The potential for energy production using sweet sorghum in southern Africa

Jeremy Woods
Life Sciences, King's College London, SE1 9NN, UK

Biofuels feature strongly in scenarios predicting future energy supplies because they can be produced anywhere plants grow, they are not intermittent and they can supply liquid fuels to the transport sector without major modifications to the existing infrastructure. Sweet sorghum can be used to supply both electricity and liquid fuels (i.e., ethanol) and recent agronomic and industrial trials in Europe, Asia and Africa have demonstrated its productive potential.

The potential for the production of bioenergy in southern Africa using sweet sorghum (Sorghum bicolor L. Moench) is evaluated in this paper. The evaluation is based on eight years of agronomic trials at the Lowveld Research Station and two full-scale industrial processing trials in 1999 and 2000 at Triangle Sugar Mill in southeast Zimbabwe. Under the existing conditions in SE Zimbabwe, varieties and technologies, sweet sorghum can produce 60 fresh weight t of above-ground biomass per hectare in 120 days growth. The resulting 46 t of fresh weight stems can produce 3000 l per hectare of anhydrous ethanol and 12.6 GJ electricity (3.5 MWh_e at 15% conversion efficiency). Whilst roughly 10% of the land area of sugarcane estates would theoretically be available for sweet sorghum growth at any one time, in the future, the main potential for the use of sweet sorghum is in the villages and small-holder farms. The remote and small-scale nature of this type of production poses a considerable challenge to identifying appropriate technologies and markets for the use of the products.

Significant quantities of both liquid fuels and electricity could be produced from sweet sorghum in southern Africa, calculated here to be about 3% of the region's electricity consumption and one-third of the liquid fuel consumption (gasoline and diesel). This level of bioenergy production would require that the equivalent of 1% of existing cropland (arable + permanent) was dedicated to the growth and processing of sweet sorghum.

1. Introduction

This article evaluates the potential for bioenergy production through new agriculturally-based bioenergy systems that integrate sweet sorghum (*Sorghum bicolor* L. Moench) with sugarcane to improve:

- the length of the harvesting season;
- the efficiency of production of ethanol and electricity; and
- the efficiency of use of land, water, equipment, personnel, and other resources,
- and to act as a mechanism to aid rural development.

It is becoming widely accepted that biomass will provide modern energy services (light, heating, cooling, etc.) well into the next century [Hall, 2000; Nakicenovic et al., 1998; Shell, 1996; IPCC, 1996]. Furthermore, its widespread use could result in a number of secondary benefits being derived [IPCC, 1995; Woods and Hall, 1994; Hall et al., 1993; Johansson et al., 1993; AFREPREN, 1997]. These benefits include:

1. sustainable rural development with job creation;
2. a strong complementarity to other intermittent renewable energy sources;
3. improved health for rural populations resulting from access to clean fuels for lighting and cooking; and
4. the potential to increase food production through the provision of locally reliable supplies of power for agriculture (e.g., irrigation) when integrated with bioenergy.

The use of sweet-stemmed crops (including sweet sorghum) to provide liquid fuels for the transport sector is not a new concept [Rothman et al; 1983]. However, the economics of liquid biofuel production are still hotly debated [Bauen, 2000] despite 25 years of large-scale experience in Brazil and other major projects elsewhere, e.g., the USA. The arguments often centre around ethanol's production in either the northern temperate climates that dominate Europe or on corn-based ethanol production in the US. The climatic conditions of Europe mean that it is difficult to take advantage of C_4 type crops such as sugarcane and sweet sorghum, which are inherently faster-growing and more efficient in their use of solar radiation under warm conditions than C_3 crops. In the US, the dominance of ethanol production based on corn, a starch-rich C_4 crop, requires the hydrolysis of the starch to more easily fermentable sugars and so is also less efficient than the use of sugarcane, resulting in a lower energy ratio and raised ethanol production costs.

In the tropical and sub-tropical climates of southern Africa, C_4 crops thrive and a large, well-established sugar industry based on sugarcane has been developed with some mills also producing ethanol from the molasses by-product. However, as with most agricultural production systems, the sugarcane based sugar industry is seasonal, with the harvesting season often lasting about 9 months of the year. Out of the harvesting season, the mill and associated harvesting, transport and processing infrastructure remain idle or are dismantled for refitting before the next season. Because of a number of beneficial characteristics of sweet sorghum outlined below, it can be grown to be harvested and processed during this "idle" period. The additional growth of sweet sorghum outside the sugar estates by small-holder farmers for processing by sugar mills outside the sugarcane season would allow these farmers to access the infrastructure and markets of this huge agro-industry, so aiding rural development.

A preliminary economic analysis carried out by the author suggests that ethanol production derived from sweet sorghum at Triangle Ltd, Zimbabwe, would cost US¢ 19 per l to produce [Woods, 2000]. This production cost is well below the current global market price for ethanol of between 30 and 35 US¢ per litre and even below Brazil's current market price for ethanol of 25 to 27 US¢ per litre [Woods, 2000; Rosillo-Calle, 2000]. The same analysis was unable to derive a cost for bagasse-based electricity production because of the way bagasse is costed within the mill. However, it would undoubtedly be less than the cost for imported hydro-electricity which currently costs Zimbabwe around 7 to 9 US¢ per kWh [Woods, 2000]. It should also be pointed out that these cost estimates are based on the existing conditions and facilities at Triangle Ltd's mill. This mill, like all other sugar mills in southern Africa, has a considerable potential for raising conversion and steam-use efficiencies and so increasing electricity production and decreasing costs in the longer term.

