4. RESULTS

The results from the data provided by the various experiments participated in by the author, or derived from literature, are presented below. In the case where information is derived from data in the literature the calculations and assumptions used are given.

After defining the system boundaries in section 4.1, the layout of this chapter follows the logical progression from the planting and production of the sweet sorghum and sugarcane in section 4.2, through the harvesting, transport and the separation of the juice (sugars) and fibre i.e. the crushing in section 4.3. From this point there are two biomass streams i.e. (i) the juice and (ii) the fibre (bagasse), and therefore two separate processing paths which are both described in section 4.4. All the data in sections 4.2 to 4.4 are brought together in section 4.5 ‘systems analysis’ which highlights the key points in the production and conversion chain for the integration of sweet sorghum and sugarcane. Finally, this data is used in the development of the Agrosystems Integration Package (AIP) as outlined in section 4.6.

4.1. System Boundaries Defined

1. Based on growth and use of sweet sorghum on existing sugarcane land
2. Triangle Ltd. Zimbabwe provides the base-case model for processing sweet sorghum
3. Existing harvesting and transport technologies
4. Existing juice extraction technologies i.e. mill and diffuser
5. Existing and novel bagasse to energy conversion technologies
6. Existing fermentation technologies
7. Novel systems analysis tools

4.2. Agronomic Data

The sweet sorghum data shown were almost exclusively derived from the sweet sorghum trials conducted at CRS using the sweet sorghum varieties cv. Keller and Cowley (see also section 3.1.). For sugarcane-specific data, no agronomic trials were carried out for the purposes of this thesis and all sugarcane specific results were derived from the detailed logistical records of Triangle Ltd. agronomy and technical services departments or from published literature.

THE GROWTH PERIOD (GP) is defined here as the period during which the land has to be dedicated to a crop i.e. for sorghum this is the number of days between planting and harvesting. For example, Figure 11 shows the fresh weight above ground biomass accumulation for cv.s Keller and Cowley during the 1998/9 CRS trial. It clearly shows that the vegetative growth stage lasted for a minimum of 80 days from planting and therefore harvesting could not occur before 80 days growth. However, as shown in section 4.2.2.1. the dynamics of production of sugars and fibre do not correlate with total above ground biomass (fresh weight) the peaks of which occur after the end of the vegetative growth phase. Therefore the growth period is longer than 80 days for both varieties. For sugarcane it is the period between harvests (for a ratooning crop) and can therefore be more easily defined as shown below.

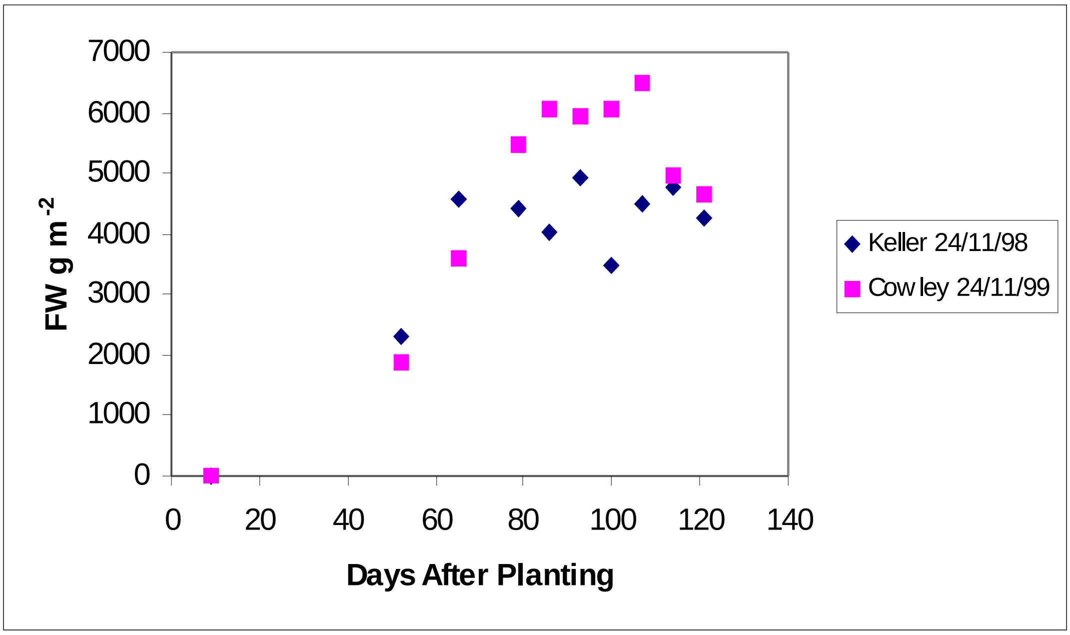


Fig. 11 Fresh Weight Biomass Accumulation for cv.s Keller & Cowley, CRS, 1998/9 Trial

Therefore:

for sorghum: GP_{ss} = 100-140 days (for cv.s Keller or Cowley)

for sugarcane: GP_{sc} = 365 days (12 month ratoon)

BIOMASS PRODUCTION (potential versus actual production) is defined by above ground production curves partitioned into the main plant organs, i.e. the stems, leaves, and tops (seeding bodies and apical meristem).

BIOMASS QUALITY is defined by the percentage of the stem, whole plant or delivered crop consisting of a desired constituent i.e. fibre, total sugars, total fermentables, sucrose, water, dry matter.

THE PERIOD OF INDUSTRIAL UTILISATION (PIU) is defined as the practical period during which a crop can be used for commercial conversion to economically valuable products. For ethanol production, this can be further defined as the period during which the biomass delivered to the mill has sufficient levels of total fermentables for it to be economically worthwhile for processing for fermentation to be continued and alcohol to be produced.

4.2.1. Climatic Data Collection & Use

Climate data derived from the CRS AWS data was used to compare seasonal data between the different experimental sorghum growth seasons. A five year continuous data series was compiled from the AWS data and associated meteorological / water balance spreadsheets for use in the AIP and also for comparative seasonal analysis.

The seasonal trend in temperature (mean, max & min) and solar radiation (Global radiation are given in Figure 12. These data clearly show why the months of November to February provide the best conditions for crop growth, particularly C_4 type crops. The positive correlation between high average daily temperatures of 25 EC or over and high solar radiation, often over 25 MJ m^{-2} d^{-1} were ideal for rapid carbon assimilation.

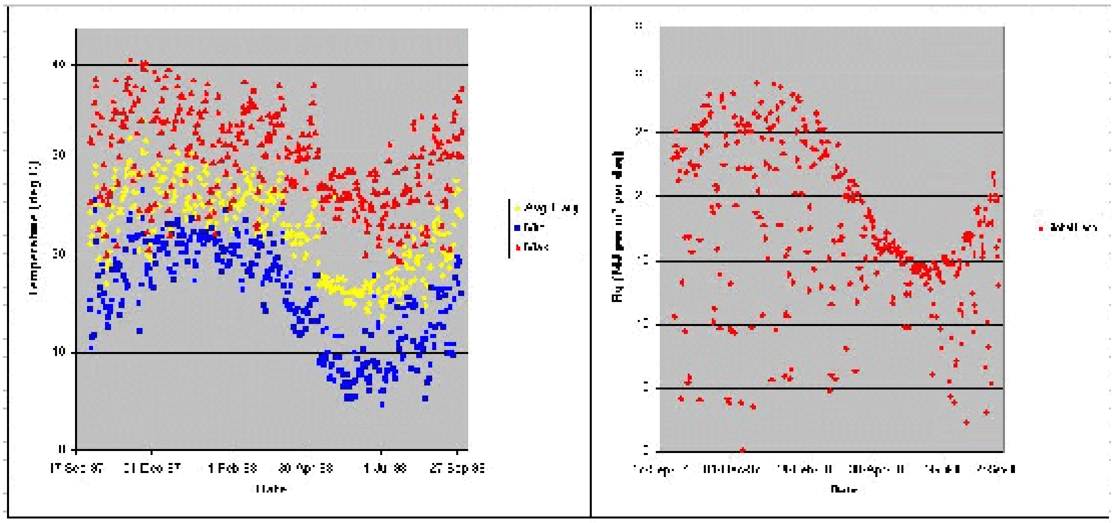


Fig. 12 Temperature & Radiation Profiles for 1997 to 1998, Chiredzi. Obtained from CRS Automatic Weather Station.

Table 4.1 highlights the variability between the 1997/8 and 1998/9 sweet sorghum growth periods in three key climatic growth factors i.e. temperature, solar radiation and rainfall.

Table 4.1: Seasonal Comparison of Climate Data (1997/8 versus 1998/9)- Chiredzi

	Cumulative Degree Days	Global Radiation (R_g) MJ m^{-2}		Rain
	dtt	Per Year	Per Day	mm
Season total				
1997/8	2694	2137	20.4	201
1998/9	2297	1944	18.5	648
% Difference (1998/9 / 97/8)	85	91	91	323
Month of February				
1997/8	696	609	21.8	26
1998/9	641	465	16.6	264
% Difference (1998/9 / 97/8)	92	77	77	1006

Notes: Climate data from the CRS AWS

4.2.2. Productivity

Trial data and literature searches have shown that sorghum is one of the most productive crop species known. This high productivity results from a combination of high light and nutrient use efficiencies and the ability of sorghum to extract relatively high fractions of these resources when conditions become limiting.

The data provided in this section on 'productivity' is structured to explain how the final 'average expected' yields for sweet sorghum and sugarcane are derived. Having provided a section above which describes the key climatic variables experienced during the main sweet sorghum trials in CRS and Triangle the following sub-sections of 4.2.2. provide data on accumulation profiles and partitioning. This data is then used in conjunction with total above ground biomass production data to define the expected growth period and total above ground dry and fresh weight yields for sweet sorghum and sugarcane.

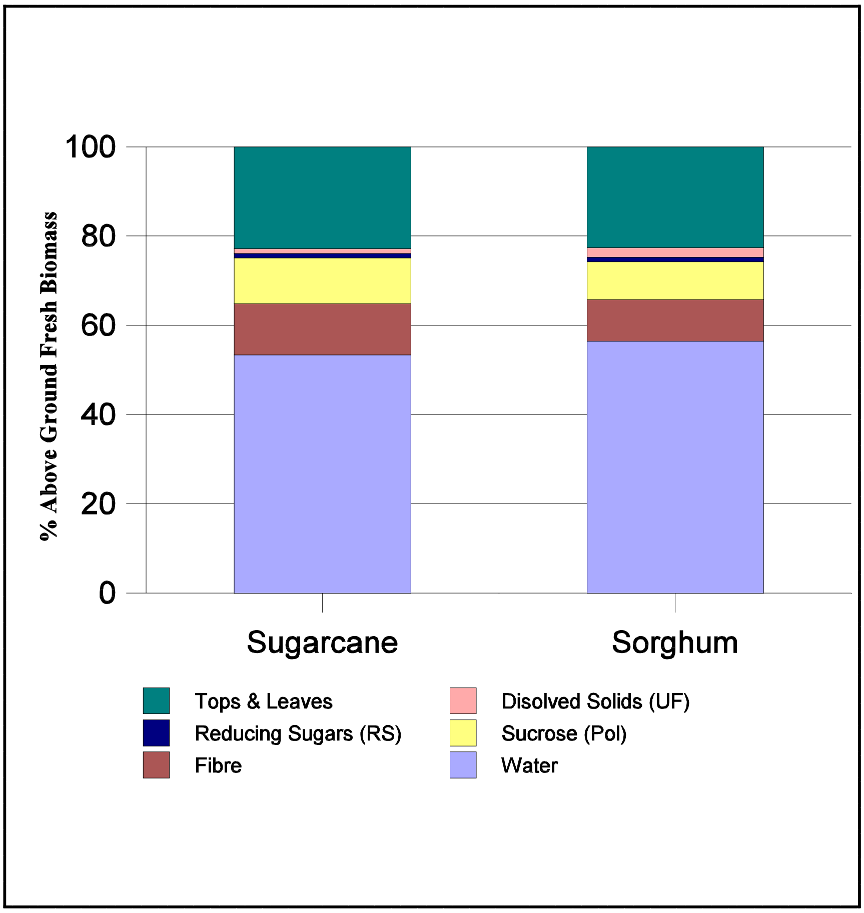


Fig. 13 Average Composition of Sugarcane & Sorghum

The average composition of sugarcane and sweet sorghum is shown in Figure 13. This figure shows how the fresh weight mass, at harvest, is partitioned between the major products i.e. water, sugars, stem fibre, tops and leaves and dissolved solids. The partitioning is based on the partitioning and accumulation data shown below for sweet sorghum (section 4.2.2.1) and sugarcane (section 4.2.2.2) and is derived from Figures 11, 15, Table 4.2, & Wenman (1999a).

4.2.2.1. Sweet Sorghum Partitioning data.

Table 4.2: Composition of Two Sweet and One Fibre Varieties of Sorghum Compared to Commercial Sugarcane

Genotype	Keller [b]		Wray [a]		H173 [a]		Sugarcane [c]	
Total Above Ground Standing Biomass: t ha^{-1} (% total above ground fresh weight)								
Total Fresh Wt	77	(100)	127	(100)	100	(100)	150	(100)
Dry	19	(25)	28	(22)	28	(28)	45	(30)
Moisture	58	(75)	99	(78)	73	(73)	105	(70)
Main Stem Biomass : t ha^{-1} (% total above ground fresh weight)								
Fresh Weight	58	(75)	101	(80)	82	(82)	115	(77)
Dry Weight	14	(18)	21	(17)	21	(21)	35	(23)
Biomass Components at Harvest: % total above ground dry weight								
Stems	68		84		80		77	
Leaves	11		15		18		23	
Panicle + Seeds	9		2		3		0	
Fermentable Sugars Content: % Stem Dry Weight								
Sucrose	33		28		8		44	
Glucose	4		9		7		3	
Fructose	3		7		5		2	
Total	41		44		20		49	
Total t ha^{-1}	7		10		4		17	
Fibre Content: % Stem Dry Weight								
Cellulose	-		25		42		-	
Hemicellulose	-		22		27		-	
Lignin	-		4		8		-	
Total	50		52		77		49	

Notes: see also Table II.5

a) Dolciotti *et al.* (1996)- 5 month growth period (1250 Growing Degree Days)

b) Sweet Sorghum var. Keller data from Chiredzi trials 97/98- 3.5 month growth period (1203 Growing Degree Days)

c) data for sugarcane are based on Zimbabwe average yields of delivered cane using conversion factors from Hall *et al.*, 1993. The sugarcane growth period is 12 months. It does not include detached leaves. (Associated with 1 t_{cane} are: 140kg bagasse, 160kg BRIX, 92 kg attached tops + leaves; not included are the 188 kg detached i.e. dead leaves)

The composition of fresh standing sweet sorghum above ground biomass:

Attached Leaves:	10-20% (default 13%, at 80% moisture content)
Panicle + seeds:	10 % (default)
Stem:	75-85% (default 77%, depending on maturity stage at harvest)

Of which (by stem fresh weight):

Sugars:	7-13% (of which sucrose >60% at grainfill, default 10% sucrose, 2% non-reducing sugars i.e. glucose and fructose)
Fibre:	12-17% (default 15% total fibres, of which, Hemi-cellulose 20-35%, Cellulose 30-45%, Lignin 5-15% (Rigal *et al.*, 1996)
Moisture:	75%

Therefore, 1 t of in-field standing sweet sorghum biomass will consist of 774 kg stem, 121 kg of leaves and 105 kg of tops (Table 4.2). The stem will contain 565 kg water, 85 kg sucrose, 10 kg reducing sugars, 93 kg fibre, and 21 kg other dissolved solids i.e.73% moisture, 12% fibre, 11% Pol (sucrose), 1.25% reducing sugars.

Fibre Accumulation

Figure 14 shows the measured rate of accumulation of fibre during sweet sorghum growth as a percentage of stem fresh weight. The fibre percentage measurements were taken at the same time as the sugar measurements shown Figure 15. The measurements were carried out during February to March 1999 from sweet sorghum samples provided from the sweet sorghum trials being carried out at CRS. Although highly variable, it can be seen that for cv. Keller the proportion of the fresh mass of stems which is fibre only exceeded 12% after approximately 120 days (not before 85 days) whilst for cv. Cowley this threshold is reached after approximately 80 days and not before 70 days. As shown by the low 'r^2' values of the linear regressions great care should be taken taken when extrapolating. In this instance the linear regression lines have highlighted the differences between cv.s Keller and Cowley.

For the sugarcane stem fibre percentage accumulation profile over an entire harvesting season (1998) see Figure 16.

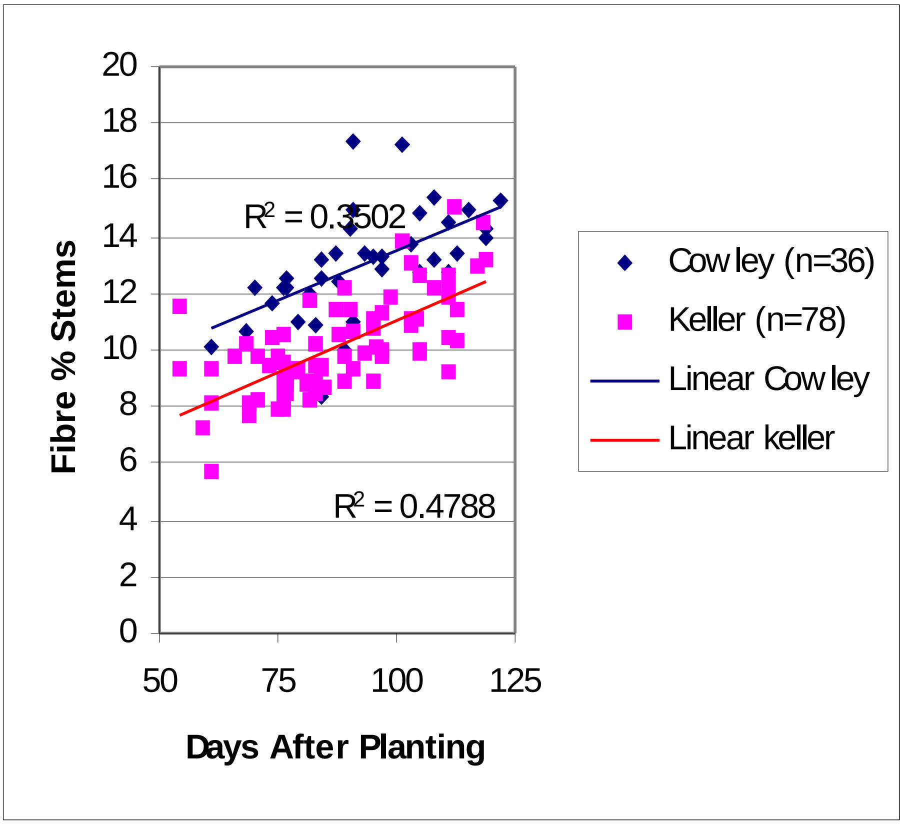


Fig. 14 Fibre Accumulation During Sweet Sorghum Growth (97/98 & 98/99 CRS Trials)

Sugar Accumulation

Data analysis carried out on samples during the trials in Zimbabwe is consistent with other trial analysis eg. Curt et al. 1995. Significant levels of sugars start to accumulate in the stem about 70 days after emergence, with this process being delayed by water stress in most varieties. Both, total fermentables and sucrose purity levels increase in all varieties with maturity. However, there is a marked difference between varieties in the dynamics of this process. Figure 15 compares the sugar accumulation dynamics cv.s Cowley and Keller for the 1993, 1997/8 and 1998/9 trials.

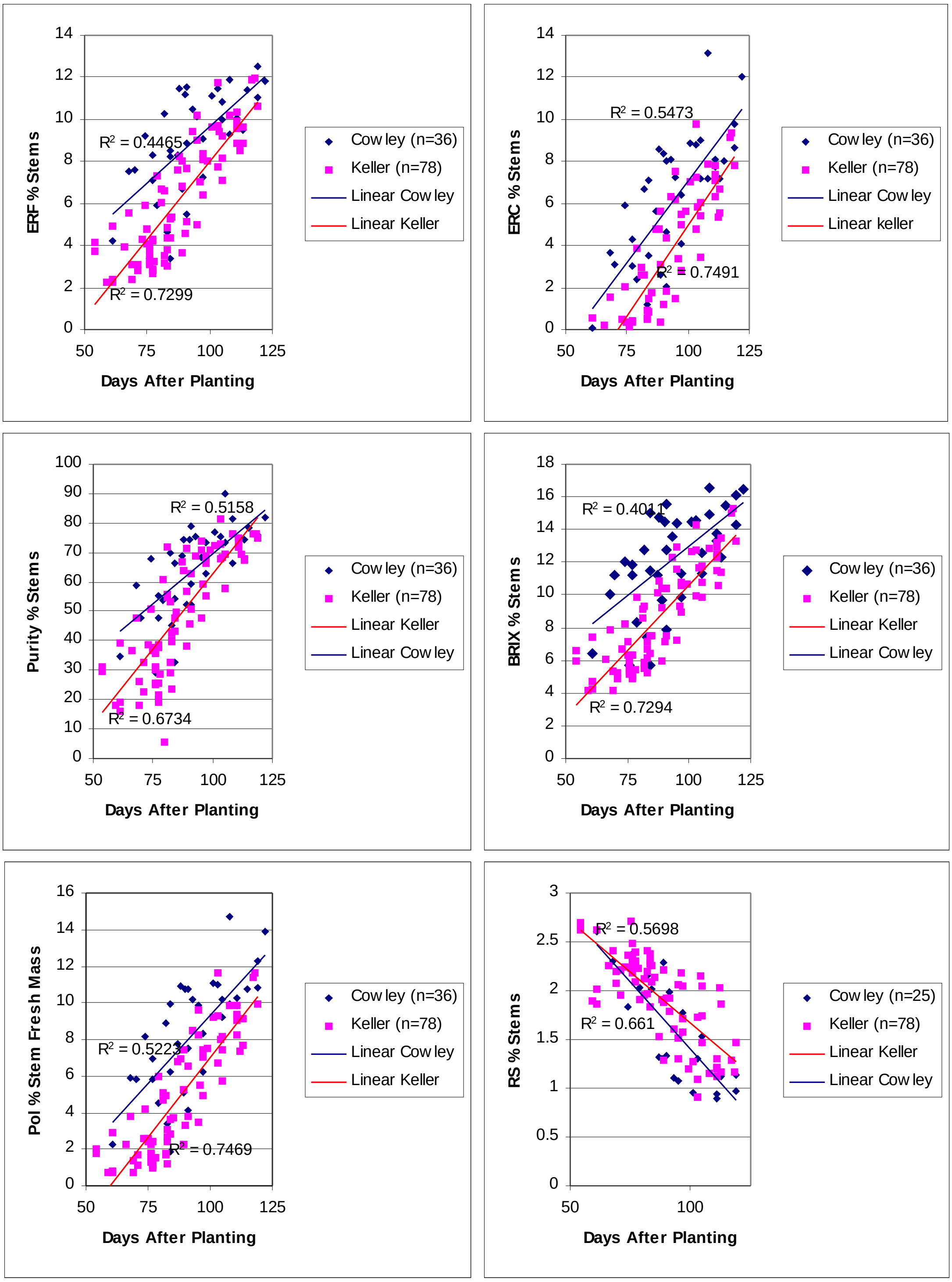


Fig. 15 Sugar Accumulation Profiles for Sweet Sorghum (Chiredzi 1993, 98 & 99)

Notes: Top Left) ERF - estimated recoverable fermentables, Top Right) ERC- estimated recoverable crystal, Centre Left) Sucrose Purity, Centre Right) BRIX, Bottom Left) Pol- sucrose, Bottom Right) RS- reducing sugars, versus days after planting.

