

MODELS OF DRY MATTER ACCUMULATION BY SUGARCANE

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Abstract

There is need in the South African Sugar Industry for a clear understanding of the effects of age and season of harvest on cane yield and quality. One of the keys to this understanding is the knowledge of how sugarcane grown with adequate water and fertilizer accumulates dry matter. Dry matter yields obtained from the literature and by sampling crops grown recently under these conditions were used to validate two models of photosynthesis and respiration in sugarcane obtained from the literature. A simple light interception model was also developed from unpublished data on the two varieties NCo376 and N14. The models explained the NCo376 data well and indicated that the gross photosynthetic efficiency of this variety is in the range 8,2 to 8,8% of photosynthetically active radiation, at least while the crop is young. Maintenance respiration appears to be about 0,3% of dry mass. Although several aspects of the models require further validation and refinement, they may be used to determine yield potential in relation to different planting and ratooning regimes and in relation to temporal and spatial variations in solar radiation.

Introduction

There is a need in the South African Sugar Industry for a clear understanding of the effects of age and season of harvest on cane yield and quality. This is because growers have been forced to cut their crops much younger than before to avoid losses due to eldana borer, and it is uncertain to what extent the productivity and quality of crops have been affected by this practice. One of the keys to this understanding is the knowledge of how sugarcane grown with adequate water and fertilizer accumulates dry matter.

Dry mass accumulation by crops grown under these conditions was measured by Gosnell,⁷ Rostron¹⁹ and Thompson²⁰ using the variety NCo376 and by Thompson²¹ with the variety N14. If their data can be explained in terms of published methods for estimating the rates of photosynthesis and respiration, then the effects of age and season, at least in relation to irrigated crops, will have been validated.

Photosynthesis

From theoretical considerations de Wit²² showed that 15 quanta of light are required to reduce one molecule of CO₂ in C₃ and C₄ plant species alike. If the 550 nm wavelength represents the range of photosynthetically active radiation (PAR) and glucose with a heat of combustion equal to 15,7 MJ/g represents the immediate product of photosynthesis, then approximately 13% of PAR is captured during photosynthesis (de Wit²²). The quantum efficiency of C₄ plants determined by Ehleringer and Pearcy⁵ was 0,05 and 0,06 mole CO₂ per mole photon and was largely independent of temperature in the 14 to 40°C range. These values are similar to the 0,067 moles per mole photon implied by de Wit.²² Jones¹¹ derived a value of 0,059 mole CO₂ per mole photon from data of aerial dry mass and absorbed PAR of a number of C₃ and C₄ crops. Thus estimates of the efficiency of gross photosynthesis (ϵ) appear to vary between 10 and 13%. At

low light intensity ϵ of single leaf blades of potted sugarcane plants two months after planting was 10,1% and in young leaves of 18 month old plants ϵ was only 4,2% (Bull²). Bull and Tovey³ showed that gross CO₂ assimilation rates of third sugarcane leaves varied during the year. The following efficiencies were apparent from their data, assuming that all CO₂ is converted to carbohydrate (CH₂O), and that CH₂O releases 4 200 cal/g on combustion (Glover⁶).

Month	g CO ₂ /dm per cal/cm ² solar radiation	t CH ₂ O/ha per cal/cm ² solar radiation	ϵ % PAR
January	0,00142	0,00097	8,2
December	0,00119	0,00081	6,8
November	0,00088	0,00060	5,0
September	0,00062	0,00043	3,6
July	0,00048	0,00033	2,7

Mishoe *et al*¹⁸ applied the photosynthesis model of Hesketh *et al*⁸ to total biomass produced by sugarcane in Florida. A value of 0,0014 was cited for the slope of the photosynthesis-light response curve reported by Bull and Tovey³ obviously obtained from the January data. Values of the slope of the CO₂ assimilation-light curve that best fitted their data varied from 0,00072 to 0,00080 t CH₂O/ha per cal/cm². In a subsequent publication a slope constant of 0,0014 was used in a similar model of dry mass accumulation by sugarcane (Lorber *et al*¹⁶).

Kortschak and Forbes¹⁵ showed that photosynthetic efficiency in sugarcane decreased by approximately 30% between 6 and 15 months after planting. This might have been due to an increase in stomatal resistance as appeared to be the case in Bull's data.² Midday abaxial stomatal resistances in well irrigated sugarcane in South Africa increased from approximately 3 s/cm in a five month old crop to approximately 5 s/cm in a nine month old crop (Inman-Bamber and de Jager¹⁰) and it may therefore be necessary to account for a reduction in photosynthetic efficiency as the crop develops.

