Field Crops Research 235 (2019) 38–53

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

New APSIM-Sugar features and parameters required to account for high sugarcane yields in tropical environments

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ARTICLE INFO

Keywords:
Saccharum spp.
Crop modelling
Photosynthetically active radiation
Sugarcane yield potential
Radiation use efficiency
Reduced growth phenomenon

ABSTRACT

Sugarcane in field plot experiments in tropical Brazil (Guadalupe, Piauí State, 6.6 °S), produced very high yields under non-limiting water and nutrients. Mean stalk dry mass at 8, 11.5 and 15 months were 40, 51 and 70 t/ha respectively for six varieties and six planting dates. These yields were explained by high but not excessive temperatures allowing the canopy to close after 73 days on average. Substantial changes were required to enable the APSIM-Sugar model to simulate canopy and yield gain processes in Brazilian genotypes for the purpose of optimising variety, planting and harvest date options. A new modelling feature was proposed to deal with the observed growth slowdown when crop was about 7–8 months old and dry mass yields higher than 40 t/ha. All new parameters and features were validated with independent experiments as well as with the original dataset used for developing APSIM-Sugar. Future studies involving irrigation, yield gap analysis and climate change in environments where high yields are expected, should consider these modifications.

1. Introduction

The traditional sugarcane industry in Brazil is based largely in the southern region (> 19 °S) and in the coastal area of Northeast region (6-10 °S), mainly in the states of Alagoas, Paraíba and Pernambuco. Considerable expansion occurred in the mid 2000s mainly in midwest (∼15 to 18 °S), and also in the north and northeast regions (IBGE, 2018) but has since slowed down because of political and economic issues (UNICA, 2018). Further expansion of the sugarcane area is now expected due to a government programme called "RenovaBio" (MME, 2017) which aims, by increasing biofuels use in the Brazilian energy matrix, to collaborate in the reduction of 43% of greenhouse gas emissions by 2030 in relation to those observed in 2005 (Brazil, 2015).

Since land demand for sugarcane production in Brazil is expected to increase with "RenovaBio", in-land tropical areas towards equator (∼14 to 2 °S) such as those in north and northeast regions, in the states of Tocantins, Maranhão and Piauí, have gained attention. There is little published information on the growth, development and yield of sugarcane under high input conditions in these areas. Two experiments for assessing sugarcane yield under irrigation, carried out by Andrade Junior et al. (2017) and Andrade Júnior et al. (2012) in the state of Piauí (∼4 to 5 °S), showed that high yields can be achieved in these regions.

Another feature of tropical Brazilian regions is the long dry periods between summer rains which may permit long harvest seasons (up to 9 months) and so raise the prospect of more options for harvest schedules than is possible with shorter harvest seasons, practiced in the south of the country. Longer harvest seasons not only improve the economy of the use of harvesting and milling infrastructure but also allow for more options for optimising production through choice of planting dates, harvest ages and varieties.

One way to integrate aspects related to crop/genotype, weather/climate, soil and management practices is through crop models. Crop models help with the understanding of genotype × environment × crop management (G × E × M) interactions (Singels, 2014). There are several types of crop models, however those based on the process-based approach (mechanistic) are used predominantly as a research aid, since they are based on processes responsible for crop growth, development, yield and quality (Singels, 2014). These crop models are useful tools for several applications in research and decision

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https://doi.org/10.1016/j.fcr.2019.02.002
Received 3 September 2018; Received in revised form 23 January 2019; Accepted 4 February 2019
Available online 05 March 2019
0378-4290/

making in different sectors, such as consulting, agroindustry, government and policy makers (Lisson et al., 2005; Singels, 2014). There are several crop models dedicated to sugarcane, but those used most worldwide are DSSAT/CANEGRO (Inman-Bamber, 1991; Jones et al., 2003; Jones and Singels, 2018; Singels et al., 2008) and APSIM-Sugar (Holzworth et al., 2014; Inman-Bamber et al., 2016; Keating et al., 1999; McCown et al., 1996; Thorburn et al., 2005). The use of APSIM-Sugar has increased in Brazil recently. This model has been applied to evaluate the impact of a green cane trash blanket on yield (Costa et al., 2014; Marin et al., 2014; Oliveira et al., 2016), for irrigation planning (Dias and Sentelhas, 2018a), for yield gap analysis (Dias and Sentelhas, 2018b) and for uncertainties under climate change scenarios (Marin et al., 2015).

Currently, the challenges in sugarcane modelling community are to simulate variety differences (Hoffman et al., 2018; Sexton et al., 2016; Singels, 2014), sucrose dynamics (O'Leary, 2000; Singels, 2014; Singels and Inman-Bamber, 2011), crop responses to carbon dioxide (Jones and Singels, 2018; Stokes et al., 2016) and genetic links (Singels, 2014). Another challenge for sugarcane modelling is the reduced growth phenomenon (RGP) (Park et al., 2005). RGP reduces radiation use efficiency (RUE), mainly in highly favourable environments possibly through lodging, an irreversible decline in leaf nitrogen content with age and/or respiration of sugars; however, its exact cause is still unknown (Park et al., 2005; Van Heerden et al., 2010). There is also some evidence that RGP occurs in traditional areas in tropical Brazil where sugarcane was grown under high input conditions, like in semi-arid (Silva, 2009) and northeast costal area (Oliveira et al., 2010; Ferreira-Junior, 2013). While the physiology of RGP is uncertain, there is a need to establish empirical parameters for simulating sugarcane growth under high input environments to avoid over-optimistic estimates of yield and errors in the gap and climate change analyses. Improved understanding and modelling of the growth and development of sugarcane in tropical areas, would allow important advances for optimisation of G × E × M interactions for yield improvement in order to meet future demands for sugar and bioenergy production in Brazil.

To this end, this paper has the following objectives:

- Assess the sugarcane canopy development and yield in a large field experiment under high input conditions in Guadalupe, state of Piauí, Brazil;
- Evaluate the current capability of APSIM-Sugar module to account for observed yield in terms of canopy development, light interception and RUE and;
- Propose a slowdown feature for models to account for RGP in sugarcane.

2. Material and methods

2.1. Field experiments

Six field experiments were carried out at the Agro-Industrial Complex of Terracal Company, in Guadalupe, state of Piauí, Brazil (6.8 °S, 43.6 °W, and 170 m asml), from 2014 to 2016. Piauí State is situated in a region where there is a transition between tropical and semi-arid climate, with different Köppen's climate types, such as Aw, As and BSh (Alvares et al., 2013). Guadalupe is classified as Aw (Tropical with dry winter).

The experiment used for model calibration is described in Section 2.1.1 and the experiments for in-site validation are described in Section 2.1.2. The weather conditions during the experiments are presented in Section 2.1.3.

2.1.1. G × E × M experiment

This experiment was designed to gain knowledge of the G × E × M interactions in tropical Brazil concerning biomass and sugar production. The experiment could consider only a limited number of G × E × M options and it was intended to enable the APSIM-Sugar model for optimising the full G × E × M interactions by testing or developing its parameters for the tropical conditions and for Brazilian varieties. The soil was classified according to the Brazilian Soil System as a *Latossolo Amarelo* with sandy loam texture, corresponding to Ferralsols in FAO system (details about the soils profiles can be found in Supplementary Table S1). The experiment design was a full factorial, randomised split–split plot, with four replications. Three factors were considered, with the levels ranging from three to six, as follows: (i) planting dates: July, September, November, January, April and May (approximately 2-month intervals); (ii) varieties: RB867515, RB92579, RB931003, RB961003, RB98710 and SP94-3206; (iii) crop ages at harvesting: approximately 8, 11.5 and 15 months. Planting dates were applied as whole plots with area of 1036.8 m^2, varieties as sub-plots with an area of 172.8 m^2, and harvest ages as sub-sub plots with net plot-areas of 14.4 m^2 for 8 months and 21.6 m^2 for 11.5 and 15 months. Larger net plot- and border-areas were required for later harvests because of the increased length of cane stalks. Sub-sub plots were demarcated clearly with pegs and rope so that they could be located with certainty after lodging.