See also Table II.3

The Zimbabwean trials show that the proportion of the stem biomass which consists of fermentable substances (as measured by 'ERF') varies between 7 and 13% after 100 days growth (Figure 15 top left and Table 4.3). Other standard sugar measurement parameters are also shown in Figure 15 which provided important yard sticks for the comparison of sweet sorghum and sugarcane. These parameters were also essential for the accurate estimation of the potential for crystalline sugar production from sweet sorghum. For example, 'Purity % Stems' is a measurement of the relative abundance of sucrose compared to other soluble substances in the juice as measure by BRIX. Although it is possible to produce crystalline sugar below purities of 75% it may not be economically viable. Therefore, if crystalline sugar is a required output from sweet sorghum in the future then Figure 15 clearly shows:

i) sweet sorghum-derived crystalline sugar is technically feasible
ii) crystalline sugar production is not feasible before 100 days growth.

Table 4.3: Sweet Sorghum Sugar Data from 1993 Zimbabwe Summer Trial (August to December 1993)

Variety	Days After Planting	Sucrose Purity[a]	% Fresh Stem Mass	
			TFAS	Fibre
Keller [b]	101	84	12	11
Korall	122	73	12	12
Cowley	108	82	13	15
Madhura	84	44	7	14
IS19674	108	71	11	14
Mean	**105**	**71**	**11**	**13**

Notes:
a Sucrose Purity is the % sucrose with respect to the other dissolved solids (i.e. Pol/BRIX)
b Data from 1997/98 CRS trial.

A full description of the extraction process and losses during processing is given in sections 2.1.1.3 & 4.3.3. However, losses of sugars during the juice separation phase were about 2-3 % of the extractable sugar contained in the biomass being processed and these losses are accounted for in the measurement of 'ERF'.

4.2.2.2. Sugarcane Partitioning data.

The composition of fresh standing sugarcane above ground biomass is given below:

Tops & Leaves:	25-35% (default 28%; 80% moisture content)
Stem:	70-80% (default 77%, 70% moisture content)

Of which (by stem fresh weight):

Sugars:	11-15% (default 13% sucrose, 1.5% reducing sugars i.e. glucose and fructose, and 1.5% other; BRIX = 16%)
Fibre:	13-17% (default 15% total fibres.)
Moisture:	70%

Therefore, 1 tonne of standing sugarcane biomass prior to harvest, will consist of 770 kg stem and 230 kg tops & leaves. The stems will consist of : 539 kg water, 115 kg stem-derived fibre, 104 kg sucrose, 11 kg reducing sugars, 10 kg other dissolved solids, and 57 kg attached tops & leaves. A further 188 kg of detached leaves will have been produced during the growth cycle but the status of this 'trash' at harvest is unknown. The data for sugarcane composition is from Wenman (1999a) and represents the 1998 season average for the sugarcane crushed at Triangle Ltd. i.e. fibre 14.7%, Pol 13.5%, and non-Pol 2.74% of stem fresh weight.

The compositional data given above for sugarcane were based on season-averages. However, crop quality varies significantly throughout the season. The trends in sugar and fibre content of delivered sugarcane stems through one harvesting season (1998) at Triangle is shown in Figure 16.

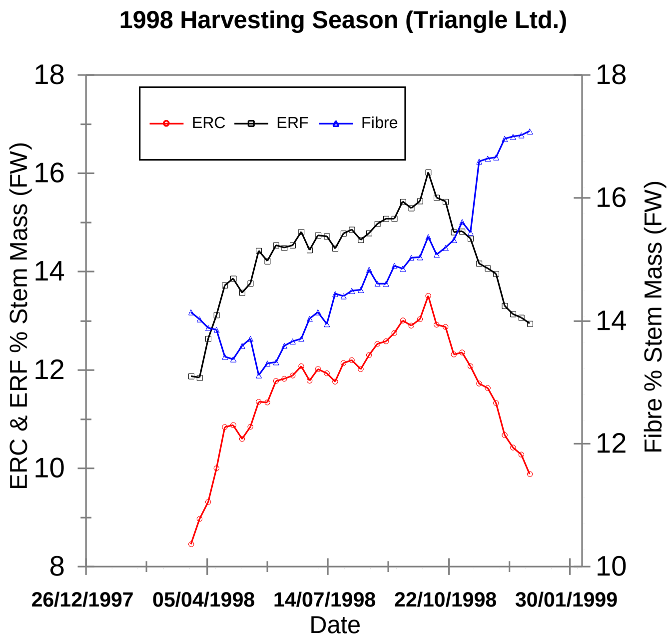


Fig. 16 Sugar & Fibre Accumulation Profile of Sugarcane Crop over Harvesting Period (Wenman, 1999a)

4.2.2.3. Energy Content

Table 4.4 provides average energy contents for bagasse and whole plant samples of sweet sorghum and sugarcane. The energy contents are based on data obtained from literature reviews and on bomb calorimetry of sweet sorghum whole plant and bagasse, and stored sugarcane bagasse (Table 4.5). Tables II.1 & II.2 also provide data on sweet sorghum and sugarcane energy contents which can be compared with other energy crops and coal. Significant differences in energy contents can be seen between sweet sorghum and sugarcane whole plant samples but not in the bagasse samples. The most likely primary determinant of energy content is likely to be fibre content which itself varies significantly through the growth cycle of both sweet sorghum and sugarcane and through the season for sugarcane.

Table 4.4: Whole Plant & Bagasse Energy Contents for Sweet Sorghum & Sugarcane

	GJ t^{-1} LHV	GJ t^{-1} HHV	Comments
Sweet Sorghum			
Whole Plant (oven dry)	15.9 ± 0.3	16.9 ± 0.3	See Table II.2
Bagasse (50% moisture)	7.6		Footnotes Table 4.5
Sugarcane			
Whole Plant	17.5	16.5	Footnotes Table 4.5
Bagasse (50% moisture)	7.6		Footnotes Table 4.5

a. LHV (Lower Heating Value or Net Calorific Value) is assumed to be approximately 6%<HHV i.e. 15.8 GJ/t; dry weight basis. See also Table II.2. in Appendix for variations in energy content of sweet sorghum.

Table 4.5: Sweet Sorghum- Measured Energy Content (Oven Dry Basis)

	Sample	HHV Recorded MJ kg^{-1}	Moisture Recorded %	Moisture Expected (EM %)	LHV [a] Calc. at EM MJ kg^{-1}
Sweet Sorghum	Bagasse	18.1	56.03	50.0	8.5
Sugarcane	Bagasse	20.3	34.93	50.0	9.5
Cowley	Whole Plant	17.0	69.63	70.0	11.2
Keller	Whole Plant	17.2	72.3	70.0	11.3
	Stems	17.6	77	75.0	12.4
	Seeds	17.4	-	-	-
	Leaves	17.5	-	-	-

Notes: Sampling carried out Matthews (1999)
Moisture % on wet weight basis (i.e. (Dry wt / wet wt)*100.
The different moisture contents in the sorghum compared to sugarcane bagasse arises because the sugarcane bagasse sample was derived from stored sugarcane bagasse, whereas, the sorghum bagasse was collected and stored without drying after the diffuser de-watering mills.

a. LHV (Lower Heating Value) calculated at 94% of HHV (Higher Heating Value) and multiplied by EM (expected moisture / 100). These LHV values are higher than the standard value used at Triangle Ltd. of 7.632 MJ kg^{-1} for 50% moist sugarcane bagasse as produced by the diffuser. A value of 7.6 GJ t^{-1} LHV is used for both sugarcane and sweet sorghum bagasse in this thesis.

In order to confirm these energy contents, bomb calorimetry was carried out on samples of sweet sorghum taken during the 17th March 1999 diffuser trial at Triangle Ltd. Whole plant samples of Keller and Cowley were also analysed, with both having energy contents of 17 GJ t^{-1} and moisture contents of approximately 70% on a wet weight basis (Table 4.5). Table 4.5 also provides the energy contents for Zimbabwean grown sweet sorghum and sugarcane for energy contents from other trials around the world (see Table II.1 also). The data shown in Table 4.5 should be treated with caution, being based on a single set of samples. Some doubts about the calibration of the bomb calorimeter used also exist as the energy contents seem consistently higher than literature derived examples (see note 'a' in Table 4.5).

4.2.2.4. Sweet Sorghum & Sugarcane Yields

Sweet Sorghum and Sugarcane yields were assessed and the results of the evaluation are shown in this section. See also section 3.1.

Sweet Sorghum

Yields from sweet sorghum trials in Zimbabwe and Thailand covering the period 1993 and 1999 are shown in Figure 17. The units provided in Figure 17 for above ground biomass are shown in 'g m^{-2}' which indicates the small plot nature of these trials and therefore the small sample sizes. To extrapolate these figures to t ha^{-1} the Y-axis data should be divided by 100, e.g. IS1152 achieved a yield with irrigation of 72 t ha^{-1} (7200 g m^{-2}) at Triangle in 1993.

Considerable variation in sweet sorghum yields has been recorded during the trials monitored by the author. Furthermore, these yields vary in both fresh mass and dry mass indicating that the underlying carbon assimilative capacity of sweet sorghum is affected by changing climatic and management conditions (Figure 12). As can be seen from Figure 17, fresh weight yields have varied from less than 20 t_{fab} ha^{-1} to over 80 t_{fab} ha^{-1} in one season's growth. In Chiredzi, improvements in yield have been achieved from a better understanding of crop water requirements and crop protection against pests and diseases (Figure 17 C).

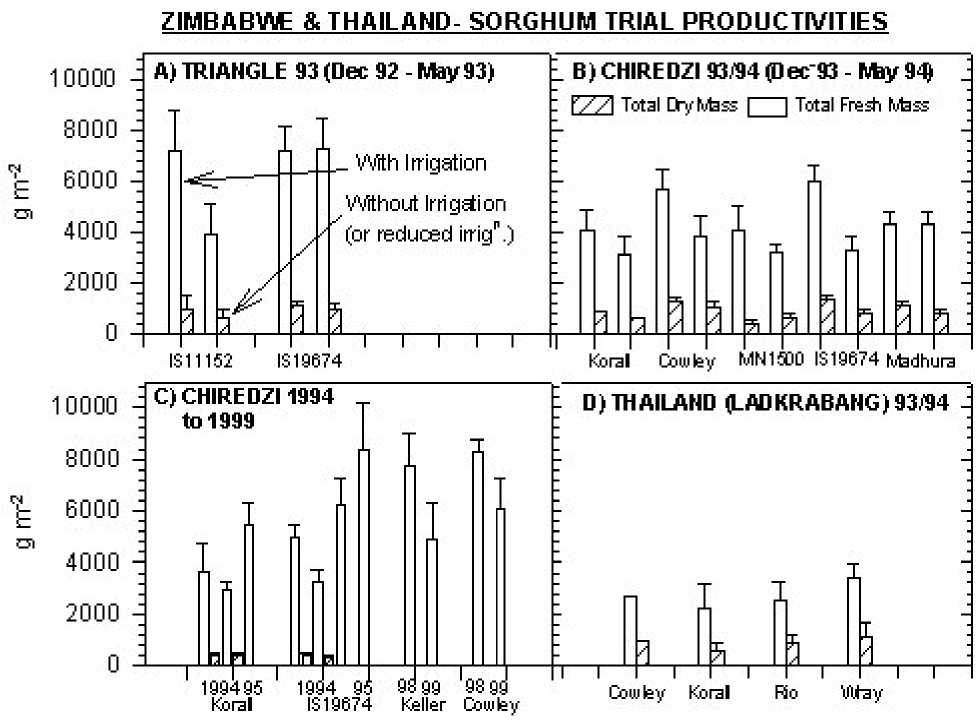


Fig. 17 Sweet Sorghum Trial Yields (1992 to 1999)

Table 4.6: Actual Yields for the 1997/8 & 1998/9 Seasons (Irrigated)

		FAB g m^{-2}	
Keller: 101 days after planting (1997/8)		7722 ± 1289	77.2 t_{fab}. i.e. 76.5 g m^{-2} d^{-1}
Keller: 104 days after planting (1998/9)		5068 ± 1476	48.7 g m^{-2} d^{-1}
Cowley: 115 days after planting		8256 ± 500	82.6 t_{fab}. i.e. 71.8 g m^{-2} d^{-1}
Cowley: 107 days after planting (1998/9)		5497 ± 577	51.4 g m^{-2} d^{-1}
Deliverable Stem Mass [a]			
Keller-	1997/8	59.8 t_{stems} ha^{-1}	
Keller-	1998/9	39.0 t_{stems} ha^{-1}	
Cowley- 1997/8		63.9 t_{stems} ha^{-1}	
Cowley- 1998/9		42.3 t_{stems} ha^{-1}	
Sugarcane 365 days after planting [b]		113 t_{stems} ha^{-1}	150 t_{fab} ha^{-1} or 41.1 g m^{-2} d^{-1}

Notes: FAB = Fresh weight Above ground Biomass

a Table 4.16, provides the proportion of above ground biomass which is harvested as stems for transport to the mill is 77 ± 5%.

b The long term average sugarcane yield for Triangle Ltd. of 115 t_{cane} ha^{-1} yr^{-1} has been used throughout this work. A yield of 115 t_{cane} ha^{-1} is equivalent to 150 t_{fab} ha^{-1} or 15000 g m^{-2} .

The growth analysis and partitioning spreadsheet for the 1998/9 season is shown in

Table II.5, detailing the time-series accumulation of fresh mass and dry mass by each of the major plant organs. It is this accumulated data over the entire series of sweet sorghum trials carried out in Chiredzi & Triangle since 1993 that has been used to define the potential for the production of sweet sorghum and its integration with sugarcane. A more detailed analysis of the sorghum production profiles is given in the various individual project publications i.e. Woods *et al.* (1996), Woods *et al.* (1995), and Mvududu *et al.* (1998).

The calculated above ground biomass yields shown in Table 4.7 are derived from the recorded delivered sweet sorghum biomass (stems) at Triangle Mill's weighing station. The recorded stem mass was converted to above ground biomass by assuming that the stem mass is 77% of total above ground biomass as shown in Table 4.16. This weigh-station provides good, 'real world' data on deliverable stem biomass as this is not extrapolated from sub-sampled data.

Table 4.7: Mass & Area Harvested for Diffuser Test (March 1999)

	Field area (ha)	**Delivered Mass (t)**	**Harvested Stem Mass (t_{stems} ha^{-1})**	**Above Ground Biomass (t_{fab} ha^{-1})**
Chiredzi Research Station				
Drip Blocks (12)	2.18	46.620	21.4	27.6
Sprinkler Section	1.35	32.794	24.3	31.4
F3	0.89	25.452	28.6	36.9
F4	0.89	25.834	29.0	37.5
Sub-Total	*5.31*	*130.70*	*24.6*	*31.8*
Triangle Ltd.				
Section 26	1	35.920	35.9	46.4
Section 62	1	35.540	35.5	45.9
Total	**7.31**	**202.16**	**27.7**	**35.7**

Notes: Above Ground Biomass is calculated by multiplying the harvested stem mass in the previous column by 1.29. This factor is derived from the proportion of total above ground biomass being harvestable stems (77.4%) see table 4.16. Delivered biomass as recorded at Triangle Mill Weighing Station.

For the rest of this thesis the following yields for sugarcane and sweet sorghum will be used:

Sugarcane: 150 t_{fab} ha^{-1} from 365 days growth, which produces 115 t_{stems} ha^{-1} delivered to the mill

Sorghum: 60 t_{fab} ha^{-1} from 110 days growth, which produces 46 t_{stems} ha^{-1} delivered to the mill.

4.2.3. Crop Management

The main requirements (inputs) for crop establishment and management were assessed and are shown below, including, tillage and the application of fertilisers and pesticides i.e. herbicides and insecticides, fungicides were not used.

4.2.3.1. Tillage

The input requirements for land preparation including labour requirements for tractor driving, weeding, bird scaring and pesticide application were recorded and are summarised here. See also sections 3.1.1.1 and 3.4.2.2.

Tillage operations for sweet sorghum production required:

1. One pass of wheeled tractor plus plough
2. Two passes of wheeled tractor plus disc
3. One mid season pass
4. Manual labour for weeding, bird scaring, and pesticide application

Field operations occur at a rate of 1.2 ha h^{-1} unless otherwise stated. Table 4.8 shows the estimated energy consumption associated with operations 1 to 4 listed above. A more detailed energy balance than carried out here would have carried out direct measurements on all aspects of actual energy use, emphasising diesel consumption by the field equipment. However, because of large discrepancies in the type, age, and condition of the equipment in use at CRS compared to the Triangle Ltd. estates, literature based estimates for in-field operations have been used based on Bowers (1992) and shown in Table II.4, II.11 and II.12.

Table 4.8: Energy Consumption (Including MTR) for Sweet Sorghum Tillage

Step	Type	Energy Use (MJ ha^{-1})
1. Ploughing	Moldboard	723
2. Discing	Harrow	636
3. Discing	Harrow	636
4. Manual labour	Various (100 man-hours)	230
Total Tillage (MJ ha^{-1})		2225

Mostly from Bowers (1992). Assumes 60 t_{fab} and a loss of 23% during harvesting including the removal of tops and leaves. MTR = "Manufacturing, Transport, and Repair" of equipment ie. the energy required for transport fuels (for delivery and use), the manufacture of farm machinery, packaging, etc- for mechanical harvesting this is assumed to be an additional 46% of fuel energy costs.

Energy requirements for sugarcane tillage operations were derived from Lewis (1984) who stated that for the 1983 sugarcane harvesting season 216 000 l of diesel were required for in-field tillage operations. The 1983 season produced 1.36 Mt_{stems} at an average productivity of 115 t_{stems} ha^{-1} . Therefore sugarcane tillage operations required:

$$((215\ 871 \times 39) / 1.36\times10^{6}) \times 115 \quad = \quad 712 \text{ MJ ha}^{-1}$$

4.2.3.2. Fertilisers & Pesticide Energy Use.

The application of fertilisers and pesticides (insecticides, herbicides and fungicides) were assessed for both sweet sorghum and sugarcane in both mass and energy terms. See sections 3.1.1.1 and 3.4.2.1. for methodology.

Fertiliser Application

During the 1997/8 and 1998/9 CRS sweet sorghum trials 300kg of 'Compound D' mixed fertiliser were applied by hand as a side-band during the seeding operation. A further application, again by hand, of Ammonium Nitrate (AN) of 220kg was carried out as a top dressing three weeks after planting. No further fertiliser applications were applied. The three main fertiliser components require very different energy inputs to produce, primarily resulting from the different production processes. Nitrogen fertilisers are nearly all produced from the initial synthesis of ammonia which is an energy intensive process. The ammonia can then either be used directly or further processed to urea or ammonium nitrate. The primary sources of phosphate and potash are mineral ores, which are predominantly derived by mining and then chemical treatment requiring further energy inputs. Further details on energy requirements for fertiliser production and application are given in Table 3.2 and Table II.11.

Calculation of Energy Requirements for Fertilisation. Assuming a fertiliser application rate of 300 kg Compound D (24 kg N, 42 kg P_20_5, and 21 kg K_2O), and 220 kg of Ammonium Nitrate (AN, 76 kg N), using the 1987 data from Bhat *et al.* (1994, Table 3.2) the fertiliser energy inputs for sweet sorghum production at the CRS trial site (1998) and for sugarcane at Triangle Ltd. in Zimbabwe are shown in Table 4.9.

Table 4.9: Total Fertiliser Energy Inputs for Sweet Sorghum (97/98 CRS Trial, Zimbabwe)

Type	Energy Content (MJ/kg)[a]	Quantity (kg)		Total Energy (MJ/ha)	
		Sorghum	Sugarcane[b]	Sorghum	Sugarcane
N	50.1	100	167	5010	8347
P_20_5	14.3	42	50	601	714
K_2O	12.1	21	104	254	1256
Total		163	320	5865	10317

Source: Bhat *et al.* (1994), 1987 energy cost data and actual application rates from CRS 1997/8 trials.

a Energy cost is the total cost of application including energy, production, packaging, and transport costs. The transport cost should be regarded as conservative as it is calculated from the mean transport distance from factory to farm field in the US.

b Revised from Rosenschein *et al.* (1991) Ammonium Nitrate application 476, Single Super Phosphate 227, and Potash 173 kg ha^{-1}.

Pesticides

Application rates per ha and bulk density values if application rates are given in l/ha and shown in Tables 4.10 and 11. The energy input calculation uses the data given in Bhat *et al.* (1994), see section 3.4.2.1.

Table 4.10: Pesticide Application During the Chiredzi and Harare Sweet Sorghum Trials (Zimbabwe, 1997/98)

Chemical Applied	Pest	Rate (ha^{-1})	Applied	Week	Cum. kg a.i. Insecticide applied [a]
Carbaryl 85%wp	leaf eaters & Stalkborer	3 – 4kg	20-12-98	1	3.4
Dipterex 2.5% granular	Stalkborer	3-4 kg	02-01-98	6	3.5
Thioflo	"	1.3l kg	05-01-98	78	4.0
*Dimethoate 40%e.c	"	500ml	24-01-98		
Dipterex 2.5% granular	"	3-4kg	10-01-98	7 ½	4.1
Thiodan 50 %wp	"	1kg	25-01-98	8 ½	4.6
*Thiodan 50% wp		1kg	01-01-98	4	
" " "		1kg	23–01-98	8	
Thioflo	"	1.3l	08/02/98	12	5.6
Energy Use (214 MJ/kg a.i. insecticide)- MJ per ha					**1203**

* Harare trial

Pari *et al.* (1998) gives an energy input for herbicide application of 'Click' (terbutylhylazine a.i.) of 91.3 MJ kg^{-1} Therefore, when applied at a rate of 2 kg ha^{-1} = 183 MJ ha^{-1}.

a 'a.i.' = active ingredient.

For sugarcane, pest control application rates taken from Rosenschein and Hall (1991) and calculated energy contents (Table II.15) are given in Table 4.11. As it was not known if this data included energy requirements for application and in order to be conservative, application energy has not been added to the Rosenschein data.

Table 4.11: Pesticide Application During the 87/88 Sugarcane Growth Season, Triangle, Zimbabwe.

Type	Quantity (kg ha^{-1} a.i.)	Energy Content (MJ ha^{-1})
Herbicides	2.0	528
Insecticides	0.3	64
Total	2.3	592

Notes: application rates from Rosenschein & Hall (1991), energy values from Table II.15.

4.2.4. Water Use Efficiency (WUE) & Irrigation

The calculation of the expected water requirements for sweet sorghum and sugarcane are provided below in terms of the volumes of water required for crop growth and the energy inputs required to provide the water to the plants. Crop water use is estimated (section 4.2.4.1) and then the requirements for irrigation (i.e. total water requirements minus rainfall) are calculated and the energy inputs are estimated. See also section 3.1.1.2.

4.2.4.1. Water Use Efficiency

Crop water use is evaluated from data in the trials monitored by the author and also from literature sources derived from various trials around the world (Table 4.12). A more detailed analysis of sweet sorghum water use efficiency was carried out by the author and the results are shown below. Figure 18 is derived from the linear regression analysis below using Sigmaplot 2.01. Curve Expert (version 1.3) was then used to ascertain if non-linear models provided better accuracy (Hyams, 1997). However, the non-linear models did not provide a significant improvement in 'fit' and so for simplicity the linear regression model was adopted. See section 3.1.1.1.