Respiration

Glover⁶ showed that respiration rates for sugarcane depend on both crop mass and ambient temperature. For rooted stalks without leaves daily respiration was equal to the following fraction of the dry stalk mass:

$$1,44 \times 10^{-3} \times (0,2495T - 3,046) \text{ units} \quad (1)$$

where T = daily mean temperature (°C). Respiration rates for leaves were three times greater than for rooted stalks.

McCree¹⁷ first distinguished between respiration required for plant growth and that required for maintenance, and Hesketh *et al*⁸ explained the significance of these rates in terms of the classical growth analysis formulae. The latter authors used a concept of maintenance respiration (R_m) for all living cells in the plant and growth respiration (R_{gr}) for cells undergoing division or for the synthesis of metabolites associated with growth. In their concept R_m was proportional to accumulated dry plant mass and R_{gr} to current rate of photosynthesis.

Methods

Two models were developed, based largely on the above considerations obtained from the literature.

The 'Lorber' model

The simple model used by Lorber *et al*⁶ can be written as follows:

$$dW/dt = (P_g - R_m \cdot W) \cdot (1 - R_{gr}) \quad (2)$$

- W = total dry mass of crop including roots (t/ha)
- dt = time interval
- P_g = gross photosynthesis (t CH₂O/ha)
- R_{gr} = growth respiration (g/g)
- R_m = maintenance respiration (g/g)

The values ascribed to maintenance (R_m) and growth (R_{gr}) respiration were 0,0030 and 0,242 (g/g) respectively. P_g was derived using a photosynthetic efficiency equal to 8,2% of PAR and the proportion (L_i) of PAR intercepted by the foliage was regarded as a function of the leaf area index (LAI) and an extinction coefficient. (k).

$$P_g = \epsilon \cdot L_i \cdot PAR \quad (3)$$

$$L_i = 1 - e^{-k \cdot LAI} \quad (4)$$

Values of k vary between 0,4 and 0,7 for grasses (Jones¹¹). The little data available for variety NCo376 indicate that k = 0,65, a value also assumed for maize (Jones and Kiniry¹²), is accurate enough to be used for the present.

LAI was obtained empirically from unpublished data of Gosnell⁷ and Inman-Bamber⁹. In the model it is assumed that leaf tips of NCo376 emerge from the whorl at intervals of approximately 100 heat units (base 12°C) and that the following function describes leaf extension rate (LER).

$$LER = -1,56 + 0,151T \text{ mm/h} \quad (5)$$

where T = mean ambient temperature °C.

The final area (LA_i) of single leaves was found to depend on the sequence (i) in which they emerge as follows:

$$\text{For NCo 376} \quad LA_i = -4,97 + 15,76i \quad (6)$$

with a maximum = 290 cm²

$$\text{For N14} \quad LA_i = -10,9 + 24,79i \quad (7)$$

with a maximum = 400 cm²

Regular stalk counts recorded by Gosnell⁷ and Boyce¹ indicate that the peak stalk population of NCo376 is approximately twice that of the final population which is a fairly stable varietal characteristic. LAI was thus the product of leaf area per stalk and twice the final stalk population for both varieties.

The Glover/Jones model (abbreviated to 'Glover model')

The respiration model of Glover⁶ was combined with the photosynthesis model used in the CERES-MAIZE model (Jones and Kiniry¹²). The latter assumes a maximum photosynthetic efficiency of 8,8%. This is multiplied by a temperature stress coefficient Q_t calculated as follows:

$$Q_t = 1 - 0,0025 ((0,25T_{min} + 0,75T_{max}) - 26)^2 \quad (8)$$

which implies that ε decreases slightly with deviations from an optimum temperature of 26°C. T_{min} and T_{max} are daily minimum and maximum temperatures respectively. ε was reduced linearly from 8,8% to 6,2% between crop ages 6 and 15 months according to the data of Kortschak and Forbes.¹⁵

