ETHANOL FROM SUGARCANE

By G. D. THOMPSON

South African Sugar Association Experiment Station Mount Edgecombe

Abstract

The relative merits of sugar beet, sweet sorghum, maize, cassava and sugarcane as raw materials for the production of ethanol are considered. If sugarcane were to be used, the varieties chosen for sugar production would probably serve the ethanol industry well. The disposal of stillage from an extensive ethanol industry could pose serious problems.

Introduction

Solar radiation reaching the outside of the earth's atmosphere is estimated to be $1{,}35 \times 10^3$ joules per square metre per second. The solar beam is then subjected to attenuation in its passage through the atmosphere (Monteith[17]), and only about half reaches the earth's surface. A small proportion of this solar energy is captured in the photosynthetic process, which may be represented simply as:

$$CO_2 + H_2O + \text{light} \xrightarrow[\text{plant}]{\text{green}} (CH_2O) + O_2 + e,$$

where e is the energy stored in the photosynthate, and it amounts to 468 kJ per mole. The amount of energy stored by plants on the earth annually is about ten times as much as the world's total current use of energy, and about 200 times the current food energy consumption (Hall[9]). On a worldwide basis, overall photosynthetic efficiency is estimated to be about 0,1 %, although on the basis of land areas only this increases to 0,2 to 0,3 %. Average agriculture probably has a photosynthetic efficiency of about 0,5 %.

It has been estimated that irrigated sugarcane under experimental conditions in South Africa and in Hawaii has a photosynthetic efficiency of 1,7 % and that commercial sugarcane in South Africa stores 1,1 % of incident radiation when it is irrigated and about 0,8 % when it is rainfed (Thompson[24]). These figures refer exclusively to the above-ground parts of the crop, and are approximately equivalent to the accumulation of 11 g and 7,5 g of dry matter (biomass) per square metre per day respectively. It was found that maximum rates of biomass production by irrigated sugarcane over 2–3 month periods represented a photosynthetic efficiency of 2,6 % for variety NCo 376.

The chemistry of the photosynthetic process of many plants has been understood for a long time. Conventionally this is now referred to as the C_3 pathway. The work of Hatch and Slack[11] in more recent years has elucidated an alternate C_4 photosynthetic pathway, and it has been shown that C_4 plants have a superior photosynthetic efficiency when compared with C_3 plants under conditions of high light intensity and temperatures (Ehleringer and Bjorkman[7]). Monteith[18] has indicated that the maximum crop growth rate for C_4 plants is 50–54 g per square metre per day, while for C_3 plants the range is 34–39 g per square metre per day.

The choice of crop

If it is intended that the dry matter or biomass produced by a crop is to be used as a source of fuel energy, three major factors need to be considered. These are the yield per unit area of land, the cost of production, and the net energy ratio (NER = total energy output ÷ total energy input). In addition, consideration has to be given to features such as the continuity of production during the year, the soil type and topography on which the crop can be produced, the relative value of and demand for the crop as a source of food rather than fuel energy, and the climatic conditions under which the crop may be produced. Since crops differ appreciably in their requirements and their productivity, it may be worthwhile to consider briefly a range of crops which could be used to produce ethanol in South Africa, and to assess their suitability to local conditions.

Sugar beet (C_3)

Average yields in Europe are about 45 tons beet or 6,3 tons sucrose per hectare, and in the USA 7,0 tons sucrose per hectare (McCann and Prince[16]). Total dry matter production in the USA varies from 11,7 tons per hectare in Minnesota to 20,9 in California (Lipinsky *et al*[13]). The crop has been studied recently under South African conditions, and in two semi-commercial plantings it was found that a sucrose yield of at least 6 tons per hectare in April could increase to about 10 tons per hectare in September in the Highland Sourveld and Mistbelt regions of Natal (Inman-Bamber[12]). The lifting period could therefore be as long as six months over a period when harvesting conditions would be ideal.

