early stress (b) and mid-season stress (c) treatments applied to a plant (P) and first ratoon crop (1R). X-axis is thickened to show periods when irrigation was denied to impose water stress treatments. Bars show standard errors of yield measurements.

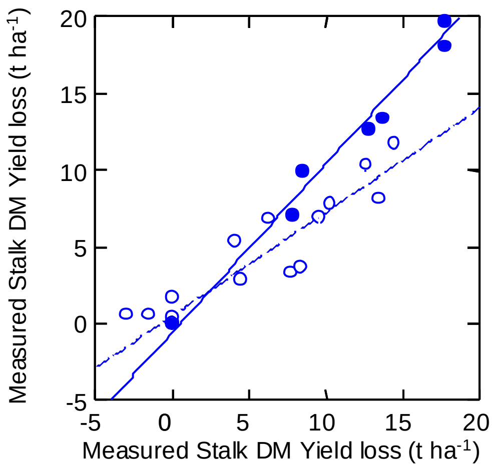

Figure 7. Measured and simulated loss in stalk DM yield due to withholding irrigation at various times in Experiments 1 plus 2 and 3 (clear and solid symbols respectively). Regression equations are: Y=0.35+0.67X, (broken line), n=27, r2=0.89, SEy=1.19 for Experiment 1 plus 2 and Y= -0.55+1.10X, (solid line), n=9, r2=0.98, SEy=1.04 for Experiment 4.

Risks of yield loss from early water stress

Risks of yield loss from water savings at various stages of growth depend firstly on the amount of water in the soil at the start of the given growth stage, the chance of rain falling during that growth phase and potential transpiration (PT) during that phase. The second component of the risk is the efficiency with which water applied during the growth phase can be converted to cane yield.

Median and maximum yield loss, irrigation and irrigation use efficiency (IWUE) for simulations conducted over a 36-year period are given in Table 6. IWUE is defined as the loss in cane yield divided by amount of irrigation withheld during the growth stage. For crops starting on a full soil profile in June or October on a duplex clay-sand or a deeper silty loam, little irrigation is required until the 10th leaf on primary stalks has matured, for the climate at Ayr and (Table 6). The maximum irrigation that could be usefully applied prior to the 10th leaf stage was 105 mm (three irrigations) for June crops on the duplex soil (Table 6). No irrigation was required before the 10th leaf stage for crops on loam in any of the 36 years of the simulation. The maximum yield penalty for withholding irrigation until the 10th leaf stage was 9 t ha^{-1} for June crops on the duplex soil (Table 6). This could be as high as 13 t ha^{-1} if the model underestimates yield loss by 30%.

For crops starting in June, median irrigation requirement during 10 to 15, 15 to 20 and 20 to 25 leaf phases was 70 to 140 mm (2 or 3 irrigations) and median yield losses without this irrigation were fairly substantial (11 to 20 t ha^{-1}). Median response to irrigation (=IWUE) applied between the 10th and 25th leaf stages (late September to late December) was 12 to 16 t cane per megalitre. In these cases IWUE was similar to or slightly greater than the efficiency of all water used by the crop (soil and crop evaporation) which was benchmarked at 12 t cane/Ml for the Australian Sugar Industry (Kingston, 1994). For June crops these phases coincided with a period when mean monthly PT exceeded mean monthly rainfall by a considerable margin (Fig. 8) giving rise to large responses from irrigation. The maximum yield penalties for failing to irrigate during 5-leaf and 10-leaf phases were 35 t ha^{-1} (20 to 25 leaves) and 80 t ha^{-1} (20 to 30 leaves) respectively (Table 6). These losses could be up to 15 and 114 t ha^{-1} if the model underestimates yield loss by 30%.

Table 6. Median and maximum yield loss, irrigation saved and irrigation water use efficiency (IWUE) resulting from withholding irrigation during various leaf appearance phases. Data were derived from simulations of crops ratooning on two dates grown on two soils for the period 1961 to 1997.

Soil	Ratoon Date	Leaf appearance phase								
		0to5	5to10	10to15	15to20	20to25	25to30	0to10	10to20	20to30
Median Yield loss (t ha^{-1})										
Duplex	October	0	0	5	6	3	5	0	11	12
Duplex	June	0	1	13	13	11	7	1	30	20
Loam	October	0	0	2	6	2	3	0	16	13
Loam	June	0	0	15	20	17	10	0	52	38
Median irrigation saved (mm)										
Duplex	October	0	0	35	35	35	70	0	105	105
Duplex	June	0	0	105	70	70	70	0	210	140
Loam	October	0	0	70	70	70	70	0	140	140
Loam	June	0	0	140	140	140	105	0	350	280
Median response to irrigation (t ML^{-1})										
Duplex	October	.	7.0	7.4	10.5	9.8	9.9	7.0	10.2	11.0
Duplex	June	.	9.6	12.9	15.9	15.6	12.3	9.6	13.4	13.2
Loam	October	.	.	5.6	11.5	7.5	7.2	.	11.3	9.9
Loam	June	.	.	12.4	13.1	13.3	9.0	.	14.5	12.9
Maximum Yield loss (t ha^{-1})										
Duplex	October	0	4	12	14	18	23	4	33	38
Duplex	June	0	9	20	21	18	17	9	46	40
Loam	October	0	0	16	25	26	28	0	41	49
Loam	June	0	0	26	34	35	28	0	72	80
Maximum irrigation saved (mm)										
Duplex	October	0	35	105	105	140	140	35	175	210
Duplex	June	0	105	140	175	140	175	105	315	280
Loam	October	0	0	210	210	210	210	0	350	350
Loam	June	0	0	210	280	280	280	0	560	560
Maximum response to irrigation (t ML^{-1})										
Duplex	October	.	10.6	34.2	37.1	22.0	20.0	10.6	28.0	20.1
Duplex	June	.	19.4	29.1	32.0	46.4	24.9	19.4	24.1	23.6
Loam	October	.	.	17.6	15.8	16.9	15.2	.	24.0	20.8
Loam	June	.	.	24.2	28.0	22.6	21.6	.	20.8	24.2

