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Development of ecophysiological simulation model to estimate a potential productivity of sugar cane in Brazil and Australia

Desenvolvimento de um modelo de simulação ecofisiológico para estimar a produtividade potencial da cana-de-açúcar no Brasil e na Autrália

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Resumo

Este estudo apresenta a construção de um modelo ecofisiológico-matemático (BrCane) para predizer a produtividade potencial - sem restrições nutricionais ou de água, a fim de analisar a sustentabilidade da expansão do cultivo de cana-de-açúcar em novas áreas para produção de etanol. A arquitetura do modelo BRCANE foi concebida para uma planta tipo C4, onde a evolução mensal da biomassa foi estimada em função da temperatura do ar e da radiação incidente. Nas simulações apresentadas a produção de biomassa levou em conta a taxa bruta de fotossíntese subtraídas as perdas para respiração de manutenção, senescência de folhas e morte de perfilhos durante o ciclo da cultura. O modelo BRCANE também foi usado para descrever o comportamento fisiológico em função das condições ambientais relacionadas ao tempo termal. A implementação de tais condições permitiu ajustar os resultados das simulações a resultados experimentais disponíveis na literatura. As estimativas de biomassa foram comparadas com dados obtidos durante o ciclo da cultura em experimentos de campo com irrigação (Cultivares RB72 454, NA 56-79, CB 41-76, CB47-355, CP51-22, Q138 e Q141) no Estado de São Paulo (Brasil) e em Bundaberg e Queensland (Austrália) e os resultados foram expressos em toneladas de colmo por hectare (Mg ha^{-1}), por meio de uma relação linear para cada variedade (R^2 = 0,89**) e superiores aos obtidos pelos modelos APSIM (R^2=0,78*) e CANEGRO (R^2 = 0,71*). O modelo apresentou resultados consistentes com dados experimentais para crescimento e produção de biomassa no ciclo da cultura da cana-de-açúcar, oriundo de canaviais paulistas (Brasil) e de Bundaberg (Austrália).

Palavras-chave: modelo ecofisiológico, Ecologia, Fisiologia vegetal, bioenergia.

Abstract

A model of sugarcane was built to simulate the potential yield (without nutrition and water restrictions) for sustainability analysis of new expanded cultivation areas to ethanol or sugar production or climate change impact studies. The potential yield in terms of dry matter of sugarcane was adjusted to estimate the carbon dioxide absorption. As photosynthetic pathway C4 plant, in relation with air temperature and solar radiation to calculate a monthly production of dry matter (DM) was calculated during the crop cycle. The DM take in account gross photosynthetic rate subtracting loses by maintenance respiration, senescence of leafs, and tillers during the cycle. The BRCANE is a dynamic simulation model, it isbuild by mathematical equations which describe the physiological behaviour due to environment conditions averaging the thermal variables, model was calibrated which constants that they was obtained through adjusts of literature results and it was validated with experimental data. The simulated DM by the model was contrasted with data which obtained during the cycle from experimental irrigated field (cultivars RB72 454, NA 56-79, CB 41-76, CB 47-355, CP 51-22, Q138, and Q141), in the São Paulo State (Brazil) and in Bundaberg SES, Queensland (Australia). The results of total DM were modified in stalk tons per hectare (Mg ha^{-1}) through linear equation for each cultivar, with regression coefficients higher than 0,89**(R^2) and higher than those obtained by APSIM (R^2 = 0.78*) and CANEGRO (R^2 = 0.71*) models. The model showed consistent simulations for DM during the crop cycle, as well as on simulated yield.

Keywords: ecophysiological, ecology, plant physiology, bio-energy.

INTRODUCTION

It is undeniable the importance of sugarcane for the country economy, whether in the renewable biofuel production or in the generation of foreign exchange by exporting sugar. In 2019 Brazilian crop, the planted area reached 8.6 million hectares, being processed 746 million tons of stalks of sugarcane, with of the total annual produce, more than half of the sugar is exported, what means an increase in the trade balance of 1.4 billion dollars per year (União da Indústria de Cana-de-Açúcar UNICA, 2019). The enhancement of agroenergy industry needs tools that aid in predicting productivity in regional and local scales, considering the parameters of soil and climate in agroecosystem modeling.

There are two clients interested in this type of strategic information: a) the sugarcane company, which wants to improve their operational programming ofideal time for cutting and agricultural planning of sugarcane production, which is essential on optimizing the profitability of the company (Scarpari & Beauclair, 2004; O'Leary, 2000); and b) the government, which uses zoning edaphoclimatic culture to minimize the risk of loss in the system of bank financing, giving credit to the local producer with appropriate time of planting so these have a probability over 80% of reaching productivity in a economic level in the property (Rossetti, 2001).

From the governmental point of view, knowing the zoning information of climate risks associated with edaphic aspects of culture for sugarcane would allow restricting access to official financial bank credit to the traditional or expansion regions which do not satisfy the criteria for technical and economic sustainability.

The national average productivity for the crop is around 73 tonnes per hectare (Agrianual, 2018), which is influenced by the number of cuts, soil, climate, cultivars and cultural management. Productivity can be modeled in three levels, each one influenced by several factors that affect sugarcane (Wit, 1965; 1982):

The Potential Productivity is explained by factors that define the photosynthetic capacity of the plant to transform solar energy into plant biomass, such as CO_2, radiation, temperature and characteristics of the vegetal cover. This productivity potential is defined by the capacity of carbon dioxide assimilation (CO_2) for photosynthesis of C4 plants respecting the temperature and solar radiation based on the methodology described by Heemst (1986). The sugarcane cultivated cultivars are selected based on attributes of biomass, allowing the straw yield reach 400 t ha-1. Year-1 (Alexander, 1985), with values close to the considered to be the genetic potential of culture.

The Real Productivity is explained by factors that restrict potential. Water and nutrients are the most important and with higher occurrence; water is the first restraining factor to potential production, whose accounts in the soil are mostly used for climatological purposes. A practical method of water balance is the Thornthwaite & Mather (1955), which consists of the evaluation between precipitation and evapotranspiration estimated by Penman-Monteith (standard method - FAO, 2000 adjusted by Barbieri & Silva (2007) and Doorenbos & Kassam (1994) for sugarcane, considering the soil capacity of water retention, according to its physical characteristics and type of vegetation cover. However, the calculation PRIESTLEY-TAYLOR requires only air temperature, which is an alternative to the model Cropsyst.The water stress in plants causes a reduction of carbon dioxide assimilation rates, the leaves cells size size, transpiration rate, plant water potential, the growth rate and stomatal opening (Hsiao, 1973). Another important aspect is the water deficit interference on flowering, elongation of tillers and final height of the stalks in sugar cane (Gascho & Shih, 1983). Next to the "permanent wilting point", photosynthesis can be reduced from 30% to 50%, according to (Hartt & Burr, 1967).

