EVALUATING THE POTENTIAL FOR IMPROVED SUGAR YIELDS BY ASSESSING THE CLIMATIC AND SOIL CONSTRAINTS TO PRODUCTION IN SOUTHERN CANE-GROWING DISTRICTS

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Sugar Research and Development Corporation

FINAL REPORT

PROJECT Nº CTA012

September 1999

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Project Title: Evaluating the potential for improved sugar yields by assessing the climatic and soil constraints to production in southern cane-growing districts

SRDC Program: Improved cane productivity in a sustainable environment N$^{o.}$ 1

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Commencement Date: 1 July 1993 **Completion Date:** 1 December 1998

Summary

This project conducted strategic research to better understand the processes of yield accumulation in low temperature NSW environments and to identify limits to yield. The fundamental knowledge gained in this project can be used to assess yield limitations and the scope for yield improvement. In addition, the findings are a pre-requisite to the design of management and genetic improvement strategies to boost production in southern sugarcane growing environments. An additional spin-off of this project is a better functional basis of the processes of yield accumulation encapsulated in the APSIM Sugarcane systems model to allow extrapolation of the findings more broadly across the sugar industry.

An analysis framework was used to express sucrose yield in terms of biomass accumulation and the proportion on biomass present as sucrose. Crop biomass was analysed in terms of radiation capture and utilisation. Partitioning was examined in terms of the proportion of crop biomass present as stalk and the stalk sucrose concentration on a dry matter basis. Crops growing under "potential yield" conditions were analysed and compared to those growing under "commercial yield conditions".

The main findings from this project have been:

- There is substantive scope for vertical expansion in productivity in low temperature NSW environments, with potential yield being above commercial yields. However, economic imperatives will dictate the adoption of improved management practices.
- Low temperature has a greater impact on reducing yields in southern environments (NSW) compared to northern environments (Burdekin and Herbert), than the receipt of incoming solar radiation.
- A considerable amount of incoming solar radiation is "wasted" due to slow canopy development associated with low temperature, and 22-24 month old crops capture significantly more radiation per unit of growth time compared to 12-month-old crops.
- Utilisation of intercepted radiation in biomass accumulation (RUE) was generally linear until cooler temperature reduced crop growth rate. Maximum RUE at 1.7 g MJ-1 was similar to that observed in other environments (e.g. north Queensland and Hawaii). However, this maximum RUE was limited to relatively short growth duration. RUE declined substantially during later growth associated with lower temperature and also biomass losses due to stalk death. Average RUE for 12 months ranged from 1.1 to 1.3 g MJ-1 and for 22-24 months ranged from 0.6 to 1.1 gMJ^{-1}.
- There was little difference between NSW crops and those observed in north Queensland in terms of total biomass partitioning to stalk biomass.
- The efficiency of partitioning of stalk biomass to stalk sucrose followed similar patterns to north Queensland in the first 12 months but was lower in the following 10-12 months. For the amount of stalk biomass produced in the second year in NSW environments, stalk sucrose concentration on a dry weight basis was less than that observed in other environments (e.g. north Queensland, South Africa). This combined with higher stalk water content contributed to lower stalk sucrose concentration on a fresh weight basis and hence lower CCS in the NSW environments. Options for genetic improvement and crop management to increase sucrose partitioning need to be explored.

The strategic research conducted in this project, in addition to other growth analysis studies (e.g. SRDC Project CTA004), is essential to underpin more applied and tactical research aimed at improving the productivity of the Australian Sugar Industry. The successful conduct of this project has furthered that endeavour.

Background

Throughout its history, the Australian sugar industry has always striven to increase productivity - a fact that is evidenced through increases in average cane yield from 31 t ha $^{-1}$ in 1900, to 98 t ha^{-1} in 1998. Today, as the industry faces intensified pressure from international competitors, the need for further productivity improvement remains as strong as ever. The industry is expanding, and likely productivity improvements need to be taken into account when planning for increases in infrastructure and milling capacity and changes to harvest scheduling. In some areas, the industry is contracting due to urban encroachment and pressure from other industries. Here, further productivity improvement is the key to future viability. Accordingly, an important question is what is the scope for further improvement in productivity per hectare.

Addressing these issues requires knowledge on the limits to sugarcane yield. This knowledge can also be used to design management and plant improvement strategies to improve sugar yield per hectare. Limits to yield can be examined using a quantitative framework relating sugar yield to the capture and utilisation of radiation, and to the partitioning of biomass to sucrose. Muchow *et al.* (1991) outlined this framework, but inadequate data were available then to quantify the key growth processes of sugarcane.

Research in north Queensland (SRDC ProjectCTA004) quantified the effects of variation in temperature (in high temperature environments) and radiation and leaf nitrogen on the key growth and yield-determining processes of sugarcane (using varieties Q96, Q117, and Q138). To extend this analysis to southern cane-growing regions, experimental work was required under low temperature cane-growing conditions.

This SRDC project (CTA012) conducted field experiments at southern sugarcane-growing locations (Harwood and Grafton) to examine the responses of biomass and sucrose accumulation to low temperature and the interaction between lower temperature and radiation and N supply on the yield-determining processes of sugarcane. In addition, the experiments quantified yield accumulation in 2-year cane. The experiments were conducted under fumigated (Harwood) and new land (Grafton) fully irrigated conditions to assess potential growth. A Plant and Ratoon crop, with two varieties (high yielding NSW variety TS65-28, and Q117 used in CTA004 for comparison with environmental conditions in north Queensland), were grown under potential yield conditions. In addition, rainfed production and a range of N applications were examined.

The research on assessing yield potential outlined in this project was identified as having a high priority at Sugar Research Council's Yield Decline Workshop held in Mackay in August 1990. The project relates to Program 1 Improved cane productivity in a sustainable environment in SRDC R&D Plan 1992-1997. This project addressed strategies 1.3 *To minimise biophysical constraints through an improved understanding and management of physical (climate and soil) factors*; and 1.4 *To optimise the cropping cycle for increased productivity and profitability through bioeconomic modelling of the production cycle for management and decision support.*

Objectives

This project aimed to conduct strategic research examining the factors limiting sugar yield to aid the development of better management strategies. Specifically, the project sought to quantify the climatic constraints under low temperature growing conditions and for 2 year cropping cycles. Only by conducting this research in both northern (CTA004) and southern (CTA012) cane-growing regions, can the findings be extrapolated to have an impact to benefit the whole Australian Sugar Industry.

Research Methodology

1. Yield accumulation framework to analyse impacts of climate on productivity

Potential crop yield varies across locations according to the temperature and radiation regime, and is defined as the yield obtained from a crop growing on a well-drained soil under water non-limiting conditions, with nutrients well supplied, and with minimal biotic disturbance. Muchow *et al.* (1991, 1997a) outlined a framework for assessing the potential yield of sugarcane, and this framework was used in this project.

Yield accumulation in sugarcane can be analysed in terms of (i) radiation capture and utilisation in biomass production; (ii) the partitioning of biomass to stalk sucrose; and (iii) the relationship between stalk sucrose and commercial measures of cane yield and CCS (Fig. 1). This framework serves as a basis (i) to analyse production constraints and opportunities for yield improvement; (ii) to link research at the biochemical, physiological, agronomic and genetic levels to examine impacts on productivity; and (iii) for simulating crop performance in the production system using crop-soil-systems models. Using this framework, the project has measured the determinants of yield in field experimentation conducted under varying radiation, temperature and N regimes with all other manageable factors controlled to ensure "potential" growth conditions.

The incident solar radiation that is "seen" by a sugarcane crop varies with location, season and growth duration (as determined by planting, ratooning and harvesting schedules) (Fig. 1). That proportion of the incident radiation that is captured by the crop is determined by canopy dynamics including stalk number, leaf area production and leaf senescence. The amount of biomass produced from the captured radiation is dependent on the photosynthetic efficiency of utilisation of radiation minus any biomass losses (Fig. 1). For many crop species grown under well-watered conditions with ample nutrition and in the absence of pests and disease, crop biomass has been shown to be linearly related to the amount of radiation intercepted (captured) by the crop canopy. This relationship sets a finite limit on yield potential, and hence was examined in detail in this project.

The relationship between crop biomass and stalk sucrose is dependent on the proportion of crop biomass in millable stalk, and the proportion of sucrose and fibre and other compounds in the millable stalk (Fig. 1). Stalk sucrose, defined as the amount of sucrose present in stalks per hectare, is a dry weight measure of yield. However, commercial yield is based on the fresh weight of millable stalks (cane yield) and the CCS (Commercial Cane Sugar), and is the basis of payment to growers (Fig. 1). The relationship between stalk sucrose and commercial yield is dependent on the stalk dry matter content and juice purity, and also on the extent of tops, trash, dirt and other extraneous matter in the cane supply.

2. Methodology to measure yield accumulation in field experiments

A major issue has been the resource requirements to regularly sample high-yielding sugarcane crops to quantify yield accumulation. To facilitate these measurements, the project used methodologies developed in project CTA004 for conducting growth analysis in sugarcane that balanced manpower and resource requirements with data precision. This methodology is shown schematically in Fig. 2 and has been described in detail in two ASSCT publications (Muchow *et al.*, 1993; Thomas *et al.*, 1993). This methodology was also adopted in other SRDC funded projects (e.g. CTA007, CTA016, CTA018, and CTA021) to enhance research efficiency.

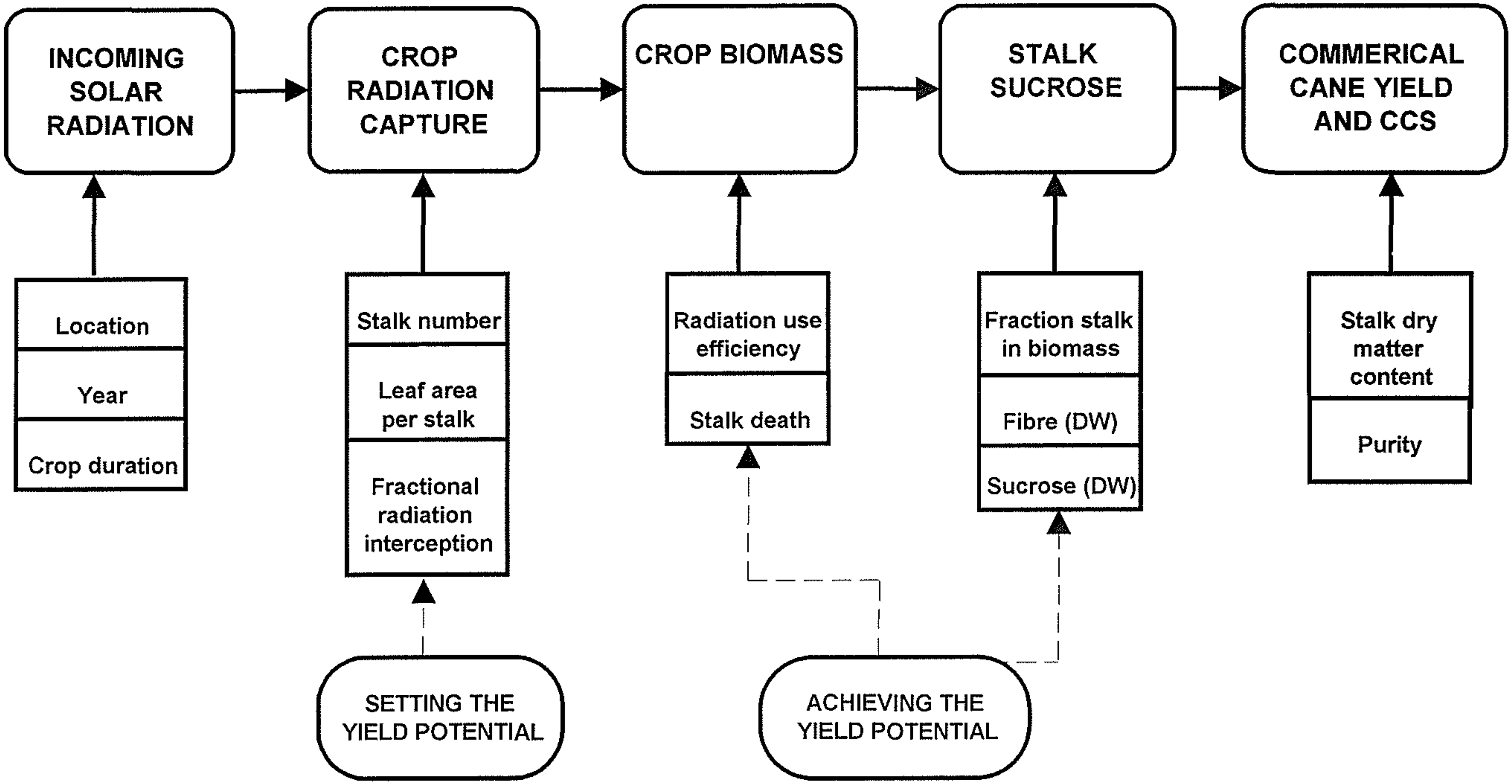

Figure 1. Framework for assessing yield accumulation in sugarcane.