The crop management applied prior to each planting date is detailed in Supplementary Table S2. The crop was planted in an alternate (dual) row spacing of 1.5 and 0.9 m with drip irrigation installed at a depth of 20 cm for each row (tube spacing of 1.4 m and 1.0 m alternately). Daily irrigation requirement was determined and applied as the product of crop coefficient (Kc), a border coefficient (Kb) and reference evapotranspiration (ETo). Kc was based on measurements of canopy development until the light interception approached 100% (initial Kc_{ini} = 0.4, maximum Kc_{mid} = 1.2–1.3). Kb was a factor of 1.25 introduced to deal with additional water possibly required by border rows but all rows received the additional water. ETo was determined by the Penman–Monteith method (Allen et al., 1998), considering the weather data from the automatic weather station next to the experiment. The effective Kc ((rainfall + irrigation)/ETo) was 1.604 ± 0.051 (data not shown). Minimal runoff and drainage were expected from the highly porous soil and root water extraction to at least 1.9 m depth was detected with capacitance sensors. An effective Kc of 1.6 with low day-to-day variation gave the assurance that water was not limiting at any stage. All planting date treatments received over 2000 mm through irrigation throughout the entire cultivation period. Irrigation was withheld (drying-off) for about 30 days prior to the final harvesting to avoid soil compaction rather than to increase sucrose content. Adequate nutrient amounts were applied through the sub-surface drip system, following technical recommendations for obtaining high yields.

A ceptometer (Accupar LP80 model, Decagon Instruments) was used to measure canopy interception of photosynthetically active radiation (PARi) while the ground was shaded between 10 and 90% and the crop was still erect. The probe contained 80 independent sensors, spaced 1 cm apart. Measurements were taken on sunny days between 10 and 14 h. Twelve readings were taken in each plot with the sensor held horizontally at the level of the ligule of the lowest green leaf (where it joins the stalk). Incoming PAR was determined for each field plot before and after the in-canopy readings were taken, by holding the sensor horizontally well above the canopy, using a ladder. An analysis of variance (ANOVA) was performed for PARi when 1500 °C d had accumulated, obtained by interpolation using the nearest measurements to this thermal time (TT base 9 °C).

The height of the ligule of the youngest fully expanded leaf was measured at about 2-month intervals for 20 stalks in each field plot while the crop was still erect. All plots lodged eventually, some as early as 5 months.

All cane stalks within the net plot-area were harvested by hand, taking care to retrieve stalks that may have 'strayed' outside the plot after lodging and avoiding stalks not rooted in the net plot area. The cane was topped as would be done for the commercial crop and then weighed to determine stalk fresh mass or cane yield. A sample of 12 contiguous stalks was removed from the net dual rows in each plot before these rows were completely harvested. Dry matter content was determined for each sample at the laboratory to determine stalk dry mass. Cane yield and stalk dry mass were subjected to ANOVA. The data was interpolated to estimate yield at the exact harvest ages since, in practice, it was not possible to carry out such samplings exactly at the intended crop ages. This procedure was necessary to remove bias in the data caused by differences between the nominal and actual harvest age.

2.1.2. Variety experiments for model validation

The modifications performed in model were validated with independent data from four field experiments at the same site that were carried out with 24 varieties, including those used in the G × E × M experiment. The four field experiments comprised two additional planting dates in two different soils, one next to the G × E × M experiment and another in a sandy soil (*Neossolo Quartzarênico* corresponding to an Arenosol in FAO system). Each experiment consisted of 12 varieties in a random block design with four replications. Gross plot area was 86.4 m^2 of which 48.0 m^2 was used for measurements to avoid border effects. Details about crop management prior planting can be found in Supplementary Table S3. Water and nutrients were managed through fertigation system to achieve the highest yield possible. Cane yield for each plot was measured at harvest when the crop was about 14 months old, all plots having lodged from about 5 months. Only data for the same varieties used in the calibration process were employed here. There were therefore four environments sampled for the purpose of validating the model's parameters that were changed to account for the results of the G × E × M experiment.

2.1.3. Climate

An automatic weather station (Campbell Scientific, CS) was installed within 1 km of all field experiments. The weather station consisted of a datalogger (CR200X model), a tipping bucket rain gauge (TE525 model), an anemometer at 10 m (03002-L Wind Sentry Set model), a pyranometer (CS300-L model, Apogee Instruments), a net radiometer (NRlite 2 CS), and a combined temperature and humidity sensor (CS215 model).

Daily weather conditions during the experiments are shown in Fig. 1. Maximum daily temperatures (Tmax) increased from April to October each year with little day-to-day variation apart from this trend. Maximum temperatures never exceeded 40 °C and were mostly greater than 30 °C (Fig. 1a). Day-to-day variation in minimum temperature (Tmin) was also small (~5 °C) around a seasonal pattern with lowest values mid-year and highest values between October and January (Fig. 1a). Temperature amplitude (Tmax - Tmin), an important variable for sucrose accumulation, reached maximum values in August each year. Incoming shortwave solar radiation (SRAD) exceeded 25 MJ/m^2/d in October each year and in February 2016, respectively around the spring and autumn equinoxes (the site is 6.6 °S) (Fig. 1b). Net radiation (Rn) is the main energy source for evapotranspiration and this exceeded 15 MJ/m^2/d during the summer months and was mostly above 10 MJ/m^2/d (Fig. 1b). High wind speeds (u2) and low relative humidity (RH) are the other factors driving up evapotranspiration. Wind speeds (downscaled from 10 to 2 m height, Monteith and Unsworth, 1990) exceeding 2 m/s were common in July to October each year (Fig. 1c), coinciding with RH values below 20% (Fig. 1d). ETo exceeded 8 mm/d on several days during August to October each year (Fig. 1c) but never exceeded 9 mm/d.

A climatic comparison between Guadalupe and two areas where sugarcane is grown in Brazil, a traditional sub-tropical (Piracicaba, São Paulo State, 22.7 °S, 47.6 °W and 546 m asml) and a semi-arid (Petrolina, Pernambuco State, 9.4 °S, 40.5 °W and 370 m asml), was performed. In addition, Ayr (Queensland Province, Australia, 19.6 °S, 147.4 °E and 17 m asml) was included in the comparison because most of the Keating et al. (1999) data for APSIM-Sugar building/development came from Ayr or similar climates in Australia. Climate data for Guadalupe were averaged from the in-site weather station (2014–2016). Data from Floriano city (6.7 °S, 43.0 °W and 126 m asml), the nearest place with long-term climate series (1994-2013) was also used, compiled from the National Institute of Meteorology (INMET). The climate data were obtained from College of Agriculture "Luiz de Queiroz" (ESALQ/USP), INMET, Australian Bureau of Meteorology (BOM), respectively for Piracicaba (1976-2016), Petrolina (1994-2013) and Ayr (1970-2018). ETo was estimated with Penman–Monteith method (Allen et al., 1998).

2.2. The APSIM-Sugar model

The APSIM-Sugar model is briefly described here only in regard to canopy development, light interception, biomass accumulation and growth slowdown, which are the most relevant processes for the present study. Further details about the model can be found in Keating et al. (1999), Singels (2014), Marin et al. (2015) and Inman-Bamber et al. (2016). The sugarcane model is incorporated as a crop module in APSIM platform (**A**gricultural **P**roduction **S**ystems **SIM**ulator, version 7.10 currently) (Holzworth et al., 2014; McCown et al., 1996). The model runs on a daily time-step and is influenced by genotype, climate (rainfall, air temperature and solar radiation), soil water, nitrogen and crop residues.

2.2.1. Canopy and light interception

Canopy development is regulated by TT with a single base temperature (Tb = 9 °C) for all canopy related processes, namely sprouting of buds, emergence, tillering and stalk growth. Shoots elongate towards the soil surface at a rate of 0.8 mm/°C d (*shoot_rate*), after a TT lag (*shoot_lag*) of 250 °C d for plant crops and 100 °C d for ratoon crops to account for the bud sprouting process. Thus, planting depth and air temperature affect sugarcane emergence. Leaf appearance rates decline according to accumulation of degree-days. The tillering process is not directly simulated and a combination of maximum number of fully expanded green leaves (*green_leaf_no*), leaf areas (*leaf_size*) and tillering factors (*tillerf_leaf_size*) according to leaf number (*leaf_size_no* and *tillerf_leaf_size_no*), is used to derive leaf area index (LAI). A constant parameter to account the initial total plant leaf area (*initial_tpla*) is set as 10 cm^2 to start leaf development.

Light interception is simulated using Beer's law and is based on SRAD, instead of PAR. The default light extinction coefficient (*k*, *extinction_coef*) is set as 0.38 according to Muchow et al. (1994). Light competition is simulated to induce senescence once SRAD interception reaches 85%.

