5. DISCUSSION

The potential for establishing sweet sorghum as a complementary crop to sugarcane for bioenergy production is discussed. The main reason for implementing such an integrated sweet sorghum system will be assessed i.e. elongating the bioenergy production season. Figure 32 shows how sweet sorghum can be used to achieve this aim by growing the sweet sorghum for harvesting in February and March in southern Zimbabwe. Eventually, with further research into the management and selection of new varieties the sweet sorghum could be harvested in December to March completely closing the 'off crop' gap and allowing year round bioenergy production. The four primary methods of optimising bioenergy production by using sweet sorghum are:

1. Elongating the agricultural production season and therefore the efficiency of using land, labour and equipment.
2. Increasing the efficiency with which biomass is converted into biofuels.
3. Minimising potential problems, primarily logistical.
4. Maximising potential benefits (environmental, economic, social)

In practice, this evaluation has meant a systematic review of the complete process chain through which sweet sorghum and sugarcane will be produced and processed to make modern biofuels i.e. ethanol and electricity. It has entailed the monitoring by the author of small-scale sweet sorghum trials in Zimbabwe and elsewhere, establishing the current state-of-the-art for sugarcane production and conversion, and the close co-operation between the author and a privately owned sugarmill located in SE Zimbabwe i.e. Triangle Ltd. It has also entailed the development of a computer-based systems analysis tool (The AIP) which models the integrated sweet sorghum and sugarcane production and processing chain to allow the impacts of novel technologies, new varieties and site specific factors, to be evaluated.

This discussion concentrates on key aspects (process steps) of the integrated system, but also tries to give an overview of the complete chain, primarily from the point of view of the development of the AIP. It follows the logical progression from crop production

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through harvesting and transport to processing and finally, the production of the biofuels.

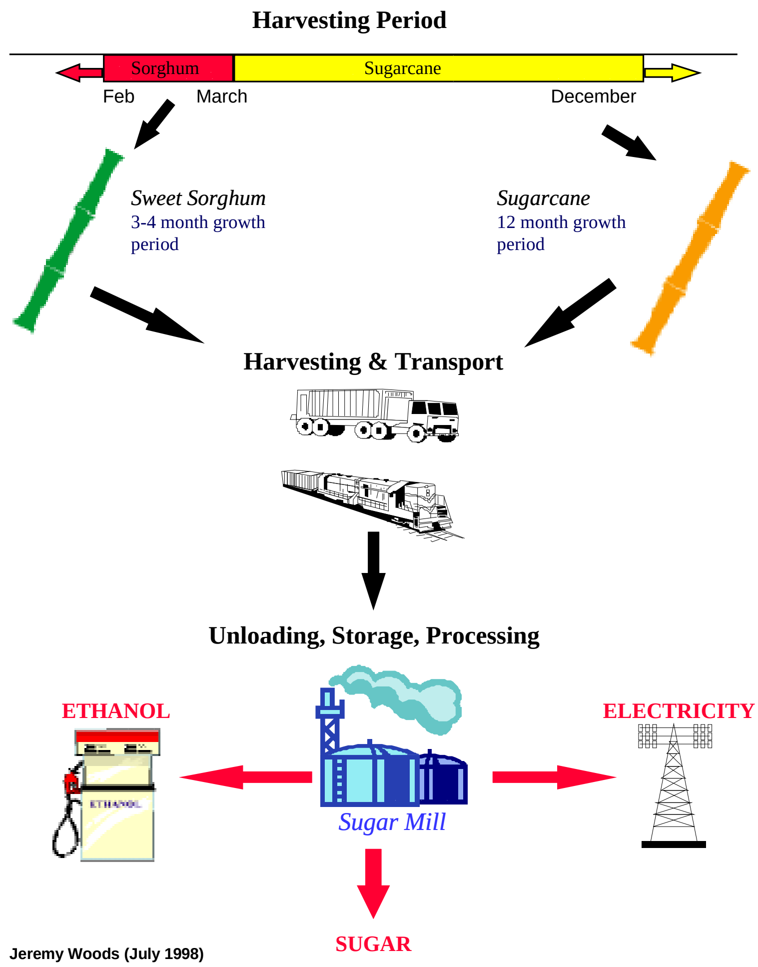

Fig. 32 Integrating Sweet Sorghum with Sugarcane at Triangle Ltd. Zimbabwe.

5.1. The Growth of Sweet Sorghum and Sugarcane

As with any agricultural system, the final outputs are closely coupled to the agronomic productivity of biomass per unit area, with the post-harvest processing simply defining the efficiency with which the products are isolated from the ‘residues’. The main focus of this research has been to establish the potential for the integration of sweet sorghum with sugarcane at the agronomic level. The agronomic aspects of the production and integration of sweet sorghum with sugarcane are discussed in the following sections.

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5.1.1. Productivity

In this thesis productivity is defined in the terms of useful products or outputs that can be derived from sweet sorghum and sugarcane, specifically:

- Ethanol (in relation to crystalline sugar)
- Electricity
- Steam for process power & heat

However, it is first necessary to establish the fundamental factors which define the potential productivity of sweet sorghum and sugarcane which is important for defining the ultimate efficiency of the agricultural system and for the development of the AIP.

5.1.1.1. The Fundamentals of Crop Productivity

The fundamental determinant of biomass productivity is the amount of sunlight falling on the leaves of the plant. The ability of the plant to utilise this resource is mediated by temperature, water and nutrient availability, the plant type and species, and the plant's, or man's, ability to deal with pests and diseases. Plants absorb photosynthetically active radiation (PAR) in the wavelengths 400-700 nm; roughly 50% of the energy of the total incoming radiative energy. Of this energy, further losses occur through reflectance by the leaves and transmission through them, interception by non-photosynthetic components both within the leaves and by the branches, twigs etc, and efficiency losses with which the energy in photons is converted into chemical energy as fixed carbon bonds. These losses dictate a maximum theoretical photosynthetic efficiency of 6.7%, if PAR is utilised throughout the year. (Bolton and Hall, 1991)

Besides water availability, temperature governs the length of the growing season ie. C_3 plants grow optimally between 20 and 30ºC (and not below 0-5ºC), C_4 plants (including sweet sorghum and sugarcane) between 30ºC and 40ºC (and not below 10ºC). Thus, away from the tropics, temperature constraints can severely limit the length of the growing season.

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Theoretical calculations of the maximum potential yields of C_4 plants, under conditions which are neither nutrient nor pest/disease limited, show the absolute potential productivities possible. Thus for Triangle (21°S), with an annual average daily insolation of 18.6 MJ m^{-2} d^{-1} (Global Radiation), for a crop with a four month growth period such as sweet sorghum, if grown between November and the end of February, a theoretical maximum yield (without pest and disease losses) of 89 odt ha^{-1} yr^{-1} is calculated, equivalent to 295 t_{fab} ha^{-1}. For a crop such as sugarcane, with a 12 month growth period and an average solar insolation of 16.9 MJ m^{-2} d^{-1}, the theoretical maximum yield is 236 (oven dry) t ha^{-1} yr^{-1}, equivalent to 787 t_{fab} ha^{-1}.[15] Therefore, it is likely that with continued R&D sugarcane yields will continue to improve. These issues are discussed further in section 5.1.5.3.

5.1.2. Climatic Conditions Necessary for Growth

Crop growth requires sufficiently high levels of temperature and solar radiation for photosynthesis and therefore net carbon assimilation to occur. Whilst in horticultural systems both of these crop growth components can be controlled with heating and solar lamps, in the type of systems where sweet sorghum is envisaged to be used the artificial control of these two factors is not practical. Therefore, temperature and radiation are the primary variables which limit the spatial and temporal scope to the use of sweet sorghum. Other factors, such as water, nutrients and the management of pests and diseases can be controlled by good crop management if economically viable.

Inter-year variation in climatic growth factors can have a strong influence on crop growth particularly in annual crops with short growth periods. For example, significant differences were observed between the sweet sorghum yields achieved during the 1997/8 and 1998/9 seasons (nominally 1st December to 15th March; Figure 12 & Table 4.1). It is believed that this reduction in yields was primarily a result of differences in climate between the seasons. From Table 4.1, it can be seen that two of the three primary climatic crop growth factors were lower in the 1998/9 season than the 1997/8

15 Assumes a whole plant energy content for sweet sorghum and sugarcane of 16.9 & 17.5 GJ t^{-1} HHV, respectively, and no temperature constraints; moisture content of mature plants = 70% wt/wt fresh basis; growth period of 120 days for sweet sorghum and 365 days for sugarcane.

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season and one higher. The change in all three of these factors has a strong impact on crop growth. The decreases in temperature and radiation can be explained by the large increase in rainfall during the month of February (i.e. the peak of vegetative growth and the onset of seed production) which resulted in decreased temperatures and radiation. However, as the sorghum trials are irrigated there was no or little positive response to rainfall but a strong negative response to the depressed temperatures and radiation.

Over the season, accumulated thermal time, which drives the phenology of sweet sorghum and which is insensitive to photoperiod, decreased by 15% over the three crucial months of December, January and February. The decrease in thermal time led to an overall increase in the growth period from planting to maturity in the 1998/9 season compared to the 1997/8 season. Furthermore, whilst the overall decrease in solar radiation over these three months was less than 10%, for the month of February radiation was depressed by an average of 23% compared to the 1997/8 season. The combination of these two factors is believed to be the primary reason that yields were on average 30 t_{fab} ha^{-1} lower for the 1998/9 season, a decrease of over 35%.

5.1.3. Crop Water Use

The results of experiments investigating WUE in sweet sorghum and sugarcane are shown in section 4.2.4. Being able to quantify biomass production per unit of water use has become essential to the assessment of the relative benefits of a particular crop type in semi-arid areas. Again, sorghum compares very favourably with other alternatives. For example, analyses carried out in Zimbabwe and Spain show that sweet sorghum is 30% to 50% more efficient in terms of water use per unit of biomass production than sugarcane under the prevailing climate conditions (Table 4.12). Considerable differences exist between varieties and continued selection for resistance to water stress is necessary. (Woods *et al.*, 1995; Wallace *et al.*, 1991) As with fertiliser application, a better understanding of the mechanisms of water stress and the selection of stress resistant varieties can significantly reduce water requirements per unit biomass production.

Other important factors influencing crop water use are:

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! soils
! irrigation (quantity, timing, and method)
! management
! timing of application

As irrigation currently accounts for 25 to 30% of agronomic energy use for sugarcane growth (Table 4.33), increases in the efficiency of application and use of water have the potential to provide significant reductions in overall energy use. New types of irrigation systems e.g. centre-pivot and drip are beginning to be adopted and may soon cover significant areas of sugarcane. These irrigation systems will result in reduced water applications for sugarcane and which would also be expected for sweet sorghum.

Any competition between sweet sorghum and sugarcane for soil water will depend on a number of factors, including:

< soil depth
< soil type
< rainfall intensity
< rainfall distribution throughout the year
< planting time
< growth period
< fallow period

Changes in requirements for irrigation water between seasons will need to be managed. For example, if rains are late, then water will be required at planting of sweet sorghum, but may not be necessary thereafter. However, water requirements for sweet sorghum are expected to be similar to ‘plant cane’ (newly planted sugarcane during its first growth season) following planting and irrigation management can be carried out as if the sweet sorghum were plant cane. This similarity was borne out by a comparison between sweet sorghum water requirements derived from the CRS trials and the standard Triangle Ltd. sugarcane irrigation schedules. (Shepherd, 1998)

Without the use of expensive in-field equipment the measurement of ‘actual’ or ‘true’

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crop water use efficiency (WUE) can be very difficult to quantify in practice. In the experiments monitored by the author a simplified method for calculating WUE has been used (see point 3 below). Above survival thresholds of water application, WUE is extremely helpful in comparing different crop types where water is a growth limiting resource. WUE can be divided into three different concepts:

1. Intercepted water-use-efficiency: water loss through soil evaporation, runoff and drainage is subtracted so that only the water actually intercepted by the plant roots is used to calculate WUE. However, intercepted WUE requires specialised equipment and trials and is thus, not often able to be calculated.
2. Precipitation-use-efficiency: total rainfall versus total above ground crop biomass accumulation, used over wider areas for rainfed crop growth.
3. WUE where rainfall and irrigated water are added and compared with crop growth. As with “2" This method makes no allowances for soil types (different drainage characteristics, water-holding capacity, albedo, etc), slopes (water runoff) or losses by evaporation off foliage and stems. (Section 4.2.4.1)

From the results shown in Table 4.12 and Figure 18, sweet sorghum is shown to require approximately 30% less water than sugarcane per unit of above ground biomass produced. However, care should be exercised in using this data as the WUE calculated for sweet sorghum is from small-scale agronomic trials, but for sugarcane it is derived from commercial sugarcane production in SE Zimbabwe.

The linear regression line shown in Figure 18 suggests that there is no (or minimal) evident drop in WUE at the higher levels of irrigation. However, it should be noted that the higher levels of irrigation and productivity are seen in the data from Bari (Southern Italy), Madrid (Central Spain) and Catania (Sicily) where the results represent a “crop intercepted” WUE. In all three of these experiments, crop-water-use is calculated using lysimeter data and not actual applied water; the Chiredzi (Zimbabwe) and Vagia (Greece) data represents actual applied water. The use of lysimeter-derived data allows factors such as soil type, and therefore, drainage / water holding capacity, and runoff to be removed from the analysis. Therefore, in applying the regression data care must be taken to realise that the growth response to water (the

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gradient ‘m’) can not be expected on the ground.

In practice, WUE would be expected to decrease at both lower and higher water input levels i.e. a sigmoidal yield response to water supply. Indeed, analysis using a computer-based curvefitting programme ‘Curvexpert’ showed a better regression fit for logarithmic and hyperbolic curves than the linear regression used here indicating that WUE decreases at both low and high levels of water input. (Hyams, 1997) However, the linear regression model was chosen because the increased accuracy provided by the other ‘fits’ did not justify the extra complexity in calculations. (Section 4.2.4.1) A decrease in WUE at lower water input levels would be expected as a result of the smaller root-length density and / or decreased capacity of the plants to use the water if crop development has been affected. At higher levels it might be expected that the crop can not intercept all the water which will be lost either through drainage to lower soil levels or as run-off on the soil surface. (Section 4.2.4.1)

Another important point to note from Figure 18 is that whilst the regression is linear the survival threshold for water supply is above 0 mm. Increasing above ground biomass reflects increasing root-length density and LAI leading to a greater ability to intercept soil water and transpire it as the crop develops. Regression analysis calculates the survival threshold of 161 mm and a response to water of 61 kg ha.mm^{-1} (6.1 g m^{-3}). The implied WUE from this relationship varies with water supply from 1.2 g m^{-3} with a water supply of 200mm to 4.9 g m^{-3} if 800mm is supplied.