2. Why sweet sorghum?

Sweet sorghum is one of an increasing number of crops that can be used to produce bioenergy at practical scales for rural communities and industries. The sugars obtained from the sugar-rich stems can be extracted and fermented to produce ethanol for use as a liquid fuel, primarily for transport purposes. Ethanol can also be used in ethanol-fuelled lights and cookers. Electricity is currently a by-product of sugarcane-based crystalline sugar production and is generated from the combustion of sugarcane bagasse. However, in the future, it may become one of the primary products as more efficient generating technologies are introduced [Walter, 1994; Gopinath, 1997]. The fibrous residues obtained from the extraction of sugars from sweet sorghum stems have similar properties to sugarcane bagasse and can be used in the same way as sugarcane bagasse to produce electricity, process heat and power [Woods, 2000].

Generally, when sorghum is considered as a crop, it is the "grain" rather than the "sweet" varieties of sorghum that are highlighted. In the poorer regions of many developing countries, grain sorghum provides the staple food for both humans and livestock [NAS, 1996].

Sorghum has now been bred into 4 distinct groups [Li, D., 1997; Doggett, 1988]:

- grain (flour, beer);
- fibre (fibre board, paper, cardboard, etc.);
- multi-purpose (grain, sugars, fibre, fodder); and
- sweet (primarily sugars).

Sorghum's robustness is the main reason that it has been the crop of choice for farmers in drought-prone regions, being able to survive low water and nitrogen (fertiliser) inputs and also being relatively tolerant to salinity and drought stress. This survivability characterises the use of grain sorghum. However, the fibre, multi-purpose, and sweet types are being developed to play an active role in engendering development as opposed to the crisis management role that is often the lot of grain sorghum. Generally, the primary aim with the non-grain types of sorghum is to optimise the productivity of high-quality products to sell as cash crops e.g., fibre for paper and board products, sucrose for syrup, sugar and ethanol, and starch for food and industrial products. Only the sweet varieties of sorghum, which maximise the potential for ethanol production, are considered here. Sweet sorghum provides high biomass yields (Table 1), which are essential for good economic and energy returns. However, unless key biomass "quality" thresholds are attained, sweet sorghum may be too difficult to process in existing sugar mills without major modifications. These key "quality" parameters are the following.

- Polarity (POL), a measure of the sucrose content of the juice. Greater than 9% in juice is generally considered the minimum required POL for crystalline sugar extraction but extractability is also dependent on sucrose "purity", see below.
- BRIX, a measure of the total dissolved solids content of the juice. 12% in juice or higher is generally required. BRIX includes sucrose (POL), reducing sugars (RS; non-crystallisable but fermentable sugars) and other dissolved solids (UF) which are neither crystallisable or fermentable.
- Sucrose purity (POL/BRIX) in the juice, used to calculate the ease with which the sucrose can be extracted and crystallised. Greater than 75% in juice is generally considered the minimum required purity for crystalline sugar extraction. However, Triangle Ltd has extracted crystalline sugar from cane juice with purities below 70% [Wenman; 1999].
- PI (preparation index), a measure of the disruption caused to the stem's cells by the milling/shredding process that allows the release of sugars from within the cells. This needs to be higher than 90%. The two varieties of sweet sorghum evaluated so far have had preparation indices in excess of 90% [Mvududu et al., 2000].

High-yielding sweet sorghum varieties such as "Keller" have demonstrated "biomass quality" parameters similar to those of sugarcane, particularly early in the sugarcane