2.2.2. Biomass production

Biomass accumulation is driven by RUE (*rue*) and transpiration efficiency coefficient (TEC, *transp_eff_cf*) approaches. Transpiration is a function of daily crop growth rate and TEC. The TEC was determined as 8.7 g kPa/kg in recent improvements in sugarcane module for water-limited environments done by Inman-Bamber et al. (2016), based on experimental data of Inman-Bamber and McGlinchey (2003). Default RUE values vary between plant (1.80 g/MJ) and ratoon (1.65 g/MJ) crops. The biomass produced is partitioned into four aboveground biomass pools: leaf, cabbage, structural stalk, stalk sucrose. An additional pool for roots is simulated separately from aboveground pools depending on growth stage. The biomass partitioned to stalks starts after 1200–1900 °C d is accumulated since emergence (*tt_emerg_to_begcane*), which is variety specific. Extreme air temperatures, water stress (deficit or surplus) and nitrogen deficiency affect RUE and canopy expansion, and consequently, stalk yields.

2.2.3. Reduced growth phenomenon (RGP)

RGP can be invoked through several processes. The first option is through the *death_fr_lodge* coefficient that decreases stalk number after lodging. A second option is through the *lodge_redn_photo* coefficient,

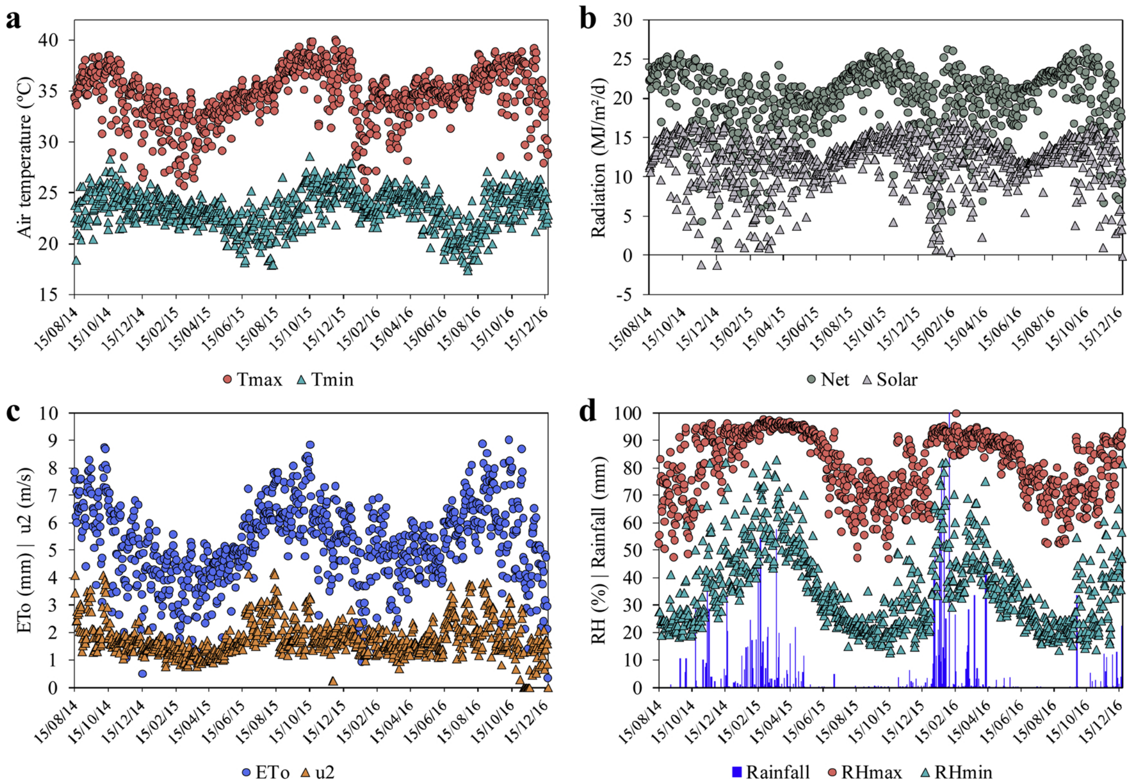

Fig. 1. Weather conditions during sugarcane field experiments, from August 2014 to December 2016. Maximum (Tmax) and minimum (Tmin) air temperatures (a), solar and net radiation (b), wind speed (u2) and reference evapotranspiration (ETo) (c) and, maximum (RHmax) and minimum (RHmin) relative humidity and rainfall (d).

which reduces RUE after lodging and a third option is that green leaf number can be reduced in case of lodging, using the *lodge_redn_green_leaf* coefficient. All these processes are strictly related to a lodging event and a certain amount of biomass is necessary as input to trigger lodging. These options are of a binary nature and once triggered they cannot be changed.

The standard version of APSIM-Sugar (version 7.5 r3124 and earlier) allows the user to change RUE as a function of the growth stages defined by the processes of emergence, start of stalk growth and flowering. In the new version (version 7.9 r4404 and later) proposed here, the user is allowed to alter RUE in relation to growth stage as defined by leaf number, which is a developmental property of sugarcane or any grass species, to account for RGP. This is a more flexible way of dealing with the RGP. A coefficient between 0 and 1 can be assigned to a given leaf number and when that phenological stage is reached, a new value for RUE is invoked until the next assigned leaf is produced. Phenologically based RGP could also include lodging effects but many crops develop rapidly even after lodging (Park et al., 2005). Single leaf or whole plant photosynthesis normally declines with crop development. Whole plant photosynthesis (per unit of leaf area) of potted plants declined when plants were about six months old, after about 9 internodes (or leaves) had emerged (Inman-Bamber et al., 2011, 2009). Maximum photosynthesis rates declined by 66% when plants were 10 months old and about 24 leaves had emerged. Bull (1969) and Hartt and Burr (1965) also reported a similar decline in leaf photosynthesis as crop became older. Allison et al. (1997) reported a smaller reduction of 27% over the same period even when very high levels of nitrogen were applied during the period of measurements. All these studies suggested that leaf number is a reasonable basis for invoking the RGP effect in sugarcane growth modelling.

2.3. Simulations with APSIM-Sugar

In this paper, we consider the G × E × M interaction on sugarcane yield. The G term in the modelling part represents the Brazilian gene pool rather differences between Brazilian varieties. In both, G × E × M and validations experiments, only plant crop data were used.

The experiments were carried out as best as possible to avoid any biotic, water and nutrients stress, therefore, the simulations should represent those conditions. The pH values were set at 6 to ensure that the plants were not stressed because of nitrification which is limited by APSIM under conditions below this level. Automatic irrigations were also used to avoid water stress. All stress factors were checked through the accumulation of stress days and all the simulations were run with minimal water stress (< 0.074 stress days) and zero nitrogen stress.

2.3.1. Default settings with variety Q117 and PAR interception adequacy

The model was run with the default settings for the Australian variety Q117 to find out which modifications would be required for Brazilian varieties and for this new environment. The TT from stalk growth to flowering (a process not simulated in the model) was increased to 9000 °C d because the accumulated degree days at Guadalupe exceeded the default setting of 6000 °C d after which stalk growth ceases in the simulations.

APSIM-Sugar may have never been tested under climatic conditions such as those observed in Guadalupe, where the crop emerged and developed rapidly. Furthermore, the gene pool used in the experiments is most likely is different from those used in model's development, which did not include any Brazilian variety data. In order to better account for the Brazilian sugarcane genotypes, leaf area was set up before calibration. The leaf profile was changed based on measurements of seven Brazilian varieties under glasshouse conditions carried out by Leal (2016). The leaf areas used were 5,800, 20,000, 36,000, 46,000, 51,000, 51,400, 50,700, 49,300 and 43,500 mm^2 for leaf stages

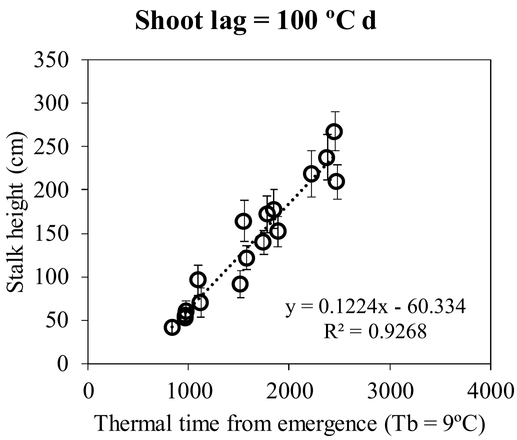

Fig. 2. Relationship between stalk height and thermal time from emergence using a *shoot_lag* coefficient of 100 °C (base temperature of 9 °C). The variety measurements were pooled.

1, 5, 10, 15, 20, 22, 24, 26 and 30 or older, respectively. These modifications were set once and remained unchanged for all simulations during both calibration and validation processes.