The Leaf Area Index (LAI) is a biophysical parameter that can be used asmeasure of plant growth models in agronomy (Teruel et al. 1997). Knowledge of variation LAI over a crop cycle to assess the capacity or speedthat the shoot of plant (leaf area) occupies the area of soil available to that plant.The increase in leaf area provides an increase in capacity fromusing solar energy to perform photosynthesis and thus can be usedfor productivity (Lucchesi, 1987). In addition, the IAF may be usedinevapotranspiration that is affected by water deficit.

According Teruel et al. (1997), the LAI for sugar cane varied with the stage ofculture, where the value reached in the cane plant without water restriction was between 6 and 7, while the first and second cycle of sugarcane ratoon maximum LAI was between 4.5 and 4. In presence of mild water stress, the IAF has not declined significantly in plant cane and in ratoon cane. However, with high water stress, LAI cane plant reduced to values around 4 and ratoon cane in values close to 3.

The second restrictive factor would be the nutrient deficiency in soil plant system, which is based on N balance and the lack of available K in soil (Silva et al., 2015). Most software that integrates home models CERES presents nitrogen as the main modeled nutrient.

The Present Production is explained by reduction factors such as pests, diseases and contamination. The sugarcane situation does not present many researches on this approach, however the literature is plentiful of restrictions of biotic factor for crops. In the international literature of sugarcane culture shaping, there are three most know models of Simulation (APSIM-Sugarcane, CANEGRO-DSSAT, and QCANE) to predict the biomass productivity and sucrose in sugar cane (O'Leary, 2000).

Such models limited themselves to evaluate the stages of vegetative growth and maturation, however do not simulate the balance of nitrogen or organic carbon in the soil, which are necessary for understanding the dynamic processes in the agroecosystem (Bergamasco & Silva, 2001).

In Brazil, the modeling researches of sugarcane growth are described in Machado (1981), Barbieri (1993) and Barbieri & Silva (2007), using the concept of degree-day based on temperature; other climate factors that affect productivity, such as solar radiation and humidity with overriding importance, being these that most directly affect production and influence since the tillage, herbicide application, until the harvest, transport and storage of products (Pereira et al., 2002). Berget al. (2000) analysis discusses the limitations of water uptake by sugar cane roots and its climate characteristics (Doorenbos & Kassam, 1994). Studies associating physical and chemical soil properties are useful for determining the productive potential of a particular culture (Bernardes et al., 2002; Teramoto, 2003; Barbieri & Silva, 2007), being the soil characteristics traditionally determined in the producing units.

There are strong evidences that crop simulation models have an important role in scientific research, in the decision to plug and analyze the factors that can increase crop production and in technology transfer for production systems. The objective of this study was to develop a model that could allow exploration for the purposes of expand the climatized zoning areas for production of ethanol from sugar cane and no detailed information about the use of complex models that require many parameters.

MATERIAL AND METHODS

In this paper was build a model of estimate of potential productivity in dry biomass monthly based on carbohydrate assimilation of CO_2, depending on air temperature, solar radiation and sunshine, which is represented schematically in Figure 1 that will be detailed in the flowchart as equations members throughout the article.It was tested in two regions contracting production of different plants in Brazil and Australia.

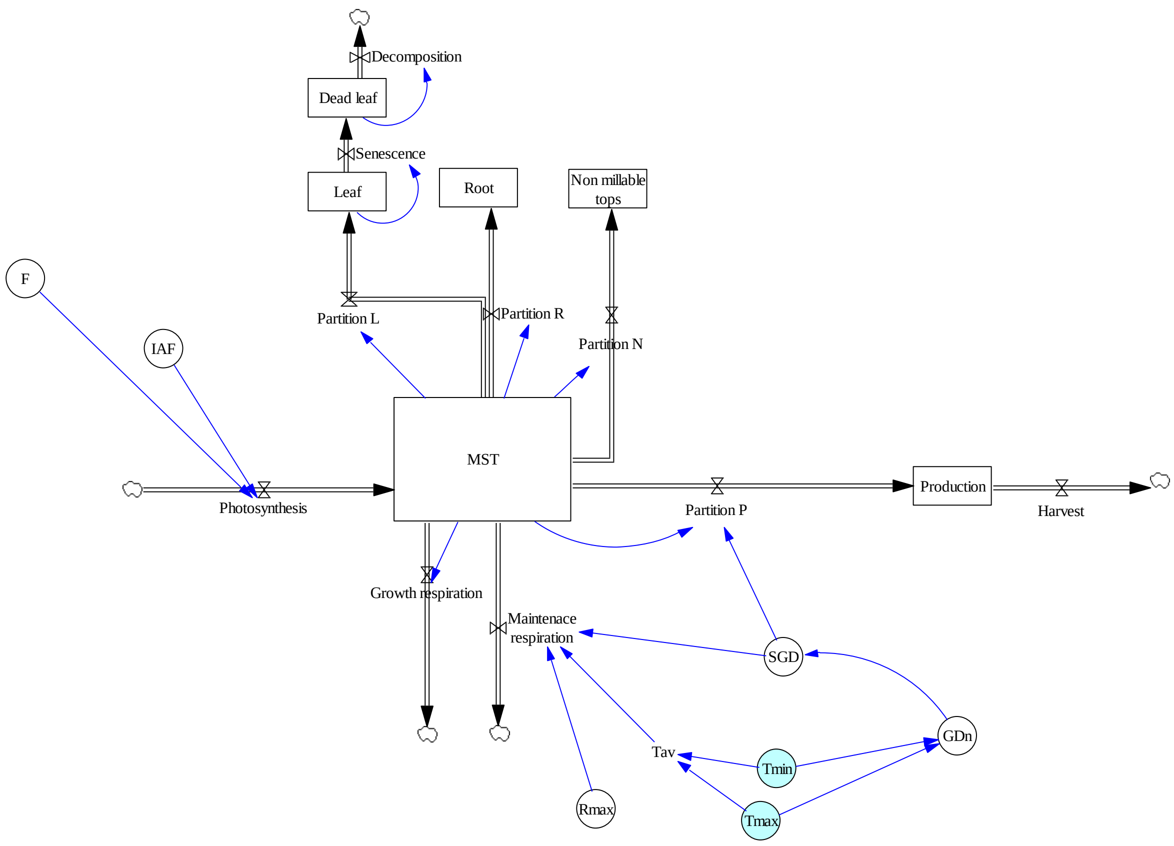

Figure 1. Flowchart model BrCane for estimating the potential productivity of sugar cane, according to climate.

Figura 1. Fluxograma do modelo BrCane para estimar a produtividade potencial de cana-de-açúcar em função do clima.

