CASUPRO: An industry-driven sugarcane model

Fernando D. Villegas

University of Florida, Frazier Rogers Hall, P.O. Box 110570, Gainesville, FL 32611-0570,

e-mail: fvillega@ufl.edu

Oscar H. Daza

Cal Poly State University, SLO, Civil & Environmental Engineering 13-263 San Luis Obispo, California, 93407.

James W. Jones

University of Florida, Frazier Rogers Hall, P.O. Box 110570, Gainesville, FL 32611-0570.

Frederick S. Royce

University of Florida, Frazier Rogers Hall, P.O. Box 110570, Gainesville, FL 32611-0570.

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Abstract. *In the Colombian sugar industry, sugarcane (S. Officinarum) is planted, harvested and processed continuously throughout the year. However, there are seasonal and spatial variations in cane and sucrose productivity that affect the profitability of sugar production. Industry research leaders believe that the availability of a practical simulation model for cane and sucrose production*

will help managers understand the causes of this variability and contribute to the design of strategies for more effective resource allocation.

The Colombian Sugar Cane Research Center (CENICAÑA) and the Crop Systems Modeling group at the University of Florida's Agricultural and Biological Engineering Department are developing the CASUPRO (CAne/SUcrose PROduction) model, based on the DSSAT-CROPGRO modular structure (Phenology, Photosynthesis, Growth, and Soil-Water balance). Like other DSSAT models, CASUPRO aspires to universal applicability; i.e., the ability to simulate growth and development under the local conditions of sugarcane producers around the world. Data are currently being collected in Colombia, Florida and Puerto Rico for calibrating and validating the model. We present the mathematical relationships that describe phenological development, leaf area development, and dry matter growth and partitioning. Preliminary simulation results are shown for leaf area and phenological development.

Keywords. Sugarcane, modeling, simulation, phenology, growth.

Introduction

The application of simulation models in the sugar industry has constituted an important strategy in some cane-growing areas in the world. These have helped improve the understanding of complex processes related to cane and sucrose production as a result of water-soil-plant-climate interactions. A summary of the history of the models' development in sugarcane was described by O'Leary (2000). There are two main sugarcane simulation models currently in use throughout the world; the Australian model, APSIM-Sugarcane (Keating et al., 1999) and the South African model CANEGRO (Inman-Bamber, 1995). CANEGRO has been included in the Decision Support System for Agrotechnology Transfer (DSSAT Version 3.5, Jones et al., 1998) suite of models, and has been used throughout the Americas, Africa and Asia. These two models, while developed independently, have similar origins and some have precursor older models that are still in use. For example, AUSCANE (Jones et al., 1989) is a precursor to APSIM-Sugarcane that was adapted from the older EPIC (Williams et al., 1984) soil erosion model. There is, however, another less well-known model that was also developed in Australia (QCANE, by Liu and Kingston, 1995) that arose from the conceptual framework of Bull and Tovey (1974).

Over the last five years, the Colombian sugar industry has been working on the development a simulation model of the growth of the cane crop based on simplified processes that incorporate the water-soil-plant-environment relationships in order to improve the understanding of variations in cane and sucrose productivity. This model is being developed as an effective tool for estimating commercial cane production (expected within a given planning horizon). This task is being carried out in cooperation with the modeling group of the University of Florida, Department of Agricultural and Biological Engineering. The result is CASUPRO (CAne/SUcrose PROduction), which is a simulation model based on simplified plant processes and structured similar to CROPGRO (Generic crop model based on the SOYGRO, PNUTGRO, and BEANGRO models) [Boote 1998]. CASUPRO is intended to be a model of universal applicability, which could be used for the local environmental conditions and local varieties in Colombia. It is expected that CASUPRO can help understand the causes of yield variations and provide more input into the design of strategies for using and assigning available resources more efficiently, leading to better decision making.

The purpose of this paper is to present the advances made thus far in development of the Cane / Sucrose Production model (CASUPRO). The mathematical relationships that describe phenological development, leaf area development, and dry matter growth and partitioning are presented. The opportunities for improving the capabilities of the model are discussed, and directions for future work are suggested.

Model development

CASUPRO sugarcane model has the following attributes: dynamic, mechanistic (based on simplified processes of the soil and the plant), modular in structure, simulation of C – water - N balance processes, applicable to different conditions, and friendly user interface (DSSAT for Windows). It was decided to follow three thematic phases in model development, which correspond to potential, attainable and actual production situations. The primary emphasis was given to potential production, and this phase consists of incorporating solar radiation, temperature and photoperiod as the factors that determine production, given ample availability of water and nutrients. It includes cane variety characteristics such as the structure of stalks and leaves, the population of stalks, the capacity of biomass and sucrose production, and phenological states such as flowering and ripening.

The structure of the model consists of four basic modules: a command module with the principal program and modules for Plant, Climate, and Water balance. The plant module is divided into phenology and growth components. There are four plant components for the C and N balance: stalks, leaves, roots and sugars. One reason to adopt the C and N balance, using photosynthesis and respiration instead of a light use efficiency approach, was to have an explicit state variable describing the stored sugars at any time and thereby be able to simulate the dynamics of sucrose content. This approach differs from other models such as CANEGRO (South Africa) and APSIM-Sugar (Australia), which incorporate an exogenous relation of the sucrose depending on the amount of dry matter accumulated.

Plant Module

1. Phenology

Like most simulation models, CASUPRO predicts phenology primarily based on temperature data over the growing season and, if the crop is photoperiod sensitive, on daylength. Inherent in this approach is the assumption that the developmental processes underlying phenology are relatively insensitive to assimilate, nutrient, or water balances of the plant. This contrasts with growth processes where these factors are of primary importance.

1.1. *Thermal Time for Phenological Stages*

Thermal time is commonly used to model plant phenology. Modeling of the phenological stages for the sugarcane plant uses a base temperature T_b = 9 °C, an optimum temperature range between T_{o1} = 27 °C and T_{o2} = 32 °C and a maximum critical temperature T_m = 45 °C (Inman-Bamber, 1994; Robertson, 1998; Clements, 1980; Ebrahim, 1998). At temperatures below 9 °C and above 45 °C, the plant ceases its growth. For temperatures above the optimum range, the process primarily affected is photosynthesis. This base temperature is also used to model leaf appearance.

The use of a generic base temperature assumes that all phenological stages of the plant have the same base temperature. Thermal time is represented in general as

$$D_i = D_{i-1} + \Delta D_i \qquad \forall\, i = 1, 2, \ldots, I$$

(1)

$$\Delta D_i = \begin{cases} 0 & \forall\, T_i < T_b \;\; or \;\; T_i > T_m \\ T_i - T_b & \forall\, T_b \leq T_i < T_{o1} \\ T_{o1} - T_b & \forall\, T_{o1} \leq T_i \leq T_{o2} \\ \left(T_{o1} - T_b\right)\left(\dfrac{T_m - T_i}{T_m - T_{o2}}\right) & \forall\, T_{o2} < T_i \leq T_m \end{cases}$$

Where i = index denoting period; T_i = mean daily temperature in period i (°C); D_i = accumulated thermal time up to period i (°C-day); D_{i-1} = accumulated thermal time up to period i-1 (°C-day); ΔD_i = thermal time increment in period i (°C-day).

Average daily temperature is calculated on the basis of the maximum/minimum daily temperatures and is expressed by

$$T_i = \frac{T_{\max i} + T_{\min i}}{2}$$

(2)

Where $T_{max\,i}$ = maximum daily temperature (°C); $T_{min\,i}$ = minimum daily temperature (°C). Other expressions could be used for the calculation of the mean daily temperature and development like the mean hourly temperature; such calculations would be possible in first order automated meteorological stations. The choice of an expression would depend on how well it represents the mean daily temperature.