After the leaf profile was set up, modifications were required for the simulation of PARi firstly by adopting a range of *k* values applicable for PAR which is used in photosynthesis rather than for SRAD which drives the energy balance in nature (and in the model). Also, previous simulations of light interception (Cheeroo-Nayamuth et al., 2000) were tested using interception of SRAD (~300 to 3000 nm) rather than PAR (~400 to 700 nm) which is absorbed and reflected more readily by green leaves (Bonhomme, 2000). Absorption of PAR is responsible for biomass accumulation and so we would expect a *k* for PAR to account better for biomass accumulation than one for SRAD. The CANEGRO model uses *k* values from the measurement of PARi (Inman-Bamber, 1991) and it is likely that the yield bias, evident in default simulations, could be corrected using *k* for PARi. In CANEGRO, *k* increases from 0.58 to 0.84 as the canopy develops. The increase is due to a reduction of a mutual shading with age and height, as stalks tend to separate (Inman-Bamber, 1991). Another possibility for increasing *k* is due to different row spacing used in the experiments, since the extinction coefficient increases with reduced row spacing (Flenet et al., 1996).

Because plants emerged so rapidly after planting (< 10 days) at Guadalupe, germination parameters in the model were considered for additional modification to improve simulations for PARi. Smit (2010) showed that for South African varieties grown in a glasshouse, the Tb for shoot emergence ranged between 16.8 and 18.1 °C, much higher than the Tb adopted in APSIM-Sugar (9 °C) and CANEGRO (10 °C). The new version of CANEGRO now considers 16 °C as Tb for this process (Jones and Singels, 2018). Tb cannot be varied for different processes of expansive growth in APSIM-Sugar. Instead, a range of TT values for sprouting was tested to better account for the rapid increase in PARi observed. It can also be genotype specific, since sprouting speed is considered as a factor to choose varieties in commercial fields (Inman-Bamber and Stead, 1990) and is distinguished in other crop models, such as CANEGRO (Singels et al., 2008) and CASUPRO (Royce, 2010).

Another parameter that could delay canopy expansion in APSIM-Sugar in a hot environment is the initial total plant leaf area. A small modification of this parameter can have a large effect on the expansion of subsequent leaves. APSIM-Sugar allows the user to enter the maximum size of each successive leaf but if there is not enough photosynthate derived from existing leaves, expanding leaves will not reach their maximum size. This in turn affects the expansion of subsequent leaves.

In order to find the best parameters to account for PARi at Guadalupe, several simulations were run using the following combinations: (i) *k* (*extinction_coef*): 0.55, 0.60, 0.65, 0.70 and 0.80; (ii) TT for sprouting (*shoot_lag*): 50, 100, 150, 200 and 250 °C d; and (iii) initial total plant leaf area (*initial_tpla*): 1000, 1250, 1500, 1750 and 2000 mm^2.

Measurements of the height of the youngest visible ligule were used to determine the TT from emergence to the start of stalk elongation (*tt_emerg_to_begcane*). TT was derived from APSIM-Sugar outputs to ensure consistency in this calculation. Planting date was recorded but not emergence date which was simulated instead, with the range of *shoot_lag* values given above (50 and 250 °C d). Thus *tt_emerg_to_begcane* was varied with *shoot_lag* to ensure that the delay from planting to stalk elongation was equal to the delay estimated from the height measurements. The values of *tt_emerg_to_begcane* thus ranged of 550–302 °C d over the range of *shoot_lag* values (50 and 250 °C d). These values are much lower than for the Australian varieties. Marin et al. (2015) and Dias and Sentelhas (2017) also found lower values in their simulation studies. Such low values can be related to genotype differences or to incorrect Tb assumed in APSIM-Sugar for some expansive growth processes. The tillering process, for example, requires at least 16° C rather than 9° C (Inman-Bamber, 1994; Singels et al., 2005), but the Tb was not the focus here and it was not changed in the model. An example of *tt_emerg_to_begcane* of 493 °C d for the *shoot_lag* of 100 °C d is presented in Fig. 2.

Coefficient of determination (R^2), root mean square error (RMSE) and its percentage (RMSEP), and Willmott's "*d*" index (Wallach, 2006) were calculated for the relationship between simulated and measured PARi values and then used to define the best parameters (*extinction_coef*, *shoot_lag* and *initial_tpla*). When the best canopy parameters were determined, attention was then given to the simulation of stalk dry mass.

2.3.2. Introducing a growth slowdown feature for accounting RGP

Growth slowdown factors (*y_rue_leaf_no_fact*) for each leaf stage (*leaf_no*) were derived using the Gompertz equation:

$$y\_rue\_leaf\_no\_fact = 1 - A \times \exp[-\exp(B - C \times leaf\_no)] \tag{1}$$

Coefficient *A* (asymptote) represents the maximum RUE decline due RGP, coefficients *B* and *C* represent the leaf stage for the onset of RGP and degree of effect on RUE, respectively. The best slowdown factors were found in the same way as for the canopy parameters described above. Several simulations were run applying the slowdown factors derived using all combinations of coefficients in Eq. (1): (i) *A*: 0.40, 0.45, 0.50, 0.55 and 0.60; (ii) *B*: 6, 7, 8, 9 and 10; (iii) *C*: 0.15, 0.175, 0.20, 0.225 and 0.25. The same statistical indices (*d*, R^2, RMSE and RMSEP) were used to define the best slowdown factors for each leaf stage.

2.3.3. Cane yield simulations

Meier and Thorburn (2016) assumed a stalk dry matter content of 0.30 in their simulations to derive cane yield from simulated stalk dry mass for the Australian variety Q124. However, dry matter content can vary considerably; 0.10–0.36 in the case of well irrigated Q96 and Q124 (Inman-Bamber, 2004). Any application of the default settings of the APSIM Sugar module shows that dry matter content varies only between 0.30 and 0.32. This is clearly inappropriate for young sugarcane crops at least. Dry matter content was determined for the G × E × M experiment but not for the validation experiments. Empirical regressions to account for dry matter content were needed to derive cane yield from simulated stalk dry mass in the validation experiments.

Stepwise multiple regression was used to select the best predictors for simulating dry matter content on a daily basis, where daily air temperature amplitude averaged over 20 days before sampling (ampd20) and TT were the most significant variables accounting for dry matter content for all varieties:

$$\text{Dry matter content} = 17.854 + \text{ampd20} \times \left(\frac{\text{TT}}{1000}\right) \times 0.115 \tag{2}$$

This regression model accounted for 69% of the variation in dry matter content (Supplementary Fig. S1) and was used with the APSIM model to simulate cane yield for Brazilian varieties at Guadalupe.

2.4. Validation using Keating et al. (1999)'s dataset

Inman-Bamber et al. (2016) introduced new features in APSIM-Sugar to account for drought resistance in the Australian gene pool and tested the modifications against the experimental results used by Keating et al. (1999) to build the model in the first place. A similar procedure was used here to test the new RGP feature as well as the canopy parameters derived for Brazilian varieties. The same experiments used by Inman-Bamber et al. (2016) were employed at this stage, considering different crop classes and types of management. Experiments where nitrogen stress was likely to be severe were excluded. Simulated and observed green (dry stalk + dry cabbage) biomass were compared. Supplementary Table S4 details the original experiments employed, which were conducted at latitudes ranging from 18.4 °S (tropical climate) to 29.5 °S (sub-tropical climate). Mean absolute error (MAE) was added to the list of statistical indices at this stage.

Keating et al. (1999) used their lodging rules (also described above) to account for reduced growth caused by lodging in some of their experiments. Our RGP process was designed to include lodging effects so we excluded the lodging options used by Keating et al. (1999) for a valid test of the new RGP process. The canopy parameters modified to account PARi were also tested. Four model configurations were employed in this analysis: (i) APSIM-Sugar default settings without any lodging feature; (ii) APSIM-Sugar default settings with Keating et al. (1999)'s lodging rules; (iii) APSIM-Sugar default settings with RGP feature only and; (iv) APSIM-Sugar default settings with the RGP feature *and* canopy parameters (*leaf_size*, *shoot_lag*, *initial_tpla*, *tt_emerg_to_begcane* and *extinction_coef*) as determined for Brazilian genotypes above.

2.5. Model evaluation

The performance of APSIM-Sugar with default coefficients and with the modifications proposed here was evaluated by common statistical indices in crop modelling, such as intercept (a), slope (b), R^2, *d*, RMSE and RMSEP (Wallach, 2006). The graphics for visual analysis were created using *ggplot2* package (Wickham, 2016) of "R" platform (R CORE TEAM, 2018).