It was necessary to estimate the proportion of total dry mass in leaves and stalks in order to apply Glover's respiration equations. The proportions of the above ground dry mass located in stalks, green leaves and dead leaves and tillers (trash) were measured by Gosnell,⁷ Rostron¹⁹ and Thompson.²¹ There was good agreement regarding the proportion of dry mass in the stalk. This proportion was clearly related to total aerial mass (Fig. 1). The relationship between the proportion of dry matter in leaves and aerial mass was not as consistent (Fig. 2), possibly because Gosnell observed

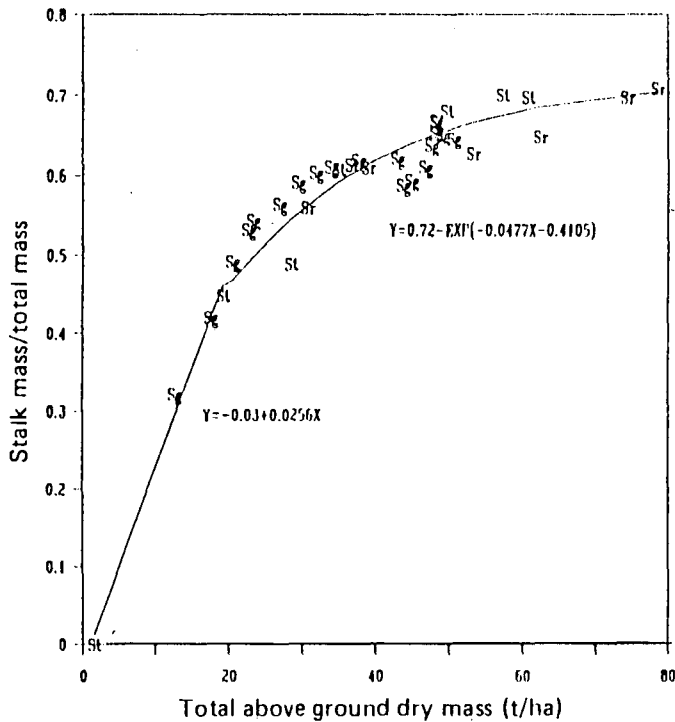


FIGURE 1 The relationship between stalk dry mass and total aerial dry mass obtained by Gosnell,⁷ Rostron¹⁹ and Thompson,²¹ Sg, Sr and St respectively.

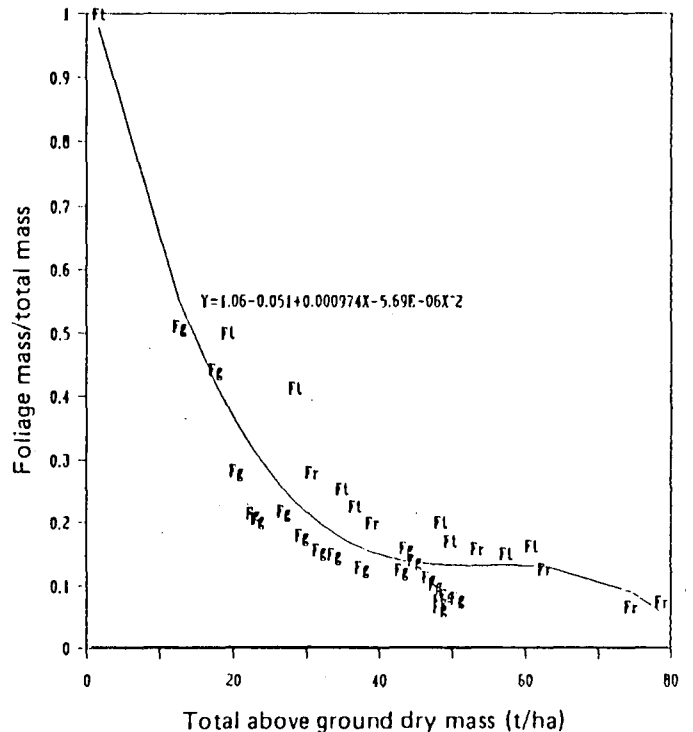


FIGURE 2 The relationship between dry mass of green foliage (sheaths and blades) to total aerial dry mass obtained by Gosnell,⁷ Rostron¹⁹ and Thompson,²¹ Fg, Fr and Ft respectively.