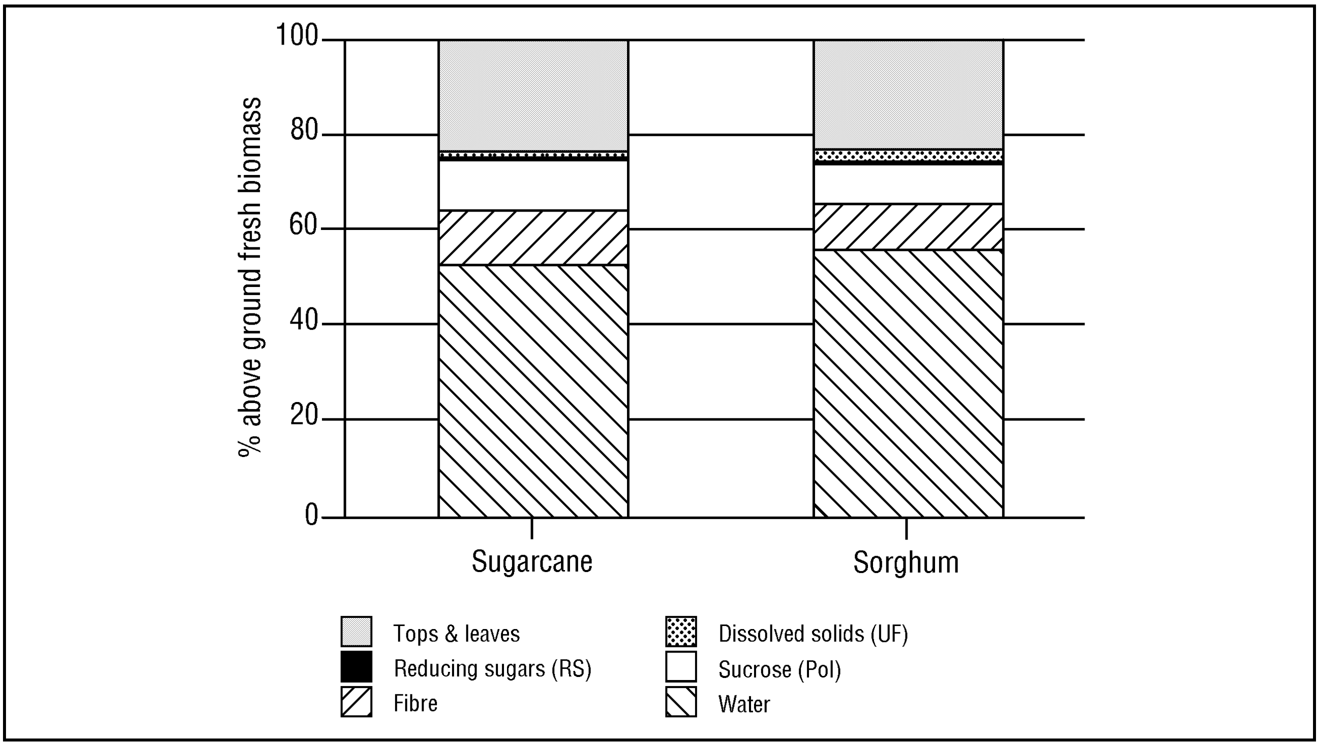

Figure 1. Biomass quality: sugarcane and sweet sorghum

Source: Woods, 2000

harvesting season, and thus have considerable potential for ethanol and electricity production (see Figure 1).

Through intensive agronomic research over the last decade in the USA, Australia, Brazil, China, India, Zimbabwe and Europe, sweet sorghum has emerged as a viable feedstock for fuel ethanol production. Its potential is based on the combination of advantageous agronomic characteristics described above. In addition, it has one of the highest intercepted radiation use efficiencies (RUEs) (3.6 g dry biomass/MJ photosynthetically active radiation (PAR) absorbed, compared with approximately 2 g/MJ PAR for a C_3 species [Gosse, 1995]) of any plant species, on a par with sugarcane, so allowing it to grow rapidly under optimal conditions. Moreover, its real potential lies in its growth under sub-optimal conditions where the combination of high RUE with high water and nutrient-use efficiencies allows it to continue producing a sugar- and fibre-rich stem when other crops would struggle [Gosse, 1995; Woods et al., 1995]

Under good conditions, sweet sorghum varieties can outperform sugarcane in terms of total biomass production over short periods. The recent full-scale processing trials at Triangle Sugar Mill suggest that although sweet sorghum juice will be more difficult to crystallise as a result of lower average levels of sucrose purity than sugarcane, it is possible to produce crystalline sugar from sweet sorghum on a commercial scale [Mvududu et al., 2000; Wenman, 1999]. The rapid growth rates also allow a sufficiently high biomass density to accumulate per unit land during the 3- to 5-month season, to make harvesting and transport using existing sugarcane techniques feasible. There are, however, additional problems and differences between sugarcane and sweet sorghum that require some alterations to standard sugarcane harvesting techniques; for example, harvesting during periods with high rainfall and having to deal with green leaves on sweet sorghum. Although feasible, as demonstrated in SE Zimbabwe [Mvududu et al., 2000], harvesting sweet sorghum is similar to green cane harvesting and is significantly more labour-intensive than manual burnt cane harvesting.

Sweet sorghum's rapid growth and ability to reach maturity in 3 to 5 months, when coupled with its lack of photoperiodism (see below), are favourable for its production on fallow sugarcane land primarily because it can be grown and harvested before the start of the sugarcane harvesting season. The same factors favour off-estate growth of sweet sorghum by small-holder farmers because the sweet sorghum can be grown during the rainy season for harvesting and delivery to the mill before the sugarcane harvesting season. High-yielding varieties have now been developed that are capable of producing well over 100 t_{fab} (fresh-weight t of above-ground biomass) in 5 months under good agronomic conditions compared with 150 to 200 t_{fab} over 12 months for sugarcane. Of course, these yields can only be achieved where climate, water and nutrient inputs are optimal and pests and diseases are fully controlled. Such yield levels have not yet been demonstrated for sweet sorghum in southern Africa. However, the production of sweet sorghum benefits from the fact that it takes one-third less water to produce per unit of above-ground biomass than sugarcane, significantly reducing the amount of water required per l of ethanol produced [Roman, 1995; Woods et al., 1995]. This is an important factor in drought-prone sugar-producing regions of the world.

