3. MATERIALS & METHODS

In order to evaluate the potential for the integration of sweet sorghum with sugarcane for the year-round production of biofuels, the author has drawn on the results derived from four research projects running from 1993 to the present. Data has also been obtained from published literature and personal communication with experts in both the private and research communities. During the process of the research for this thesis it has also been necessary to define the system parameters, as outlined in section 4.1., within which this work has been conducted. However, many of the results are applicable to a more broadly defined system e.g. the inclusion of other crop types in addition to sweet sorghum and sugarcane and or the systems replication in other geographic locations. Finally, using the methodology outlined below novel technologies will also be able to be evaluated in terms of their potential to optimise or expand the production of biofuels.

3.1. Agronomic Data

Small scale agronomic trials to monitor the productive potential of sweet sorghum have been planted at three locations in Zimbabwe. The location where the bulk of the research and monitoring is carried out is the Zimbabwe government owned Lowveld Research Station, locally called Chiredzi Research Station (CRS) based 10 km outside the town of Chiredzi and 15 km from the Triangle sugar mill in the Lowveld region of SE Zimbabwe. Trials were also planted in the sugarcane fields of Triangle Ltd., and in agricultural research area of the Science and Industry Research and Development Centre (SIRDC) located in the Highveld region of Zimbabwe, 15 km to the north of Harare. Low yields and problems with pests and water-logging experienced with this site which was only recently (1997) cleared for agriculture have meant that the data obtained to date is highly variable and may not be characteristic of the 'Highveld' area it is supposed to represent. Because of these problems the results from this site are not evaluated here.

The main aim of these trials was to follow the primary production parameters for sweet sorghum growth through complete growth cycles to allow an accurate definition of variety specific yields and growth periods. Where possible the data generated by the trials has been compared with other sweet sorghum productivities from around the world.

Chiredzi Research Station (CRS): 21ES 31EE. Three fields, separated by not more than 1 km, were used for sweet sorghum growth and monitoring at CRS. These are the Drip Section, F- Section, and S- Section fields, with the F- and S- Section fields being primarily used for seed bulking and biomass production for the crushing trials at Triangle Mill and are both sprinkler irrigated. The soils on the station are classified as Red Sandy Loam but do vary across the station, primarily in sandiness.

A total of 7.3 ha of land was planted with sweet sorghum during the months of November and December 1998 as shown in Table 3.1. Of this land 2.2 ha was planted with a combination of cv.s Keller and Cowley in the drip irrigated section at Chiredzi Research Station where water inputs can be precisely monitored using a water flow meter mounted immediately after the pump supplying the drip system. Some blocks of the drip section have now been planted with sweet sorghum at least once, and occasionally twice, a year since 1995 when the drip system was installed. Problems arising from the virtually continuous growth of sweet sorghum in one area over a number of years are now becoming apparent, such as the build up of pests and diseases, and it is clear that growth is not optimal in these blocks. Whilst the data derived from these blocks has not been discarded it has been treated with caution, and a break crop will be planted this year.

Triangle: 21ES 31EE (400 m above sea level) In order to ensure there will be no unforeseen problems with planting sweet sorghum on land which has been used for sugarcane production, 2 ha of ex-sugarcane fields were also planted with the sweet sorghum variety cv. Keller. Two separate 1 ha fields were chosen which were due to be replanted with sugarcane in December 1998. One of these fields is furrow irrigated (section 62) and the other sprinkler irrigated (section 26). The sugarcane fields immediately surrounding these fields were planted with sugarcane at the same time as the sweet sorghum seeding occurred enabling a visual comparison of growth rates between the sweet sorghum and sugarcane. The sweet sorghum in these fields was irrigated using the existing sugarcane irrigation protocol for 'Plant' cane (newly planted sugarcane).

Growth monitoring on these fields was not as intensive as the monitoring at CRS for logistical reasons i.e. proximity to lab facilities with accurate scales and oven drying equipment. The fields were regularly monitored for pests and diseases and control measures taken when necessary. A rainfall gauge was installed in both these fields so that rainfall could be measured individually as the fields are approximately 20 km apart. The soils on both fields are sandy loams but the section 62 field was considerably more stony and the soil depth more variable.

3.1.1. Trial Protocol

The trial protocol for the 1998/9 season at CRS is given below which was similar to the 1997/8 season. Therefore, the 1998/9 data can be regarded as directly comparable with the 1997/8 data. The aim of the sampling procedure was to sample sufficient sorghum biomass at regular intervals to provide an accurate estimate of the standing biomass at any given time during the crop growth time course. The sampling procedure was developed to predict dry and fresh mass accumulation by the primary plant organs i.e. stem, leaves, and panicle allowing the final destination of the assimilated carbon to be followed during each stage of crop growth. The leaf area was also measured during each sample so that the leaf area index (LAI) could also be calculated throughout the crop growth cycle.

The objectives of this trial were:

< establish correct planting dates

< verify (ascertain) period of high sugars and monitor rate of biomass accumulation, with the ultimate goal of determining accurate harvesting dates,

which could then be used by future growers as a guide to achieving maximum yields.

A total of 0.2ha was also devoted to a rainfed trial.