Actual water use, resulting from rainfall and irrigation will vary significantly from site to site, depending on:

Soil type- field capacity, water holding capacity, wilting point, drainage coefficients, slope, and water penetration, fertility...

Climate- radiation, temperature, intensity and frequency of rainfall, timing of rainfall (regular, intermittent, early season, late season...), wind strength and duration..

Management- The ability of the crop to intercept both water and nutrients depends on the crops ability to develop an extensive root system at an early stage,

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lack of moisture or nutrients, or instances of diseases or pest attacks will affect crop growth.

Crop models can use the relationship between water use and photosynthesis to limit crop growth when soil water falls below threshold levels i.e. the crop becomes water stressed. However, in the CERES crop model (and the AIP), the relationship between crop growth and water stress is a simple "on / off" switch, with no photosynthesis allowed to occur at all below threshold levels and full photosynthesis occurring above the threshold. There are therefore, no intermediate levels of water stress making the model less sensitive than it could be. However, in practice the model copes well with water stress because of the empirical nature of these relationships and the daily time step used for calculations as discussed in section 5.8.

5.1.3.1. Integration with Sugarcane

The integration of sweet sorghum with sugarcane could result in a competition for water resources. In the co-cropping system proposed here where sweet sorghum is grown on fallow sugarcane land, potential competition for water resources may still exist between the two crops. Such competition could occur in two ways i.e. 'direct' and/or 'indirect'. Direct competition would occur where soil-water is exhausted by sweet sorghum or flows of water across or through the soil to neighbouring sugarcane fields are interrupted. Indirect competition for water would be expected where water becomes scarce and therefore expensive requiring a comparative costs benefit analysis between sweet sorghum and sugarcane comparing the outputs per unit of water applied.

Even in good rainfall years and when the sorghum is planted at the start of the rainy season there may be an apparent competition for soil water. For example, in the Lowveld region of Zimbabwe, rainfall is unlikely to exceed 600 mm during the sweet sorghum growing season. However, an optimum water input of 800 mm is required for maximum growth. Therefore, even with even distribution of rainfall, a purely rainfed sorghum crop would experience periods of water stress and thus lower eventual yields. Where sufficient irrigation water is available and its application is cost-effective, no competition will result. However, in years where reserves of irrigation water are low,

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commercial estates will need to carry out a cost-benefit analysis comparing the return of commercially valuable product per unit of water used. It is clear that sweet sorghum production will require significantly less water per litre of ethanol production than sugarcane i.e. 1.4 and 2.7 $m^3 l^{-1}$ EtOH for sweet sorghum and sugarcane derived ethanol production respectively. (Section 4.2.4.1)

Therefore, sweet sorghum is calculated to require about 50% less water than sugarcane for ethanol production given that water requirements at the mill for the conversion and production will be the same for the two crop types. The use of the linear relationship shown in section 4.2.4.1. for sweet sorghum probably overestimates the WUE of sweet sorghum grown under commercial conditions which could reduce the relative WUE efficiency between sweet sorghum and sugarcane to a third less water required per t_{fab} produced. In addition, for a comprehensive comparison between the relative water requirements of sweet sorghum and sugarcane, sweet sorghum would have to be grown year round including through the winter. However, this type of evaluation has not yet been carried out.

Thus, the growth of sweet sorghum for processing during the off-crop should result in an increase in the production of ethanol and electricity per unit of water, and because sweet sorghum will be grown through the rainy season, significant requirements for irrigation water are not expected. A more detailed assessment of water requirements could be carried out using the AIP. However this has not been considered necessary here. The potential energy requirement for the irrigation of sweet sorghum and sugarcane have been evaluated in this thesis and are discussed below.

Detailed energy accounting for irrigation use is very complex due to problems associated with estimating indirect energy use. Gravity fed irrigation systems are almost entirely indirect energy systems requiring estimates for the energy cost of construction of dams, irrigation canals, valves, etc. Ground water-based irrigation systems which require the pumping of water from below surface reservoirs and which are then probably associated with pressurised sprinkler or drip systems are predominantly direct energy systems.

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Sloggett (1992) provides a methodology for calculating direct energy requirements:- "i) how much area is to be irrigated with water that has been lifted and / or pressurized; ii) how much water is to be lifted and / or pressurized to irrigate that area; iii) the distance the water must be lifted; iv) pressure requirements- the type of distribution system(s) used and the extent of their use; v) the type and extent of the various kinds of power- mechanical, animal, human- used for lifting and pressurizing irrigation water and: vi) the type and extent of the various kinds of lifting and pressurizing devices needed." This methodology has been used to calculate the energy costs for irrigation of sweet sorghum in Section 4.2.4.2. The expected higher WUE, shorter duration of crop growth and timing of production for sweet sorghum when compared to sugarcane are reflected in the lower share of energy required for irrigation, requiring 9% and 25% of the energy required to grow and harvest for sweet sorghum and sugarcane respectively. (Table 4.33)

5.1.4. Land Availability

As a result of the sensitivity of the overall viability of biofuel production systems to transport costs and therefore distances, a detailed evaluation of land availability has been carried out. As it is proposed in this thesis that sweet sorghum should be integrated with sugarcane, it is likely that the bulk of the land surrounding the sugarmills will be in-use for sugarcane growth. Therefore, sweet sorghum production needs to be carefully integrated into the sugarcane agronomic schedules to minimise any potential disruption to sugarcane production. Fortunately, the period most suitable for sweet sorghum growth, if it is to harvested and processed during the off-crop, is also the period when there are relatively large areas of fallow sugarcane land available and climatic conditions are most suitable for sweet sorghum's growth.

In evaluating the land areas potentially available for sweet sorghum production the following types of land have been considered:

- i fallow land
- ii as a break crop for sugarcane disease control
- iii areas prone to Nitrogen leaching or not suitable for sugarcane growth

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iv	commercial and communal land where water is not available all year round

v	land where growers do not wish to commit their land to one crop for 12 months

5.1.4.1. Fallow Land

Once old sugarcane ratoons are removed, the land is ploughed and left fallow for three months, or an alternative crop is planted, such as cotton. However, because of the 12 month growth cycle and the need to leave the land unplanted for at least three months, land under 10 year old ratoons harvested less than 3 months before the end of the harvesting season is left for replanting until the beginning of the next season. It is this land, which will be left fallow for a minimum of 4 months (during the "off crop") that provides the best opportunity for sweet sorghum growth for ethanol production (Woods *et al.*, 1996).

The theoretical amount of land available for sweet sorghum growth is about 5 % of an estate's area if the sorghum is to be available for processing during the off-crop. For the Triangle Estates, this area is about 700 ha capable of producing over 2 million litres of ethanol per year if no crystalline sugar is produced from the sweet sorghum (derived Table 4.29). This land could produce about 35 000 t_{stems} of sweet sorghum, which Triangle's mill is capable of processing in about four 24-hour days. Clearly, when compared to the overall scale of the Triangle operation the use of fallow land alone will not have a significant effect on the mills profitability or the overall levels of bioenergy production. Therefore supplementary sources of land will be required if the system is proven to work.

At full capacity (490 t_{stems} h^{-1}), Triangle Ltd. is capable of processing over 10 ha of sweet sorghum per hour assuming a sweet sorghum yield of 60 t_{fab} or 46 t_{stems} ha^{-1}. However, processing rates at Triangle Ltd.'s mill can be reduced from 490 t_{cane} h^{-1} to less than 200 t_{cane} h^{-1} if either the 66" mill tandem line or the diffuser is used with only one tail of the evaporators (Wenman, 1999). At a processing rate of 150 t_{stems} h^{-1} the mill could be run for 215 hours i.e. nine 24 hour days, from 700 ha of sweet sorghum. An important point to note here is that only one of the two processing lines would be required allowing one to be refurbished whilst the other was being used. Of course this

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would not be true of the crystalline sugar production processes or the ethanol plant, but with careful management of mass flows and storage of either syrup or molasses it is likely that down time could be much reduced.

Another possible way of increasing the land available for sweet sorghum production on sugar estates would be by altering cropping patterns. However, it is unlikely that inter-cropping (as opposed to co-cropping as proposed here) will be adopted to increase ethanol and electricity production when the maximum amount of fallow land has been utilised. Managing the competition between sweet sorghum and sugarcane for nutrients and water if the two crops were to be grown in the same field would be too complex for such large commercial operations. Further expansion of sweet sorghum production for ethanol and electricity production in Zimbabwe will most probably be based on small scale commercial and more importantly on communal farms, some of which already grow grain sorghum for beer and seed production. Thus, sweet sorghum could represent a significant cash crop to communal farmers who currently rely on maize which has been prone to drought and disease failure over the last decade. Importantly, a number of communal farmers already produce grain sorghum which is sold to Triangle Ltd for cattle fodder and beer production and is already a significant "cash crop" for rural farmers.

5.1.5. Yields and Harvest Index

The integration of sweet sorghum with sugarcane to optimise productivity per unit land area requires careful integration of the agronomic schedules and detailed investigation. There are a number of possible systems but all rely on exploiting the short season nature of sweet sorghum (i.e. 3 to 5 months growth period) and the perennial 12 month or more growth period of sugarcane. Of the five possible sources of land for sweet sorghum growth discussed in section 5.1.4, the use of fallow sugarcane land during the off-crop is the most likely during the initial phases of the commercial exploitation of sweet sorghum. (See above) Therefore, the yields discussed below are based on the growth of sweet sorghum during the off-crop on sugarcane fields.

Representative (realistic) yields for both sweet sorghum and sugarcane with irrigation

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were evaluated in section 4.2.2.4 and given as:

- C 60 t_{fab} ha^{-1} (46 t_{stems}) for sweet sorghum over 4 months growth.
- C 150 t_{fab} ha^{-1} (115 t_{stems}) for sugarcane over 12 months growth.

The long term commercial yields of sugarcane for the Lowveld region of Zimbabwe are well quantified, reliably estimated and reported annually by the FAO. (FAO, 1999) Although these yields may vary between years, the use of 115 t_{cane} ha^{-1} (150 t_{fab} ha^{-1}) is easily justified by the longer term statistics. For example see Table 2.2.

Establishing a representative yield for sweet sorghum which is likely to be achievable on commercial sugar estates was more difficult. The two main factors responsible for this difficulty are:

i The relatively shorter growth period of sweet sorghum compared to sugarcane makes the yields of sweet sorghum inherently more sensitive to variation in climatic factors during its growth period. For example, heavy and prolonged periods of rainfall over one or two months of the growth of sweet sorghum can significantly effect the radiation budget and thus yields. However, for sugarcane decreased radiation during one or two months out of the 12 months will have a relatively smaller effect on final yields. Therefore the yields of sweet sorghum will be inherently more variable than sugarcane (Figure 17)

ii The yields of sweet sorghum are derived from small-scale research station-based trials. It is widely known that yields achieved on research stations are rarely achievable under commercial or small-holder conditions where both the level of expertise and monitoring will be lower. For example, an analysis carried out by Carpentieri *et al.* (1992) showed that yields of Eucalyptus clones grown on research stations were likely to be 1/3 higher than achieved on commercial estates.

An average yield of 60 t_{fab} ha^{-1} (46 t_{stems})for sweet sorghum was chosen because it represents a good achievable yield under commercial conditions for the lowveld region of Zimbabwe. The higher yield of around 80 t_{fab} ha^{-1} achieved in the CRS 1997/8 trials

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was not chosen because it was likely that these yields were high primarily because of the favourable climatic conditions experienced in the 1997 / 98 season as shown in Figure 12. The lower yields experienced in the 1998 / 99 season, of around 50 t_{fab} ha^{-1}, were unusually low, primarily as a result of the very high rainfall experienced in February 1999. (Section 4.2.1.)

An important opportunity to cross-check the yields being recorded through the sampling procedure used for the sweet sorghum trials at CRS arose during the harvesting and diffusion trials of March 1999. The estimated yields derived from the stem weight as measured by the Triangle Ltd. weigh bridge in March 1999 and compared to the yields given in Section 4.2.2. The comparison indicated that there may be significant overestimation of yields occurring from the biomass sampling procedure as used in the CRS trials. However, because of the small scale nature of the trial samples further work is required to show if this represents an artefact or if there is consistent over-estimating in the sampling procedure. Furthermore, the scale of the yields reported in the literature from research trials around the world indicate that the yields achieved so far at CRS are at the low end of the possible yields which is also bourne out by the AIP model runs. See for example Figures 11, 17 and 25, which indicate that yields of over 90 t_{fab} ha^{-1} (30 odt ha^{-1}) should be possible in southern Zimbabwe giving yields of 70 t_{stems} ha^{-1}.

The data shown in Tables 4.2, II.3, and Figure 17 were used to define the productivity data discussed in the previous two paragraphs. Other factors which may have influenced the yields measured at CRS arose from problems with having used the drip irrigation block for 6 years continuously, sometimes with 2 crops per year. Such intensive and continuous use inevitably leads to a build of pests and diseases and where not fully controlled will lead to a reduction in yields.

5.1.5.1. Harvest Index

The Harvest Index is usually defined as the proportion of a mature crop's total above ground biomass which has commercial value and is therefore harvested. As with sugarcane, the stem biomass has the highest levels of sugars and is therefore selectively

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removed from the fields with the other biomass (the tops and leaves) cut away from the stem and left in the field. In order to assess the proportion of the above ground biomass which was removed by the sugarcane cutters for delivery to the Triangle sugar mill (March 17th, 1999; Section 3.1.2) an experiment was carried out to provide actual harvest index and proportion of plant that is stem, heads, and leaves (Table 4.16). This experiment showed that the cutters were harvesting a stem mass between 70 and 82% of total above ground biomass with an average stem mass proportion of 77%. This is very similar to sugarcane with the harvested stem mass comprising about 75% of the fresh above ground biomass. Results from European trials with mechanical harvesters by Pari (1996b) gave similar proportions of above ground biomass harvested i.e. for a yield of 107 t_{fab} ha^{-1}, 75.5% (83 t ha^{-1}) was stems, 12.2% panicle i.e. tops and seeds (13 t/ha), and 10.3% leaves (11 t ha^{-1}) when compared to the results from the 1999 CRS trial.