The off-crop period, when a sugar mill is not being

Table 1. Actual yields for the 1997-8 and 1998-9 seasons (Zimbabwe, irrigated)

Sweet sorghum variety / sugarcane	t_{fab} per ha	Specific growth rates
Total above-ground biomass		
Keller: 101 days after planting (1997-8)	77.2 ± 12.9	76.5 g/m^2d
Keller: 104 days after planting (1998/9)	50.7 ± 14.8	48.7 g/m^2d
Cowley: 115 days after planting	82.6 ± 5.0	71.8 g/m^2d
Cowley: 107 days after planting (1998/9)	55.0 ± 5.8	51.4 g/m^2d
Deliverable stem mass[1]		
Keller: 1997-8	59.8 t_{stems}/ha	
Keller: 1998-9	39.0 t_{stems}/ha	
Cowley: 1997-8	63.9 t_{stems}/ha	
Cowley: 1998-9	42.3 t_{stems}/ha	
Sugarcane 365 days after planting[2]	115 t_{stems}/ha	150 t_{fab}/ha or 41.1 g/m^2d

Notes

1. The proportion of above ground biomass (t_{fab}) which is harvested as stems (t_{stems}) for transport to the mill is 77% ± 5.
2. The long-term average sugarcane yield for Triangle Ltd. is 115 t_{stems}/ha.yr. A yield of 115 t_{stems}/ha is equivalent to 150 t_{fab}/ha or 15,000 g/m^2.

used to process sugarcane, provides an ideal opportunity for sweet sorghum to be processed if logistical problems with mill refits can be resolved. It is this potential to use sweet sorghum to extend the milling season in existing sugarcane processing facilities that has opened up the possibility of generating economically viable supplies of bioenergy from sweet sorghum. The potential for exploitation is critically sensitive to the logistics of the integration, which needs to be carried out in such a way as to exploit the synergies between sugarcane and sweet sorghum and to minimise potential problems. For example, minimising the time between harvesting and processing is particularly important when processing sweet sorghum.

3. Integrating sweet sorghum with sugarcane

A number of paper-based studies have attempted to calculate the potential impact of an integrated sweet sorghum/ sugarcane energy production system [Woods, 2000; Li, 1997; Ferraris, 1988; Energy Authority of NSW, 1986]. It is generally proposed that sweet sorghum could be planted on fallow sugarcane land, for harvesting and processing during the off-crop season, i.e., before the sugarcane is mature. In southern Africa, the length of the period during which sweet sorghum is available for processing will depend on:

- the planting date;
- the land area available from September to March and the length of the sugarcane "off-crop" season, both on and off the sugarcane estates;
- the season length of variety planted, i.e., short (3 months), medium (4 months), or long (5 months);
- crop management, including any feedback loops between sorghum and sugarcane, particularly regarding soil water use and pests and diseases; and
- the minimum biomass quality parameters acceptable to the mill for both sweet sorghum and sugarcane, as this dictates the start and end of the sugarcane processing season.

Other important factors governing the successful adoption of sweet sorghum include:

- the processing rate of the mill;
- the market for products;
- the impact of new technologies if introduced;
- government policies towards energy and environmental issues; and
- the perception/ acceptability of sweet sorghum by existing sugarcane growers/ millers and potential smallholder growers.

Whilst it is beyond the scope of this paper to provide a detailed analysis of the impacts of the integration of sweet sorghum with sugarcane in the sugarcane estates, a report by Mvududu et al. [2000] indicates that they can be managed and may even be beneficial in some circumstances. The increasing intensification of land use inherent with this type of co-cropping will inevitably have impacts on the soils and on the inputs required to control pests and diseases. However, the perennial nature of sugarcane production, which only requires re-planting and therefore ploughing every 5 to 10 years, means the soils are relatively undisturbed when compared with arable agricultural systems. Undoubtedly, longer-term trials with careful monitoring of soil biotic and abiotic factors will be crucial before the full impacts of co-cropping sweet sorghum with sugarcane are fully understood. Where sorghum is grown outside the sugar estates, careful monitoring and management are also required as with any other type of annual crop production if sustainability is to be ensured.

The potential for ethanol and electricity production from sweet sorghum in southern Africa is evaluated below. The evaluation is based on the assumption that 5% of sugarcane land, i.e., "fallow land", is available for growing sweet sorghum or that the equivalent of 1% of

Table 2. Potential ethanol production from sweet sorghum

Variety	Brix[1]	Pol[1]	Sucrose purity[1]	TFS[1]	EtOH[2]	EtOH[3]
	% fresh weight stems					l/ha
1) Ethanol only						
Sorghum						
Keller	17.4	12.1	69.7	13.1	4.6	2677
Cowley	18.5	12.8	69.2	14.7	5.1	2993
IS19674	13.7	6.6	48.2	9.3	3.3	1904
Monori edes	11.0	6.3	57.3	7.7	2.7	2057
Sugarcane[3]	16.8	14.1	83.6	14.6	5.1	7458
(2) Ethanol + crystalline sugar						
Sorghum (Keller)	-	1.1	-	2.1	0.7	561
Sugarcane	-	1.3	-	1.8	0.6	936

Source: adapted from [Woods, 2000].