1.2. *Phenological Stages*

Table 1 shows the phenological stages and the associated phases proposed in the model, as well as the thermal time required or threshold to reach a phenological stage. These phenological stages have been adapted from Robertson et al. (1998) and Kiker and Iman-Bamber (1998) (Figure 1). For example, sprouting of the buds in the seeding occurs after 350 °C-day for plant crops and 100 °C-day for ratoon crops. Next, the sprouts grow toward the ground surface at a rate of 0.8 mm soil depth $(°C\text{-}day)^{-1}$, under the assumption that soil moisture is adequate in the layer containing the seed cutting. The thermal time that elapses between emergence and the beginning of stalk growth is specific to the genotype and ranges from 1200-1800 °C-day. Finally, given the complexity and lack of knowledge associated to the flowering process, it is only modeled as a phenological stage and not as a process.

Table 1. Phenological stages defined in the CSM.

Stage[a]	Event	Phase[b] (subevents)		Estimated Phase Duration (Thermal Time)
1	Planting			
		P_1	Germination • Filling and elongation of vegetative buds • Maximum growth of the primary roots of the shoots or the rations	Crop type Plant: 350 °C-day Ratoon: 100 °C-day
2	Sprouting of shoots			
		P_2	Initiation of growth of primary stalk	0.8 mm soil depth $(°C\text{-}day)^{-1}$
3	Emergence of the stalk/leaf structures on the surface			
		P_3	Growth of the first tillers and leaves above the ground surface	1200-1800 °C-day
4	Beginning of stalk growth			
		P_4	Tillering and establishment of the foliage • Initiation of tillering • End of effective tillering • Limit of the number of millable stalks	>6000 °C-day
5	Flowering			

[a] Stage (or developmental stage) refers to events
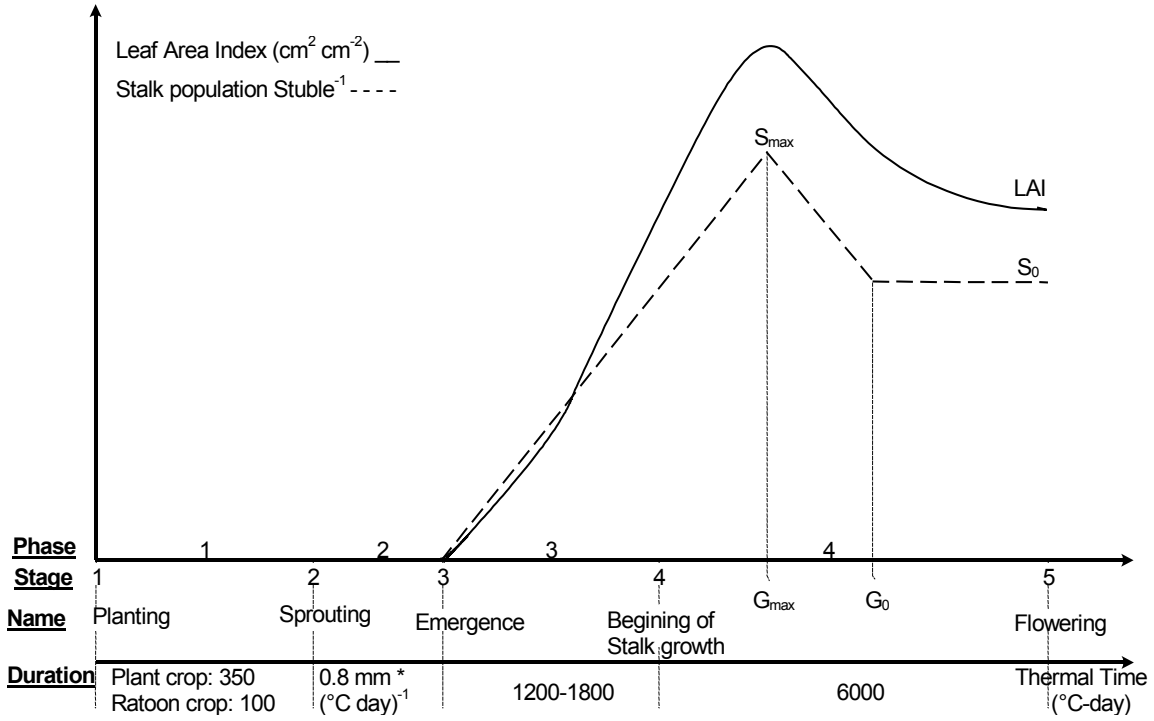[b] Phase refers to interval between stages

Figure 1. Phenological stages, phases and duration defined in the cane and sucrose production model.

1.3. *Leaf Appearance*

Air temperature mostly drives leave appearance on the stalk. It has been found the sugarcane plant follows a relatively regular pattern of leaf (or phyllocron) appearance (Inman-Bamber, 1994; Robertson, 1998). This type of response is a characteristic of each cane variety.

First of all, thermal time is accumulated each day for each stalk individually following a state equation expressed by

$$d_{i,j} = d_{i-1,j} + \Delta d_i \qquad \forall\, i = 1, 2, \ldots, I;\; j = 1, 2, \ldots, J \tag{3}$$

Where $d_{i,j}$ = accumulated thermal time in period i for stalk j (°C-day); $d_{i-1,j}$ = accumulated thermal time in period i-1 for stalk j (°C-day); Δd_i = thermal time increment for leaf appearance in period i (°C-day), calculated as ΔD_i in equation 1.

The rate of leaf appearance is expressed in terms of thermal time by a piece-wise linear function (Figure 2) as

$$\Delta l_{i,j} = \begin{cases} \dfrac{\Delta d_i}{Ph1} & \forall\, 0 \leq d_{i,j} \leq d_O \\[2em] \dfrac{\Delta d_i}{Ph2} & \forall\, d_{i,j} > d_O \end{cases} \qquad \forall\, i = 1, 2, \ldots, I;\; j = 1, 2, \ldots, J \tag{4}$$

Where j = index denoting stalk number; J = maximum number of stalks a stubble can yield (# stalks stubble^{-1}); $\Delta l_{i,j}$ = leaf number increase at period i in stalk j (# leaves (°C-day)$^{-1}$); P_{h1}, P_{h2} = inverse slopes of the linear relationship for phyllocron interval 1 and 2 (# leaves (°C-day)$^{-1}$); d_o = threshold of thermal time (T_b = 9 °C) corresponding to a given leaf number at which phyllocron interval changes (°C-day). Phyllocron intervals and threshold values are proper of a given cane variety (genotype).

Leaf number is accumulated in each period for each stalk with a state equation defined by

$$l_{i,j} = l_{i-1,j} + \Delta l_{i,j} \qquad \forall i = 1,2,\ldots,I; \; j = 1,2,\ldots,J \qquad (5)$$