A second important result from this experiment was that the share of above ground biomass made up from the heads (i.e. the seeds) was roughly the same as the leaves at 10%. The seeds may have value either as cattle feed or for beer making. If the seeds prove to commercially valuable then the harvest index will rise from 77% to 87% on a fresh mass basis for sweet sorghum. Under commercial conditions sugarcane does not produce a head.

5.1.5.2. Year Round Growth of Sweet Sorghum

In order for sweet sorghum to be considered as a potential candidate for growth throughout the year which is necessary if it is to be used as a break crop in the control of pests and diseases in sugarcane, it must satisfy two criteria:

i it is not susceptible to the major pests or diseases (to be controlled)

ii it can be grown all year round i.e. it will germinate in the dry (winter) season

Both experimental data and model runs indicate that sweet sorghum will germinate throughout the dry season as shown in Figure 27, and an experiment carried out at CRS which was planted in August, harvested in December 1993 and achieved 40 t_{fab} ha^{-1}.

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(Woods *et al.*, 1995)

AIP model runs using 1997 climate data show that planting date is likely to influence both the length of growing period and the total yield. Figure 28 shows that the shortest growth period is likely to occur with sweet sorghum planted during the period from August to December (growth period between 141 to 152 days[16]) and the longest growth period in sweet sorghum planted from January to July (growth period between 196 to 160 days). Should this trend be borne out in practice the shorter growth period arising from planting in the second half of the year would support planting for elongating the overall harvest season and less so as a break crop where the variability in length of growing season may cause problems with sugarcane scheduling.

5.1.5.3. Future Yields of Sugarcane & Sweet Sorghum

Alexander (1985) quotes a theoretical maximum fresh weight yield (stems + tops + leaves) of 358 t_{fab} ha^{-1} yr^{-1} for sugarcane, whilst agronomic trials of sugarcane often attain yields between 200 and 300 t_{fab} ha^{-1} yr^{-1}. For example, agronomic trials of sugarcane hybrids in Louisiana and Puerto Rico developed primarily for energy and not sugar production, have obtained yields of 240 and 280 t_{fab} ha^{-1} yr^{-1} respectively, with one hybrid clone yielding 307 t_{fab} ha^{-1} yr^{-1} (Legendre and Burner, 1995). Giamalva *et al.* (1984) also report an annual average productivity of 220 t_{fab} ha^{-1} yr^{-1} for an Argentinean variety grown over eight years in Louisiana. Therefore, it is likely that yields of sugarcane will continue to improve as new clones and management techniques are developed.

However, R&D into sugarcane has been carried out for over 100 years which has resulted in the current high commercial yields. R&D into sweet sorghum is still in its infancy with commercial areas and production of sweet sorghum still too small to be recorded in statistics. That sweet sorghum can already be compared to sugarcane in

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[16] The actual growth period will be shorter than indicated by the model runs as the model derived growth periods are from planting to crop maturity. In order to harvest during peak sugars, sweet sorghum is likely to be harvested during the grain filling stage reducing the overall growth period by about 15 to 20 days.

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terms of daily rates of production and biomass quality today is a testament to its inherently high potential.

In fact, the sweet sorghum data in Table 4.6 should be considered as conservative, representing the average current sweet sorghum productivity data for Zimbabwe. Undoubtedly, only the best varieties would be used in commercial production which would be selected for their high yield and water use efficiency. Such varieties would also exhibit good sugar and fibre qualities. It is interesting to note that the varieties used in European trials have produced significantly higher yields than trials so far conducted in Zimbabwe, for example, 110 t_{fab} ha^{-1} per growth cycle was reported in Romania by Roman (1995). Since, climatic and soil conditions are favourable in southern Zimbabwe, yields greater than 100 t_{fab} ha^{-1} may well be attainable in the future. It is significant that this region of Zimbabwe has produced one of the world's highest average sugarcane yields over the last 15 years (115 t_{cane} ha^{-1} yr^{-1}) , and these yields have been maintained or improved on (except in the 1992/3 drought year; FAO, 1994 & 1999 Woods *et al.*, 1994).

Commercial Production

That sugarcane yields of the magnitudes quoted above can be obtained under commercial conditions is evident from personal communications with farm managers of Triangle Ltd, Zimbabwe; published average yields are 115 fwt_{cane} ha^{-1} yr^{-1} (cane stems only, over 13 500 ha) over the last 40 years. However, the farm managers have reported that site specific (field-scale or less) maxima of over 250 fwt_{cane} ha^{-1} yr^{-1} are obtainable under good conditions where clones and soils are well matched.
Whilst average sugarcane yields of over 200 t_{fab} ha^{-1} yr^{-1} will not be easily obtained under the present conditions at Triangle, where yields are optimised for sugar and not biomass production, it is clear that very high yields can be attained with sufficient water and suitable incentives for biomass production instead of concentrating solely on sugar.

Although no large-scale commercial production of sweet sorghum has occurred outside China, it is expected that commercial systems will be able to achieve, or even better, yields achieved through the small scale trials at CRS. That this may be possible was shown by the 1998/9 trials where sweet sorghum was grown on both the research

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station and sugar cane land. The sweet sorghum yields achieved on the sugarcane land were higher than those of the research station with a stem yield of 36 t_{stems} ha^{-1} for the sugarcane land and 25 t_{stems} ha^{-1} for the research station (Table 4.7).

With the improved varieties and management which will inevitably emerge from large scale commercial production, average yields of 80 t_{fab} ha^{-1} (60 t_{stems} ha^{-1}) should be achievable with a 4 to 5 month growth period. In fact, the sweet sorghum varieties Cowley and Keller have achieved yields of 80 t_{fab} ha^{-1} for one season's growth in Zimbabwe which can be compared to yields of 150 t_{fab} ha^{-1} for sugarcane grown over 12 months (Figure 17). Given the average four month growth period of sweet sorghum, there is the theoretical potential for three seasons growth in one year. However, two crops per year is probably a practical maximum giving a combined potential yield of 160 t_{fab} ha^{-1} per year.

Over the longer term, improving the overall productivity of crops may be achieved by improving the light use efficiency (LUE) which in turn can only be achieved by a better understanding of canopy photosynthesis, and the selection and breeding of crops which are better able to intercept and utilise the solar radiation. It is likely this will be achieved primarily through increased resistance to high light conditions under stress (photoinhibition) and through better canopy structure and establishment dynamics. Due to the C_4 photosynthetic pathway, sorghum is an efficient utiliser of light being able to produce 3.6 g MJ^{-1} PAR absorbed, compared to about 2 g MJ^{-1} PAR for a C_3 species. (Gosse, 1995a)

5.1.5.4. Fibre Production

The fibre produced as a residue from the crushing process during extraction of the fermentable sugars has a number of potential uses. Usually, in the sugar industry this residue (bagasse) is primarily regarded as a disposal problem, even though it is burnt and provides steam to be used as process energy and electricity to run the mills and sugar crystallisation processes. In the case of Triangle, the steam is also used to provide energy for the fermentation and distillation for ethanol production. Typically, the bagasse combustion plant used to raise steam is thermodynamically inefficient as it

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is designed to ensure that the fibrous residue does not build up and present disposal problems. More recently, with the development of modern systems for the efficient conversion of biomass into high value energy carriers such as electricity, fibre may come to be regarded as a valuable commodity. The fibrous residue could, in fact, be used to provide far more energy than just the basic energy requirements of the processing and conversion facilities representing a novel source of income to the mill if significant amounts of electricity can be generated and exported (Broek *et al.*, 1998). See sections 5.5 & 5.6.

The stem of sweet sorghum contains the predominant amount of sugars and fibre, and thus energy. However, towards maturity, the leaves may comprise 12% of total above ground biomass on a fresh weight basis and could therefore be considered as a supplementary source of biomass for steam and electricity production (Table 4.16 & Figure 13). If all the leaves were available an additional 7.2 t ha^{-1} of fresh weight leaf biomass would be available for combustion. However, it is important to note that the primary sink for nitrogen and other nutrients is the leaves, and excessive removal (more than 50% of total leaf biomass) may result in decreased soil fertility (Braunbeck and Cortez, in Press; Woods *et al.*, 1994). Therefore, if 50% of the leaves are available for the sustainable production of energy 1.08 odt of leaf biomass ha^{-1} (3.6 t fresh weight) with an energy content of 17.3 GJ (16 GJ per odt) would be available for steam production producing an additional 13 GJ ha^{-1} of steam. Thus, the leaves could increase steam production by up to 20% from bagasse-only production, but careful monitoring of soil nutrients and organic matter would be necessary.

The potential to use the tops and leaves as a supplementary energy source also exists with sugarcane as the tops and leaves are generally left in the field after harvesting or burnt off before harvesting. The use of the tops and leaves is still a controversial topic as it may encourage whole cane harvesting techniques which could result in a decrease in fertility and organic matter content of the soils.

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5.1.5.5. Sugar Accumulation & Use [17]

In discussing the importance of sugar accumulation in sweet sorghum and the timing of that accumulation, it is important to be clear about the role envisaged for sweet sorghum i.e. the sorghum is to be grown for:

i harvesting and processing during the off-crop (e.g. planting July to December in Lowveld, Zimbabwe), or,

ii as a break crop (e.g. planting March to December)

A number of factors will influence the desirability of using sweet sorghum in sugarmills out of season and will depend strongly on the final products required i.e. ethanol only, or sugar and ethanol. If crystalline sugar is to be produced then a number of sugar quality parameters, primarily 'sucrose purity,' become essential to the evaluation. However, if only ethanol is to be produced 'total fermentables' rather than 'sugar quality' is the important parameter. A secondary consideration of ethanol production concerns the disposal of stillage during the rainy season which is discussed below.

Sweet sorghum, like sugarcane, produces significant amounts of sugars during the growth period. These sugars accumulate during growth primarily in the stem, and at maturity are predominantly composed of sucrose (>70% of sugars) and to a lesser extent the reducing sugars (glucose and fructose, <30%). The relative level of sucrose, compared to total sugars, increases towards maturity, which is essential for economic production of crystalline sugar (virtually pure sucrose). The accumulation profile of the key sugar parameters for sweet sorghum are shown in Figure 15. This is not true for fermentation where sucrose is hydrolysed during fermentation to glucose and fructose by the invertase enzyme which is secreted by Saccharomyces yeast cells. This lack of specificity for sucrose in fermentation results from yeasts' ability to convert sucrose to glucose and fructose, with the glucose and fructose being the primary feedstocks for ethanol production within the yeast (Section 4.4.2.1). The implications for the growth

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17 All discussions in this section are based on the integration of sweet sorghum with sugarcane in the Lowveld region of Zimbabwe as without a detailed understanding of the local climatic & seasonal patterns it is difficult to generalise.

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of sugarcane, if managed for ethanol production, are discussed in detail by Cackett (1981) and reflect the decreased emphasis on 'sucrose purity' and greater importance of TFAS.

If the sweet sorghum has been planted for harvesting in the off-crop and crystalline sugar is to be produced, then the levels of sugars (primarily sucrose as measured by 'Pol' and 'Sucrose Purity') should be better or comparable with the early maturing sugarcane which has been grown for harvesting in March and April. Through the sweet sorghum trials held at CRS and Triangle, it has been demonstrated that this is possible. However, for crystalline sugar manufacture higher levels of sucrose purity would be desirable. For example, a comparison between ERF and ERC at 115 days after planting for sweet sorghum (mid-March) and for sugarcane (to be harvested mid-March) show that ERF for sweet sorghum is between 10 and 12% stem fresh weight and for sugarcane between 11 and 12%. A similar situation exists for ERC, where sweet sorghum ERC is between 8 and 10% (Figure 15, 110 days after planting) with sugarcane showing a similar range as shown in Figure 16. Therefore, as has been demonstrated, sweet sorghum is capable of being grown for ethanol and crystalline sugar production for harvesting in mid-March in the Lowveld region of Zimbabwe. Furthermore, it is expected that reasonable yields of both total biomass and sugars can be achieved throughout the off-crop period in the Lowveld. This has yet to be demonstrated in practice.

5.1.5.6. Fertilisers & Pesticide Energy Use

Sweet sorghum develops a root and canopy system rapidly, and is thus able to access light, nutrients and water efficiently. During its first season's growth, 'plant cane' develops a comprehensive root system that is maintained through harvesting and the successive ratoons. This gives sugarcane an advantage when compared to annual crops (and weeds) in that it does not need to re-develop its roots after the first year's growth and can thus rapidly establish new shoots and a canopy. Research has shown that C_4 species have lower leaf and plant nitrogen contents than C_3 species, and are therefore able to produce more leaf area per unit nitrogen (Anten *et al.*, 1995). Under optimum fertiliser levels, the difference between C_4 and C_3 species in terms of NUE is small, but

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significant. However, as nitrogen application levels are decreased, C_3 plant productivities are more sensitive and yields may suffer as a result; furthermore, nitrogen requirements per unit dry mass decrease with increasing total plant mass (Lemaire and Chartier, 1992 Greenwood *et al.*, 1990). Understanding the N and C partitioning dynamics in crop growth is proving important for more accurate targeting of fertiliser applications, thereby helping to reduce over-application of fertilisers and excess nutrient leaching.

Both over and under application of fertilisers can be associated with environmental problems. Under application can cause “nutrient mining” resulting in decreasing yields and the degradation of soil structures, water and nutrient holding capacities, and erosion. Over application has been associated with a number of problems, of which the most highly visible has been nutrient leaching into water courses and the linked increase in Biological and Chemical oxygen demand (BOD & COD), and the growth of toxic algal blooms. In addition, fertilisers and pesticides can consume large amounts of energy during their manufacture representing about 50% of the energy inputs required for crop growth for both sweet sorghum and sugarcane; see Table 4.33.

Without careful management, the introduction of sweet sorghum into sugarcane production systems could result in a net increase in inputs per unit output. Table II.13 provides data on average fertiliser inputs in a number of crop production systems (see section 4.2.3.2. also). Using the data from this table the nitrogen requirements for sweet sorghum production are calculated as 1.4 kg N per t_{fab} and for sugarcane 1.2 kg N per t_{fab}. Therefore, from this data it might be concluded that sugarcane is more efficient at using fertilisers than sweet sorghum. However, it is important to note that the fertilisation regime so far applied in the sweet sorghum trials in Zimbabwe has been designed to ensure that nutrients are non-limiting for crop growth and are therefore applied to excess. Further experiments would be required to optimise fertiliser applications with significant reductions likely with carefully managed applications. Furthermore, in Europe, no response to nitrogen was seen in nitrogen application trials carried out in the early 1990's. It is believed this lack of response was a result of the high residual levels of nitrogen in Europe’s agricultural soils as a result of decades of over fertilisation with residual nitrogen able to supply the crop requirements fully

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(Gosse, 1995a).