Model, Construction and Parametrization

The proposed model to estimate the yield of sugar cane (p), expressed as monthly total dry matter (TDM) and the end of the a cycle of n days, in kg dry matter (DM) per hectare, obtained by equation 1, for before and after the formation of the 9th leaf stem, do no less the mulch on the soil (MP):

$$MP = MST_n \cdot \left(\frac{13/100}{1+\exp(9.62-0.00881\cdot(220-\sum GD))}\right) - MST_{n-1} \cdot \left(\frac{13/100}{1+\exp(9.62-0.00881\cdot(200-\sum GD))}\right)(1)$$

MST = dry matter accumulated at the end of the month in question (kg/ha)
MS0 = dry matter (MS) remaining at the beginning of the month (kg MS/ha) (considering the losses of leaves and stems)

$$\sum MS = \frac{\overline{MS}\left(C_r^{day}\right)}{C_r - 1} MS_0 \quad (2)$$

Cr = coefficient of maintenance respiration (g MS/g MS.day)
For the daily dry matter produced (CBC x 0.79/day), the adjustment will be made depending on the number of days of the following:
MS = MS/day = average daily dry matter produced (kg/ha day)
day = number of days of the month

During the crop cycle, the older leaves are continually replaced, the remaining material is called a straw. Once outside the plant, this straw does not consume further energy, so it is needed the subtraction of a term referring to the deposited straw (MP), in equation 2. The energy coefficient 0.79 is obtained from ratio of 1g of CH2O/1.27 g of CH2O photosynthesized (Heemst, 1988).

Production of net carbohydrate: monthly and accumulated

The correction of the breath is multiplicative and must be applied daily, requiring the use of the established value MSCn (dry matter, m.s. portuguese acronym) corrected after n days of the month (kg m.s./ha.month).

Considering the MS0 as the values of CBC turned into dry matter by a factor of growth respiration (conversion efficiency) that was 0.79g m.s./g CH2O (Machado, 1981), the end of 4 days of the month, has the corrected initial dry matter:

$$MSC_n = MS_0 CR_n \quad (kgm.s./ha) \qquad (3)$$

CR_n = multiplicative correction of breathing

Maintenancerespiration (CRn)

The maintenance respiration applies to the dry matter originates from carbohydrate corrected gross (CBC) and occurs due to consumption of energy for maintenance of plant physiological processes, as described by Bull & Tovey (1974), which provide measures of nocturnal respiration rates in leaves of sugar cane showing a good correlation between the rate of daily gross photosynthetic assimilation and total nocturne respiration (maintenance respiration), which makes about 10% of gross photosynthesis. Correction of respiration and multiplication is expressed by the equation:

$$CR_n = 1 - R_{max} C_r(t) C_r(i) \qquad (4)$$

Rmax = 0.023 g/g - maximum breathing
Cr (t) = correction of Rmax in function of temperature
Cr(i) = correction of Rmax as a function of plant age
CRn = correct breathing (multiplicative)
Cr(t) = correction of breath due to temperature
Cr(i) = correction of breath due to age of culture

The values of maximum respiration (Rmax) were obtained based on the results of Medina (1970) and Machado (1981), which occurs at a temperature of 30°C, where estimated the maximum respiration (Rmax) as being equal to 0.023 g m.s. lost in the process, for 1g of dry matter in the living plant. The Cr(t) values were calculated according to the results of Medina (1970), correlating the values of the local temperature with the maintenance respiration, where he met the following relationship:

$$C_r(t) = e^{-4.11+0.1383t} \qquad (5)$$

For values of temperature (t) in °C, when t > 28.5 °C, it is Cr(t) = 1.

The value of Cr (i) was similarly obtained, using data from Medina (1970), correlating the maintenance respiration with "degree days", during the crop cycle. We used the average values of respiration of stems. This analysis originated the following relationship:

$$C_r(i) = 1.26 * 0.9995^{\sum GD} \qquad (6)$$

For ∑GD (Sum of Grades Day) < 372, it is $C_{r(i)} = 1$.

Stalk yield and total dry matter

From the value of the net MST (gross MST subtracted from maintenance respiration) is calculated theweight of culms (stems per ha), assuming a factor derived from linear regression equations, adjusted to the measured data:

MSTl = b*MST

Y = MSTl = Pp in t stalk/ha (estimated) or and X = MST (Mg/ha).
b = slope of the line MST/MSTl.

The values of the slope experimentally varied depending on variety and harvest time, being obtained for the cultivars: RB72 454 (b=2.01, r =0.951**); NA 56-79 (b=1.87; r = 0.960**); CB 41-76 (b=1.68; r =0.914**), CB 47-355 (b=1.81; r=0.951**), CP 51-22 (b=1.82; r =0.934**), Q138 (b=1.78; r =0.934**), and eQ148 (b=1.62: r =0.887**).

The net MST is obtained by gross MST subtracting the monthly losses of leaves (Pfolhas), death of tillers (Pperfilhos), and roots (Praize) based on accumulated degree-days in the month, as is noted in:

$$MST = P_p + P(folhasmortas) + P(perfilho) + P(raiz) \quad \left(\frac{m.s}{ha.ciclo}\right)$$

(7)

The partition values were obtained by equations 8 to 11.

The roots, according with results obtained by Medina (1970), have its weight approximately equal to the weight of fresh (alive) leafs, during all the crop cicle. We have obtained 1000 kg leaves/ha.IAF, according to the results obtained by Machado (1981), who found 1g m.s./dm² by leaf. Thus, knowing the IAF in the given month, we can estimate the weight of roots (Medina et al., 1970). Earlier calculations found in literature show that is possible to fit a root weight [P(raiz)] equation based on Degree-days:

$$P(raiz) = MST\left(\frac{0.9995\mathrm{GD}^{2} + 0.0217\mathrm{GD}}{100}\right) \quad (8)$$

With respect to the stumps that are left on the field during harvest, according to results presented by Medina et al. (1970), it is estimated an amount close to the roots, of course, the value adopted here depends on the manner of harvesting (manual or mechanical, which are estimated by the equations below):

$$P(toco) = \frac{3000\mathrm{GD}_{c}}{100 * 2} Dias \quad (9)$$

ΣGDc = Sum of degree days of the month set by photoperiod (GD * N/12)

As the leaves (green or burned) left in left field, considering that at harvest are going to be discarded by means of fire whose values are calculated by Medina et al. (1970), we can say that the production potential is equal to:

$$P(folha) = \left(MST_{n}\frac{13}{1+e^{9.62-0.00881*\left(200+\sum GD\right)}}/100\right) - \left(MST_{n-1}\frac{13}{1+e^{9.62-0.00881*\left(200+\sum GD_{n-1}\right)}}/100\right) \quad (10)$$

The core temperature of 18°C was considered.

The values of loss is a function of growth rate of total sugarcane, based on accumulated degree days, expressed as a percentage of gross MST, in its various components.The coefficients were estimated from the biometric data of Van Dillewijn (1951), which were comparable to resultsof Glover (1972), Inman-Bamber & Thompson (1989) and Bull &Tover(1974). The values estimated by the parties' accumulated biomass estimated by the model proposed for the partition of dry matter accumulation in stems, leaves, roots, and shoots dead the cycle (Figure 2).