3. Results

3.1. Sugarcane performance in Guadalupe, PI, tropical Brazil

3.1.1. Guadalupe climate in comparison to those from other sugarcane regions

As expected, Guadalupe and Floriano are more similar to Petrolina than to Piracicaba and Ayr, in regard to climate (Fig. 3). From May to September, SRAD (Fig. 3a) and maximum temperatures (Fig. 3b) are higher in Guadalupe, resulting in a relatively high crop water demand (between 4.6 and 6.7 mm/d) particularly in August, whereas maximum ETo occurs in September in Floriano and in November in Petrolina, always equal to, or above 6 mm/d (Fig. 3d). During the summer, SRAD in Guadalupe and Floriano is lower than observed in the other assessed regions, a consequence of the cloud cover during the rainy season from December to March (Fig. 3c). Compared to Ayr and Piracicaba, Guadalupe is hotter during most of the year, which impacts sugarcane growth and development since this crop is favoured by warmer climates in yield-building processes (Inman-Bamber, 2014; Sage et al., 2014). A comparison of annual TT, ETo and rainfall can be found in Supplementary Table S5.

3.1.2. ANOVA of PARi and yields

The ANOVA of PARi performed using data at TT = 1500 °C d (Tb = 9 °C) showed that there were significant differences between varieties and between planting dates (Table 1). In terms of canopy development, varieties SP94-3206 and RB98710 were the fastest ones and RB961001 and RB931001 were those with the slowest growth. For sugarcane planted in September and November (spring crops) the canopy developed rapidly, whereas for those planted in May (autumn crop), a longer period for canopy development was required.

Sugarcane canopy closure occurs when PARi exceeds 0.70 (Inman-Bamber, 1994). In the experiments conducted in Guadalupe, canopy closure averaged between 63 and 82 days for different varieties and between 61 and 99 days for different planting dates, all under high input conditions. There was no interaction between planting date × variety.

Considering all varieties and plantings months, mean yields at 8, 11.5 and 15 months were 40, 51 and 70 t/ha for stalk dry mass and 172, 206 and 235 t/ha for cane yield, respectively. Stalk dry mass of 65, 75 and 105 t/ha when crops were 8, 11.5 and 15 months old were the maximum achieved by the most productive varieties (RB961003, RB931003 and RB92579). Considering all the data, the average gain in cane yield was 10.2 t/ha per month from 8 to 11.5 months and 9.5 t/ha from 11.5 to 15 months for January, April, May and July planting dates (data not shown), which was considerably lower than the gain observed from planting to 8 months (~23.0 t/ha per month). The slowdown can be partly attributed to lodging experienced in the experiment.

The ANOVA showed that the effect of crop age on stalk dry mass (Table 2) and cane yield (Table 3) was significant, meanwhile there was no interaction between planting date and variety when all harvest ages were pooled, although this interaction was observed for just two cases when harvest age was analysed separately (data not shown). There was a high interaction between planting date and harvest age for both stalk dry mass and cane yield. Harvest age and variety also interacted strongly ($p < 0.001$).

3.2. APSIM-Sugar modelling

The simulations with the default settings for the Australian variety Q117 were surprisingly good for stalk dry mass ($y = 1.50x - 22.06$, $R^2 = 0.87$ and RMSE = 11 t/ha), nevertheless not for the right reason, since PARi simulation was poor (see next section), failing to capture the rapid increase of such interception observed in the field.

3.2.1. PARi simulations

The PARi simulated by APSIM-Sugar model using default Q117 settings is presented in Fig. 4. The model did not capture the fast canopy development for Brazilian varieties at Guadalupe in all planting dates assessed (Fig. 4a). PARi was mostly underestimated, with large errors for values < 0.85 (Fig. 4b). There were no values > 0.90 simulated in these conditions, which can be related to the onset of senescence due light competition of 0.85 used in the model.

The performance of APSIM-Sugar using the several combinations of *k*, *shoot_lag* and *initial_tpla* are presented in Fig. 5. The *k* of 0.65 was the best considering all varieties at Guadalupe (Fig. 5a and b). The TT for sprouting (*shoot_lag*) after planting was reduced from 250 to 100 °C d for plant cane (Fig. 5c and d). It seems that TT change was plausible, since the minimum air temperature measured in the 30 days after planting was 18.7 °C considering all planting dates for Guadalupe. The initial total plant leaf area was increased from 10 to 20 cm^2 (Fig. 5e and f).

After changing canopy parameters, PARi was simulated quite well (Fig. 6a). Only few underestimated and overestimated values occurred beyond the 15% deviation lines, (Fig. 6b). The statistical analysis for the performance of APSIM-Sugar with canopy parameters calibrated for Brazilian varieties planted at different dates are presented in Table 4. The precision, expressed by R^2, increased from 0.72 to 0.83, whereas the accuracy, measured by *d*, reached 0.95, much higher than the prior 0.74. The RMSE was markedly reduced from 39%, for the default

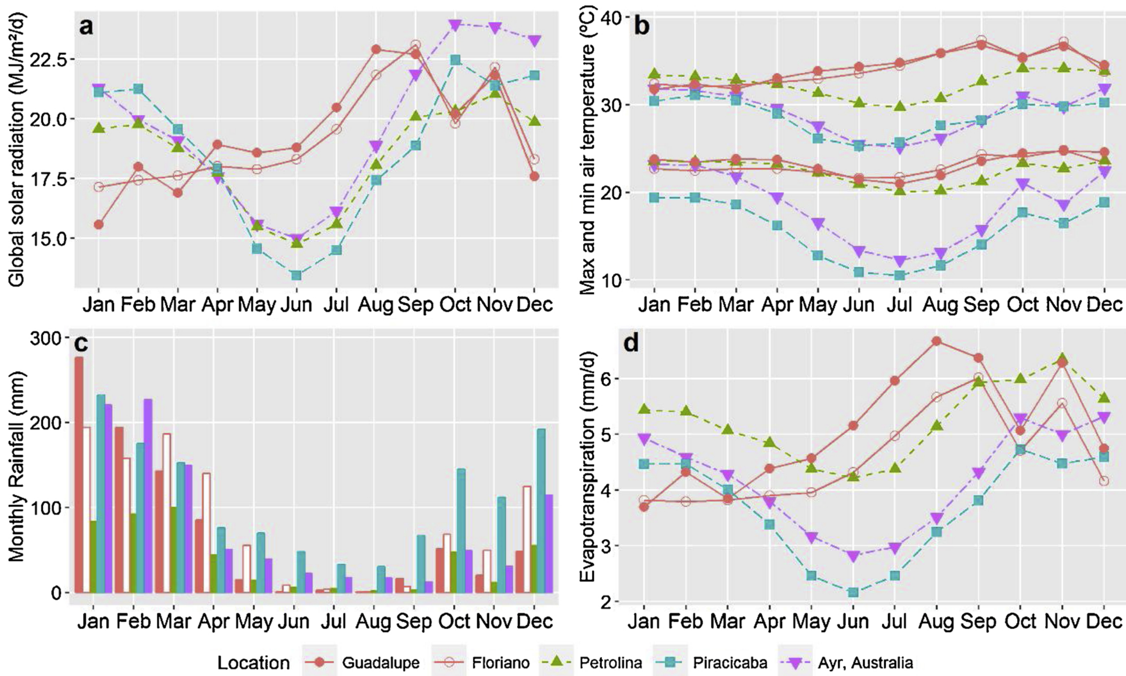

Fig. 3. Comparison between climatic conditions for Guadalupe, Floriano, Petrolina, Piracicaba (Brazil), and Ayr (Australia): monthly mean daily solar radiation (a), average minimum and maximum air temperature (b), monthly mean total rainfall (d) and monthly mean daily reference evapotranspiration (d).

Table 1
Analysis of variance based on a split plot design with planting date as whole plot treatment and sugarcane varieties as sub-plot treatment for fractional photosynthetically active radiation interception (PARi). The average number of days after planting (DAP) to reach PARi of 0.70 is presented.

Variety	PARi at 1500 °C d	DAP to reach PARi of 0.70	Planting date	PARi at 1500 °C d	DAP to reach PARi of 0.70
RB867515	0.78	72	July	0.82	69
RB92579	0.79	76	September	0.94	65
RB931003	0.72	81	November	0.88	61
RB961003	0.73	82	January	0.70	72
RB98710	0.85	66	April	0.80	74
SP94-3206	0.86	63	May	0.61	99
p[a]	0.004	–	*p*	< 0.001	–
LSD[b]	0.081	–	LSD	0.067	–

[a] *p*-Value (5%).
[b] Least significant difference.

parameters, to 12% after the calibration. A summary of the modifications performed in the .xml file to account PARi in comparison to variety Q117 can be found in Supplementary Table S6.