3.1.1.1. CRS Trial Experimental Layout and Management

For the 1998/9 season experiment, each block (100m x 18m) was subdivided into 12 plots (18m x 8m), with the two outmost plots being used as border plots and therefore not sampled. Drip Block 1 was planted entirely with Keller and used for seed bulking only, as its proximity to an irrigation reservoir was believed to bring the water table on the edge of the plot closest to the reservoir to about 0.5m beneath the soil surface. Drip Block 8, also planted solely with Keller, was used for a rainfed-only experiment.

Three central drip blocks were used to assess the impact of different planting dates. In order to achieve 5 replicates for each of the three planting dates and two varieties, a total of 30 plots (5x3x2) on 3 blocks were planted with Keller and Cowley:

< Inter-row spacing 0.75m; Intra-row spacing 0.1m .

< The three blocks were planted on 3 different dates as follows: 24/Nov/98, 4/Dec/98, and 14/Dec/98.

The remaining blocks were planted for seed bulking and to provide stem biomass for the diffuser test on 18th March 1999. (See below) A 2m section of one row was used for each sampling, with a total of two samples per row possible in a plot. With a sampling rate of once every two weeks and a total trial duration of 5.5 months, a total of 24 samples per variety were required, using 11 rows per plot. Between row spacing was 0.75m therefore the total width of the plot (minus the buffer rows each side) was 8.25m. The total block width, including buffer rows, was 12m.
Length of each row (within a plot) was 8m consisting of:

C 2m x 2 samplings = 4m

C 2m between the samplings = 2m

C 1m x 2 either end = 2m

Drip Block Layout: 14 blocks (blocks1 to 6- 18m x 130m, blocks 7 to 14- 18 x 100m)

Plot	1	2	3	4	5	6	7	8	9	10
Block	<				130m					>
1	K	K	K	K	K	K	K	K	K	K
2	L1	L2	L1	L2	L1	L2	L1	L2	L1	L2
3	K	K	K	K	K	K	K	K	K	K
4	K	K	K	K	K	K	K	K	K	K
5	K	K	K	R	K	I	K	M	K	C
6	K	M	K	I	K	C	K	R	K	K
7	K	M	K	K	K	I	K	C	K	R
8	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}	K_{rf}
9 to 14	K	K	K	K	K	K	K	K	K	K

Key: K=Keller, K_{rf} = Keller (rainfed), L1&2 = Li Dajue 1 & 2, R = Rona H, I = IS19674, C = Cowley, M = Monero Edes

Seed Requirements

The average seed weight between varieties is variable. However, experience has shown with Keller, for example, with an average seed weight of 20 mg seed^{-1} requires approximately 10 kg seed per hectare if planting is carried out by hand i.e. standard inter and intra row-spacing of 0.75m and 0.1m, respectively. Seeding using a mechanical planter would reduce the seeding requirements to less than 5 kg ha^{-1} as a result of the precise positioning and number of seeds applied per planting point.

Tillage

Includes mechanical and manual operations which disturb the soil including, ploughing, discing and hoeing. Also included are the requirements for the carriage of fertiliser to and within the fields, manual weeding, bird scaring and the application of pesticides. The methodology outlined below in monitoring the sweet sorghum trials at CRS has provided much of the data required to evaluate the inputs required for the tillage of sweet sorghum as shown in section 4.3.2.1.

Land Preparation

Land preparation started in early September 1998. A total of 7ha (2ha more than the 97/98 trial) were ploughed and then disced. Row marking was carried out using a spring cultivator with tines spaced at 0.75m.

During the 1999 dry season, trials were carried out with a tractor drawn Massey Ferguson mechanical seed drill to evaluate mechanical planting techniques for establishing large areas of sweet sorghum on sugarcane fields. Preliminary results show that this may be a more efficient method of planting than manual techniques, as row-marking, seed application and covering with soil are all carried out in one operation. In addition, seeds are only planted at the desired intra-row spacing and inter-row spacing and at a consistent depth. Observations during these preliminary tests indicated very good germination rates. Under field conditions the drill is expected to plant between 0.5 and 0.7 ha h^{-1} according to Nyabanga (1999).

Fertiliser & Pesticide Application

Both fertiliser applications were applied in bands by hand as a surface application. Nitrogen applications totalled 100kg N ha^{-1}. Compound D (7:14:8 N: P_2O_5: K_2O), a granular fertiliser with minimum Sulphur content of 6.5%, was applied as a side-band at a rate of 300kg ha^{-1} during the seeding operation.

Ammonium Nitrate (34.5% N, granular) was applied once, six weeks after germination, at a rate of 100 kg AN ha^{-1} as a top dressing.

Quantities of N (nitrogen), P_20_5 (phosphate), K_2O (potash) were recorded (section 4.2.3.1). As application rates are generally given as kg of the compound i.e. P_20_5, K_2O and not kg of the element, where necessary, fertiliser applications were converted by:

- phosphate to P is carried out by dividing by 2.3.
- potash to K by dividing by 1.2.

Pesticides were applied as necessary to control pests and diseases. Regular scouting took place in the fields to check for the incidence of dangerous pests and diseases. Intervention thresholds exist for pests and diseases and once the pest or disease builds up to the threshold this triggers intervention by chemical application, weeding, or other control measure. Control measures taken were noted and recorded.

Seed Bulking

A total of 2ha was planted on 12/Dec/98 exclusively for seed bulking. The inter-row spacing of 0.75m and intra-row spacing 0.1m used in the rest of the trial was maintained.

Water Use Efficiency

Above ground biomass accumulation was compared to total water supply i.e. rainfall and irrigation. Irrigation was measured using a water flow metre and averaged to the total application by the area covered.