Where $l_{i,j}$ = leaf number in period i and stalk j (# leaves stalk^{-1}).
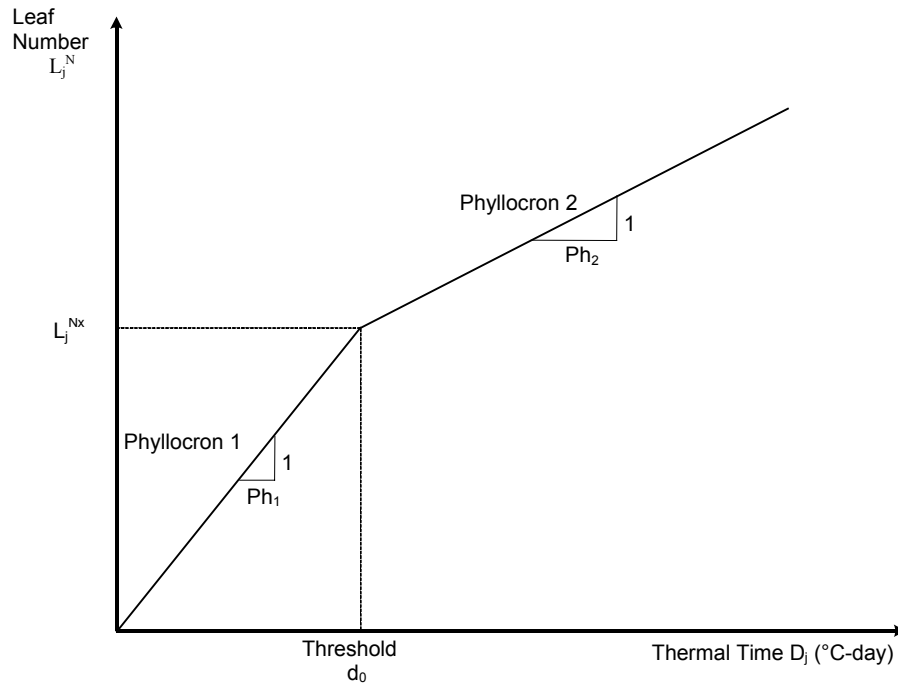

Figure 2. Rate of leaf appearance and phyllocron change in terms of thermal time in the sugarcane plant.

1.4 *Stalk Appearance*

Stalk appearance is a dynamic process, and modeling attempts to describe stalk population have used different approaches. One of these approaches incorporated a fourth order polynomial, using thermal time as an independent variable, obtaining the greatest coefficient of determination with a base temperature of T_b = 16 °C (Inman-Bamber, 1994). In a ratoon crop, the maximum population was obtained at a thermal time of 500 °C-day and stabilized after 1200 °C-day. In a plant crop, the stalk population reached a maximum at a thermal time of 1400 °C-day from emergence, after which stalk population is decreased until reaching a stable number. Generally, the stalk population depends on crop type (plant or ratoon crop), cane variety and bud planting density (# buds ha^{-1}).

Sugarcane develops tillers in a fixed pattern. Dillewijn (1952) reported a tillering pattern described as (1a, 3b, 3c) where: 1a = main stalk; 3b = three secondary stalks (b_1, b_2, b_3); 3c = three tertiary stalks (c_1, c_2, c_3) (Figure 3). This rule would mean that each bud develops

potentially 7 stalks for a plant (or stubble). The rate of appearance of each stalk generation would be constant based on a thermal time threshold (after a number of °C-day accumulates a new stalk appears) and can be a genetic coefficient of each cane variety. In principle, the number of stalks at a given time would be the sum of stalks of different generations.

In the same way as for leaf appearance, stalk appearance is modeled using a base temperature T_b^s = 16 °C for which a new thermal time is defined as

$$G_i = G_{i-1} + \Delta G_i \qquad\qquad \forall\, i = 1, 2, \ldots, I$$

(6)

$$\Delta G_i = \begin{cases} 0 & \forall\, T_i < T_b^s \ \ or \ \ T_i > T_m \\ T_i - T_b^s & \forall\, T_b^s \leq T_i < T_{o1} \\ T_{o1} - T_b^s & \forall\, T_{o1} \leq T_i \leq T_{o2} \\ \left(T_{o1} - T_b^s\right)\left(\dfrac{T_m - T_i}{T_m - T_{o2}}\right) & \forall\, T_{o2} < T_i \leq T_m \end{cases}$$

Where G_i = accumulated thermal time for stalk appearance up to period i (°C-day); G_{i-1} = accumulated thermal time for stalk appearance up to period i-1 (°C-day); ΔG_i = thermal time increment for stalk appearance in period i (°C-day); T_b^s = base temperature for stalk appearance (°C).
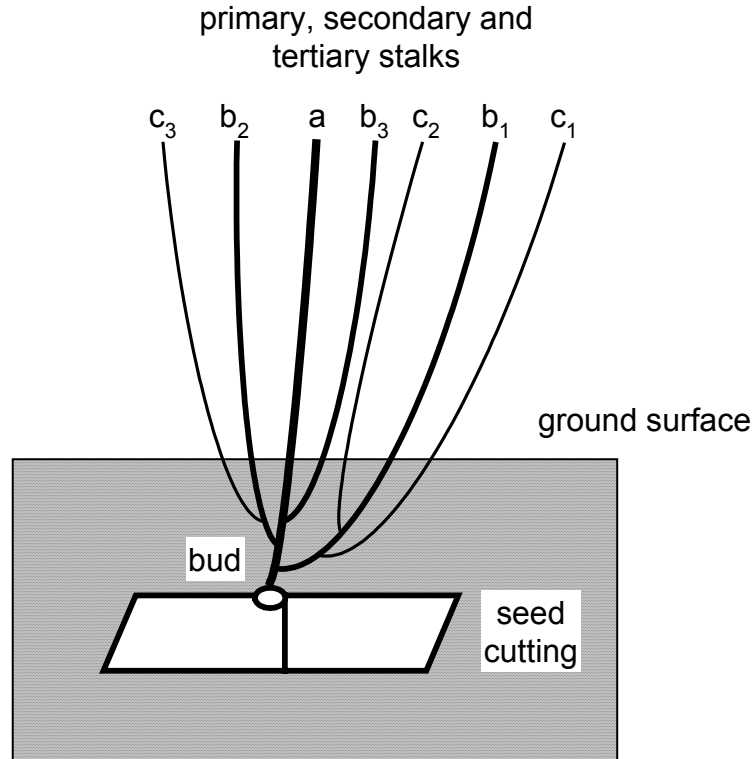

Figure 3. Sequence of stalks generated from a single bud in a sugarcane plant (*S. Officinarum*).

The number of stalks that potentially can stand in a plant out of a bud at a given period is currently given by

$$\Delta s_i = \begin{cases} \left(\dfrac{S_{max} - 1}{G_{max}} \right) \Delta G_i & \text{if } G_i \leq G_{max} \\[4mm] \left(\dfrac{S_o - S_{max}}{G_o - G_{max}} \right) \Delta G_i & \text{if } G_{max} < G_i \leq G_o \\[4mm] 0 & \text{if } G_i > G_o \end{cases} \tag{7}$$

Where Δs_i = stalk number increase in period i (# stalks stubble^{-1}); S_{max} = maximum number of stalks a variety can yield (# stalks stubble^{-1}); S_o = stable stalk number in a plant (# stalks stubble^{-1}); G_o = threshold thermal time at which the stable stalk number is set (°C-day); G_{max} = threshold thermal time at which the maximum stalk number is reached (°C-day).

Stalk number is accumulated in each period with a state equation defined by

$$s_i = \begin{cases} 1 & \text{if } G_i = P_{h1} + P_{h2} \\[2mm] s_{i-1} + \Delta s_i & \text{if } G_i > P_{h1} + P_{h2} \end{cases} \qquad \forall i = 1, 2, \ldots, I \tag{8}$$

Where s_i = stalk number in a stubble in period i (# stalks stubble^{-1}); s_{i-1} = stalk number in a stubble in period i-1 (# stalks stubble^{-1}); P_{h1} + P_{h2} = duration of phase 1 and phase 2 (°C-day).

Variable G_i is initially set to 0 (Equation 6) and starts accumulating only after the time the first leaves have appeared on the ground surface (on completion of phase 1 and phase 2, after sprouting and emergence of the first stalk). Also at this time, variable s_i is set to 1 indicating the first stalk has started growth.