Median yield losses for crops starting in October were comparatively low in all the stress treatments. This was due to low irrigation requirements as well as low IWUEs. IWUE for the 5-leaf phase stress treatments were particularly low apart from the 15 to 20 leaf phase, because of relatively high mean rainfall during this growth phase in October crops (Fig. 8). Mean monthly rainfall was similar or exceeded mean monthly PT when October crops had fewer than 30 leaves (Fig. 8). However rainfall in this environment is extremely variable and strategies to save water should take low rainfall years into account. Penalties for not irrigating October crops were as high as 28 t ha^{-1} for a 5-leaf stress period (25 to 30 leaves) and up to 49 t ha^{-1} (20 to 30 leaves) for a 10-leaf stress period applied on the duplex soil. These yield losses could be as high as 41 and 70 t ha^{-1} if the model underestimates response to irrigation by 30%.

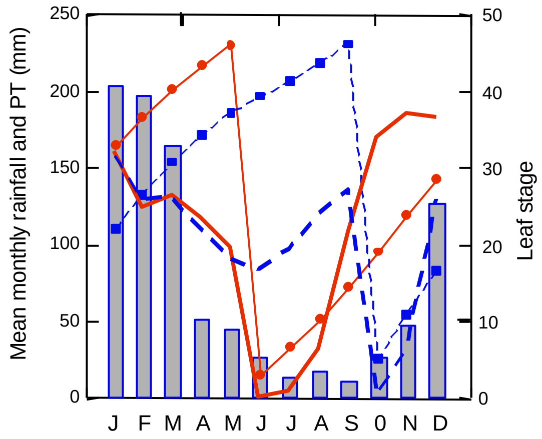

Figure 8. Mean monthly rainfall (bars), potential transpiration (PT) for June crops (solid line) and October crops (broken line) and leaf stage of June crops (solid line and symbols) and of October crops (broken line and symbols). Rainfall was measured and other variables were simulated.

Late water stress (drying-off) - Field experiments

Cane yield and CCS responses to drying-off

The response to drying-off differed in the two seasons. In 1994/95, the 8 and 13-week treatments produced higher CCS and sugar yield than the minimal drying-off treatment (Table 7). Cane yield was unaffected. The lack of a reduction in cane yield in 1994/95 was possibly due to lodging occurring 6 weeks before harvest in the minimal drying-off treatment. In 1995/96, the 9/4 and 13 week treatments produced higher CCS, but in contrast to 1994/95, cane and sugar yield was reduced compared to the minimal drying-off treatment.

Table 7. Cane yield, CCS, and sugar yield in two seasons of drying-off experiments at Ayr. Within an experiment, values followed by the same number were not significantly different at P< 0.05.

Drying-off treatment (weeks before harvest)	Season	Cane yield (t/ha)	CCS	Sugar yield (t/ha)
5		149 a	15.4 a	23.0 a
8	1994/95	159 a	16.7 b	26.7 b
13		155 a	16.2 b	25.2 b
4		125 a	15.3 a	19.1 a
9/4	1995/96	111 b	16.0 b	17.8 b
13		103 c	17.0 c	17.5 b

Studies on drying-off are rare in Australia. This is in contrast to southern Africa (South Africa, Swaziland and Zimbabwe) where there have been over 30 drying-off experiments conducted from 1966 to 1995 (Robertson and Donaldson, 1998). The responses to drying-off measured in the two experiments at Ayr in terms of CCS and sugar yield are compared with a survey of responses obtained in southern Africa (Table 8). Out of the 137 drying-off regimes studied in the southern African trials, a total of 83 (61%) resulted in a statistically significant change in CCS, cane yield or sugar yield. This illustrates the inherent riskiness of drying-off, where interruption by rain or insufficient time between withholding irrigation and harvest can prevent the development of crop water stress. Robertson and Donaldson (1998) found that generally, drying-off is more often associated with an increase in sucrose concentration, than with an increase in sucrose yield. This was also the case with the Ayr results where CCS increased in all treatments, but sugar yield was reduced in 1995/96 (Table 7). Interestingly, the survey also shows that in those drying-off treatments which reduced cane yield, the average response in CCS was no better than treatments where cane yield was not reduced. This was also the case at Ayr with CCS increase on average being no better in the 1995/96 season when sugar yield was reduced. In 1994/95, the increase in CCS was similar to the average for the African studies, while in 1995/96, the Ayr result was closer to the maximum ever recorded in southern African experiments.