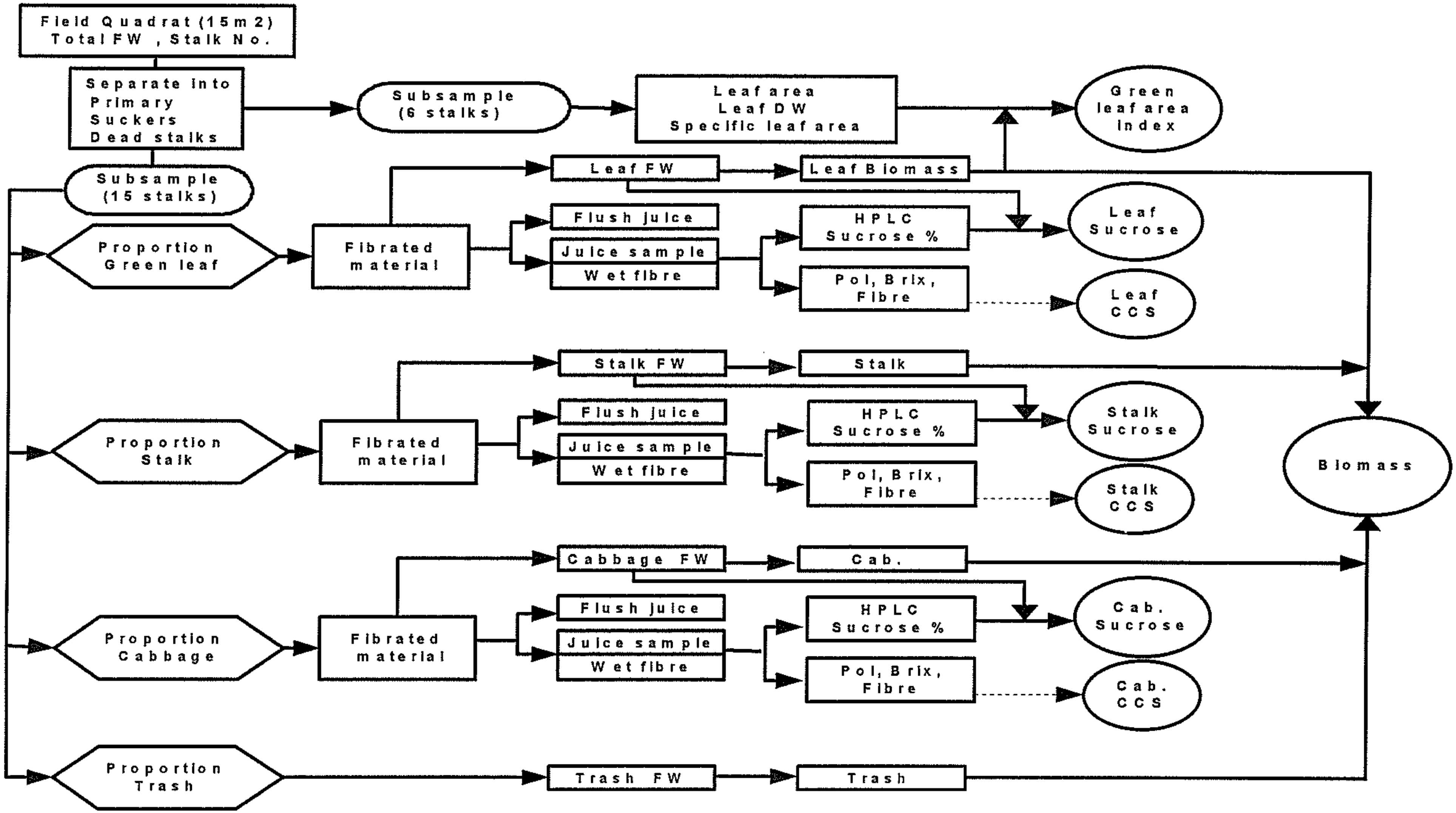

Figure 2. Methodology for measuring yield accumulation in sugarcane.

3. *Overview of experiments conducted in the project*

Field experiments were conducted at Harwood and Grafton. The climatic conditions during the field experimentation are given in Appendix 1. The soils of the two sites are shown in Table 1. The experiments conducted at Harwood are summarised in Table 2 and those conducted at Grafton are summarised in Table 3. All experiments had a fully irrigated "potential" yield treatment. In addition, other treatments were applied including fumigation, nitrogen and commercial rainfed conditions.

Table 1. Site location and soil types.

Site	Harwood	Grafton
Location	Harwood Mill Farm	Grafton Agricultural Research and Advisory Station
Lat/long	29.30°S; 153.20°E	29.37°S; 152.57°E
Soils	Silty clay loam (0-25 cm)	silty clay loam (0-11 cm)
	Medium/heavy clay (25-63 cm)	silty light/medium clay (11-64 cm),
Soil	1. Humic gley[1]	1. Prairie soil[1]
Classification	2. Dy 3.11[2]	2. Gn 3.22 (ridge tops)[2]
		Gn 3.92 (lower slopes)

[1]Australian Great Soil Group Scheme (Stace *et al.* 1968)
[2]A Factual Key (Northcote 1979).

Table 2. Summary of experiments conducted at Harwood

Expt. Code	Crop Start	Crop Finish	Variety & Crop class *	Irrigation**	Fumigation ***	Cane yield ($t\ ha^{-1}$)	HPLC Sucrose yield ($t\ ha^{-1}$)
H1	21/09/93	18/09/95	TS65-28 P	R	F	271	33.0
H2	21/09/93	18/09/95	Q117 P	R	F	238	28.0
H3	21/09/93	18/07/95	TS65-28 P	R	NF	166	17.8
H4	21/09/93	18/07/95	Q117 P	R	NF	170	18.1
H5	21/09/93	18/07/95	TS65-28 P	I	F	295	31.2
H6	21/09/93	18/07/95	Q117 P	I	F	277	31.2
H7	24/10/95	25/08/97	TS65-28 1R	R	NF	226	28.4
H8	24/10/95	25/08/97	Q117 1R	R	NF	216	28.5
H9	24/10/95	25/08/97	TS65-28 1R	I	F	245	28.5
H10	24/10/95	25/08/97	Q117 1R	I	F	269	30.8

* P = Plant crop; 1R= 1st ratoon
** R = Rainfed; I = Irrigated
*** F = Fumigated; NF = Non-Fumigated

Table 3. Summary of experiments conducted at Grafton

Expt. Code	Crop Start	Crop Finish	Variety & Crop class *	Irrigation **	Fumigation ***	Nitrogen Applied (kg ha-1)	Cane yield (t ha-1)	HPLC Sucrose yield (t ha^{-1})
G1	28/09/94	05/09/95	TS65-28 P	I	F	200	152	14.2
G2	28/09/94	05/09/95	Q117 P	I	F	200	164	12.8
G3	28/09/94	05/09/95	TS65-28 P	I	NF	0	157	11.2
G4	28/09/94	05/09/95	TS65-28 P	I	NF	75	150	10.0
G5	28/09/94	05/09/95	TS65-28 P	I	NF	200	151	10.9
G6	28/09/94	05/09/95	TS65-28 P	R	NF	200	142	12.5
G7	20/09/95	22/09/97	TS65-28 1R	I	F	200	297	33.6
G8	20/09/95	22/09/97	Q117 1R	I	F	200	223	23.1
G9	20/09/95	22/09/97	TS65-28 1R	I	NF	0	348	34.5
G10	20/09/95	22/09/97	TS65-28 1R	I	NF	75	294	33.5
G11	20/09/95	22/09/97	TS65-28 1R	I	NF	200	328	37.4
G12	20/09/95	22/09/97	TS65-28 1R	R	NF	200	266	30.4
G13	23/10/97	20/10/98	TS65-28 2R	I	F	200	116	15.2
G14	23/10/97	20/10/98	Q117 2R	I	F	200	122	16.3
G15	23/10/97	20/10/98	TS65-28 2R	I	NF	0	158	20.2
G16	23/10/97	20/10/98	TS65-28 2R	I	NF	75	137	17.9
G17	23/10/97	20/10/98	TS65-28 2R	I	NF	200	115	14.2
G18	23/10/97	20/10/98	TS65-28 2R	R	NF	200	110	14.1

* P = Plant crop; 1R= 1st ratoon; 2R=2nd ratoon
** R = Rainfed; I = Irrigated
*** F = Fumigation; NF = Not Fumigated

Results and Discussion

1. Yield at final harvest

Whilst the main focus of this project was on growth analysis under potential growth conditions, it is instructive to analyse performance of the different treatments at final harvest. Tables 2 and 3 show final yields based on quadrat sampled plots. Note that at Harwood, the Plant and Ratoon crop were harvested at 22 months. At Grafton, the Plant crop was harvested at 12 months, but frosted at ca. 10 months, the first Ratoon crop was harvested at 24 months and the second Ratoon crop was harvested at 12 months.

The highest yield for 22-month-old cane at Harwood was 295 t ha^{-1} of cane and 31.2 t ha^{-1} of sugar. At Grafton, a 24 month yield of 328 t ha^{-1} of cane and 37.2 t ha^{-1} of sugar was recorded. Agronomically, this project has shown substantial yield improvement under "potential yield" conditions compared to "commercial yield" conditions. Scope for vertical expansion in production through the use of irrigation and changed management practices appears high, but economic considerations need to be accounted for in changed management practices.

2. Yield accumulation over time using growth analysis

During the course of this project, the crops were sampled regularly at 4-8 week intervals to better quantify the components and processes of yield accumulation. This wealth of data for each experiment is available on request and some are presented in the publications in Appendix 2. These data have been used in subsequent sections of this report to analyse yield limits using a quantitative framework relating sugar yield to the capture and utilisation of radiation, to the partitioning of biomass to sucrose, and to growth duration.

An analysis of yield accumulation over time has been analysed in several publications from this project and these papers are included in Appendix 2. Hughes *et al* (1995) compared 12 month old sugarcane production between north Queensland and northern NSW. Temperature played a major role in determining the lower yield in NSW, with lower temperature in NSW during early growth and during winter. Radiation differences between the two locations were of lesser impact. Hughes and Muchow (2000) examined the time course of sucrose accumulation for 24 month old crops in NSW. Sucrose concentration on a fresh weight basis (which is a similar measure to the factory determined CCS) peaked at 12 to 15 months, but then declined and rose again during the final 4 months. This variation was analysed in terms of changes in sucrose accumulation and stalk dry matter content.

The growth analysis data collected in this project have also been used to examine the relationship between temperature and leaf area expansion in sugarcane (Robertson *et al.*, 1998). This paper is included in Appendix 2.

A significant contribution of the growth analysis data has been the development and enhancement of the APSIM Sugarcane systems model. The growth analysis data from this project were used in the testing of the model (Muchow *et al.*, 1997b; Keating *et al.*, 1999). On-going enhancement of modelling capability is continuing using the data from this project. An application of modelling analysis has been the benchmarking of potential yield using APSIM Sugarcane (Muchow *et al.*, 1997b). The analysis showed that based on latitude, the yield potential in NSW is similar to that indicated for South African environments.

3. Yield analysis using a radiation-based framework

The physiology of crop yield can be described in terms of the amount of growth and the proportion of that growth present as economic yield. Hence for sugarcane, sucrose yield can be expressed in terms of crop biomass and partitioning – both the proportion of crop biomass present as stalk and the stalk sucrose concentration on a dry weight basis. Here, we only consider crop biomass and analyse it using the framework of radiation capture and utilisation.

Under potential growth conditions, radiation capture is dependent on the incident solar radiation, and leaf canopy development as moderated by temperature, and growth duration. Table 4 shows the proportion of the incident radiation intercepted at 12 months, and at 22-22 months. For the Plant crop at Harwood for variety TS65-28, after 12 months only 57% of the incoming radiation was captured for growth, but due to larger canopies for the second 10 months of growth, the average proportion of the incoming radiation intercepted over 22 months was 72%. In the corresponding ratoon crop, the proportion was 66% for 12 months and 76% for 22 months, showing more rapid canopy development in the ratoon crop compared to after planting.

The relationship between proportion of radiation intercepted and canopy development can be examined by the exponential relationship shown in Fig. 3. The relationship: $f_i=1-\exp(-kL)$, where k is the radiation extinction coefficient, was fitted to the data from each experiment, until the tube solarimeters were removed due to lodging. The estimated radiation extinction coefficient (0.35, Fig. 3) is similar to that estimated for north Queensland crops at 0.38 (Muchow *et al.*, 1994).

Taking account of the difference in incident radiation from year to year and the growth duration, the amount of radiation captured for each crop is shown in Table 4. It is concluded from these data that a considerable amount of incoming solar radiation is "wasted" due to slow canopy development associated with lower temperature, and that 22-24 month old crops capture significantly more radiation per unit of growth time compared to 12 month old crops.