3.2.2. Yield simulations using growth slowdown feature

The simulation of yields at 8 months was mostly correct (Fig. 7) after matching observed and simulated PARi. However, the rapid canopy development and the use of k for PAR instead of one for SRAD, were also responsible, in most cases, for overestimating yields at 11.5 and 15 months (Fig. 7). Notable exceptions were for RB961003 when observed and estimated yields were close at least for some planting dates (data not shown). All field plots were lodged after 8 months contributing to the observed RGP. Other factors such as respiration and reduced leaf nitrogen could also have contributed.

In order to account the RGP observed at Guadalupe experiment, we only used one option for reducing growth rate after 7–8 months and this was by decreasing RUE with respect to leaf stage. Using the same calibration procedure for canopy parameters, the best simulations of stalk dry mass was achieved when the coefficients A, B and C of the Gompertz equation (equation 1) were, respectively, 0.5, 7 and 0.25, to generate the slowdown factors. The slowdown factors, derived using the mentioned coefficients, are presented in Table 5. RUE was kept unchanged up to around leaf #25 and then it declined 42% when around leaf #35 appeared in the simulation. According to the simulations, leaf #35 appeared shortly before the 8-month sample-harvest when stalk dry mass and cane yields were already greater than 40 t/ha and 150 t/ha, respectively, in most cases. The maximum decline in RUE due to RGP was 50%.

The improvements in the simulations offered by the growth slowdown feature to account for RGP in APSIM-Sugar are shown for each planting date in Fig. 8. The start of the RGP seemed to be consistent for all varieties; between seven to eight months, which corresponds roughly to 4000 °C d (ranging from 3660 to 4350 °C d), irrespective of planting date (data not shown). The performance of APSIM-Sugar for simulating stalk dry mass before and after the calibration of growth slowdown feature is presented in Table 6. The precision (R^2) was slightly reduced (0.86–0.82) with the calibration of such parameter, however the accuracy (d) was substantially improved with the changed parameters, increasing from 0.64 to 0.95 (Table 6). Consequently, RMSE decreased markedly from 26.2 to 5.6 t/ha or from 49.4 to 10.6%. The model performance for cane yield was also very good, with a RMSEP as low as 9.2% (Table 6).

Table 2
Analysis of variance based on a spilt-split plot design with planting date as whole plot treatment and varieties as a sub-plot treatment and harvest ages as a sub-sub-plot treatment for sugarcane stalk dry mass (t/ha).

	Variety						
Age	RB867515	RB92579	RB931003	RB961003	RB98710	SP94-3206	Mean
8	40	41	43	39	37	41	40
11.5	53	48	56	56	43	52	51
15	70	74	73	78	58	66	70
LSD[a]			5.4 ($p < 0.001$)[b]				2.2 ($p < 0.001$)
Mean	55	55	58	59	46	54	54
LSD			3.1 ($p < 0.001$)				
	Planting date						
Age	Jul	Sep	Nov	Jan	Apr	May	Mean
8	42	43	39	42	38	38	40
11.5	37	49	50	54	52	58	51
15	75	62	67	66	80	77	70
LSD			5.4 ($p < 0.001$)				2.2 ($p < 0.001$)
Mean	51	54	52	54	57	57	54
LSD			2.5 ($p < 0.001$)				

[a] Least significant difference.
[b] p-Value (5%).

3.2.3. In-site validation of modifications

The validation of APSIM-Sugar with the calibrated parameters for Brazilian sugarcane varieties was performed with data from four independent experiments presented in Fig. 9. Experiment 1 had four and Experiment 2 had two varieties in common with the G × E × M experiment, which was used to develop the new parameters for the APSIM-Sugar model. Dry matter content and stalk dry mass were not determined for the four experiments used to validate the modifications to the model. However, using equation 2 for estimating dry matter content and the identical modifications for PARi and RGP for the G × E × M experiment, cane yield was simulated within the standard error of the measured cane yield in each of the four independent tests (Fig. 9). The calibrated parameters that accounted for the rapid increase in PARi, the rapid initial increase and later slowdown in stalk dry mass accumulation were considered as valid at least for sugarcane growing in different conditions under high input at Guadalupe experiments.

3.2.4. Validation using Keating et al. (1999) dataset

The validation of the RGP feature in APSIM-Sugar for simulating green (dry) biomass using the original dataset of model development is depicted in Fig. 10. Simulations without any modification to account for growth slowdown (Fig. 10a), over-estimated observed green biomass when this exceeded about 60 t/ha. The lodging rules applied by Keating et al. (1999) corrected these estimates to some extent but still over-estimated yields by as much as 30 t/ha (Fig. 10b). When applying the RGP feature (Table 5) as for Brazilian genotypes under climatic conditions of Guadalupe, high yields were estimated well, within 15% of measured yields, but lower yields were consistently under-estimated (Fig. 10c). This under-estimation was corrected when adding the new canopy parameters applicable to Brazilian varieties but yields of plant

Table 3
Analysis of variance based on a spilt-split plot design with planting date as whole plot treatment and varieties as a sub-plot treatment and harvest ages as a sub-sub-plot treatment for cane yield (t/ha).

	Variety						
Age	RB867515	RB92579	RB931003	RB961003	RB98710	SP94-3206	Mean
8	169	176	172	185	158	171	172
11.5	213	193	209	234	175	207	205
15	235	249	236	272	196	221	235
LSD[a]			18.2 ($p = 0.006$)[b]				7.4 ($p < 0.001$)
Mean	208	207	207	233	177	201	206
LSD			10.9 ($p < 0.001$)				
	Planting date						
Age	Jul	Sep	Nov	Jan	Apr	May	Mean
8	184	180	148	169	173	178	172
11.5	203	174	188	214	211	218	205
15	248	210	244	237	260	236	235
LSD			18.2 ($p < 0.001$)				7.4 ($p < 0.001$)
Mean	212	194	193	208	215	213	206
LSD			8 ($p < 0.001$)				

[a] Least significant difference.
[b] p-Value (5%).

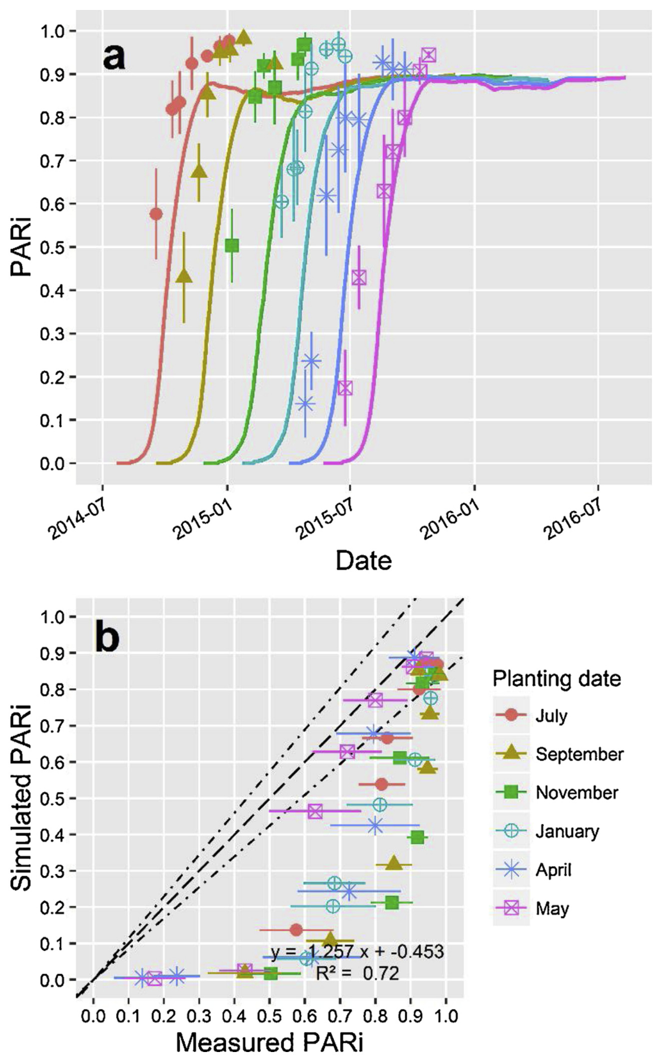

Fig. 4. Fractional photosynthetically active radiation interception (PARi) measured (points plus bars) and simulated (lines) by APSIM-Sugar model using default settings of Q117 Australian sugarcane variety for the Brazilian varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter plot of simulated and measured values (b), where 1:1 line (dashed lines) and ± 15% deviation (dotted dashed lines) are shown.

crops tended to be over-estimated. This error was more serious for low yields (young crops) than for high yields (mature crops) when crops are normally harvested in commercial practice. With observed green biomass yields of 50 t/ha and above, the new RGP feature together with Brazilian canopy parameters gave the best result in terms of MAE (Table 7). Simulation of PARi was improved before optimisation of the RGP parameters for the large G × E × M experiment, so RGP parameters were dependent on correct PARi and canopy parameters. The international varieties (Australian and South African) used by Keating et al. (1999) may differ from Brazilian varieties in regard to PARi, onset of stalk elongation and the dual row spacing adopted in Guadalupe may also affect PARi compared to the single (~1.5 m) spacing used for most of Keating's experiments. These simulations of Keating's experiments suggest that canopy development is more rapid for Brazilian than for the varieties, largely Australian, used by Keating et al. (1999).