a rainfed crop which probably supported fewer green leaves than the irrigated crops observed by Rostron and Thompson. The proportion of total dry mass in roots was assumed to be 0,12 (van Dillewijn⁴). Stalk and leaf mass were derived as follows:

$$W_a = 0,88W \tag{9}$$

$$W_i/W_a = 1,06 - 0,051W_a + 0,000934W_a^2 - 5,691 \cdot 10^{-6}W_a^3 \tag{10}$$

$$W_s/W_a = -0,03 + 0,0256W_a \text{ for } W_a < 20 \text{ t/ha} \tag{11}$$

$$W_s/W_a = 0,72 - e(-0,04777W_a - 0,4105) \text{ for } W_a > 20 \text{ t/ha} \tag{12}$$

where W = total plant dry mass, W_a = above ground mass, W_s = mass of stalk and W_i = mass of green leaves (t/ha).

The models were driven by daily T_{min} , T_{max} and duration of sunshine (n) obtained from meteorological stations at Pongola (27° 24'S, 31° 35'E) and Shakaskraal (29° 27'S, 31° 12'E). Apart from one experiment where short wave solar radiation (R_i) was measured directly, R_i was obtained using the Angstrom formula and Smithsonian values of the duration of sunshine on a clear day and theoretical radiation incident on the earth's surface in the absence of an atmosphere.

Validation data

The results obtained using the models were compared with total dry matter yields obtained for sugarcane by Gosnell,⁷ Rostron,¹⁹ Thompson.^{20,21} Details of these experiments are:

Author	Location	Variety	Crop	Period of measurement
Gosnell (1968)	Shakaskraal	NCo376	Plant	01-10-63 to 07-10-65
Rostron (1974)	Pongola	NCo376	1R	14-01-70 to 13-07-71
Thompson (1986)	Pongola	NCo376	Plant	12-11-67 to 08-08-68
	Pongola	NCo376	1R	10-10-68 to 05-11-69
Thompson (1988)	Pongola	N14	Plant	12-11-86 to 11-10-87
	Pongola	N14	1R	12-11-86 to 11-10-87
Thompson (unpublished data)	Pongola	N14	1R	12-10-87 to 12-10-88
	Pongola	N14	2R	12-10-87 to 12-10-88

A period of 21 days was allowed for germination of the plant crops to take place.

Results and Discussion

Variety NCo376

The total dry mass (biomass) derived from the models and by Gosnell and Thompson, who also measured % ground covered vertically by the canopy, are given in Figures 3 to 6. L_i should be greater than vertical ground cover since the solar altitude ranges daily from 0° to 90° for Thompson's plant crop of NCo376 (Fig. 5). However, derived L_i was considerably lower than measured ground cover and it is likely that this crop germinated sooner than the 21 days assumed in the model. A germination sub-model would obviously improve the light interception calculations.

It is encouraging that both models predicted dry matter (DM) yields similar to those obtained in the field for all four crops when they were less than 300 days old. Gosnell's data (Fig. 3) for the later stages of crop development were variable and either model could be appropriate. The Lorber model appeared to be more appropriate for estimating increments during the later stages of growth recorded by both Rostron (Fig. 4) and Thompson (Fig. 5 and 6). The reduction in photosynthesis with advanced crop age in the Glover model may be too severe and this could be verified by *in situ* CO₂ exchange measurements.