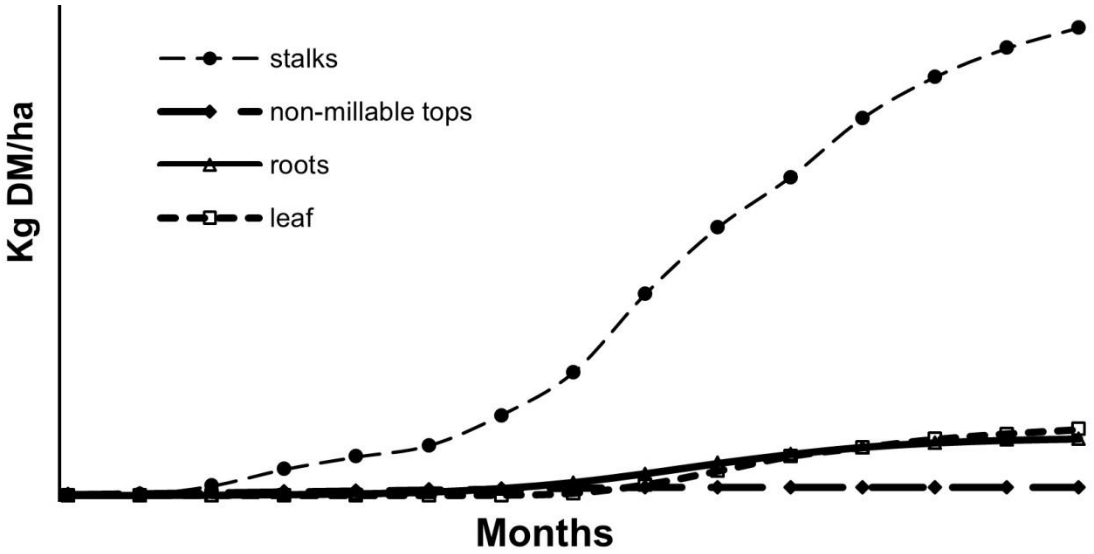

Figure 2. Distribution of dry matter accumulation of sugarcane plants along the cycle (kg DM/ha), in the stalks, stumps, root and dead leaf obtained by model simulation, depending of degree days accumulated.

Figura 2. Distribuição da acumulação de matéria seca das planas de cana-de-açúcar ao longo do ciclo (kg DM/ha), em caules, raízes e folhas mortas obtids pelo modelo de simulação dependendo do dos graus-dia acumulados.

Carbohydrate Adjusted Gross Production (CBC)

To estimate the MST is necessary to know the monthly production of crude carbohydrates (CBmax) and of the reason MSn/ CBmax obtained by equations 11 and 12, from CBc e Cbn.

$$MS_n = \frac{CBC}{1.27} \quad (11)$$

According to data from Machado (1981), the conversion efficiency of dry matter would require 1.27 g of crude carbohydrate (CH2O) photosynthesized to produce 1g of dry matter (MS). To produce the gross CH2O, according to Heemst (1986) the maximum monthly production of crude carbohydrate cycle is given by:

$$CB_{max}(t) = day * \left(F * CB_n * C_n(t) + (1-F) * CB_c * C_c(t)\right), \quad (12)$$

Cbmax(t) = total monthly production of not adjusted carbohydrates (kg/ha/month)
day = number of days in the month
F = fraction of day it was cloudy
(1-F) = fraction of day it was clear (no clouds)
CBn = Average daily production of carbohydrates, on a cloudy day (kg/ha.day)
Cbc = average daily production of carbohydrates in a clear day (kg/ha.day)
Cn(t) e Cc(t) = corrections due to air temperature for cloudy days and clear, respectively.

Later due to corrections of physiological factorsthat determine changes in the CB, once these factors are different from the conditions of calibration standards, that is, from the energetic point of view, are consumed 0.27 g of CH_2O in the process, consumption reported by Heemst (1986), as growth respiration, therefore:

$$CR_n = \frac{1}{1.27} = \frac{0.79\ g\ MS}{g\ CH_2^0} \quad (13)$$

$$CBC = CB_{max}(t) * C(IAF) * C(ip) * C(If) \quad (14)$$

C(IAF) = correction due to the IAF
C(ip) = correction due to plant age
C(if) = correction due to leaf age

About the correction coefficients used for CBC, using the data of dry matter accumulation at different temperatures (Bull, 1969), for six clones and three different cultivars, which also incorporates data from the FAO Group C4 (Barbieri & Silva, 2007), in relation to air temperature. Making necessary to correct it in the estimate of accumulated DM, which can be done using the Cc(t), which is represented in the equation:

$$C_c(t) = \frac{-186.4 + 17.3 * (t+2) - 0.29(t+2)^2}{-186.4 + 17.4 * 23 - 0.29 * 23^2} \quad (15)$$

It was considered as a unit value (reference) obtained on 22.4 °C air temperature, where Cc (t) = 1; Cc (20) = 0.72; Cc(t) = correction of crude carbohydrate temperature observed (day light), whose air temperature is about 2 oC lower than the leaf average (Barbieri, 1993).

For cloudy days, temperature is approximately equal to the air, the equation then becomes:

$$C_n(t) = \frac{-186.4 + 17.3\mathrm{t} - 0.29\mathrm{t}^2}{-186.4 + 17.4 * 23 - 0.29 * 23^2} \quad (16)$$

Correction due to Age of Culture (C(ip)):

$$C(i) = 0.6 + \frac{73{,}000}{\left(\sum GD * 0.893\right)^{2{,}5}} \quad (17)$$

C(i) = correction due to plant age.
SUM GD = sum of degree-days.
The factor 0.8903 comes from the adjustment of SUM GD to correction the photoperiod (N/12).
This equation has a value equal to 1 to the values of GD <166 (Barbieri, 1993).

Correction due to Leaf Area Index (C (LAI))

The correction due to the LAI is obtained by equation (16) and is necessary because CBmax was determined for a maximum LAI (IAF), which only occurs in one phase of the cycle.

$$C_{(IAF)} = 0.645e^{-\left(\frac{\left(\sum GD - 900\right)}{500}\right)2} + 0.998e^{-\left(\frac{\left(\sum GD - 1{,}868\right)}{1{,}080}\right)2} \quad (18)$$

Since the R^2 = 0952**, when C(IAF)> 1, then it is considered 1.