The next question is how efficiently do these crops utilise the radiation that is intercepted by the leaf canopy. Here, it is necessary to look at the accumulation of biomass in relation to intercepted radiation (Figs 4 to 8). Utilisation of intercepted radiation in biomass accumulation (RUE) was linear until cooler temperature reduced crop growth rate.

Fitting maximum RUE based on stepwise linear regression (Robertson *et al.*, 1996) gave a maximum RUE over all experiments of 1.73 g MJ^{-1} (Table 4). This compares with a maximum RUE of 1.75 g MJ^{-1} observed for a Plant crop at Ayr (Muchow *et al.*, 1994). It is concluded that in NSW environments, maximum RUE under potential growth conditions is similar to that observed in other environments.

However, this maximum RUE was limited to relatively short growth duration as observed in Figs 4 to 8. It is noted that direct measurements of intercepted radiation ceased once the crop lodged. Thereafter radiation interception was calculated based on canopy leaf area using the method of Muchow *et al.* (1994). This estimate of intercepted radiation may be biased upwards given the difficulty of measuring radiation interception in heavily lodged crops where "holes" appear in the canopy. Nevertheless, the analysis shows that RUE declined substantially during later growth (Table 4, Figs 4 to 8) associated with lower temperature and also biomass losses due to stalk death (Muchow *et al.*, 1994; Robertson *et al.*, 1996a). Average RUE for 12 months ranged from 1.1 to 1.3 g MJ^{-1} and for 22-24 months ranged from 0.6 to 1.1 gMJ^{-1} (Table 4).

Table 4. Interception of radiation and radiation-use efficiency (RUE) at Harwood (fumigated, irrigated crops) and Grafton (fertigated, irrigated, 200 kg N ha^{-1} crops). See Tables 2 and 3 for experiment code explanation. Note for each Expt code that estimates at 12 months, and at 22-24 months are given.

Expt. Code	Season	Variety & Crop class	Seasonal Incident radiation ($MJ\ m^{-2}$)	Seasonal fractional interception	Seasonal intercepted radiation ($MJ\ m^{-2}$)	Seasonal RUE ($g\ MJ^{-1}$)	Maximum RUE ($g\ MJ^{-1}$)
H5	93-94	TS65-28 P	6386	0.573±0.001	3658±6	1.20±0.04	1.83
H5	93-95	TS65-28 P	11924	0.720±0.009	8581±108	1.11±0.04	1.83
H6	93-94	Q117 P	6386	0.589±0.011	3763±68	1.26±0.02	1.70
H6	93-95	Q117 P	11924	0.737±0.003	8790±37	1.03±0.11	1.70
H9	95-96	TS65-28 1R	6615	0.655±0.100	4330±664	1.12±0.15	1.71
H9	95-97	TS65-28 1R	12013	0.761±0.054	9145±646	0.878±0.038	1.71
H10	95-96	Q117 1R	6615	0.714±0.013	4723±88	1.06±0.05	1.50
H10	95-97	Q117 1R	12013	0.810±0.006	9728±69	0.878±0.040	1.50
G1 *	94-95	TS65-28 P	5989	-	-	-	1.80
G2 *	94-95	Q117 P	5989	-	-	-	1.66
G7	95-96	TS65-28 1R	6458	0.616±0.002	3981±49	1.17±0.02	1.79
G7	95-97	TS65-28 1R	12703	0.745±0.003	9470±69	0.941±0.004	1.79
G8	95-96	Q117 1R	6458	0.644±0.014	4156±54	1.28±0.07	1.83
G8	95-97	Q117 1R	12703	0.769±0.002	9773±14	0.552±0.099	1.83
G13**	97-98	TS65-28 2R	5966	0.697	4161	1.14	1.70
G14**	97-98	Q117 2R	5966	0.665	3970	1.26	1.83

* Due to frost damage, frint could not be estimated at the end of the experiment as lai data was not available.

** Could not calculate standard errors as only 1 rep (EAST) used. WEST suffered storm damage part way through the experiment.

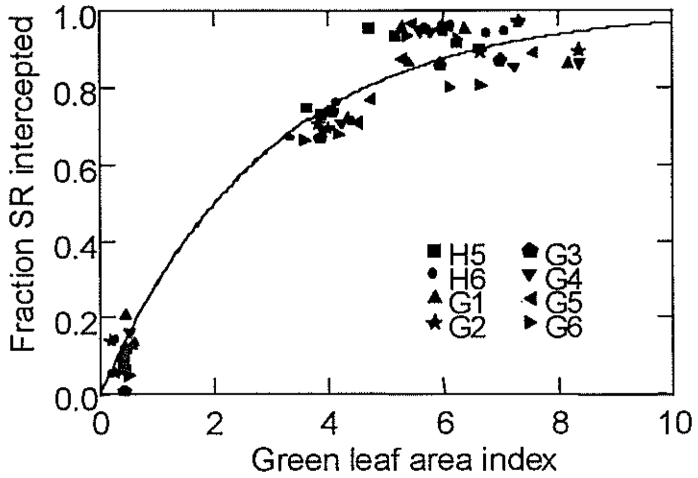

Figure 3. Relationship between the daily fraction of solar radiation intercepted and the green leaf area index from different treatments (Expt codes H5 and H6 from Harwood and G1-G6 from Grafton). The fitted curve yields a radiation extinction coefficient of 0.35.

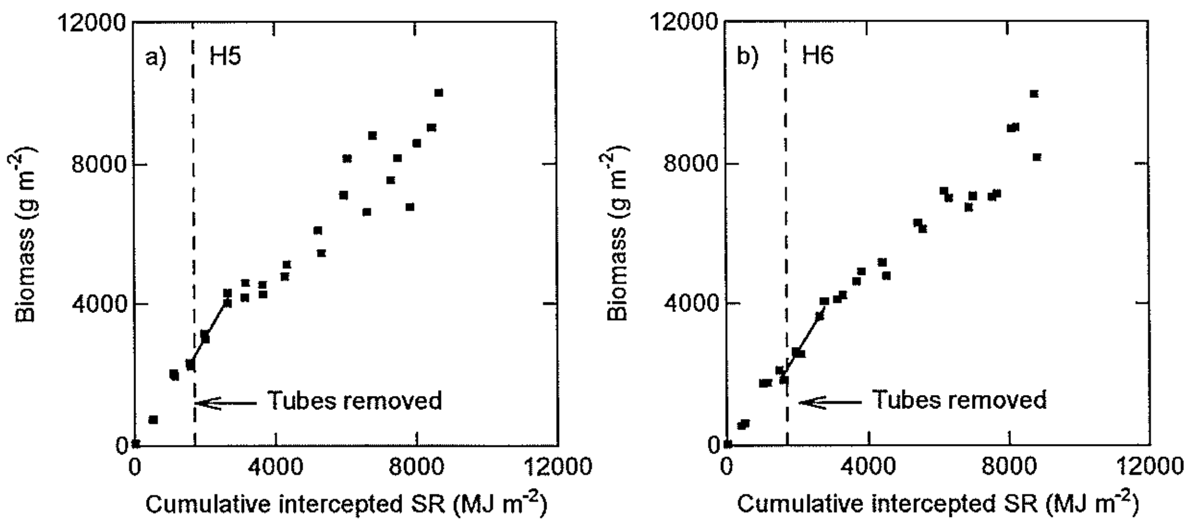

Figure 4. Above-ground biomass with cumulative intercepted solar radiation for H5 (TS65-28) and H6 (Q117) grown under potential yield conditions at Harwood in 1993-95. Waterlogging occurred between sampling 3 and 4, and low temperature between sampling 6-8. Maximum RUE (Samp 4-6) for TS65-28 was 1.83g MJ^{-1}. Maximum RUE for Q117 was 1.70g MJ^{-1}.

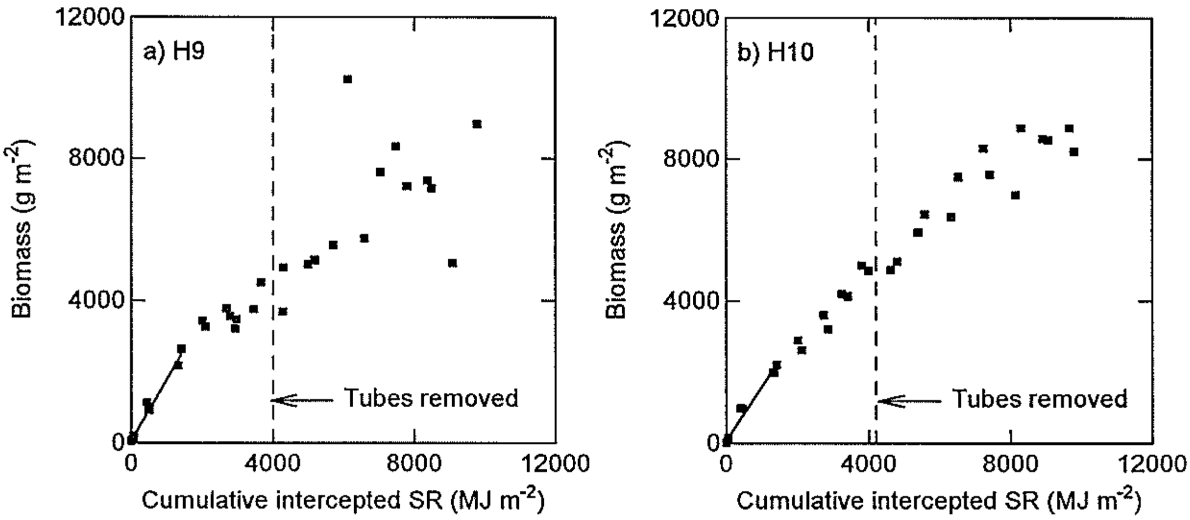

Figure 5. Above-ground biomass with cumulative intercepted solar radiation for H9 (TS65-28) and H10 (Q117) grown under potential yield conditions at Harwood in 1995-97. Maximum RUE for TS65-28 was 1.71g MJ^{-1}. Maximum RUE for Q117 was 1.50g MJ^{-1}.

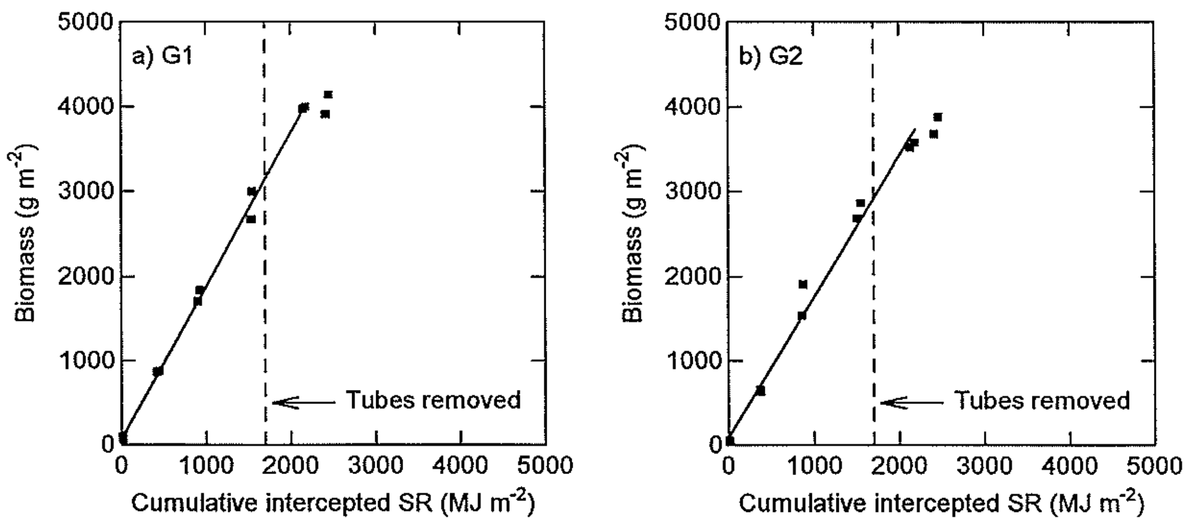

Figure 6. Above-ground biomass with cumulative intercepted solar radiation for G1 (TS65-28) and G2 (Q117) grown under potential yield conditions at Grafton in 1994-95. Maximum RUE for TS65-28 was 1.80g MJ^{-1}. Maximum RUE for Q117 was 1.66g MJ^{-1}.