The approach shown above is an over simplification of stalk population dynamics as a function of physiological age. However, this approach needs to be revised to include the rate of stalk mortality. One way would be to assume a fixed rate of stalk extinction based on a light level reaching the lower leaves, which would not be able to perform photosynthesis, thus affecting the life span of the stalk in a reverse rule (e.g., last stalk would die first and so on). Also, carbon allocation priorities could be used to limit newer stalk growth. The self-thinning process of stalk population could be modeled more realistically using a plant carbon balance approach. Generally, stalk population depends on crop type (plant or ratoon crop), cane variety and bud planting density (# buds ha^{-1}). In a plant crop, the first stalk appears after phases 1 and 2 have been completed as is indicated by the first term of the equation (8). Afterward, population increases or decreases in accordance with Δs_i as is indicated by the second term of equation (8) and by equation (7). In a ratoon crop, many stalks appear at the same time and this aspect is not yet considered in the model.

1.5 *Leaf Area of a Stalk*

Cumulative leaf area on each stalk can be determined by expressing the leaf area per leaf in terms of leaf number either using an exponential or a piece-wise linear function. From these an

expo-linear function that relates the change in cumulative leaf area leaf in terms of leaf number can be obtained (Figure 4).
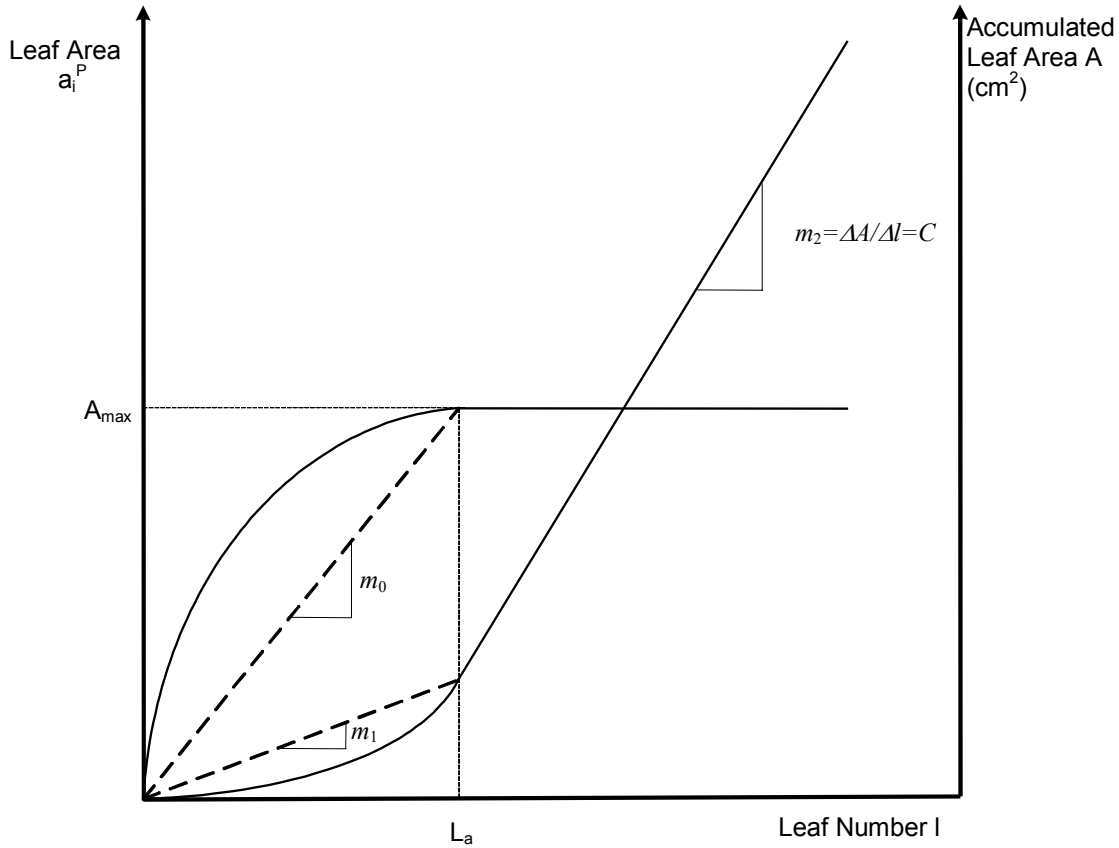

Figure 4. Leaf area and accumulated leaf area per stalk in a sugarcane plant.

Another way of calculating the cumulative leaf area that corresponds to a certain leaf position can also be determined from measurements in field experiments of total leaf area of individual plants grown widely spaced under conditions of prolific tillering and from plants where just the main stalk is allowed to grow (Figure 5). This would allow studying more easily with plant (or stubble) spacing. Usually one seed cutting (30-45 cm long) has 2-3 buds; a bud normally develops a stubble from which several tillers grow.

The increment of leaf area in each stalk is calculated by

$$\Delta A_{i,j} = \begin{cases} m_1 \Delta l_{i,j} & \text{if } l_{i,j} \leq L_a \\ \\ m_2 \Delta l_{i,j} & \text{if } l_{i,j} > L_a \end{cases} \quad \forall\, i = 1,2,\ldots,I;\; j = 1,2,\ldots,J \qquad (9)$$

Where $\Delta A_{i,j}$ = increment of leaf area in period i and stalk j (cm^2); m_1, m_2 = slopes of the linear relationship of accumulated leaf area in terms of leaf number (cm^2 leaf^{-1}); L_a = leaf number at which the area of the leaves do not change, unless there are stresses or nutrient limitations.
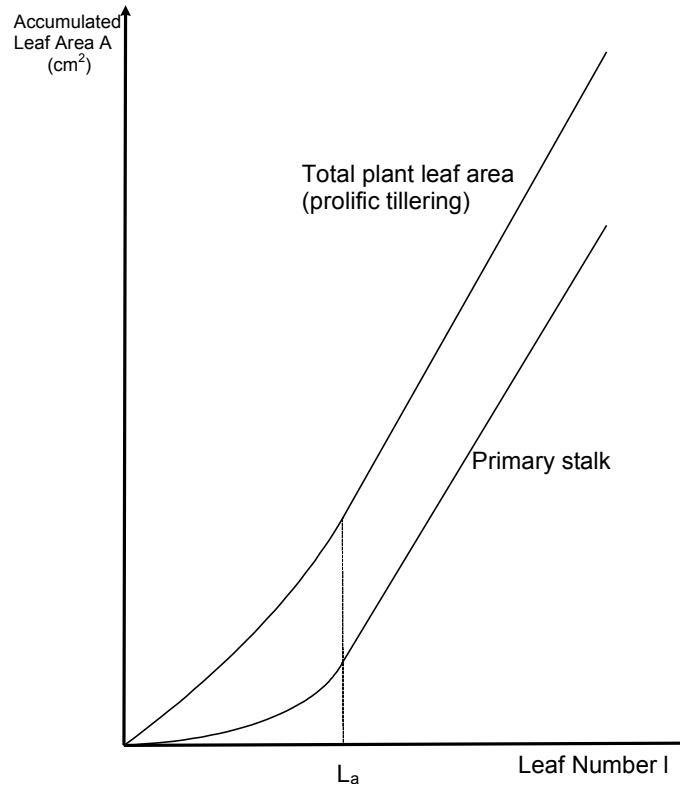
Figure 5. Leaf area for primary stalk and total leaf area per plant under prolific tillering.

Following the nomenclature given above for the parameters required it appears that

$$m_1 = \frac{1316 - 0}{4} = 329 \; cm^2 \; leaf \; number^{-1}$$

$$m_2 = 600 \; cm^2 \; leaf \; number^{-1}$$

$$L_a = 4$$

The parameters m_1 and m_2 are variety dependent.

Leaf area in each stalk is expressed by

$$A_{i,j} = A_{i-1,j} + \Delta A_{i,j} \qquad \forall \, i = 1,2,\dots,I; \; j = 1,2,\dots,J \qquad (10)$$

Where $A_{i,j}$ = leaf area in period i and stalk j (cm^2 stalk^{-1}). The increment of leaf area in each stalk $\Delta A_{i,j}$ will need to be modified later. Stalks become shaded and their leaves do not expand at the same "potential" rate, and assimilates may be limiting.