SigmaPlot 1st Order Regression Data of Growth versus Water Supply Graph (Figure 18) Coefficients:

y-intercept 'c'	=	-9.8161 t ha^{-1}
gradient 'm'	=	0.0609 t ha^{-1} mm^{-1}
r^2	=	0.8264

Using the straight line equation ($y = mx + c$) it is possible to deduce from Figure 18 both the theoretical minimum water supply for survival (the y intercept 'c' = 161 mm) and the return in terms of extra biomass per mm of water supplied (the gradient 'm' = 60.9 odkg $ha.mm^{-1}$). For example, for a likely rainfall (x) during the growth period of between 200, 400, and 800 mm, and assuming that water supply is the only limiting factor, the expected yields (y) of sweet sorghum can be calculated- see below:

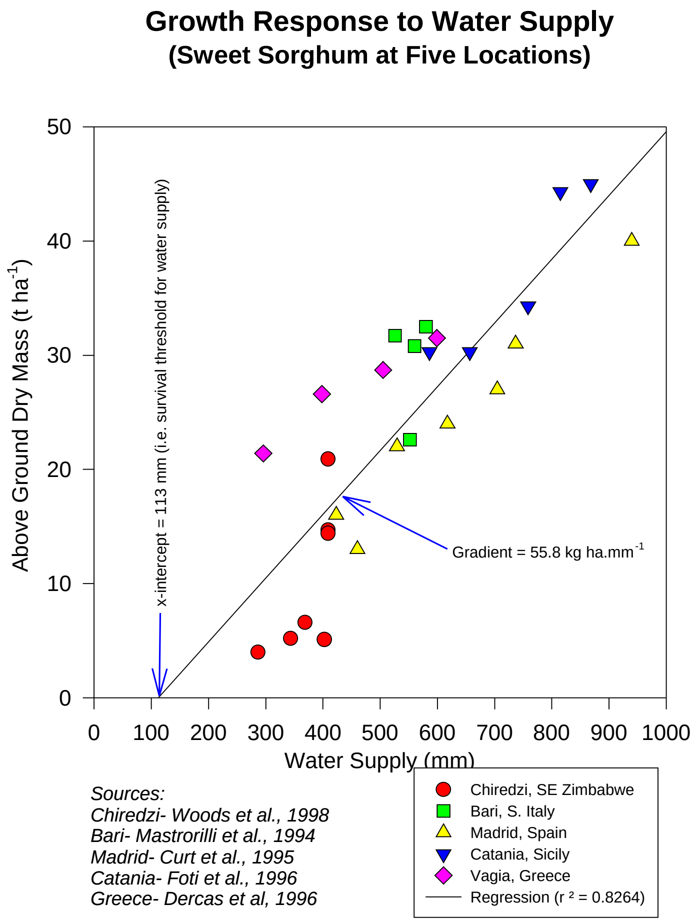


Fig. 18 Growth Response of Sweet Sorghum to Water Supply (in Spain, Italy, Greece, & Zimbabwe).

if:

$$y = mx + c$$

i.e. at 200mm rainfall and no irrigation:

y =	0.0609*200 -9.816	=	2.36 odt ha^{-1}
implied WUE = 2.36/200		=	11.8 kg ha.mm^{-1}

and, at 400mm rainfall and no irrigation:

y =	0.0609*400 -9.816	=	14.54 odt ha^{-1}
implied WUE =14.54/400		=	36.35 kg ha.mm^{-1}

and, at 800mm rainfall and no irrigation:

y =	0.0609*800 -9.816	=	38.904 odt ha^{-1}
implied WUE = 38.9/800		=	48.63 kg ha.mm^{-1}

The correlation between water supply and dry mass yield is very highly significant (Table II.6). What is perhaps surprising is that this relationship appears to hold true even at the higher levels of water supply.

Table 4.12: Sweet Sorghum Water Use Efficiency [1]

VARIETY	**Location**	**Water Treatment**	**Planting Date / Comment**	**litres H_20 per t_{fab}** [2]
SWEET SORGHUM				
Keller	Zimbabwe, CRS	Irrig	17-Nov-97	52448
Korall	Zimbabwe, CRS.	1 PET [3]	07-Jan-95	89776
IS19674		1 PET	07-Jan-95	74916
Korall		1/3 PET	07-Jan-95	123581
IS19674		1/3 PET	07-Jan-95	84067
Korall		1 PET	27-Jan-95	77711
IS19674		1 PET	27-Jan-95	70017
Korall		1/3 PET	27-Jan-95	121414
IS19674		1/3 PET	27-Jan-95	92862
IS19674 + IS11152	Zimbabwe,Triangle Ltd.	510 mm	1989 (84 t_{fab} ha^{-1})	60714
Keller	Spain, (4.6 g DM / l H_20)	17.1 mm day^{-1}	1992 (75 t_{fab} ha^{-1})	217391
Mean				96809
Stds				45741
SUGARCANE [4]				
All average	Zimbabwe, Triangle Estates	10^6 l H_20 per 8 t_{cane}	Commercial rates	125000
Theoretical		2000 mm	115 t_{cane} ha^{-1}	133333
Puerto Rico (1983) [5]	National Average	1676 mm rainfall + irrigation		275926
	Energy Cane (2nd Gen)	as above		79873

Source: Woods *et al.* (1995), Curt et al. (1995) for data obtained in Spain on cv. Keller. Stds = standard deviation of the population.

Footnotes:

1 No distinction is made here between Precipitation / Irrigation Use efficiency and actual Water Use Efficiency. The Spanish Sorghum Trial Data represents actual WUE, whilst all others are simple ratios of water application (rainfall & irrigation) to above ground fresh matter production and do not account for water lost through drainage.

2 t_{fab} = fresh weight tonne of total above ground biomass

3 PET stands for Potential EvapoTranspiration as calculated by the revised Penman method- in these trials irrigation was supplied to resupply all PET (1 PET) or only one third PET (1/3 PET).

4 t_{cane} = total above ground biomass - (attached tops & leaves + detached leaves); therefore for every t_{cane} stems harvested there are 0.188 t detached leaves + 0.092 t tops and attached leaves ie. 1 t_{cane} = 1.28 t_{fab}

5 Calculated from Alexander (1985), based on national average sugarcane productivity of 24 ton per acre, 3 feet of rainfall and 2.5 feet of irrigation. Energy cane (2nd generation) of 125 ton per

acre and same water application.

Calculation of water required per litre Ethanol Produced:

Sweet sorghum: 60 t_{fab} ha^{-1} will produce 2993 l EtOH (Table 4.29, cv. Cowley)

60 t_{fab} at 75% moisture = 15 odt ha^{-1}

y=mx+c where y= yield i.e. 15 odt, m = 0.060939 and c = -9.81082, therefore,

$$15 = 0.06093x-9.816082$$

$$x = 407 \text{ mm ha}^{-1} \text{ or } 4073 \text{ m}^3 \text{ water}$$

Therefore, the production of 1 l EtOH from sweet sorghum requires 1.36 m^3 water (4073/2993).

Sugarcane (150 t_{fab} ha^{-1}) will produce 7458 l EtOH (Table 4.29)

150 t_{fab} ha^{-1} at 70% moisture = 45 odt ha^{-1}, requiring 2000mm water or 20000 m^3 to produce 7458 l EtOH,

Therefore, the production of 1 l EtOH from sweet sorghum requires 2.68 m^3 water (20000/7458)

4.2.4.2. Irrigation

Energy requirements for the irrigation of sweet sorghum and sugarcane are calculated, based on the methodology of Sloggett (1992).

Irrigation Requirements for Sugarcane Production. An estimate of the direct energy requirements for sugarcane irrigation at Triangle Ltd. was derived from the diesel and electricity consumption by the irrigation pumps for irrigating the total field area at Triangle (Lewis, 1984). A significant area of Triangle's cane fields are irrigated by syphons. However, it is assumed that the energy requirements for this type of irrigation are accounted for in the pumping required to raise the water to the height above the fields necessary for syphoning to work. Significant areas are also irrigated by overhead sprinkler systems which are very energy intensive. More recently below ground drip systems were tested and their increased use may result in a significant decrease in irrigation energy requirements in future.

The direct energy requirements for pumping and sprinkler irrigation of sugarcane are estimated in Table 4.13.

Table 4.13: Direct Energy Use for Sugarcane Irrigation- Triangle (1983)

Type	Quantity per ha.	Energy Use (MJ ha^{-1})
Diesel Pumps (l ha^{-1})	21	831
Electricity (MWh ha^{-1})	3.01	10842
Total		11672

Notes: Source- data revised by the author from Lewis (1984). The production of 1.36 Mt_{cane} required 252 000 l diesel & 35.6 GWh_e in 1982. Diesel energy content (39 MJ per litre)

Energy Costs for Irrigating Sweet Sorghum with 300mm water. An estimate of direct energy requirements for irrigation can be obtained using the equation shown below derived by Slogget (1992).

By estimating the energy use factors given in Equation 1 below, the direct energy requirement for the irrigation of sweet sorghum was calculated and is shown in Table 4.14.

For sweet sorghum grown at CRS energy inputs for irrigation were estimated to equal:

$$DE = ((98.1*0.3)/(0.17*0.7))*(0.3/(0.72*0.7)) * 11.5788 = 1543 \text{ MJ} = 1.54 \text{ GJ ha}^{-1}$$

where:

$$DE_{ha} = (EU/(EF_p \times EF_1))*(PQ_{ha} /(Ef_c*EF_f)) * TDH \quad \text{.................... Equation 1}$$

EU (Lift Energy) :

1 ha.m of water = 10 000 m^3 or tonnes, and requires 98.1 MJ to lift this quantity one m vertically. (Potential Energy (J) = mgh, where m=mass of water i.e. $10x10^6$ kg, g = 9.81883 m s^{-2} , and h = 1 m.) Assume water in reservoir is 1m above field level- therefore this figure represents the amount of energy required to raise (or pump with 100% efficiency) the water up to the reservoir.

EF_p (Power unit efficiency):

very sensitive to fuel source i.e. diesel or electricity, and if electricity then fossil, hydro, or nuclear powered? It is also sensitive to the scale of the power unit and the capacity at which it is operated. Diesel engines are approximately 25% efficient in converting diesel fuel to mechanical power, whilst a 1-2 hp electrical motor is about 75% efficient and increases to 90%+ when 30 hp (22 kW) electrical motors are used. Electrical power stations are extremely variable in the efficiency at which they convert fuel to electricity, with fossil fuel powered systems being anything between 20 & 45% efficient (advanced IGCC gas powered systems), nuclear about 35% efficient and hydro about 70% efficient. Efficiency of transmission of this electricity is also variable but Sloggett quotes an 85% average efficiency. Therefore the overall efficiency of the motor OE = GE (generating efficiency)*TE(transmission efficiency)*motor efficiency. For a 30 hp electric motor this would mean OE = 0.25*0.85*0.8 = 0.17

EF_1 (Lifting device efficiency- pump):

Efficiencies for pumps are extremely variable, and dependent on technology and size

PQ_{ha} :

Plant water requirement in m per ha (and is equivalent to 1000mm rainfall)

Ef_c (Conveyance and distribution efficiency) :

conveyance= “the system to deliver water from its source through main and secondary canals” and distribution= “the ditches or pipes which deliver water to the field inlet”.
“.. The average conveyance efficiency was 78% with a range of 50-98%.
For the purposes of this study I will use a conveyance efficiency of 0.8 (due to concrete lined canals and large scale in Zimbabwe) and a distribution efficiency of 0.9 resulting from a combination of sprinkler and drip systems used.

Ef_f (Field efficiencies) :

a measurement of the losses of water occurring after the water leaves the delivery mechanism. These losses result from evaporation in the air, plant structures, and the soil surface, surface run-off, and percolation past the root zone i.e. water that the plants are unable to intercept.

TDH (Total Dynamic Head) :

TDH is measured in metres and includes the Lift (head of the field distribution system) and head of friction loss in distribution lines i.e. lift+drip system head+distribution line head. I assume Lift at Chiredzi = 1m, drip system head = 4.0788 m (40*0.10197), Distribution Line Head = 6.5 m (3 to 10m in well designed system) Total TDH = 4.0788+1+6.5 = 10.58 m
To convert kilopascals (kPa) of pressure to m, the quantity of pressure is multiplied by 0.10197 (010197m is the length of a column of water exerting 1kPa of pressure). Thus, for example, the head for a centre pivot would range from 14.06m (137.9*0.10197) to 63.27m (620.5*0.10197). This function allows for friction losses in pressurised systems and would be added to the head of water if it had to be pumped up from a below ground source.

Table 4.14: Estimated Energy Costs for Irrigating Sweet Sorghum at Chiredzi

Direct Energy for Irrigation (MJ ha^{-1})	1534
Irrigation Applied (mm)	300
Irrigation Pressure (kPa)	40

Other Factors [a]						
EU	EF_p	EF_1	PQ_{ha}	Ef_c	EF_f	TDH
29.4	0.17	0.7	0.300	0.8	0.7	11.6

Notes:
a see below for definitions for these factors.

4.3. Harvesting, Transport, and Crushing

This section describes the processes of delivering and processing the stem biomass in a sugar mill. Each major stage of this process is described in terms of biomass flow, process rate and resource use including manpower and energy requirements where data is available.

4.3.1. Harvesting

Both manual and mechanical harvesting of sweet sorghum are evaluated below in terms of logistics, energy requirements, and costs. The methodology for this evaluation is described in section 3.1.2.

4.3.1.1. Manual Harvesting

Tests were carried out during the March 1998 trials to see if leaf stripping, prior to harvesting was:

< feasible

< affected the sugar content

< rate of stripping could be increased

< relative difficulty compared to sugarcane

These tests found that it is feasible to manually strip the leaves. However, it is time consuming but fortunately the stripping of the leaves maintained the levels of sugars in the stems at the time of stripping. This is an important finding, since it may provide a method for storing the sorghum in the field if there is no capacity at the mill and the sorghum has reached peak sugar levels; the levels of sugars in sweet sorghum decrease after flowering, or after harvesting if the stems are left un-processed for a period of a few days or more.

A survey of the cutters when asked about the ease of harvesting of sweet sorghum highlighted some significant differences between sugarcane and sweet sorghum manual harvesting. The consensus of those asked believed sweet sorghum was much easier to harvest when compared to sugarcane (Nyabanga, 1999). The main reasons for this included:

1. the thinner stem and cuticle of sweet sorghum making cutting physically easier
2. the leaves were much ‘softer’ and less sharp making removal without being cut easier.

The relative ease with which the sorghum was harvested and the below expected stem-mass yields meant that virtually all the harvesting was completed by 1:00pm on 17th March, taking 6 hours in total including water and lunch breaks. This can be compared with a normal shift comprising 8 to 10 hours.

Table 4.15: Labour & Fuel Requirements for Harvesting & Transport of Sweet Sorghum in Zimbabwe

	Section 26	Section 62	CRS	Total
Harvested Area (ha)	1	1	5.3	7.3
Harvested Stem Mass (t)	35.9	35.5	130.7	202.1
Number of Labour Shifts for Harvesting				
Total	64	135	209	408
per ha	64	135	39	56
per t_{stems}	1.8	3.8	1.6	2.0
Number of Labour Shifts for Transport				
Total	7	5	13	25
per ha	7	5	2	3
per t_{stems}	0.20	0.14	0.10	0.12
Diesel Use (litres)				
Total	65	71	337	473
per ha	65	71	64	65
per t_{stems}	1.81	2.00	2.58	2.34

Notes: See Tables II.9. and 4.7 for details
Diesel use for sections 26, 62 and CRS includes the diesel used to transport the labour to site e.g. approx 20 l diesel for each site (return).

Another important finding from these trials was that harvesting techniques will have to cope with harvesting during periods of intense rainfall. The expected sweet sorghum harvesting period, prior to sugarcane harvesting, is within the normal end of the rainy season and if the period of commercial sorghum processing is extended, harvesting will need to be carried out earlier in the rainy season. One significant result of this need to cope with wet, potentially water-logged, soils is that heavy mechanical equipment may not be able function in the fields and that the harvested sorghum may need to be manually carried to the edges of the field.

Harvesting Rates = 3 t_{stems} per day per person if trashing required
5 t_{stems} per day if burnt

Fuel Consumption = 2.3 l diesel per t_{stems} (Table 4.15)

Costs	=	Z$ 50 per day per person. Actually paid per t_{cane} harvested
Equipment	=	knives, protective clothing, ...

4.3.1.2. Biomass Harvest Index

Sub-samples of the actual above ground biomass harvested and stacked for transport to Triangle Mill were recorded. The recorded delivered mass was compared to the estimates of total above ground biomass to provide a 'harvest index' as shown in Table 4.16 which shows the stem mass as a percentage of total mass. See section 3.1.2.1. for methodology.

Table 4.16: Proportion of Above Ground Biomass Harvested by Hand (Chiredzi, March 15th 1999) [a]

Location	Tops (heads)		Leaves		Stems		Total	
	kg	%	kg	%	kg	%	kg [b]	t ha^{-1} [c]
S- Block	0.484	9.2	0.446	8.5	4.308	82.2	5.24	69.8
F-block	0.45	7.5	0.942	15.7	4.602	76.8	5.99	79.9
Drip Block	0.268	16.1	0.226	13.6	1.166	70.2	1.66	22.1
Drip Block	0.364	9.2	0.414	10.5	3.178	80.3	3.96	52.7
Mean	0.39	10.5	0.51	12.1	3.31	77.4	4.21	56.2
Standard Dev.	0.10	3.8	0.31	3.2	1.56	5.3	1.90	25.3

Notes:

a Derived from 4 separate samples taken on same day. Sorghum harvested by different cutters at each location. 1m of a sorghum row was removed for each sample. The sample was cut in the normal way and samples removed on cutting for weighing. All figures are fresh weight as sampled.

b Total Biomass sampled at each location

c Provides a rough estimate of total above ground fresh weight biomass from each sample and location assuming exactly 1 m per row sampled at each location.

4.3.1.3. Mechanical Harvesting

Mechanical harvesting is not practised on the Triangle or the adjacent Hippo Valley sugarcane estates and is not evaluated in any detail in this thesis. However, EU studies on the use of sweet sorghum also funded the development of small scale (1 ha per hour) harvesters, the use of which may not be applicable for estate-grown sorghum, but would probably be more applicable for small-scale farmers. (Pari, 1996) Trials have also been carried out in Australia using sugarcane harvesters (Claas) without apparent problems, but again leaves were not removed and all the above ground biomass was harvested. Using the data shown in Table 4.17, the energy requirement for mechanical harvesting are estimated in Table 4.18 and compared with the energy requirements for manual harvesting.

Table 4.17: Mechanical Harvester Specifications

	Units	Claas 1400	OTMA	Pasquali
Rate	$t_{stems}\ h^{-1}$	60	13.3	27.4
Power	kW	125	95.6	58
Diesel Consumption [a]	$kg\ h^{-1}$	37.5	28.7	17.4
	$MJ\ t_{stems}^{-1}$	28.3	97.8	28.8
Labour Req.	persons	1	1	1
Capital Costs [b]	ECU	90000	20580	42100
Working Life	Years	8	9	8

Notes: Data for mechanical harvesting are based on Pari (1996b) and Pari (1996a).
a Mass density for diesel of 0.86 kg l^{-1} and 39 MJ l^{-1} HHV.
b Capital costs for Claas harvester estimated from ECU 1 500 per tonne harvesting capacity (i.e. 60*1500). Otma & Pasquali capital costs from Pari (1996b).

Table 4.18: Energy Use For Manual & Mechanical Harvesting

Step	Type	Energy Use (MJ ha^{-1})	% Total Tillage & Harvesting Energy
Manual harvesting	1 t / man-hour	106	5
	0.5 t / man-hour	212	9
	0.25 t / man-hour	423	16
Mechanical Harvesting		1948	47

Notes:
Estimated energy use per man hour = 2.3 MJ. Tillage energy from Table 4.8
Mechanical Harvesting data from Table 4.17 Diesel energy density = 39 MJ/l (HHV), harvesting 46 $t_{stems}\ ha^{-1}$ requires 29 MJ per t_{stems} plus an additional 46% of fuel energy content as MTR.

4.3.2. Transport

The delivery of the sorghum stems harvested for the diffuser trial (18th March 1999) required different transport methods for CRS and Triangle (Table 4.21). The equipment requirements are discussed in section 3.2.

Labour and energy costs for loading and transport of sweet sorghum to Triangle sugar mill on the 17th March 1999 are given in Tables 4.15 & 4.20. Data on the mass and number of sweet sorghum bundles produced during the March 1999 harvesting trial is provided in Table 4.19.

Table 4.19: Average Sweet Sorghum Bundle Mass for Transport

Site	Field	Bundles No.	Total Mass t	Average Bundle Mass t
CRS	Drip	21	38.380	1.83
CRS	F3	10	25.452	2.55
CRS	F4	10	25.834	2.58
CRS	Sprinkler	12	24.554	2.05
Triangle	Section 26	10	35.920	3.59
Triangle	Section 62	8	35.540	4.44
Total		**71**	**185.7**	**2.6**
Standard Dev.				**1.0**

Notes: Data from Triangle Ltd. Weighing Station printout for Sweet Sorghum deliveries on the 17th & 18th March 1999.

4.3.2.1. Transport Energy Cost Estimation

Considerable variation exists in the literature for average energy consumption per t.km for biomass transportation. Some examples are provided below.

1) The direct energy cost of transport for sugarcane is based on Lewis (1984). He provides data for both diesel consumption and labour used during the transport of 1.36 million t_{cane} to Triangle mill from the estate during one harvesting season. During this season, 785714 l diesel and 11 340 man hours were consumed for cane transport (i.e. $8.34x10^{-3}$ hr t_{cane}^{-1}, or 0.96 hr ha^{-1}). A diesel consumption rate of 0.58 l t_{cane}^{-1} with an average transport distance of 10 km results in a transport diesel requirement of 0.029 l t^{-1} km^{-1} or 2.26 MJ t^{-1} km^{-1}.

The direct energy cost for transport resulting from diesel use is therefore 2591 MJ ha^{-1} ((785 714 * 39)/$1.36x10^6$)*115)

With an energy consumption rate of 2.3 MJ per man hour the labour energy cost for transport is 2.2 MJ ha^{-1}. (0.96x2.3)

2) Howe and Sreesangkom (1990) evaluated data from trials run by Winrock International in Thailand calculating the cost of baling and transporting sugarcane tops and leaves for supplementary energy production. Fuel use for transporting the bales to the factory over a number of distances is given. For 20 km the 6-wheel (2 t) trucks use 3.19 l diesel t^{-1} transported (round trip consumption, i.e. 124.3 MJ = 6.2 MJ t^{-1} km^{-1}) and the 10-wheel trucks (5 t) use 0.622 l t^{-1} per round trip(i.e. 24.23 MJ = 1.2 MJ t^{-1} km^{-1}). Figures given for round bale transportation costs include the costs of using tractors to transport the bales to an interim storage area about 1 to 2 km from the fields and then using trucks for transport to the factory after the harvesting season has ended. Tractor fuel consumption is 0.97 l t^{-1} and for the trucks 1.15 l t^{-1} (8.7 t per load). Therefore total fuel consumption is 2.12 l t^{-1} (82.6 MJ t^{-1} = 4.13 MJ t^{-1} km^{-1}).

3) Bowers (1992) quotes data for transport of hay by tractor and trailer, giving a total energy requirement (including Manufacturing, Transport, & Repairs (MTR) and manual labour) = 19.2 MJ t^{-1} km^{-1} giving a total energy requirement for transport of (80*0.8*0.98)*19.2*20 = 24 085 MJ ha^{-1}.(6)

4) Turhollow and Perlack (1991) give a transport energy cost 7.3 l diesel per odMg of sorghum transported for 40km (0.1825 l / Mg.km) giving an energy input of 7.11 MJ per dry t.km. Therefore, assuming a 2% harvesting loss (Turhollow and Perlack, 1991) the total volume of sorghum biomass needed to be transported in this study = 80*0.8*0.98*0.25=15.68 odMg. This biomass would need to be transported on average 20km to the mill giving a total energy requirement for transport of 15.68 * 7.11*20= 2230 MJ ha^{-1}.

5) Fluck (1992) gives an average figure for transportation by Truck in the US of 1.8 MJ t^{-1} km^{-1} giving an energy cost for transportation of = (80*0.8*0.98)*1.8 * 20 = 2258 MJ ha^{-1}.

6) Pari *et al.* (1998) gives an estimated energy transport cost of 95 MJ t^{-1} ethanol produced where the sorghum is delivered 10 km by a 20 t truck. Given a stated ethanol conversion efficiency of 1 kg EtOH per 16.6 kg sweet sorghum stems a specific transport energy consumption of 9.5 MJ t^{-1} km^{-1} results (including direct and indirect energy inputs).