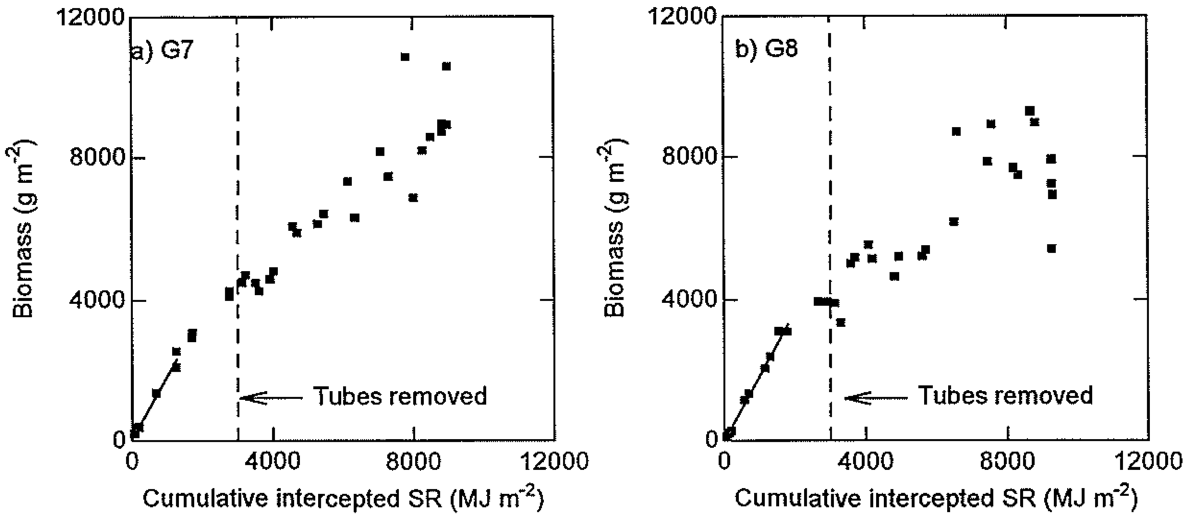

Figure 7. Above-ground biomass with cumulative intercepted solar radiation for G7 (TS65-28) and G8 (Q117) grown under potential yield conditions at Grafton in 1995-97. Maximum RUE for TS65-28 was 1-4 1.79g MJ^{-1}. Maximum RUE for Q117 was 1.83g MJ^{-1}.

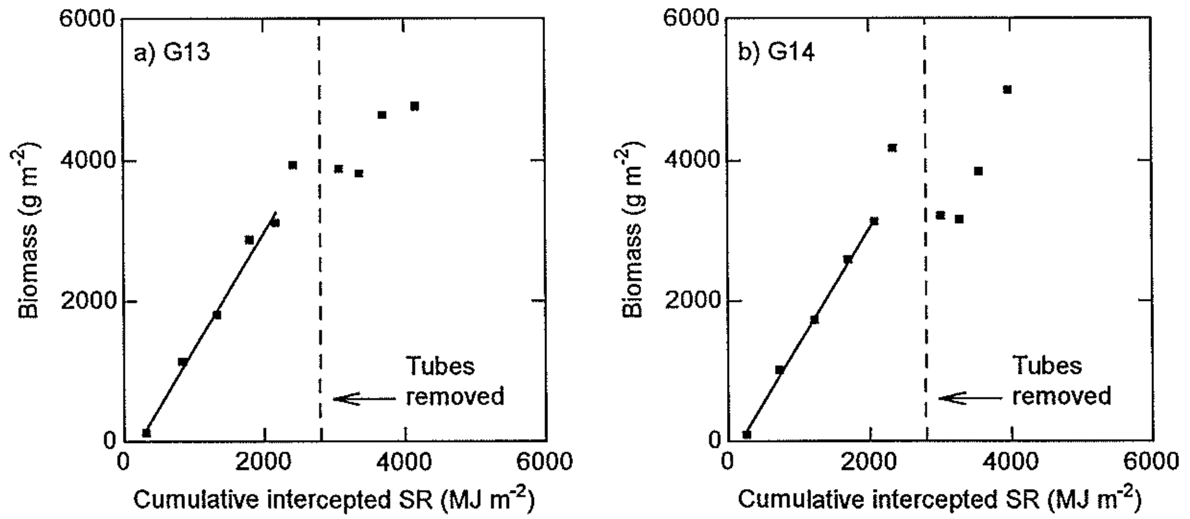

Figure 8. Above-ground biomass with cumulative intercepted solar radiation for G13 (TS65-28) and G14 (Q117) grown under potential yield conditions at Grafton in 1997-98. Maximum RUE for TS65-28 was 1.70g MJ^{-1}. Maximum RUE for Q117 was 1.83g MJ^{-1}.

Sucrose Partitioning

The partitioning of biomass to economic yield is analysed firstly in terms of the proportion of total growth (crop biomass) partitioned to stalk. Data for NSW are shown in Figs. 9 to 13. In essence, a linear relationship described the accumulation of stalk biomass but the proportion on crop biomass present as stalk increased with increasing biomass given the significant intercept on the x-axis (Figs 9 to 13). There was little difference between NSW crops and those observed in north Queensland (Fig. 19) in biomass partitioning to stalk.

The partitioning of biomass to sucrose is examined firstly in terms of the relative contributions of different stalk classes to yield and their sucrose concentration both on a dry weight and fresh weight basis (Tables 5 to 14), and secondly in terms of the relationship between stalk biomass and stalk sucrose (Figs. 14 to 18). Data in Tables 5 to 14 show that suckers are similar if not higher in sucrose concentration on a dry weight basis at final harvest compared with primary stalks. Suckers tended to have a lower stalk dry matter content than primary stalks. Hence the effect of suckers on total sucrose concentration on a fresh weight basis (and hence CCS) depend on these relative effects of sucrose concentration and dry matter content. Figs. 14 to 18 show that partitioning of biomass to sucrose differed between the first and second year of growth. The efficiency of partitioning of stalk biomass to stalk sucrose followed similar patterns to north Queensland in the first 12 months but was lower in the following 10-12 months. For the amount of stalk biomass produced in the second year in NSW environments, stalk sucrose concentration on a dry weight basis was less than that observed in other environments (e.g. north Queensland, South Africa; Robertson *et al.*, 1996b). This combined with higher stalk water content appears to contribute to lower stalk sucrose concentration on a fresh weight basis and hence CCS in the NSW environments. Options for genetic improvement and crop management to increase sucrose partitioning need to be explored.

Table 5. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for TS65-28 grown under potential yield conditions at Harwood in 1993-95 (Expt. Code H5, see Table 2).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	22	6		
Cane yield (t ha^{-1})	233	46.3	15.5	295
Sucrose yield (t ha^{-1})	26.5	4.3	0.5	31.2
Sucrose conc. (g g^{-1} FW)	0.114	0.090	0.049	0.106
Sucrose conc. (g g^{-1} DW)	0.397	0.403	0.227	0.392
Dry matter content (g g^{-1})	0.286	0.224	0.203	0.271

Table 6. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for Q117 grown under potential yield conditions at Harwood in 1993-95 (Expt. Code H6, see Table 2).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	22	6		
Cane yield (t ha^{-1})	260	5.5	11.3	277
Sucrose yield (t ha^{-1})	29.9	0.5	0.9	31.2
Sucrose conc. (g g^{-1} FW)	0.115	0.092	0.078	0.113
Sucrose conc. (g g^{-1} DW)	0.424	0.423	0.357	0.422
Dry matter content (g g^{-1})	0.271	0.218	0.219	0.268

Table 7. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for TS65-28 grown under potential yield conditions at Harwood 1995-97 (Expt. Code H9, see Table 2).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	22	10		
Cane yield (t ha-1)	128	88.5	28.1	245
Sucrose yield (t ha-1)	16.3	11.5	0.7	28.5
Sucrose conc. (g g-1 FW)	0.127	0.130	0.0239	0.116
Sucrose conc. (g g-1 DW)	0.430	0.469	0.114	0.415
Dry matter content (g g-1)	0.296	0.277	0.211	0.278

Table 8. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for Q117 grown under potential yield conditions at Harwood 1995-97 (Expt. Code H10, see Table 2).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	22	10		
Cane yield (t ha-1)	216	19.0	33.7	269
Sucrose yield (t ha-1)	26.0	2.2	2.6	30.8
Sucrose conc. (g g-1 FW)	0.120	0.109	0.0775	0.115
Sucrose conc. (g g-1 DW)	0.432	0.488	0.357	0.427
Dry matter content (g g-1)	0.279	0.224	0.218	0.268

Table 9. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of one stalk class (primary stalks only) for TS65-28 grown under potential yield conditions at Grafton 1994-95 (Expt. Code G1, see Table 3).

	Total
Age (months)	11
Cane yield (t ha-1)	152
Sucrose yield (t ha-1)	14.2
Sucrose conc. (g g-1 FW)	0.092
Sucrose conc. (g g-1 DW)	0.429
Dry matter content (g g-1)	0.214

Table 10. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of one stalk class (primary stalks only) for Q117 grown under potential yield conditions at Grafton 1994-95 (Expt. Code G2, see Table 3).

	Total
Age (months)	11
Cane yield (t ha^{-1})	164
Sucrose yield (t ha^{-1})	12.8
Sucrose conc. (g g^{-1} FW)	0.078
Sucrose conc. (g g^{-1} DW)	0.417
Dry matter content (g g^{-1})	0.186

Table 11. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for TS65-28 grown under potential yield conditions at Grafton in 1995-97 (Expt. Code G7, see Table 3).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	24	10		
Cane yield (t ha^{-1})	193	73.2	31.1	297
Sucrose yield (t ha^{-1})	23.3	9.2	1.1	33.6
Sucrose conc. (g g^{-1} FW)	0.121	0.123	0.050	0.113
Sucrose conc. (g g^{-1} DW)	0.448	0.474	0.234	0.442
Dry matter content (g g^{-1})	0.270	0.259	0.194	0.256

Table 12. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of three stalk classes for Q117 grown under potential yield conditions at Grafton in 1995-97 (Expt. Code G8, see Table 3).

	Primary Stalks	Suckers	Dead Stalks	Total
Age (months)	24	10		
Cane yield (t ha^{-1})	128	45.8	49.4	223
Sucrose yield (t ha^{-1})	15.4	4.9	2.8	23.1
Sucrose conc. (g g^{-1} FW)	0.120	0.109	0.055	0.104
Sucrose conc. (g g^{-1} DW)	0.453	0.446	0.328	0.434
Dry matter content (g g^{-1})	0.266	0.245	0.169	0.240

Table 13. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of two stalk classes for TS65-28 grown under potential yield conditions at Grafton in 1997-98 (Expt. Code G13, see Table 3).

	Primary Stalks	Dead Stalks	Total
Age (months)	12		
Cane yield (t ha-1)	111	5.8	116
Sucrose yield (t ha-1)	14.7	0.5	15.2
Sucrose conc. (g g-1 FW)	0.133	0.0832	0.130
Sucrose conc. (g g-1 DW)	0.467	0.346	0.462
Dry matter content (g g-1)	0.284	0.243	0.282

Table 14. Millable fresh stalk (cane) yield, sucrose yield, stalk sucrose content and stalk dry matter content of two stalk classes for Q117 grown under potential yield conditions at Grafton in 1997-98 (Expt. Code G14, see Table 3).

	Primary Stalks	Dead Stalks	Total
Age (months)	12		
Cane yield (t ha-1)	113	9.4	122
Sucrose yield (t ha-1)	15.4	1.0	16.3
Sucrose conc. (g g-1 FW)	0.136	0.0998	0.133
Sucrose conc. (g g-1 DW)	0.490	0.476	0.489
Dry matter content (g g-1)	0.278	0.210	0.274

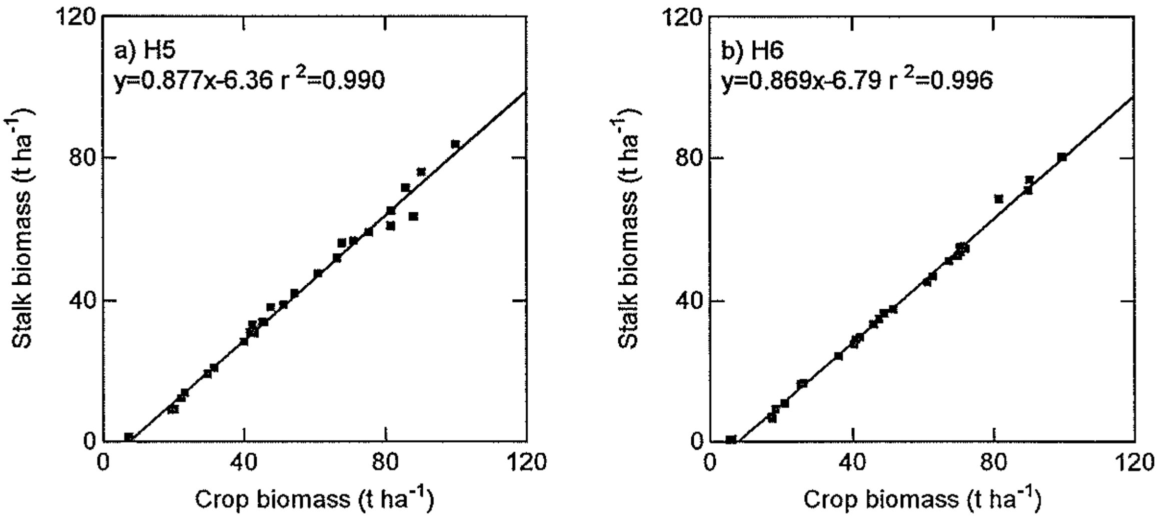

Figure 9. Relationship between stalk biomass and crop biomass for experiments H5 and H6 conducted at Harwood during 1993-1995.

