

SHORT, NON-REFEREED PAPER

SIMULATING SOURCE AND SINK CONTROL OF STRUCTURAL GROWTH AND DEVELOPMENT AND SUGAR ACCUMULATION IN SUGARCANE

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Abstract

Crop simulation modelling can assist plant breeding by simulating the contribution of sub-traits such as leaf elongation rate to complex traits such as sucrose yield and by simulating realistic interactions between the genetic traits and environmental factors. In the current Canegro sugarcane model, while canopy area development is a major component of carbon availability (source) through photosynthesis, leaf area and leaf dry mass as a sink for carbon are not linked. Also, carbon partitioning is largely unresponsive to changing demand of structural sinks for carbon. This study aimed at linking photosynthesis and canopy development via a conservative carbon balance based on source-sink principles. New model concepts and a preliminary evaluation of model behaviour are briefly described in this communication.

Keywords: internode, shoot, trait parameters, partitioning, modelling, Canegro, leaf, sugar, carbon

Introduction

Crop simulation modelling can assist plant breeding, via the prediction of complex traits (e.g. sucrose yield) by simulating interactions between simple genetic traits (e.g. leaf elongation rate per unit thermal time) and environmental factors (e.g. temperature) (Hammer and Jordan, 2007). The Canegro sugarcane model (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002) is unsuitable for this task because structural growth and development are not affected by carbon availability (source), and carbon partitioning is largely unresponsive to changing demand of structural sinks. The objective of this study was to modify Canegro to address these shortcomings and make it suitable for gene-to-phenotype modelling. Model concepts and a preliminary evaluation of model behaviour are briefly described in this communication.

Model description

The new model (named GTP-Canegro) was implemented in DSSATv4.5 Canegro framework (Singels *et al.*, 2008) and simulates processes as follows:

The germination and emergence of primary shoots, and tillering per primary shoot, are determined by thermal time accumulation (base 16 °C), bud density and planting depth. Tillering is limited by intra-row light interception (Singels and Smit, 2009). Final shoot

population is estimated from peak population. Tiller senescence commences at the start of stalk elongation.

Leaf appearance rate is determined by thermal time (base 8 °C), based on an approach by Bonnett (1998). Leaf senescence is calculated so that green leaf number cannot exceed the genetically-determined maximum (12) and is modified by water stress (as in Canegro).

Gross photosynthesis rate (Pg) and growth respiration rate (Rg) are calculated as in Canegro. Maintenance respiration rates (Rm) can be calculated separately for stalk fibre, leaves/sheaths, stalk hexose and stalk sucrose. Net photosynthesis (Pnet) is the difference between Pg and Rg+Rm, and is referred to as 'source' further on.

Root dynamics are calculated as in DSSATv4.5 Canegro, but with a new value for root elongation rate per unit thermal time (RER, 2.2 mm/°Cd).

Potential elongation rates of leaves (LER) and stalks (SER) are calculated from thermal time (base 10 °C and 16 °C respectively) and limited by water stress. Leaf width is calculated using a similar approach to Canegro and stalk diameter equals leaf width up to a genetically-determined maximum (2 cm). Leaf expansion creates a demand for carbon through the specific leaf weight (SLW_{min} = 120 g/cm²). Five leaves can expand simultaneously at rates determined by leaf age.

Up to six internodes elongate simultaneously, creating a carbon demand via minimum stalk fibre density (0.04 g/cm³). This is termed 'primary' stalk fibre. Surplus source is stored as secondary stalk fibre up to a maximum stalk fibre density of 0.12 g/cm³.

Actual LER and SER are limited by source availability when Pnet is less than structural sink demand (excluding secondary stalk fibre): a daily source-sink balance determines the fraction of potential LER and SER at which sink strength ≤ Pnet.

Stalk hexose mass is based on daily respiration rates. Remaining source, after meeting leaf and stalk fibre expansion (primary and secondary) and hexose requirements, is distributed as sucrose along the stalks, subject to a per-internode maximum brix concentration of 0.7 g/g internode dry mass.

Model structure is illustrated in Figure 1.