Table 8. Summary of responses to drying-off in terms of CCS and sucrose yield from a survey of experiments conducted in Southern Africa from 1966-1995 (Robertson and Donaldson, 1998), and from 2 seasons of experiments conducted at Ayr. A response to drying-off was defined as when there was a statistically significant change over that of the control, which was not dried-off

Response to drying-off	Summary of 84 southern Africa studies (Robertson and Donaldson, 1998)			Ayr 1994/95		Ayr 1995/96	
	Proportion of drying-off treatments	Average	Maximum increase	8 wks	13 wks	9/4 wks	13 wks
Change in CCS (% units)	64%	+1.03	+2.1	+1.3	+0.8	+0.5	+1.5
Change in sucrose yield (t ha^{-1})	23%	+1.3	+2.5	+3.8	+2.17	-2.00	-2.24

Physiological responses

When drying-off is imposed, the crop exhibits a number of physiological changes associated with the increase in CCS. At the cessation of irrigation, stalk elongation declines rapidly. In the 1994/95 experiment, it halted when about 70 mm of the total plant available water of ca. 150 mm had been depleted. Stalk elongation recovered after the rainfall on 8 May (day 128), but then declined soon after (Fig 9a). Along with the fall in stalk elongation rate was a slowing of the rate of appearance of leaves, and an increased rate of leaf senescence and hence a fairly rapid reduction in the number of green leaves per stalk (Fig. 9b). For example, after 5 weeks of drying, green leaf number was 8.7 versus 12 in the irrigated plots. Also, after the imposition of drying in the 4 week minimal drying-off treatment, green leaf number declined rapidly. Coincident with the fall in stalk elongation and leaf appearance, the stalk dry matter content and sucrose concentration increased rapidly (Fig. 9c). In this case, after 5 weeks of drying-off, dry matter content was 0.274 versus 0.262 g g^{-1} ($P < 0.01$) and sucrose DM concentration was 0.501 versus 0.482 g g^{-1} ($P < 0.01$). This illustrates that early in a drying-off cycle, increases in sucrose FM concentration are rapid (Fig. 9d) and are due to roughly equal increases in stalk dry matter content and sucrose DM concentration. After 8 weeks of drying, these differences between the treatments had been maintained. At final harvest, after 13 weeks of drying and 4 weeks of drying in the minimal treatment, dry matter content was similar while sucrose DM concentration was still higher in the 13 week treatment.

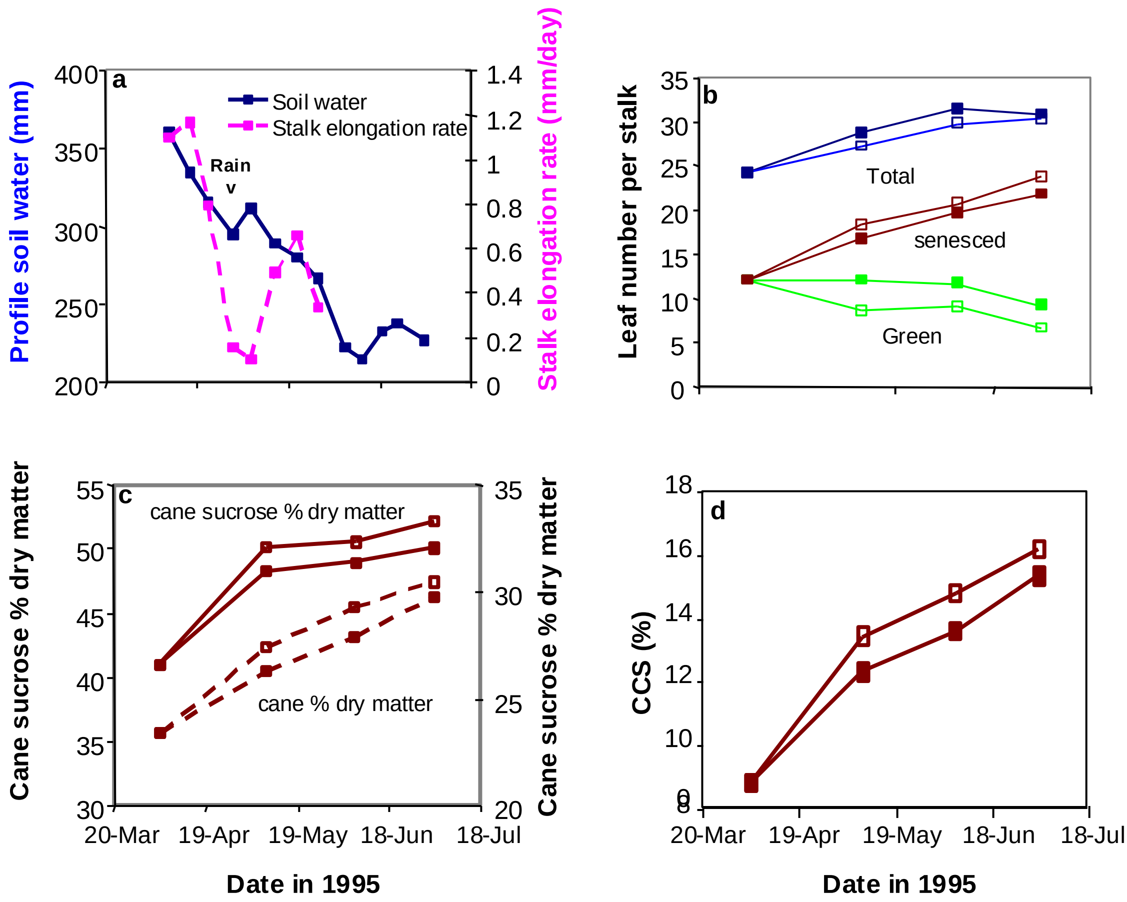

Figure 9. Stalk elongation rate and profile soil water content in the 13-week treatment (a), total leaf number per stalk and number of senesced and green leaves (b), Sucrose content of stalk dry matter and dry matter content of stalks (c), CCS (d) of 5 and 13 week dry-off treatments (solid and hollow symbols respectively).