Notes

1. Brix = total dissolvable solids; pol = polarity (measure of sucrose); sucrose purity = % brix which is sucrose (pol/brix × 100); TFS = total fermentable sugars
2. Percentage of fresh weight sweet sorghum stems recoverable as EtOH on a mass basis (assumes 35% recovery). EtOH density = 0.789 g/l.
3. This column calculates the expected recovery of ethanol if 46 t_{stems}/ha of sorghum (115 t_{stems}/ha sugarcane) are delivered to the mill.

the existing cropland (arable[1] + permanent crop land) could be used for sweet sorghum production. The realities of these assumptions are open to debate but the analysis does highlight the large potential for the use of sweet sorghum for clean and sustainable energy production where the incentives and management systems are conducive.

3.1. Ethanol production

Table 2 provides the primary characteristics determining the production of ethanol from sweet sorghum and sugarcane. The data are derived from fermentation tests carried out at Triangle Ltd's Laboratories on sweet sorghum stem samples before a full-scale crushing test [Mvududu et al., 2000]. This table calculates potential ethanol yields for two scenarios: (1) where all the sugars are used for ethanol production and (2) crystalline sugar is extracted first and the residual molasses (molasses "C") is used for ethanol production. It is based on the results of two full-scale crushing trials carried out at Triangle Ltd's mill at the start of the 1999 and 2000 sugarcane harvesting seasons using both the 66″ mill tandem and the diffuser lines to separate the juice from the fibre. The results from these full-scale crushing trials above and lab tests have been used to provide the data for the analysis carried out below [Woods, 2000; Mvududu et al., 2000].

3.2. Electricity

The potential for sugar mills to become net energy exporters has been widely evaluated elsewhere, showing that with a commitment to high steam pressures and steam-use efficiencies within mills up to 150 kWh/t cane of surplus electrical power could be produced [Gopinath, 1997; Walter, 1994]. A more modest assumption of 75 kWh/t is assumed to be possible here as there are large capital costs incurred in retro-fitting sugarmills to become steam- and energy-efficient [Woods, 2000]. With the current progressively deteriorating exchange rates of all southern African countries, major external investment will be hard to achieve cost-effectively until the currencies stabilise.

Table 3 calculates the potential for ethanol and electricity production from sweet sorghum on "fallow" sugarcane land or on the equivalent of 1% of the existing cropland area (arable + permanent) as taken from the FAO Production Yearbook 1994. In this table, it is assumed that the yields of sweet sorghum achieved outside the sugar estates will be half those achieved on the estates. Whilst these are difficult to quantify without long-term trials on small-holder farms, these farmers' reduced infrastructure and access to fertilisers, pesticides, water and expert advice will undoubtedly mean that they will find it much harder to attain optimum yields. In addition, as can be seen from Table 1, the average expected yield of sweet sorghum stems used here is lower than the maximum obtained during the sweet sorghum agronomic trials carried out in Zimbabwe. Being a relatively short season crop, particularly when compared with perennial sugarcane, sweet sorghum will be much more susceptible to seasonal climatic variations. Thus, yields will fluctuate significantly from year to year and optimum growth conditions will be more difficult to maintain than for sugarcane.

4. Potential energy production and greenhouse gas (GHG) savings from sweet sorghum

The calculations provided in Tables 4 and 5 below show the potential for the use of sweet sorghum as a biofuel, but do not address the site-specific realities on the ground in the five southern African countries under consideration. However, if the recent apparent shift in emphasis in these countries from "top-down" to "bottom-up" community-based resource management continues, then modern biomass energy systems may play a significant role in the

Table 3. Land areas under sugarcane and potential energy production from sweet sorghum in southern Africa

Country	Total cropland area	Land area under sugarcane 1999	Potential sorghum production on 5% sugarcane land	Potential sorghum production on 1% of cropland	Potential energy from sorghum on 5% of sugarcane land		Potential energy from sorghum on 1% of cropland	
	kha	ha	t_{stems}	t_{stems}	kl EtOH	MWh_e	kl EtOH	MWh_e
Malawi	9408	17000	39100	2163840	2125	2933	117600	162288
Mauritius	203	65000	149500	46690	8125	11213	2538	3502
Mozambique	78409	28000	64400	18034070	3500	4830	980113	1352555
South Africa	122104	315753	726232	28083920	39469	54467	1526300	2106294
Zambia	74339	16000	36800	17097970	2000	2760	929238	1282348
Zimbabwe	38685	43000	98900	8897550	5375	7418	483563	667316
Total	323148	484753	1114932	74324040	60594	83620	4039350	5574303

Source for land areas and sugarcane production: FAO, 2000 and FAO, 1994.