1.6. *Leaf Area of the Plant*

Leaf area of the whole plant can be derived from the summation of the total leaf area in each stalk over the total number of stalks in the plant,

$$Ap_i = \frac{1}{10000}\sum_{j=1}^{J} A_{i,j} \qquad \forall i = 1,2,\ldots,I \qquad (11)$$

Where Ap_i = leaf area of the plant in period i (m^2 $plant^{-1}$).

1.7. *Stalk Population Density*

Stalk population density is calculated from the bud density planted that develops tillers. This latter is expressed by

$$B_d = \frac{1}{B_s r_s} \qquad (12)$$

Where B_d = bud planting density (# buds m^{-2}); B_s = bud spacing along the row of plants (m); r_s = row spacing between rows of plants (m).

Then stalk population density can be calculated as

$$P_i = B_d s_i \qquad (13)$$

Where P_i = stalk population density in period i (# stalks m^{-2}).

1.8. *Green Leaf Area Index*

The experimental basis for describing the expansion of foliage in the model is described by Robertson et al. (1998) and Inman-Bamber (1994). The basic unit of modeling is a stalk in which the dynamics of the foliage is based on the balance of green area existing in a given period; thus, dry area that is lost as a result of aging of foliage needs to be discounted. The expansion of the foliage in a given day is expressed in terms of the leaf area index (LAI) and is obtained as the product of net foliage (green foliage minus senesced leaves) of an individual plant to perform photosynthesis multiplied by the stalk population density,

$$Ag_i = \left(Ap_i - As_i \right) Bd_i \qquad (14)$$

Where Ag_i = Green leaf area index (m^2 leaf m^{-2} of soil surface); As_i = senesced leaf area (m^2 $plant^{-1}$).

Green leaf area consists of green leaves capable of performing photosynthesis. It is calculated by adding the area of fully expanded leaves, corresponding to the successive order they appear on a stalk but limited by the number of green leaves the plant can sustain, including a correction for the area of those leaves permanently in expansion. This correction corresponds to the area of leaves (-1, 0, 1 and 2), above the leaf corresponding to the TVD (Topmost Visible Dewlap) leaf 3; it is relatively constant during the crop growth cycle, although this may need more discussion (Clements, 1980).

1.9. *Senescing Leaf Area of a Stalk*

The dry leaf area is calculated on the basis of the daily rate of aging of the green leaf area. Such a rate corresponds to the maximum of four factors, which are determined by age, competition for light, water stress and presence of frosts,

$$f^a = \max\left(f^e, f^l, f^w, f^f \right) \qquad (15)$$

Where f^a = factor of aging of the leaves (fraction); f^e = factor of aging due to duration of the leaves (fraction); f^l = factor of aging due to competition for light (fraction); f^w = factor of aging due to water stress (fraction); f^f = factor of aging due to frosts (fraction).

Those factors are estimated as follows: factor of aging due to duration of the leaves occurs by not allowing more than 13 completely expanded green leaves per stalk; competition for light occurs each time that the fraction of interception of radiation reaches a value of 0.85; stress due to water deficit induces aging whenever the factor for photosynthesis falls below 1.0. The frosts reduce 10% of the LAI per day if the minimum temperature reaches 0°C, increasing in linear fashion to 100% when the temperature reaches a minimum of –5°C.

Senescing area is then calculated as

$$A_{S\,i} = f^a A_{g_{i-1}} + A_{S_{i-1}} \tag{16}$$

1.10. *Preliminary simulation results for development*

Examples of phenology and leaf area development simulations are shown in Figure 6. This module has been programmed in the DSSAT-CSM; the growth module is currently being programmed. Graphs in Figure 6 show nodes on the main stalk, number of stalks, leaf area per stalk, and leaf area index using initial estimates of the parameters used in equations (1) – (16). Weather data (06/01/1997 – 10/02/1998) used for these simulations were taken from Cenicaña – Colombia located at 3° 21' N and 76°18' W, 1024 meters above sea level, with annual averages of temperature 23.5 °C, rainfall of 1160 mm and relative humidity of 77 %.

2. Growth

According to the phenological stage of the crop, the amount of biomass produced (net assimilate) is distributed among the different components of the plant: Tops (the immature part of the stalk plus the leaf sheaths), leaves, structural stalks, sucrose (and other solids), residues, and roots.

The rates of change of these components are modeled as a result of changes in the processes of photosynthesis, respiration, tissue and sucrose synthesis, and senescence. Assimilates, product of photosynthesis and respiration, which are not utilized in the production of energy are incorporated in the plant in the form of dry matter and thus constitute a reservoir of potential energy (Dillewijn 1952). The carbohydrates involved in the whole process are simple sugars or monosaccharides (e.g., glucose and fructose, 6 carbon units, $C_6H_{12}O_6$, are reducing sugars, inverted sugar), double sugar or disaccharides (e.g., sucrose or saccharose, cane sugar, two simple sugars, double the amount of carbon units of monosaccharides, $C_{12}H_{22}O_{11}$), multiple sugars or polysaccharides (e.g., starch; cellulose, the main component of the fiber of sugarcane), and enzymes (e.g., diastase promotes conversion of starch into glucose, invertase promotes conversion of sucrose onto invert sugar, glucose plus fructose)

The sugars formed in the leaves move to all parts of the plant where they are partly utilized in respiration and in the synthesis of the plant tissue (translocation of carbohydrates, Dillewijn, 1952). Carbohydrates remaining after photosynthesis and respiration are stored in stalks. The model of sugarcane biomass growth consists of non-linear first order differential equations (dry matter rates of change) and the application of the carbohydrate supply and demand principle.
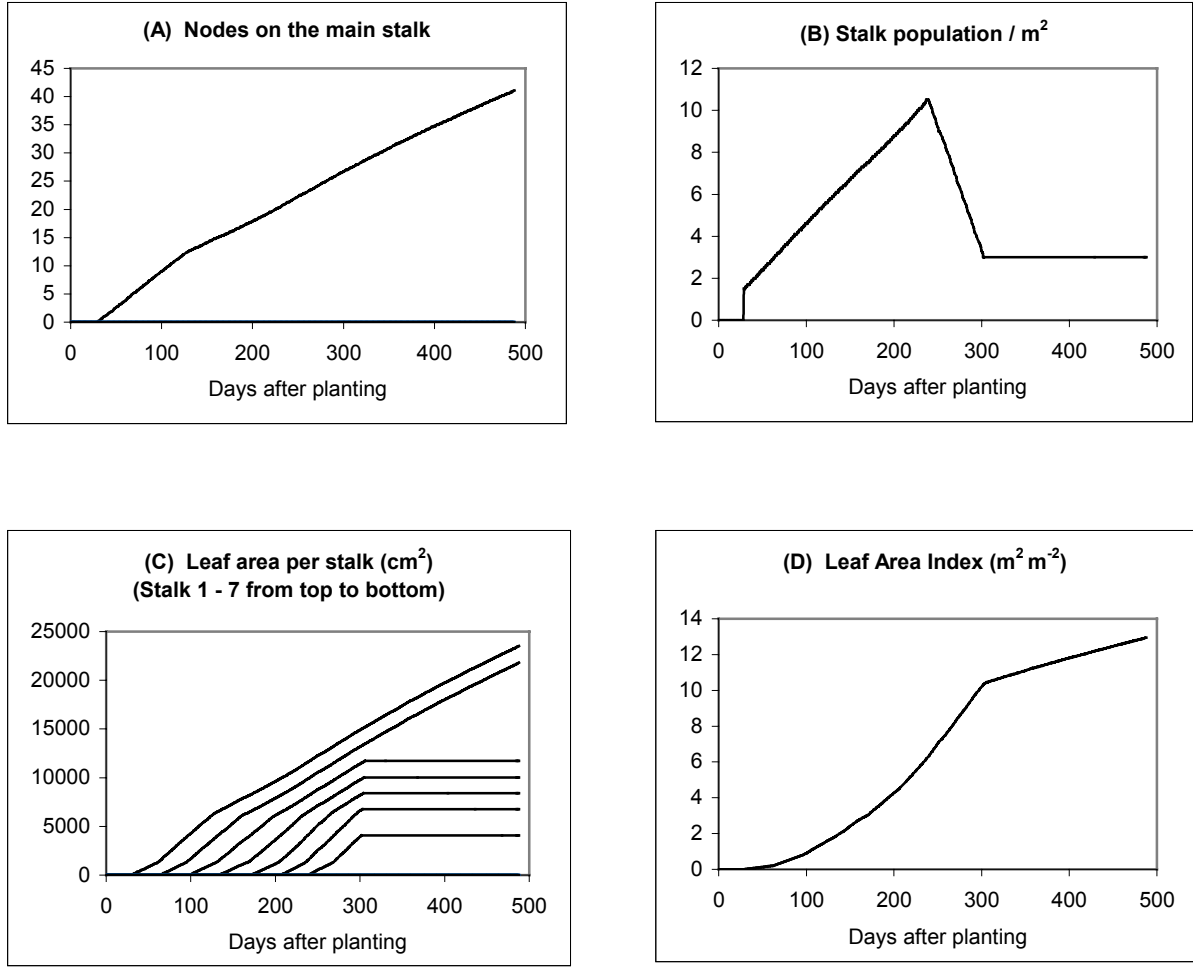
Figure 6. Number of nodes on the main stalk (A), number of stalks (B), leaf area per stalk (C), and leaf area index (D) simulated by CASUPRO.