In order to ascertain if the WUE for sweet sorghum calculated by the water use data gathered from the CRS trials was consistent with other sweet sorghum trials carried out around the world, a comparison was made between the calculated CRS WUE and WUE's quoted in the literature. Figure 18 shows this data plotted as growth response (yield) versus water supply for each of the sweet sorghum trial locations. Regression analysis was carried out using a simple linear regression model (Sigma Plot) and using Curve Expert ver 1.3 (Hyams, 1997) to evaluate if non-linear regression models more accurately fitted the data. The results from this analysis are shown in section 4.2.4.1.

The energy requirements for the irrigation of sweet sorghum (Table 4.14) and sugarcane (Table 4.13) were calculated and are shown in section 4.2.4.2. and are based on the methodology of Slogget (1992).

Sugarcane irrigation requirements were calculated by using the average water consumption for Triangle Ltd. sugarcane estates (Shepherd, 1998).

3.1.1.2. Growth Analysis

Fresh weight sampling was carried out every two weeks using a Waymaster 1125K (100kg ±0.1kg) and Tanita BSE-860 (5kg ± 0.1g) set of scales. Dry weight samples were taken after every two weeks for the first two months and thereafter monthly.

Growth analysis was carried out on exactly 2m of one row per sample with the first metre being used to provide total above ground fresh weight data. The plants removed from the second metre were partitioned into leaves, stems, and panicles (seeds & tops) and sub-samples were dried in an oven at 80EC for three days. The leaves from the 2ndm were measured using a DELTA –T digital leaf area metre before being dried to give oven dry measurements.

Parameters measured on these plots included; leaf area index on partitioned plants, plant height, fresh weight and dry weight. Root length measurements for Keller were also carried out during the 1998/9 trial. This was carried out in order to establish the root zone at each growth stage required for determining irrigation schedules. In previous trials literature-based estimates of root zones for grain sorghum were used to calculate irrigation schedules. The data derived from the growth analysis evaluation is shown in section 4.2.2.

3.1.1.3. Sugar Analysis

This commenced at booting[12] stage with samples taken weekly after that.
Samples were analysed at the Zimbabwe Sugar Association (ZSA) laboratories for industry standard sugar measurement parameters including BRIX, Pol, reducing sugars (RS), fibre and moisture contents as percent extract and percent fresh weight stems (by weight; see Glossary). During the crushing period samples were also analysed at Triangle Ltd. Laboratories. The results from the sugar analysis monitoring are evaluated in section 4.2.2.1. and figure 15.

The stems of approximately 20 plants per variety per sample were analysed for sugars. Sugar measurements are carried out on the juice extracted from the stems using small-scale crushers which are designed to mimic the full-scale crushing process. As a result of this methodology, all sugar data reported, with exception of ‘PI’ (section 3.3.1.1) is a measurement of ‘extractable’ and NOT total stem sugar content.

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12 ‘Booting’ is the initial growth of the reproductive bodies marked by a swelling at the top of the stem and occurs after about 2 months growth. See Abbreviations.

Light Use Efficiency

Global radiation (Rg) data was collected from the Automatic Weather Station (AWS) at CRS for the growth period of the 1998/9 sweet sorghum trial. Above ground biomass accumulation and measured leaf area index (LAI) were also collected using the same protocol as Section 3.1.1. Absorbed PAR was calculated after Varlet-Grancher *et al.* (1989) and Mastrorilli *et al.* (1995).

3.1.2. Sweet Sorghum Harvesting

On the 17th March 1999 at 07:00 sweet sorghum harvesting commenced by-hand on all sections at CRS and on Sections 26 and 62 at Triangle Ltd. (Figure 7) The harvesting was carried out manually by Triangle Ltd.'s sugarcane cutters using standard sugarcane harvesting equipment and practices. Because the harvesting period for sweet sorghum is optimum when the sorghum still has green leaves, they must be removed, in this case manually, before transport to the mill. During the rainy season i.e. during the first weeks of the sugarcane harvesting the sugarcane is often too wet to burn and it is common practice to remove sugarcane leaves manually.

Fig. 7 Harvesting and Carrying Sweet Sorghum (CRS, March 1999- J.Woods)

A second problem associated with harvesting during the end of the rainy season is that the soil may be too wet to allow any machinery in-field. Therefore, all the sorghum stems must be manually carried to the field edge where they are stacked into bundles for collection and loading onto the main transport equipment (truck or Hilo) by a mobile crane. This requirement adds to both the labour and equipment required per delivered tonne of stems.

Detailed records of labour and diesel use were taken by Triangle Ltd. for billing purposes and these records have been used in assessing the resource requirements for harvesting. For example see Table 4.15.

A total of 7.3ha of sweet sorghum was harvested on 17th March for delivery and processing by the diffuser on 18th March. This harvested area comprised the bulk of the land area planted with Sweet Sorghum (predominantly cv. Keller) during November and December 1998. Details of the areas used are provided in Table 3.1.