Table 4.20 compares the energy costs of transport between these six sources with the calculated average energy cost of sweet sorghum during harvesting and delivery to Triangle mill on the 17th March 1999. (See also Table II.9)

Loading

During harvesting, the stems are stacked into bundles of 2.6±1.0 t_{stems} each (maximum bundle mass is 5 t_{stems}, Table 4.19). The loading process can take between 5 to 10 minutes per bundle and can represent a significant investment in time, equipment and manpower i.e. a 30 t flat bed truck requires a load of between 8 to 16 bundles which can take over 1 hour to load. See section 3.2 also.

Delivery

The type of transport used depended on the distance to the mill, size of load and quality of the road surface between the harvest site and the mill.

For transport from CRS a Leyland 30t flat-bed truck was used (Figure 9, Table 4.15).

Maximum transport load 30 t. See section 3.2.1 also.

Unloading

The bundles were unloaded from the transport vehicles using one of the two gantry cranes servicing the two diffuser loading trays. The unloading of sweet sorghum and sugarcane bundles is shown in Figure 10, section 3.2.

Table 4.20: Energy Costs for Loading & Transport to Mill

Operation	Fuel	Labour	MTR [a]	Total
	MJ t^{-1} km^{-1}			
Lewis (1984) [d]	2.25	0.001	1.0	3.3
Howe and Sreesangkom (1990) [c]	4.13	0.2	1.9	6.2
Bowers (1992) [b]	13	0.2	6	19.2
Fluck (1992) [g]	-	-	-	1.8
Pari *et al.* (1998) [h]	-	-	-	9.5
Woods *et al.* (1999) [e]	9.74	0.1	4.5	14.3
Bresler (1999) [f]	1.70	0.1	0.8	2.6
Mean				**8.1**
Standard Deviation				**6.6**
Est. Transport to factory (**MJ ha^{-1}**) [i]	46 t_{stems} sweet sorghum 15 km o/w			**5524**

Source: Bowers (1992) op. Sit. Bridges and Smith (1979)- Labour taken at 2.3 MJ per man-hour. Fuel = diesel (39 MJ l^{-1})

a MTR - Manufacture, Transport, & Repair. Transportation: costs for sweet sorghum transport are taken from Howe and Sreesangkom (1990), based on sugarcane trash collection. However this data didn't include labour or MTR so Bowers (1992) data has been used for labour and MTR = 46% of Fuel energy . See transport section below.

b Transporting baled hay by tractor and trailer. MTR calculated by Bowers (1992).

c Transporting baled cane tops & leaves, Round Bales, firstly by tractor to holding area then by 10t truck 20 km to mill. (Howe and Sreesangkom, 1990)

d Sugarcane Transport energy costs as calculated by Lewis (1984) for the 1982/83 season at Triangle- these are direct energy costs only.

e Calculated using data in Table 4.15 and a weighted average distance form field to mill of 9.38 km. (Table II.10) Includes one off activities associated with a small-scale trial. The calculated energy cost should therefore be regarded as an upper limit. MTR 46% of direct energy.

f Bresler (1999), pers comm., calculates Triangle Ltd.'s average fuel consumption for the season to date (March to July 1999) is 23 t.km per litre of diesel. Labour and MTR calculated as with footnote 'e'.

g Fluck (1992). Probably doesn't include MTR or labour

h Pari *et al.* (1998) includes direct + indirect energy costs

i Calculated by taking the mean transport cost shown above and multiplying by the total load per ha of 46 t_{stems} and the average transport distance of 15 km.

Table 4.21: Transport Type, Distance and Road Type

	Distance to Mill (km) [a]	Main Road Surface	Transport Type	Speed (km h^{-1})
CRS	16.0	Tarmac	Tractor + Truck	80
Triangle Section 62	14.6	Dirt Roads	Hilo	40
Triangle Section 26	6.0	50% Dirt 50% Tarmac	Hilo	20

Notes:
a One way distance from Fields to Mill

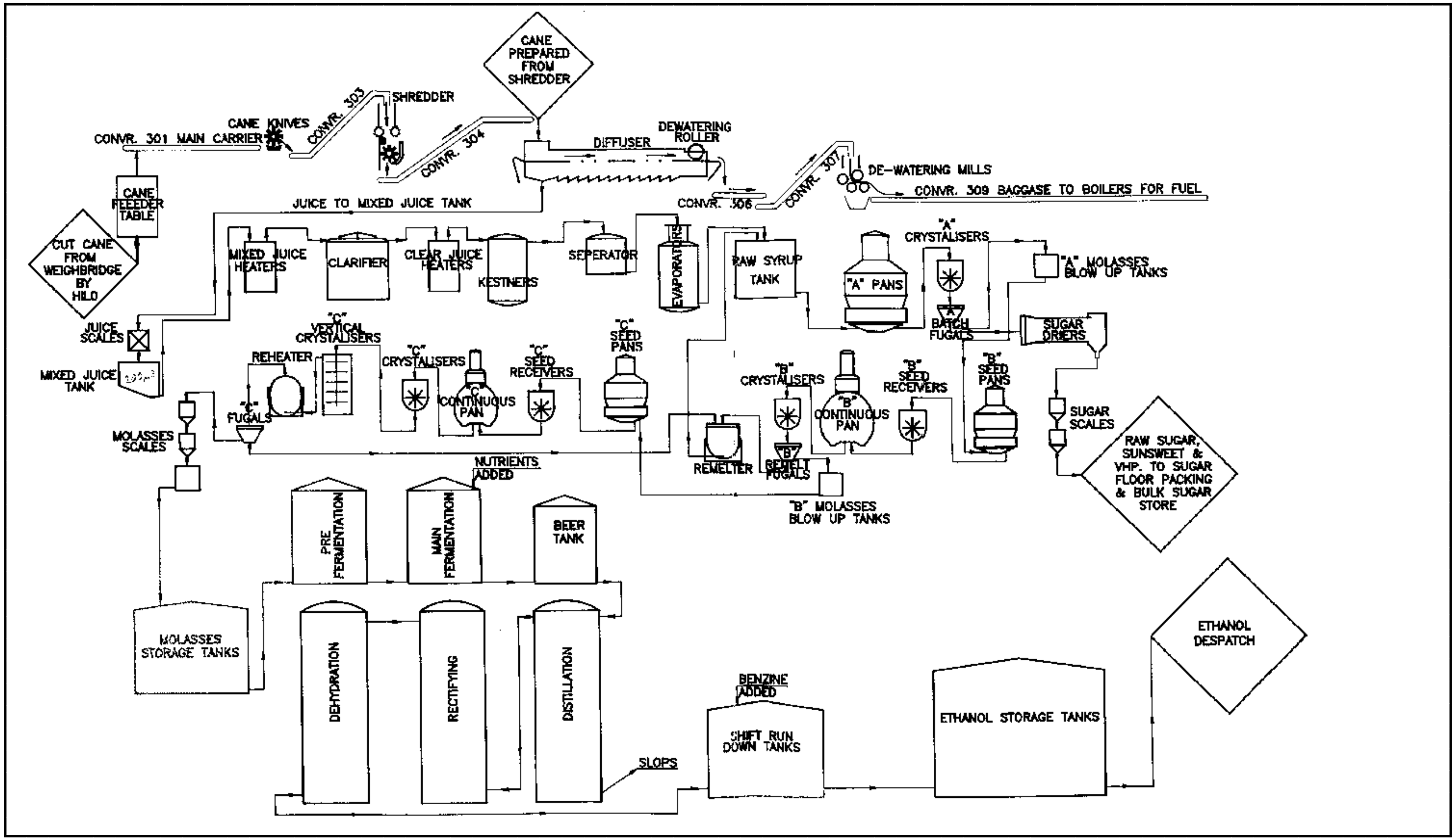


Fig. 19 Process Flow Diagram of Sugar and Ethanol Production at Triangle Ltd. Mill, 1998

4.3.3. Crushing: Sugars and Fibre Separation.

Results from tests on ability of Triangle mill to process sweet sorghum are derived from the diffuser test (carried out 18th March 1999) and the 66" Mill Tandem test (carried out 16th March 1998) are given below. See Section 3.3.1. for a description of these processes.

4.3.3.1. The diffuser processes

The Triangle Ltd. diffuser can process 304 t_{cane} h^{-1} (maximum process rate) producing 98 t bagasse and 381 t of 'juice', consisting of 206 t of cane-derived juice and 175 t of imbibition water.

Separation of the sugars from the fibres in the diffuser results from the flow of the solvent (in this case hot water) through the fibres. This is a gravity fed process with the water percolating down through the bed of shredded stems. Different fibre contents and compositions result in variation in the rate of this percolation and thus given that the bed width and height are constrained by the dimensions of the diffuser either the residence time in the diffuser or the volume of water, or a combination of the two must be altered to optimise sugar extraction. By controlling the velocity at which the fibre is moved through the diffuser and the imbibition rate (the volume of water flowing through the diffuser) the bed height is maintained at a constant level and the sugar extraction is maximised.

The cutting and shredding of the stems requires significant energy inputs with the rotary knives and shredders being driven by large electrical motors:

> The shredder is powered by an 1800 kW slip ring motor and the knives are powered by 2 x 600 KW motors. See Table II.8.

Diffuser Test

Between 11:00am and 1:00pm on the 18th March at Triangle Ltd., 202 t_{stems} of sweet sorghum stems were cut, shredded and processed using the diffuser line.

Safety trip switch problems on Loading Trays delayed startup from 8:00am to 11:00. Problems with one of the stirring motors on the diffuser also halted processing for one hour at about 11:30am. These delays combined with reduced percolation rates, lower in-diffuser bed height, and increased imbibition rates explain the actual processing rate of 67 t_{stems} h^{-1} compared to the rated capacity of 304 t_{cane} h^{-1}.

During the tests the diffuser bed height was maintained at between 0.7 and 0.9 m compared to 1.5m or more in normal operation. A reduction in bed height allows more time to react if the percolation velocity drops suddenly and with an associated increase in bed height can be rectified before the diffuser floods by over-flowing.

Bed height was controlled by:

1. Varying the rate at which the shredded biomass is fed into the diffuser
2. Varying the velocity at which the biomass is drawn through the diffuser on the percolation conveyor
3. Varying the amount of imbibition water added and its flow rate through the diffuser.

It was found that the sorghum mass was not enough to run the diffuser for a sufficient length of time to optimise these three parameters. Whilst valuable data were gathered, it will be necessary in the future to run the diffuser for a minimum of 12 hours continuously using sweet sorghum as the sole feedstock to optimise sugar extraction in the diffusion process.

In order to estimate the percolation velocity of shredded sweet sorghum biomass, two percolator tests were carried out on the 15th and 16th March 1999 at Triangle Mill using the percolation test apparatus designed and constructed by Muchatibaya (1997), Triangle Mill's senior plant engineer. Due to time constraints, the inability of the mill to provide hot water and constraints on the amount of shredded sweet sorghum available the results cannot be regarded as conclusive. However, the data do show a significant decrease in percolation velocity compared to older varieties of sugarcane grown on the Triangle Estates. The results are summarised in Table 4.22.

Table 4.22: Sweet Sorghum Versus Sugarcane Percolation Velocities & Preparation Indices (PI)

	Year	m min^{-1}	Bed Height mm	P.I. [c]	Fibre %	Pol %
Sugarcane Varieties [a]						
NCo 376	1997	2.6	1700	91	15.4	14.2
ZN1L	1997	1	1700	92	15.2	14.7
ZN2E	1997	0.5	1700	91	11.6	16.3
Sweet Sorghum Variety [b]						
Keller	1999	0.9	1200	91	16.9	8.9

Notes: PI = Preparation Index (an indication of fibre particle size after shredding)

a. Sugarcane percolation test data from Muchatibaya (1997).

b. Sorghum data from percolation tests and Triangle Ltd. Laboratory analysis carried out during the diffusion tests in March 1999. See also Table II.7.

c. PI (Preparation Index) is the percent of sugars extracted cf. the total sugar content in the sample. An index of 91 means that 91% of the sugars present in the sample are extractable using a standardised extraction protocol.

Steam is injected into the diffuser which raises the temperature of the imbibition water and juice to 80EC, aiding sugar removal and sterilising the juice. The energy requirements for the diffuser are assessed in section 4.4.1.

4.3.3.2. The 66" Mill Tandem Processes

Triangle Ltd.'s Mill Tandem can process 186 t_{cane} h^{-1} producing 232 t juice (124 t cane-derived + 107 t imbibition water).

Crushing tests carried out on 15th March 1998 demonstrated that sweet sorghum stems were physically capable of being processed using milling technology. Other observations of the 66" mill test were the distinctive "pea" smell and the red colour of the bagasse most likely being derived from secondary infection of the stems by rust-type bacteria following stem-borer attacks.

Because of the relatively small volume of sweet sorghum being processed compared to sugarcane it was impossible to keep either the bagasse or juice separate from the sugarcane bagasse and juice, and therefore no other data were recorded.

In normal operation, the mixed juice streams from the diffuser and the 66" mill are combined with the juice from the diffuser, producing a stream of 705 t h^{-1} being sent to the evaporators after being clarified. However, in the case of the 66" mill line test there was insufficient juice for processing and it was sent directly for disposal, and the juice derived from the diffuser test was used to make crystalline sugar.

4.4. Conversion & Use of Biomass

In sugar mills, the bagasse is burnt in conventional suspension boilers to produce high pressure steam which is then used to produce electricity, direct power and provide heat. The sugars, once separated from the fibre are processed further to separate the sucrose from the other sugars and dissolved solids. The sucrose is crystallised to produce crystalline sugar for the food market, and in some mills, the remaining sugars and dissolved solids are fermented to produce ethanol and an effluent called stillage. The production of crystalline sugar is an energy intensive process with Triangle Ltd. for example, requiring 5.6 PJ of energy during 1997. See Table II.21 for details.

The 1997 sugarcane processing season at Triangle Ltd. started on the 1st April and ended on the 29th December. During this period 2.404 million tonnes of cane were crushed, producing 697 250 t bagasse (50% moisture), 293 796 t crystalline sugar, and 25 million litres of ethanol including ethanol produced from imported molasses (Wenman, 1999a).

The logistics of using sugarcane (and therefore sweet sorghum) stems to produce electricity, heat, ethanol and crystalline sugar were evaluated and the results provided in this section. The section is sub-divided into the use of the fibre for steam, electricity and heat generation, and the sugars, for ethanol and crystalline sugar production.

An energy flow diagram for the sugar mill and ethanol plant is provided (Figure 20) and the use of coal and imported electricity is also evaluated below. See section 3.4. also for a description of the methodology used.

Energy Flow Diagram

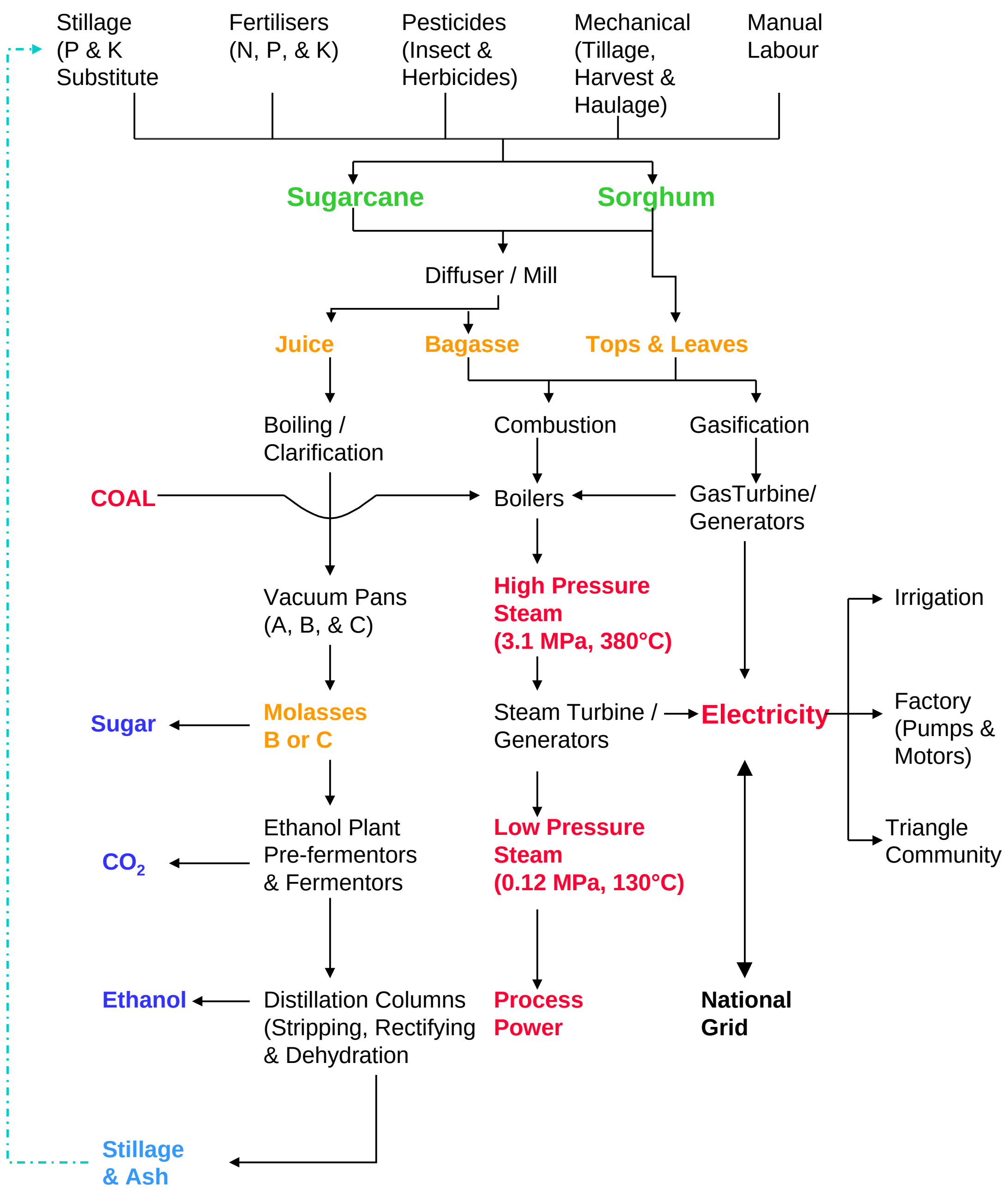


Fig. 20 Energy Flow Diagram for Sugar & Ethanol Production at Triangle Ltd.

4.4.1. Use of the Bagasse (Fibre)

During the crushing season, Triangle provides virtually all its own power by burning the bagasse to raise superheated (high pressure) steam. Figure 21 illustrates how this steam is used to drive steam turbines to provide electricity and mechanical power, with the exhaust steam used to provide process energy (heat) in the mill. This exhaust steam (low pressure) is used to provide heat for fermentation, distillation and sterilisation.

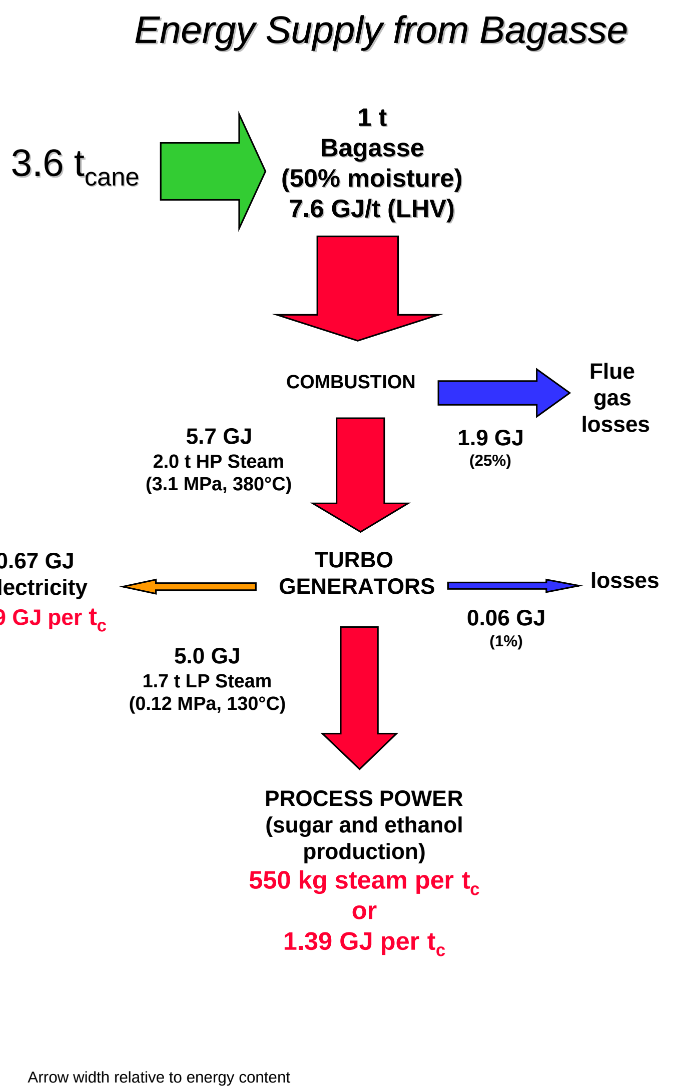


Fig. 21 Energy Production from Bagasse: Steam, Electricity & Process Power

Sugarcane derived bagasse production occurs at a rate of 290 kg bagasse (50% moisture content) per t_{cane} crushed. The energy content of the fibre is 7.63 GJ $t_{bagasse}^{-1}$ or 2.22 GJ

t_{cane}^{-1} i.e. 255 GJ ha^{-1} at a sugarcane productivity of 115 t_{cane} ha^{-1} (Table 4.4. and 4.5) Sweet sorghum-derived bagasse (based on cv. Keller) production occurs at a rate of 186 kg bagasse (50% moisture content) per t_{stems}. The energy content of the fibre is 7.6 GJ $t_{bagasse}^{-1}$ or 1.82 GJ t_{stems}^{-1} i.e. 83.9 GJ ha^{-1} at a sorghum productivity of 46 t_{stems} ha^{-1}.

4.4.1.1. Steam Generation

When operating normally, all the power requirements of the estate, mill, factory, ethanol plant and village are met through the steam-raising capacity of the boilers by burning bagasse. The boilers produce high pressure steam for electricity generation, process power, and direct heat requirements as shown in Table 4.23.

Table 4.23: Triangle Ltd. Boiler Specifications [a]

Boiler No.	Steam Capacity	Efficiency [b]	Bagasse	Energy Input	Energy Output [c]
	t hr^{-1}	%	t h^{-1}	GJ	GJ
7	45	73.4	23	177	130
8	45	74.2	23	175	130
9	100	76.6	49	376	288
10	100	76.6	49	376	288
Total	**290**	**75.7**	**145**	**1103**	**835**

Notes:

a. All boilers produce steam at 370EC and 30 Bar (3.1 MPA) with an Energy content = 2.88 GJ t^{-1}. Bagasse energy content = 7.63 GJ t^{-1}. Other specifications (except boiler efficiencies, see below) are from Vengesai (1999).

b. Energy content of steam / LHV Bagasse. Total Efficiency is a weighted average assuming all boilers run at full steam generating capacity. Individual boiler efficiencies are from Nyamuzihwa (1999)

c. Energy Output = energy content of steam (i.e. total = 290 t_{steam} h^{-1} * 2.88 GJ t^{-1} = 835 GJ h^{-1}). Energy Input = Energy content of bagasse (i.e. Output/(efficiency/100))

The processing of 490 t_{cane} h^{-1} (maximum capacity) produces 142 $t_{bagasse}$ (50% moisture). However, over the 9 ½ month season, full capacity is not available all the time and for the 1997 season Triangle achieved 78.4% of full capacity (Wenman, 1999a). Therefore the working operating capacity = 490 x 0.784 = 384.2 t_{cane} h^{-1} producing 111.4 $t_{bagasse}$ h^{-1} with a bagasse energy content of 850 GJ (111.4 x 7.63 GJ t^{-1}).