The AIP can be used to develop strategies to optimise nitrogen application by balancing fertiliser applications with plant nutrient use. Thus, the economic return per unit of nutrients applied can be maximised which will also minimise nutrient losses through leaching if the timing of application is balanced with crop use. Whilst the nature of the response to phosphate and potassium stress is beginning to be introduced into models, only the nitrogen routines are sufficiently robust to be utilised by the AIP as a result of the long history of research into the mechanisms of nitrogen stress. Thus the AIP is currently limited to evaluating the effects of nitrogen fertiliser application and soil N-leaching utilising the existing routines within CERES (Boote, 1996).

Pesticide Use

Because of the perennial nature of sugarcane and the commercial exploitation of its ratooning capacity, after harvesting sugarcane can use its mature root system to re-grow very rapidly, establishing a canopy which inhibits weed growth. As a result herbicide use is rarely necessary for the control of weeds except during the first year of growth after planting. Sweet sorghum also establishes a closed canopy very rapidly, often within one month of sowing under good conditions and herbicides have not been necessary to date in the sweet sorghum trials in Zimbabwe (Section 4.2.3.2). However, where winter planting is considered with the probability that emergence will be delayed by cold weather, herbicide use may be necessary.

As a result of the similarities between sweet sorghum and sugarcane, a number of insect pests for which sugarcane is a host can also infect sweet sorghum and will therefore need to be controlled using insecticides. The thinner cuticle of sweet sorghum stems compared to sugarcane, may in fact, make it more susceptible to these pests than sugarcane. Therefore, it is expected that sweet sorghum will require more intervention in the form of pesticides and herbicides than sugarcane per unit biomass produced.

Tables 4.10 and 4.11 quantify herbicide and insecticide inputs used during the sweet sorghum trials at CRS and for commercial sugarcane production at Triangle Ltd. Recently, the practice of leaving the trash over the tops of the harvested and newly

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planted sugarcane fields to suppress weed growth, improve soil organic matter content and maintain soil moisture, has become more prevalent. It is too early to quantify the impacts of these practices but discussion with a local sugarcane farmer suggests that there are measurable benefits occurring and that the practice will become more wide-spread (Kriederman, 1999). These practices may also be applied to sweet sorghum but research is needed to establish their efficacy.

5.2. Harvesting & Delivery of Biomass to Mill

This section discusses the main factors associated with linking the biomass production to the harvesting, loading, haulage and processing sections of the chain efficiently. This section is based on the results given in section 4.3.

5.2.1. Harvesting

Harvesting is effectively a pre-processing step where a portion of the in-field, above ground, biomass is removed either by hand or by machine or a combination of both. As the complete removal of above ground biomass is not desirable on either environmental or economic grounds, the harvesting procedure is selective in that it tries to ensure that the sugar : fibre ratio in the material to be transported is maximised. To this end, the leaves and tops of each plant (which have the lowest sugar but highest nitrogen content) are removed and left in-field and only the bulk of the stem (highest sugar content) is transported from the field to the mill. Where whole plant harvesting occurs it is usually for the purpose of silage production and not for ethanol or crystalline sugar production. Whole plant harvesting may also prove important for sugarcane based ethanol and electricity production systems where crystalline sugar production is not a significant component. Where whole plant harvesting occurs, careful monitoring of the in-field soil nitrogen and organic matter content is required and increased levels of fertiliser must be applied to replace the lost nutrients.

Harvesting can be carried out manually where labour is plentiful and cheap or mechanically in other circumstances and where the capital costs of purchasing

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mechanical harvesters can be justified. Both manual and mechanical harvesting techniques are described below but this thesis concentrates on manual harvesting as this is the predominant harvesting method used in the sugar estates of southern Africa.

The high ambient temperatures and humidity which coincide with the proposed off-crop harvesting period can result in rapid sugar-loss which starts to occur as soon as the stem is cut. Naturally occurring fermenting organisms invade the stem through the cut ends converting sugars to ethanol which is lost through evaporation. The aim is to manage these losses by minimising the amount of time between harvesting and processing with an expected maximum duration of 48 hours. However, further experimentation is necessary to accurately define this period for sweet sorghum. The combination of the need to minimise storage times and deliver sufficient biomass to supply the mill capacity dictates that the harvesting rate is very closely coupled to the processing rate. Therefore the harvesting and transport of the biomass to the mill is a crucial step in the logistics of the mill operation, representing about a fifth of the financial costs of producing and delivering the biomass (Table 4.38).

One consequence of the need to harvest sweet sorghum during periods when soil moisture levels may be high, is that the use of heavy machinery in-field might not be possible. Therefore, harvesting methods may need to be modified to suit ‘rainy season’ harvesting, primarily by the continued use of manual harvesting and also hand carrying to the field edge. In order to test that the manual stripping of leaves and harvesting was feasible, sweet sorghum harvesting trials carried out using manual harvesting techniques during March 1998 and 1999 in Zimbabwe were monitored. These trials highlighted a potential problem in the use of sweet sorghum on an industrial scale; in comparison to sugarcane, sweet sorghum maintains a significantly higher level of green leaves when peak sugar levels are achieved. (Mvududu *et al.*, 1998) The tops and leaves (including seed)[18], which contain minimal levels of sugars (particularly sucrose), hinder harvesting (if carried out manually) and result in a higher fibre percentage in the delivered biomass. The higher percentage of low-sugar biomass in effect dilutes the sugars, decreasing the sugar content in the delivered biomass e.g if sugars were 12% of

[18] See Table 4.16 for a breakdown of the mass partitioning of sweet sorghum to leaves, panicle, stem, and roots at harvest.

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stem fresh weight (50 t_{stems} delivered), then if total above ground biomass (70 t_{fab}) is harvested and delivered the sugar concentration decreases to 8.6%. Therefore, where crystalline sugar production is required, the tops and leaves must be removed from the stems. However, for ethanol and electricity production without crystalline sugar production, the removal of tops and leaves may not be necessary and may in fact decrease the potential production of biofuels.

Removal of the tops and leaves may be possible by using chemical ripeners which are sprayed on to the plant to cause the leaves to mature early, either drying out and dropping from the stem or becoming susceptible to removal by burning. However, to the author's knowledge this has not been attempted on sweet sorghum to date. If such a strategy is not feasible, manual or mechanical removal of the leaves are alternatives. The manual stripping of the leaves prior to cutting was carried out during the harvesting of the 1998/9 CRS and Triangle sweet sorghum trials which clearly showed that whilst this practice increases labour requirement it is possible as shown in sections 3.1.2 & 4.3.1.

In fact, considerable variation between the three field locations can be seen in both the labour and diesel requirements per hectare and tonne of stems harvested during the 1998/9 sweet sorghum trial. (Table 4.15) However, care should be taken when extrapolating the data from this harvesting trial primarily because in planning the harvesting, estimates of labour requirements were based on:

i expected trashing (leaf removal) and harvesting rates for sugarcane, and
ii the need to use high estimates of standing sweet sorghum biomass

Therefore, the estimated labour requirement was deliberately calculated to be in excess to ensure that all harvesting was completed in time to allow the harvesting delivery of the sweet sorghum to Triangle Mill in one day i.e. by the end of 17th March, 1999. Table 4.15 shows that only 0.5 t_{stems} were harvested per person during this trial compared to the expected 3 t d^{-1} for sugarcane, including the removal of leaves 'trashing'. In fact, the harvesting was finished in less than one shift and it is expected that labour requirements can be reduced substantially in practice, but larger-scale tests

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are necessary to gain better estimates of labour quotas.

In many parts of the world the management input required to supervise large numbers of seasonal labourers is a major factor in choosing mechanical harvesting systems. Despite the high capital and maintenance costs associated with the use of mechanical harvesters, a single unit can replace a large number of workers. For example, the Claas harvester evaluated in Table 4.17, can harvest 60 t_{stems} h^{-1} (480 t per 8 hour shift) and when compared to the 3 to 5 t_{stems} d^{-1} per person means that a single Claas unit could replace up to 100 people. However, given that very low labour costs are likely to continue for the foreseeable future it is unlikely that such heavy machinery could be used in the off-crop. Specialised equipment, such as tracked mechanical harvesters and tractors could be used to reduce soil compaction problems. However, their purchase would have to be justified by the increased revenue from the sweet sorghum alone and therefore seems unlikely.

5.2.2. Transport

Transport is the crucial link between the agronomic and the industrial parts of the production and processing chain, and for sweet sorghum it is essential that the existing sugarcane based infrastructure will allow its effective transport to the mill. Fortunately, the equipment used for loading, transport and unloading of the stems at Triangle Ltd. has been demonstrated to work well with sweet sorghum (Sections 3.2 & 4.3.2).

A variety of transport systems are available at Triangle Ltd. with the choice of which one to use being dependent on distance, road surface, proximity of rail link (if available, see Table 4.21). In practice the choice of transport method is a compromise between the need to ensure rapid delivery and the number of separate operations needed between the harvesting and final delivery. For example, the delivery of the sorghum stems from CRS to Triangle's Mill posed a number of problems. Firstly, the fields were too wet to allow in-field access by the larger 'prof' crane, requiring the stems to be carried to the field edge for stacking into bundles. The bundles were then trans-shipped by 'Perry Loader' to a central marshalling area on the station capable of supporting the loaded weight of a 30 t truck. The bundles were then loaded by the 'Prof' crane onto the truck

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for final delivery to the mill. Therefore, four separate operations were required between cutting and delivery to the mill i.e. i) carrying and stacking, ii) transport to the central marshalling area, iii) loading on a truck (Hilo) by a Prof. crane, and iv) delivery to the mill. This method was chosen at CRS because:

< Tarmac roads between CRS and the mill are government owned and only licenced vehicles could use them i.e. the 30 t flat-bed trucks.

< Direct transhipment by the Hilos to the mill would have taken a longer overall time as they are slower than the trucks.

< The 'Prof' crane was too heavy and large to gain easy access to the fields for rapid collection and direct loading of the bundles onto the truck.

The transport costs associated with biofuel production are closely correlated with the energy density of the biomass. Biomass feedstocks such as sorghum or sugarcane are relatively expensive to transport in both economic and energy terms as their primary constituent is water (>75% FW). However, practices to overcome this problem, e.g. in-field drying, result in the rapid loss of the sugars and to some extent the biomass through decomposition. Such losses can be very rapid with significant losses occurring over two or more days, in fact, harvesting using a US maize chopper harvester resulted in a 50% loss of sugars in 24 hours through unwanted fermentation. (Pari, 1996) Whole stem harvesting and transport to the mill significantly reduce the losses of sugars when compared to chopper harvesting or sillage harvesting, and it is expected that less than 5% of the sugars in the stems will be lost in a 48 hour period following harvesting at Triangle Ltd. and CRS.

5.3. The Separation of the Sugars from the Fibre

For crystalline sugar and ethanol production, it is essential that the sugars are separated from the fibrous part of the stems. The sugars are stored within the cells of the stem and therefore, the crushing and diffusion processes are designed to rupture the cell walls to release the sugars which can then be washed or squeezed out of the resulting pulp. The extent to which the cells are disrupted by the cutting and shredding process

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determines the overall efficiency of sugar extraction and is measured by the 'preparation index' (PI; South African Sugar Assoc., 1995). In general, the cells are sufficiently disrupted by the commercial systems in use to release just over 90% of their sugars i.e. PI = 90% or higher. Whilst the PI's for sugarcane are well established and carefully monitored it was essential to demonstrate that PI of 90% or more could be achieved with sweet sorghum in order for processing using existing sugarcane equipment to be considered feasible (Section 3.3.1.2). Measurements of PI were carried out on sweet sorghum, achieving PI's of greater than 90% (Sections 4.3.3.1. and Table 4.22). This indicated that sweet sorghum stems were suitable for processing using diffusion systems which was demonstrated for the first time in March 1999 at Triangle Ltd. when sweet sorghum was processed by the diffuser line.

Despite demonstrating that diffusers can process sweet sorghum, differences between the fibre content and composition when compared to sugarcane, mean that the process dynamics are different. Factors such as the 'bed height', 'residence time' and 'feeding rate' all need to be optimised to maximise sugar extraction from sweet sorghum whilst minimising sugar dilution which will in turn reduce the energy requirements for evaporation and crystallisation. A much longer diffusion test is planned for March 2000 which will allow the diffuser line at Triangle Ltd. to be run for a continuous 24 hour period using sweet sorghum stems as the sole feedstock. During this 24 hour period it is expected that many of these factors will be optimised.

By the end of the diffuser or mill tandem lines, two separate streams are produced, one containing virtually all the sugars[19] called the 'mixed juice' stream and the other containing the fibrous residues called the 'bagasse' stream. Once separated from the fibre, two potential paths for the processing of the sugar-rich juice are possible:

i clear juice is sent directly to the ethanol plant after clarification

ii crystalline sugar (sucrose) is extracted and molasses (B, or C) is sent to the

[19] 9% of total stem sugars remain in the un-disrupted cells and a further 3% of the remaining sugars are not separated from the residues i.e. the bagasse, therefore in total 88.3% of the stem sugars are recovered by the diffuser line. It is important to note that in general, measurements of sugar, measured as 'Pol', 'BRIX', 'Reducing Sugars', etc., do not represent total stem sugars, but only the percentage of total extractable sugars.

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ethanol plant for ethanol production.

5.4. Processing of Sugars for Ethanol Production

The two possible processing routes for sorghum-derived sugars once separated from the rest of the stem material are evaluated below. In both possible processing routes i.e. crystalline sugar then ethanol, or ethanol-only production, the juice must first be clarified in order to remove the filter mud and other impurities. After the clarification process, the juice which is now also sterilised can be sent through the evaporators to crystalline sugar production, or directly to the ethanol plant.