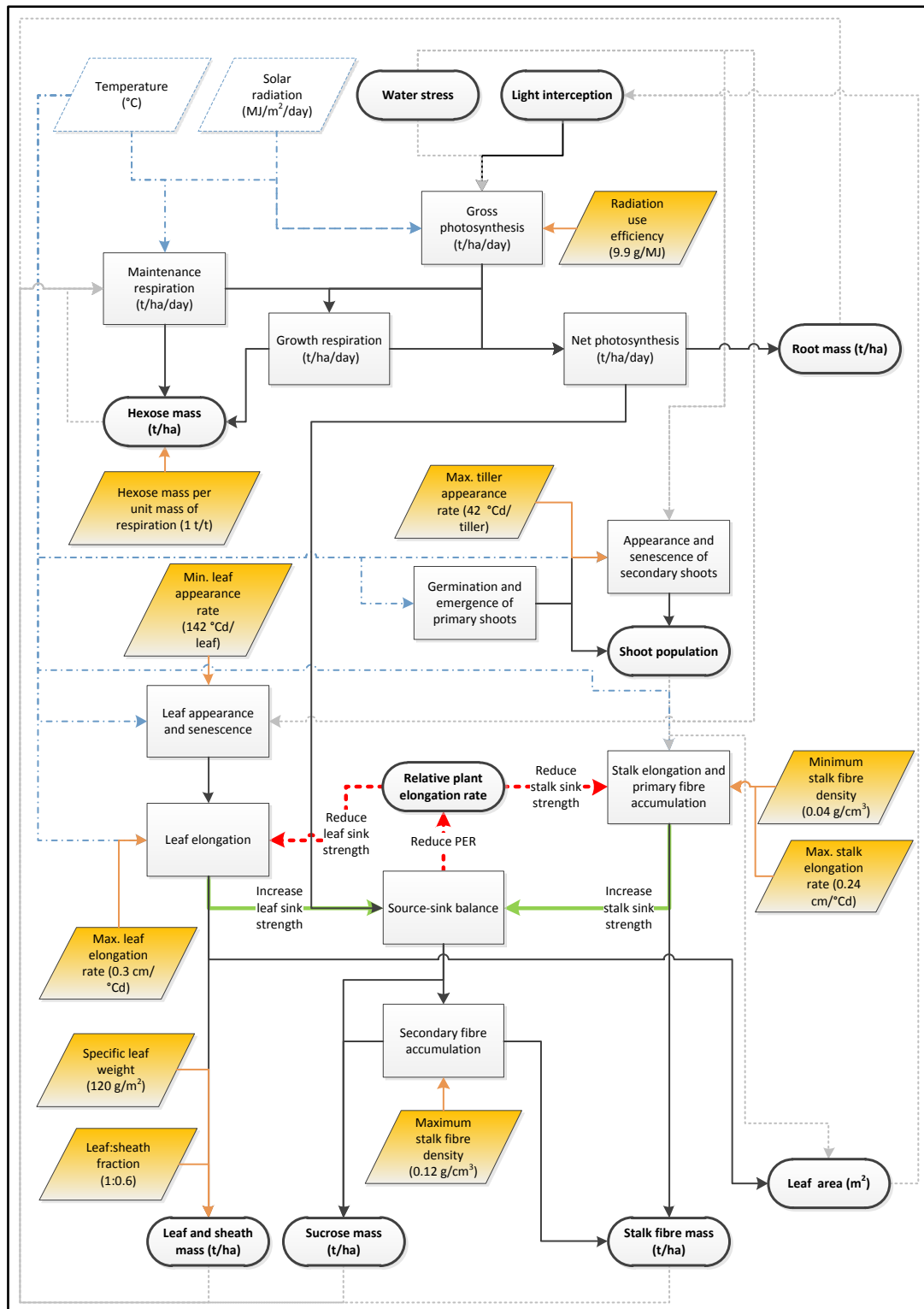


Figure 1. Structure of the GTP-Canegro model. Square boxes (□) are model processes, and rounded boxes (◻) are state variables. Dashed blue parallelograms (▭) are sources of weather data, while solid shaded parallelograms (▨) represent genetic trait parameters (values for NCo376 shown). Solid black lines (→) indicate data flow from calculations made from the current day's values, while dashed grey line calculations (---→) are based on the previous day's values. Dashed blue lines (---→) represent weather data flow; solid orange -lines (→) represent genetic trait parameter inputs; and thick arrows (positive: →; negative: ---→) show the calculation of feedback via the source-sink balance. Processes are explained in the text.

Model evaluation

The new model was calibrated using tiller population and light interception data from the 1.5 m row spacing treatment of an experiment conducted at Mount Edgecombe (Singels and Smit, 2009). Mass samples taken at harvest (11 months' age) for the 1.37 m and 1.8 m row spacings were averaged, because no samples were taken at a row spacing of 1.5 m. Observations, and DSSATv4.5 Canegro simulations, were compared with GTP-Canegro simulations to assess its performance.