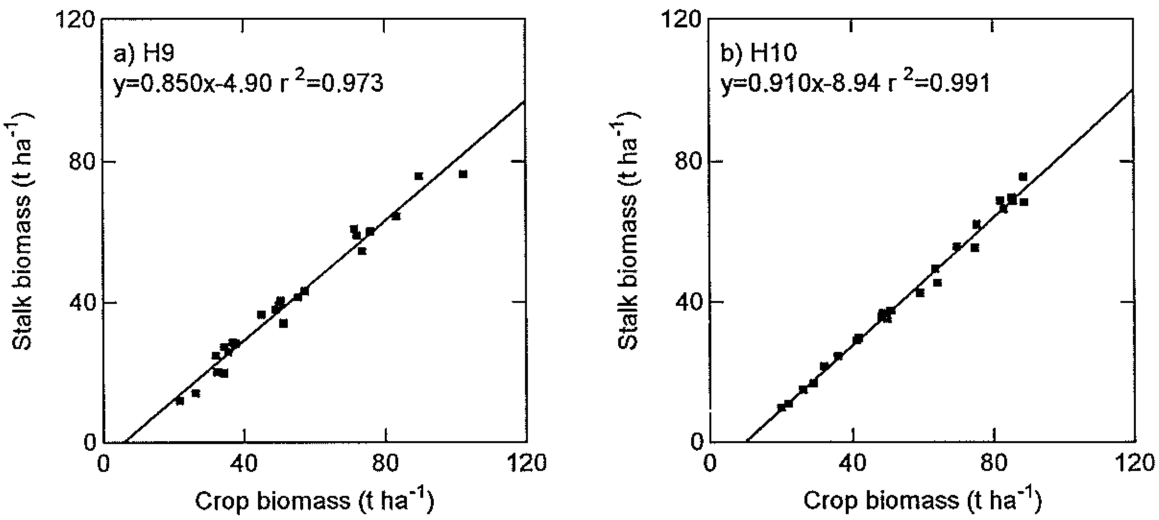

Figure 10. Relationship between stalk biomass and crop biomass for experiments H9 and H10 conducted at Harwood during 1995-1997.

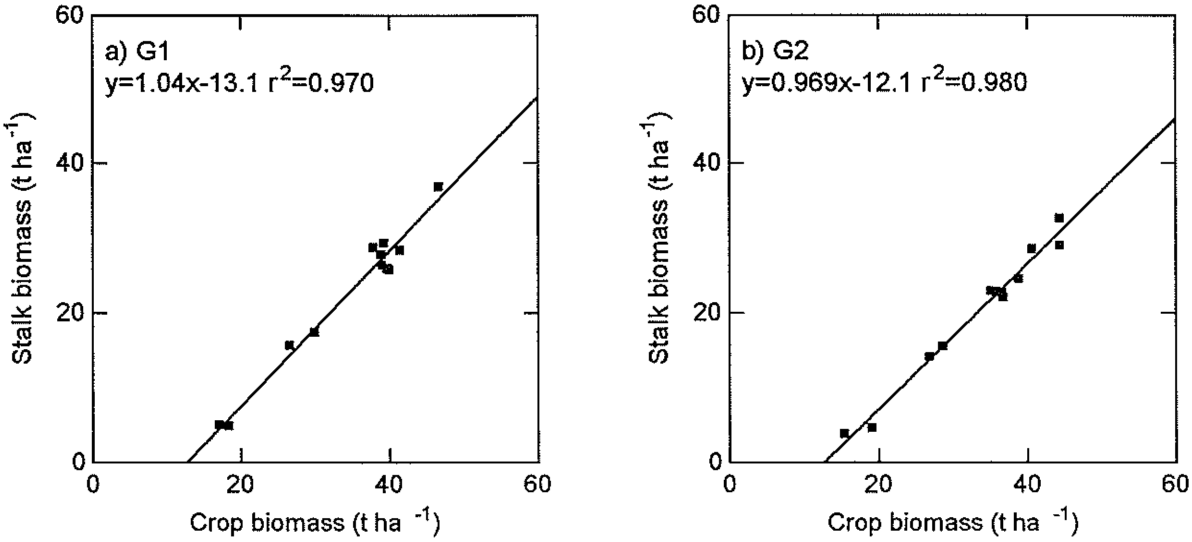

Figure 11. Relationship between stalk biomass and crop biomass for experiments G1 and G2 conducted at Grafton during 1994-1995.

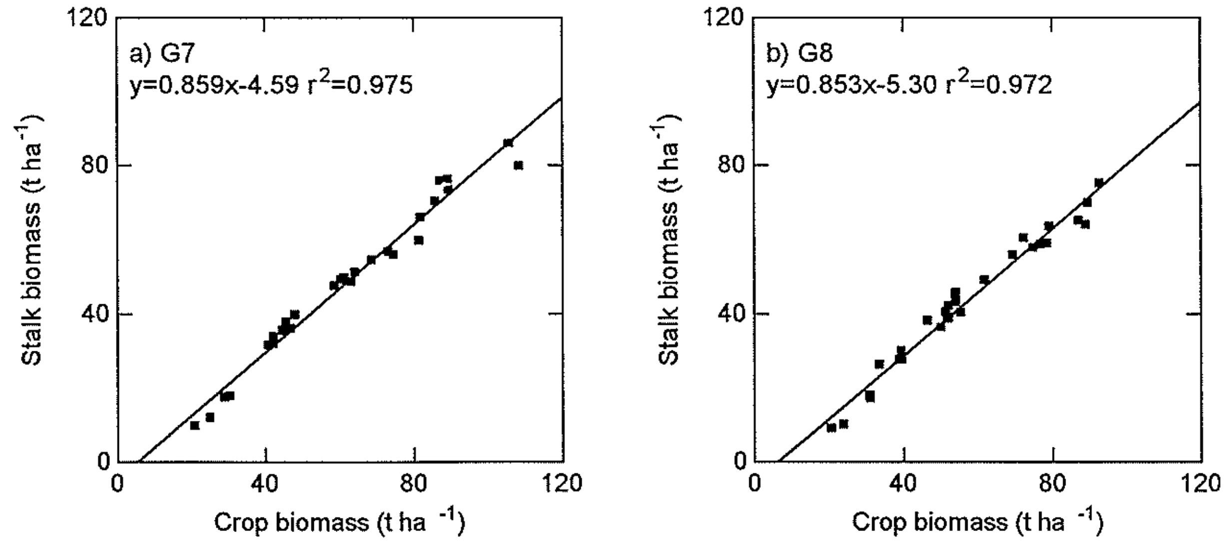

Figure 12. Relationship between stalk biomass and crop biomass for experiments G7 and G8 conducted at Grafton during 1995-1997.

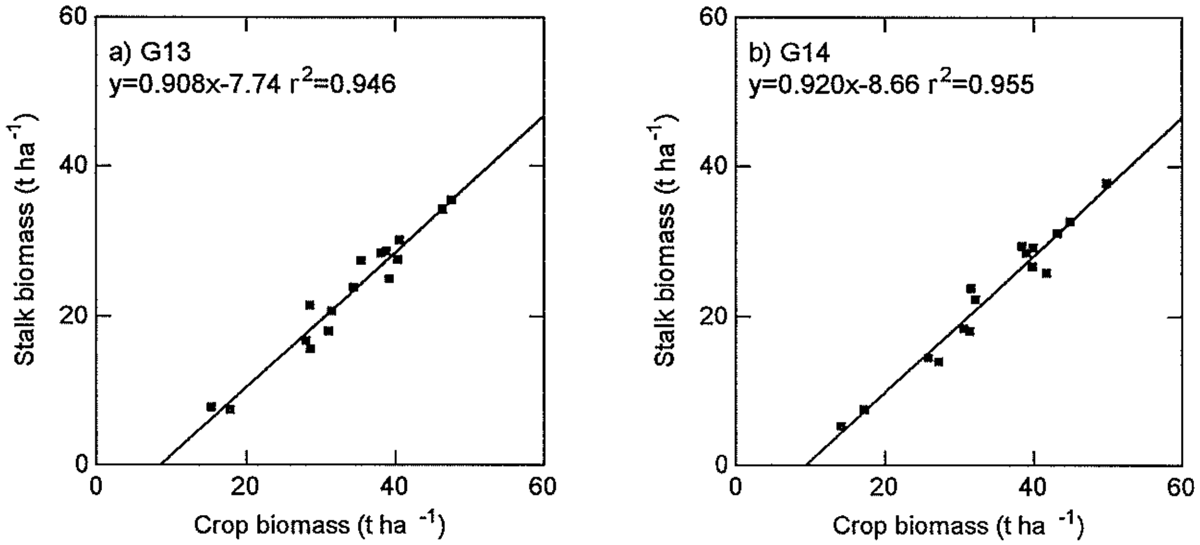

Figure 13. Relationship between stalk biomass and crop biomass for experiments G13 and G14 conducted at Grafton during 1997-1998.

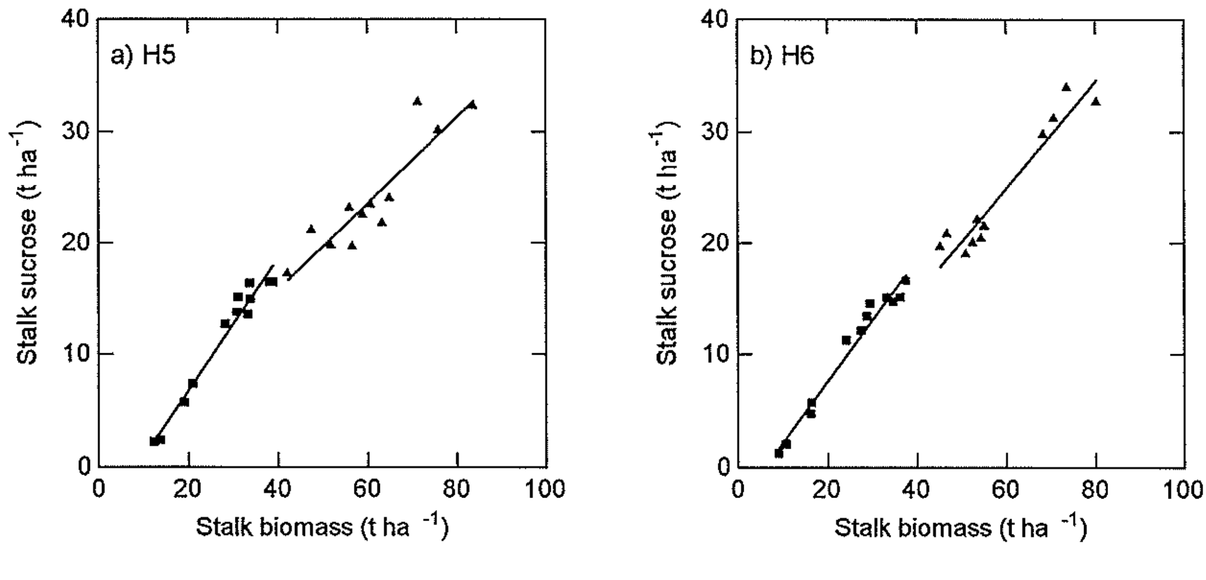

Figure 14. Relationship between stalk sucrose and stalk biomass for experiments H5 and H6 conducted at Harwood. For TS65-28 (a), up to 13 months (■) y=0.590x-5.01 r^2=0.960, from 13 to 22 months (▲) y=0.388x+0.329 r^2=0.808. For Q117 (b), up to 13 months (■) y=0.547x-3.39 r^2=0.968, for 13 to 22 months (▲) y=0.480x-3.83 r^2=0.905.