4. Discussion

The canopy closure was as rapid as 61 and 72 days on average for crops planted in November and January, respectively, and slower than that for crops planted in May (Table 1). The rapid canopy development for the Brazilian varieties at Guadalupe can be compared with a ratoon crop of the variety NCo376 which reached a similar stage 65 days after harvesting in February at La Mercy, South Africa (29 °S) (Inman-Bamber, 1994). For simulating cane growth, an additional TT of 250 °C d was considered for sprouting by Keating et al. (1999) for plant crops compared to ratoon crops and we would expect ratoon crops of these varieties in Piauí to reach the full canopy stage in about two weeks earlier than plant crops with a mean temperature at the site of 28.6 °C (Fig. 3). Canopy development for sugarcane crops planted in autumn and winter was also rapid in Guadalupe compared to other sugarcane growing environments. The South African variety NCo376, ratooned in April at La Mercy required 165 days for canopy closure which would be about twice as long for a May ratoon in Guadalupe (99 days for a plant crop and 14 days less for a ratoon crop). Variety RB92579 took as long as 120 days to close the canopy when crop was ratooned in June in Petrolina (Silva, 2009), while the same variety planted between May and July in Guadalupe took, on average, only 72 days (Table 1). Variety RB98710 planted in August in Rio Largo, Alagoas State (9 °S) took around 100 days to achieve 0.70 of PARi (Ferreira-Junior, 2013), while the same variety in Guadalupe took just 66 days in average for all planting dates (Table 1). Despite ratoon crops being faster for closing the canopy than plant crops, plant crops in Guadalupe developed more rapidly than plant or ratoon crops in Petrolina and Rio Largo, which are both in tropical environments in Brazil.

The rapid sugarcane canopy development in Guadalupe was attributed to high temperatures throughout the year even during winter where the mean monthly minimum temperature is 21 °C for July (Fig. 3). Leaf and tiller production are both dependent on temperature and soil water (Inman-Bamber, 2004, 1994) and crop management (Bell and Garside, 2005; Singels and Smit, 2009), which all affect the light interception. Slow canopy development was responsible for 'wasting' as much as 39% of annual PAR available for photosynthesis in La Mercy region, South African (Inman-Bamber, 1994). The warmer is the climate, the faster is the canopy development and thus less radiation is 'wasted' if water is not limited, thus, high biomass accumulation should be achieved in environments like Guadalupe. Plantings in the first half of the year allow the canopy to develop before the high radiation peak in August and September (Table 1, Fig. 6), thus favouring high yields at 12 months for crops planted between January and May (Table 2). A crop planted later in the year would also experience this high radiation if allowed to develop for 15 months or more. Because of that, yields at 15 months were not consistently lower for crops planted in the second half of the year (Table 2).

Sugarcane yields for plant crops obtained in Guadalupe were remarkable in spite of the decline in RUE due to RGP after 8 months (Tables 2 and 3, Fig. 8). In Petrolina, semi-arid Brazil, variety RB9579 ratooned in June yielded as much as 51 t/ha of stalk dry mass at 389 days (Silva, 2009), which was the same for the same variety planted in July at Guadalupe but after only 317 days. Oliveira et al. (2010) reported stalk dry mass of 81 and 58 t/ha for RB92579 and RB867515, respectively after 360 days in Carpina, in northeast Brazil, slightly higher than the average yield obtained before 350 days for the same varieties (53 and 48 t/ha, respectively), averaged over all planting dates (Table 2). For cane yield, Andrade Junior et al. (2017) reported 211 t/ha for variety RB867515 planted in July in Teresina, whereas the same variety yield 227 t/ha when planted in that month at Guadalupe approximately 200 km away. The warmer climate in Guadalupe, characterised by high but not excessive maximum air temperatures during winter, helps in yield-building processes (Inman-Bamber, 2014; Sage et al., 2014). The yield data from the large G × E × M experiment at Guadalupe and the measured climate variables indicated that this region is highly favourable for sugarcane production with full irrigation compared to existing sugarcane tropical regions in Brazil and can help to meet the demand for sugar and bioenergy production.

Calibration of APSIM-Sugar canopy parameters was essential to account for the observed PARi indicating the need for model

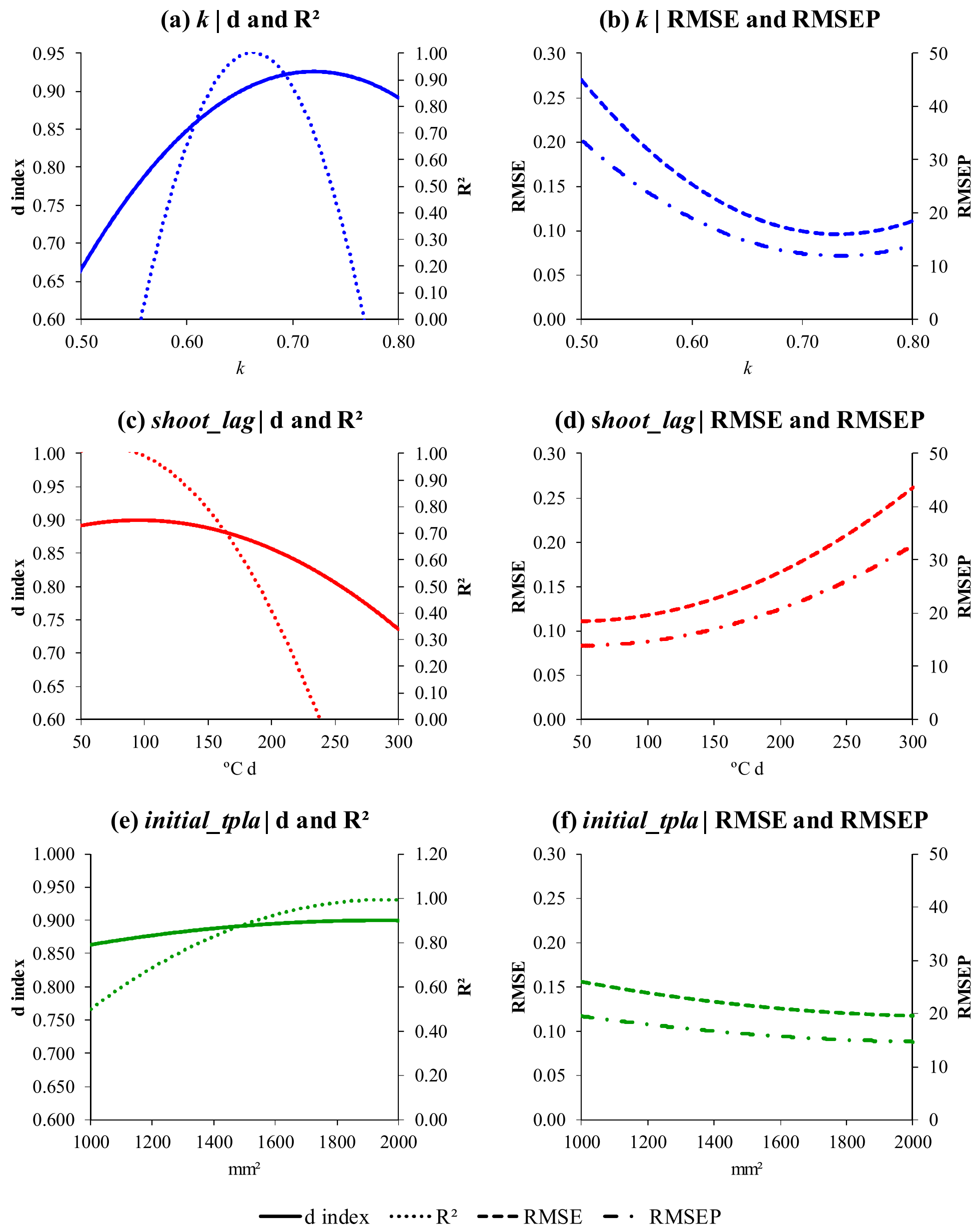

Fig. 5. Optimisation of *k* (a, b), *shoot_lag* (c, d) and *initial_tpla* (e, f) parameters in APSIM-Sugar for simulating sugarcane fractional photosynthetically active radiation interception, based on "*d*", R^2 (a, c, e), RMSE and RMSEP (b, d, f) indices.

improvement in certain processes. The initial total plant leaf area parameter had a significant effect on PARi (Fig. 5). Values for this parameter for sugarcane were not available in the original description of the APSIM-Sugar model (Keating et al., 1999). LAI at emergence for maize is assumed to be 0.0074 in the WOFOST model (Boons-Prins et al., 1993) compared to 0.020 for a sugarcane crop with 10 stalks per m^2 (each with a 20 cm^2 leaf) in the APSIM model. While little attention has been given to the initial LAI in crop simulations in the past, we suggest that this is an important parameter for rapidly developing canopies in conditions such as those at Guadalupe. We suggest that the initial leaf area per stalk or shoot should be increased to 20 cm^2, which worked best in Guadalupe. Sensitive parameters that are difficult to measure are suitable for statistical calibration (Sexton et al., 2016), which seems to be the case of the initial total plant leaf area parameter in APSIM-Sugar.