2.1. *Potential carbon demand for leaves, stems, roots and total sugars*

Potential demand for carbon to grow leaves, stalks, roots and total sugars is the summation of the potential growth of each plant component,

$$
\left(\frac{\Delta W_{CH_2O}}{\Delta t} \right)^{pot} = \left(\phi' + G'_r \right)_L \left(\frac{\Delta W_L}{\Delta t} \right)^{pot} + \left(\phi' + G'_r \right)_S \left(\frac{\Delta W_S}{\Delta t} \right)^{pot}
$$
$$
+ \left(\phi' + G'_r \right)_R \left(\frac{\Delta W_R}{\Delta t} \right)^{pot} + \left(\phi' + G'_r \right)_{Su} \left(\frac{\Delta W_{Su}}{\Delta t} \right)^{pot}
$$

(17)

Where $(\Delta W_{CH2O}/\Delta t)^{pot}$ = rate of potential demand of carbohydrate for growth of leaves, stalks, roots and total sugars (g CH_2O m^{-2} d^{-1}); $(\Delta W_L/\Delta t)^{pot}$ = rate of potential leaf growth (g m^{-2} d^{-1}); $(\Delta W_S/\Delta t)^{pot}$ = rate of potential stalk growth (g m^{-2} d^{-1}); $(\Delta W_R/\Delta t)^{pot}$ = rate of potential root growth (g m^{-2} d^{-1}); $(\Delta W_{Su}/\Delta t)^{pot}$ = rate of potential total sugars deposition (g m^{-2} d^{-1}); $(\phi' + G'_r)_c$ = CH_2O required to produce one gram of dry weight of plant component (c = leaf, stalk, root, sugars) (g CH_2O g^{-1} plant component of dry matter).

The former equation can be generalized as

$$\left(\frac{\Delta W_{CH_2O}}{\Delta t}\right)^{pot} = \sum_{c=1}^{m}\left(\phi_c' + G_{rc}'\right)\left(\frac{\Delta W_c}{\Delta t}\right)^{pot} \tag{18}$$

Where c = plant component; m = number of plant components; (CH_2O) = Carbohydrate; $(\Delta W_c/\Delta t)^{pot}$ = rate of potential demand for plant component growth (g m^{-2} d^{-1}); (ϕ' + G'$_r$)$_c$ = CH_2O required to produce one gram of dry weight of plant component (c = leaf, stalk, root, sugars) (g CH_2O g^{-1} plant component of dry matter).

2.2. *Potential leaf growth*

Potential demand of carbon for leaf growth is obtained from the relation between accumulated leaf area per stalk and the leaf number determined by the phonological stage (Figure 7). This relationship is established for each stalk in the stool. l_o indicates the transition leaf number at which leaf size becomes constant and therefore leaf area accumulation increases at a constant rate (Figure 8).

The weight of the leaves varies during the phenological stages of the plant. Thus the increase in weight of leaf tissue is obtained from the rate of increase of leaf area and the Specific Leaf Weight (SLW) for a given leaf number,

$$a_{i,j} = \left(\frac{\Delta A}{\Delta t}\right)^{pot}_{i,j} = \left(\frac{\Delta l}{\Delta T}\right)_{i,j}\left(\frac{\Delta T}{\Delta t}\right)_{i}\left(\frac{\Delta A}{\Delta l}\right)_{i,j} \qquad \forall\, i = 1,2,\ldots,I;\ j = 1,2,\ldots,J$$

$$\tag{19}$$

$$\left(\frac{\Delta W_L}{\Delta t}\right)^{pot} = B_d \sum_{j=1}^{J} a_{i,j} SLW_{j,k} \qquad \forall\, i = 1,2,\ldots,I;\ j = 1,2,\ldots,J;\ k = 1,2,\ldots,K$$

Where B_d = bud planting density (# buds m^{-2}); $(\Delta W_L/\Delta t)^{pot}$ = potential leaf growth (g m^{-2}); $a_{i,j}$ = rate of change of leaf area of stalk j in day i (cm^2 d^{-1}); SLW_k = Specific Leaf Weight of leaf number k (g cm^{-2} leaf).

2.3. *Potential stalk growth*

Stalk weight accumulation takes place as described in Figure 9. Potential demand of carbon for stalk growth can be expressed in terms of the potential stalk growth rate as a function of leaf number appearance per stalk.

$$w_{i,j} = \left(\frac{\Delta l}{\Delta T}\right)^{pot}_{i,j}\left(\frac{\Delta T}{\Delta t}\right)_{i}\left(\frac{\Delta W}{\Delta l}\right)^{pot}_{j,k}$$