The function that allows the estimation of IAF was obtained using data measured by Machado (1981), Barbieri (1993) throughout the crop cycle, correlated with the values of "Degree Days" calculated by the following equations (19 or 20):

As for Tb <Tm; the calculation of GDD is performed according to the following criteria:

When Tm> Tb, then: $GDD = \frac{(TM + T_m)}{2} - T_b$

(19)

and when Tb ≤ Tm, then: $GDD = \frac{TM + T_m^2}{2.(\mathrm{TM} + T_m)}$

(20)

GDD = Accumulation of degree days.
TM = Daily maximum temperature.
Tm = Minimum daily temperature.
Tb = Basal temperature (according to BACHI & SOUZA (1978) basal temperature of sugar cane growth is 18 ºC).

The values of GDD for each day should be corrected with the ratio between the length of day in hours and 12 hours as follows:

$$GDD_{st} = \frac{GDD * N}{12} \quad (21)$$

GD = monthly degree day (OC.day)
TM = maximum monthly mean temperature (OC)
tm = minimum monthly mean temperature (OC)
tb = base temperature (18OC) BACCHI(1978)
N = number of hours of daylight of the month

The correlation between these values (LAI x GDD) resulted in roles for plant cane, ratoon. The leaf area index (LAI or IAF, $m^2.m^{-2}$) was calculated for each day of the cycle according to the methodology described by Teruel et al. (2003) for plant cane (22).

$$IAF_{Pl} = \left(e^{-13.521}\right) * \left(\sum GDD_{st}\right)^{2.784} * \left(e^{-0.004023 * \sum GDD_{st}}\right)$$

(22)

The equation coefficients are modified by the number of court in case of sugarcaneratoon (IAF_pc), the figures would be: a = -17.707, b = 3.373 and c =- 0.004265.

Carbohydrate production by sugar cane crop

Assuming that the values of "a" (6.193 10^{-3}) and "b " (0.261)are constant coefficients and dependent on cultivating sugarcane obtained by Barbieri (1993) using data Bull (1965), and the coefficient solar attenuation by the canopy (k = 0.58) obtained by Barbieri (1993) earlier, and leaf area index (LAI) equal to 5, the equations 21 and 26. Is estimated the crude carbohydrate (CH2O/ha day kg) produced by a culture of sugar cane, at the stage of LAI greater than 5, the air temperature of 23 ºC in a day whose radiation in the upper atmosphere was Qo (cal / cm^2.dia), N and photoperiod (hours) is:

CBc = kg CH_2O/ha day produced in one day completely clean.
CBn = kg CH_2O/ha day produced in one day completely overcast.

According to Heemst (1986), the daily fraction that was cloudy is conceptually the intercepted energy by the clouds divided by the maximum possible interception in the range of fraction PAR (Assunção, 1994), obtained by equation 23:

$$\bar{F} = \frac{(0{,}308 * [0{,}4 - (0{,}5 - 0{,}1 * \frac{\mathrm{n}}{\mathrm{N}})] * (0{,}26 + 0{,}51 * \frac{\mathrm{n}}{\mathrm{N}}))}{0{,}208}$$

(23)

N = photoperiod cycle average per month (hours) en / N is the ratio of monthlyaverage insolation (during). In this case, it is possible to consider the values of 0.8 and 0.2 are the fractions of Qo transmitted in one day completely clean, and in one day quite cloudy (Lorderet al., 1984), respectively.

To estimate the photosynthetic active radiation fraction, uses the F-value and estimates of CBN and CBC, which depends on the CO_2 assimilation by sugar cane, which is using physiological data Bull (1969), the air temperature and LAI were considered to 23 °C and 25 °C, respectively and the age of 2 months after planting. Adapting and doing the analogy with Beer-Lambert law. It is admited that sugarcane has a spherical spatial distribution of leaves (Wit, 1965), and solar radiation to penetrate the canopy is attenuated according to the equation proposed by Monsi & Saeki (1953), obtaining the o of 0.58 (Barbieri, 1993), expressed in cal/cm^2 min. Integrating the equation 22, the total synthesis of CH_20 for the entire canopy will be:

$$CB_{IAF} = \frac{\int a \cdot I_0 \cdot e^{-k(IAF)z\prime}}{1 + b \cdot I_0 \cdot e^{-k(IAF)z\prime}} \cdot d(IAF)$$

(24)

The integration of energy transmitted from the first layer (full) with the remaining layers of the leaf canopy, gets in equation 25, will be:

$$CB_{LAI} = 10^3 \cdot \frac{a}{b \cdot k} \cdot \ln\left(\frac{1 + b \cdot I_0}{1 + b \cdot I_0 \cdot e^{-k(LAI)}}\right)$$
(25)

CIAF = CB (LAI 0-5) / CB (LAI = 5), there is the curve CIAF.
CB (IAF) = CH2O synthesized by a given leaf area index (kg / ha.hour).
Io = global radiation incident on top of culture.
a, b. and k = constant quantified before (a = 6.193 10^{-3}, b = 0.261, k = 0.58).

According to equation 26, its defined a good approximation to the daily production of carbohydrates for one day completely clean, which is approximately 0.4 RFA fraction of Radiation Global 33 (Doorenbos & Kassam, 1994), considering an average value Daily per hour (Ioc), and multiplying this figure by the number of sunshine hours (N) (day length).In the newsletter of the FAO number 33 (Doorenbos & Kassam, 1994) has "a" + "b " (Angstron) = 0.25 + 0.50 = 0.75, it is local constant, considering that 75% Qo is transmitted to the culture. When RFA is maximum then n/N = 1. So RFAmax Qo = (a + b) 0.4. When RFA is limited then n/N = 0, So = Qo RFAmin. A.0, 5, then replacing the CBC:

$$CB_c = \frac{10^3 \cdot a}{b \cdot k} \cdot \ln\left(\frac{1 + 0.0125 \cdot b \cdot Q_0/N}{1 + 0.0125 \cdot b \cdot e^{-k \cdot LAI} \cdot Q_0/N}\right) \cdot N$$
(26)

CBC = carbohydrates produced (kg / ha day) in a day completely clean.
Qo = radiation in the upper atmosphere (cal/cm^2 day)
N = length of day (hours)
a, b, and k = constant
To replace local values: a = 6.193 10^{-3}, b = 0.261, and k = 0.58.

The found value of K of 0.58 is next to the one used in Model CANEGRO, the extinction coefficient varies with age: approximately 0.5 (new cane) to 0.8, but this may be different for different cultivars. However, it is assumed that all RFA is intercepted when LAI> 3 (Thompson, 1989). In practice, field conditions in Brazil occurs when the IAF < 4.5 (Machado, 1981; Barbieri, 1997) and (Stanhill& Fucks, 1977; Assunção, 1994).

Validation experiment and statistics

It was proceeded the compare between values estimated by the model yields BRCANE and the results obtained experimentally on yield under irrigation and adequate fertilization, which were installed in the regions of Piracicaba, Araras (Fig. 3, Brazil) and Bunadberg (Australia).