For Australian conditions it has been estimated that 50 tons of beet per hectare containing 20 % fermentable solids would yield 110 litres of ethanol per ton at a crop cost of Australian $12–18 per ton (McCann and Prince[16]). The severest limitation to the use of sugar beet as a source of ethanol is that it has no fibrous residue suitable to provide the heat energy required for processing. On these grounds it has not been recommended for future consideration in the USA (Lipinsky *et al*[14]). The average total amount of energy used to produce a ton of beet in the USA is 0,95 GJ (Lipinsky *et al*[13]), whilst the overall NER has been estimated to be 0,56 when the energy value of the tops left in the field is disregarded (Sheehan *et al*[22]). Thus for each unit of energy used to grow and process a crop of beet, only half a unit is likely to be recovered in the ethanol produced.

Sweet sorghum (C_4)

Sweet sorghum varieties with a high total sugar content are a relatively recent development in the USA, and data on the suitability of this crop for sugar and ethanol production are therefore not yet widely available.

Yields ranging from 34 to 85 tons of unstripped stalk per hectare have been recorded, and the growing season lasts from 110 to 140 days after planting (Lipinsky *et al*[13]). In trials conducted at Greytown in Natal during 1977, the yields of six imported varieties after 130 days varied from 25 to 63 tons per hectare, and the sucrose contents from 3,5 to 7,3 % (Anon[1]).

Being a fibrous crop, sweet sorghum provides the fuel requirements for processing the extracted juice, and the NER has been estimated by Sheehan *et al*[22] to exceed 1,0, i.e. more energy is recovered in the ethanol produced than is used to grow and process the crop. Sweet sorghum reputedly requires less rainfall and nutrients than does sugarcane. However, it can only be harvested over a relatively short period of time and as a raw material for an ethanol distillery it would therefore have to be integrated in a programme incorporating other crops.

Maize (C_4)

The evaluation of any crop in terms of its suitability for ethanol production depends largely on the boundaries prescribing the exercise, and probably never more so than when considering maize. This crop serves both as a direct source of food and as a feed for cattle, and it produces a significant amount of stover. It has been stated (Scheller[20]) that, when both the farming operation and the fermentation process are considered, and with efficient use of all the biomass produced, then for every three litres of grain alcohol produced, at least one is new energy (solar energy) entering the economy. In contrast, Lipinsky *et al*[15] report that 2,2 GJ are required agriculturally to produce one ton of dry biomass, and that the NER is only 0,74 when the stover is used as fuel in the ethanol process. The advantages of maize appear to be that it can be grown in many parts of South Africa where sweet sorghum, cassava and sugarcane cannot be produced, and the grain can be stored relatively conveniently to prolong the processing season. The collection and transporting of the stover as a separate agricultural product might present some difficulties.

Cassava (C_3)

Cassava (*Manihot esculenta* Crantz), also known as manioc or tapioca, is a tuberous crop not generally grown in South Africa. The yields of tubers reported in the literature vary widely. Stumpf[23] states that present yields in Brazil are about 15 tons per hectare per annum, but this is expected to increase to 25 tons in the future. A yield of 19 tons per hectare per annum on a 15-hectare farm is predicted by Schmidt-Holthausen and Engelbart.[21] Bull and Batstone[3] predict that yields of 40 tons per hectare over extensive areas is probably reasonable but by no means certain in Australia, whilst Evenson and Keating[8] recorded experimental yields of 25 tons per hectare at 40 weeks of age, and 47,4 tons at 80 weeks. In coastal Queensland, Harris[10] harvested experimental crops of seven varieties and yields ranged from 31 to 62 tons of tubers per hectare after 450 days. In assessing the crop as a source of ethanol, McCann and Prince[16] reported yields between 40 and 50 tons per hectare. These authors estimated that a crop of 50 tons per hectare would yield 168 litres of ethanol per ton of tubers containing 30% fermentable solids. This would provide 8 400 litres of ethanol per hectare at a cost between Australian $10 and $15 per ton of tubers. Stumpf[23] reports an actual production of 2 700–4 500 litres of ethanol per hectare per annum in Brazil.

The mass of fresh tops of the cassava plant is about 60% of that of the tubers (McCann and Prince[16]).