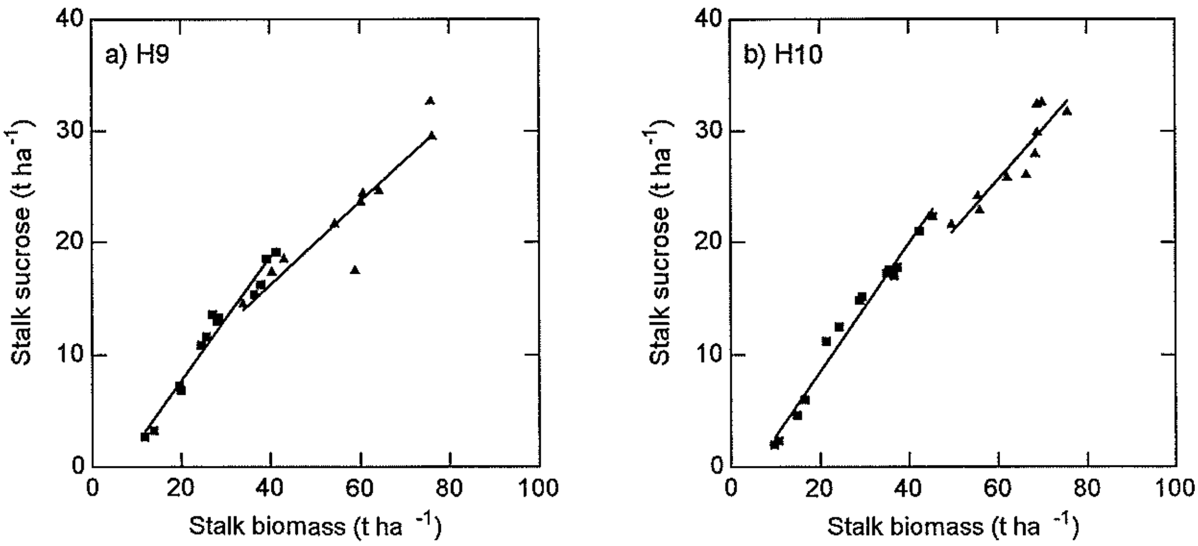

Figure 15. Relationship between stalk sucrose and stalk biomass for experiments H9 and H10 conducted at Harwood. For TS65-28 (a), up to 13 months (■) y=0.550x-3.36 r^2=0.957, from 13 to 22 months (▲) y=0.372x+1.20 r^2=0.824. For Q117 (b), up to 13 months (■) y=0.571x-2.97 r^2=0.976, for 13 to 22 months (▲) y=0.454x-1.60 r^2=0.805.

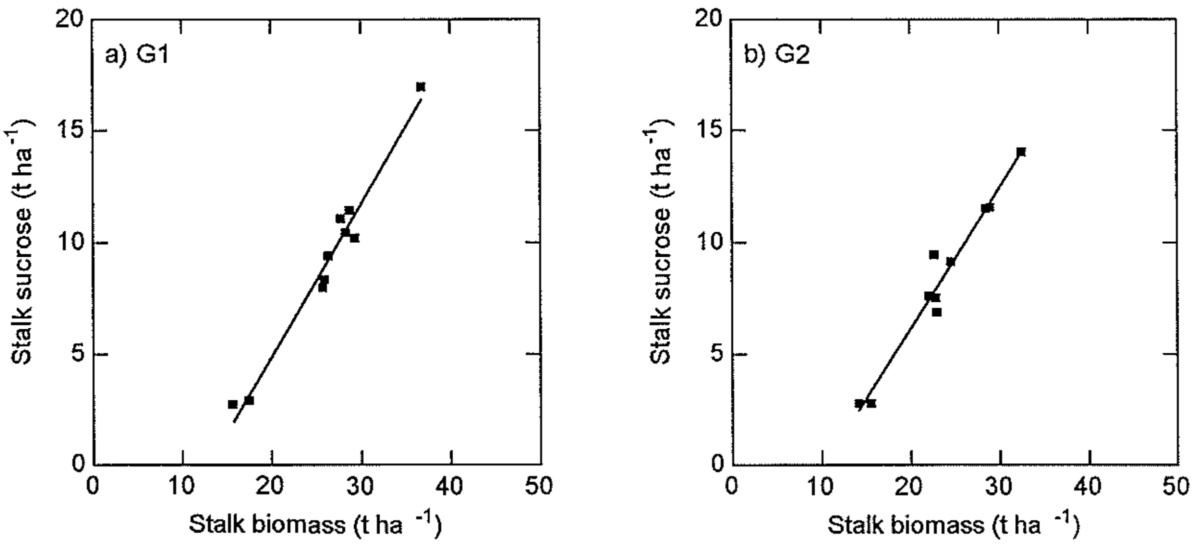

Figure 16. Relationship between stalk sucrose and stalk biomass for experiments G1 and G2 conducted at Grafton. For TS65-28 (a), 11 months (■) y=0.685x-8.82 r^2=0.969. For Q117 (b), 11 months (■) y=0.631x-6.49 r^2=0.958.

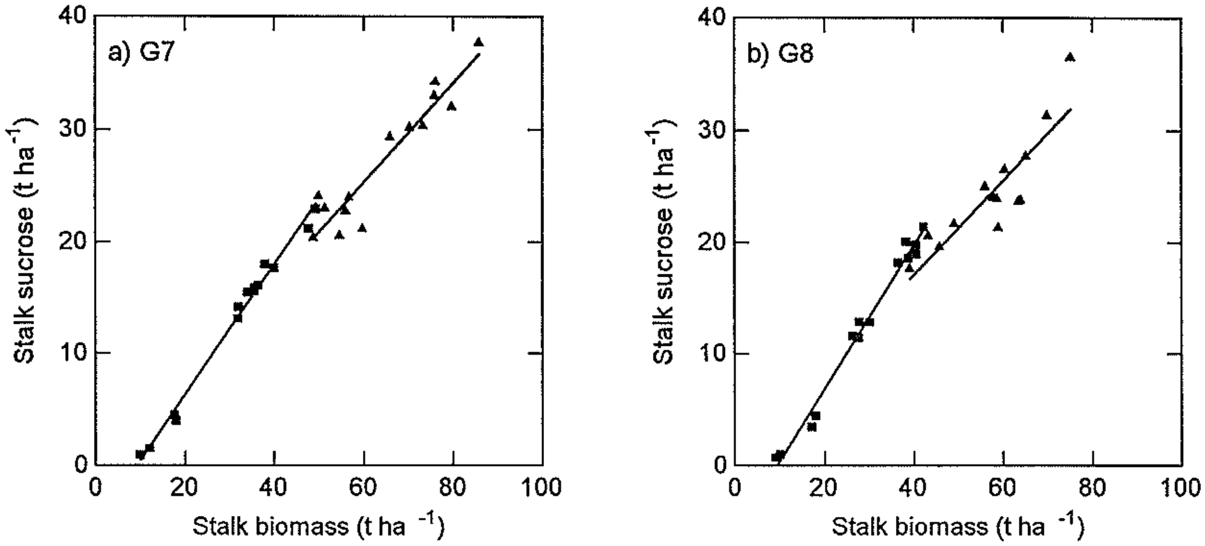

Figure 17. Relationship between stalk sucrose and stalk biomass for experiments G7 and G8 conducted at Grafton. For TS65-28 (a), up to 13 months (■) $y=0.582x-5.28$ $r^2=0.989$, from 13 to 22 months (▲) $y=0.438x-0.974$ $r^2=0.879$. For Q117 (b), up to 13 months (■) $y=0.645x-6.11$ $r^2=0.984$, for 13 to 22 months (▲) $y=0.421x+0.263$ $r^2=0.758$.

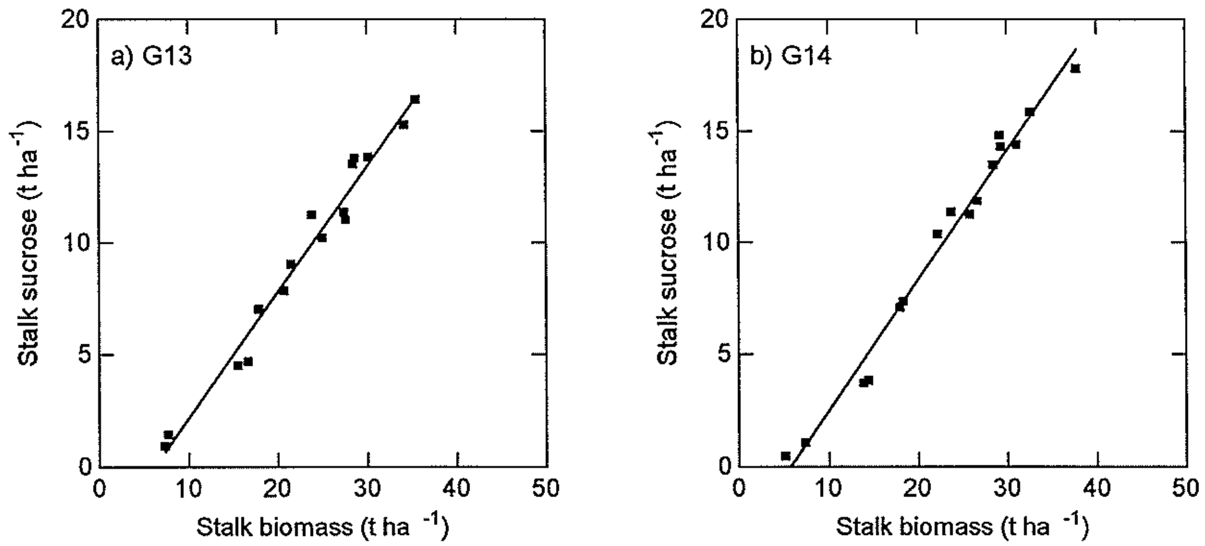

Figure 18. Relationship between stalk sucrose and stalk biomass for experiments G13 and G14 conducted at Grafton. For TS65-28 (a), 12 months (■) $y=0.562x-3.42$ $r^2=0.973$. For Q117 (b), 12 months (■) $y=0.582x-3.33$ $r^2=0.982$.

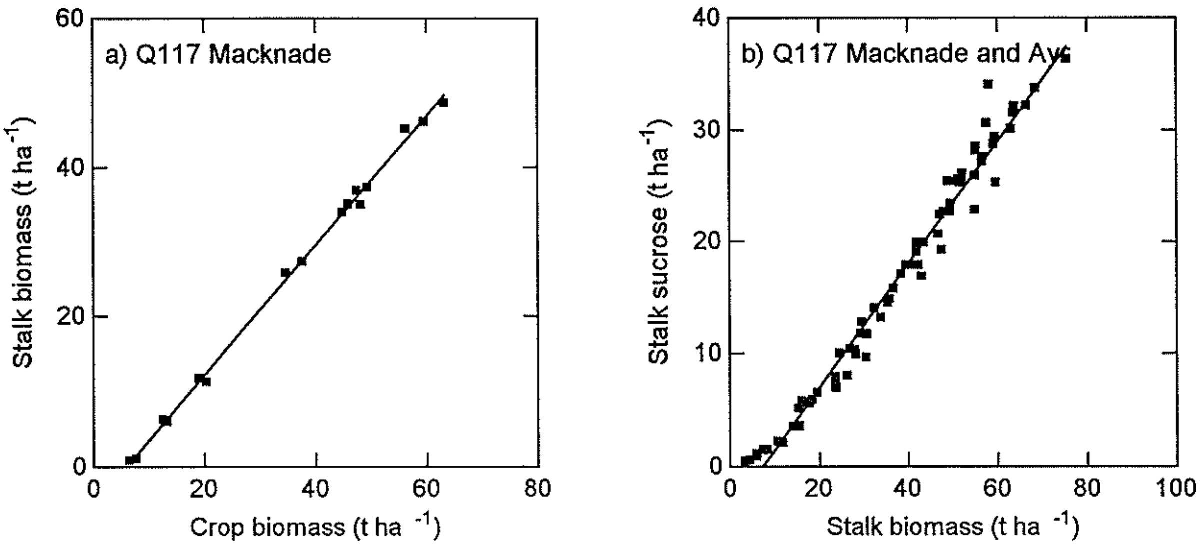

Figure 19. Relationship between stalk biomass and crop biomass (a) for Q117 grown under potential yield conditions at Macknade planted 10 September 1993 y=0.867x-5.13 r2=0.997 and (b) relationship between stalk sucrose and stalk biomass for Q117 grown under potential yield conditions at Macknade and Ayr y=0.549x-3.89 r2=0.976.

Publications

HUGHES, R.M., ROBERTSON, M.J., MUCHOW, R.C. and WOOD, A.W. (1995). A comparison of 12-month sugarcane crop production between North Queensland and Northern New South Wales. *Proceedings of the 17th Conference, Australian Society of Sugarcane Technologists*, pp. 149-154.

HUGHES, R.M. and MUCHOW, R.C. (1998). The contribution of first and second year growth to the yield of two-year cane in NSW. *Proceedings of the 1998 Conference, Australian Society of Sugarcane Technologists*, pp. 280-287.

HUGHES, R.M. and MUCHOW, R.C. (2000). Variation in sucrose concentration with crop age in primary, sucker and dead stalks in NSW Environments. *Proceedings of the 2000 Conference, Australian Society of Sugarcane Technologists.*

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MUCHOW, R.C., HAMMER, G.L., KINGSTON, G. (1991). Assessing the potential yield of sugar cane. In: Egan, B.T. (Eds). *Proceedings of the 13th Conference of the Australian Society of sugar cane Technologists*, pp. 146-151.

MUCHOW, R.C., WOOD, A.W., SPILLMAN, M.F., ROBERTSON, M.J. and Thomas, M.R. (1993). Field techniques to quantify the yield-determining processes in sugarcane. I. Methodology. *Proceedings of the 15th Conference, Australian Society of Sugarcane Technologists*, pp. 336-343.

MUCHOW, R.C., SPILLMAN, M.F., WOOD, A.W. and THOMAS, M.R. (1994). Radiation interception and biomass accumulation in a sugarcane crop grown under irrigated tropical conditions. *Australian Journal of Agricultural Research* **45**: 37-49.