High Pressure Steam Specifications[13]:

Steam Temp:	380 ± 15 EC
Steam Pressure:	3.1 MPa (30 Bar)
Steam Energy content:	2877 kJ kg^{-1} (2.88 GJ t^{-1})

After juice extraction the bagasse is sent directly to the boilers where it is burnt in suspension with high pressure (HP) steam being produced at 3.1 MPa and 380°C (3.2 GJ t^{-1}). Triangle now has 10 separate boilers, 5 of which are capable of burning bagasse or coal- only boilers 7 to 10 are currently used with 1 to 6 being mothballed. Boilers 7 to 10 are each capable of producing between 20 to 150 t_{steam} hr^{-1} from bagasse or coal, with the maximum output coming from the newest boiler (built 1997). This latest boiler can burn 70.9 t bagasse per hour or 12.7 t coal per hour. See Table 4.23.

With an average energy conversion efficiency (bagasse energy to steam energy) of 75%, HP steam production of 191 (255*0.75) and 63 (84*0.75) GJ ha^{-1} for sugarcane and sorghum, respectively, (66.3 and 21.9 t HP steam ha^{-1}) is possible.

Using the parameters above, it is possible to calculate the maximum steam output (tonnes and energy) that can be generated for given maximum biomass and seasonal processing rates:

1. Maximum processing rate (490 t_{cane} h^{-1})

    490 t_{cane} provides 142 $t_{bagasse}$ at 7.63 GJ t^{-1} = 1083.5 GJ
    1083 x 0.757 (boiler efficiency) = 820 GJ
    820 / 2.88 (HP steam energy content) = 285 t_{steam}

---

13 Temperature and pressure from MacIntosh (1999). Steam Energy Content calculated using ‘Thermodynamics’ software (Moran and Shapiro, 1991).

2. Season Average Processing rate (384 t_{cane} h^{-1})

384 t_{cane} produces 111.4 $t_{bagasse}$ at 7.63 GJ t^{-1} = 850 GJ

850 x 0.757 (boiler efficiency) = 643 GJ

643 / 2.88 (HP steam energy content) = 223 t_{steam}.

The stated steam consumption at Triangle is 550 kg steam per t_{cane} processed as shown in Figure 21. Therefore at the seasonal average processing rate of 384 t h^{-1}, process steam requirements are 384 x 0.55 = 211.2 t_{steam} h^{-1}

Surplus bagasse generation is calculated as follows:

223 - 211	=	12 HP t_{steam} surplus h^{-1}
x 2.88	=	34.6 GJ
÷ 0.757	=	45.7 GJ bagasse energy
÷ 7.63	=	5.98 $t_{bagasse}$ surplus
÷ 384	=	0.016 $t_{bagasse}$ surplus t_{cane}^{-1} processed

Therefore a slight bagasse surplus is available of 16 kg bagasse per t_{cane} processed and a surplus of up to 40 000 $t_{bagasse}$ is generated each season some of which is used for cattle feed and other purposes and the rest stored for use off-season or during mill down time.

When operating at full capacity, the boilers need to produce 157.7 t_{steam} h^{-1} for the turbo-alternators (electricity), 44.6 t_{steam} h^{-1} for direct power turbines, and 77.5 t_{steam} h^{-1} is allowed to expand through a 'let-down' valve (de-superheater), when it is then mixed with water and the exhaust steam from the mill turbines. The exhaust steam provides heat energy for evaporation, distillation and sterilisation. (Hoekstra, 1997)

4.4.1.2. Electricity Generation & Consumption

High pressure steam is fed directly to the 6 Turbo-altenators (TA) with a total rated output of 35.5 MW_e. However, as some of these turbines are over 30 years old the maximum operational capacity is well below the rated capacity of 32 MW_e. In fact, maximum electricity demand never exceeds 23 MW_e and with a typical demand of 12 MW_e for the Mill, ethanol plant, factory and village and 7 MW_e for irrigation, a normal in-season load on the power station is 19 MW_e requiring 158 t_{steam} per hour from the boilers (19 x 8.3; Table 4.24).

The value of the steam after electricity generation depends on the turbine technology used. Old back-pressure turbines which allow a pressure of 0.1 to 0.15 MPa to be maintained after the turbine provide low pressure steam usable for all process power requirements. Condensing extraction steam turbines are more efficient as the steam is condensed to water after the turbines and is therefore not available for process power.

Table 4.24: Triangle Ltd. Turbo-Altenator Specifications [a]

Turbine	Type	Rated Output	Operational Output	Steam [c]	Electrical Efficiency [b]	Priority [c]
		MW_e	MW_e	$t\ MWh_e^{-1}$	%	
TA1	BP	7.5	6.0	9	13.8	5
TA2	C	3.0	3.0	6	20.7	6
TA3	BP	2.0	1.5	8	15.5	4
TA4	BP	7.5	6.0	9	13.8	3
TA5	BP	8.0	8.0	10	12.4	2
TA6	BP	7.5	7.5	8	15.5	1
Total (avg)		**35.5**	**32.0**	**8.3**	**15.3**	

Notes:
a General Specifications from Vengesai (1999). BP = Back Pressure and C = Condensing. TA = Turbo-Alternator.
b. Electrical Efficiency calculated as energy content of electricity generated / energy content of input steam.
c. Exhaust steam Energy content = 2.60 GJ t^{-1} Input Steam Energy content = 2.90 GJ t^{-1}
d Increased demand is met by using the turbines in the order shown

From the efficiency of the boilers (75%; Table 4.23) and TAs (15.3%, Table 4.24) it is possible to calculate the overall efficiency of electricity generation at Triangle Ltd. which results from a combination of thermal energy loss and incomplete combustion losses in the boilers and the conversion efficiencies of the turbines and alternators.

Electricity Generating Efficiency at Triangle is: 0.757 x 0.153 = 11.6%

An overall analysis of energy use at Triangle mill as provided in Table II.21 shows that over a complete production cycle 9% of the total energy content of the bagasse used for energy production was for electricity production. The remainder was used for direct power, heat applications and losses. (Table II.21)

Electricity Consumption

The distribution of electricity to the primary consuming areas is shown in Figure 22 below for the 1997/8 production year. Gross consumption of electricity for this year amounted to 140 GWh or 504 TJ, of which the alcohol plant consumed 2.7%, and the mills and sugar factory combined a total of 28%. Irrigation demanded the largest share of electricity consumption (34%) reflecting the low rainfall and good growth conditions during this season. Electricity consumption data has been derived from Triangle's Monthly Power Station Balance Sheets (April 1997 to March 1998).

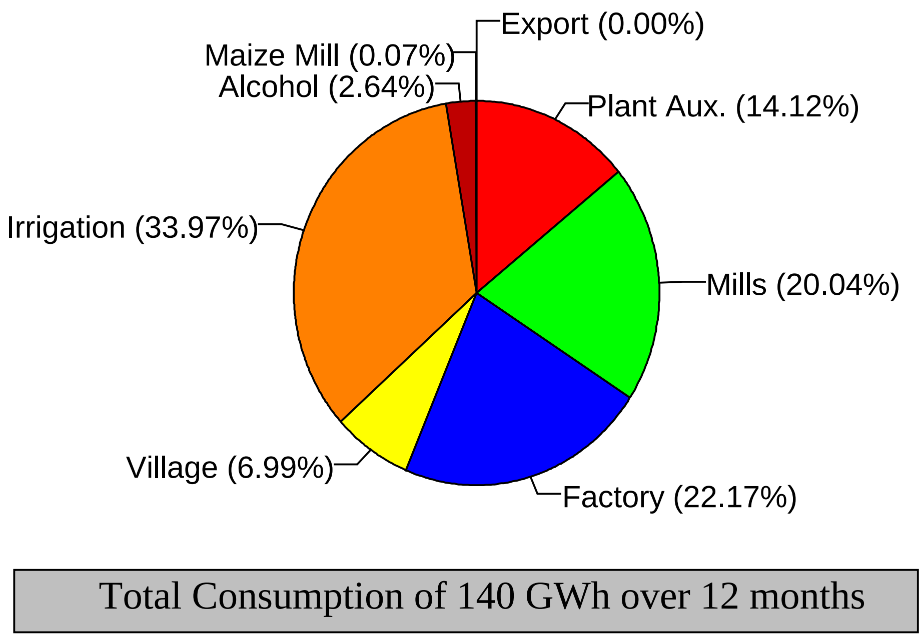


Fig. 22 Triangle Ltd, Electricity Consumption April 97 to March 98

The data shown in Figure 22, was then used to calculate the use of electricity per t_{stems} processed, which was then allocated as MJ per hectare of sweet sorghum or sugarcane production i.e. the last two columns of Table 4.25.

The Power Plant Auxiliaries power losses have been assigned to the crystalline sugar production and juice separation with these losses being divided equally i.e. 50% of the power plant auxiliary losses are assigned to each one in the final energy balance calculations (Tables 4.25 & II.21).

Table 4.25: Electricity Consumption; Triangle (April 97 to March 98)

Section				Sugarcane	Sorghum
	MWh_e	TJ	MJ t_c^{-1}	MJ ha^{-1} [a]	
Power Plant Auxiliaries	14598	52.6	21.9	2514	1006
Mills	20719	74.6	31.0	3568	1427
Factory	22925	82.5	34.3	3948	1579
Village	7228	26.0	10.8	1245	498
Irrigation	35125	126.5	52.6	6049	2420
Alcohol	2725	9.8	4.1	469	188
Maize Mill	71	0.3	0.1	12	5
Exported	0	0.0	0.0	0	0
Imported from Grid	2986	10.8	4.5	514	206
Generated on Site	102364	368.5	153.3	17628	7051
Tonnes Cane Crushed			2404000		

Notes:

a Assumes 115 t_{cane} and 46 t_{stems} ha^{-1} for sugarcane and sorghum respectively (Section 4.2.2.4)

Assuming a national generation efficiency of 30% (energy basis), total net electricity inputs to Triangle are calculated at 0.8 GJ ha^{-1} for sugarcane (0.3 GJ ha^{-1} for sorghum). It should be noted that the imported electricity appears to primarily cover off-crop electricity requirements for irrigation of sugarcane (76%) and for domestic consumption in the Triangle village (18%). Off-crop electricity use is approximately half the rate of use during the cropping season.

Irrigation requirements for electricity calculated from the 97/98 Triangle monthly electricity Power Station Balance sheets show a total electricity consumption of 126 TJ over 12 months. With 2.4 Mt_{cane} crushed an electricity consumption rate for irrigation of 52.5 MJ t_{cane}^{-1} or 6.0 GJ ha^{-1} is derived.

Non-irrigation requirements for electricity (minus exports) were 243 TJ (369 - 126) and result in a total non-agronomic electricity consumption of 101 MJ t_{cane}^{-1} or 11.6 GJ ha^{-1}.

4.4.1.3. Direct Power Production

The other consumers of HP steam in addition to the turbo-alternators are the 5 major direct power turbines or 'prime movers' as shown in Table 4.26.

Table 4.26: Triangle Direct Power Turbines

	Power (kW)	Steam ($t\ h^{-1}$) [a]	Bagasse ($t\ h^{-1}$)
Diffuser Dewatering Mill 1	480	12.50	6.233
Diffuser Dewatering Mill 2	480	12.50	6.233
Mill No. 6	333	8.67	4.324
Feed-Water Pump	210	5.47	2.727
Feed-Water Pump	210	5.47	2.727
Total	1713	44.61	22.243

Source: SLOB run data from Hoekstra (1997) for power ratings.
Notes:
a assumes turbine efficiency steam energy in to power out of 4.8%

Calculated turbine efficiencies are derived from data supplied by MacIntosh (1999) and steam consumption rates from Hoekstra (1997). Whilst this efficiency is extremely low, the direct power turbines consume only 0.85% of Triangle's total energy consumption as shown in Table II.21.

4.4.1.4. Heat

Direct heat applications such as temperature regulation, evaporation, and distillation represent the largest use of energy in the mill and estates, consuming a total of 89% of the primary energy consumed at Triangle. (See Table II.21)

All heat applications are supplied by using exhaust steam, the majority of which is derived from the steam after it has passed through the turbines. Any shortfall is made up from let-down steam which is HP steam which has passed through the de-superheater where water is added to reduce the temperature and pressure from 370EC and 3.1 MPa down to 110 kPa and 120EC.

4.4.1.5. Gasification Technologies

In this section the key parameters in installing and deriving useful energy from gasifiers and gas turbines are assessed. See section 2.3.2.1 for more details about gasification and its relevance to this work.

Key assumptions:

1. Gasifier is a fluidised bed gasifier (CFB) with a 95% efficiency in converting energy in biomass to energy in output gas (which is typically a low calorific value gas). This is a conservative conversion efficiency with efficiencies of 98% quoted (Bauen, 1999).
2. Gas turbine is 30% efficient in converting the energy in the input gas to energy in electricity. In practice efficiencies can range from 20% to 36% (Table 4.27).
3. Steam is generated by feeding Gas Turbine exhaust gases into the existing mill boilers which have an efficiency of 75.7 % energy in exhaust gases to energy in steam. This is a major assumption since the properties of bagasse as fed into the boilers under normal operation and of the exhaust gas from the gas turbines, will be very different.
4. Bottoming cycle steam turbines are 15% efficient in converting energy in steam to energy in electricity. In practice efficiencies can range from 12% to 25%.
5. Theoretical fuel feed rate of 20 MW_{th} i.e. for bagasse this is equivalent to 9.44 $t_{bagasse}\ h^{-1}$ ((20*3.6)/7.63).

Given the assumptions above, a 20 MW_{th} energy input gasifier (i.e. 9.44 $t_{bagasse}\ h^{-1}$):

1. Electricity production (calculated overall efficiency of 27.8%):
   20*0.95*0.3 = 5.7 MW_e from the gas turbine
   thermal output from gas turbine = (20*0.95)-5.7 = 13.3 MW_{th}

(13.3*0.757)*0.15 = 1.5 MW_e from the steam turbines

Total Electricity production = 5.7 + 1.5 = 7.2 MW_e

2. Low Pressure Steam:

Back Pressure Steam = (13.3*0.757)-1.5 = 8.57 MW = 8.57-2.53 = 3.39 t

For comparison, the existing configuration at Triangle Mill would produce:

1. Electricity (overall efficiency of 11.6%):

20*0.116 = 2.32 MW_e

2. Steam:

20*0.757)/2.88 = 5.26 t

Therefore, gasification would increase electricity production by 3.1 times (7.2 / 2.32) and decrease steam production by 35 % (3.39 / 5.26). Because gasification technologies are still at the border between demonstration and near-market application, the specifications of the four major demonstration projects currently under construction or now running are given in Table 4.27.

Table 4.27: Major Gasification Projects- System Parameters

	Batelle / Ferco Burlington [a]	TPS ARBRE [b]	TPS BRAZIL [c]	BIOFLOW Värnamo, Sweden [d]
Gasifier efficiency	95	95	95	95
Gas energy content (MJ Nm^{-3})	11	4 - 7	4 - 7	5
Electrical efficiency	32	31		32
Capital Cost (US\$ kW^{-1})	1037	1600	1300	1700
Electricity cost (USc kWh^{-1})	4.7	--	--	5
Size MW_e	5-15	8	32	6
Type	Atm CFB	Atm CFB	Atm CFB	Press. CFB
Cycle	CC	CC	Open	CC

Notes: ‘Atm’ = atmospheric, ‘CFB’= circulating fluidised-bed, ‘CC’ = Combined Cycle, ‘Open’ = open cycle

a Paisley *et al.* (1997)

b Beenackersand Maniatis (1997)

c Rensfelt (1997)

e Beenackersand Maniatis (1997) and Ståhl *et al.* (1997). First plant in operation, powered by wood chips.

4.4.2. Use of the Sugars

The production of ethanol and crystalline sugar is described below in terms of the resource requirements and the trade-off between maximising ethanol production or crystalline sugar production. The potential for the use of sweet sorghum is also compared to the existing sugarcane production system.

4.4.2.1. Ethanol Production

Only conventional batch process industrial scale fermentation technologies are assessed here. Novel fermentation technologies and their potential impact if implemented are discussed in section 5.

According to Sen (1989), *Saccharomyces cerevisiae* “will convert 1.00 g glucose into 0.51 g ethanol and 0.49 g CO_2 following about a dozen enzymatic steps of the Embden-Meyerhof-Parnas pathway. However, slightly less than the theoretical amount of ethanol (0.46 g) and CO_2 (0.44 g) is produced because part of the glucose is used up for the production of biomass.”

Under commercial conditions, the ‘loss’ of carbon to biomass production is estimated at 5% of the sugar mass and a further 7.5% is estimated to be lost as a result of the production of other organic chemicals (fusel oils, glycerine, acetic acid, esters, etc.) In addition, 1.5% is lost during distillation (Energy Authority of NSW, 1986), and a further 3% is lost during the juice extraction process, either in the bagasse or in the filter mud. Finally 48.9% is lost as CO_2. Therefore, the total amount of sugar that ends up as ethanol on a mass basis is (100-(48.9+3+1.5+7.5+5%)) = 34.1% . A mass balance based on Triangle Ltd. is carried out in Table 4.28.

The specific gravity of ethanol is 0.789, therefore, 1 g of sugar in sorghum or sugarcane stems will produce 0.432 cc ethanol (0.341 / 0.789), if used directly for ethanol production. Given that sweet sorghum may be expected to produce 12% sugars (stem fresh weight basis) and a yield of 60 t_{stems} ha^{-1} (80 t_{fab}), an ethanol yield of (60*0.12*0.341= 2.46 t EtOH) = 3 100 litres ha^{-1} (51.7 l t^{-1} FW stems) will be produced. At 46 t_{stems} ha^{-1} the maximum theoretical yield would be (46 x 0.12 x 0.341 = 1.87 t EtOH) = 2 380 l ha^{-1}.

The ethanol yields calculated here are significantly lower than the theoretical potential or the potential calculated elsewhere (El Bassam, 1998), as shown in Textbox 2.

Dallianis (in El Bassam 1998) provides a formula for a theoretical ethanol yield from sweet sorghum as below:
Total Sugar Content (%) in fresh matter x 6.5 (conversion factor) x 0.85 (conversion efficiency) x total biomass (t/ha of fresh matter) i.e. *for sweet sorghum under Zimbabwean conditions = 13x6.5x0.85x80 = 5746 l* ha^{-1}.

A maximum theoretical ethanol yield (assuming no losses during harvesting, transport and conversion; an ethanol plant conversion efficiency of 600 l per t sugars):
For Keller is calculated as = 0.13*60*600 = 4 680 l ha^{-1}.
For Sugarcane = 0.155*115*600 = 10 350 l ha^{-1}.

The average ethanol plant conversion efficiency for the Triangle Ltd. Ethanol plant is:
600 litre anhydrous EtOH produced per tonne sugar (reducing + non-reducing)

Text box 2: Estimates of Potential Ethanol Production Per Unit Land Area

Table 4.28 shows the 'loss' in sugar (carbon) mass at each stage of the ethanol production process, showing that about 65% of this mass is lost by the time absolute ethanol is produced. However, the bulk of this loss is as CO_2 arising from the respiration of the yeast during fermentation which accounts for 49% of the total sugar mass.

Theoretical ethanol yields from 4 sweet sorghum varieties and from sugarcane were calculated and are shown in Table 4.29. The ethanol yields were calculated on the basis of: i) all stem sugars being used for fermentation, and ii) crystalline sugar extraction first then fermentation of molasses 'C'. The data shown in Table 4.29 was calculated using real-time production factors derived from Triangle Ltd. and may therefore be more realistic than the estimates shown in Textbox 2. The ethanol yield data from Table 4.29 is used as the basis for all related calculations in this work.

Table 4.28: Theoretical Ethanol Production Mass Balance

Process Step		Mass Loss		Mass
		% per step	cum.%	Kg
TFS in stems (fresh weight)				1000
Harvesting, Transport & Storage		5.0	5.0	950
Juice Extraction		3.0	7.9	922
Fermentation [a] (61.4% total loss)	Biomass Production	5.0	12.5	875
	Organic Chemicals	7.5	19.4	806
	CO_2	48.9	64.4	356
Ethanol (Final)	Distillation losses	1.5	65.0	350

Notes: this table calculates the cumulative losses on a mass basis of TFS (Total Fermentables as Sugars) resulting in 350 kg EtOH being produced from 1000 kg TFS in the original in-field sugarcane or sorghum stems i.e. a loss of 65% of the original mass of sugars can be expected in the production of ethanol of which the inevitable production of CO_2 represents 45%.

a Percentage Fermentation losses shown for 'Biomass Production', 'Organic Chemicals', and 'CO_2' represent mass losses during this stage as they occur simultaneously e.g. the 48.9% loss to CO_2 is 48.9% of 992 kg and not 48.9% of 806 kg.

It is interesting to note that the proportion of sugars as RS in sweet sorghum is generally 10 times higher than in sugarcane, and that whilst it is assumed that approximately 5% of sugarcane RS are un-fermentable around 10% of sweet sorghum RS are measured as un-fermentable.

Table 4.30 shows the results from the fermentation tests carried out at Triangle Ltd.'s Laboratory during March 1998 on sweet sorghum samples from the trials at Chiredzi. These results showed that sweet sorghum juice is a more suitable fermentation substrate than molasses 'C' derived from sugarcane juice. For a direct comparison between sugarcane and sweet sorghum, fermentation tests are required on pure sugarcane juice and on molasses 'C' derived from sweet sorghum. It is unlikely that sugarcane juice fermentation would result in a significantly better ethanol yield as results shown in Table 4.30 are already very close to the theoretical maximum yield from a yeast-based batch fermentation system.

Table 4.29: Ethanol Production from Sweet Sorghum and Sugarcane

	Brix	Pol	Sucrose Purity %	TRS	UFRS	TFS	EtOH [1]	EtOH [2]
Variety	% FW Stems			% FW Stems				l ha^{-1}
i) Ethanol Only								
Keller	17.4	12.1	69.7	13.5	0.4	13.1	4.6	2677
Cowley	18.5	12.8	69.2	15.0	0.3	14.7	5.1	2993
IS19674	13.7	6.6	48.2	9.6	0.3	9.3	3.3	1904
Monori edes	11.0	6.3	57.3	8.0	0.3	7.7	2.7	2057
Sugarcane [2]	16.8	14.1	83.6	14.7	0.0	14.6	5.1	7458
ii) Ethanol + Crystalline Sugar [3]								
Keller	-	1.1	-	2.5	0.4	2.1	0.7	561
Sugarcane	-	1.3	-	1.9	0.0	1.8	0.6	936

Notes: Brix = Total Dissolvable Solids; Pol = polarity (measure of sucrose); Suc. Purity = %Brix which is Sucrose (pol/brix *100); TRS = Total Reducing Sugars; UFRS = Unfermentable Reducing Sugars; TFS = Total Fermentable Sugars (TRS-UFRS)

1 Percentage of FW sweet sorghum stems recoverable as EtOH on a mass basis (assumes 35% recovery). EtOH density = 0.789g l^{-1}.

2 This column calculates the expected recovery of ethanol if 46 t_{stems} ha^{-1} of sorghum (115 t ha^{-1} sugarcane) are delivered to the mill. It includes losses as outlined in Table 4.28, totalling 65% of the original fermentable sugars. 5% sugarcane RS (0.6% stem wt are UFRS).

3 9% Pol remaining after crystalline sugar removal. Assumes no loss of Reducing Sugars (RS) during sucrose extraction.

Table 4.30: Fermentation Efficiency (Triangle Ltd. Lab Results, 1998)

Sample	**Absolute Ethanol Yield kg^{-1}**						**TFS Conversion Efficiency [1]**
	Juice		**TRS**		**TFS**		
	ml	**g**	**ml**	**g**	**ml**	**g**	
Keller	84.9	67.0	640	505	659	520	1.18
Cowley	87.8	69.3	665	525	682	538	1.22

IS19674	74.4	58.7	699	551	717	566	1.29
Monori edes	43.8	34.6	551	435	570	450	1.02
SC Molasses 'C'	-	-	510	402	558	440	1.00

Source: Siwela (1998) Triangle Ltd. Laboratory Fermentation Test Results.
Notes:
1 calculates the relative efficiency of conversion of TFS (Total Fermentable Sugars) to ethanol compared to sugarcane (SC) molasses 'C'.