Components of cane yield

A number of factors interact where cane yield is reduced by drying-off. Firstly, biomass production is decreased due to decreased photosynthesis. Secondly, stalks will accumulate less water and hence increase in dry matter content. These two processes will tend to act together to decrease cane yield. However, this may be counteracted to some extent by the decrease in the non-millable portion of the stalk tops shown as an increased proportion of millable stalk in biomass. In 1995/96, there was a significant reduction in cane yield in response to drying-off (Tables 7 and 9). What was the relative importance of each of these factors on cane yield reduction?

After 8 weeks of drying, there were clear responses to drying-off observable with sucrose FM concentration 0.015 g g^{-1} higher and green leaf number 2.8 leaves lower in the dried-off plots. However, there was no effect on biomass or cane yield at this stage (Table 9), showing the insensitivity of biomass production to drying-off compared to sucrose concentration. The lack of effect on cane yield was despite cane dry mater content being 9% higher. This was due to the compensatory effect of millable stalk being a greater proportion of biomass (0.801 versus 0.769). The millable stalk was a greater proportion of biomass under drying-off because of a reduced proportion of non-millable stalk, and not due to less leaf material in the total biomass (data not shown). After 13 weeks of drying-off, cane yield was 20% less than in the minimal drying-off treatment. The effects of a higher cane dry matter content (5%) and greater proportion of millable stalk in biomass (2%) acted in opposition, so that the cane yield reduction could be explained solely by the 20% reduction in total biomass. This result shows that cane yield reduction under mild levels of drying-off will be buffered to some extent by higher partitioning to millable stalk, and that this effect is of similar importance as the effect of increased cane dry matter content. The degree to which the higher partitioning to millable stalk is realised in the field at commercial harvest will be determined by the degree to which harvester topping height is adjusted in dried-off crops. Of course, in lodged crops this will not be an issue.

Table 9. Changes in the components of cane yield under drying-off. Results from 1995/96 experiment at sampling on 21 May 1996 after 8 weeks of drying-off, and 17 June 1996 after 13 weeks of drying-off. NS = not significant, *** = significant at P<0.05.

Drying-off treatment	Cane yield (t ha^{-1})	Cane dry matter content (g g^{-1})	Millable stalk biomass (t ha^{-1})	Proportion millable stalk in biomass	Biomass incl. trash (t ha^{-1})
At 8 weeks					
1	109	0.289	31.6	0.769	41.2
3	102	0.317	32.2	0.801	40.0
Signif.	NS	***	NS	***	NS
At 13 weeks					
1	128	30.6	39.1	0.738	52.8
3	103	32.0	33.1	0.754	42.4
Signif.	***	NS	***	***	***

Key to treatments:
1 Dried-off for 4 weeks from week 9
3 Dried-off for 13 weeks from week 0

Response to re-watering after a period of drying-off

The management of drying-off is subject to the risk of rain interrupting the drying cycle and causing a possible reversal of the positive effects of drying-off. To what extent are increases in sucrose concentration gained under drying-off, reversible if rain occurs? Treatment 2 in 1995/96 was designed so this question could be examined, where 9 weeks of drying-off was followed by an irrigation, to mimic the effects of rain interruption, followed by a further 4 weeks of drying before harvest.

Table 10 shows that sizeable increases in sucrose FM concentration of 0.015 g g^{-1} over the minimal treatment were achieved during the first drying cycle of 9 weeks. Green leaf number had been reduced from 11.9 to 9.1, but there was no effect on cane yield. At 9 weeks, treatment 2 was rewatered while treatment 3 was maintained under continuous drying-off. Sucrose concentration was measured on 5 June 1996 (week 11 sampling), 18 days after the re-watering. At this time there had been little change in sucrose concentration in all treatments. However, 2 weeks later at final harvest sucrose concentration in the 13 week treatment had increased from 0.158 to 0.166 g g^{-1} and in the 4 week minimal treatment it had increased from 0.148 to 0.153 g g^{-1}, but there was no change in sucrose concentration in the re-watered treatment (Table 10). The treatments showing significant increases in sucrose concentration also showed reductions in green leaf number. The re-watered treatment clearly had resumed leaf growth with green leaf number increasing from 9.1 to 10.7 following the re-watering, while green leaf number declined by 2 leaves in the other treatments. As a result, the sucrose concentration was no better than that achieved in the plots dried-off for only 4 weeks. The plateau in sucrose concentration following re-watering was due to no further increase in dry matter content and a slight decrease in sucrose DM concentration (data not shown). These results suggest that gains achieved by drying-off cane may be lost if substantial rain interrupts the drying cycle, associated with a resumption of stalk growth.