Table 3.1: Areas Harvested for Diffuser Test (March 1999)

Field ID.	Irrig. Type	Date Planted	Field Dimensions (m)	No. Fields	Total Area (ha)
CRS					
Blocks 1 to 8	drip	26/11/98	18 x 101	8	1.45
Blocks 11 to 14	drip	26/11/98	98 x 18	4	0.73
Sprinkler Section	sprinkler	02/12/98	97 x 92	5	1.35
F3		11/12/98	97 x 92	1	0.89
F4		12/12/98	97 x 92	1	0.89
Triangle Ltd.					
Section 26	sprinkler	27/11/98	100 x 100	1	1
Section 62	furrow	28/11/98	100 x 100	1	1
Total					**7.32**

An evaluation of the comparative ease or difficulty in harvesting sweet sorghum versus sugarcane was carried out by questionnaire which was given to the cutters and carriers immediately after finishing their shifts. A summary of the results of this questionnaire are given in Section 4.3.1.

In order to assess labour and fuel requirements for harvesting, Triangle Ltd. billing data (used for billing customers and internal auditing) has been used. The invoice itemised labour requirements by shift and category, and when combined with the recorded delivery of sorghum stems at the weighbridge, have been used to calculate indices such as labour requirements per tonne stems or per ha (Table II.9 and Section 4.3.1).

Biomass Harvest Index

Harvesting samples were taken during the main harvesting period using 4 separate cane cutters, three of whom were at separate fields on CRS. When approached, the cutters were asked to harvest the next 1m of sweet sorghum row and instead of discarding the tops and leaves and stacking the stems, they were collected and tagged as: i) tops, ii) leaves, and iii) stems, with the location and time of harvesting noted.

After collection, the four samples were weighed using electronic scales. The fresh weight mass of the tops, leaves and stems were recorded with the location of harvesting. From this data the percentage of total sample biomass comprised of tops, leaves, and stems was calculated and recorded in tabular form (Table 4.16). The total number of plants for each sample was not recorded. Dry mass measurements were not taken as the oven was unavailable. See section 4.3.1.2. for results.

3.2. Loading, Transport & Unloading

The results derived from the observations carried out during the loading, transport and unloading of the sweet sorghum during the 1998/9 sweet sorghum trial are shown in section 4.3.2. Triangle Ltd.'s standard sugarcane loading, transport and unloading procedures were used to deliver the sweet sorghum stems to the mill. This involved stacking the sweet sorghum stems into bundles weighing between 1.5 and 5.0 t. Two heavy metal chains were then secured around each bundle in such a way that the picking up and manoeuvring of the bundles could be carried out using tractor driven cranes as shown in Figures 8 & 9.

Once the chains are secured around the bundles, they are collected from the field edge by a specialised tractor mounted crane/trailer system called 'perry loaders' (Figure 8) and taken to a hard standing area where the bundles can be marshalled and loaded onto the main transport equipment for delivery to the mill using specialised loading equipment. At CRS, a 'Prof' crane (Figure 9) was used to load the bundles onto a 30 t (approximately 10-15 bundles per load) flat-bed truck for the 16 km journey to the mill.

Fig. 8 Transport of In-field Bundles by Perry Loaders to Loading Area (CRS, March 1999- J.Woods)

Normally, these trucks are only used for transporting firewood. However, the need to use public roads to deliver the sorghum stems meant that only licenced vehicles could be used.

Fig. 9 Loading of Bundles Onto Flat-bed Truck by A Prof Crane (CRS, 1999- J.Woods)

3.3. Mill Conversion Data

In this section the materials and methodology used to evaluate the potential for the processing of sweet sorghum using the existing equipment and management practices of the Triangle Ltd. mill are described. Where novel or new equipment or management practices are relevant the methodology used to evaluate their potential introduction is also described.

3.3.1. Juice and Fibre Separation

As part of the sweet sorghum trials carried out in CRS and Triangle over the 1997/8 and 1998/9 seasons, large samples of sweet sorghum stems were harvested and delivered to Triangle Mill for processing. Because of the small-scale nature of these trials it has not been possible to deliver sufficient quantities of sweet sorghum stems to the mill to evaluate the entire ethanol, electricity and crystalline sugar production processes, but where possible laboratory tests were carried out to evaluate the potential for full-scale processing when insufficient sorghum derived material was available for full-scale tests.

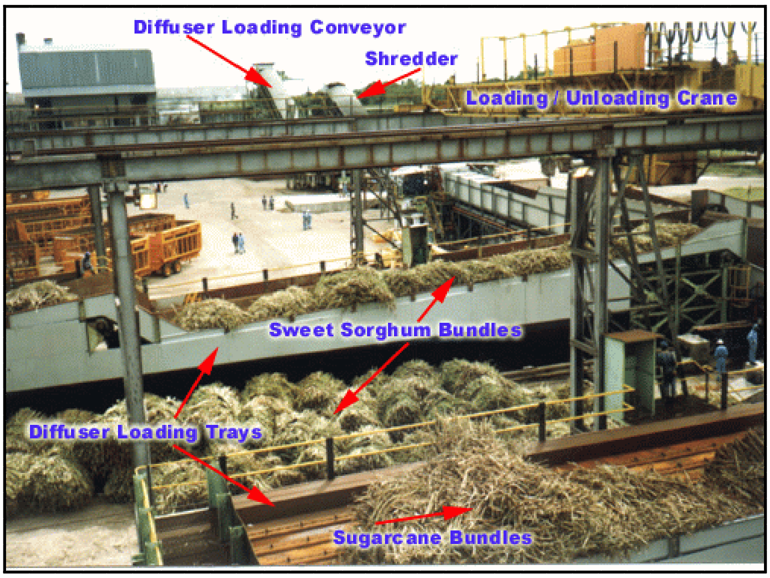

Fig. 10 Diffuser Loading Trays with Sweet Sorghum & Sugarcane Bundles Ready for Processing (J.Woods)

On arrival at Triangle mill, the transport vehicle and payload of stems were weighed together providing a record of the gross mass (vehicle + payload). The time of weighing, field identification details identifying where the load was harvested, number of bundles were also recorded and each bundle given a unique identification tag so that the time it was fed through the knives and shredders could be noted. On departure the unloaded mass of the vehicle was recorded and the net weight of the delivered biomass calculated.