Between 1st April 1997 and 30th March 98 Triangle had produced 89 000 t 'C' molasses and 290 000 t crystalline sugar. Triangle also imported 36 000 t molasses from other sugarmills in the region (Wenman, 1999a).

Total ethanol production for this period was 25 million litres which, with a nominal energy consumption of 0.18 GJ t_{cane}^{-1} and a season's total crush of 2.404 Mt cane results in energy consumption of 17.2 MJ l^{-1} for the ethanol plant only (Table II.21). This can be compared to an expected energy consumption of 14.2 MJ l^{-1} (Table 4.32) when the ethanol plant is operating continuously at full capacity.

4.4.2.2. Sugar and Ethanol Production

The extraction of the sucrose as crystalline sugar results in the primary revenue stream to sugarmills. It is also the single largest user of energy requiring 45% of the entire energy consumption of the mill, ethanol plant and estates to evaporate the water and concentrate the sucrose to crystallisation point. (Table II.21) The extraction of sucrose resulted in a direct reduction of fermentables available for ethanol production, for example see Table 4.32.

Existing sugarcane-based ethanol production at Triangle Ltd. uses molasses 'C' both from Triangle's own sugar production, and from molasses purchased from the nearby Hippo Valley Estate (HVE) and from Zambian sugar mills. If sufficient molasses can be purchased then the ethanol plant will run all-year round using stored molasses and coal to power the fermentation and distillation processes out of the harvesting season. However, in good rainfall seasons irrigation is not required and the disposal of stillage becomes problematic. Under these circumstances, even if there is molasses available the ethanol plant cannot be run. Triangle also has the capacity to by-pass the ‘C’ pan crystallisation process and send ‘B’ molasses directly to the ethanol plant thereby increasing ethanol production. However, it is currently more profitable to extract crystalline sugar using the ‘C’ pan than produce ethanol from ‘B’ molasses. Therefore all ethanol production at Triangle is currently based on ‘C’ molasses. It is worth noting that about 3% of Pol (sucrose) is lost through incomplete extraction from the bagasse and filter cake losses, and a further 2% during transport and handling (Table 4.31).

Table 4.31: Triangle Pol (Sucrose) Balance (1997).

Process Point	% Original Pol in Cane
In Cane	100
Milling Loss in Bagasse	3
In Juice	97
In Crystalline Sugar	87
In ‘C’ Molasses[a]	7
In Filter Cake	0
Total Factory Loss	3
Overall Recovery	87
Boiling House Recovery	90

Notes: Triangle Ltd. Weekly Factory Performance Summary: 25th December 1997.
a. ‘C’ molasses contains approx. 45% fermentable sugars by weight.

Energy Consumption by the Ethanol Fermentation Plant

A more detailed evaluation of energy consumption for ethanol production was carried out and is summarised in this section. This was achieved by dissagregating the energy inputs required for each stage in the processing of juice to ethanol. The energy required for the production of absolute ethanol in the Triangle Ltd. ethanol plant is shown in Table 4.32.

Energy budgeting for ethanol production using molasses ‘C’ is derived by calculating total energy consumption required to produce molasses ‘C’ and dividing it by the percentage share of Pol directed to the ethanol plant. According to Rosenschein and Hall (1991), for Triangle's 'B' molasses-derived ethanol production, energy consumption for the sugar destined for ethanol production represented 16.6% of total mill energy consumption. The result of increasing sugar production by adding the Pan 'C' extraction stage resulted in a reduction of Pol directed to ethanol production by 8%.

Table 4.32: Energy Requirements in Triangle's Ethanol Plant.

Input Type	Where Utilised	Details	KJ l^{-1} Anhydrous EtOH	
Steam (120 kPa, 130°C; 2.52 GJ/t)				12096
	Stripping Column	16 t_{st} h^{-1}	8064	
	Dehydration Column	4.5 t_{st} h^{-1}	2268	
	Other	3.5 t_{st} h^{-1}	1764	
Electricity		3342.6 MWh		396
	Fermentation	5969 hr @ 500 kW	353	
	Distillation	5969 hr @ 60 kW	42	
Chemicals & Additives				429
	Diammonium Phosphate	4.67x10^{-3} kg l^{-1} @ 15.6 MJ kg^{-1}	73	
	Urea	2.57x10^{-3} kg l^{-1} @ 23.0 MJ kg^{-1}	59	
	Sulphuric Acid	4.00x10^{-3} kg l^{-1} @ 37.5 MJ kg^{-1}	150	
	Benzene	4.00x10^{-3} kg l^{-1} @ 36.7 MJ kg^{-1}	147	
Labour		19 pers x 300 days x 18 MJ	3.38	3.4
Maintenance & Repairs		10% of above		1292
Total				14216

Source: based on Lewis (1984) for Electricity and Chemicals & Additives components, and Rosenschein and Hall (1991) for steam consumption. The energy density of the diammonium phosphate and urea has been changed to the standard values used in this study (see fertiliser section). Hourly alcohol production = (120000/24) = 5000 l h^{-1}.

Therefore, from Table 4.29, for sugarcane, 936 l ethanol were produced per ha from 115 t_{cane}. Total energy consumption by the ethanol plant was 14.216 MJ l^{-1} giving an energy consumption for the ethanol plant of 13.3 GJ ha^{-1}.

For sweet sorghum, 561 l ethanol was produced per ha from 46 t_{stems}. Total energy consumption by the ethanol plant was 14.216 MJ l^{-1} giving an energy consumption for the ethanol plant of 8.0 GJ ha^{-1}.

Total Steam Consumption in the Ethanol plant was calculated at:

1.	Sugarcane:	936*12.096=	11.3 GJ ha^{-1}
2.	Sorghum:	561*12.096 =	6.8 GJ ha^{-1}

Total Electricity Consumption in the Ethanol plant is calculated at:

1.	Sugarcane:	936*0.396 =	371 MJ ha^{-1}
2.	Sorghum:	561*0.396 =	222 MJ ha^{-1}

Energy Equivalent Value of Stillage

According to Lewis (1984) stillage is produced at a rate of 15 l stillage per litre anhydrous ethanol. Stillage contains 0.5% phosphate and 0.5% nitrate on a volume basis. Therefore equal quantities of phosphate and nitrate are produced i.e. 75 cm^3 per litre stillage.

4.4.3. Biogas Production From Anaerobic Digestion of Stillage

Biogas can be derived as a secondary product of stillage treatment. It is therefore a by-product of a necessary environmental processing step in which the biological and chemical oxygen demand of stillage is reduced through an anaerobic digestion process. However, although the gas produced is a LHV gas, it is a clean gas. The potential for this gas production is beyond the scope of this work and was not quantified.

4.5. Systems Analysis

The previous sections calculated the logistical and energetic parameters for each stage in the production of ethanol and electricity from sweet sorghum and sugarcane. In this section, an evaluation of the complete system is carried out by integrating the results shown above.

4.5.1. Energy Balances

Energy balances for sugarcane and sweet sorghum are calculated from the existing technologies in use at Triangle Ltd. for crystalline sugar and ethanol production. The calculations were based on the data obtained and analysed in the previous sections which are summarised below. Energy use for crop production (agronomy) and conversion (mill energy consumption) are aggregated and compared to the energy content of the outputs.

Table 4.33: Direct & Indirect Energy Use in the Production, Harvesting & Delivery of Sugarcane & Sweet Sorghum (CRS & Triangle, 1997/98)

Step	Sugar and Ethanol Energy Cost					
	MJ ha^{-1}				MJ t_{stems}^{-1}	
	Sweet Sorghum		Sugarcane		SS	SC
	Manual	Mech.	Manual	Mech.	Manual	
Tillage [a]	2225	2225	712	712	48	6
Fertilisation [b]	5865	5865	10317	10317	127	90
Pesticides [b]	1203	1203	592	592	26	5
Irrigation [c]	1534	1534	8832	8832	33	77
Harvesting [d]	212	1948	2370	4869	5	21
Agronomic Total	**11038**	**12774**	**22822**	**25321**	**240**	**198**
Transport [e]	5524	5524	14031	14031	120	122
Delivered Total	**16562**	**18298**	**36853**	**39353**	**360**	**320**

Notes:	Mech. = Mechanical, SS = sweet sorghum, SC = sugarcane
	Sorghum yield = 60 t_{fab} = 46 t_{stems} ha^{-1}, Sugarcane yield = 150 t_{fab} = 115 t_{stems} ha^{-1}.
a	See Table 4.8 for details of sweet sorghum tillage, Lewis (1984) for sugarcane
b	Section 4.2.3.
c	Section 4.2.4.2
d	Section 4.3.1. For sweet sorghum harvesting data see Table 4.19. Lewis (1984) for sugarcane
e	see Table 4.21. Transport costs for sweet sorghum assume 46 t_{stems} ha^{-1} transported 15 km one way and for sugarcane 115 t_{stems} ha^{-1} also 15 km one way.

4.5.1.1. Agronomic Energy Use

Table 4.33 provides a summary of the data in sections 4.2, 4.3 and 4.4. It is interesting to note that although the energy use data for sorghum and sugarcane are derived from very different sources the final specific energy consumption for both systems is similar i.e. for sorghum the specific energy consumption is 360 MJ t_{stems}^{-1} and for sugarcane 320 MJ t_{cane}^{-1} (assuming 46 t_{stems} and 115 t_{cane} per hectare respectively).

4.5.1.2. Mill Energy Use

Once the biomass has been delivered to the conversion facility, in this case Triangle Sugar Mill, the biomass must be unloaded (possibly stored temporarily), transferred to the mill or diffuser lines where it then undergoes a series of physical and thermochemical processes. The energy inputs required to process the biomass are considerable. Virtually all the energy inputs required are provided from the combustion of bagasse. The remaining energy requirements are provided through: i) importing electricity (section 4.4.1.2, and ii) from coal burnt on-site (see below). A summary of energy consumption for the sugar mill and ethanol plant is given in Table 4.34, and is based on a spreadsheet-based model of total energy consumption in 1997. More detail is provided in Table II.21.

Table 4.34: Energy Consumption by Triangle Ltd.'s Sugar Mill & Ethanol Plants

	GJ t_{cane}^{-1}	Percent

Total Energy Consumption from Steam:	**2.34**	100%
Mill + Ethanol + Sugar [a]	**2.25**	96%
Juice Separation Only: [b]	**0.97**	41%
Ethanol Plant Only:	**0.18**	7%
Sugar Crystallisation Only [c]	**1.04**	44%

Notes: Table II.21 provides a more detailed breakdown
a includes 50% of Power Plant Aux. energy costs
b includes 37.5% of Direct Heat 'Losses'
c includes 37.5% of Direct Heat 'Losses'

Coal

The boilers at Triangle are capable of burning both coal and bagasse. The capacity to burn coal allows Triangle to provide power for:

i the ethanol plant out of the harvesting season, and

ii power during planned down times for maintenance (8 hrs per week during the crushing season)

Data for the 1997 crushing season (Table II.20) gives a coal consumption rate of 5 kg t_{cane}^{-1} or 0.140 GJ coal equivalent.

Therefore coal consumption is calculated at 16.1 GJ ha^{-1} (115 t_c ha^{-1}) for sugarcane and 6.4 GJ ha^{-1} (58 t_{cane} ha^{-1}) for sweet sorghum. This coal consumption will also result in the production of 4.23 or 1.6 t steam and 0.518 or 0.206 MWh_e ha^{-1}, for sugarcane and sweet sorghum respectively.

4.5.1.3. Energy Output to Input Ratios

For sugar and ethanol production at Triangle Ltd, using the current configuration, an overall energy ratio of 1.92 is calculated which includes the energy content of the bagasse, crystalline sugar and ethanol (Table 4.35). The shortfall in bagasse energy compared to total energy inputs is made up by using coal and imported electricity. The use of these imported fuels are accounted for as bagasse equivalent in Table II.21.

According to revised data based on Lewis (1984) total energy consumption for crystalline sugar production (probably to 'B' Molasses only) was 87.15 GJ ha^{-1} at a sugarcane productivity of 111.5 t_{cane} ha^{-1} i.e. 0.78 GJ t_{cane} processed.

With the mill re-configured for ethanol-only production (i.e. no crystalline sugar production), but using the current technologies employed by Triangle Ltd. the energy ratio's were recalculated for sorghum and sugarcane, see Table 4.36.

Table 4.35: Energy Ratio for Triangle Mill- 1997

	t product t_{cane}^{-1}	Total t	GJ t^{-1}	GJ Total
Sugar	0.124	298133	17.0	5068267
Ethanol	0.008	19886	26.9	534120
Bagasse (50% mc)	0.29	697247	7.6	5299079
Total Energy Output [a]				10901466
Total Energy Input [b]				5627741
Overall Energy Ratio				**1.94**

Notes: 2.4 Mt_{cane} were processed by Triangle Ltd. during the 1997 season for crystalline sugar and ethanol production (as shown). Average energy consumption is calculated as 2.34 GJ t_{cane}^{-1} (Table II.21).

a Sum of sugar, ethanol and bagasse energy contents

b See Table II.21 for total energy consumption (1997)

On the energy output side of the equation, assuming a delivered sorghum biomass production of 12.2 oven dry t ha^{-1} (energy content of 16.9 GJ t^{-1} HHV) the gross agronomic energy output from sweet sorghum would be 207 GJ ha^{-1}. This calculation incorporates: i) leaf & tops removal (23% of total above ground biomass), and ii) a harvesting, transport and storage loss of 2% of the remaining transported biomass. Thus delivered biomass = 60*0.77*0.98*0.23 = 12.2 odt delivered (207 GJ ha^{-1}). For sugarcane delivered biomass = 115*0.3=34.5 odt @ 17.5 GJ t^{-1} HHV (604 GJ ha^{-1}).

Thus, for Triangle, the **delivered agronomic energy ratio for sweet sorghum** would be:

207/16.6 = **12.5**

where total energy consumption in the growth, harvesting, and delivery of sweet sorghum is 16.6 MJ ha^{-1} (Table 4.33).

The **delivered agronomic energy ratio for sugarcane** would be:

604/38.4 = **15.7**

where total energy consumption in the growth, harvesting, and delivery of sweet sorghum is 38.4 MJ ha^{-1} (Table 4.33).

Table 4.36: Energy Ratio for Ethanol Production from Sweet Sorghum & Sugarcane- No Crystalline Sugar Production

		Manual Harvesting			Mechanical Harvesting		
	Unit	Sugarcane	Keller		Sugarcane	Keller	
Stem yield	t_{stems} ha^{-1}	115	60	46	115	60	46
Delivered [d]	GJ ha^{-1}	36.85	21.60	16.56	39.35	23.87	18.30
Ethanol Plant [e]	GJ ha^{-1}	91.8	43.0	36.8	91.8	43.0	36.8
Ethanol Yield [f]	l ha^{-1}	7458	3492	2993	7458	3492	2993
Juice Separation	GJ ha^{-1}	112.0	58.4	44.8	112.0	58.4	44.8
Conversion Total	GJ ha^{-1}	203.8	101.4	81.6	203.8	101.4	81.6
Ethanol Energy Content [c]	"	158.1	74.0	63.5	158.1	74.0	63.5
Bagasse Energy Content:	"	254.6	132.8	101.8	254.6	132.8	101.8
Bagasse Energy Surplus	"	50.8	31.4	20.2	50.8	31.4	20.2
Electricity from Bagasse [a]	"	6.0	3.7	2.4	6.0	3.7	2.4
Electricity from Bagasse [b]	"	15.3	9.4	6.1	15.3	9.4	6.1
Net Energy Out [a]	"	164.1	77.7	65.8	164.1	77.7	65.8
Net Energy Out [b]	"	173.4	83.5	69.5	173.4	83.5	69.5
Energy Ratio [a]	out:in	**4.5**	**3.6**	**4.0**	**4.2**	**3.3**	**3.6**
Energy Ratio [b]	out:in	**4.7**	**3.9**	**4.2**	**4.4**	**3.5**	**3.8**

Notes:

a Electricity produced at 11.8% efficiency

b Electricity produced at 30.0% efficiency

c Ethanol plant energy consumption 12.3 MJ l^{-1}, including chemicals + maintenance + repairs
Ethanol plant direct (only) energy consumption 10.6 MJ l^{-1}.

d Table 4.33

e Ethanol yield (footnote 'f') times ethanol plant energy req. Table 4.32.

f see Table 4.29

g   Stem yield x ‘Juice Separation Only’ Table 4.34

4.5.2. Economics

A comprehensive micro-economic analysis was not carried out during this work. However, key economic factors including land use, transport costs and the value of the ethanol produced are evaluated below.

4.5.2.1. Economic Factors Concerning Land Availability

Equation 1 below is the intermediary stage between equations 7 & 8 in Overend (1982) and assumes circular geometry:

$$\bar{R}\ '\ \text{ô}\frac{2}{3}\sqrt{\frac{n\left(\frac{cP}{100M\text{ö}}\right)}{\text{ð}}} \qquad \text{Equation (1)}$$

Where:

R   average transport distance (km)

ô   ‘Tortuosity’ factor (TF)- actual distance travelled to straight line distance. Taken as 1.5 as according to Overend (1982) “ a regular rectangular road grid superimposed over a flat terrain has a value of 1.27 to an excess of 3 for a complex or hilly terrain constrained by geographical features such as lakes and swamps.”

n   number of ‘slices’ to complete a circular geometry; assumes a “pie slice” shape for the harvest area with the processing plant at the apex (taken as 1.5 for near circular geometry)- Complete circular geometry filled with crop would give an ‘n’ value of 1 with complex or hilly terrain would be in excess of 3.

c   capacity factor (number of days per year plant operates i.e. 11 months = 330 days)

P   plant capacity (6400 fresh weight tonnes per day raw material, see below)

M yield per ha (46 t_{stems} ha^{-1}; the 100 factor converts 'M' into yield per km^2)

ö fraction of total area planted to crop (assumed to be 0.1 for a 10% use)

The Triangle Sugar Mill Ethanol Plant is capable of producing 120 000 l anhydrous ethanol per day or 40 Ml per year (330 days per year operation). 0.68 l EtOH are produced per kg fermentable sugars, (Table 4.30), therefore, 176 t sugars per day are required (120000 l / 0.68). Sweet sorghum stems are approximately 12% sugars at maturity with an overall expected recovery of sugars after juice separation of approximately 95% (2 % lost during harvesting and transport and 3% lost during juice extraction at the mill).

Therefore mass of sweet sorghum stems required to run ethanol plant for one day:

P = (176/0.95)/0.12 = 1544 t_{stems} per day equivalent to 33 ha (46 t_{stems} ha^{-1})

1. Scenario- Ethanol plant run on Sweet Sorghum as sole feedstock for 11 months and 10% of land area planted to Sweet Sorghum.

$$\bar{R} \text{ ' ô} \frac{2}{3}\sqrt{\frac{1.5(\frac{330x1540}{100x60x0.1})}{\text{ð}}}$$

With these assumptions the average transport distance: **mean R = 20.1 km**

2.a. Scenario- Ethanol plant run on Sweet Sorghum as sole feedstock for 2 months, using 3% of land area planted to Sweet Sorghum

$$\bar{R} \text{ ' ô} \frac{2}{3}\sqrt{\frac{1.5(\frac{60x1540}{100x60x0.03})}{\text{ð}}}$$

With these assumptions the average transport distance: **mean R = 15.7 km**

2.b. Scenario- double EtOH plant capacity 240 000 l anhydrous ethanol per day. All other factors as with 2.a.

$$\bar{R} = \frac{2}{3}\sqrt{\frac{1.5\left(\frac{60x3080}{100x60x0.03}\right)}{\pi}}$$

With these assumptions the average transport distance: **mean R = 22.1 km**

Actual land area requirements for sweet sorghum to supply the ethanol plant for 2 months per year would be 2000 ha ((1540t day^{-1} x 60 days) / 46 t ha^{-1}) or approx. **10 %** of Triangle’s existing estate area under sugarcane (20 000 ha total).

Another way of calculating the expected average transport distance for the delivery of sweet sorghum to an ethanol plant or sugar mill is:

1. Ethanol plant requirements for 2 months are 92 400 FW t_{stems} (1540 t day^{-1} * 60 days).
2. No. ha sweet sorghum required to supply 92 400 t_{stems} at 60 t_{stems} ha^{-1} = 2 000 ha
3. At 3% land area planted to sorghum total land area = 66 700 ha (667 Mm^2)
4. Distance to edge of planted zone (assuming circular) = 14.6 km
5. Average distance for transport assuming even distribution of planting = 9.7 km (14.6 * 2/3)
6. Average distance including ‘tortuosity’ factor of 1.5 = 14.6 km.

The average transport distance for sugarcane at Triangle is approximately 20km for the 20 000 ha under cane (using $A=\pi r^2$), the maximum distance for 20 000 ha (i.e. the radius) for cane to be transported assuming 80% utilisation would be 8.9 km and therefore the mean would be 5.9 km, indicating a TF exceeding 3. However, this higher TF is probably a result of the Triangle estate having outlying supply areas e.g. the Mkwasine estate. Individual TFs for both Triangle Ltd. and the Mkwasine estate would need to be measured to derive an accurate average TF for Triangle Ltd. and this data is not available in disaggregated form. Therefore, it can be concluded that the true TF for Triangle is less than 3 and probably lower than 2.

4.5.2.2. Estimating Transport Costs

Having a quantitative approach to calculating average transport distances which accounts for the percentage land area planted to a specific crop is critical for calculating realistic transport costs. According to Nguyen and Prince (1996), using figures based on a 125 Ml Ethanol plant, an ethanol recovery efficiency of 1 000 l ethanol per 12.5 tonnes of cane is expected. The average cane productivity for NSW of 52 t ha^{-1} gave a land requirement of 1.56 Mha. Using a land use factor of 70% gives a maximum transport distance of 84 km with an average distance of 56 km. Using a tortuosity factor of 2 gives an average transport distance of 112 km. The average transport cost was A$[14] 9 t^{-1} or US$ 7 giving a per unit distance transport cost of US$ 0.064 t^{-1} km^{-1}. It is assumed because of the scale of this operation and the distances involved that a considerable proportion of the cane transport is carried out by rail which is one of the cheapest methods of transport once the infrastructure is in place.

Chapman and Milford (1997) give average transport costs for hauling sugarcane a distance of 100km at approximately A$9 to A$11 t^{-1} (US$ 0.068 to 0.083 t^{-1} km^{-1})

Actual Triangle data from Mugozumbe (1998) gives a 1997/8 average transport cost of Z$ 1.60 t^{-1} km^{-1} but due to fluctuating exchange rates it is difficult to accurately translate this value into US$. However, using an exchange rate of Z$ 15 per US$ gives an average transport cost for Triangle Ltd. of US$ 0.11 t^{-1} km^{-1}.

Actual direct transport cost data i.e. excluding vehicle costs, from the harvesting and transport of 202 t_{stems} of sweet sorghum to Triangle Mill on 18th March 1999 is evaluated below. See Table II.9 for details.

The transport of 130 t_{stems} from CRS (16 km) required:

1 driver shift (Z$107) + 1 chainman shift (Z$112) + 337 l diesel (Z$ 11 121)
Total Z$ = Z$ 11 340 i.e. Z$ 87.2 t^{-1} or Z$ 5.5 t^{-1} km^{-1} (US$ 0.14 t^{-1} km^{-1})

Bresler (1999) gives a breakdown of the costs and revenues derived from the processing

---

[14] See Appendix I for exchange rates

of the 202 t_{stems} of sweet sorghum during the diffuser test on 18th March 1999 at Triangle Ltd. Haulage costs of Z$3.13 per t.km for Hilo transport (US$ 0.08), loading costs (crane onto trucks) of Z$6.26 per t (US$ 0.16) and weighbridge costs of Z$2.82 per t (US$ 0.07) were charged. The $3.13 per t.km is broken down by Bresler as: Labour Costs = 7%, Fuel = 13%, Vehicle Costs = 48% and other costs including depreciation = 32%.