To validate the proposed model with a view to final production, were used data from the production of irrigated and fertilized (potential production (Pp), measured in irrigated experiments with 11 to 20 months of cultivation, between the years 1974 to 1986, led Experimental Station, sugarcane, IAA - Institute of Sugar and Alcohol - Planalsucar - the counties of Araras (latitude: 22º 18' S, longitude: 47º 23' O and altitude: 617m) (Delgado-Rojas, 1998) and Piracicaba (latitude: 22º 42' 30" S, longitude: 47º 38' 00" E Altitude: 546 meters), in the State of Sao Paulo measured by the Center for Sugarcane Technology (CTC) in the years 1984 to 2000 and by the Brazilian Agricultural Research Corporation - Embrapa, in the years 2001 to 2006 (Silva et al., 2006), being climatic data from Meteorological stations originating from UFSCar and ESALQ-USP.

The Australian experience was conducted in Euchrozem soil (Rhodic Eutrudox), in the Experimental Stationof Sugar Cane in Bundaberg (Bundaberg SES), Queensland (lat. 24.83 ° S, 152.43 ° E), from 1991 to 1995. In the experiments, it was used cultivars Q138 and Q141, which were made up of six plantations to determine phenological dates in the development, two of them were grown up to look like cane and four of them were reared at 16 months old and then knuckles by over 16 months. The model parameters were determined from crops planted on 13 August 1991 and May 27, 1992 and brass knuckles on 5 November 1993 and February 18, 1994 being considered the thermal time with a corresponding visual observation of the cane, established using the data in all planting dates. From the maturation process, the accumulated biomass partition was made of sugar, using the experimental data of ratoon crop on 18 August 1992, planted on 19 November 1992, planted on 24 February 1993 and sugarcane grown in the June 3, 1993 and additional information (soil moisture was monitored by neutron probe) to maintain the desired water supply (Liu & Bull, 2001). About the maturation process, the gradual drop in temperature and decreased rainfall are crucial for the occurrence of the maturation process, thus, in southeastern Brazil, the process is naturally occurring from April / May, with the climax in the September month. Temperatures of 17-18 °C seem to be particularly favorable for the accumulation of high levels of sucrose.

There are interactive effect between sunlight, temperature and cultivars of sugarcane in response to the maturation process. To estimate the stress degree to promote the ripening of sugarcane stalk was used negative degree-days accumulated by the plant and the level of water stress in soil.To simulate using the monthly average data of solar radiation (Qg), photoperiod (sunshine hours), minimum (Tm) and maximum (TM) air temperature in the period covered by cultivation and astronomical data locations, for the monthly averages for each of the two regions, as input parameters required by the proposed model, by proceeding to the estimates for seven cultivars of sugar cane, between the harvests of 1974/1986 (Araras) and de1998/2005 (Piracicaba) in Brazil and 1991/1994 (Bundaberg) in Australia (Bull & Liu, 2001). Cultivars to be analyzed: 454 RB72, NA 56-79, CB 41-76, CB 47-355, CP 51-22, Q138 and Q148.

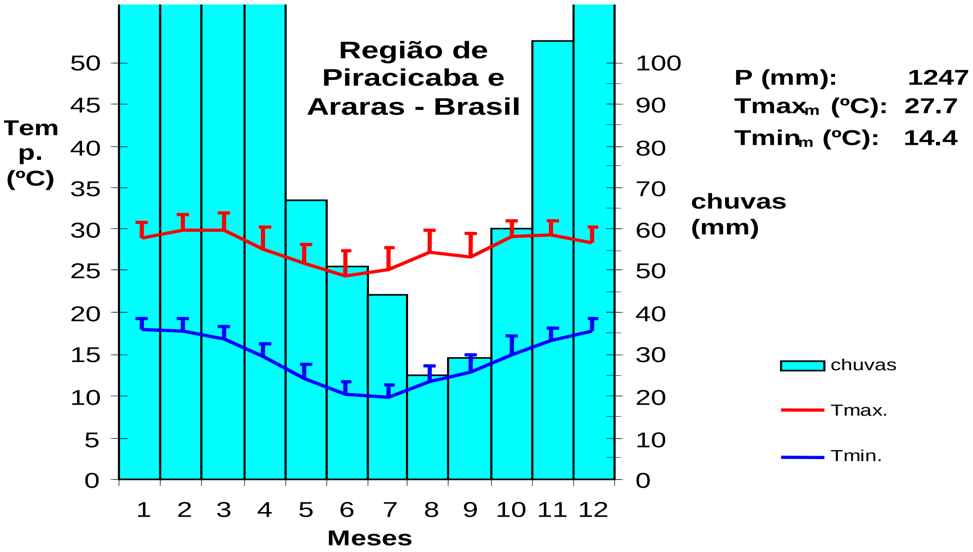

Figure 3. Monthly weather conditions in the region of Piracicaba, Araras - SP (Brazil).
Figura 3. Condições climáticas mensais na região de Piracicaba, Araras – SP (Brasil).

Statistics Analysis
Formity of productivity estimates, by comparison with the measurements, which is evaluated using the difference Ei (estimated or simulated) - Mi (measured or observed) or differences for the same point, the best rates are specified for both conditions Experimental Brazil and Australia, considering the pairs X and Y to the measured and simulated values, respectively. The confront between the measured and simulated values was done by linear regressions (t-test). Analyses are being made individually for different cultivars of sugarcane, also analyzing the set as a whole. To evaluate the model, were used the program IRENE (Integrated Resources for Evaluating Numerical Estimates), as described by Fila et al. (2003), and it is a tool for analyzing data pairs designed to provide easy access to a set of testing techniques. The emphasis is given on statistical techniques, that must be applied when the estimates (EI) are compared, facing the measurements (Mi). Mainly, estimates that do not repeat are compared with the pairs estimates, but without repetition. The parameters for the utility of the BRCANE model applied for analysis assessment techniques are: a) deviation of the median - SB (Kobayashi & Salam, 2000), b) Square root of the variance of the error - RMSV (Kobayashi & Salam, 2000); c) “Root mean squared error”- RMSE (Fox, 1981); d) “General

standard deviation” – GSD (Jørgensen et al., 1991); e) “Modeling efficiency” – EF (Greenwood et al., 1985); f) “Índex of. agreement”- d (Willmott & Wicks, 1980); g) “Mean bias error” – MBE (Addiscott & Whitmore, 1987) and h) “Coefficient of residual mass” – CRM (Loague & Green, 1991).The total dry matter production results were corrected to include the application of a linear equation for variety in Australian conditions, correlated with yield estimated by the models APSIM and CANEGRO / DSSAT and BRCANE.

RESULTS AND DISCUSSION

BRCANE calibration model

The corresponding values of total dry matter estimated by the model ranged from 79 to 142 Mg/ha. Irvine (1983) and Barbieri (1993) mention a series of dry matter values found by different authors in various climate conditions in the world, with a peak of experimentation between 75 to 140 Mg/ha year.Considering that the current study was used in cycles ranging from 11 to 20 months of cultivation, corresponding to the cycles of years and years and a half, the values obtained range from 79 to 140 Mg/ha, found in the literature.