Once through the weigh-bridge, the bundles of stems were unloaded near the diffuser (1999) or mill line (1998) loading trays into temporary holding areas. From these areas the bundles were craned onto the loading trays as can be seen in Figure 10. Once on the trays, the bundles were moved onto the diffuser or mill loading conveyors where the stems were fed through rotary knives and then a shredder before finally entering the diffuser or mill tandem.

Triangle Ltd. Mill has two juice extraction lines based on different technologies i.e.:

- 66" Mill Tandem Line
    - line consists of a tandem of 6 sets of rollers (mills)
    - juice is physically squeezed out of the fibre by a combination of 4 rollers in each mill
    - clean imbibition water added at mill 6 is extracted (with the sugars) by the mill and added to mill 5. Extracted juice from mill 5 is added as imbibition ‘water’ to mill 4, and so on to mill 1.
    - rated capacity of 186 t_{cane} h^{-1}
- Diffuser Line
    - juice washed out of fibre by counter current of hot water/juice
    - 60 m long with 12 juice collection wells
    - Megasse flow rate 1 m min^{-1} but variable
    - rated capacity of 304 t_{cane} h^{-1}

Juice from the two lines is fixed after being weighed and temporarily stored in the mixed juice tank (Figure 19).

3.3.1.1. Diffuser Tests (March 1999)

On 17th March 1999, the areas of the sweet sorghum planted in November and December 1998 at CRS and Triangle (sections 26 & 62) and designated for use in the diffuser test, were harvested as shown in Table 3.1.

The harvesting was carried out by Triangle Ltd. sugarcane cutters using standard sugarcane harvesting equipment. From 11:00am to 1:00pm on the 18th March 1999, 202 t of sweet sorghum stems were processed through the diffuser at Triangle Ltd. and a number of observations were made. In addition, samples of sorghum material were taken for analysis throughout the diffuser test in order to compare sweet sorghum with sugarcane. 1000 t of sugarcane was processed immediately following the sweet sorghum. The sample analysis was carried out by Triangle Ltd. Laboratory technicians under the control of Mr. D. Siwela (Triangle Laboratory Manager). The samples were tested for Brix, Pol, Fibre, Reducing Sugars, and Moisture. The results are shown in section 4.3.3.1.

Percolation Tests

Percolation velocity tests using bagasse derived from cv. Keller and using the small-scale crushing facilities at the Triangle Laboratories were carried out on the 15th and 16th March, 1999. The laboratory scale crushing facilities at Triangle Ltd. are designed to replicate the cutting and shredding processes as seen in the full-scale 66" mill and diffuser. The test protocol, after Muchatibaya (1997), was followed as closely as possible. However a shortfall in the amount of shredded sweet sorghum stems was experienced and no hot water was available. The results from the percolation tests are shown in Table 4.22.

3.3.1.2. 66" Milling Tests (March 1998)

At about 4:30 pm on the 15th March 1998, 20 t of sweet sorghum stems (cv's Keller and Cowley) were processed through the 66" mill at Triangle Ltd., in conjunction with 1000t sugarcane stems. This test was carried out as part of the overall pre-mill startup tests. The time to process the 20 t of sweet sorghum stems through the 66" mill was extremely short i.e. <7 minutes and thus no substantive quantitative data was collected because:

i) post mill-tandem mixing of sweet sorghum and sugarcane juice and bagasse, and
ii) no samples were able to be collected because of the short duration and small quantities of juice and bagasse produced.

Visual observations were made and are shown in section 4.3.3.2.

3.3.2. Juice Processing- Ethanol and Crystalline Sugar Production

The quantities of sweet sorghum juice derived from the 66" mill crushing test (15th March 1998) were insufficient to: i) keep pure (unmixed) from sugarcane juice, ii) clarify. No further tests were carried out on this juice.

Sweet sorghum juice derived from the diffuser test (18th March 1999) was of sufficient quantity to take through to the 'A' Pans in an unmixed state i.e. no sugarcane juice was mixed with the sorghum juice. However, an accident with the exhaust steam line meant that all process steam was lost and the crystallisation tests could not be completed.

The Preparation Index (PI) of the shredded sorghum (18th March 1999) from the diffuser loading conveyor was assessed at Triangle Ltd.'s laboratories using the standard PI protocol from the 'Laboratory Manual for South African Sugar Factories' (South African Sugar Association, 1995). See also section 3.3.1.1. and Table 4.22. The PI is an index of the physical extractability of sugars as a result of the preparation by the shredders and knives, allowing a comparison to be made between sugarcane and sorghum.

Fermentation tests on the sweet sorghum juice produced from the small scale crushers operated by Triangle Mill laboratories during March 1998 were carried out using the laboratory fermenters and standard procedures, see Table 4.30 for the results.