Triangle Ltd. currently charges:
Hilo rates are Z$3.13 per t.km (US$ 0.078)
Mini-Hilo rates are Z$4.06 per t.km.
Rail haulage charges are (July 1999):

- Mbizi (66km o/w) = Z$71/tonne ie Z$1.07 per t.km,
- Mutirikwe (27km o/w) = Z$41/tonne ie Z$1.51 per t.km,
- Runde (18km o/w) = Z$41/tonne ie Z$2.27 per t.km.

Cost vary between US$ 0.010 and US$ 0.016 per t.km for rail transport of cane in Zimbabwe. (Z$38.00 : US$1.00, July 1999)

Given Besler's delivery costs and using Scenario's 2.a. and 2.b. above, transport costs (Hilo) are calculated as:

2.a. Average transport distance of 15.7 km

Haulage (Z$3.13 per t.km)	=	15.7*3.13	=	Z$49.14
Loading (Z$ 6.26 t^{-1})	=	6.26		
Weighbridge (Z$ 2.82 t^{-1})	=	2.82		
Total			=	Z$ 58.22
				US$ 1.53 t^{-1}

2.b. Average transport distance of 22.1 km

Haulage (Z$3.13 per t.km)	=	22.1*3.13	=	Z$69.17
Loading (Z$ 6.26 t^{-1})	=	6.26		

Weighbridge (Z$ 2.82 t^{-1}) = 2.82

Total = Z$ 78.25

US$ 2.06 t^{-1}

4.5.2.3. Profitability of Ethanol from Sugarcane Molasses in Zimbabwe

The profitability of the ethanol operation at Triangle is very much dependant on the price of the raw materials, namely molasses. Prior to the commissioning of the ethanol plant there was a large excess of molasses in Zimbabwe and Zambia. With the molasses demand for ethanol production now well established, the price has risen steadily over the past 5 years. As with any commodity, different markets are prepared to pay a different price for molasses, and the ethanol plant is now considered the buyer of last resort. However, it is a guaranteed consumer of molasses. At the beginning of each year, Triangle declares a price that it is prepared to pay for molasses up until the start of the season. This price is generally based on an export parity price for world market sales of molasses, and includes the cost of transport, handling and port storage. During 1996, this price was Z$170 per tonne (US$ 19 per t).

Table 4.37: 1996 Costs- Triangle Ethanol Plant (Based on Sugarcane)

Item	Z$	% Share of Total Costs	USc l^{-1}
Plant maintenance costs	1071000	4.3	0.007
Plant Operational costs	659000	2.7	0.004
Chemicals	638000	2.6	0.004
Steam	3524000	14.2	0.022
Electricity	762000	3.1	0.005
Management	3400000	13.7	0.021
Raw Materials	14685000	59.4	0.091

TOTAL	24,739,000	100	0.153

Based on nineteen million litres of ethanol production, (requiring 78,000 tonnes of molasses, revenue is expected to reach Z$ 37,819,000 approx. USc 29 l^{-1}. Costs equate to around USc 15.3 per litre.

4.5.2.4 Estimated Profitability of Ethanol Production from Sweet Sorghum

Table 4.38: Estimated Costs of Ethanol Production from Sweet Sorghum: Based on Triangle Ltd, Zimbabwe (1996 Prices and Exchange Rates)

Fresh stem mass required	t_{stems}	15000		
Ethanol value [a]	US$/l	0.19		
	Units	**Mean**	Low	High [b]
Sorghum productivity (fresh weight)	t_{stems} ha^{-1}	**50**	30	80
Land required	ha	**300**	188	500
OUTPUTS	Units	**Mean**	Low	High
Ethanol value (gross)	$	**171000**	110000	246000
Ethanol production	litre	**900000**	579779	129033
Bagasse production. (50% mc)	tonnes	**1875**	1500	2250
INPUTS	Units	**Mean**	Low	High
Agronomic [c]	$ ha^{-1}	**277**	189	407
	$ l^{-1}	**0.092**	0.061	0.158
Irrigation	Total m^3	**517**	0	6247
	$ ha^{-1}	**103**	0	1249
	$ l^{-1}	**0.034**	0.000	0.646
Harvest & Transport	$ ha^{-1}	**110**	54	208
	$ l^{-1}	**0.037**	0.018	0.081
Conversion				
steam	$ l^{-1}	**0.01**	0	0.05
fermentation (fixed)	$ l^{-1}	**0.04**	0.04	0.04
Production cost per litre [b]	$ l^{-1}	**0.18**	0.10	0.89
Total cost	$	**158700**	58558	115391
Balance (total cost-ethanol value)	$	**12300**	-90791	51442

Note: M=million (10^6) mc = moisture content
Unless stated t = fresh weight tonne (approx 75% moisture, wet basis)

a Price received by Triangle Limited under Zimbabwe Government Contract, set to gasoline import price at Z$ 1.60 per litre (1996). Zimbabwe $ 8.5 per US$ (1996)

b "Mean, Low and High" are always respected for each row of the table. For example the "Low" ethanol production cost is the lowest possible production cost, resulting from a combination of high productivity and low production and conversion costs, and represents a "best possible case scenario" (under the assumptions used here)

c Agronomic costs derived from blanket cost for sugarcane land preparation + growth (not shown), irrigation, harvesting and transport at Triangle Ltd. Transport distance assumed to be 20km o/w.

d Calculates expected reduction in irrigation requirements as a result of rainfall.

Ethanol production costs are broken down into agronomic and conversion costs, and potential revenue is estimated from the internal (Zimbabwe) value for fuel ethanol (19 US cents per litre). These costs are based directly on Triangle Ltd's sugarcane agronomic production, transportation and processing costs. Agronomic costs provide total costs for all inputs, harvesting and transport. Raw material storage costs are excluded because sugar levels in sweet sorghum are sensitive to storage and rapid processing is required after harvesting. Irrigation costs are based on the assumption that 400 mm rainfall occurs during the summer (off crop) season. Conversion costs include the fixed and variable costs associated with ethanol production at Triangle's facilities. Depreciation costs on machinery and equipment are not included, except for transport (where costs are factored in per t.km transported) as these costs will initially be written off against sugarcane production and conversion. Since the sweet sorghum-based ethanol and electricity production will utilise existing sugarcane equipment, which will be idle during the sweet sorghum harvesting and conversion period, the capital costs of this equipment are not included.

High, mean and low cost estimates generated from the trial data are provided based on one standard deviation, above and below the mean. Where sufficient data were not available a ± 20% deviation was used. A mean transportation distance of 20km was used to derive feedstock transportation costs.

4.6. Modelling

An overview of the AIP is provided below and summarised in Figure 23. A more detailed diagram of the AIP is provided in Figure 31 which shows the underlying structure and linkages between the modules comprising the AIP. Section 4.6.1 gives an overview of the AIP and 4.6.2 describes the three main logical components of the AIP. Section 4.6.3 describes how the CERES-Sorghum crop module is integrated in to the AIP to provide dynamic sweet sorghum productivity estimates. Section 4.6.4 explains how the graphical user interface (GUI) can be used by the user to interact with the AIP and perform practical calculations. The underlying data management system is also described. Two spreadsheet based models were also produced by the author to model energy flows within Triangle mill and the economics of ethanol production as part of the analysis of the previous sections and will not be described further here.

4.6.1. The Agrosystems Integration Package (AIP)

Within the Agrosystems Integration Package (AIP) the bioenergy chain has been divided into three logical areas as shown below and in Figure 23.

I. **Resources**

Resources are defined under a data management "Resource module" which stores and maintains the databases, providing the data needed for both CERES-Sorghum and the rest of the AIP.

II **CERES-Sorghum** (Crop Production)

A modified CERES-Sorghum model is used to provide temporal and productivity data. This data then provides the basis for all other resource and energy production calculations within the AIP. The INRA-modified CERES-Sorghum provides the capability to calculate the yield of a specific sweet sorghum variety if planted on a given date and site. It therefore allows a user to carry out and optimise crop scheduling and logistical calculations depending on the yield and the timing of crop maturity.

III **The AIP Shell**

Provides the 'User-Interface' and calculates estimated electricity and ethanol production and costs based on crop productivity data from CERES-Sorghum.

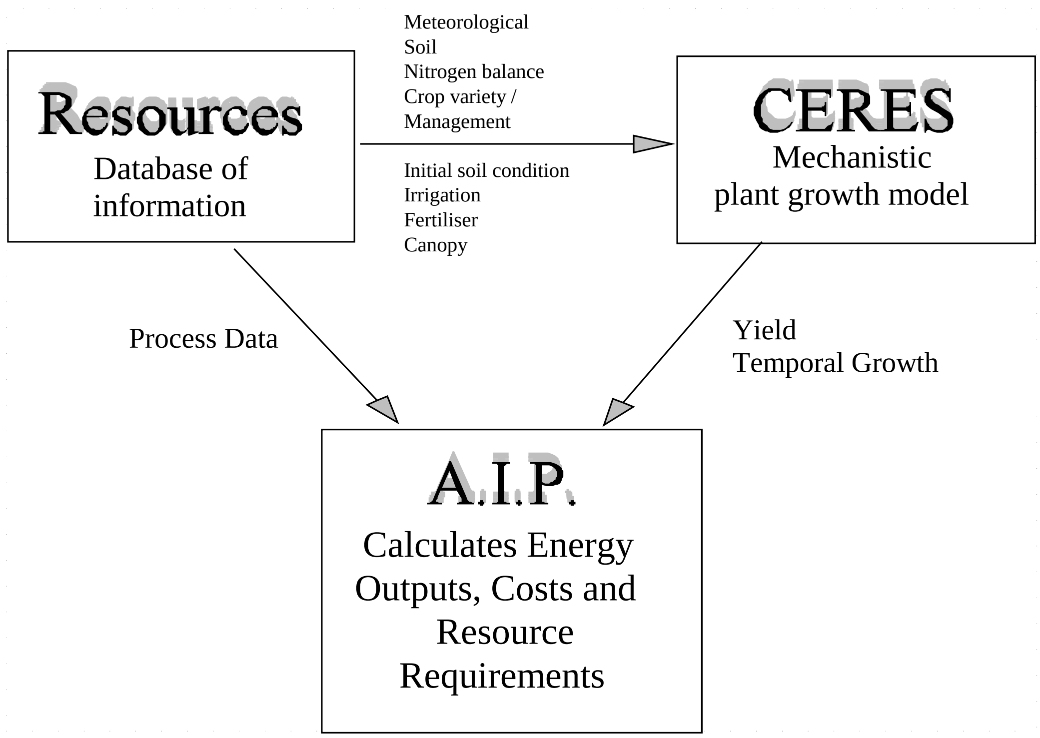


Fig. 23 AIP Overview.

Future AIP development will include the ability to request specific quantities of ethanol and electricity production and the AIP will calculate likely land requirements and optimal planting dates and variety selection.

4.6.2. System Functions

The three modules which are responsible for data management within the AIP i.e. the resources, soil and weather modules, are outlined below.

4.6.2.1. The Resources Module

This module stores and manages the data required to perform an AIP calculation. The Resource Module is divided into eleven sub-modules which represent the individual process steps comprising a complete agro-industrial process to be modelled in the AIP. Each sub-module includes technical and economic parameters, process rates, conversion efficiencies and resource requirements. These sub-modules are:

< crop variety
< harvesting
< loading
< transport
< unloading
< milling or crushing
< juice extraction
< process energy
< manpower skills
< soils
< weather

The sub-module databases are maintained in a Microsoft Access file, ‘Sorghum.mdb’, where the data is organised and stored for use by the AIP. Because of the complexity and diversity of soils, and the existence of the DSSAT soils database which is compatible with CERES, the soil data is stored and manipulated within its own database called ‘soils.mdb’. Other database tables for plant residue, stillage, and biogas production will be required in the full AIP package and are not yet present in this version of the AIP. During a calculation the AIP interrogates these sub-module databases in order to obtain the data necessary for estimating the various outputs of the energy system.

This database construction is designed to reflect a real world simulation of an entire agro-industrial process e.g. the production of fuel ethanol from sweet sorghum by Triangle Ltd., Zimbabwe. It is also designed to enable the simple introduction of novel technologies or new process techniques at any stage of the energy chain. Should new technologies, or modified conventional technologies, be required within the AIP in order to carry out sensitivity analysis, this can be done by modifying existing sub-modules or by defining an entirely new module if necessary. For example, a gasifier / gas turbine system could be introduced instead of, or in conjunction with, the existing conventional steam raising combustion facilities as described in section 2.3.2.1 and 4.4.1.5.

Most of the above sub-modules are needed for the AIP process calculation shown in section 4.6.4.3. However, the soil and weather sub-modules are specifically required by the CERES-Sorghum module. Because of their unique roles they are described in more detail below.

4.6.2.2. The Soil Sub-Module

Soil data were input and managed so that site specific soil types are available for selection by CERES-Sorghum as shown in Figure 24. Each soil type must be described in 5 or 10 centimetre layers. Each layer is described by characteristics such as soil moisture, water holding capacity, sandiness, acidity, available nitrogen content, soil organic matter content, etc., which are necessary for accurate CERES plant productivity estimates. The overall slope and stoniness are also required inputs, being important for estimating surface drainage and evaporative potential.

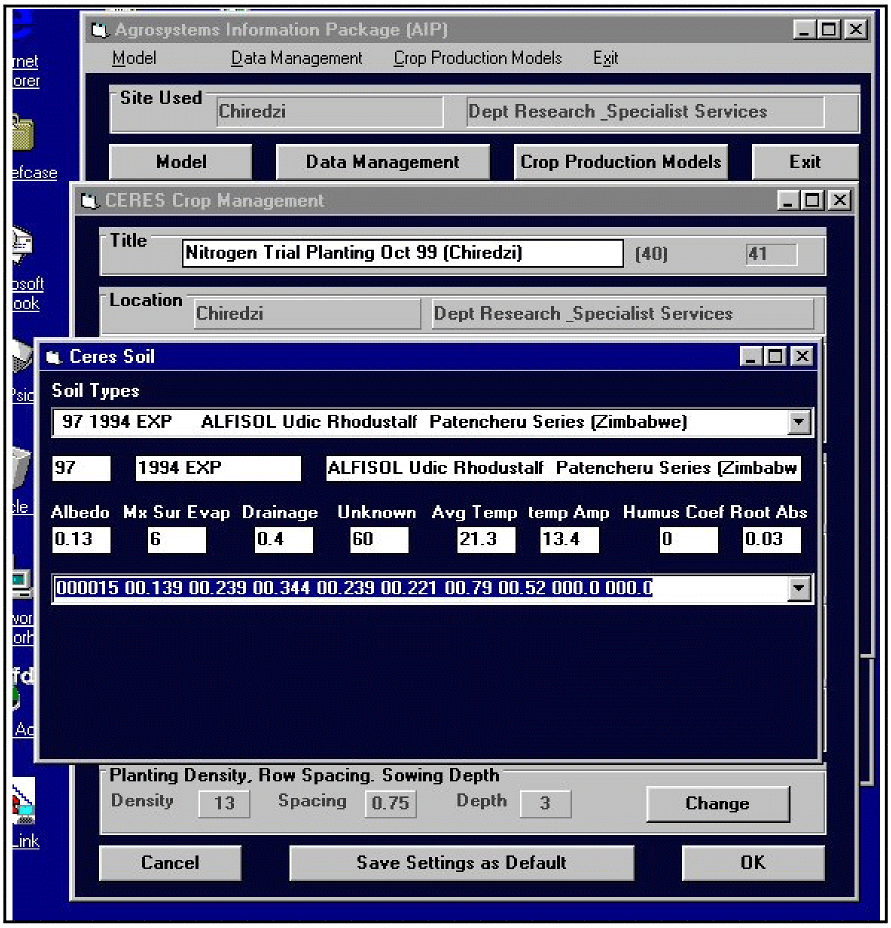


Fig. 24 Selecting Soil Types in the AIP

4.6.2.3. The Weather Sub-Module

Site specific weather data sets are required for CERES-Sorghum. Data set runs of at least one growth season are necessary. However, multi-year data sets allow predictions of likely variability of yields due to natural variation in climate. Daily weather data required by CERES are: i) Max and Min temperatures, ii) Global radiation, and iii) rainfall. These data are required in a specific format which can be achieved by utilising the weather data routines in the AIP (integrated from hourly data).

A five year continuous weather data set obtained from the CRS automatic weather station was manipulated with the AIP and is now present in the AIP weather database for use in the crop growth module as described in section 4.6.3)

4.6.3. The Crop Production Module

The role of the crop production model is very different for the two potential uses of the AIP that is:

1) What-if scenario's where the likely range of biomass productivities for a given site are required, and
2) Optimisation, where more accurate predictions of yields will be required in order to optimise the energy production chain in terms of scale (minimising excess capacity) and timing (tighter integration with sugarcane).

In the AIP the same crop production models will be used for both the above applications. However, in the optimisation role much more attention will be required in providing the highest quality input data, including the variety-specific genetic coefficients, soil, and climate variables.

4.6.3.1. The Four Primary Functions

i) To generate the 9 site specific data input files necessary for a CERES simulation (4.6.3.2).

ii) To run the CERES-Sorghum using the above input files.

iii) To analyse the CERES-Sorghum output files and extract the productivity data required for an AIP calculation.

iv) To incorporate the CERES-Sugarcane and other potential Sorghum crop models. These models are not yet implemented within the AIP.

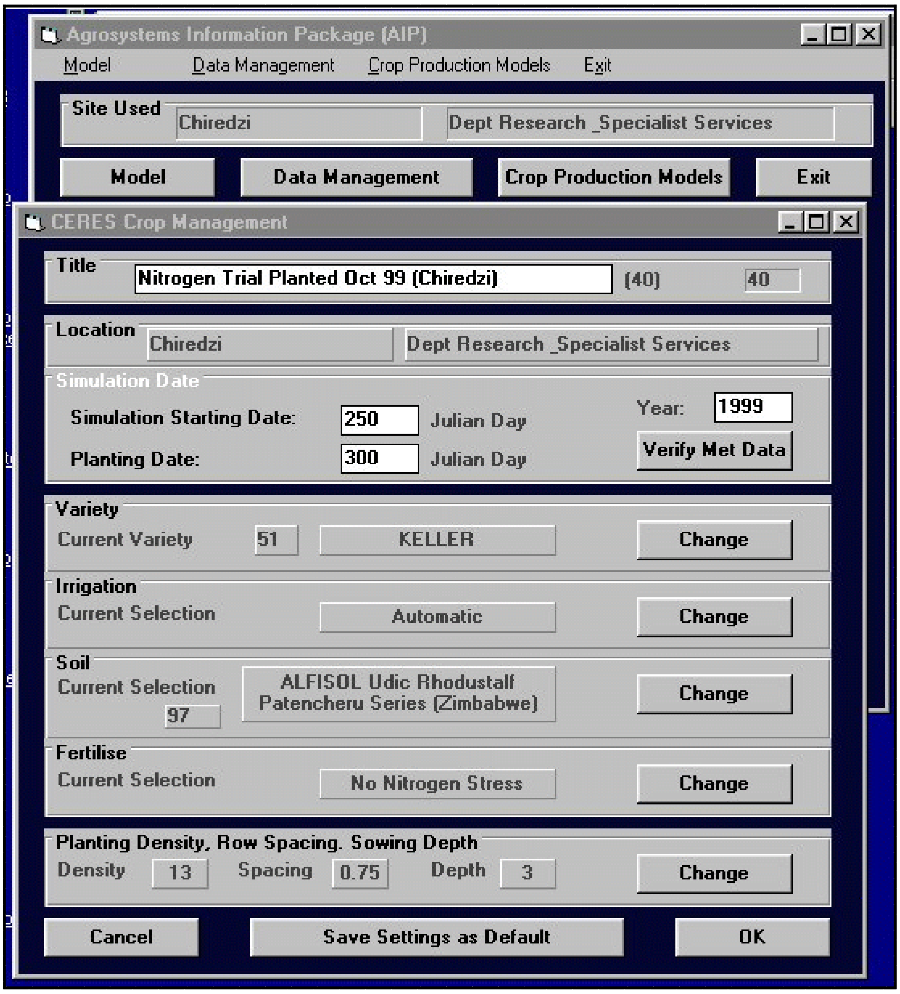


Fig. 25 Crop Management in the AIP

4.6.3.2. The CERES Input Files

< Meteorological file

< Soil file

< Nitrogen balance file

< Initial soil conditions file

<	Irrigation file
<	Fertiliser file
<	Canopy file
<	Crop variety file
<	Crop management file

A significant objective of this system is to provide an easy to use, intuitive, interface for using CERES-Sorghum, allowing easy manipulation of input data (Figure 25). Data selection for these CERES input files are derived from the Resource Module or by direct input. Also available within the AIP is the ability to archive data not immediately required for a current simulation e.g. weather and soil data for other sites / locations.

The CERES-Sorghum model can be directly managed from within the AIP (Windows) which provides the ability to carry out iterative simulations necessary for the calculations described below.

4.6.3.3. Overview of a CERES-Sorghum Crop Growth Calculation

CERES crop growth is calculated on a daily time-step which has required the use of empiricisms to integrate phenomena which occur over time periods of less than 24 hours, for example, solar radiation and the day/night cycle (section 1.5.2). Because of the complexity of this type of process-driven model where all the main physiological processes occurring during crop growth are described mathematically, only an overview will be given below.

The main routine of the CERES model is responsible for deriving crop growth parameters on a daily time-step. This routine calculates potential carbon assimilation through photosynthesis, actual C-assimilation, partitioning of the carbon, germination, rates of development i.e. ontogeny / phenology, and final yield.
Crop growth is controlled by the genetic factors listed below in response to the climate (including temperature and radiation), water and nutrient status, and management.

The CERES-Sorghum genetic factors are (Tsuji *et al.*, 1994):

P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.
P20	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P20.
P5	Thermal time (degree days above a base temperature of 8°C) from beginning grain filling (3-4 days after flowering) to physiological maturity.
G1	Scaler for relative leaf size
G2	Scaler for partitioning of assimilates to the panicle.
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

Potential carbon assimilation is calculated using a classic Montieth type approach which estimates the percentage of incoming radiation absorbed by the canopy and is therefore a function of radiation and leaf area index. Potential carbon assimilation is reduced by water and nitrogen availability amongst other factors the status of which are provided by separate sub-routines.

Leaf Growth, Canopy Establishment and Radiation Use

The relationship between leaf growth and therefore canopy establishment (as measured by the leaf area index) and radiation use is central to all Monteith-type crop models. As the leaves are the organs which contain the photosynthetic apparatus and provide the structure to hold this apparatus in the appropriate orientation to the solar radiation, they are critical to crop growth. The relationship between crop growth (dry matter accumulation) and global radiation has been exhaustively explored by Varlet-Grancher *et al.* (1989) and others, where:

$$DM = \%.3PAR_a$$

i.e. dry matter accumulation is proportional to the amount of time-integrated accumulated Photosythetically Active Radiation (PAR_a). Radiation Use Efficiency (%) under non-growth limiting conditions has been measured to be around 3.5 to 4.0 g MJ^{-1} PAR (Curt *et al.*, 1997; Dercas *et al.*, 1995, Gosse, 1995b)

$$PAR_a \quad = \quad 0_i \, . \, PAR_i$$

where $PAR_i = 0.48 \pm 0.15 \times R_g$ (Global Radiation (R_g) is total incoming solar radiation (MJ m^{-2} d^{-1})) is multiplied by the interception efficiency (0_i) of the crop calculated over the entire crop growth period (see below)

$$0_i \quad = \quad 0_{max} \, . \, (1 - e^{-K.LAI})$$

where 0_{max} is the maximum efficiency of interception (0.95), K is the extinction coefficient (measured as 0.6; (Mastrorilli *et al.*, 1995)), and LAI (leaf area index) is extrapolated to daily values from measurements.