Notes

It is assumed that yields of 46 t sorghum stems and 2500 l ethanol per ha can be achieved on sugarcane land per season and that half this yield is achievable on "cropland", i.e., 23 t_{stems}/ha and 1250 l of ethanol/ha. Sorghum bagasse energy content 7.6 GJ/t (50% moisture content, LHV); 186 kg bagasse (50% moisture) per t_{stems} [Woods, 2000].

future development of this region [Woods, in press]. For example, by using a community-based approach, small-holder sugarcane production has been successfully encouraged in South Africa where there are now about 50,000 farmers commercially growing 30 ha or less each of sugarcane [Eweg, 2000]. However, outside the higher rainfall areas of southern Africa that are primarily along the east coast, sweet sorghum could be a more advantageous crop for small-holders to grow because of its lower water use and increased tolerance of environmental stress. The sweet sorghum crop would also be mature before the sugarcane, helping to eliminate potential competition for milling quotas between small-holders and larger-scale commercial sugarcane growers and estates. In addition, the input costs (fertiliser and pesticides) would be lower than for sugarcane, requiring lower investment levels by small-holder farmers.

Work is continuing in Zimbabwe on the development and demonstration of sweet sorghum as a feedstock for sustainable energy production [Mvududu et al., 2000]. In this analysis, a number of models for its exploitation are being evaluated, including the following.

1. Off-crop, using existing sugar mills and distilleries
2. Autonomous distilleries (as in Brazil)
3. Village-level crushing and delivery of juice to mills/ distilleries
4. Chinese model – village level production, primary ethanol production, then "beer" to distillery. Residues used for fodder (leaves and seeds) and residual fibre upgraded (through fermentation process) and then used for biogas and fertiliser [Li, 1997]
5. Village level sugar/ syrup production, with residues used locally for energy production and fodder as with Chinese model

However, before such novel ethanol, heat, and electricity-producing systems can be regarded as acceptable, they will have to demonstrate:

- positive energy balances;
- sustainability;
- economic viability;
- applicability; and
- complementary integration with existing processes.

In the three sections below, the potential for the use of sweet sorghum for electricity and liquid fuel production is estimated for the southern African region and the greenhouse gas abatement impacts are also calculated. These estimates highlight the enormous physical potential for biofuel production but do not assess the social or economic impacts that a biofuel programme would have if introduced on a significant scale.

4.1. Potential use of fallow sugarcane land

The use of fallow sugarcane land for the growth and harvesting of sweet sorghum out of the sugarcane harvesting season could have many advantages in terms of logistics and shared costs. However, the share of the existing electricity and liquid fuel markets that could be supplied is limited (Table 4) when compared with what could be achieved with a wider programme using non-sugarcane land as well (Table 5). During the optimum period for planting (October to December), growing and harvesting (January to March) of sweet sorghum only about 5% of sugarcane land would be fallow and available for sweet sorghum. In addition, very careful long-term monitoring of soils would also be necessary to ensure that the growth of sweet sorghum does not deplete nutrients and water and that the soil biology is not damaged. In terms of percentage of current energy supplies that could be substituted with energy from sweet sorghum, the greatest impact would be in Malawi and Mozambique, because these two least developed of the southern African countries are start-

Table 4. Potential share of electricity and liquid fuel production from sweet sorghum grown on "fallow" sugarcane land[1]

Country	Electricity consumption (1990)	Motor gasoline (1990)	Gas- diesel oils (1990)	Potential energy from sorghum on 5% sugarcane land		Ethanol % of motor gasoline consumption[2]	Sorghum electricity as % of total electricity consumption
	GWh	kt	kt	kt EtOH	MWh_e	%	%
Malawi	587	48	86	1.68	2933	3.5	0.50
Mauritius	770	56	97	6.41	11213	11.5	1.46
Mozambique	810	39	195	2.76	4830	7.1	0.60
South Africa	161748	4350	4465	31.15	54467	0.7	0.03
Zambia	6291	106	185	1.58	2760	1.5	0.04
Zimbabwe	10433	171	376	4.24	7418	2.5	0.07
Total	180639	4770	5404	47.83	83620	1.0	0.05

Source for electricity, gasoline and diesel consumption: UNSO, 1992.

Notes

1. About 5% of sugarcane land would be available for the growth of sweet sorghum for harvesting and processing out of season.
2. It should be noted that although ethanol (23.4 MJ/l; HHV) has a lower energy density than gasoline (34.9 MJ/l; HHV), its superior combustion characteristics (RON and MON) have led analysts to conclude that one litre of ethanol is equivalent to 90 to 100% of a litre of gasoline when blended with gasoline [Rosillo-Calle et al., 2000; Goldemberg et al., 1993]. For simplicity, direct equivalence has been assumed here.

Table 5. Potential share of electricity and liquid fuel production from cropland

Country	Potential energy from sorghum on 1% cropland		Ethanol % of motor gasoline consumption	Sorghum electricity as % of electricity consumption
	kt ethanol	GWh_e	%	%
Malawi	93	162	193	27.7
Mauritius	2	4	4	0.5
Mozambique	774	1353	1984	167.0
South Africa	1205	2106	28	1.3
Zambia	733	1282	692	20.4
Zimbabwe	382	667	223	6.4
Total	3188	5574	67	3.1

ing at very low levels of commercial energy supplies today.