3.4. Production & Use of Energy

The energy requirements of Triangle Mill and Estates are supplied from four primary sources:

1.	Bagasse	steam (direct power and heat)
		electricity (from high pressure steam)
2.	Coal	as with bagasse
3.	ZESA	electricity (irrigation, lights and electric motors)

4. Transport fuel petrol & diesel

The bagasse and coal are burnt in the mill's four main boilers producing high pressure (HP) steam at 370EC and 3.1 MPa.. The HP steam is used in three ways:

1. Electricity Generation (6 turbo altenators, 5 backpressure + 1 condensing)
2. Direct Power Turbines (3 de-watering mills + 2 feed-water pumps)
3. Let down to produce Low Pressure (LP) steam through the de-superheater.

Electricity, either from the turbo-altenators or ZESA, is used to provide power for irrigation, rotary power, and lighting. ZESA electricity is used when electricity can not be provided from the mill power station, providing an emergency power source and electricity during scheduled maintenance periods.

Once the temperature and pressure of the steam was known its energy density was calculated using software developed by Moran and Shapiro (1991). A knowledge of the energy densities and flows of steam at the different stages in the steam use pathway allowed the efficiency of conversion to be calculated for individual pieces of steam consuming equipment.

Low pressure (LP) steam is used to provide heat throughout the crystalline sugar and ethanol production process where it is used for sterilisation, temperature regulation, and for evaporating water.

Data on the production and use of energy at Triangle Ltd. has been derived from data provided by the Technical Director, Wenman (1999a+b), and the Engineering Manager, MacIntosh (1999). Petrol and diesel is used to supply Triangle's fleet of vehicles, including tractors, graders, bulldozers, lorries, locomotives, vans and cars. Data on costs and energy consumption were supplied by Bresler (1999). The results from the assessment of the production and use of energy at Triangle Mill are shown in section 4.4.

3.4.1. Energy Contents of Sweet Sorghum & Sugarcane

The energy contents of the various sweet sorghum and sugarcane derived feedstocks are important in the analysis carried out in the process of this research. These include the energy content of:

- Whole plants
- Stems & major plant organs
- Bagasse
- Ethanol
- Coal
- Diesel
- Electricity
- Steam (high and low pressure, see above)

Whilst the energy contents of ethanol, diesel, steam and electricity are uniform if used with standard specifications, the energy contents of coal and vegetable matter can vary considerably with location. For example see Table II.1. In order to be sure that the appropriate energy contents of sorghum, sugarcane and coal are used in this thesis, where possible only locally measured values have been used. For sugarcane bagasse and sweet sorghum (bagasse, whole plant, and major plant organs) the values have been measured directly as outlined below.

The above ground biomass of eight whole Keller and eight whole Cowley plants were collected from the centre of the drip and sprinkler sections of the CRS on the 28th March 1999. These samples were taken directly to be processed using the small-scale crushers at the Zimbabwe Sugar Association (ZSA) Laboratories.

The sugarcane bagasse samples were collected from stored samples at the Triangle mill laboratories. This ensured that the bagasse samples would be representative of the full-scale bagasse process stream from the diffusers.

The samples were then dried at 110 EC for 20 hours at ZSA before being transported to the Institute of Mining Research (University of Zimbabwe, Harare) for bomb calorimetry analysis. The gross calorific value of the samples was measured on 6th April

1999 at this location. A comparison was made with the data supplied by John Thompson, Africa (1995) for fuel specifications.

3.4.2. A Life-Cycle Energy Balance Based on Triangle Ltd.

As a part of the development of a Systems Analysis Model (AIP) a life-cycle energy balance methodology has been designed. This methodology uses both the integrated mechanistic sorghum-specific plant growth model (a modified CERES model) and the harvesting, transport and energy conversion modules of the AIP to generate site and time-specific estimates of energy balances. A worked example of an energy balance calculation based on the 1997 / 98 sweet sorghum productivity trial and the utilisation of sweet sorghum in the Triangle Ltd. Sugar Mill for energy production was carried out.

3.4.2.1. Methodology

Energy use is estimated for each step of the crop growth and conversion process. Energy use for: i) tillage includes- land preparation, planting, weeding, and harvesting (manual and mechanical), ii) fertiliser and pesticide application, iii) irrigation, iv) harvesting, v) transport, and vi) conversion. Both direct and indirect energy use were estimated. Direct energy use was defined as the actual energy used in carrying out the various operations during crop growth and conversion, whilst indirect energy use estimated the energy requirements for the manufacture, delivery, and repair of the equipment used.

The primary energy input for tillage resulted from the diesel fuel used by the machinery required to prepare and maintain the land for crop growth i.e. discing, ploughing and the movement of sprayers. The energy sequestered in the machinery during manufacture, transport to their location from the factory and repairs was also accounted for. However, this equipment is not solely used for the growth of one season of sorghum and therefore this “sequestered energy” was allocated according to the share of the total life time of the equipment used in the sorghum growth. This energy analysis was based on Bowers (1992) which itself was based on data gathered in the 1970's. It is likely therefore that improvements in the efficiency of mechanical equipment will have occurred. However, these improvements are unlikely to have a significant effect on the overall energy use in crop growth, which has been dominated by improvements in the efficiency of manufacture of fertilizers, and / or the increase in share of liquid fertilizers in use. Table 3.2. shows two estimates for the energy requirement to produce and deliver fertilisers highlighting the improvements in modern production techniques. The quantities and energy input requirements for fertilisers and pesticides are shown in section 4.2.3.2.