Table 10. The effect of re-watering after drying-off on cane yield (t ha^{-1}), sucrose FM concentration (SFMC) and number of green leaves per stalk. Measurements were made at weeks 9,11 and 13 in a drying cycle. Results are from 1995/96 experiment at Ayr. NM = not measured. Values followed by the same number were not significantly different at P< 0.05.

Drying-off treatment	Week 9 Cane yield	Week 9 SFMC	Week 9 Green leaves	Week 11 SFMC	Week 13 Cane yield	Week 13 SFMC	Week 13 Green leaves
1	109 a	0.141 a	11.9 a	0.148 a	128 a	0.153 a	10.9 a
2	101 a	0.156 b	9.1 b	0.157 b	111 b	0.155 a	10.7 a
3	101 a	0.156 b	9.1 b	0.158 b	103 c	0.166 b	7.0 b

Key to treatments:
1 Dried-off for 4 weeks from week 9
2 Dried-off for 9 weeks from week 0, then irrigated and dried –off for a further 4 weeks
3 Dried-off for 13 weeks from week 0

Late water stress – Best bet drying off management

Optimal length of drying-off for 4 or 8% loss in cane biomass

Targets for drying off were established by Robertson and Donaldson, 1998, in terms of reductions in biomass yield (4 or 8%) which coincided with maximum dollar and breakeven returns due to increased CCS. The days of drying-off required to reduce cane biomass in 50% of seasons by at least 4 or 8%, varied with harvest date and soil type (Table 11). With 15 May harvest, optimal drying-off (a 4% reduction in cane biomass) ranged from 49 to >150 days for low to high PAWC soil types, whereas a 15 October harvest date required only 29-43 days, depending on soil type.

The results suggest that it is possible to dry-off for too long (*i.e.* exceed 8% reduction in cane biomass), particularly on low PAWC soil types when evaporative demand is high. For example, at Ayr for October harvest on the low PAWC soil type, 4% reduction in cane biomass would be achieved in 50% of years by drying-off on average for 29 days, and a 8% reduction would be achieved by drying-off for only 12 days longer. At cooler times of the year and on higher PAWC soils, the margin for error between the 4 and 8% reduction is greater. For example, for a July harvest the difference in days drying-off between the 4 and 8% cut-off is 19-23 days.

Due to climatic variability, when a grower dries-off for a duration that achieves a 4% reduction in cane yield in 50% of seasons, there will be some seasons in which drying-off is not long enough and others when drying-off is too long. Both states are undesirable. No cane biomass reduction implies that little or no water stress was induced through drying-off and hence sucrose concentration or sucrose yield are unlikely to have been increased. On the other hand, a cane biomass reduction of 8% indicates that drying-off has been too severe. In between these two extremes, cane biomass reductions can be classified in terms of whether they fell between 0 and 4% or between 4 and 8%.

Table 11. Drying off period (days) required to reduced biomass yields by target levels of 4 and 8% which correspond to maximum and breakeven $ returns due to increased CCS. Different soils and harvest dates are considered.

Harvest date	**15 May**		**15 June**		**15 July**	
Yield reduction	4%	8%	4%	8%	4%	8%
Low PAWC	49	111	54	70	52	71
Medium PAWC	134	>150	73	89	73	92
High PAWC	>150	>150	87	>150	84	106
Harvest date	15 August		15 September		15 October	
Yield reduction	4%	8%	4%	8%	4%	8%
Low PAWC	42	58	35	51	29	41
Medium PAWC	62	80	48	67	40	53
High PAWC	74	96	58	78	43	59

As drying-off duration is lengthened, the proportion of years in which no yield reduction occurs, declines, and the proportion of years in which a cane biomass reduction of greater than 8% occurs, increases (Fig. 10). By superimposing the median (*i.e.* 50% of seasons) drying-off periods presented in Table 11 onto Fig. 10 one can analyse the proportion of years that fall into each category when drying-off for the median duration. In general, when drying-off for a 4% reduction in 50% of years, there was a less than 10% chance of imposing no water stress (*i.e.* zero yield reduction). There were often situations where there was a 20% chance of incurring a cane biomass reduction of greater than 8%, implying that drying-off is highly risky. The choice of the exact duration to dry-off will depend on the grower's attitude to risk. Overall however, the duration that achieves a 4% reduction in cane yield 50% of the time gives yield reductions between 0 and 8% in 60-70% of seasons.