GTP-Canegro simulations showed excellent agreement with observations for shoot population and stalk height, and good agreement for fractional light interception (F_i) (Figure 2). GTP-Canegro simulated values at harvest were closer to observed values than the values simulated by DSSATv4.5 Canegro for all biomass components (see Table 1). The simulated leaf and stalk fraction (of aerial biomass) was lower than that observed and calculated by DSSAT4.5 Canegro (leaf - 38% compared to 41 and 47%; stalk - 53% compared to 59 and 54%). The stalk fibre fraction was higher than that observed and calculated by Canegro, while the sucrose fraction was lower (stalk fibre - 32% compared to 29 and 30%; sucrose - 20% compared to 24 and 24.5%).

The new model was also evaluated by assessing the impact of genetic trait parameters on key state variables. Typical values for minimum leaf appearance rate (LAR_0), maximum tiller appearance rate (TAR_0), maximum stalk elongation rate (SER_0) and maximum leaf elongation rate (LER_0) were derived from experimental data (Inman-Bamber *et al.*, 2010, 2011; Singels *et al.*, 2010; Smit and Singels, 2007). The value of one trait parameter was varied at a time, leaving the remaining parameters at values determined for cultivar NCo376 (Table 1).

Decreasing TAR_0 reduced peak and final shoot population, but only minimally reduced light interception (Table 1). The lower stalk fibre mass resulted in more source availability for sucrose accumulation. Decreasing LAR_0 meant that tillering ceased and stalk growth commenced 29 days later than the standard NCo376 run. This increased peak shoot population, peak LAI and root mass. Stalk fibre decreased markedly (20%) while sucrose mass increased by 11%. Decreasing LER_0 resulted in less leaf area per shoot. More light transmission into the stool allowed faster tillering and increased shoot population, but this was insufficient to offset the effect of smaller leaves, leading to a lower peak LAI. Stalk fibre mass increased resulting in lower sucrose mass. Decreasing SER_0 had no effect on shoot population, but significantly reduced demand for structural stalk fibre, thus allowing a marked increase (28%) in sucrose mass. Simulated hexose mass at harvest was insensitive to these parameter adjustments.

Conclusion

In the new model photosynthesis, structural growth and development and sugar accumulation were linked using source-sink principles. Simulation accuracy for shoot population, light interception and stalk height was excellent for the calibration experiment. The new model under-predicted mass variables but less so than the old model. The sensitivity analysis revealed mostly realistic responses to changes in genetic trait parameters.

The new model provides a platform for simulating dynamic interactions between processes at an internode level, but additional model development and targeted experimental work are required before the model is sufficiently robust to assist plant breeding.