Table 3.2: Two Estimates of Average Energy Requirements for Production and Delivery of N, P & K (GJ/t or MJ/kg)

Nutrient	Production	Packaging	Transportation	Application	Total
N[a]	69.5	2.6	4.5	1.6	78.2
N[b]	41.5	2.6	4.5	1.6	50.1
P_20_5[a]	7.7	2.6	5.7	1.5	17.5
P_20_5[b]	4.5	2.7	5.7	1.5	14.3
K_2O[a]	6.4	1.8	4.6	1.0	13.8
K_2O[b]	4.8	1.8	4.6	1.0	12.1

[a] Source: Helsel (1992)

[b] Source: Bhat *et al.* (1994)- op cit Mudahar & Hignett (1981, 1982). Production energy (1987 data) for N is the weighted average for ammonia production from reciprocating and centrifugal production, for P_20_5 is the weighted average between Single Super Phosphate (SSP), Triple Super Phosphate (TSP), Diammonium Phosphate (DAP), Monoammonium Phosphate (MAP) and other types of Phosphate production.

A similar methodology for fertiliser applications was followed to estimate energy costs associated with the use of pesticides (insecticides and herbicides). Data on pesticide application (type, amount and date of application) were collected (Tables 4.10 and 4.11). The energy costs for application, production and delivery were calculated using the methodology of Bhat *et al.* (1994), for example see Tables 3.3 and II.15.

Table 3.3: Comparative Energy Requirements in Diesel Fuel Equivalent of Various Application Methods

Method of Application	Application Energy		Pesticide Energy		Total	
	(l/ha)	MJ ha^{-1}	l ha^{-1}	MJ ha^{-1}	l ha^{-1}	MJ ha^{-1}
Liquid Herb. Broadcast pre-plant	2	66	4	155	6	221

Liquid Herb. Broadcast pre-plant incorporated	6	217	4	155	10	371
Liquid Herb. Broadcast pre-emergence	0	8	4	155	4	162
Liquid Herb. Banded pre-emergence	0	4	2	62	2	66
Liquid Herb. Broadcast post-emergence	2	58	4	155	6	212
Granular Pest. Broadcast	2	66	5	193	7	259
Granular Herb. Banded pre-emergence	0	4	2	77	2	81
Liquid Herb. Aerial broadcast pre-plant	2	77	4	155	6	232
Post-emergence cultivation for weed control	12	445			12	455
MEAN						229
Standard Deviation						118

Source: Bhat *et al.* (1994)

The methodology of Slogget (1992) was used to calculate irrigation energy requirements for sweet sorghum and the results are shown in section 4.2.4.2. The irrigation requirements for sugarcane are also shown in section 4.2.4.2. Crop water use for sweet sorghum during the 1997/8 and 1998/9 CRS trials was recorded and used to estimate water-growth response curves in section 4.2.4.1. See also section 3.1.1.1.

3.4.2.2. Energy Outputs

In this study the final energy outputs are considered to be the energy carrier which is exported "from the factory gate," i.e. ethanol and electricity. Other products which don't necessarily have a direct 'energy' use, such as, CO_2 (used in the drinks industry), or bagasse or molasses (cattle feed), have a monetary value and both an energy cost for production and an energy content. However, as these products are essentially by-products, the energy cost of their production is included in the energy cost of the ethanol and electricity production and no energy is credited to the energy output side of the ratio.

The energy output side of the balance is calculated by using the sweet sorghum productivity levels achieved during the 1997 / 98 trial, assuming that this level of production will be achieved during commercial growth. The management conditions, resource requirements and biomass quality parameters are also assumed to be similar i.e. the levels of sugars and fibres will be maintained in commercial production.

In order to calculate the energy outputs accurately, it is necessary to know the total biomass productivity per ha in a given year, and the losses resulting from the processes which lead to its conversion to the final energy carrier. In the case of this system, where sweet sorghum is integrated with sugarcane and thus, crystalline sugar is also an output, it is necessary to allocate a share of the energy inputs to each of the outputs even though some of the energy intensive processing steps are shared. For example, the juice separation stage which separates the sugar-rich juice from the fibre-rich bagasse requires significant amounts of energy. There are three possible routes for the processing of this juice depending on the required products, i.e.:

i) all the juice (and therefore the sugars) are sent directly to the fermentation plants; i.e. only ethanol is produced,

ii) crystalline sugar is first extracted from the juice and the residual molasses is sent to the fermentation plant; i.e. ethanol and sugar is produced (as in Triangle), or

iii) only crystalline sugar is extracted; i.e. only sugar is produced.

If the second processing route is chosen a number of factors have to be considered in allocating the share of energy inputs between the two outputs i.e. sugar and ethanol. In this calculation, the energy inputs for the processes which are shared between the two outputs are divided using the share of POL which ends up at the fermentation plant or as crystalline sugar. This methodology is outlined in Rosenschein and Hall (1991).

Another likely ethanol production strategy is that different routes are adopted for sugarcane and sorghum. If the removal of aconitic acid, which hinders crystal formation during sugar production, proves difficult, then sweet sorghum juice, which is relatively rich in aconitic acid compared to sugarcane, may be sent directly for fermentation after juice extraction i.e. route ‘i’ above. However, sugarcane will still be processed using route ‘ii’ and the ‘C’ molasses used for ethanol production.