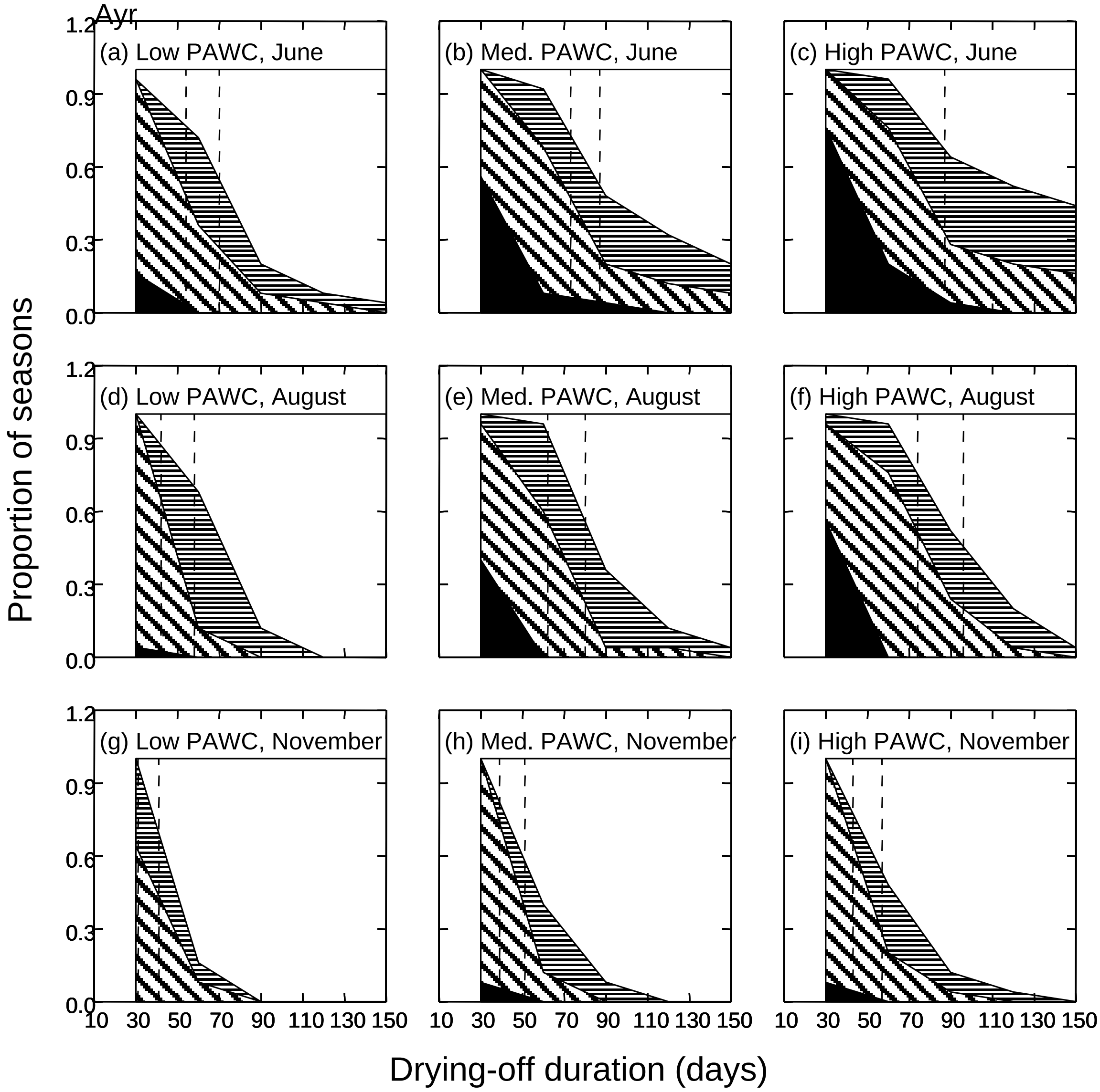

Figure 10. Risk of drying-off, expressed as the proportion of seasons falling into four categories; no reduction in cane biomass (■), a reduction of between 0 and 4% (⑊), a reduction of between 4 and 8% (≡) and a reduction greater than 8% (□), as a function of drying-off duration. Simulations are presented for the June, August and November harvest dates for the low, medium and high plant extractable soil water (PAWC) soil types. The two vertical dashed lines are the durations of drying-off required to reduced cane biomass by either 4 or 8% in 50% of years.

Rule-of-thumb for drying-off

A practical rule-of-thumb to guide the length of the drying-off period must be able to take account of variation in soil type (*i.e.* PAWC) and the crop water demand and rainfall occurring prior to particular harvest dates, across the industry. The severity of soil drying during drying-off will be related to the balance of evapotranspiration and effective rainfall (total rainfall minus runoff and deep drainage). This balance can be represented roughly as the net crop water demand, defined here as evapotranspiration minus effective rainfall occurring during the designated drying-off period. Net crop water demand can be normalised across soil types by dividing it by PAWC. This is the basis of the South African rule-of-thumb, which states that sugarcane should be dried-off for a period sufficient for total potential evapotranspiration to be approximately twice the PAWC of the soil. Effective rainfall is ignored in their calculation, as it is assumed that growers will schedule assuming no rainfall, and re-schedule if rainfall occurs during the drying-off period.

The net crop water demand during drying-off required to produce an average 4% reduction in cane biomass is presented in Table 12. While net crop water demand varied widely with soil type and harvest date, when expressed as a multiple of PAWC of the soil type it varied less, from 1.6 to 1.0, suggesting a relatively stable rule-of-thumb, particularly within a soil type across harvest dates.

Table 12. Evapotranspiration minus effective rainfall during drying-off periods required to reduce cane biomass yield by 4% in the Burdekin; divided by low, medium and high plant available water-holding capacity (PAWC, 114, 162 and 210 mm).