5.4.1. Crystalline Sugar and Molasses Production

Because of the possibility of using molasses for ethanol production it was necessary to evaluate the process of crystalline sugar production in Section 4.4.2. In addition, Figure 19 provides an overview of the entire sugar and ethanol production process from the delivery of biomass to the mill, the diffuser line, and finally crystalline sugar and ethanol production.

The juice destined for crystalline sugar production must go through a number of energy intensive processes before virtually pure crystalline sugar is produced. A detailed explanation will not be given here. However, it is important to note that if crystalline sugar is to be produced, higher levels of sucrose relative to other dissolved solids in the stem biomass are required than for ethanol-only production. In fact, ethanol production does not require sucrose, only the precursors to its production i.e. glucose and fructose. Other hexose sugars contained in the juice or molasses are also suitable substrates for fermentation. The requirement for high levels of 'sucrose purity' and indeed overall levels of sucrose in the harvested stem biomass has significant implications for the selection of sweet sorghum varieties and their subsequent growth and management as has been discussed above.

The production of crystalline sugar also has significant implications for the overall

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energy balance of the ethanol and electricity production system as the amounts of energy required in evaporating the water to produce and separate the crystals are considerable, as shown in Tables 4.34 & II.21.

Finally, the removal of most of the sucrose as crystalline sugar results in a significant reduction in the potential for ethanol production per tonne of stems processed, with 87% of the extractable sucrose (Pol) ending up as crystalline sugar (Table 4.31).

5.4.2. Fermentation

The fermentation of sweet sorghum juice or molasses is expected to present no major problems and this has been borne out by the laboratory tests carried out by the Triangle Laboratories during the sweet sorghum trials over the last 6 years in the Lowveld region of Zimbabwe as summarised in Table 4.30. The fermentation technologies in industrial use are both robust and efficient. For example, the fermentation efficiency and potential ethanol yields calculated here (Table 4.30) equate well with the 50 l t_{stems}^{-1} quoted as the likely yield in northern NSW by the Energy Authority of NSW (1986). Table 4.31 shows that although only 7% of the original extractable sucrose (Pol) in the sugarcane stems ends up in ‘C’ molasses, virtually all the reducing sugars will also be present in the molasses. However, as with the sucrose, some of the reducing sugars will also be lost in the bagasse and through the various processes in crystalline sugar production.

These processes may also concentrate fermentation inhibitors and fermentation tests are still required on sweet sorghum-derived molasses before it can be certain that sweet sorghum molasses is a good substrate for ethanol production. The impact of the concentration of such inhibitors is expected to be similar to inhibitors found in sugarcane ‘C’ molasses which result in a noticeable, but not significant, reduction in fermentation efficiency (Table 4.30). However, it is known that starch and aconitic acid levels in sweet sorghum juice and other non-fermentable sugars are higher in sweet sorghum than sugarcane which may result in both a decreased ability to produce crystalline sugar and increased rates of fermentation inhibition in the molasses. It is important to note that no inhibition has been seen in fermentation tests on pure sweet sorghum juice to date (Table 4.30; Liu and Yu, 1998; Nimbkar, 1997).

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Fermentation Technologies

A number of commercially proven fermentation technologies now exist, many of which try to overcome the problem of ethanol toxicity to the yeast. Some of these technologies try to achieve higher efficiencies by maintaining the ethanol concentration in the fermentation medium (beer) at a sufficiently low level to avoid yeast toxicity. The traditional fermentation process is through batch culture in which the beer is inoculated with the yeast and fermentation is allowed to proceed to the point where toxic effects of high ethanol concentrations effectively halt fermentation. If a flocculent yeast is used it can be removed from the final beer, and recycled to the next batch. This avoids some of the loss of sugars which would be needed in the growth of new yeast, also helping keep the yeast concentration high and so increasing the speed of fermentation. Another yeast removal system is via centrifugation.

Other technologies use either fully-continuous fermentation or semi-batch systems. For example, the "Biostil" process uses centrifugal yeast reclamation and continuous evaporative removal of the ethanol. This allows the fermentation medium to be continuously sterilised and minimises water use. The Biostil process markedly lowers the production of stillage[20], whilst the non-stop nature of the fermentation process allows substrate concentrations to be constantly kept at optimal levels and therefore fermentation efficiency is maximised (Hall, 1991). Improved varieties of yeast, produced through clonal selection techniques have also raised the tolerance levels of the yeast to high alcohol concentrations, again improving efficiency.

Other novel fermentation technologies are being developed; for example, Cao *et al.*(1997) have developed an immobilised yeast fermenter where the yeast is fixed in small beads which wash around the reactor. This allows the yeast to be easily removed and the reactor to be stratified, with the higher alcohol volume beer being removed in a continuous stream.

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20 Stillage is a liquid effluent from the fermentation plant. It is the residual product from distillation, and is hot and acidic. It also contains a number of important plant-growth nutrients and is currently mixed with irrigation water to recycle these nutrients. Stillage also has a high BOD.

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However, industrial-scale fermentation is already an efficient process with over 90% of the theoretical maximum of the carbon in sugars being converted to ethanol-carbon as described in Textbox 2, section 4.4.2.1. More recently, the main emphasis on fermentation technology development has been in the saccharification of cellulose, either enzymatically or thermochemically for the production of ethanol and methanol, respectively. Advances in the use of cellulosic feedstock may allow the competitive production of alcohol from woody agricultural residues and trees to become economically competitive in the medium term. Since 1982, prices have continued to fall from about US$ 45 per GJ (95 c/l) to about US$ 13 per GJ (28 c/l) for ethanol and for methanol, projected prices have been reduced from US$ 16 per GJ (27 c/l) to $15 per GJ (25 c/l) and could fall to prices competitive with gasoline produced from oil priced at US$ 25 per barrel. (Wyman ***et al.***, 1993)

Stillage Production & Disposal

Stillage, the highly acidic by-product of fermentation and distillation is produced at the rate of 15 l per litre of anhydrous EtOH and has a high nitrate and phosphate content (see footnote ‘c’ Table II.20). The nitrate and phosphate content gives it a value as a fertiliser if recycled through irrigation and can reduce fertiliser requirements if its application is carefully managed. Other methods of disposal are limited i.e. spraying roads to suppress dust, and therefore the ethanol plant can be shut down directly as a result of not being able to dispose of, or store large amounts of stillage.

Because storage capacity for stillage is limited, the production of stillage during the rainy season remains a problem and further work is required to allow environmentally acceptable disposal of stillage during this season. Whilst it can be mixed with irrigation water at sufficient dilution levels to avoid any harmful effects during the dry season, during the rainy season this is not an option and alternative methods of treatment are required.

One potential solution to stillage disposal is its pre-treatment by anaerobic digestion which will reduce the biological and chemical oxygen demand (BOD and COD) to acceptable limits. Anaerobic pre-treatment would also produce methane gas which could be used for as a biofuel improving the overall energy balance.

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5.5. Processing of Fibre for Electricity & Process Energy

The second biomass stream produced by the diffusion of mill tandem lines is the bagasse. Bagasse has a number of potential uses including:

i combustion for heat and power

ii bulking agent for animal feed

iii particle board manufacture

iv paper production

The work here concentrates solely on the use of bagasse for the production of process heat and electricity which is the most common use for bagasse in the world's sugarmills. Table 5.1 shows the potential for electricity and steam production from two years of sweet sorghum trials and compares the sorghum-derived values with those for sugarcane, and therefore summarises much of the data from the results chapter.

Table 5.1 : Potential Energy Outputs from Sweet Sorghum

	KELLER		COWLEY		Sugarcane
Units	97/98	98/99	97/98	98/99	
t_{fab} ha^{-1}	77	48	80	50	150
t_{stems} ha^{-1} [a]	59	37	62	38	115
ERF [b]	0.13	0.11	0.15	0.11	0.15
Fibre [b]	0.11	0.12	0.12	0.14	0.15
litres Ethanol [c]	5101	2646	5964	2717	11213
MWh_e [d]	3.2	2.2	3.7	2.6	8.4
t_{steam} [e]	25.8	17.8	30.6	21.3	69.2
t_{steam} / t_{stems}	0.44	0.48	0.49	0.56	0.60

Notes:

a Calculated from fresh weight biomass data, as 77% of total above ground biomass is stems

b Mass fraction of stem fresh weight

c Ethanol fermentation efficiency is 65ml per 100g ERF

d Electrical production efficiency 11.6% energy content of fibre. Bagasse (50% moisture) has an energy content of 7.6 GJ/t.

e Boiler conversion efficiency is 76% on an energy basis. Steam energy content is 2.88 GJ/t_{steam}.

A number of important points are highlighted by Table 5.1, particularly when converted to specific production rates (daily basis) for comparison between sweet sorghum and

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sugarcane. For example, the derived daily rate of potential ethanol production for sweet sorghum varies between 24 and 54 l EtOH ha^{-1} d^{-1} and for sugarcane is 31 l ha^{-1} d^{-1}. Likewise, potential specific electricity production rates for sweet sorghum vary between 70 and 120 kWh ha^{-1} d^{-1} and for sugarcane 80 kWh ha^{-1} d^{-1}. Therefore, this data points out the high variability in sweet sorghum productivity compared to sugarcane as a result of its shorter growth period. It also highlights the potential for sweet sorghum which in good years is approximately 30% higher than sugarcane on a daily productivity basis. Given the historical lack of research and development into sweet sorghum compared to sugarcane, the potential for sweet sorghum can only improve if given sufficient R&D resources in the future.

A final point worth noting from Table 5.1 results from the expected lower average fibre content of sweet sorghum when compared to sugarcane. The lower fibre content is expected to result in a decreased steam output per tonne of stems processed from about 600 kg steam per t_{cane} for sugarcane to between 440 to 560 kg steam per t_{stems} which could have important ramifications for the overall energy balance from sweet sorghum. For example, an analysis carried out by Walter (1999) calculates that the average steam consumption for 96 electricity producing sugarcane-based sugar mills in Brazil is 504 kg_{steam} t_{cane}^{-1}. A similar calculation for Triangle Ltd. shows a requirement for 550 kg_{steam} t_{cane}^{-1} processed (Figure 21). Therefore, with the current configuration of equipment for steam production, Triangle Ltd. would probably have to raise its steam-use efficiency when processing sweet sorghum to avoid the need to import energy. That this is feasible and at minimal expense was confirmed during discussions with the Triangle Mill Engineer (MacIntosh, 1999) who stated that a steam efficiency of 450 kg_{steam} t_{cane}^{-1} could be achieved at Triangle with minimal redesign. This statement also demonstrates that the Mill steam use efficiency is manipulated to dispose of excess bagasse. However, if no crystalline sugar is manufactured the energy requirements to process a t_{cane} would decrease by approximately 50% and likewise the steam requirements, significantly increasing the potential to export rather than import energy (Tables 4.34 & II.21).

The AIP

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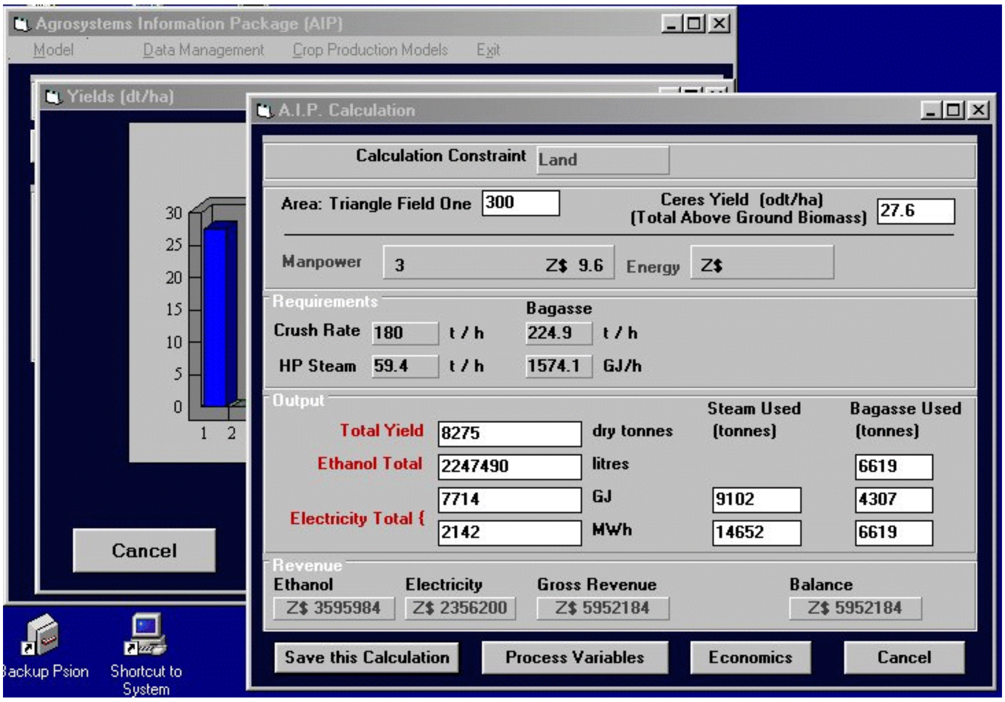

Fig. 33 AIP Calculation of Potential Ethanol and Electricity Production

The AIP calculates the potential electricity production in its standard configuration by using a boiler and a turbo-alternator conversion efficiency factor as shown in Figure 30. Once these factors are set as described in section 4.6.4. and the crop model has been run to provide the biomass, a calculation can be carried out, see Figure 33.

Novel technologies can be 'installed', for example gasification / gas turbines, by altering these factors to represent the new technology and the calculation re-run. For a full description of the factors involved in setting up the AIP to carry out a calculation such as the one shown in Figure 33, see section 4.6.4.3.

5.6. Energy Balances

For a biofuel production system to be successful it must demonstrate a strongly positive energy balance i.e. that the energy content of the biofuels produced is greater than the energy required to produce the biofuels (often dominated by fossil fuels). Through the work in this thesis a positive energy ratio of 1.9 has been derived for the existing

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sugarcane-based production of ethanol, electricity and crystalline sugar at Triangle Ltd. A predicted energy balance for ethanol and electricity only from both sugarcane and sweet sorghum of 3.3 to 4.7 was calculated (Tables 4.35 & 4.36).

The energy ratios calculated here are lower than other estimates, both for Triangle and for Brazil. For example, Macedo (1998) carried out a revised energy balance for ethanol production from sugarcane in Brazil for 1995/6, stating that the national average is calculated to lie between 9.2 and 11.2. Despite using a very different methodology, the energy balances calculated here closely match those calculated by Rosenschein and Hall (1991) for sugarcane-based ethanol production at Triangle Ltd. During the 1980's, they calculate an actual energy ratio of 1.9 and a potential with improvements in production efficiency of 4.1. Positive energy ratios for sweet sorghum to ethanol have also been published by Turhollow and Perlack (1991).