The total energy input for ethanol production from cassava has been estimated at 3,93 GJ per m^3 of ethanol, in comparison with 2,76 GJ per m^3 from sugarcane (de Carvalho *et al*[4]). Values of the NER for cassava reported in a review by Sheehan *et al*[22] were 0,44; 0,69 and 3,56. The same authors predict a value of less than 1,0 unless the above-ground parts of the crop are used effectively as an additional source of energy. Bull and Batstone[3] have calculated an agricultural cost of 8,76 Australian cents per litre of ethanol produced from cassava.

Evenson and Keating[8] suggest that cassava can be grown between the 30° parallels of latitude and up to an altitude of 2 000 m. The crop tolerates light frost, but the mean monthly winter minimum temperature should not be less than 13° C. About 1 000 mm of rainfall should be well distributed through the growing season. Soils should be light textured and the land fairly level. Satisfactory field germination is not attained when mean soil temperatures at the 100 mm depth fall below 18° C.

Based on these criteria, the South African cane belt is not ideal for the crop because mean minimum temperatures in July are seldom above 13° C. Germination would generally be affected adversely in May, June, July and August. Rainfall would invariably be inadequate for maximum production, but as cassava is reputedly more drought-tolerant than sugarcane, this should not be a severely limiting factor.

Sugarcane (C_4)

Yields of sugarcane in the South African sugar industry vary widely according to rainfall and the standard of management. Although yields equivalent to 9 tons cane per hectare per 100 mm of rainfall are sometimes attained on a farm or estate basis, the industrial average is closer to 6 tons. The rainfall generally varies about a mean of approximately 900 mm per annum.

The high quality Australian cane should yield 90 litres of ethanol per ton (Bull and Batstone[3]), whereas a figure of 70 litres per ton is recorded by Stumpf[23] in Brazil. A commercial yield of 4 000 litres of ethanol per hectare per annum can therefore reasonably be expected in the rainfed parts of the South African cane belt. McCann and Prince[16] suggest that in Queensland 85 tons per hectare containing 16% fermentable solids should yield 87 litres of ethanol per ton of cane, or 7 400 litres per hectare at a crop cost between Australian $12 and $18 per ton of cane.

The NER for sugarcane when bagasse is used as fuel to produce ethanol is always greater than 1,0, i.e. more energy is contained in the ethanol than is consumed in growing and processing the crop. Sheehan *et al*[22] quote figures of 1,1; 2,8 and 1,8 from the literature. Deicke *et al*[5] suggest a ratio of about 3 to 1. Using the estimates of energy input on South African cane farms provided by Donovan,[6] and assuming that 70 litres of ethanol, having an energy value of 21,5 MJ per litre, are produced per ton of cane, the following data are obtained:

	Input, MJ/ton cane	*NER*
Rainfed farms	558	2,7
Irrigated farms	808	1,9
All farms	595	2,5

Discussion

If an energy gain due to ethanol production is a criterion for producing a crop, then sugar beet is not suitable and maize and cassava can only be considered if the entire crop is harvested to provide fuel for distillation. Sweet sorghum and sugarcane enjoy the advantage of leaving a fibrous residue after removal of the fermentable solids from the crops, and this can be used as furnace fuel.

In terms of ethanol per hectare, current sugarcane production in South Africa is equivalent to about 4 000 litres per hectare, which is more than average current production per hectare from cassava in Brazil, similar to expected future production in Brazil, but less than predicted production in Australia.

The cost of ethanol produced in an entirely new venture in Australia appears to be significantly less than that for ethanol from sugarcane. In South Africa the difference may be smaller due to poorer yields of cassava, different farm production costs, and different crop nutrient requirements. The cost of ethanol produced in distilleries attached to existing mills is likely to be lower than the cost in a new project.

The production of ethanol from crops such as maize, sweet sorghum, cassava and sugar beet will be more seasonal than it would be from sugarcane. Continuous annual production of ethanol from sugarcane might be warranted. In Table 1 the yields of sucrose, estimated recoverable sugar (ers) and brix are shown for annual crops at Pongola, expressed as a percentage of the maximum yield in September. If brix can be regarded as an acceptable measure of total fermentable solids, the yield does not fall below 76% of the maximum, whereas yields of sucrose and ers fall to 70% and 67% of the maxima respectively.