$$\tag{20}$$

$$\left(\frac{\Delta W_S}{\Delta t}\right)^{pot} = B_d \sum_{j=1}^{J} w_{i,j}$$

Where $(\Delta W_S/\Delta t)^{pot}$ = potential growth of stalks (g m^{-2} d^{-1}); $w_{j,k}$ = rate of change of weight of stalk j in day i (g d^{-1} stalk^{-1}).
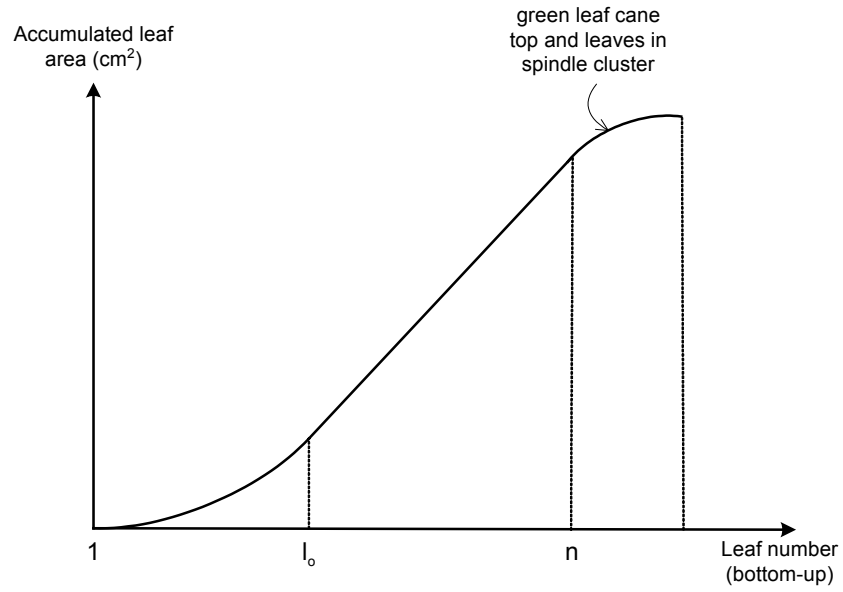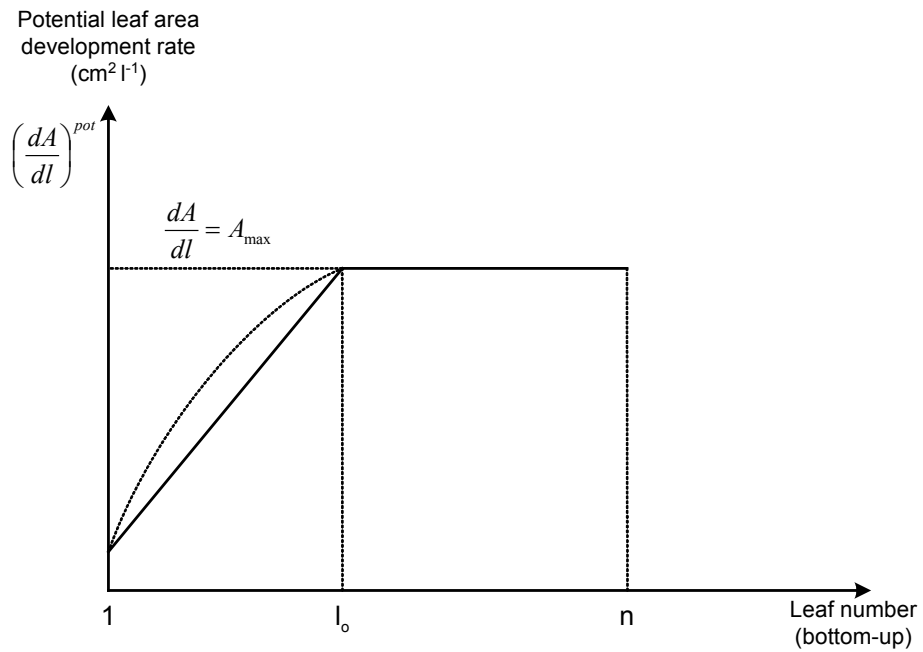
Figure 7. Accumulated leaf area per stalk.

Figure 8. Potential growth rate of leaf area vs. leaf number appearance per stalk.
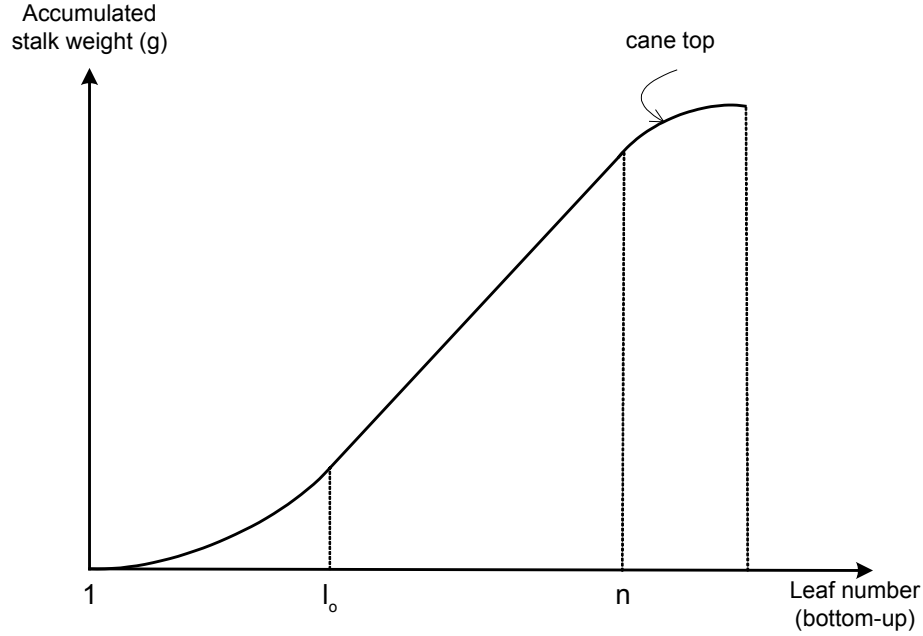
Figure 9. Accumulated stalk weight vs. leaf number.

2.4. *Potential root growth*

Potential root growth is defined as a fixed ratio of the sum of the potential demand of carbon for leaf and stalk growth accumulation,

$$\left(\frac{\Delta W_R}{\Delta t}\right)^{pot} = f_k^R \left[\left(\frac{\Delta W_L}{\Delta t}\right)^{pot} + \left(\frac{\Delta W_S}{\Delta t}\right)^{pot}\right] \tag{21}$$

Where k = leaf number in main stalk; f_k^R = fraction of potential growth of leaves and stalks growth that is partitioned for potential root growth.

2.5. *Potential sugar deposition*

Potential sugar deposition is defined as a ratio of the sum of potential leaf and stalk growth that varies with leaf number,

$$\left(\frac{\Delta W_{Su}}{\Delta t}\right)^{pot} = f_k^{Su} \left[\left(\frac{\Delta W_L}{\Delta t}\right)^{pot} + \left(\frac{\Delta W_S}{\Delta t}\right)^{pot}\right] \tag{22}$$

Where k = leaf number in main stalk; f_k^{Su} = fraction of potential leaves and stalk growth that is partitioned for potential sugars deposition (e.g., f_k^{Su} = 0.10). This fraction is given as a function of leaf number on each stalk.

2.6. *Photosynthesis*

The gross photosynthesis rate per unit area can be modeled by the simple daily photosynthesis (Wilkerson et al., 1983)

$$P_G = k_p P_G^{max} f_L f_{\theta 1} f_N f_T \tag{23}$$

Where $P_G{}^{max}$ = maximum CH_2O production rate for a full crop canopy and a given amount of radiation (g m^{-2} d^{-1}); k_p = P_G calibration constant; f_i (i = L,θ,N,T) = reduction in P_G due to suboptimal leaf area, soil water content, leaf nitrogen and temperature.

2.7. *Net photosynthate*

Net photosynthate is given by the sum of photosynthate remaining after respiration and the photosynthate taken from the sugars storage,

$$P_N = P_G - R_m + f_{Su}W_{Su}$$ (24)

Where P_N = net photosynthate (g CH_2O m^{-2} d^{-1}); P_G = gross photosynthate production rate per unit area (CO_2 respired in photorespiration is not included since it is not a factor in C_4 plants); R_m = maintenance respiration (g CH_2O m^{-2} d^{-1}); f_{Su} = fraction of sugars taken from sugars storage; W_{Su} = weight of long term stored sugars (g CH_2O m^{-2}). P_N constitutes the daily carbohydrate available to build biomass, but some questions remain: Can f_{Su} be defined as a fixed fraction? Is this always taken? How can the conditions be set for the use of this resource? This needs to be defined in field experiments involving different light levels.

2.8. *Respiration*

$$R_m = R_o W + R_A P_G$$ (25)

Where R_o = carbohydrate (CH_2O) required to maintain cell membranes and ion gradients (g CH_2O g^{-1} d.m. d^{-1}); W = total dry weight of crop per unit area (g m^{-2}); R_A = carbohydrate (CH_2O) required in maintenance respiration for protein turnover (g CH_2O g^{-1} CH_2O d^{-1}).

$$R_O = f(T) \quad ; \qquad R_A = g(T)$$ (26)

Where T = temperature (°C).