Whilst the integration of sweet sorghum with sugarcane could result in year round biofuel production, it seems possible that the integration will reduce the overall energy balance slightly (Table 4.36) unless other energy efficiency measures are adopted in parallel (see below). This reduction in the overall integrated energy balance will be caused by the introduction of an annual energy crop with its increase in energy intensity, primarily as a result of the need for yearly land preparation. Figure 34 shows that the energy requirement for the harvesting and tillage of sweet sorghum (15% of delivered total) are greater than sugarcane (8%).

It is estimated that total energy inputs for sweet sorghum growth and harvesting, which are essentially fixed energy inputs total between 17 and 18 GJ ha^{-1} (37 and 40 JG ha^{-1} for sugarcane) depending on the use of manual or mechanical harvesting (Table 4.33). Of this input energy, fertilisers represent the largest single component, with an energy cost of 5.9 GJ ha^{-1} or about 53% of total energy inputs (46% if mechanical harvesting is used). The other major energy input requirement for crop growth is tillage which is estimated to require between 2.4 and 4.2 GJ ha^{-1} depending on whether manual or mechanical harvesting methods are used or about 22 or 33%, respectively, of total energy inputs for crop growth and harvesting. In common with all biomass crops, both the energy balance and the economic viability of the system are very sensitive to the

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transport component. For example, for sweet sorghum with an average transport distance of 15 km (one way) about one third (30 and 33%) of the total energy required to produce and deliver the crop to the mill is consumed by haulage as shown in Table 4.33.

The two largest energy consumers for both sweet sorghum and sugarcane are the

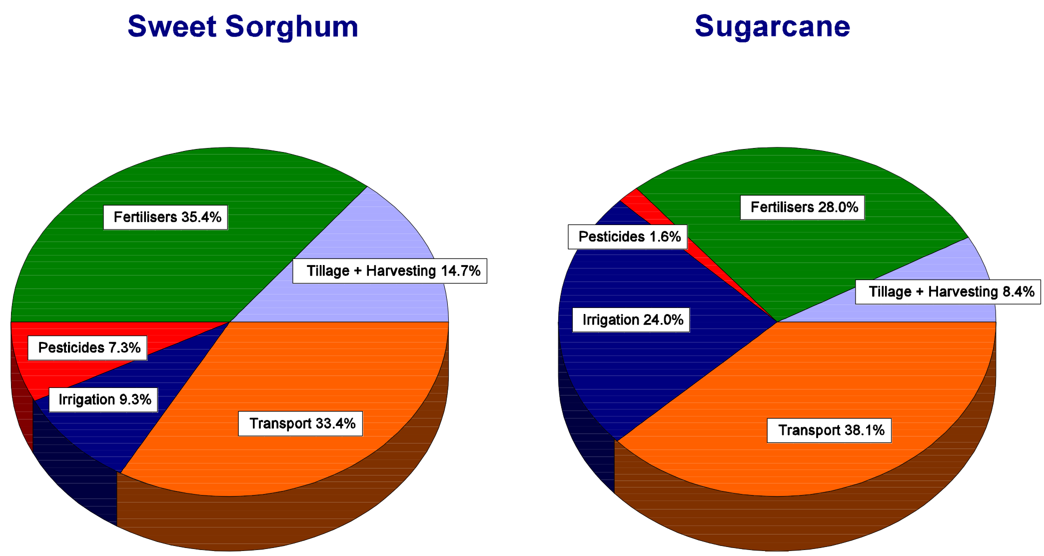

Fig. 34 Energy Inputs for Sweet Sorghum & Sugarcane Production and Delivery

fertilisers and transport inputs requiring approximately 70% of the total inputs; for both crops transport represents the greatest single energy input. The calculated fertiliser inputs for sweet sorghum are relatively high compared to sugarcane. However, it is believed that fertiliser requirements can be reduced substantially once a better understanding of the practical management of sweet sorghum is acquired from larger scale trials and commercial growth.

5.6.1. Energy Efficiency in Sugar Mills

The efficiency with which the energy in bagasse is converted into steam is only one of the key factors for successfully increasing the production of bioenergy in a sugarmill. Despite the bagasse boilers in sugar mills functioning as much to dispose of bagasse as to generate steam and electricity, improvements in electricity production for export will

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result in decreased amounts of heat energy available for process power in the mill unless the overall conversion efficiency is improved. Therefore, the efficiency with which sugarmills use steam to provide process power and energy must also be significantly increased. For example, the current average steam consumption for sugarcane mills around the world of 500 $kg_{steam}\ t_{cane}^{-1}$ will need to be decreased significantly to around 400 $kg_{steam}\ t_{cane}^{-1}$ if electricity production is to become a significant export commodity from sugarcane mills[21] (Gopinath, 1997; Walter, 1994). This reduced steam efficiency can be compared to the current steam consumption of Triangle Mill of 550 $kg_{steam}\ t_{cane}^{-1}$ and indeed decreasing steam use to around 450 $kg_{steam}\ t_{cane}^{-1}$ could be achieved at Triangle with minimal investment according to MacIntosh (1999). More efficient steam-use technologies exist but require expensive retrofitting.

Gopinath (1997) discusses the potential to retrofit Indian sugar mills for power production by increasing the steam pressure and temperature, new technologies, bagasse storage, etc. In fact, fifteen mills in India are already carrying out retro-fits funded by themselves and more are expected to do so. Typically, the energy consumption by Indian sugar mills is 500 kg steam and 30 kWh_e per t_{cane}, but highly efficient mills might reduce this to 300 kg steam and 15 kWh_e per t_{cane} processed. The major features of a highly efficient sugar mill are identified by Gopinath as:

1) Optimum boiler / turbine configuration,
2) Year round operation offering firm (baseload) power,
3) Alternative biomass fuels,
4) Energy efficient sugar processing,
5) Efficient bagasse / biomass storage handling and retrieval systems,
6) Effective grid interface systems.

With this kind of configuration, Gopinath believes that sugar mills can produce a surplus of power of 150 kWh_e (0.54 GJ) per tonne cane. The potential for power generation from surplus bagasse alone in the Indian sugar industry is estimated at about 3,500 MW_e and sixteen mills currently export 56 MW_e. This has proved that bagasse

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21 Data obtained for 96 Brazilian sugar mills (Walter, 1994) showed an average steam consumption of 504 kg steam per tonne cane processed.

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based cogeneration is commercially viable in India and adds revenue to the sugar mills.

Whilst an energy balance calculation is not yet possible within the AIP, these routines could be programmed using the methodology developed here. Once these routines are present in the AIP, the relative benefits of retro-fitting, to improve the efficiency and the potential to export electricity will be more easily evaluated on a site specific basis.

5.7. Economics

Evaluating the overall economics of an integrated sweet sorghum and sugarcane biofuel production system at the micro-level is beyond the scope of this work. However, because the economics of the system will be the final arbiter of viability, the key areas are discussed below. Firstly, however, it is important to state that the relative economics of sugarcane versus sweet sorghum are not the issue. Instead, the overall impact of integrating sweet sorghum with sugarcane with the eventual aim of near year-round biofuel production is the central theme. However, in order to achieve a realistic economic evaluation, a detailed audit evaluating the return on capital from the greater efficiency of use of equipment and labour would be required, and again this is beyond the scope of this work. Instead a partial framework for such an evaluation, which could be developed within the AIP is discussed below.

All biofuel production systems have to contend with the relatively low energy density of the raw biomass as grown and harvested. The low energy density of the raw biomass inevitably makes biofuel production systems sensitive to transport costs and hence distances. Overend (1982) carried out an analysis for the Canadian Forestry Department to calculate the average transport distances for biomass power plants based on forestry-derived biomass. Despite the differences between a forestry-powered biomass system and ethanol + electricity production from a sorghum / cane hybrid system, the basic mathematical functions remain true.

Overend's approach makes the assumption that a factory is situated in the centre of a circular catchment area from which its raw materials are derived. Assumptions must

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then be made concerning productivity, transport distances, costs per unit mass and unit distance, and a factor called 'tortuosity' which allows for the actual distance travelled to get to the collection point relative to the straight line distance as shown in section 4.5.2. Further developing Overend's methodology and still assuming a circular geometry, Nguyen and Prince (1996) have shown that transport distance (R) varies with the square root of plant capacity (P) i.e. $R \% P^{0.5}$ but that transport costs (C) vary with plant capacity to the power of 1.5 i.e. $R \% P^{1.5}$. Therefore, increasing plant capacity benefits from economies of scale within the conversion facility but is adversely affected by increasing transport costs. Increased productivities effectively reduce the land area requirements needed to meet the plant's capacity by reducing the average transport distance.

The impact of doubling the capacity of the Triangle Ltd's ethanol plant on estimated transport costs is calculated in Section 4.5.2 and shows that it would result in an increase in the costs of delivered biomass of over one third i.e. rising from US$ 1.46 to US$ 1.96 per t_{stems}. Clearly, given a fixed market value for ethanol even where significant economies of scale could be gained, increasing plant capacity will eventually result in a lack of viability purely as a result of increasing transport costs. By building this type of analysis into the AIP, an optimum capacity for a given site could be obtained by accounting for multiple variables such as:

- stem yield & biomass quality
- land availability
- climatic factors
- 'tortuosity'
- transport type and costs

The extreme volatility of sugar and ethanol markets will make calculating an optimum configuration for ethanol (& sugar) production difficult. Indeed, tools such as the AIP can be used to assess the sensitivity of production to key factors allowing a dynamic evaluation of the viability of production. Furthermore, it is considered that improvements are possible in the economics of sweet sorghum for ethanol production,

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when compared to the costs shown in Table 4.38. Successful ethanol production from sweet sorghum is dependent on good integration with sugarcane production, thereby optimising the use of equipment and resources during a period in which they would otherwise be unused. A detailed evaluation of the benefits of this integration will only be possible after the conversion parameters are better understood for sweet sorghum which should occur after the 24 hour diffuser trial to be held in March 2000.

Estimated Ethanol Production Costs from Sweet Sorghum

Depending on assumptions made regarding sweet sorghum productivity, biomass yield, ethanol yields and agronomic input costs, the estimated cost of ethanol from sweet sorghum varies between 18 and 89 US cents per litre under Zimbabwean conditions (Table 4.38). 1996 ethanol production costs from sugarcane molasses at Triangle Ltd. were about 20 US cents per litre, which can be compared with a US import price for ethanol of 35.6 - 36.9 US cents per litre. Much of this US ethanol is used in gasoline/ethanol blends, where the ethanol is used as an oxygenate.

A Global Market for Ethanol from Sweet Sorghum?

Sorghum-derived ethanol would be competitive with conventional gasoline if produced at a cost below USc 20 per litre of anhydrous ethanol even given today's low oil prices (approx. US$ 15 per barrel). The estimated low and mean costs (10 to 18 US cents respectively) for ethanol production from sweet sorghum would be competitive with current US gasoline prices. However this estimate is a production cost and not a delivered cost estimate (Table 4.38). Importantly, this estimated ethanol production cost is cheaper than the imported cost of gasoline into Zimbabwe, and the ethanol has a greater value on the World markets, especially if sold through a regional trade quota. For example, ethanol used as an oxygenate in gasoline formulations attracts a much higher value and has traded in world markets in 1996 at around US cents 35 per litre. World Ethanol Market prices for ethanol as an oxygenate are expected to decline over the next few years to around US cents 28 per litre (Berg, 1998b). At this price, ethanol from sweet sorghum would still remain profitable. However prices may fall further but this could stimulate demand.

For example, in Brazil which has recently substantially reduced its support for fuel

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ethanol prices, the price consumers pay at the petrol pump for neat ethanol has dropped to USc 22 l^{-1} i.e. 0.39 reals compared to a petrol price of 1.09 reals. Because of this price differential there is a renewed demand for ethanol-only vehicles and VW has restarted low volume production. In addition, trials are continuing in Brazil with blending of ethanol with diesel at 3% and 11% (Moreira, 1999).

At the macro scale, world sugar and ethanol markets are highly volatile and inter-related. The depressed market for fuel ethanol in Brazil leads Brazilian producers to switch to sugar production from ethanol production which, over recent years has coincided with depressed Asian markets for sugar as a result of the Asian economic crisis. Both markets are strongly controlled by quotas and ‘free’ trade agreements which makes establishing a reliable ‘World Market’ price extremely difficult, especially for ethanol (Berg, 1998b). Despite these ‘difficulties’, and the large scale of the existing ethanol production, Berg expects the market for biologically derived ethanol to expand from today’s level of production as discussed below.

In 1998, a total of 32.4 billion litres of ethanol were produced globally, of which 60% (19.4 billion litres) was derived from sugar crops i.e. sugarcane and sugarbeet. A further 33% (10.7 billion litres) was produced from grain crops, and the remaining 7% (2.3 billion litres) from synthetic resources, primarily natural gas. Over the last 20 years, the consumption of ethanol for fuel purposes has risen from about 20% (2 billion litres, 1980) to 66% (12.8 billion litres, 1998) of total production. This dramatic increase in the use of ethanol has been the main factor in the increase in total production of ethanol from 10 billion litres in 1980 to an estimated 35 billion litres by the turn of the century (Berg, 1998a). The increased demand for fuel ethanol has resulted almost entirely from the fuel alcohol programmes of Brazil, USA and more recently France, who have adopted these programmes in response to environmental and rural development pressures. Despite the size of these programmes, each of the three countries has highly protected internal markets and provides direct financial support to the ethanol price of between USc 12 and 60 per litre. The level of this support has not only created large and powerful internal ethanol producing industries, but has also obscured the real production price of ethanol.

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Given the recent concerns over climate change and the need to reduce GHG's, where bioethanol production can be demonstrated to be produced with a good energy balance (i.e. >2) then demand may increase significantly over the next decades. However, whilst the fuel alcohol markets are dominated by internal protection mechanisms both the world market price and trade will remain fragmented making a realistic economic evaluation difficult. (Berg, 1998b) This protectionism is likely to have the greatest effect on the developing country producers who have the lowest cost of production and highest energy ratios.