4.2. Wider potential for energy production on cropland

The huge potential for biofuel production in general, and specifically from sweet sorghum, is demonstrated in Table 5. The combination of the relative wealth of cropland available and current low energy consumption, as a result of low levels of industrialisation, makes southern Africa one of the most favourable regions for biomass energy production. The two countries with the greatest cropland area as compared with their levels of development, Zambia and Mozambique, show that between 20% and 167% of their national electricity respectively and one-third (32%) of the whole region's liquid fuel requirements (gasoline + diesel) could theoretically be supplied by growing sweet sorghum on 1% of their cropland area.

4.3. Potential GHG reduction benefits

Emissions trading and the Kyoto protocol are likely to set a value of US$ 10 to 50 per tC (1 to 5 US¢/kg) [Grubb et al., 1999]. If a 1:1 substitution of ethanol for gasoline is accepted on a volume basis, ratification of the Kyoto protocol could effectively mean a reduction in costs for ethanol production of between 0.8 and 3.8 US¢ per litre of ethanol given a carbon content of 0.76 kgC per litre of gasoline. Overall, if all the ethanol potentially derived from sweet sorghum (Table 3), i.e., 4.0 Gl, were used as a gasoline substitute, emissions of 3.1 Mt of Carbon (4.0×0.76) could be avoided with an estimated total value of between US$ 31 and 154 million.

However, the carbon substitution value for ethanol would vary under the "Clean Development Mechanism" (CDM) on a project-by-project basis depending on the fossil fuel to be substituted. For example, although diesel and fuel oil have a higher carbon content they also have a significantly higher energy content and different combustion characteristics than either ethanol or gasoline, and so direct substitution on a volume basis would not be applicable. This is equally true for calculating the avoided carbon emissions for electricity generation as the actual quantities of carbon saved would depend on the percentage share of the generating mix, i.e., coal, oil, gas and hydro. A further complication in calculating potential GHG reduction benefits is caused by the need to integrate the energy ratio (output:input) of the ethanol produced. For ethanol produced from sweet sorghum in SE Zimbabwe the energy ratio is calculated as 4 and so only 3/4 of the carbon substitution potential shown above should be used, i.e., 0.75 to 3.75 US¢ per litre [Woods, 2000].

5. Conclusions

The continuing work in Zimbabwe has clearly demonstrated that sweet sorghum can be grown and processed without any modifications to an existing sugar mill, i.e., Triangle Ltd, and processing can occur before the start of the sugarcane harvesting season. The agronomic trials have so far have been limited to either research station or sugar estate fields. Therefore, if sweet sorghum is to be grown by small-holder farmers, new trials are required on their fields in order to obtain a realistic estimate of yields under local conditions, as discussed above. These trials on small-holder land will be established this year but continued trials with long-term monitoring are essential if the full impacts of the use of sweet sorghum are to be properly understood.

Given good incentives wisely directed at local people, bioenergy systems hold considerable potential for Africa, southern Africa in particular. Despite the failure to ratify the Kyoto protocol at the Hague meeting this year, the protocol's CDM holds the potential to support bioenergy systems which can demonstrate a reduction in emissions of GHGs in general and CO_2 in particular. As discussed above, mechanisms such as the CDM should effectively reduce the cost of ethanol from sweet sorghum or sugarcane by between 0.8 and 3.8 US¢/l, further encouraging the adoption of biofuels. If successful, bioenergy systems could offer southern Africa an alternative route for development which does not follow the carbon- and fossil energy-intensive pathway of the OECD countries. In addition it would make efficient use of the enormous land resources of the sub-continent. ■

The author can be contacted at:
E-mail: jeremy.woods@kcl.ac.uk
Tel: +44 (0)20 7848 4315
Fax: (0)20 7848 4500

Note

1.“Arable”: FAO definition, i.e., one to two crops per year and a period when no crops are being grown.

References

African Energy Policy Research Network (AFREPREN), 1997. *Biomass Energy Policy in Africa: Selected Case Studies,* London, UK, Zed Books.

Bauen, A., 2000. Comments on International Workshop on Integrating Biomass Energy with Agriculture, Forestry and Climate Change in Europe, held at ICCEPT, Imperial College, London, UK, 4-5 Dec.

Campbell, C.J., Geneva, Multi-Science Publishing Company and Petroconsultants SA, pp. 173-182.

Doggett, H., 1988. *Sorghum,* Harlow, UK, Longman Scientific & Technical, 512 pp.

Energy Authority of NSW, 1986. *Sugar Cane to Fuel Ethanol: Feasibility Study,* Sydney, Australia, Energy Authority of NSW, ISBN 0-7305-2799-9:1-159.

Eweg, M., 2000. *Small-Holder Sugarcane Production in South Africa: Historical Trends 1979 to 2000,* SA Sugar Research Station, Mount Edgecombe, 4300, South Africa.

Ferraris, R., 1988. *Sweet Sorghum: Agronomic Evaluation and Potential Application for Australian Agro-Industry,* 5, Research Report, CSIRO (Commonwealth Scientific and Industrial Research Organisation), Brisbane, Australia, pp. 1-49.

Food and Agriculture Organisation (FAO), 2000. *FAOSTAT Database,* http://www.fao.org.