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MUCHOW, R.C., ROBERTSON, M.J., WOOD, A.W., and KEATING, B.A. (1997a). Assessing limits to sugarcane yield. *Proceedings of the 19th Conference, Australian Society of Sugarcane Technologists*, pp. 221-228.

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PRESTWIDGE, D.B., ROBERTSON, M.J., MUCHOW, R.C., HAMMER, G.L., HUGHES, R.M., KEATING, B.A., KINGSTON, G., LIU, D.L. and WOOD, A.W. (1994). SUGARBAG: A database system for sugarcane crop growth, climate, soils and management data. CSIRO Aust. Division of Tropical Crops and Pastures, Trop. Agron. Tech. Mem. No. 84, 36p.

ROBERTSON, M.J., WOOD, A.W. and MUCHOW, R.C. (1996a). Growth of sugarcane under high-input conditions in tropical Australia. I. Radiation use, biomass accumulation and partitioning. *Field Crops Res*earch **48**: 11-25.

ROBERTSON, M.J., MUCHOW, R.C., INMAN-BAMBER, N.G. and WOOD, A.W. (1996b). Relationship between biomass and sucrose accumulation by sugarcane. In: J.R. Wilson, D.M. Hogarth, J.A. Campbell, and A.L. Garside (Eds.) *Sugarcane: Research towards efficient and sustainable production*, CSIRO Division of Tropical Crops and Pastures, Brisbane, pp. 84-86.

ROBERTSON, M.J., BONNETT, G., HUGHES, R.M., MUCHOW, R.C. and CAMPBELL. (1998). Temperature and leaf area expansion of sugarcane: integration of controlled-environment, field and model studies. *Australian Journal of Plant Physiology* **25**: 819-828.

THOMAS, M.R., MUCHOW, R.C., WOOD, A.W., SPILLMAN, M.F., and ROBERTSON, M.J. (1993). Field techniques to quantify the yield-determining processes in sugarcane. II. Sampling strategy analysis. *Proceedings of the 15th Conference, Australian Society of Sugarcane Technologists*, pp. 344-351.

Implications and Recommendations

The strategic research conducted in this project CTA012 in low temperature southern environments and in project CTA004 for northern environments can underpin more applied and tactical research aimed at improving the productivity of the Australian Sugar Industry. The following recommendations should be considered:

1. This project has used a new research approach for sugarcane. The framework developed for other crops and outlined by Muchow *et al.* (1991, 1997a) has been successfully tested for sugarcane. A further extension of this framework is the development of minimum dataset protocols to ensure that data from field experimentation can be used in extrapolation across locations and seasons. It is recommended that this approach to data collection and analysis be widely adopted in research examining production constraints in the sugarcane production system. This has occurred in further SRDC Projects e.g.. CTA016, CTA018 and in Program 3 for the CRC for Sustainable Sugar Production. The SUGARBAG Experimental Database System (Prestwidge *et al.*, 1994) has been developed for this purpose by CSIRO Tropical Agriculture and in partnership with other agencies currently stores in excess of 100 sugarcane experiments. Wider adoption of these protocols across the Australian sugar industry is recommended.
2. Similarly to Project CTA004, this project has highlighted the difficulties of comparing production data using fresh weight measures of cane yield and CCS. Clearly, these commercial measures of yield are important as they are used as a basis of payment in the Australian Sugar Industry. However, the highly variable stalk dry matter content makes biological comparisons to identify production constraints and opportunities to overcome them, extremely difficult. In a research context, it is recommended that dry weight measures of crop performance (crop and stalk biomass etc) be routinely measured. The value of research data would be maximised, as comparisons and insights from different trials across seasons and locations could be made using standardised dry weight measures. In addition, using these measures to understand yield constraints is essential given the confounding that occurs with commercial measures associated with the inclusion of tops, trash, dirt and other extraneous matter in the cane supply.
3. This project has examined the control of potential sugarcane productivity as determined by the temperature and radiation regime. It has additionally examined the contribution to yield by suckers and dead stalks and has examined differences between 12 and 24 month cane. An extension of the approach taken here is recommended to understand the contribution of suckers to yield and CCS in northern wet tropical environments.
4. The power of using crop simulation modelling as an adjunct to field experimentation to identify opportunities for improving the sugarcane production system has been demonstrated by this project. By benchmarking productivity in relation to climate, the climatically determined yield can be used to identify potential yield constraints and the scope for yield improvement. Data as collected in this experiment are essential for validation of this approach.
5. Whilst this project has concluded that there is considerable scope for increasing commercial yields in NSW environments, further investigation into partitioning of sucrose is warranted given that it contributes to low CCS in NSW environments. This work should be linked to variety management in relation to time of harvest and a possible evaluation of the role of ripeners.

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.

Technical Summary

The methodologies developed in this project have been described in detail by Muchow *et al.* (1993). No new software or equipment was developed in the project.

Acknowledgments

The authors acknowledge the assistance of Phil Hirst, Frank Biddle and farm staff of NSW Agriculture, and Peter Harland, Di Prestwidge and Mike Spillman of CSIRO Tropical Agriculture. Heidi Horan (née Vogelsang) assisted with data analysis and presentation.

APPENDIX 1. CLIMATIC CONDITIONS DURING THE FIELD EXPERIMENTATION AT HARWOOD AND GRAFTON

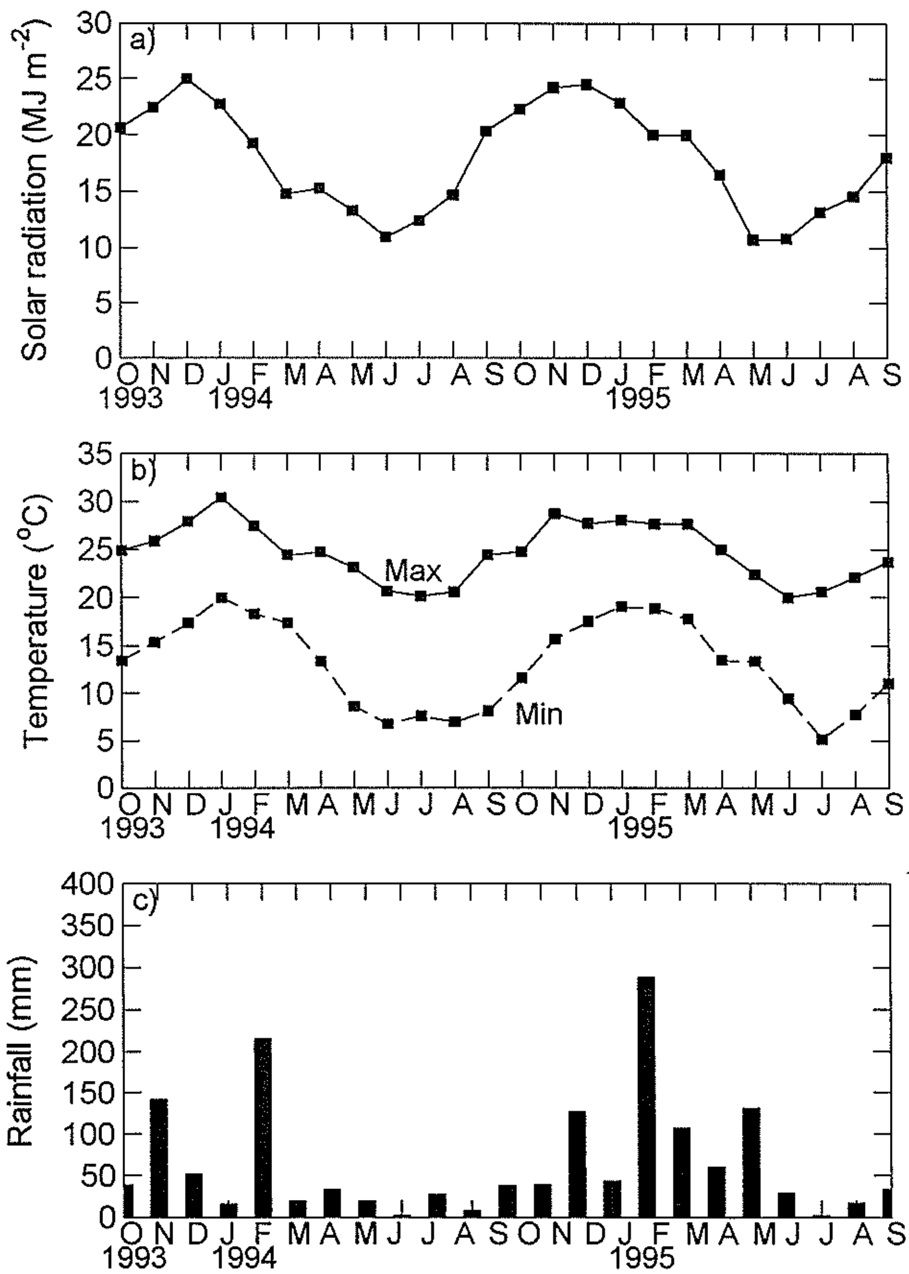

Figure 1.1 Harwood (a) mean monthly solar radiation, (b) mean monthly maximum and minimum temperature and (c) monthly total rainfall for the period October 1993 to September 1995.

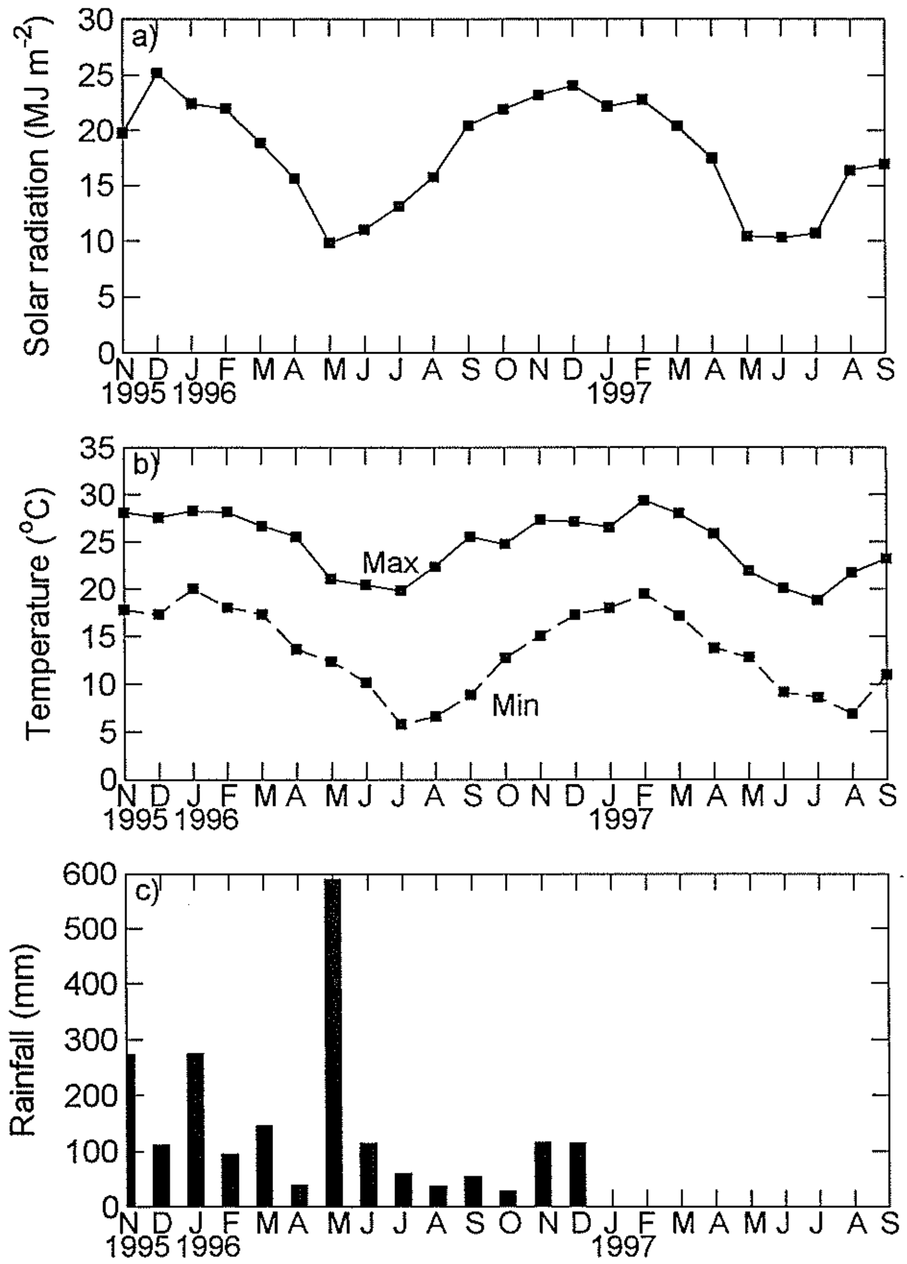

Figure 1.2 Harwood (a) mean monthly solar radiation and (b) mean monthly maximum and minimum temperature during the period November 1995 to September 1997 and (c) total monthly rainfall for the period Nov 1995 to December 1996. Rainfall was not recorded in 1997.