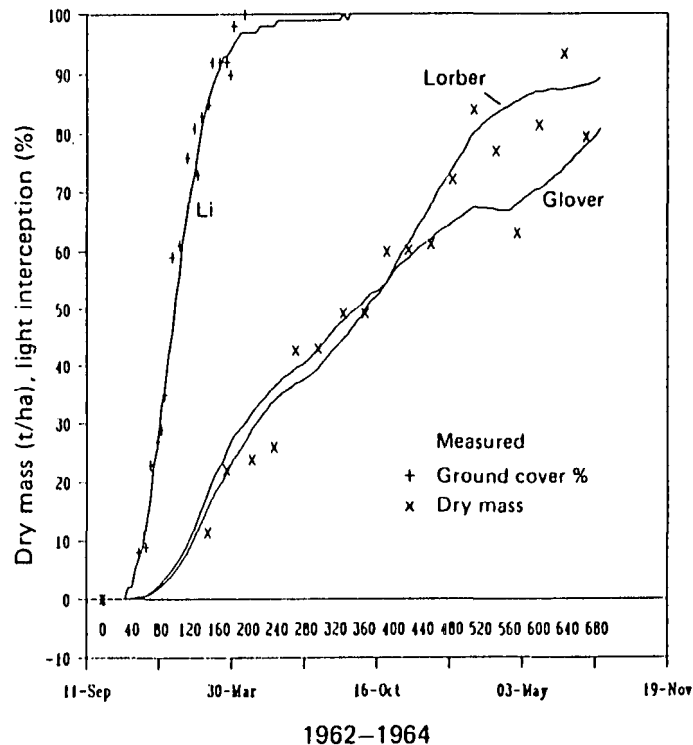


FIGURE 3 Model predictions (lines) and field measurements (symbols) of dry mass accumulation by an irrigated plant crop of NCo376 at Shakaskraal (Gosnell⁷). Measured ground cover % and % light interception (L_i) according to equation 4 are given.

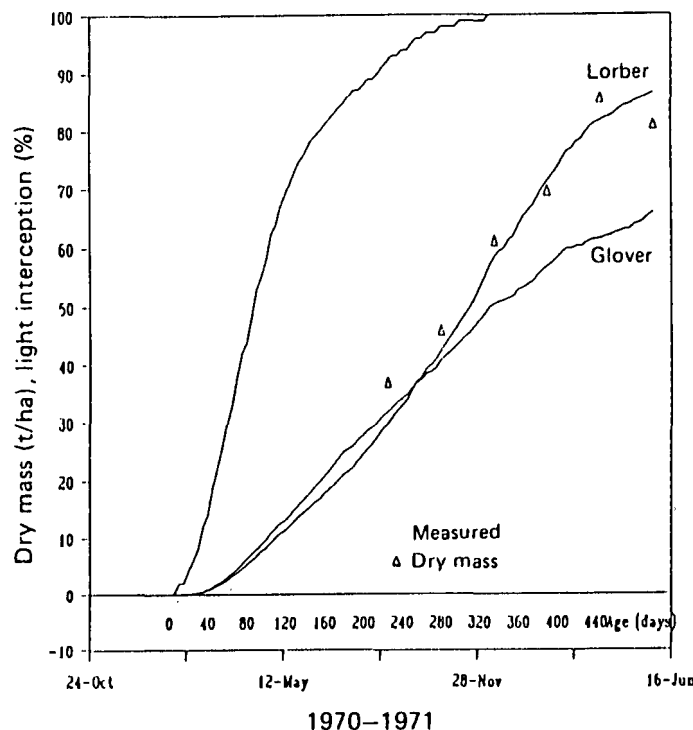


FIGURE 4 Model predictions and field measurements (Rostron¹⁹) of dry mass accumulation by an irrigated ratoon crop of NCo376 at Pongola.

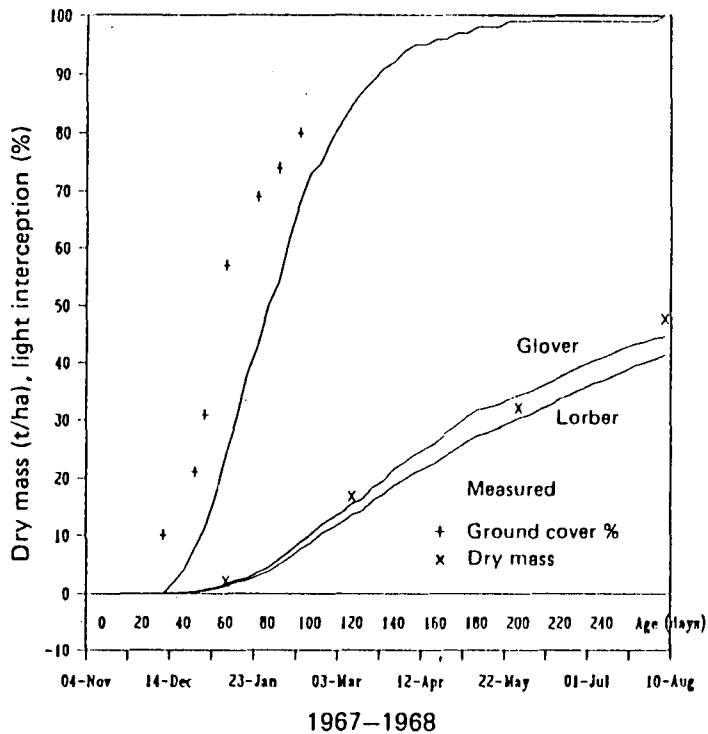


FIGURE 5 Model predictions and field measurements (Thompson²⁰) of dry mass accumulation by an irrigated plant crop of NCo376 at Pongola. Measured ground cover % and L_i according to equation 4 are given.