PAWC	Harvest month						
(mm)	May	Jun	Jul	Aug	Sep	Oct	Nov
114	1.6	1.6	1.8	1.6	1.7	1.7	1.6
162	1.3	1.2	1.3	1.3	1.3	1.3	1.3
210	1.1	1.2	1.2	1.1	1.2	1.0	1.0

It is clear that the PAWC multiples derived here are considerably smaller than the values of around 2, which are currently used for drying-off in Southern Africa (simulations indicated PAWC multiples of around 1.0 for Pongola in South Africa (data not shown)). There are at least three possible reasons for the discrepancy.

Firstly, the South African rule ignores effective rainfall. Non inclusion of rainfall in the calculation of the PAWC multiple will therefore contribute somewhat to the discrepancy in some months. Secondly, estimates of PAWC in devising the original South African rule may have been too small. Thompson (1977) proposed for practical purposes that the available water content of a range of South African soils be based on a maximum effective rooting depth of 120 cm, which is the depth of sampling with a conventional auger. Using this criterion, he found that PAWC ranged from 46 mm on shallow sandy soils to 168 mm on deep clay soils (Table 6; Thompson, 1977). More recent observations of soil water extraction on a range of soil types in South Africa has confirmed that sugarcane roots may extract water from depths in excess of 300 cm (Inman-Bamber *et al.*, 1997), and that consequently PAWC based on the 120 cm effective rooting depth may in some instances, grossly under-estimate the true PAWC, which is used in the model simulations. It is possible that the original formulation of the 2 x PAWC rule was based on the earlier approximation of PAWC and an effective rooting depth of 120 cm. This points to the need for clear and consistent definition of soil water properties when developing drying-off guidelines. The third possible reason for the discrepancy between the 2 x PAWC rule and the model results, it that the use of pan evaporation in the original South African rule. Pan evaporation will over-estimate crop water use (Thompson, 1976) compared to the model, which uses a transpiration efficiency approach.

CONCLUSIONS

This study has shown the comparative insensitivity of sugarcane yield at harvest to early-season water deficit. On the other hand, water deficit imposed when the canopy is well-established will have more deleterious impacts on final yield of total biomass, stalk biomass, and stalk sucrose. The effect of mid-season stress is compounded because of reduced proportion of stalk biomass in total biomass and reduced sucrose mass in stalk biomass.

The field experiment results were consistent with the simple concepts of a carbon and water balance embodied in the APSM-Sugar model. While it was not possible to accurately determine all the soil and plant attributes required to configure the APSIM-Sugar model to simulate the experiment, it was possible to remove much of the uncertainty about the major plant and soil input parameters. It is possible that errors in some soil parameters required by the model contributed to relatively small errors in the simulation. A more detailed experiment is required to determine the source of errors in the simulation process which includes concepts in the model, quantification of these concepts and soil or plant characterisation.

An important deduction from the validation exercise is that phenology (developmental phases) do not play a major role in cane yield response to water stress. The use of developmental phases to devise irrigation strategies as in the work of Ellis and Lankford (1990) is convenient but has more to do with water supply and demand than with crop phenology. Another deduction is that while compensatory growth may well occur after water stress is relieved, this is not an important mechanism in the so-called ‘catch up’ phenomenon. There is no concept of compensatory growth in the model and the comparison of experimental data with model output indicates that none may be necessary for the purpose of determining yield responses to irrigation. In Experiment 1, simulated yield loss was in fact less than measured yield loss, and in Experiment 2, there was no significant difference between measured and simulated yield loss due to withholding irrigation for various periods after ratooning. The latter is a notable achievement for a model that was required to predict yield differences rather than absolute yields as in previous validation tests (Keating *et al.*, 1999).

The field experiments and the simulations indicate that there are possibilities for saving water in the Burdekin by using irrigation sparingly before 10 leaves appear on primary shoots provided the soil profile is filled after harvesting. This has implications not only for the reducing water use and increasing water use efficiency but also for reducing deep drainage during the early stages of crop development while nutrients are being rapidly taken up by roots.

The relatively low efficiency of irrigation water used by October crops during 5-leaf stress phases from leaf 10 to leaf 30 provides further opportunities for saving water in the Burdekin if this becomes necessary. When yield lost due to water savings is less than the 12 t cane/ML benchmark for the Australian sugar industry, it is worth considering the use of this water elsewhere or at other times.

These studies have also increased understanding of the physiological basis of drying-off in sugarcane. Some of the key findings on this process are:

- Sucrose concentration changes within a few weeks of drying, whereas more prolonged drying is required to lower cane yield. While stalk desiccation under drying-off lowers cane yield, this is mitigated somewhat by a greater proportion of the stalk being millable.
- Increases in sucrose concentration can be attributed equally to increases in dry matter content and sucrose DM concentration. These changes are most noticeable at the base and near the top of the stalk.

- Interruption of drying-off by rain can reverse increases in sucrose concentration, due to resumption of stalk growth.

This improved understanding can be utilised in crop simulation models, which can be used to analyse the consequences of different drying-off strategies in variable climates with the aim of improving profitability.