TABLE 1
Yields of sucrose, estimated recoverable sugar and brix for 12-month-old cane at Pongola, expressed as a percentage of the yield in September

Month	% of September yield		
	t suc/ha	ters/ha	t brix/ha
December	81	81	79
February	79	73	80
April	70	67	76
June	93	92	83
July	99	100	96
September	100	100	100
November	92	91	93
January	84	84	82

The growing and processing of sugarcane have been the subjects of intensive research for many years. This cannot be said of cassava. Perhaps the world-wide research being inaugurated will serve to improve the status of cassava as an energy crop, and it should certainly be considered as a long-term competitor with sugarcane. Unfortunately, being an annual crop it is unsuited to the highly erodible and steep terrain of the Natal coastal belt and would probably have to be produced under irrigation on sandy soils in the north. The crop is susceptible to some pests and diseases. The gains to be made from better varieties and management would need to exceed any losses due to a build-up of these effects through monoculture.

Maximum energy production

Experimental programmes and management techniques in the South African industry have always been developed with a view to producing the maximum amounts of sucrose or recoverable sugar per hectare. In the future it may become more important to produce the maximum amount of biomass per hectare, and the proportions of cellulose, lignin and pentosans in the cane fibre may also become important. For ethanol production from sugarcane in the immediate future, however, it is likely that the total amount of fermentable solids in the harvestable stalks per hectare will be the only important criterion. This crop characteristic may be affected by the choice of variety and by the management of the crop.

Varietal effects

Twelve to fourteen years elapse between the time that two parent varieties are crossed and the time when a selected seedling may be released for commercial propagation. Should a new programme be embarked upon immediately to provide the ethanol-producing varieties that may be needed more than a decade from now?

In the sugarcane breeding programme at Mount Edgecombe, parent varieties are often those which have previously given a relatively high proportion of promising seedlings for sucrose production per hectare, but a very wide range of parent types is nevertheless included in the programme. It may be that more emphasis could in future be given profitably to parent varieties which produce a high yield of fermentable solids per hectare, but selections for the production of sucrose and fermentable solids probably have a great deal in common.

In the first selection stage, the single stools, the most vigorous plants are chosen, so that selection for biomass rather than sucrose production is already a feature of the programme. In the following single line stage, sucrose content or brix content is taken into account, and from the ensuing observation stage onwards, sucrose content is an important criterion. Total fermentable solids are not determined for cane samples normally, but brix or total soluble solids content is an available substitute. In Table 2 are shown the brix rankings of the ten best sucrose

TABLE 2
Comparative rankings of varieties in observation plots at Mount Edgecombe and Pongola in terms of tons ers and tons brix per hectare

Ranking ters/ha	Mount Edgecombe		Pongola	
	Seedling No.	Ranking t bx/ha	Seedling No.	Ranking t bx/ha
1	645	1	1777	1
2	314	3	2514	7
3	186	2	3462	5
4	722	5	1362	2
5	231	9	2673	9
6	611	10	438/59	6
7	12	7	3429	14
8	208	6	R469	19
9	687	4	728	18
10	705	11	2811	4

TABLE 3
Comparative rankings of varieties in primary variety trials at Mount Edgecombe and Shakaskraal in terms of tons ers and tons brix per hectare

Ranking ters/ha	Mount Edgecombe		Shakaskraal	
	Seedling No.	Ranking t bx/ha	Seedling No.	Ranking t bx/ha
1	347	2	510	1
2	195	12	1192	3
3	280	3	1195	2
4	332	5	1210	4
5	275	4	853	5
6	796	13	1583	6
7	1 199	10	1199	7
8	910	9	531	10
9	965	1	781	13
10	293	15	1022	9

TABLE 4
Comparative rankings of varieties in pre-release and released variety trials at Pongola and Melmoth in terms of tons ers and tons brix per hectare