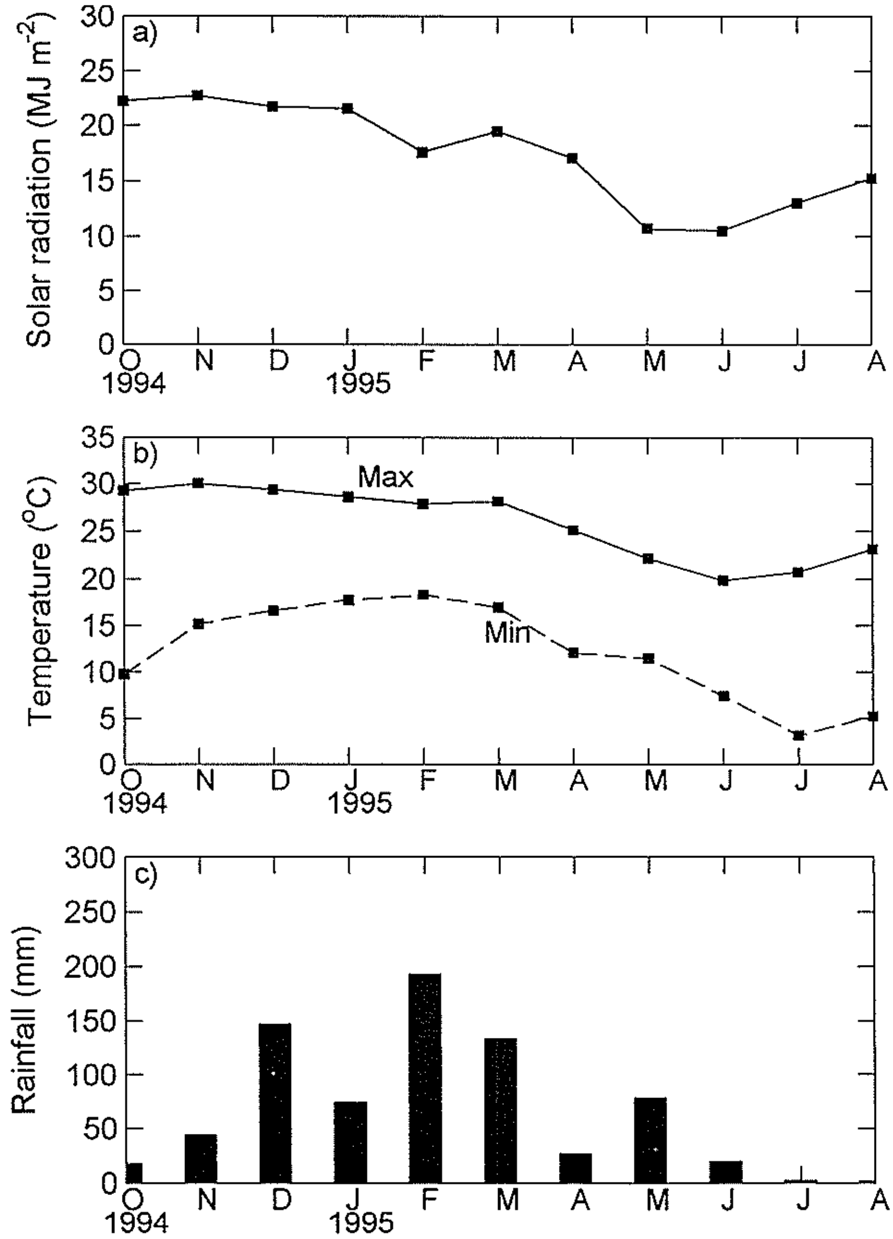

Figure 1.3 Grafton (a) mean monthly solar radiation, (b) mean monthly maximum and minimum temperature and (c) monthly total rainfall for the period October 1994 to August 1995. Frost occurred on 21 and 22 July 1995 which affected the crop (leaves died and stems became brittle).

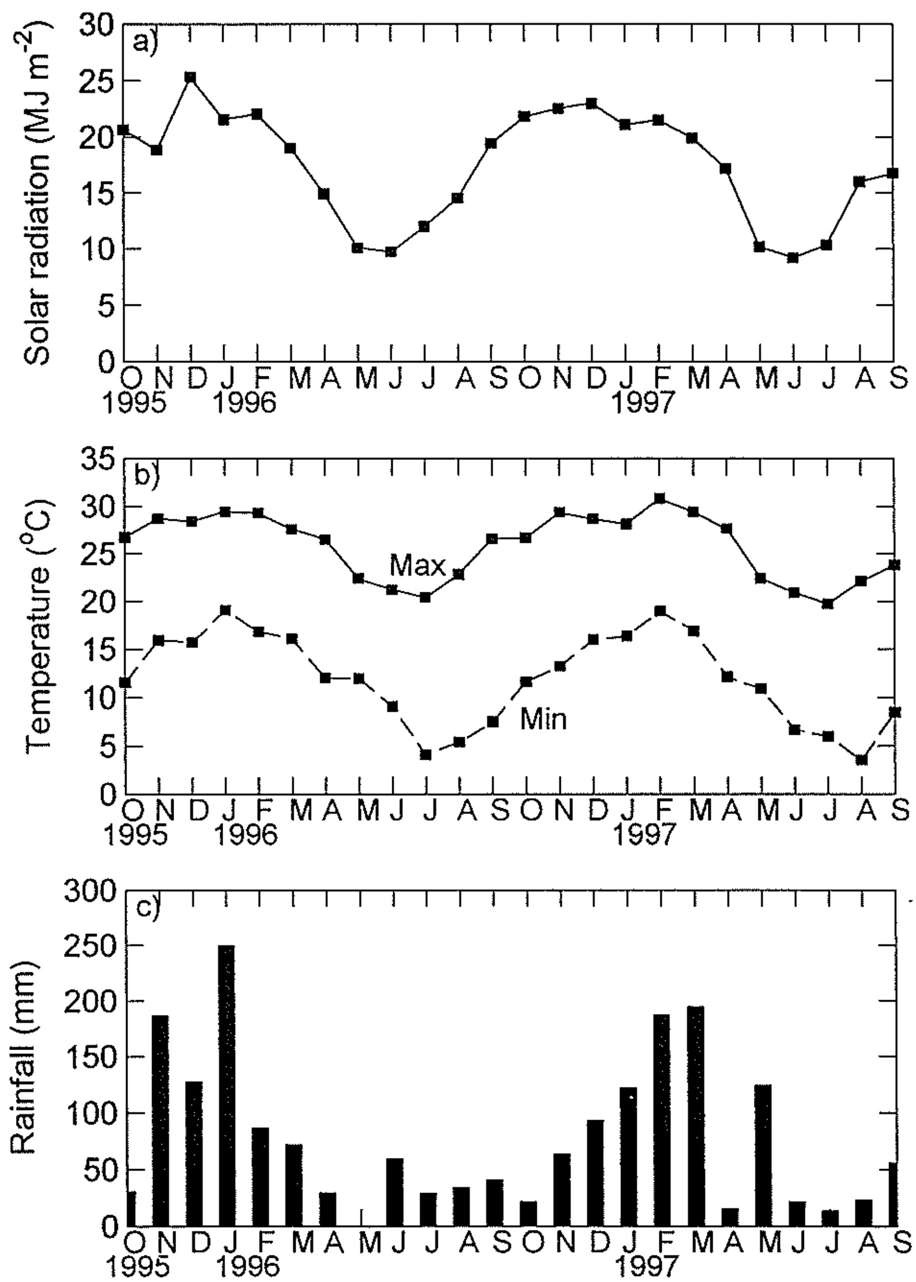

Figure 1.4 Grafton (a) mean monthly solar radiation, (b) mean monthly maximum and minimum temperature and (c) monthly total rainfall for the period October 1995 to September 1997.

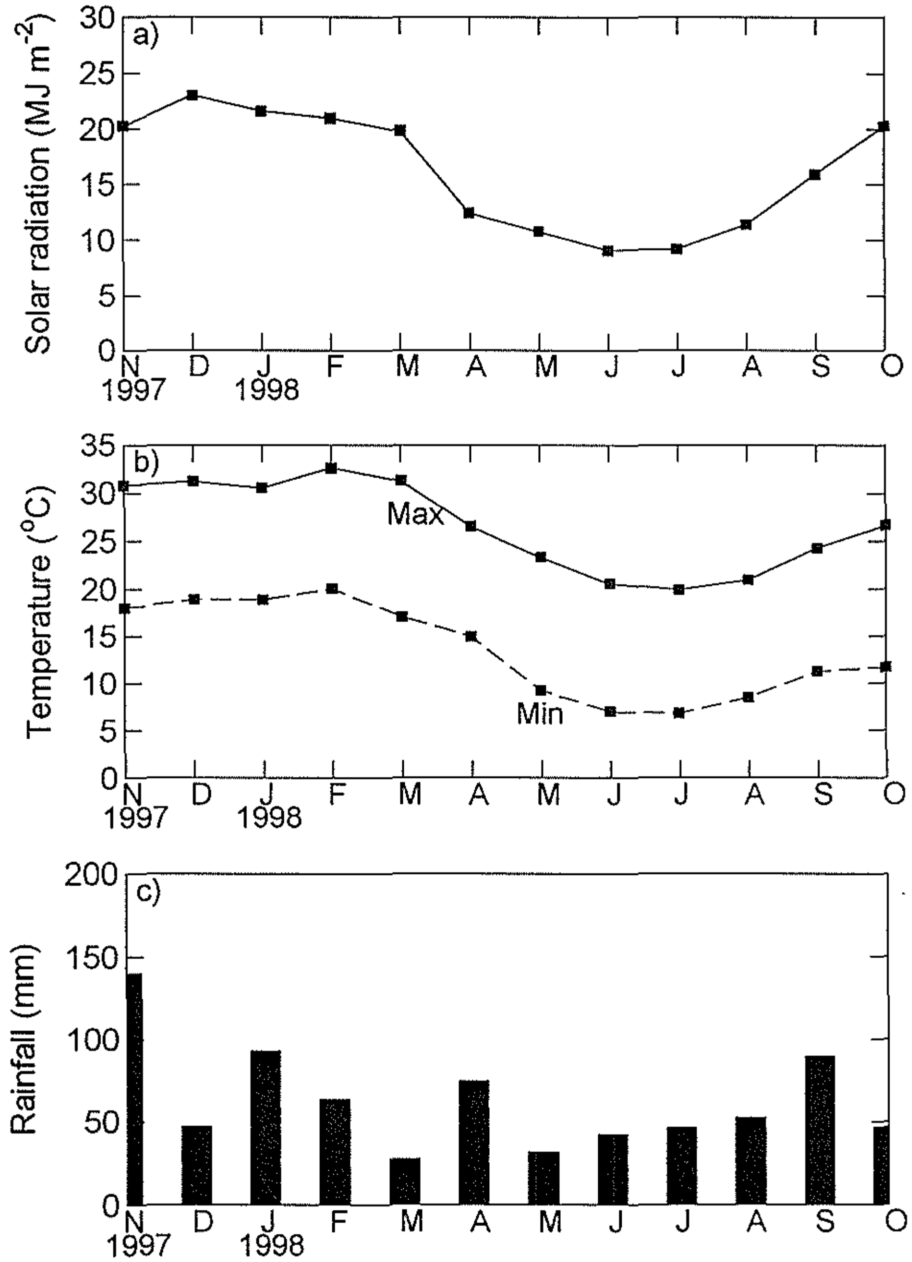

Figure 1.5 Grafton (a) mean monthly solar radiation, (b) mean monthly maximum and minimum temperature and (c) monthly total rainfall for the period November 1997 to October 1998.

APPENDIX 2. SOME PUBLICATIONS RESULTING FROM THIS PROJECT

2.1 HUGHES, R.M., ROBERTSON, M.J., MUCHOW, R.C. and WOOD, A.W. (1995). A comparison of 12-month sugarcane crop production between North Queensland and Northern New South Wales. Proceedings of the 17th Conference, Australian Society of Sugarcane Technologists, pp. 149-154.

2.2 ROBERTSON, M.J., BONNETT, G., HUGHES, R.M., MUCHOW, R.C. and CAMPBELL. (1998). Temperature and leaf area expansion of sugarcane: integration of controlled-environment, field and model studies. *Aust. J. Plant Physiol.* **25**: 819-828.

2.3 HUGHES, R.M. and MUCHOW, R.C. (1998). Contribution of first and second year growth to the yield of two-year cane in NSW. Proceedings of the 1998 Conference, Australian Society of Sugarcane Technologists, pp. 280-287.

2.4 HUGHES, R.M. and MUCHOW, R.C. Variation in sucrose concentration with crop age in primary, sucker and dead stalks in NSW environments.