4.6.3.4. Model Crop-Growth Validation

A comparison has been made between the above ground sweet sorghum biomass yields during the 1997/8 trials at CRS, and AIP model runs incorporating the climatic and management parameters used in the trial i.e. the planting dates and irrigation and fertilisation schedules were used in the model runs.

Climate data from the CRS automatic weather station was input to the model as were the fertilisation and irrigation data. The fertilisation parameters used in the model run incorporating nitrogen and water routines used 300 kg N equivalent because the soil nitrogen parameters were not known and were set to zero prior to planting.

The above ground dry biomass accumulation profiles are shown in Figure 26 below showing 3 model runs and the actual measure biomass accumulation from the sampling protocol. The three model runs were:

1. No nitrogen stress (nitrogen routine off, water routine on)
2. No nitrogen or water stress (both nitrogen & water routines off)
3. Nitrogen and water inputs as per trial.

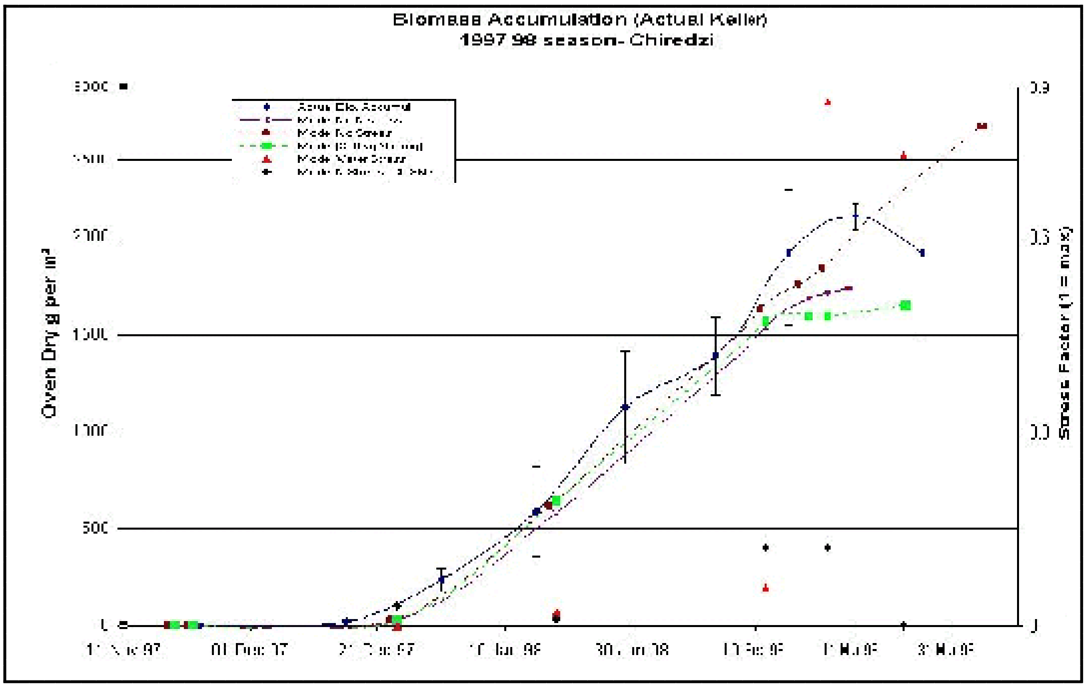


Fig. 26 Crop Model Versus Actual Biomass Accumulation

In order to test the performance of CERES-Sorghum within the AIP to ensure that the model was producing realistic yields it was necessary to:

1. Set up the model using the 1997/8 trial parameters such as, planting data, fertiliser management and irrigation
2. Ensure that the correct soil and weather data set were selected within the AIP
3. Carry out a model run to obtain the predicted biomass accumulation against time
4. Plot the model accumulated biomass against each sample data point for the 1997/8 trial.

The model run was carried out and compared with the CRS trial data and the data were plotted with the 'observed' data on the y-axis and the model-derived data on the x-axis as shown in Figure 27.

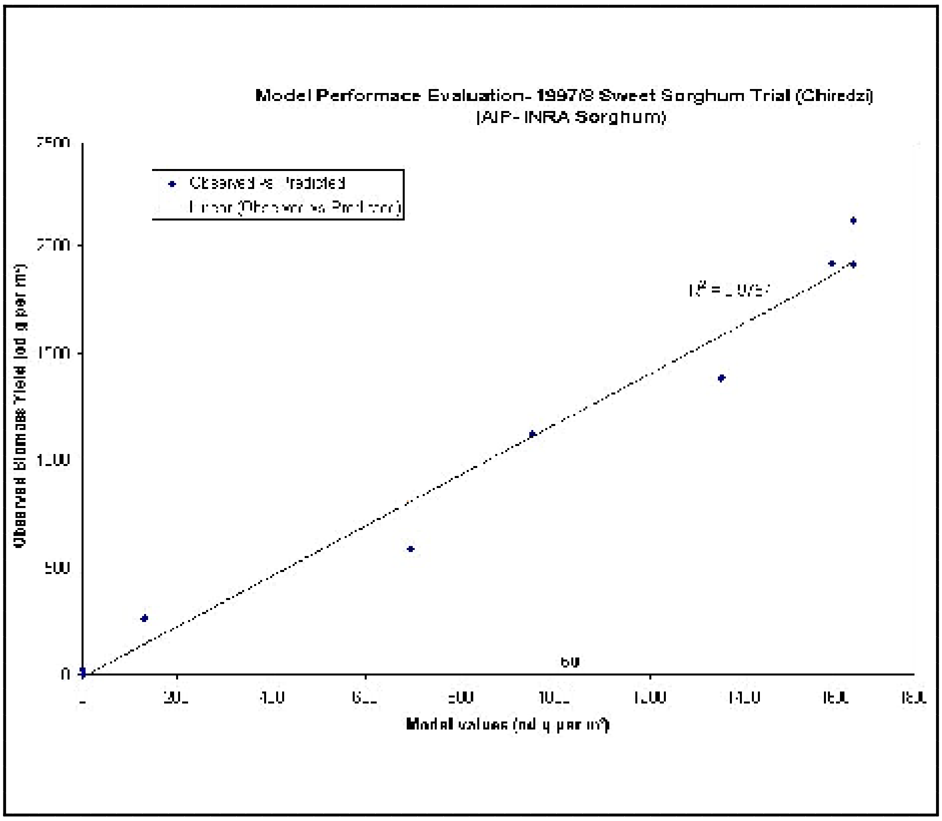


Fig. 27 Observed Versus Predicted Biomass Accumulation

Photoperiod and Thermal Time

That sweet sorghum could be grown throughout the year in southern Zimbabwe was evaluated using the AIP with the results shown in Figure 28.

The response of a crop to photoperiod and thermal time defines the seasonality of that crop. In order to evaluate the impact of changing day length on the growth of sweet sorghum, model runs were carried out at 30 day intervals between planting and the duration from planting to 'End of Grain Fill'. The model runs were continued until a complete 12 month cycle based on 1997 weather data at CRS, was completed. The above ground yield (odt) and length of growing period were noted and plotted against planting date as shown in Figure 28. The implications of photoperiod and thermal time using this analysis are discussed in section 5.8.

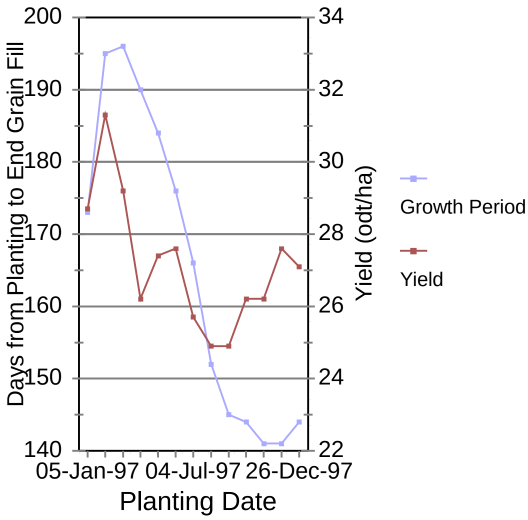


Fig. 28 Influence of Planting Date on Yield and Length of Growing Period of Sweet Sorghum

Soil Water Balance

$$dW/dt = P + I - R - D - E_s - E_p \quad \ldots\ldots\ldots\ldots \quad \text{(Bowen, 1996; Ritchie, 1995)}$$

where:

dW/dt	=	Net rate of change in stored soil water (Units- $mm^3_{H_2O}\ mm^{-2}_{ground\ area}\ d^{-1}$, i.e. $mm\ d^{-1}$)
P	=	Precipitation (during day t, $mm\ d^{-1}$)
I	=	Irrigation (during day t, $mm\ d^{-1}$)
R	=	Surface runoff (during day t, $mm\ d^{-1}$)
D	=	Drainage from bottom of soil profile (during day t, $mm\ d^{-1}$)
E_s	=	Soil evaporation (during day t, $mm\ d^{-1}$)
E_p	=	Plant Evaporation i.e. transpiration (during day t, $mm\ d^{-1}$)

The influence of plants on the soil water balance is accounted for in the calculations of soil and plant evapo-transpiration and is basically a function of soil water mass-balances (by soil layer) and LAI. Two calculations for both Plant Evaporation (transpiration) and Soil Evaporation are carried out. One calculates the maximum potential rates, and the second is a process-based calculation. If the process-based calculation exceeds the 'potential' then the potential is adopted as the 'actual' rate. This method tries to ensure that the rates of water loss conform to physical limits. According to Bowen (1996) the water balance is calculated by a routine which follows the following eight steps in sequence:

1. Potential ET is calculated using the FAO Penman methodology to give Et_o (Smith, 1992)
2. Et_o is partitioned between Potential Plant and Soil Evaporation using an exponential function (based on LAI) to give EP_o & ES_o
3. Soil limited evaporation is then calculated for each soil layer to give ES_s
4. Actual Soil evaporation is then the smallest of either ES_o or ES_s to give ES
5. Potential Plant evaporation (EP_o) is now recalculated as ET_o minus ES-EP_o revised
6. Soil-limited Root Water Uptake is now calculated to give EP_r
7. Actual Plant Water uptake (and therefore loss) is the smallest of either the revised EP_o or EP_r to give EP
8. Actual Evapotranspiration (ET) can now be calculated as: EP + ES

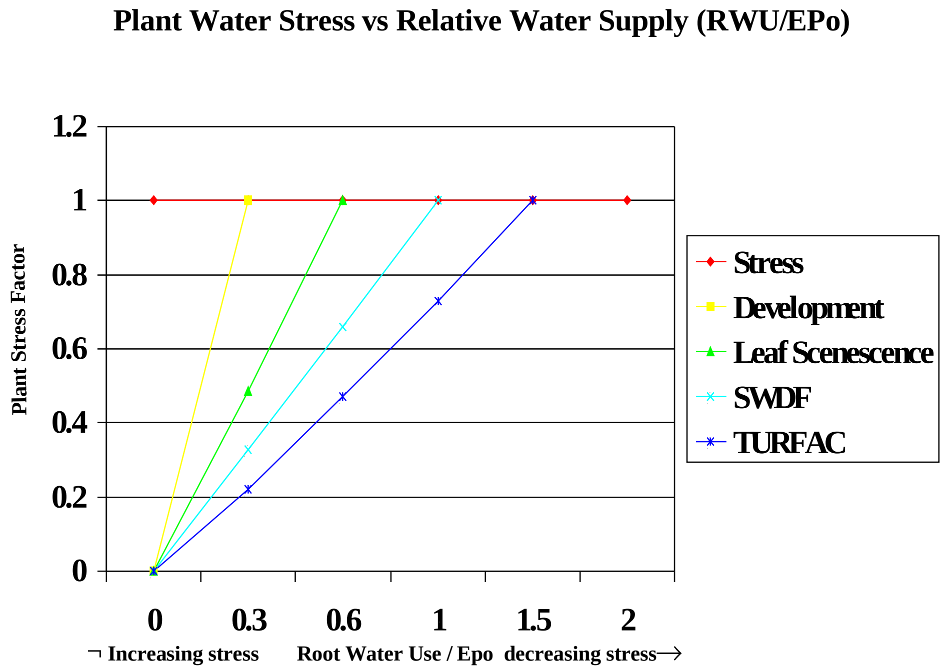
In this way the water status of the soil, and crop canopy and the relationship between the two can be accounted for i.e. shading of the soil surface by the canopy reduces soil evaporation but increases potential transpiration, whilst low water levels in the soil limit extraction by plant roots and therefore transpiration. In this way, water use / loss is controlled by the "law of the limiting" (Ritchie, 1995).

Water Stress is accounted for by specific routines which affect the physiological areas affected during plant growth (Bowen, 1996) i.e.

1. Expansive Growth
2. Stomatally-regulated processes
    a. Photosynthesis
    b. Transpiration
3. Leaf Senescence
4. Plant Development
    a. Organogenesis (including new leaf appearance)
    b. Reproductive phase development

The factor used to assess water stress is the ratio of Root Water Uptake to potential transpiration (RWU/EP_o) e.g. a value of 1 or higher for this ratio means that there is sufficient soil water. The four physiological effects listed above have varying sensitivity to the water stress ratio (RWU/EP_o) with development, leaf senescence, stomatally-regulated processes, and finally expansive growth being progressively less sensitive, respectively as shown in Figure 29.

It should be noted that RWU is itself a function of root-length density (by soil layer), the soil water balance (also by layer), and actual transpiration. As the plant stress factor decreases from 1 to 0 as a result of an increase in potential plant transpiration relative to root water uptake, the four physiologically based growth rates are multiplied by a fraction and hence decreased. Sensitivity to water stress is governed by the slope for each process (Figure 29).



Slource: Bowen (1996)

Fig. 29 CERES Plant Water Stress Factors

Soil Nitrogen Dynamics (Godwin and Jones, 1991)

Nitrogen dynamics in the soil are handled by four basic sub-routines which are described below:

a. Nitrate and Urea movement

The water soluble fractions of soil-based nitrogen (i.e. Nitrate and Urea) are allocated to each soil layer. It is then assumed that this nitrogen is evenly distributed within the water. Therefore, if 5% of the water 'drains' out of layer 'x' then 5% of the nitrate and urea is 'leached' with that water and ends up in the layer below. This lower layer may, in turn, 'lose' nitrogen through drainage, removal by roots, or immobilisation.

b. Soil N-transformations ('NTRANS' sub-routine)

Six types of transformation are handled by this routine i.e.: i) decay of organic matter, ii) mineralisation or immobilisation, iii) ammonia nitrification, iv) de-nitrification, v) additions from fertilisers, and vi) urea hydrolysis. The last two transformations are handled primarily by the next sub-routine.

c. Fertiliser addition and urea hydrolysis

The fertiliser is assumed to be uniformly distributed within the layer to which it is added i.e. if it is spread on the surface then it is assumed to be evenly distributed within the top layer. The nitrogen is then partitioned to nitrate, ammonia and urea pools, where it is then available to sub-routines 1, 2, and 4.

d. Mineralisation and Immobilisation

In this routine the net release of mineral nitrogen resulting from the decay of organic matter and immobilisation resulting from transformation to organic matter are calculated. These processes are highly dependent on the C/N ratio, moisture content, and temperature of the soil. Soil organic matter is divided into two pools, i) the fast decaying 'Fresh Organic Matter' pool which is in turn sub-divided into three pools i.e. carbohydrate, cellulose and lignin are assigned different decay rates, and ii) the more slowly decaying 'Humus' pool.

Crop Nitrogen Uptake. (Godwin and Jones, 1991) Crop nitrogen uptake is controlled in a similar way to crop water use in that the 'law of the limiting' applies. (Godwin and Jones, 1991). For nitrogen, potential crop demand and soil availability are calculated separately and the lower of the two is then used i.e. nitrogen uptake cannot exceed the soils capacity to supply it, nor can uptake exceed the plants capacity to use it. Demand and supply are controlled by mathematical relationships which are defined by factors such as the critical nitrogen concentration for tops (TCNP) and the actual N concentration for tops (TANC), the water and nitrogen status of the soil, root development, temperature (soil and air), etc.

4.6.4. The AIP User-Interface and Shell

The AIP orchestrates the management and data flow between the modules and sub-modules needed to carry out a simulation of potential energy production from sweet sorghum and its likely impacts and resource requirements. The three main sections to this module are described below.

4.6.4.1. Default settings

Default selections for the Process Modules are stored together with other important system variables. These are loaded automatically each time the AIP system is started. These default values are used to provide the initial settings in each of the Process Modules which can then be manipulated to describe other locations and technologies. The default settings are currently based on the existing set of technologies and management procedures used by Triangle Ltd., and define, for example, harvesting type (manual), transport type (hilo), crushing, combustion, etc.

4.6.4.2. Process Modules

Default values based on Triangle Ltd. provide the base case conditions of a calculation and are loaded into the process modules at startup. Other conventional or novel process types are available for selection as required; alternatively, the technical parameters which describe each process can be altered from within the AIP.

The Process Modules are:

< Crop Variety
< Harvesting
< Loading
< Transport
< Unloading
< Storage
< Crushing Type
< Juice Extraction
< Process Energy
< Fermentation
< Electricity production

Any of the parameters may be changed for a calculation without changing the stored data, allowing the likely impacts of the introduction of new technologies or techniques to be assessed.

Crop Varieties

Four sweet sorghum and one fibre varieties are stored within the AIP. The variety specific data includes, genetic factors as outlined in section 4.6.3.3, and biomass quality factors. The biomass quality factors include: i) the share of above ground biomass comprising, stem mass, seeds (panicle) and leaves, ii) sugars (of which sucrose), iii) fibre, and iv) moisture content. These biomass quality factors are derived from the work outlined in section 4.2.2.1.

Harvesting

Parameters describing manual and mechanical harvesting are stored within the resources database of the AIP. These factors include, harvesting rate, capital cost of equipment, fuel consumption rates, fuel type, manpower requirements, and equipment manufacturer and model.

Loading, Transport and Unloading

Data derived from section 4.3. including transport type and resource use factors as shown in ‘Harvesting’ above.

Storage

Not yet implemented

Crushing Type

Diffusion or Mill-Tandem, as described in section 4.3.

Process Energy

Figure 30 shows the data input screen for the 'Energy Conversion' module in the Resources section. Three separate fuel types can be defined and the conversion efficiency with which they are converted to steam can also be defined by fuel type. In Figure 30, the 'Standard' conversion system is defined which was based on Triangle Ltd.'s boilers as described in section 4.4.1.1. Other 'Conversion Systems' can be defined and added to the database, including gasification systems.

Fermentation and Electricity

These two modules are currently implemented within the 'Calculation' module's base code with the parameters based on section 4.4.1.1. and 4.6.4.3.

4.6.4.3. Calculation

An AIP calculation is carried out by:

i. Selecting modules from the various process modules available in the resource module.

ii. Running CERES-Sorghum using input files generated from the Resource module. CERES outputs time-specific growth and yield data.

iii. Altering specific values for each of the Process Modules if a user wants to change default values.

iv. Typing in the land area available for sweet sorghum growth.

As described above, a calculation is triggered by setting the available land and transport distance variables in the Calculation Module.

After the land available and transport distances are put in, the final calculations are automatically carried out giving estimates of yields, ethanol, biogas and electricity production and costs, together with mass balances, energy ratios and resource requirements. The AIP calculation results may be reviewed as text or graphically, and may be printed. Also, the results will be available in a form suitable for transfer to a spreadsheet. An example of the calculation dialog box (screen) is given in section 5.5, Figure 33.

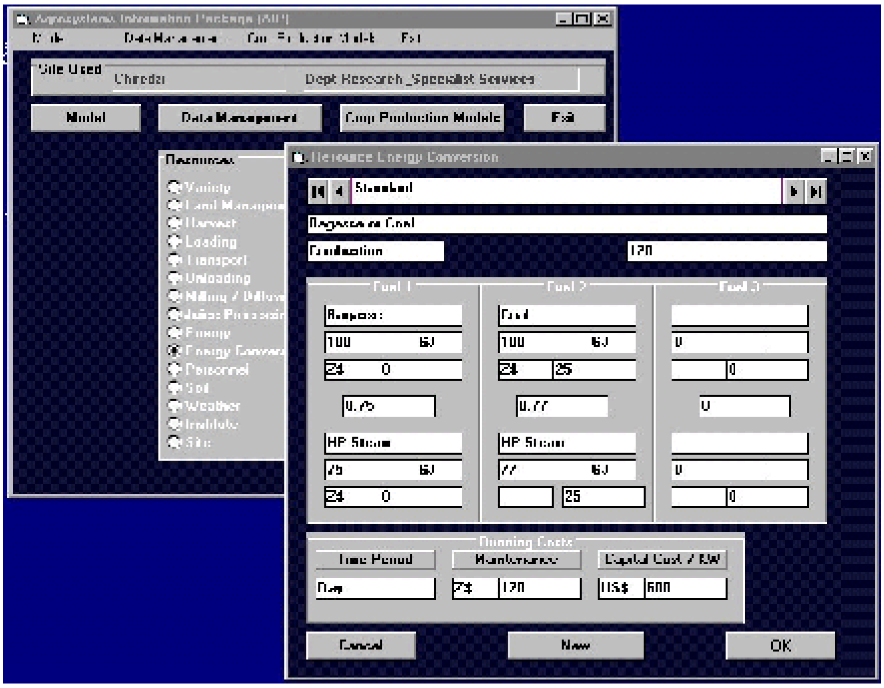


Fig. 30 AIP Steam Production Module: 'Standard Configuration'

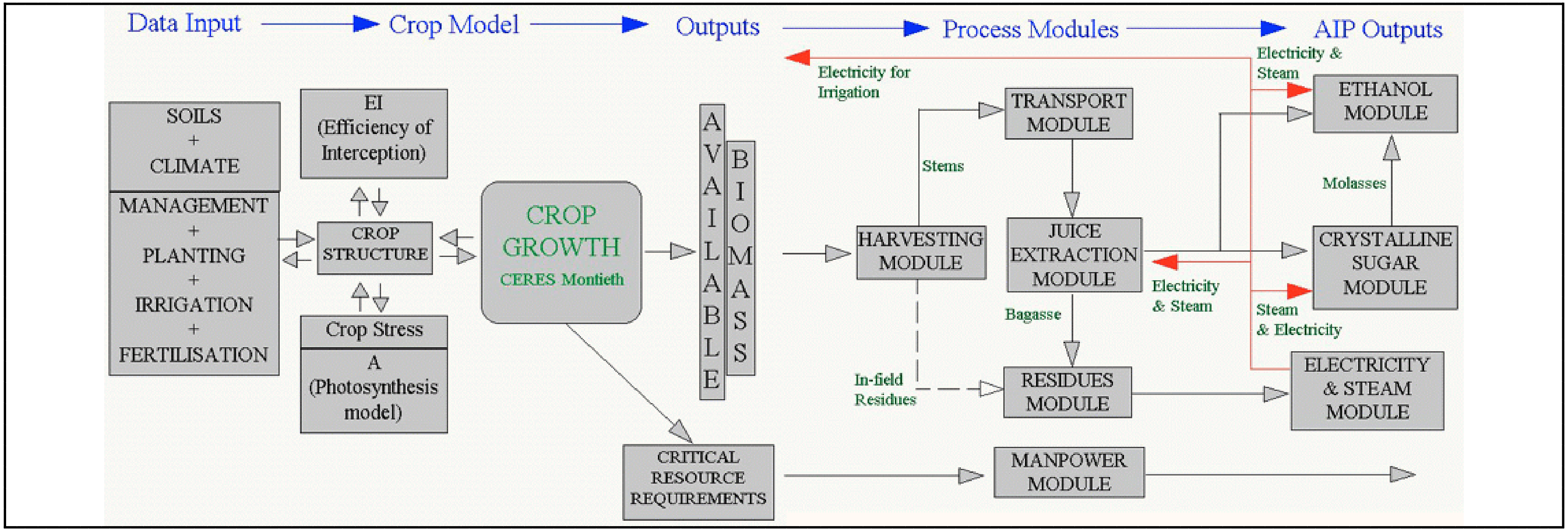


Fig. 31 Flow Diagram For Complete Process Chain