Current recommendations for drying-off management in the Burdekin are 20-30 and 55-70 days for low and high PAWC soils, respectively. The results in Table 11 indicate that these durations are similar to those for a 4% target reduction in cane yield for harvests from August onwards. However, the simulation results indicate an interaction of soil type with harvest date such that that recommendations should be made specific to time of harvest as well as soil type. The information in Figure 10 can refine recommendations further by allowing assessment of the risk of various drying-off options. The results in this project indicate that drying-off periods can be devised using the PAWC multiple for any given harvest date and soil type based on records of potential crop water use, soil water holding capacity and expected effective rainfall. While experienced irrigators probably do not require refined advice on drying-off management, the new methodology is particularly useful for the expanding areas of sugar industries and districts in which the practice of irrigation is increasing, or for harvest dates outside the current harvesting season. In these situations, this systems approach can supplement limited local experience. However, it must be emphasised that the systems approach used here depends on quality historical climatic data, and information on plant available water capacity (PAWC) for the major soil types of interest.

In summary, this project has successfully achieved its aim by enhancing knowledge on the impact of water supply on the yield determining processes of sugarcane, and by facilitating the development of management strategies that best utilise the water resources available to the Australian sugar industry.

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IMPLICATIONS AND RECOMMENDATIONS

The strategic research conducted in this project CTA016 can underpin more applied and tactical research aimed at improving profitability and water use efficiency in fully irrigated and supplementary irrigated production areas of the Australian sugar industry. The following recommendations should be considered:

1. This project has quantified the crop response to drying off and to water deficits at various growth stages, but two areas of knowledge need to be improved to develop management strategies for best use of water. The first is the demand for water by crops in various conditions (partial canopy, erect, lodged, partially stressed) and the second is soil water supply including water extraction beyond the readily available limit, water rising from water tables and water entering the profile via lateral flow. These issues are being considered in the new SRDC project CTA038 "Irrigation risk management strategies to reduce water use and maximise profitability: a paradigm shift in performance to $ per unit of water".
2. The findings from this project need to be used to benefit the industry in terms of best use of water resources. Risk analyses need to be conducted to identify strategies for saving water and improving water use efficiency for various regions, soil types and irrigation systems.
3. This project has enhanced the APSIM-Sugarcane simulation capability. This tool can be used to facilitate the development of best practice guidelines that address the multiple goals of profitability and water use efficiency in the highly variable climatic and economic conditions of Australia's diverse sugarcane production systems. However, the use of these tools requires quality historical climatic data, and information on the plant available water capacity for the major soil types under sugarcane production. It is recommended that the industry make a strategic investment to enhance climate and soil databases so that best-bet irrigation strategies can be developed for Australia's highly variable and diverse sugarcane production systems.

DESCRIPTION OF INTELLECTUAL PROPERTY

The information obtained in this project should be freely available to the Australian sugar industry and overseas industries. There are no Intellectual Property considerations that require attention. We strongly believe that opportunities to further build on this strategic research knowledge should be actively encouraged in applications that best use water in the Australian sugar industry.

TECHNICAL SUMMARY

The methodologies developed in this project have been described in detail in the journal publications arising from this work. No new software or equipment was developed in the project. The data have been used to enhance the simulation capability of APSIM-Sugarcane.

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Mr Mike Spillman, CSIRO Senior Technical Officer at Davies Laboratory, Townsville was responsible for the technical leadership of the field work in this project. Mr Steve Attard, CSIRO Technical Officer, Kalamia Estate, Ayr was responsible for the day-to-day management of the field experiments at Ayr. Mr Damien Mazzucchelli, CSIRO Technical Officer provided technical assistance during the first two years of this project. Their dedication, skill and enthusiasm under the trying field conditions of sampling high-yielding lodged crops is very much appreciated.

Ms Leonie Baker and Naomi Mackee, Laboratory Analysts at CSR Technical Field Department took overall responsibility for the sucrose analyses (HPLC and CCS) for this project. They assisted the project greatly and the quality of the analytical determinations was exceptional. Most importantly, their pleasant personalities and willingness to help under pressure contributed to excellent team performance.

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APPENDIX. SOME PUBLICATIONS RESULTING FROM THIS PROJECT

1. ROBERTSON, M.J. AND MUCHOW, R.C. (1994). Future research challenges for efficient crop water use in sugarcane production. *Proceedings Australian Society Sugar Cane Technologists* **16**: 196-202.
2. ROBERTSON, M.J. and DONALDSON, R.A. (1998). Changes in the components of cane and sucrose yield in response to drying-off before harvest. *Field Crops Research* **55**: 201-208.
3. ROBERTSON, M.J., MUCHOW, R.C., DONALDSON, R.A., INMAN-BAMBER, N.G. and WOOD, A.W. (1999). Estimating the risk associated with drying-off strategies for irrigated sugarcane before harvest. *Australian Journal Agricultural Research* **50**: 65-77.
4. ROBERTSON, M.J., MUCHOW, R.C. and WOOD, A.W. (1999). A physiological basis for response of sugarcane to drying-off before harvest. *Proceedings Australian Society Sugar Cane Technologists* **21**: 196-202.
5. ROBERTSON, M.J., INMAN-BAMBER, N.G., MUCHOW, R.C. and WOOD, A.W. (1999). Physiology and productivity of sugarcane with early and mid-season water deficit. *Field Crops Research* **64**: 211-227.
6. ROBERTSON, M.J., MUCHOW, R.C., INMAN-BAMBER, N.G. and WOOD, A.W. (1999). Developing guidelines for the length of drying-off of irrigated sugarcane before harvest in the Burdekin. *Proceedings Australian Society Sugar Cane Technologists* **21**: 212-218.