Ranking ters/ha	Pongola		Melmoth	
	Variety	Ranking t bx/ha	Variety	Ranking t bx/ha
1	NCo 310	3	N55/805	2
2	N55/805	1	NCo 376	1
3	NCo 376	2	N52/219	3
4	CB 36/14	4	NCo 293	4
5	NCo 334	5	N7	5
6	NCo 293	7	L76	6
7	CB 38/22	8	CB36/14	7
8	N53/216	9	N6	8
9	NCo 382	6		
10	N50/211	10		
11	N51/168	11		
12	N51/539	12		

varieties at two sites in observation trials. At Mount Edgecombe 70 seedlings were compared and at Pongola 92 seedlings. Only one of the ten best sucrose varieties at Mount Edgecombe did not feature in the ten best brix varieties, but at Pongola three varieties were ranked in the first ten without having featured in the best ten sucrose varieties.

In the succeeding stage of selection, the primary variety trial stage, comparisons were made between 21 varieties at Mount Edgecombe and 39 at Shakaskraal. The results in Table 3 show that three different varieties entered the top ten at Mount Edgecombe when brix was made the criterion, but only one at Shakaskraal. Proceeding to the pre-release and post-release stages, the results of trials at Pongola and Melmoth, shown

TABLE 5
Yields of sucrose per hectare from plant and 1st ratoon crops of NCo 376 at different spacings under irrigation at Pongola

Spacing, m	Tons suc/ha
3,66 m square	14,2
2,29 m square	26,1
1,44 m square	33,8
0,91 m square	31,4
0,57 m square	36,8
0,36 m square	36,6
0,23 m square	35,2
1,44 m x 0,09 m	39,2

in Table 4, indicate that the varieties reaching this advanced situation differ little in their rankings in terms of yield of ers and brix per hectare.

The indications seem thus to be that, whilst some slight gains might be made by selecting for fermentable solids rather than sucrose content, large gains would have to evolve from the choice of much more suitable parents, if these exist.

Management techniques

The effects of a number of management factors on the production of biomass have been considered by Thompson.[24] Although significant increases in yield due to very close spacings have been reported elsewhere, similar responses have not been obtained in South Africa (Thompson and du Toit[25]). The results of experiments conducted by Boyce[2] at Pongola, shown in Table 5, illustrate that square spacings of NCo 376 plants growing from single-budded setts gave maximum yields when the spacing was 0,57 m or less, but the highest yield was obtained from eyes placed 9 cm apart in rows 1,44 m apart.

The general recommendation in South Africa is not to use very large amounts of nitrogen fertilizer for sugarcane, and not to apply it late in the life of the crop for fear of suppressing sucrose content and reducing cane quality. These restraints might not apply to the same extent if ethanol were to be produced instead of sugar. The value of different types of chemical ripeners might also warrant further investigation to determine their effects on the production of fermentable solids, and the topping height for harvested sugarcane could possibly be increased if all fermentable solids are to be exploited efficiently.

Disposal of stillage

The waste product from distilleries producing ethanol from sugarcane or molasses, called stillage, dunder or vinasse, may eventually be processed and used for cattle feed or other purposes. In the immediate future, however, it is likely to be spread on cane fields, as is presently done in Brazil. Saranin[19] reports that one ton of cane yields 70 litres of ethanol and 900 litres of vinasse. If the mean cane yield were 60 tons per hectare, then an application of 5,4 mm of vinasse per hectare would return to the land that amount produced from the crop harvested from one hectare. It would contain nearly 1½ tons of organic material, and the major mineral component would be potassium (92 kg K/ha). Only about 5 kg of nitrogen would be returned to the land per hectare and the total nutrient value would be little more than R20 per hectare. The residual effect of stillage is to raise the pH of the soil.

On an irrigated estate it would be most convenient to dispose of the stillage by adding it to the irrigation water. A mixture of 1 part stillage with 9 parts water would be the minimum acceptable dilution, but 1 in 50 would be more desirable. If it were necessary to return the stillage to the fields by means of road transport, considerable cost and some inconvenience would be incurred. In the northern areas of the industry and in the flatter parts of the midlands, the material could be carted by tankers with a capacity of 10 tons, either on lorries or drawn by tractors, and sprayed onto the fields. On the steeper fields near the coast tanker capacity would probably have to be 5 tons or less. Where the land is very steep and there is a trash layer in the field, it would probably be necessary for the tanker to operate from contour roads, spraying the stillage on to the land by means of a "big gun" type of irrigator.