Food and Agriculture Organisation (FAO), 1994. *FAO Production Yearbook 1994,* Vol. 48, FAO, Rome, Italy.

Goldemberg, J., Monaco, L.C., Macedo, I.C., 1993. “The Brazilian fuel-alcohol program”, Ch. 15 in Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H., (eds.), *Renewable Energy: Sources for Fuels and Electricity,* Island Press, Washington D.C., pp. 841-64.

Gopinath, S., 1997. *Biomass Based World Class Sugar Mill for Maximum Power Export in India,* Bangalore, BUN-India, Newsletter 2.2, (Ed.) Gayathri, V., gayathri@cgpl.iisc.ernet.in.

Gosse, G. 1995. “Rendement energetique et bilan de CO_2 d'une culture”, *C.R. Acad. Agric. Fr.* 81 (5), pp. 93-107.

Grubb, M., Vrolijk, C., and Brack, D., 1999. *The Kyoto Protocol: A Guide and Assessment,* London, UK, Royal Institute of International Affairs, 342 pp., ISBN-1853835803.

Hall, D.O., 2000. “Introduction”, in *Industrial Uses of Biomass Energy,* (ed.) Rothman, H., Rosillo-Calle, F., and Bajay, S.V., London, Francis and Taylor, pp. 1-38.

Hall, D.O., Rosillo-Calle, F., Williams, R.H., and Woods, J., 1993. “Biomass for energy: supply prospects”, in *Renewable Energy: Sources for Fuels and Electricity,* (eds.) Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H., Washington D.C., Island Press, pp. 593-652.

Nakicenovic, N., Grübler, A., and McDonald, A., (eds.), 1998. *Global Energy: Perspectives,* International Institute of Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge, UK, Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC), 1996. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses,* Cambridge, UK, Cambridge University Press, 879 pp.

Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H., 1993. “Renewable fuels and electricity for a growing world economy: defining and achieving the potential”, in *Renewable Energy: Sources for Fuels and Electricity,* (eds.) Johansson, T.B., Kelly, H., Reddy, A.K.N., and Williams, R.H., Washington D.C., Island Press, pp. 1-72.

Li, D., 1997. “Developing sweet sorghum to accept the challenge of problems on food, energy and environment in 21st century”, Li, D., (ed.), *Proc. First International Sweet Sorghum Conference,* Chinese Academy of Sciences, Beijing, China, Sep 25, pp. 19-34.

Mvududu, E., Nyabanga, L., Gopo, J., and Woods, J., 2000. *3rd Year Report: Demonstrating Increased Resource Use Efficiency in the Sugar Industry of Southern Africa Through Environmentally Sustainable Energy Production,* Common Fund for Commodities (CFC) Sweet Sorghum Project Progress Reports, CFC, Amsterdam, the Netherlands.

Roman, G.V., 1995. *Bioethanol Production from Sweet Sorghum: Interchange of Research Experience Between EC and Two East European Countries (Romania and Hungary): Romania Report,* EU DGXII PECO Project Reports, Brussels, EU.

Rosillo-Calle, F., 2000. Pers. com., “The value of anhydrous ethanol in Brazil”, London, Dec.

Rosillo-Calle, F., Bajay, S.V., and Rothman, H., (eds.), 2000. *Industrial Uses of Biomass Energy,* Taylor & Francis; London, UK, pp. 1-273, ISBN 0 7484 0884 3.

Rothman, H., Greenshields, R., and Rosillo-Calle, F., 1983. *Energy from Alcohol: the Brazilian Experience,* University of Kentucky Press, Lexington, Kentucky, USA, pp. 1-188.

Shell, 1996. *The Evolution of the World's Energy System,* London, SIPC.

United Nations Statistical Office (UNSO), 1992. *Energy Statistics Yearbook: 1990,* United Nations, New York.

Walter, A.C., 1994. *Viabilidade e Perspectivas da Cogeração e da Geração Termoelétrica Junto ao Setor Sucro-Alcooleiro,* PhD thesis, Universidade Estadual De Campinas Faculdade De Engenharia Mecânica, pp. 1-264.

Wenman, C., (Technical Director, Triangle Ltd, Zimbabwe), 1999. Pers. comm., “Potential for crystalline sugar production from sweet sorghum”.

Woods, J. (ed.), in press. “The sustainable use of southern African savannas: synthesis on Botswana”, *South African Geographical Journal,* Special Edition (in press).

Woods, J., 2000. *Integrating Sweet Sorghum and Sugarcane for Bioenergy: Modelling the Potential for Electricity and Ethanol Production in SE Zimbabwe,* PhD thesis, King's College London.

Woods, J., Hall, D.O., Muzondo, M.I., Gosse, G., and Soontornchainackseng, P., 1995. *Bioethanol Production from Sweet Sorghum: Interchange of Research and Experience between EU and Developing Countries (Zimbabwe and Thailand),* Brussels, EU, pp. 1-74.

Woods, J., and Hall, D.O., 1994. *Bioenergy for Development: Technical and Environmental Dimensions,* Environment and Energy Series, (ed.) Best, G., Rome, FAO, 13, pp. 1-78.