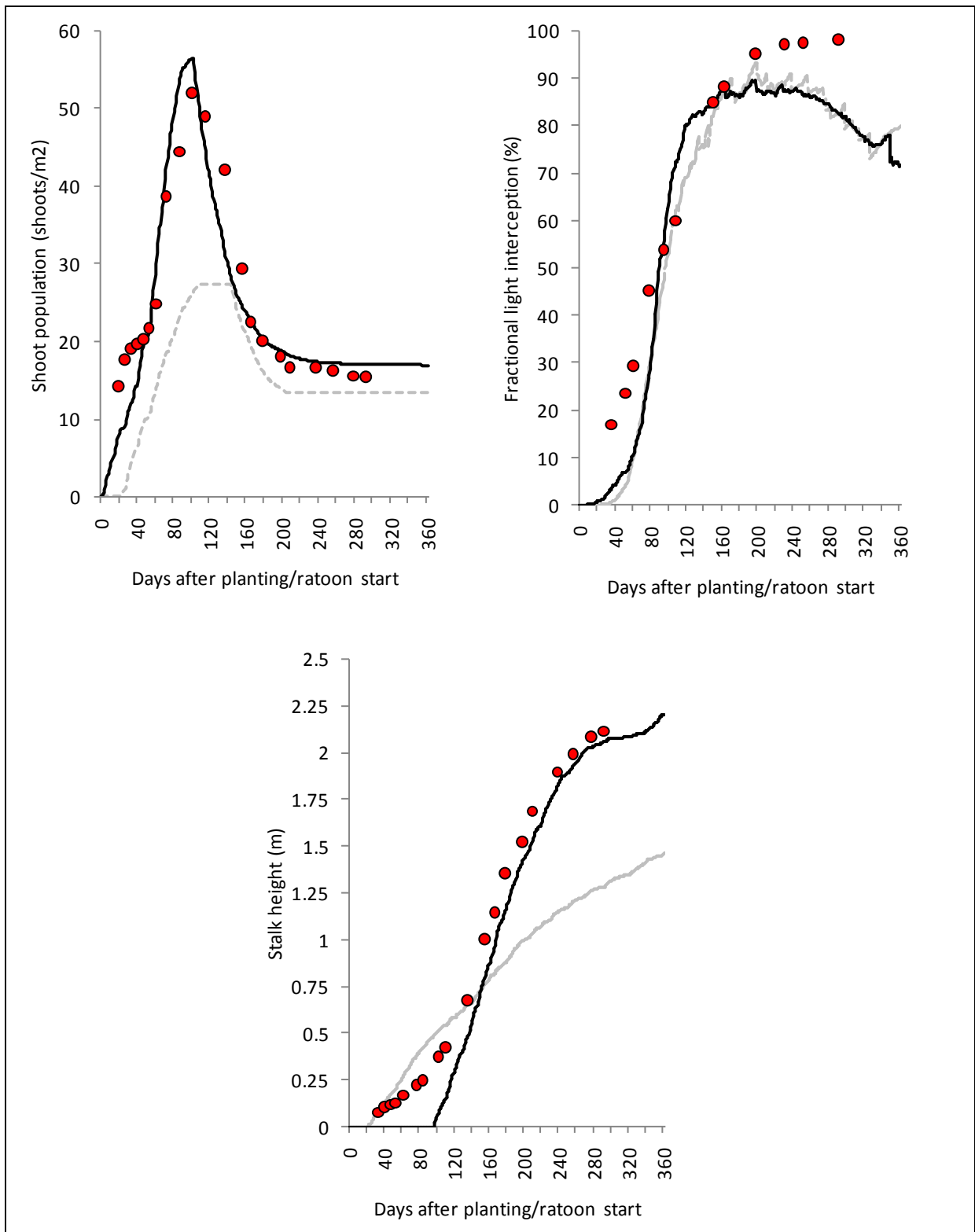


Figure 2. Results of GTP-Canegro model calibration: shoot population, fractional light interception (%) (simulated: green leaves only; observed: total) and stalk height for the DSSATv4.5 Canegro model (dashed grey lines: ----), the GTP-Canegro model (solid black lines: —), and observations (red dots: ●).

Table 1. Performance of DSSATv4.5 Canegro with NCo376 trait parameter values and GTP-Canegro with NCo376 parameters, and high (H) and low (L) values for the following trait parameters: minimum leaf appearance rate (LAR₀), maximum tiller appearance rate (TAR₀), maximum stalk elongation rate (SER₀) and maximum leaf elongation rate (LER₀). All values at harvest (11 months) unless otherwise indicated. All mass values are for dry biomass.

Run description	Peak pop. (shoots/m ²)	Final pop. (shoots/m ²)	Max. leaf area index (m ² /m ²)	Root mass (t/ha)	Aerial biomass (t/ha)	Leaf + trash mass (t/ha)	Stalk mass (t/ha)	Stalk fibre mass (t/ha)*	Sucrose mass (t/ha)	Hexose mass (t/ha)
Observed	52.1	15.5	-	-	59	24	35	17.2	14.2	-
DSSATv4.5 Canegro	27.3	13.3	2.77	6.4	35.2	16.3	18.9	10.4	8.6	-
GTP-Canegro with standard NCo376 parameter values ¹	56.5	17.0	3.07	7.9	40.8	17.0	23.8	14.6	9.0	0.2
TAR ₀ = 0.0236 shoots/°Cd (42.4 °Cd/shoot) (H)	56.5	17.0	3.07	7.9	40.8	17.0	23.8	14.6	9.0	0.2
TAR ₀ = 0.0118 shoots./°Cd (84.7 °Cd/shoot) (L)	40.4	15.3	2.83	7.6	38.5	14.3	24.2	13.8	10.2	0.2
LAR ₀ = 0.0072 leaves/°Cd (139 °Cd/leaf) (H)	56.2	16.9	3.04	7.8	40.9	16.9	24.0	14.7	9.1	0.2
LAR ₀ = 0.0047 leaves/°Cd (213 °Cd/leaf) (L)	60.9	17.8	3.70	8.5	39.3	17.5	21.8	11.7	10.0	0.2
LER ₀ = 0.36 cm/°Cd (H)	54.1	16.7	3.54	8.2	43.2	19.3	23.9	14.0	9.7	0.2
LER ₀ = 0.24 cm/°Cd (L)	59.8	17.3	2.62	7.5	38.6	15.1	23.5	15.3	8.1	0.2
SER ₀ = 0.276 cm/°Cd (H)	56.5	17.0	3.04	7.8	41.2	17.1	24.1	16.6	7.3	0.2
SER ₀ = 0.184 cm/°Cd (L)	56.5	17.0	3.11	8.0	40	16.8	23.2	11.4	11.6	0.2

* Stalk fibre is not calculated directly in Canegro. This is non-sucrose stalk mass.

¹ See Fig. 1 for parameter values.

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