Because of the low pH and high temperature (> 65° C) of the stillage, stainless steel tanks would have to be used, and special compounds would be needed for the piping. It has been estimated that the cost of transport and distribution of one ton of stillage 10 km from the distillery would be 63 cents in a 10-ton truck, 117 cents in a 10-ton tractor-drawn trailer, and 167 cents in a 5-ton tractor-drawn trailer. These costs represent 0,8; 1,5 and 2,1 cents per litre of ethanol produced, respectively.

Apparently it would be wise to plan for the disposal of stillage over as great an area of land as possible. It has already been shown in the South African industry that where effluent becomes excessively concentrated in a disposal scheme, the soil may be adversely affected by the large amounts of organic compounds deposited. If preference according to soil type had to be shown, the following orders of priority would be recommended:

Midlands

(i) strongly buffered humic clays, e.g. Inanda, Sprinz and Balmoral series;
(ii) moderately buffered clay loams, e.g. Trevanian, Clovelly, Farningham and Griffin series;
(iii) lightly buffered sands and sandy loams, e.g. Cartref and Longlands series.

Coast lowlands

(i) red structured clays, e.g. Shortlands and Glendale series;
(iia) black clays and clay loams, e.g. Rydalvale, Dansland, Mayo and Milkwood series;
(iib) freely drained loams, e.g. Swartland, Rosehill, Williamson, Glenrosa, Cartref and Clansthal series;
(iii) poorly drained soils, e.g. Katspruit, Phoenix and Waldene series.

Lowveld

(i) red clays and loams, e.g. Glendale, Shortlands, Makatini and Shorrocks series;
(ii) freely drained soils, e.g. Grovedale and Glenrosa series;
(iii) slow to poorly drained soils, e.g. Bonheim, Rensburg, Estcourt and Avoca series.

Conclusions

Ethanol can be produced from a number of crops which can be grown under South African conditions. From the point of view of energy gain, sugarcane and sweet sorghum are to be preferred at present. Because the agricultural technology and processing methods are already well developed for sugarcane, this crop should probably give the best economic returns in the immediate future, the more so because it can be harvested over a protracted season. Sweet sorghum could constitute a supplementary raw material over a short part of the season. When more experience has been gained with cassava and the technology has been improved for its production and processing, this crop might become viable in parts of South Africa. Sugar beet is not a strong candidate for use as a source of ethanol. Because maize can be so widely grown, it might be useful in order to reduce reliance on conventional liquid fuels, but it cannot show a net energy gain unless the stover is used efficiently as an additional source of energy.

There is apparently no great improvement of sugarcane yields for ethanol production to be expected from changed breeding and selection procedures, nor from altered management practices. Further research will be necessary to confirm these observations.

The disposal of stillage may prove to be the most intractable problem associated with ethanol production from sugarcane. There is a strong incentive to devise economic alternative uses for this effluent, and particularly for those having a low energy demand for processing and handling.

Acknowledgements

The author is indebted to Dr P. L. Greenfield for a literature review concerning cassava, and to Dr A. G. de Beer and Messrs J. H. Meyer and M. A. Johnston for notes concerning the disposal of stillage.