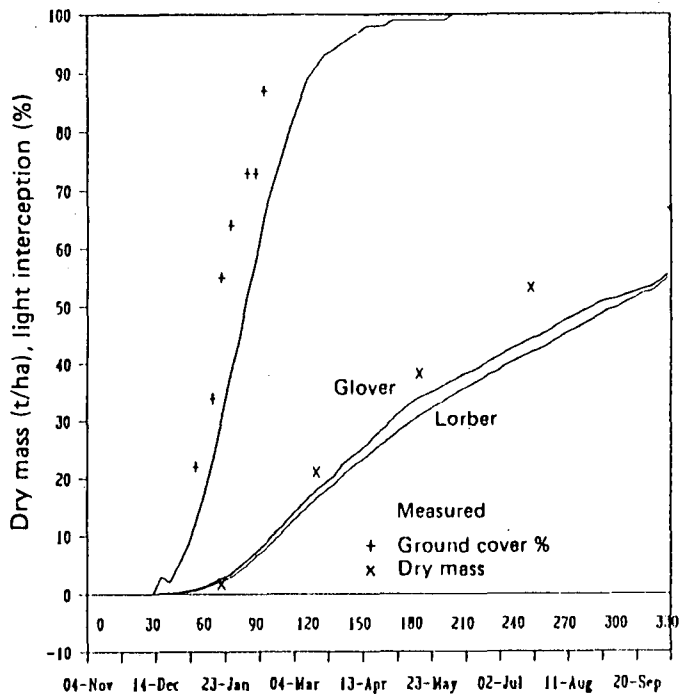


FIGURE 7 Model predictions and field measurements (Thompson²¹) of dry mass accumulation by an irrigated plant crop of N14 at Pongola. Measured ground cover % and L_i according to equation 4 are given.

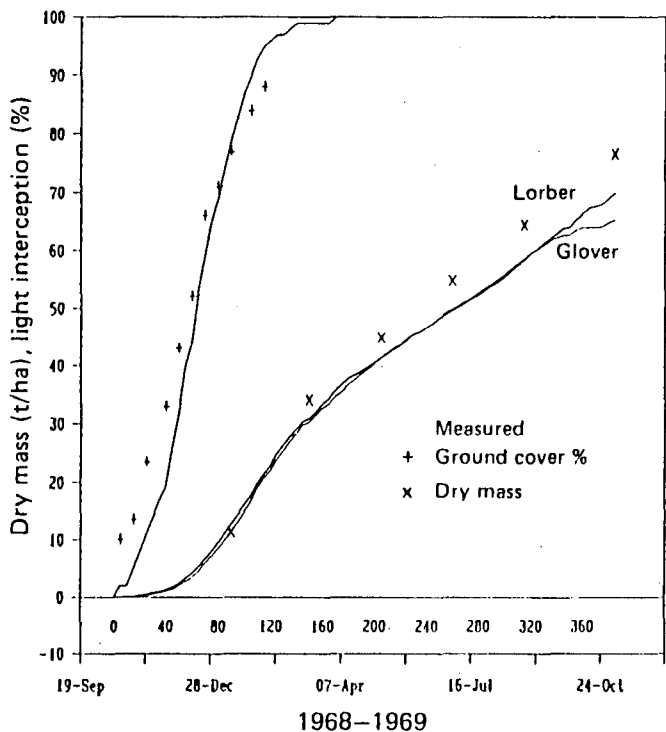


FIGURE 6 Model predictions and field measurements (Thompson²⁰) of dry mass accumulation by an irrigated ratoon crop of NCo376 at Pongola. Measured ground cover % and L_i according to equation 4 are given.