Electricity Costs & Value

Whilst the discussion so far has been dominated by ethanol and crystalline sugar production, the efficient use of the bagasse for electricity production has an important role to play for environmental, developmental and economic reasons. However, the supply of electricity to the local markets neighbouring sugar mills which are often heavily subsidised and centrally controlled, may be difficult. For example, until very recently, the Zimbabwean electricity price was set by law at about USc 2 kWh^{-1}. At this price the electrical utility (ZESA) could not afford to offer a reasonable purchase price for Triangle-derived electricity making the investment required by Triangle to ensure significant supplies of electricity for export from the mill unviable.

In addition, grid capacity in the area neighbouring the mills may be weak which could have both positive and negative implications for sugar mills wishing to supply significant amounts of electricity for export from the mill. On the positive side, sugar mills can be large embedded power generation facilities able to supply remote areas of a national grid. In this role, the sugarmill would help avoid expensive strengthening of the national grid as local demand develops. However, it does require that the sugarmill is able to supply secure year-round, base-load, electricity and may also need expensive interconnection equipment between the mill and the grid. The need to supply year-round reliable electricity often means that existing electricity generating and steam using equipment needs overhauling or replacing in order to minimise internal energy requirements and maximise electricity exports. In order to justify the expenditure required for this kind of retro-fit, stability in long-term electricity markets and a realistic price for electricity are needed. Whilst the potential for electricity generation from

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sugarcane mills is not disputed the conditions necessary for investment can inhibit the expansion of electricity production.

The economic evaluation by the mill owners must involve the relative benefits and rates of return from the costs of the retrofit, and this is where the greatest problem often lies. The scale of investment to supply electricity to the domestic market in rural areas usually ensures that only governments (particularly in developing countries) can raise the capital to develop such a supply infrastructure. The installation of rural supplies of electricity are not often governed by purely economic factors, with governments taking into account rural development and health issues in their assessments. The implementation of a free and fair market from both the producer's and consumer's points of view, is proving extremely difficult to achieve, even where the electricity market has been liberalised e.g. UK, Australia, and the EU. It is clear that achieving a reliable market for surplus mill-derived electricity production is a pre-requisite to retro-fitting. For example, expected costs in India to retrofit a mill are in the range of US$ 800-1400 per installed kW_e generating capacity, with a typical mill requiring 20 to 30 MW_e production capacity needing to invest US$ 16 to 42 million (Gopinath, 1997).

These cost analyses are based on the use of existing demonstrated technologies. However, the potential for gasification / gas turbine systems makes them very attractive, but only after the technology has been demonstrated to work at the appropriate scales of power production. Therefore, it is worth noting that these costs are generally extrapolated costs for the N^{th} plant, which tries to account for both the increased costs inherent in a 'first-of-a-kind plant' and mass-production economies of scale. For example, it is estimated that an 'Open Cycle' BIG/GT plant in Brazil (fired by plantation-derived Eucalyptus wood) will cost about US$ 1 500 to 1 300 per kW installed, generating electricity at USc 5 per kWh. The first plant is expected to cost around US$ 2 600 per kW_e (Waldheim and Carpentieri, 1998; Elliott and Booth, 1993).

Given the potentially large costs of retro-fitting a sugar mill, the sugarcane industry may find it difficult to embark on a large scale programme of retrofitting and adopting new technologies such as gasification. However, additional benefits which could be derived by raising the energy conversion efficiency, such as the reduction in atmospheric CO_2

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emissions, may prove important in developing and enabling policy framework for the sugarcane industry. Furthermore, if the growth of the biomass is well-managed and shown to be sustainable, net emissions of CO_2 are close to zero[22]. In fact, net CO_2 emissions can be regarded as negative if the increased power production derived from the biomass substitutes for the energy that would otherwise have been produced by inefficient use of fossil fuels i.e. the so-called "carbon substitution" benefits.

5.8. Modelling

The development of the AIP is not 'complete' and it is doubtful, given the nature of the role anticipated for this type of systems analysis model/tool that it will ever be complete. The AIP is described in more detail in section 4.6.4. With further development, it will be able to calculate energy ratios, logistics, and resource requirements (eg. manpower, water, fertilisers, etc.,) once provided with the land area available for sweet sorghum growth and the time of planting. Presently, the user must insert an available land area and is provided with the outputs described above. The AIP has been programmed in a modular way specifically to allow the development of each individual module as befits a specific situation. This approach was highly successful in the development of the CERES crop models and it is hoped that if the AIP is successful, it can follow a similar model of development where individual groups can develop the modules most closely describing their areas of interest whilst passing on their development expertise for the development of the model as a whole. It is described in detail on the author's web site and is available as a Windows installable package on request. However, an important lesson from the development of the CERES models is that increasing complexity does not necessarily lead to increased accuracy in the predictive capability of models primarily as a result of increase in possible sources of error.

Initially, it was envisaged that the AIP will be used for two types of calculation:

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22 CO_2 emitted during combustion of the bagasse is re-absorbed by the re-growth of the crop during the next season.

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1. ‘What if?’ types of application i.e. what if 300 ha was available
2. ‘Optimisation’ i.e. crop or mill management schedules

In the what-if scenario, the crop production module plays a useful role by responding in a realistic fashion to variations in climate or management inputs providing an estimate of sensitivity of crop production to these factors, without the need for detailed “validation” of the crop model functions. The role of the crop production module for optimising the energy production chain will require more accurate prediction of total biomass production in order to reduce the error in the prediction of likely biomass quality from total above ground biomass production i.e. total sugars, sucrose, and fibre.

In the Crop Production module, crop growth is described through mathematical functions which describe the inter-relationship between:

< Solar Radiation
< Temperature
< Soil type
< Genetics
< Water
< Nutrients
< Management of pests, diseases, and competition for resources

These relationships moderate photosynthesis, carbon assimilation, and partitioning, and therefore, crop growth. Mathematical relationships, defined by the interaction between variables which describe the physiological and genetic characteristics of a variety, describe crop growth in response to water and nitrogen inputs, climate, soil type and management.

According to Boote (1996b) the driving variables for Crop development are:

1. Temperature
2. Photoperiod

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Limiting factors to development are:

< Water status

< Food supply (weak)

< Nutrient supply (N, P, & K- weak)

The effect of stress on the crop is to delay the onset of reproductive growth and to accelerate maturity, and therefore, “development is not very dependent on growth rate” (Boote, 1996b). Instead, thermal time is the primary driver for crop development and controls development in conjunction with photoperiod sensitivity in sensitive crop types.

The insensitivity to photoperiod of some sweet sorghum varieties (El Bassam, 1998) means that the crop growth is driven by thermal time and not affected by day length. Various refinements to the calculation of thermal time have been devised, but at its simplest thermal time (degree days) is calculated as the daily average temperature above the base temperature set for sweet sorghum at 9EC i.e. any day whose daily mean temperature (tmax+tmin/2) is above 9EC, has the number of degree days calculated as the daily mean temperature (i.e. a daily mean temperature of 20E C would accrue 20 degree days for that day.) Therefore, if the average daily temperature is sufficiently high (>9E C, preferably >20E C and <35E C) the sweet sorghum will continue through each of the growth stages to maturity when other crops, including sugarcane remain dormant at a specific growth stage until the correct photoperiod occurs. For crop models the concept of thermal time is central to driving crop growth, with each stage of growth being driven by accumulated degree days. Photoperiod and stress factors such as water and nitrogen stress usually interact with thermal time using a crude “on/off” switch by stopping thermal time accumulating (even if above base temperature) if a preset “stress” or photoperiod threshold is not reached.

The interaction between thermal time, photoperiod, and water / nitrogen stress and variety-specific genetic factors form the basis of the CERES crop model, dictating the rate of canopy establishment and carbon assimilation. More recent versions of the models allow a subtler approach to the “on/off” switch approach to stress management,

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and incorporate modules for other nutrients (primarily P and K), soil organic matter dynamics and better soil water routines. However, the essential mechanism for crop growth is still based on accrued thermal time. Further refinements include the ability to track soil organic matter and water over periods longer than one season or year allowing the effect of crop rotation, fallow periods, and residue removal to be modelled. Therefore, photoperiod and thermal time are crucial in defining the period of industrial utilisation (PIU) and the growth duration to reach PIU as shown by Figure 28, section 4.6.3.4.

The period of industrial utilisation (PIU) dictates the time-window available for the use of sweet sorghum, as this peak in sugar production in the crop can be managed to occur before the equivalent levels arise in the sugarcane. The relatively more rapid growth rate of sweet sorghum compared to sugarcane and the lack of photoperiod sensitivity in many varieties of sweet sorghum allows the planting to be managed to produce a total PIU for the entire sorghum crop of about 2 months prior to the initial harvesting of the sugarcane under Zimbabwe conditions. Using the AIP, as shown in Figure 28, the expected yields and planting dates for the provision of sweet sorghum throughout the year including the off-crop can be calculated. A similar PIU for sweet sorghum is given by the Energy Authority of NSW (1986) in a study of potential for fuel ethanol production, predominantly from sugarcane, in the northern area of New South Wales, Australia.

In this thesis the AIP has been used to help define the integrated sweet sorghum and sugarcane system and has proved a useful tool primarily through helping to define the factors which govern the PIU of sweet sorghum. Its application in the various parts of the production and processing chain have been discussed as the issues arose and so will not be discussed again here. The integration of a CERES-Sugarcane type model, one of which is under development at the Mount Edgecombe SA Sugar Association's Experiment Station, will allow the AIP to be used directly in assessing the impacts of the integration (Hoogenboom *et al.*, 1999; Inman-Bamber, 1991).

The future utility of the AIP lies in its ability to encompass the complete production and conversion chain accounting for the impacts of a change in management or the use of

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new equipment at one point of the chain on another part of the chain. The use of the integrated crop models enables the AIP to be site specific, and with sufficient data, the impact of implementing the integrated system at new locations can be evaluated. Despite its development being at the early stages, it is already useful in assessing the feasibility of integrating sweet sorghum with sugarcane and continued development will make the AIP into a practical tool for implementing sweet sorghum systems around the world.

5.9. The Future for Sweet Sorghum

Sweet sorghum's future may lie in a number of directions. Where water supply is constrained then it may be used for sugar and energy production and grown as a stand-alone crop. If temperature constraints allow, then sweet sorghum may be grown in one or two cropping cycles per year. It also has a major role to play as a fodder crop as is now occurring in China for large-scale dairy production around Beijing (Li, 1997). The focus of this thesis has been to assess the potential to integrate sweet sorghum with sugarcane to extend the processing and therefore biofuel production season to a virtually year-round operation. That this is theoretically possible has been demonstrated through the small scale agronomic and industrial trials carried out in Zimbabwe and discussed above. The practical demonstration of the processing and production of biofuels from sweet sorghum at a meaningful scale will take place at Triangle Ltd. in March 2000, and allowing for the natural variability in any agricultural product, few problems are foreseen. Therefore, in terms of the potential for improving the integration of sweet sorghum with sugarcane for biofuel production the future development of sweet sorghum must concentrate on:

- improved cultivars
- novel cultivars, possibly derived from local germplasm. A comprehensive survey of indigenous sweet sorghum germplasm is urgently needed.
- improved or novel conversion technologies (relevant to both sweet sorghum and sugarcane).
- a better understanding of the impacts of large-scale growth of sweet sorghum on

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sugarcane land.

Land Area

The potential land area available for sweet sorghum on sugarcane estates is limited and may not be sufficient to meet the mill's full-capacity out of the sugarcane harvesting season. As a result, novel sources of land may be needed for sweet sorghum production during the off-crop. Sorghum's tolerance to environmental stress means that it is widely grown throughout Africa in drought prone regions. For this reason it is grown by many poor farmers in Africa, and Central and South America, making them good candidates for the production of sweet sorghum off the sugar estates. Whilst there is the potential to produce significant amounts of additional ethanol from sweet sorghum on existing fallow sugarcane land, the potential for wider expansion through the growth of sweet sorghum by small scale farmers as a cash crop should be explored. However, transport distances from the point of harvest to the mill are critical for economic production of ethanol. Therefore, alternatives to the agro-industrial system proposed above need to be considered.

One possibility is the growth and harvesting of sweet sorghum off the sugar estates by small holder farmers. In this system, it is envisaged that the sweet sorghum stems will be crushed locally and only the juice will be transported to the mill. This is because on-site crushing in or near the field would considerably reduce the mass of material to be transported to the mill, effectively increasing the sugar content of the transported material. It may, however, be offset by the cost of small scale mobile crushing equipment and the need to use the residues to pasteurise the juice before transportation. Whilst the bagasse may be used locally for energy production, the supply of raw juice to the mill without the associated 'bagasse' means that the mill will need to supply the energy to process the juice. Clearly, further work is required to evaluate the use of sweet sorghum off the sugar estates in order to ensure that it is sustainable and profitable.

5.9.1. Biofuel Conversion Systems

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The conversion of ‘raw’ biomass to modern biofuels often results in the loss of more than 50% of the energy content of the original energy carrier, so why is this conversion necessary? The fundamental reason behind the need to convert raw biomass to more flexible energy carriers is the demand for modern energy services which are safer, more convenient, and less damaging to health. The real demand is not for energy per se but for energy services including lighting, cooling, heating, transport. The convenience of electricity is why it dominates the energy supply market. However, electricity has still not directly penetrated some energy supply areas such as household heating and transport because it is difficult to generate economically at the 1 to 100 KW_e scale. It is still, simply too inconvenient at the household level (5 to 10 KW) to utilise fuels such as wood, coal, or even gas at these scales to produce electricity to supply all the energy services needed. However, the benefits from large-scale electricity production systems of the 500 MW_e or more scale are now being questioned by energy planners and policy makers. This is partly because the economies of scale promised when these power-producing giants were being built have not been fully realised, the cost of transmission from such large and centrally located plants is extremely high as there are significant transmission losses, and the cost of maintenance of a national electricity grid is also very high (Feinstein *et al.*, 1997).

The development of smaller-scale ‘embedded’ electricity supply systems are now beginning to be evaluated because such plants are closer to demand and larger numbers of smaller generating plants are inherently more stable than small numbers of large generating plants (Williams and Larson, 1993). This change in scale is more appropriate to biomass energy technologies and is of particular relevance to sugarcane sugar mills which want to invest in new technologies to increase their efficiency and electricity production potential. As discussed previously, novel technologies such as BIG/GT are potential candidates, and the AIP is able to account for these technologies through the ‘Energy Conversion’ module discussed in Section 5.5. Novel technologies which are potentially applicable to the integrated sweet sorghum and sugarcane system are discussed below.