A computer-based (Spreadsheet) model of energy production and consumption at

Triangle Ltd. has been developed and used in this thesis to calculate the Mill-based energy requirements for processing the sugarcane and sweet sorghum stems. The model results are summarised in section 4.5.1. and Table II.21.

3.5. Modelling (Programming)

The decision to use a 'Windows' type graphical user interface (GUI) to aid the use of the AIP and to ensure compatibility with modern computing systems had a number of ramifications with regard to the choice of programming language and the method for integrating the crop model(s).

MS Visual Basic (VB) 3.0®, later upgraded to VB 4.0, was chosen because of its simplicity of use in designing the interface, which aided the rapid development of the model interface and the underlying code. A second but equally important consideration in choosing the programming language was that a mechanism had to be developed to communicate with the CERES crop models and the AIP. Specifically, the revised CERES-Sorghum model being developed by Gosse's group at INRA (France), was programmed in FORTRAN 77. Therefore, by using Salford's Clearwin® compiler the CERES code could be compiled to produce a Windows 3.1 executable (the primary part of a software program) which was compatible with VB 3 or later.

A model such as the AIP requires the manipulation and storage of data both during and between model runs i.e. the system has to be capable of storing data when the computer is turned off. For this purpose VB is compatible with the MS Jet database engine. Programmes written in VB can be tightly coupled to Jet databases which are themselves compatible with the MS Access database program shipped with the MS Office group of programs.

A final, but critical consideration, was the necessity of recruiting a skilled programmer to help with the integration of the CERES models with the AIP and provide guidance in the overall programming development of the AIP. This role was kindly and very ably undertaken by Allan Vincent without whom the AIP would not have been possible. Mr.

Vincent helped the author to:

i) write the visual basic code linking the GUI and the underlying databases

ii) in compiling the CERES-Sorghum Fortran 77 code using Salford's ClearWin® compiler which enabled the integration of the CERES program with the AIP

The author explained the requirements for the AIP to Mr Vincent who then in conjunction with the author wrote or prototyped the Visual Basic code. The departure of Mr Vincent for New Zealand by boat in 1997 meant all further development of the AIP has been carried out by the author alone.

3.6. Model Data Gathering

Data for each stage of the production and processing chain has been collected, and is primarily based on Triangle Ltd. However, where relevant technologies both existing or under development have been used elsewhere and relevant technical and economic data was available then this was used instead. For example, European Union work on developing small-scale sorghum harvesters for use in the relatively small fields found in the Mediterranean area has been followed and the data for the Ottma harvester included.

Genetic coefficients for the INRA CERES-Sorghum model are derived from European Sweet Sorghum Network research (see section 1.5.2) and a considerable amount of detailed information and working knowledge was gained by the author from attending the DSSAT workshop held at the University of Georgia, Athens, Georgia, USA in 1996.

The data derived from the agronomic trials carried out at CRS using a number of different varieties of sweet sorghum have been used to validate the INRA CERES-Sorghum crop model. This was achieved by comparing experimentally derived data with model runs where the crop management mimicked the management of the trials in terms of irrigation, nitrogen applications, and climatic conditions (section 4.6.3). The climate data using the model is derived from the Automatic Weather Station based at CRS- see below.

3.6.1. Climatic Data Collection & Use

During this research, climate data have been used to:

1. Calculate potential evapotranspiration (PET) and crop evapotranspiration (CET)
2. Provide daily climate data for use in the CERES-Sorghum crop model within the AIP. (Section 4.6.)
3. Evaluate differences in sweet sorghum yields between the 1997/8 and 1998/9 seasons (section 4.2.1.)

Climate data, five minute averaged to one hour intervals, from the automatic weather station (AWS) at CRS was collected at regular intervals from the AWS's Campbell CR10 data logger (collected at weekly or less intervals) using a Toshiba T1900 laptop and UK Institute of Hydrology data capture / comms software 'Term.exe'.

The AWS has an array of 7 sensors:

1. Global radiation (R_g- units W m^{-2})
2. Net radiation (R_{net}- units W m^{-2})
3. Air temp (EC)
4. Wet bulb air temp (EC)
5. Wind speed (m s^{-1})
6. Dew (minutes present)
7. Rain (mm)
8. Battery voltage (V)

Historical data series downloaded from the Chiredzi AWS which was installed in 1989, have also been re-assembled and cross-checked. Where available, recorded climate data has been imported into a Corel Quattro Pro® spreadsheet developed by the author.

Through a series of spreadsheet based calculations, the hourly data was used to provide hourly PET values which along with the other recorded hourly data are integrated to daily values.

The original data files, as downloaded from the AWS, are stored on computers in the

UK and in Chiredzi and are backed up in the form of compressed (zipped) archives at both locations.

On separate worksheets in the spreadsheet PET was converted to CET (Crop Evapo-transpiration) for each experimental block and soil water balances were carried out.

The spreadsheet derived daily values for global radiation (R_g W m^{-2}), daily max and min temperatures (t_{max}, t_{min},EC), rainfall (mm) and for DSSAT versions of CERES-Sorghum windspeed (m s^{-1}) have been exported from the spreadsheet and converted into text values which can be used by CERES-Sorghum.

Soil data was taken from the UK Institute of Hydrology soil data for CRS and converted into the correct format for CERES models by the author.