It was found that throughout the cycle in question, the value of BCC was around 2.5 times higher than CBN, as seen in Figure 4. It is known that in terms of global radiation (Qg), a clear day has about four times more energy than a cloudy day.

It is considered that, on a clear day (no clouds), the incident energy is around 0.8 of Qg, while in a cloudy day is around 0.2 to Qg. Considering the PAR fraction RFA in a cloudy day on average 0.7 of Qg, and on a clear day is around 0.4 to Qo. Therefore, on a cloudy day this fraction (RFA) will be around 0.15 of Qg, and on a clear day, around 0.32 for Qg, as recommended by Stanhill & Fucks (1977) and Assunção (1994). This partly explains the difference of 2.5 times between CBC and CBN.

The summer months are potentially more productive. However, in these months the F value is higher indicating that the ratio of sunshine (n / N) was lower, or more months are cloudy, and almost invariably are the wettest. When n is even lower, it can result in a low productivity of sugarcae. Especially this culture, under low light intensity, its production has decreased since CBmax tend to values closer to CBN. These observations that have been cited and described by Van Dillewijn (1952), in a study on the effects of sunlight on nitrogen fertilization.

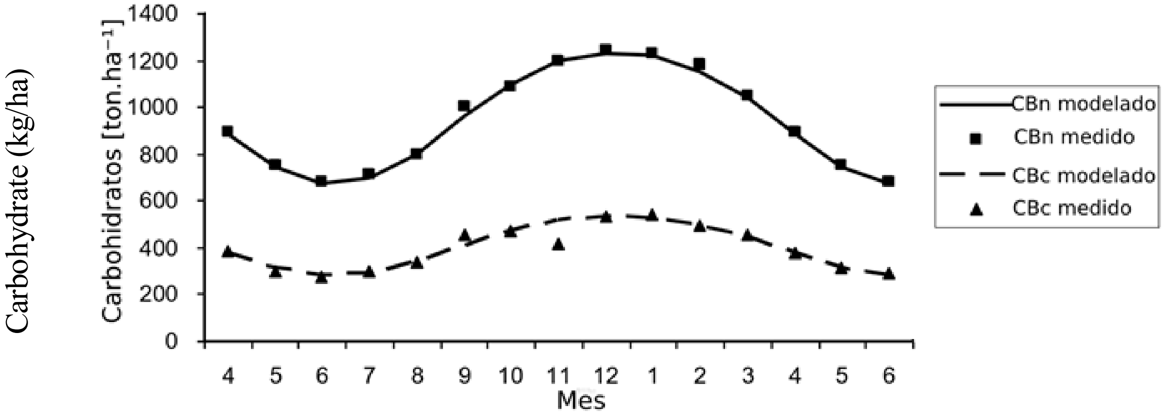

Figure 4. Simulated values of Carbohydrate production CBC (clear day) and CBN (cloudy day) in climatic conditions of the study period in Month 1 season. Carbohydrates (kg CH2O/ha month) compared with original data from Machado (1981).

Figura 4. Valores simulados de CBC (dia claro) e CBN (dia cubierto) nas condições climátics do período de estudo na safra 1980/81.(kg CH2O/há mês) comparados com os dados originais a partir de Machado (1981).

During the winter approaches CBmax approaches to CBC, and to CBN during the summer, as noted byMachado (1981). It should be noted then that irrigation in quantity and distribution of rain, that can promote higher yields, not to decrease the brightness, as occurs on rainy days.

So the amount of energy intercepted by the leaves is very low as indicated by the correction factor [C (IAF)], which leads to low values of CBC (Fig. 4). From October forward, the value of LAI at a marked rate increases and despite the age factor, (C (i)), decreasing the rate of photosynthesis, the values of CBC and CBN remain high (Figure 4).

Adding all these effects, the values of CBC will remain high until the month of March in the following year. From this month on until the end of the cycle, the decrease of available energy, temperature and the age increasing determine hte falling value of the CBC (Chang et al., 1965).

This whole has it maximum value in October, while planting up this month, the dry matter accumulation did not reach very high values. The fraction consumed (Rm) by respiration was estimated at 15% of dry matter produced this month. During the top of respiration, gross production of dry matter was 7414 kg / ha andaccumulation of dry matter until the end of this month was 14183 kg / ha (Figure 5). At this stage the energy consumed by respiration, to maintain vital body functions, maintains a very high compared to production.

The conduct of these results is explained by Barbieri (1993). The general growth of consumer bodies, while producing organs remain largely stabilized or decreased in capacity. The values presented of gross dry matter (Fig. 5a) and net (Fig. 5b), calculated by the model is similar to the measured by Medina et al. (1970), Glover (1972), and estimated by Machado (1981).

The capacity of the model to estimate values of net biomass, showed lower adherence to the results of Machado (1981), compared with estimated values of dry gross climatic conditions considered. Although the error is less than 5%, those coefficients of linear equation for determining the estimated values (Y) comparing with the ones observed by Machado (1981) was above 0.95.

Should be take into account that the correction factor of r max, on old Cr (i) was modeled using data covering, short period of time is approximately 300 days. Were not found in the bibliography, Brazilian research conducted with older sugar canes. The mathematical-physiological function that estimates Cr (i) may be revised or modified by bibliographic information or collected experimentally to estimate dry matter settles. Another important factor is the values of the breathing cycle, which according to Bull & Tover (1974), around 10% of photosynthates are summarized over the cycle on average.

Validation

The productivity of sugarcane obtained in the irrigated experiments varied by variety as follows (Mg/ha): RB72 454 (102-131); NA 56-79 (95-140), CB 41-76 (89-125) 47-355 CB (92 to 140), CP 51-22 (79-133), Q138 (100 to 121) and Q141 (102 to 122).

It was noted that the model offered overestimated productivity values for CB41 and CB47-76-355 at 3% and underestimated by 0.5% to CP5122, NA5679 and RB72454, hence the low value of CR (0.001).

In the case of Australian cultivars were slightly underestimated by the productivity model (CR = 0.01) in the order of 2%.