2.9. *Distribution of Photosynthate*

Partitioning of assimilates is performed in the model by comparing the supply and demand for carbohydrates as

$$R = \frac{P_N}{\left(\dfrac{\Delta W_{CH_2O}}{\Delta t}\right)^{pot}}$$ (27)

Where R = ratio of carbohydrates available to carbohydrate demand; P_N = net photosynthate (g CH_2O m^{-2} d^{-1}).

In the case of R $\geq$ 1.0, supply exceeds demand, for which potential demands for growth of leaves, stems, roots and sugars are fulfilled and the excess is assumed partitioned as fixed ratios between stems and sugars. This means,

$$if \ R \geq 1 \qquad E = P_N - \left(\frac{\Delta W_{CH_2O}}{\Delta t}\right)^{pot} \quad ; \qquad \hat{w}_L^+ = \left(\frac{\Delta W_L}{\Delta t}\right)^{pot} \quad ;$$

$$\hat{W}_S^+ = \left(\frac{\Delta W_S}{\Delta t}\right)^{pot} + \gamma E \quad ; \quad \hat{W}_R^+ = \left(\frac{\Delta W_R}{\Delta t}\right)^{pot} \quad ; \quad \hat{W}_{Su}^+ = \left(\frac{\Delta W_{Su}}{\Delta t}\right)^{pot} + (1-\gamma)E \quad \text{(28)}$$

Where E = excess of carbohydrate supply (g CH_2O m^{-2} d^{-1}); $\hat{W}_c$ = increase in dry weight of plant component per unit time (c = leaf, stalk, root, sugars) (senescence not included) (g m^{-2} d^{-1}); γ = fraction of excess carbohydrates that are partitioned for stalk growth and sugars accumulation, which must be discussed.

In the case of R < 1.0, supply is less than demand, for which potential demands for growth of leaves, stalks, roots and sugars are not fulfilled and the supply is partitioned proportionally among all the pools. This means,

$$if\ R < 1 \quad E = 0 \quad ; \quad \hat{W}_L^+ = R\left(\frac{\Delta W_L}{\Delta t}\right)^{pot} \quad ; \quad \hat{W}_S^+ = R\left(\frac{\Delta W_S}{\Delta t}\right)^{pot} \quad ;$$

$$\hat{W}_R^+ = R\left(\frac{\Delta W_R}{\Delta t}\right)^{pot} \quad ; \quad \hat{W}_{Su}^+ = R\left(\frac{\Delta W_{Su}}{\Delta t}\right)^{pot} \quad \text{(29)}$$

The set of equations above can be generalized as

$$if\ R \geq 1 \quad E = P_N - \left(\frac{\Delta W_{CH_2O}}{\Delta t}\right)^{pot} \quad ;$$

$$\hat{W}_c^+ = \left(\frac{\Delta W_c}{\Delta t}\right)^{pot} + \gamma_c E \quad \forall c = 1,2,\ldots,C; \gamma_c \neq 0\ for\ c = stalks, sugars \quad \text{(30)}$$

$$if\ R < 1 \quad E = 0 \quad ; \quad \hat{W}_c^+ = R\left(\frac{\Delta W_c}{\Delta t}\right)^{pot} \quad \forall c = 1,2,\ldots,C \quad \text{(31)}$$

2.10. Senescence

Senescence of leaves is modeled as a result of the effects derived from natural senescence, nitrogen mobilization from the leaves, light level reaching the lower leaves in the stalk, and water stress.

The fraction of natural leaf senescence is given by

$$f_L^r = 1 - f_L^s \quad \text{(32)}$$

Where f_L^s = proportion of leaf weight grown which will have been senesced by a given leaf number if no water stress has occurred prior to this leaf number, normal vegetative senescence does not occur if prior water stress has already reduced leaf; f_L^r = proportion of leaf weight grown which will have been senesced if no water stress has occurred prior to this leaf number.

The leaf area index that is required to reach the light compensation point in the lower leaves is calculated as,

$$L_c = -\frac{1}{k} \ln\left(\frac{I_c}{I_o}\right) \tag{33}$$

Where L_c = LAI at which today's light compensation is reached (m^2 [leaf] m^{-2} [ground]); k = canopy light extinction coefficient for daily PAR, for equidistant plant spacing, modified when in-row and between row spacing are not equal; I_c = light compensation point for senescence of lower leaves because of excessive self-shading by crop canopy (moles m^{-2}–d^{-1}); I_o = PAR daily photosynthetically active radiation or photon flux density (moles [quanta] m^{-2}-d^{-1}).

Senescence of stalks will be modeled as a function of carbon availability, soil water content, and nitrogen content.

Daily root senescence (g m^{-2} d^{-1}) will be modeled as a function of carbon availability and soil water content: excess/deficit, but it needs more detailed study for better understanding.

2.11. *Overall crop dry matter*

Crop dry matter accumulation is given by

$$\frac{\Delta W}{\Delta t} = \hat{W}^+ - \hat{S}_L - \hat{S}_S - \hat{S}_R \tag{34}$$

Where $\Delta W/\Delta t$ = rate of total crop dry weight accumulation per unit area per unit time (g m^{-2} d^{-1}); $\hat{W}^+$ = increase in dry weight of crop per unit time (senescence not included) (g m^{-2} d^{-1}); $\hat{S}_L$, $\hat{S}_S$, $\hat{S}_R$ = leaf, stalk, and root dry weight senesced per unit time (g m^{-2} d^{-1}).

Conclusion

CASUPRO is still an in-progress model. The conceptualization and construction of the model was proposed for simulating cane and sucrose production so that production managers and industry researchers have a better analytical tool for their decision-making processes. CASUPRO will also be useful as a research tool through the analyses of scenarios under the different agroecological conditions of the sugar sector as a strategy for reducing the gap existing between potential and actual productivity. The model can be used to detect gaps of information and knowledge to help improving the model itself, since many of the parameters required by the model are still unknown.

The model is a part of the DSSAT-CSM (Jones et al., 2003), which allows it to utilize all cropping system modules, such as weather, soil water, soil nitrogen, ET, etc. From an operative point of view, it can run in DSSAT v 4.0, but it is necessary to continue its development to obtain reliable results for Potential Production (determinant factors), then for Attainable Production (limiting factor) in conditions of excess or deficit of water and availability or deficit of N and P, and finally for Actual Production (reducing factors) according to the three thematic phases in which the model development was divided. CASUPRO phenology will provide the basis for CH_2O demand, then actual (potential) dry weight growth will be computed as the minimum of this demand and growth that is possible based on supply of CH_2O via photosynthesis and respiration. The growth limitation will then limit new stalk appearance and, in severe cases, cause stalk senescence. This will provide potential growth and yield. For actual growth and yield, the water balance stress factor will operate reducing leaf expansion and photosynthesis. The N and P balances in the plant will be also modeled.

Special attention will be given to specify partitioning and senescence, and define how stalk number should decline in the model. Possibly, it will be necessary to reformulate stalk

appearance and include a rate of stalk extinction based on a light level reaching lower leaves. Those leaves are not able to perform photosynthesis, thus affecting the life span of the stalk in a reverse rule (e.g., last stalk would die first and so on). It is also important to consider the effect that water and N stresses have in the senescence of leaves and stalks.

In the future, the predictive capacity of the model will depend on the parameters that need to be obtained through experimentation for calibration and validation of the model. For instance, the threshold values for the phenological stages need to be determined for the cane varieties of major interest. These values should be determined on the basis of the Genotype x Environment (GxE) interaction. Without the required parameters, the model is only a number cruncher without much utility, although the continuation of the model development is not conditioned on the accomplishment of experiments because these are independent activities.

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