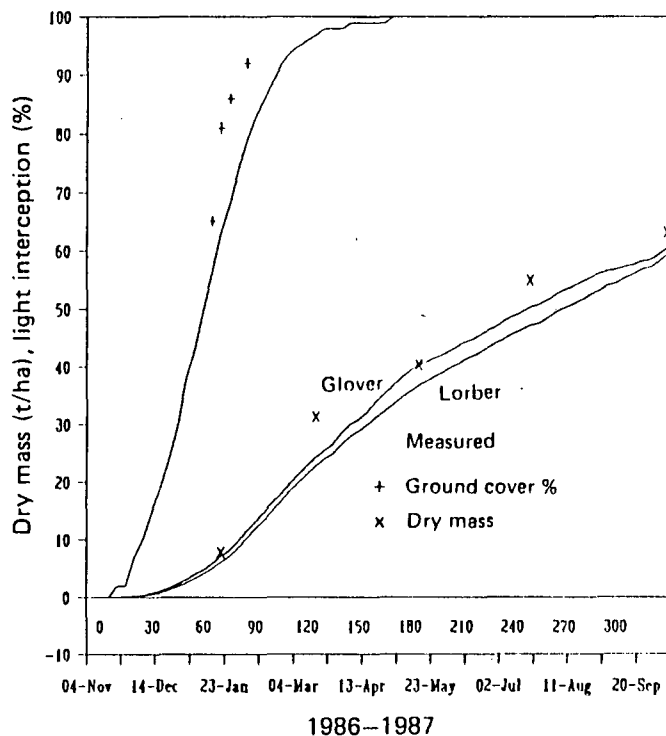


FIGURE 8 Model predictions and field measurements (Thompson²¹) of dry mass accumulation by an irrigated ratoon crop of N14 at Pongola. Measured ground cover % and L_i according to equation 4 are given.

Variety N14

The only difference that was assumed to exist between NCo376 and N14 was in the final area of individual leaves. The comparisons of derived L_i and measured ground cover of N14 shown in Fig. 7 to 9 indicate that the differences

between the two varieties may be more substantial. Leaf appearance and extension rates of N14 will need to be measured to ascertain the extent of these differences. The models under-estimated dry matter accumulation by the plant crop of N14 during 1986/87, presumably because the assumed

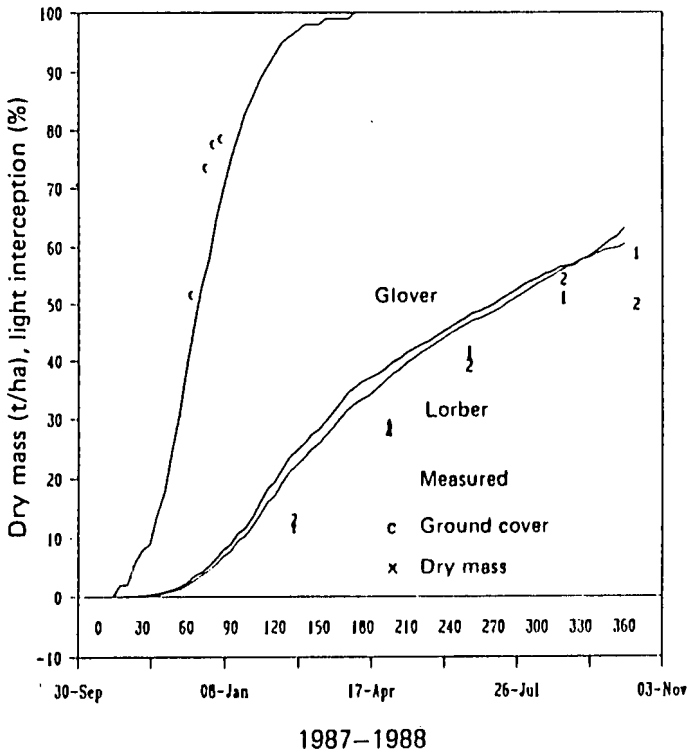


FIGURE 9 Model predictions and field measurements of dry mass accumulation by an irrigated 1st (1) and 2nd (2) ratoon crops of N14 at Pongola. Measured ground cover % and L_i according to equation 4 are given.

germination period was too long. The calculated DM yields were greater than those measured in ratoon crops of N14 during 1988 (Fig. 9), but the August estimate was realistic. The 1987/88 crop of N14 flowered profusely and this may have influenced the accumulation of dry matter, although Julien *et al*¹³ found that flowering enhanced rather than reduced growth.

Conclusion

The Lorber and Glover models provided a satisfactory explanation of dry matter accumulation by irrigated sugarcane in South Africa based on measurements of radiation and temperature. Gross photosynthetic efficiency of NCo376 appears to be 8,2 to 8,8% of PAR, at least while the crop is young. Maintenance respiration appears to be about 0,3% of dry mass, rather than 1,0% suggested by van Keulen and Wolf⁴ for cereal crops. The Lorber model is at present preferable to the Glover model because it provides data in better agreement with field measurements and because it is simple.