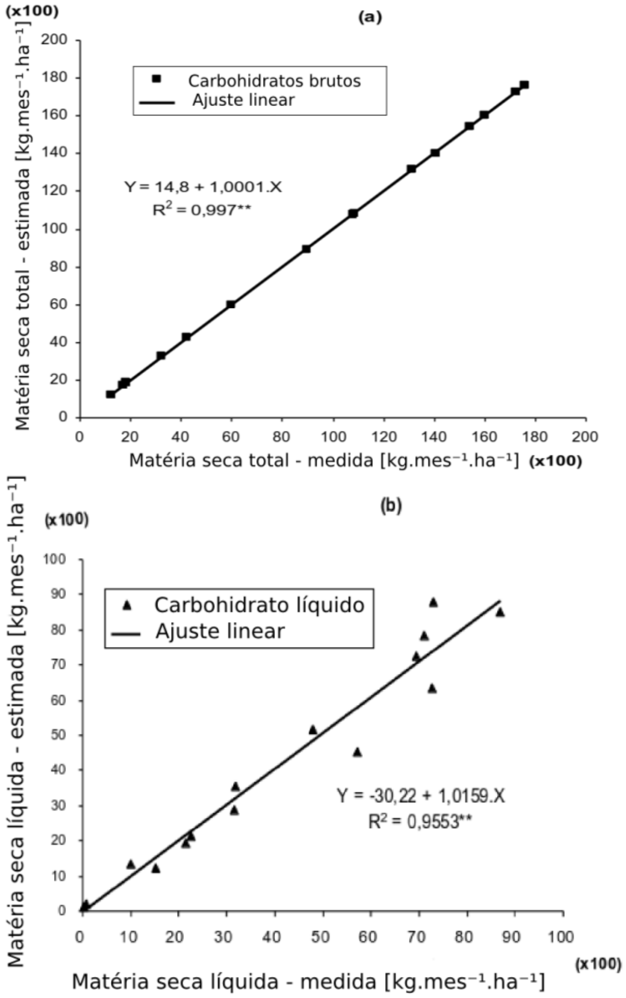

Figure 5. Values of gross dry matter (a) and net dry matter (b), expressed in kg MS /ha.month, estimated by the model, compared to the results of Machado (1981).

Figura 5. Valores de materia seca bruta (a) e materia seca líquida (b) in kg MS/ha mês estimadas pelo modelo e comparados com resultados obtidos por Machado (1981).

It is noticed that there is bigger variability in the estimated Australian conditions, which shall not include the calibration data of that country, only in Brazil. The R^2 values of linear regression between the productivity estimates and measurements were in the order of 0.94 and 0.88, as is noted in Figure 6, for Brazil and Australia, respectively. Comparing the estimated and measured values, it was found that the biggest mistake was the overestimate of CP51-22 (Feb-79 to Sep-80), that error by 11.6 tonnes per hectare, estimating the actual productivity of 133 tons per area missed in less than 9%.

Considering only the cases of productivity that overestimated the productivity of sugarcane, is always obtained a difference of less than 10% of the observed result, which is consistent with the research Lima Catania (1997), that was explained by the authors as influence of maximum air temperatures for September, the average and minimum in April and November and water deficit.

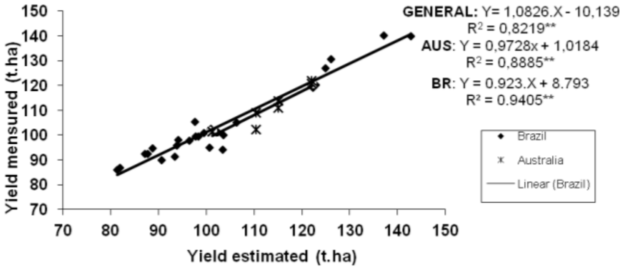

Figure 6. Linear regression between simulated data ("Estimated yield") and observed (“yield mensured”) in yield of cane in Brazil and Australia.

Figura 6. Regressão linear entre dados simulados e observados na produção de cana no Brasil e Austrália.

For the evaluation of conformity of the estimates in comparison with the measurements is evaluated using the difference Ei (estimate) - Mi (measured) or differences for the same point, the best rates are specified for both the experimental conditions in Brazil and Australia, respectively:
Simulation bias (SB): 0.009 and 1.8477;
Root mean squared variation (RMSV): 4.5187 and 2.7262;
Root mean squared error (RMSE): 4.5197 and 3´.2062;
General standard deviation (GSD): 4.5095 and 3.4162;
Modeling Efficiency (EF): 0.9162 and 0.8089;
Index of Agreement (d): 0.9785 and 0.9563;
Coefficient of residual mass (CRM): 0.001 and 0.0149.

The values of basic statistics (squared) are generally very sensitive to extreme values, one notices that were below 4.5 in the data sets that are not large. The lower limit of SB RMSV, RMSE and GSD is 0, which means full adherence between the yields offered by the model estimates and field measurements. The use of EF is an extension to any class of common models, which use R2 in linear regression procedures. EF may begin either with positive or negative values, one being the upper limit, while the negative infinity is the theoretical lower bound. Since the values of EF obtained from 0.916 and 0.810 indicate an appropriate model.

The index of agreement is either a value that approaches 1. The values of EF less than 0, offer an adjust result worse than the average of the measurement. PFor all of them unless CRM (0.001 and 0.01) a negative value indicates that, on average, the model underestimate the estimates to the measured data.

The efficiency of the proposed model, adding up estimates for sugarcane a year and a year and a half, was superior to that proposed by Scarpari & Beauclair (2004) and Doorenbos & Kassam (1979) in testing Teramoto (2003) in studies in Brazil and comparable estimates of potential productivity of sugar cane QCANE using the same test 1991/1994, led in Bundaberg in Australia, published by Liu & Bull (2001), but the model is easier to use and with smaller number of variables involved.

In the final validation phase, we proceeded to compare the BRCANE model with other models in use worldwide, from a set of data Bundeberg - Australian, from 1991-95 published by Liu & Bull (2001) (Table 1).

Table 1.Estimated values of minimum, average and maximum productivity by different models, tons of cane per hectare - TCH, and level of assertiveness in conditions of Australia.

Tabela 1. Valores estimados de produtividade mínima, média e máxima por diferentes modelos, toneladas de cana por hectare - TCH e nível de assertividade em condições da Austrália.

Suource of data	Productivity estimates by the models and the actual value (TCH)			Correlation
	Average	Minimum	Maximum	R^2
Experimental Data / Models	51.0	46.1	55.5	----------
QCANE	51.1	45.4	56.0	0,97**
BRCANE	51.0	45.9	55.4	0,89**
APSIM	51.2	48.4	54.0	0,78*
CANEGRO	50.4	46.7	58.7	0,71*

CONCLUSIONS

The model presented to be effective in estimating the productivity of irrigated sugar cane, both for cultivation of year and a half years, having possibility of being used for predictions throughout the season. Allow to estimate one rate of photosynthesis minus - as losses by maintenance respiration, senescence of leaves and deaths tillers throughout the cycle.The DM estimated by the model was contrasting with data obtained during the course of experimental field irrigated cultivars (RB72 454, NA 56-79, CB 41-76, CB 47-355, CP 51-22, Q138, and Q141) in Sao Paulo State, Brazil and Bundaberg, Australia.The results of total DM were modified to yield in tons per hectare by the linear equation for each variety, with regression coefficients higher than 0.88. The model was shown consistent with MD simulations during the cycle, as well as the revenue forecast.

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