REFERENCES

1. Anon (1978). Ann. Rep. Exp. Stn. S. Afr. Sug. Ass., 1977-78: 28.
2. Boyce, J. P. (1970). Plant population studies in irrigated sugarcane. Unpubl. MSc thesis. Univ. of Natal.
3. Bull, T. A. and Batstone, D. B. (1978). Potential for multi-crop processing within the sugar industry. Alcohol fuels conf. Sydney. 4-13 to 21.
4. De Carvalho Jr, A. V., Milfont Jnr, W. M., Yang, V. and Trindade, S. C. (1977). Energetics, economics and prospects of fuel alcohols in Brazil. Proc. int. symp. on alcohol fuel technology. Vol. 3, 5-6 (1 to 9).
5. Deicke, R., Mueller, R. L. and Bieske, G. C. (1978). Growing sugar cane for ethanol production. Alcohol fuels conf. Sydney. 7-10 to 15.
6. Donovan, P. A. (1978). A preliminary study of the energy inputs in the production of sugarcane. SASTA Proc **52**, 188-192.
7. Ehleringer, J. and Bjorkman, O. (1977). Quantum yield for CO_2 uptake in C_3 and C_4 plants. Plant physiol. **59**, 86-90.
8. Evenson, J. P. and Keating, B. (1978). The potential of cassava (*Manihot esculenta* Crantz) as a harvester of solar energy. Alcohol fuels conf. Sydney. 7-1 to 5.
9. Hall, D. O. (1979). Plants as an energy source. Nature **278**, 114-117.
10. Harris, N. V. (1978). The potential of cassava in coastal Queensland: some observations at the Yandaran plantation. Alcohol fuels conf. Sydney. 7-6 to 9.
11. Hatch, M. D. and Slack, C. R. (1966). Photosynthesis by sugarcane leaves. A new carboxylation reaction and the pathway of sugar formation. Biochem. J. **101**, 103-111.
12. Inman-Bamber, N. G. (1979). Sugar beet production in Natal. Unpubl. report. Exp. Stn. S. Afr. Sug. Ass. p. 36.
13. Lipinsky, E. S., McClure, T. A., Nathan, R. A., Anderson, T. L., Sheppard, W. J. and Lawhon, W. T. (1976). Systems study of fuels from sugarcane, sweet sorghum and sugar beets. Vol. 2. Agricultural considerations. Batelle Colombus Laboratories, Columbus, Ohio.
14. Lipinsky, E. S., Nathan, R. A., Sheppard, W. J., McClure, T. A., Lawhon, W. T. and Otis, J. L. (1977). Systems study of fuels from sugarcane, sweet sorghum and sugar beets. Vol. 1. Comprehensive evaluation. Batelle Columbus Laboratories, Columbus, Ohio.
15. Lipinsky, E. S., Sheppard, W. J., Otis, J. L., Helper, E. W., McClure, T. A. and Scantland, D. A. (1977). System study of fuels from sugarcane, sweet sorghum, sugar beets and corn. Vol. 5. Comprehensive evaluation of corn. Batelle Columbus Laboratories, Columbus, Ohio.
16. McCann, D. J. and Prince, R. H. G. (1978). Agro-industrial systems for ethanol production. Alcohol fuels conf. Sydney 4-22 to 30.
17. Monteith, J. L. (1962). Attenuation of solar radiation: a climatological study. Quart. J. Roy. Met. Soc. **88**, 508-521.
18. Monteith, J. L. (1978). Reassessment of maximum growth rates for C_3 and C_4 crops. Exptl. Agric. **14**, 1-5.
19. Saranin, A. P. (1977). Brazil's national plan for power alcohol from sugarcane. Producer's Review, Dec. 1977, p. 23.
20. Scheller, W. A. (1977). The production of ethanol by the fermentation of grain. Proc. int. symp on alcohol fuel technology. Vol. 3. 5-1 (1 to 4)
21. Schmidt-Holthausen, H. J. and Engelbart, W. (1977). Economical and technical aspects of ethanol production from maniok. Proc. int. symp on alcohol fuel technology. Vol. 3, 5-2 (1 to 4).
22. Sheehan, G. J., Greenfield, P. F. and Nicklin, D. J. (1978). Energy, economics, ethanol — a literature review. Alcohol fuels conf. Sydney 6-11 to 19.
23. Stumpf, U. E. (1978). The Brazilian alcohol fuel program. Alcohol fuels conf. Sydney.
24. Thompson, G. D. (1978). The production of biomass by sugarcane. SASTA Proc **52**, 180-187.
25. Thompson, G. D. and Du Toit, J. L. (1965). The effects of row spacing on sugarcane crops in Natal. ISSCT Proc **12**, 103-111.

For Discussion see page 18