More data on photosynthesis and respiration are required to refine the Glover model. Although the model of the leaf canopy appears to be satisfactory for NCo376 it may contain compensating errors. The light extinction coefficient needs to be checked and the influence of changes in stalk population with time needs to be ascertained. However the model can be used to provide reasonable estimates of yield potential in relation to different planting and ratooning regimes, and in relation to temporal and spatial variations in solar radiation.

REFERENCES

1. Boyce, JP (1970). *Plant population studies in irrigated sugarcane*. Unpub MSc Thesis, University of Natal, Pietermaritzburg, RSA.
2. Bull, TA (1969). Photosynthetic efficiencies and photorespiration in Calvin cycle and C_4 dicarboxylic acid plants. *Crop Sci* 9: 726-729.
3. Bull, TA and Tovey, DA (1974). Aspects of modelling sugarcane growth by computer simulation. *Proc int Soc Sug Cane Technol* 15: 1021-1032.
4. Dillewijn van C (1952). *Botany of sugarcane*. Waltham, Mass. USA.
5. Ehleringer, J and Pearcy RW (1983). Variation in quantum yield for CO_2 uptake among C_3 and C_4 plants. *Plant Physiol*. 73: 555-559.
6. Glover, J (1972). Practical theoretical assessments of sugarcane yield potential in Natal. *Proc S Afr Sug Technol Ass*. 46: 138-141.
7. Gosnell (1968). *The growth of sugarcane*. Unpub PhD Thesis, University of Natal, Pietermaritzburg, RSA.
8. Hesketh, Baker and Duncan (1971). Simulation of growth and yield in cotton: respiration and carbon balance. *Crop Sci* 11: 394-398.
9. Inman-Bamber, NG (1987). *The reaction of sugarcane to water stress*. Unpub PhD Thesis, University of Orange Free State, Bloemfontein, RSA.
10. Inman-Bamber, NG and de Jager, JM (1986). Effect of water stress on growth, leaf resistance and canopy temperature in field grown sugarcane. *Proc S Afr Sug Technol Ass* 60: 156-161.
11. Jones, CA (1985). C_4 Grasses and Cereals: *Growth, development and stress response*, pp 419. John Wiley and Sons, NY
12. Jones, CA and Kiniry, JR (1986). CERES-MAIZE model: *A simulation model of maize growth and development*. Texas A & M University Press, pp 194.
13. Julien, MHR; Soopramanien, GC; Martine, JF and Medan (1980). The role of side shoots in flowered stalks of sugarcane. *Proc int Soc Sug Cane Technol* 17: 571-582.
14. Keulen van H and Wolf, J (1986). *Modelling of agricultural production, weather, soils and crops*, pp 479. Purdoc Wageningen.
15. Kortschak, HP and Forbes, A (1969). The effects of shade and age on the photosynthesis rate of sugarcane. *Prog. Photosynth. Res.* 1: 383-387.
16. Lorber, MN; Fluck, RC and Mishoe JW (1984). A method for analysis of sugarcane (*Saccharum sp*) biomass production systems. *Transactions of the Am Soc Agric Engr.* 27: 146-158.
17. McCree (1970). *In Prediction and measurement of photosynthetic productivity*, Ed Setlik, I. pp. 221-229, Purdoc, Wageningen.
18. Mishoe, Jones and Gascho (1979). Harvesting scheduling of sugarcane for optimum biomass production. *Transactions of the Am Soc Agric Engr* 22: 1299-1304.
19. Rostron, H (1974). Radial energy interception, root growth, dry matter production and the apparent yield potential of two sugarcane varieties. *Proc int Soc Sug Cane Technol* 15(2): 1001-1009.
20. Thompson, GD (1986). Agrometeorological and crop measurements in a field of sugarcane. *Mount Edgecombe Research Report* 5.
21. Thompson, GD (1988). Comparisons of the growth of plant and first ratoon crops of sugarcane at Pongola. *Proc S Afr Sug Technol Ass* 62: 180-184.
22. Wit de CT (1978). *Simulation of assimilation, respiration and transpiration of crops*. Wageningen.