Co-firing

A second method to increase the production of energy during the off-crop could be ‘co-

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firing'. This is a modern practice which has allowed biomass feedstocks an early and cheap entry point into the energy market and is the practice of co-firing a fossil-fuel (usually coal) with a biomass feedstock. Co-firing has a number of advantages, primarily by guaranteeing the supply of electricity during the off-crop. If the agro-processor can guarantee electrical supply year-round through the burning of alternative fuel supplies (i.e. coal and bagasse in Mauritius) then it will make efficient use of its equipment and will receive premium payments for its electricity by the distribution facility (GEF, 1992).

Table 5.2: Thermochemical Conversion Technologies and Products

Technology	Temperature °C	Pressure Atm	Oxygen % Stoichiometric	Product
Combustion	900 - 1100	1	>120	heat
Gasification	800 - 1200	1 - 20	25	gas
Fast Pyrolysis	500	1	0	liquid
Liquefaction	300	30	0	liquid

a. taken from Bridgwater (1997)

5.9.1.1. Thermochemical Processes for Biomass Upgrading

These processes do not necessarily produce useful energy directly, but under controlled temperature and oxygen conditions are used to convert the original biomass feedstock into more convenient forms of energy carriers (fuels), such as producer gas, oils or methanol. These biofuels are either more energy dense and therefore reduce transport costs, or have more predictable and convenient combustion characteristics allowing them to be used in internal combustion engines and gas turbines. Kaltschmitt and Dinkelbach (1997) suggests there are three main thermochemical processes of relevance to biomass upgrading i.e. i) charcoal production, ii) gasification, and iii) pyrolysis. A fourth technology which might be added to this is "liquefaction" where biomass is subjected to high pressure (30 atm), 0% oxygen levels and relatively low temperatures (300°C) which liquefies the biomass. However, this technology is still in its infancy and won't be discussed further (Bridgwater, 1997).

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Gasification

Gasification technology has existed since the turn of the century when coal was extensively gasified in the UK and elsewhere for use in power generation and in houses for cooking and lighting. Gasifiers were also used extensively for transport in Europe during World War II due to shortages of oil, with a closed top design predominating.

High temperatures and a controlled environment leads to virtually all the raw material being converted to gas. This takes place in two stages. In the first stage, the biomass is partially combusted to form producer gas and charcoal. In the second stage, the CO_2 and H_2O produced in the first stage is chemically reduced by the charcoal, forming CO and H_2. The composition of the gas is 18 to 20% H_2, an equal portion of CO, 2 to 3% CH_4, 8 to 10% CO_2, and the rest nitrogen (Makunda *et al.*, 1993). These stages are spatially separated in the gasifier, with gasifier design very much dependent on the feedstock characteristics.

For gasification technologies, the end of use of the upgraded biomass product is critical in the design of the gasification system as it dictates the quality of the output gas in terms of energy, particulates, alkali, tar, NO_x and dust, contents. Unfortunately there is a complex interplay between these requirements as increasing the temperature to crack tars results in an increased likelihood of ash sintering, increased levels of NO_x, and a decreased energy content of the gas (Rensfelt, 1997).

The use of BIG/STIG (Biomass Integrated Gasifier STeam Injected Gas turbine) initially and BIG/GTCC (Biomass InteGrated Gasifier Gas Turbine Combined Cycle) as the technology matures, is predicted to allow energy conversion efficiencies of 40% to 55%. Modern coal electrical plants have efficiencies of about 35% or less. Combined Heat and Power systems could eventually provide energy at efficiencies of between 50% and 80%. The use of low-grade feedstocks combined with high conversion efficiencies makes these systems economically competitive with cheap coal-based plants and energetically competitive with natural gas-based plants (Johansson *et al.*, 1993; Williams and Larson, 1993).

The introduction of gasification (directly coupled to gas turbines) is expected to

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increase electricity production by three times and decrease steam production by a third. As a result, steam consumption would need to be reduced from 570 kg t_{cane}^{-1} to 365 kg t_{cane}^{-1} if gasification were to be implemented at Triangle Ltd. as the sole source of electricity generation from bagasse. At the same time, electricity production would be increased from the current maximum potential of 35 MW_e to 108 MW_e assuming a cane processing rate of 490 t_{cane} h^{-1} producing 142.1 $t_{bagasse}$ h^{-1} as shown in section 4.4.1.

However, the development of bagasse fed gasification systems have not been without their problems. The main problem is with the development of reliable fuel feeding systems. For these feeding systems to be able to supply the gasifier with a continuous and reliable stream of bagasse, the bagasse will probably need to be dried to well below the 50% moisture content of fresh bagasse exiting the crushing systems. Fortunately, as Matthews (1999) has shown, bagasse drying systems heated by the flue gas from the boilers are already an established technology. Indeed, these flue gas driers can deliver significant benefits to existing conventional bagasse boilers in terms of energy outputs and it is not anticipated that bagasse drying systems will present a significant barrier to the implementation of gasification systems.

Pyrolysis

The biomass feedstock is subjected to high temperatures at low oxygen levels, thus inhibiting complete combustion, and may be carried out under pressure. Biomass is degraded to single carbon molecules (CH_4 and CO) and H_2 producing a gaseous mixture called "producer gas." Carbon dioxide may be produced as well, but under the pyrolytic conditions of the reactor it is reduced back to CO and H_2O; the water further aids the reaction. Liquid phase products result from temperatures which are too low to crack all the long chain carbon molecules so resulting in the production of tars, oils, methanol, acetone, etc. Once all the volatiles have been driven off, the residual biomass is in the form of char which is virtually pure carbon.

Pyrolysis has received attention recently for the production of liquid fuels from cellulosic feedstocks by "fast" and "flash" pyrolysis in which the biomass has a short residence time in the reactor. A more detailed understanding of the physical and chemical properties governing the pyrolytic reactions has allowed the optimisation of reactor conditions necessary for these types of pyrolysis. Further work is now

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concentrating on the use of high pressure reactor conditions to produce hydrogen and on low pressure catalytic techniques (requiring zeolites) for alcohol production from the pyrolytic oil. (Bridgewater, 1997) Its application to sweet sorghum and sugarcane bagasse is as yet un-tested but may have a role in the future for liquid fuel production if costs can be significantly reduced.

5.9.1.2. Ethanol Production

Industrial fermentation processes are efficient processes with by far the largest proportion, over 60%, of carbon losses resulting from the unavoidable growth and respiration of the yeast. By contrast, about 10% (Table 4.31) of the carbon in the fermentable sugars is lost in the delivery and processing of the biomass. Therefore, whilst some improvements in efficiency of ethanol production are possible by improving the delivery and processing techniques, significant increases in the conversion efficiency could only be delivered by changing the fundamental fermentation technology in order to reduce the respiratory losses arising from the yeast-based process. Technologies which can increase the fermentation efficiency are being developed, including thermophylic systems, but none of these technologies is yet proven to be commercially viable.

Methods to overcome problems with stillage disposal could include anaerobic digestion of stillage which decreases COD and BOD making direct release into the rivers feasible. Another method might be the adoption of fermentation / distillation processes which inherently produce less stillage e.g. the biostill process. The technical feasibility of using biodigestion to treat stillage has been demonstrated in Brazil , and indeed, in a number of Brazillian mills and distilleries these systems have been in use on a commercial scale for a number of years (Cortez *et al.*, 1998).

5.9.2. Sweet Sorghum and Triangle Mill

The work outlined here has demonstrated the agronomic and technical integration of sweet sorghum with sugarcane at Triangle Ltd. is feasible. Furthermore, the economic

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potential is positive, but more work is required to demonstrate clearly that there are significant long term economic benefits to be gained by integrating sweet sorghum with sugarcane. The economic, social and environmental benefits which could be gained from the proposed system have the potential to aid the development of the region. The developmental benefits will be strengthened if sweet sorghum can be grown away from the sugar estates on small-holder farms and sold to Triangle Ltd. as a cash crop.

A number of obstacles to implementing an integrated sweet sorghum and sugarcane system exist. However, all of these obstacles can be overcome without substantial capital expenditure. The main obstacle is non-technical. It arises from the understandably risk-adverse nature of much of the sugar industry. However, Triangle Ltd. has shown a highly innovative and open minded approach to the potential for the use of sweet sorghum, having instigated the research in Africa into its use at the industrial scale.

Sweet sorghum could be introduced into Triangle mill almost immediately at a relatively modest scale and indeed 10 000 t_{stems} of sweet sorghum will be processed by the diffuser 23rd March 2000 in a 24 hour continuous (sorghum-only) run. This run will demonstrate that sweet sorghum is a viable feedstock for industrial scale processing and allow the optimisation (by calibration) of the process flows within the diffuser.

Through this research and the EU and CFC funded projects participated in by the author, sweet sorghum has reached the point where it can be regarded as a viable feedstock for bioenergy and possibly crystalline sugar production by the management of Triangle Ltd. However, it is likely that the Triangle management currently view sweet sorghum as:

i) an alternative feedstock if future droughts threaten sugarcane production
ii) a rotation crop which still allows the production of sugar whilst managing important sugarcane-based pests such as ‘Eldana’ and Ratoon Stunting Disease.

However, there is considerable potential to develop sweet sorghum for roles outside these niches by isolating and developing new sweet sorghum germplasm with higher

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yields and biomass quality characteristics. It is highly likely that indigenously bred and grown sweet sorghum germplasm will have superior productivity and quality characteristics for southern Africa compared to the varieties currently being assayed which are predominantly US and Asian varieties. Beyond the on-estate role for sweet sorghum discussed in this work, a major role for sweet sorghum exists in helping the development of the rural communities of Zimbabwe and indeed southern and central Africa, where it could be used as a cash, fodder and food crop and a source of modern bioenergy.

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6. CONCLUSIONS

The conversion of sweet sorghum and sugarcane to modern biofuels which can be sold through general energy markets was evaluated from the perspective of the complete production chain. This evaluation has focussed on the potential to grow and harvest sweet sorghum so that it can be processed out of the sugarcane processing season, thereby elongating the overall season to a near year-round operation. It necessitated the development of a computer-based systems analysis model, the 'Agro-systems Integration Package' (AIP) and the construction of a life-cycle energy balance.

The potential for the integration of sweet sorghum with sugarcane has been evaluated in detail in terms of:

1. Productivity and agronomic scheduling, and
2. Processing (including harvesting and transport)

The evaluation has resulted in the conclusion that sweet sorghum is capable of being grown to supply sugar mills throughout the off-crop period which is primarily a result of its lack of photoperiod sensitivity when compared to sugarcane which is photoperiod sensitive and therefore, seasonal. Furthermore, existing sugarcane equipment, management techniques and biofuel markets can be used for sweet sorghum, although significant increases in electricity production for export from a mill will require planning and investment. In fact, the most likely energy products from an integrated sweet sorghum and sugarcane system would not differ from the existing outputs from those of a sugarcane-based ethanol producing sugar mill i.e. electricity and ethanol

The application of a systems analysis approach through the development of the AIP has allowed the complete process chain to be integrated within the AIP (really two models with a combined interface and data set). The AIP is a useful tool for assessing the potential for the integration of sweet sorghum across a range of locations using existing and novel technologies. With further development, it is expected that the construction of the AIP in a modular form will allow parallel development and use in assessing the potential for implementing an integrated sweet sorghum and sugarcane system in other

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locations.

In addition to the positive impacts to be derived from the integration there will also be negative impacts and consequences which require further evaluation. For example, a shorter 'off crop' period will reduce the time available for re-furbishing the mill. The impacts of a shorter refurbishment period (or none at all) are not well understood and will need detailed evaluation. This evaluation will need to incorporate a cost-benefit analysis covering the expansion of capacity so that parallel maintenance could be carried out without requiring the entire process to be shut down.

Sweet sorghum's shorter growth season will make the yields achieved inherently more variable than sugarcane, and this variability will need to be incorporated into planning. Whilst variability does exist within any agricultural production system, the perennial nature of sugarcane ensures that variability is minimal when compared to short duration annual crops like sweet sorghum. However, it is expected that continued research and development (including breeding) will reduce the variability in the yields produced by sweet sorghum and that large-scale commercial growth will improve crop management techniques, again reducing variability in yields.

Perhaps a more important problem will be the disposal of residual stillage from ethanol production from sweet sorghum during the rainy season. The inability to dispose of stillage via irrigation during these months and the limited storage facilities for stillage when combined with tighter environmental controls on effluent disposal mean that stillage disposal has become an important factor in ethanol production. Technologies exist to treat stillage and the pre-treatment of stillage prior to disposal needs further work.

It is accepted that the availability of land is a constraint on sugarcane estates, with the areas of fallow land available during suitable periods being too small to allow sufficient quantities of sweet sorghum stems to be grown to operate the mill at full capacity during the off-crop. The evaluation of other potential sources of land has highlighted the potential for small-holder farmers to grow sweet sorghum as a cash crop. However, future expansion of sweet sorghum production to small-holder farmers will require

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more research but has considerable potential for development of rural communities including village level electricity generation and new cash crop.

Modern energy conversion technologies such as the gasification systems discussed above could have a considerable impact on the costs and benefits to be derived from the integrated sweet sorghum and sugarcane system. These benefits may include:

- embedded power generation,
- the provision of rural supplies of electricity,
- better energy ratios than other biomass energy crops or sugarcane alone,
- decreased environmental impacts, and
- overall benefits to the environment at the local, national, regional and global level, particularly the production of carbon neutral biofuels.

The historic lack of R&D into sweet sorghum, particularly in comparison to sugarcane needs to be addressed. Future development of sweet sorghum could promote the use of sweet sorghum to new levels, maximising its potential by exploiting its high RUE, NUE and WUE. Better varieties, in terms of sucrose purity for on-estate growth are required but different characteristics will be required for off-estate grown sweet sorghum. The work here has shown that sweet sorghum is capable of being processed by existing sugarmills, and that an opportunity exists for its processing during the off-crop. Future work will need to establish the potential for sweet sorghum outside the sugar estates and show that its growth and the products derived from it will be beneficial. Much of the future of sweet sorghum lies through the development of the existing germplasm. However, sweet sorghum is grown extensively by communal farmers and there undoubtedly exists the exciting potential of this broad genetic base to select new varieties of sweet sorghum with even better characteristics. This is where the real potential of sweet sorghum lies.

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