Keating et al. (1999) assumed that the TT for sprouting after planting was 350 °C d while a value of 250 °C d appears in the default parameters of the APSIM-Sugar software. Brazilian varieties required a 60% reduction in TT, from 250 °C d to 100 °C d for plant crops, when calibration was performed with data from field experiments. Tb for sprouting and emergence defined by Smit (2010) was 16-18 °C for South African varieties, which is nearly twice the value (9 °C) assumed for all expansive processes (cell division and expansion) in APSIM-Sugar (Keating et al., 1999). While Tb can be changed in APSIM-Sugar software, such changes will affect all expansive growth processes. Tb for sprouting and tillering is clearly higher than for leaf appearance and elongation (Inman-Bamber, 1994; Singels and Smit, 2009) and this needs to be captured in future revisions of APSIM-Sugar for yield projections, especially under climate change (Jones and Singels, 2018; Wang et al., 2017).

Negative feedback on PARi later in the crop development occurred in the simulations, which was caused mainly by the growth slowdown factors. Unfortunately, because of lodging no PARi measurements were done after canopy completion to verify this feedback mechanism captured by the model. PARi simulated by APSIM-Sugar never achieved the high values observed (nearly 100%), even without the negative

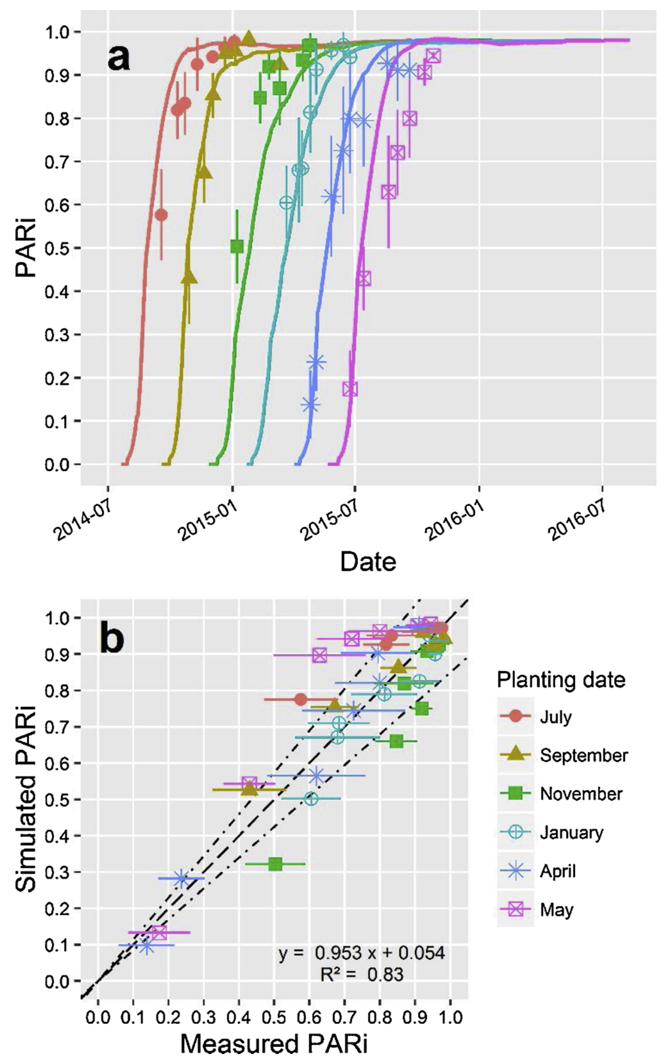

Fig. 6. Fractional photosynthetically active radiation interception (PARi) measured (points plus bars) and simulated (lines) by APSIM-Sugar model after canopy parameters calibration for Brazilian sugarcane varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter plot of simulated and measured values (b), where 1:1 line (dashed lines) and ± 15% deviation (dotted dashed lines) are shown.

Table 4
Performance of APSIM-Sugar to simulate fractional photosynthetically active radiation interception (PARi), with default settings for canopy parameters and after their calibration under high input conditions for Brazilian sugarcane varieties in tropical Brazil.

Index	Default settings (Q117 variety)	Canopy parameters modifications
Simulated mean	0.53	0.79
Measured mean	0.77	0.77
a	−0.45	0.05
b	1.26	0.95
R^2	0.72	0.83
RMSE	0.30	0.10
RMSEP (%)	39.19	12.48
d	0.74	0.95

feedback of slowdown factors, which raises another aspect that should be possibly tested in APSIM-Sugar model for new improvements.

According to the simulations, the slowdown on RUE occurred when crop had produced about 25 leaves per stalk, which agrees with the decline on photosynthesis found by Bull (1969), Hartt and Burr (1965)

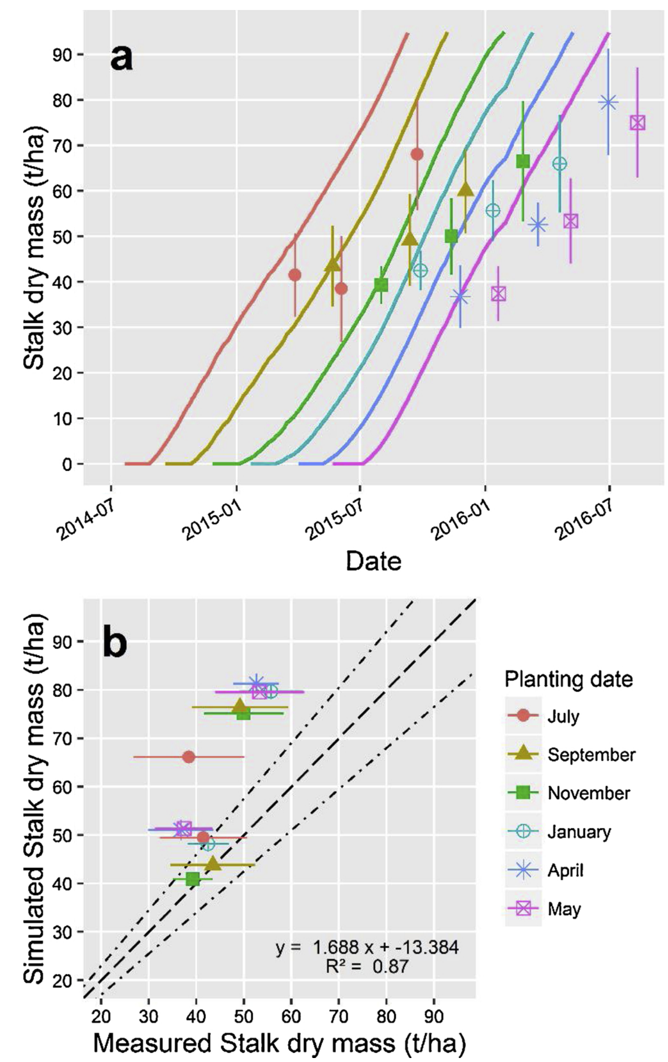

Fig. 7. Stalk dry mass measured (points plus bars) and simulated (lines) by APSIM-Sugar model after canopy calibration for Brazilian sugarcane varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter plot of simulated and measured values (b), where 1:1 line (dashed lines) and ± 15% deviation (dotted dashed lines) are shown.

Table 5
Calibrated growth reduction (slowdown) factors applied to radiation use efficiency at distinct sugarcane growth stages defined by the number of fully emerged leaves on primary stalks.

Leaf stage	Slowdown factor
1	1.00
20	1.00
25	0.90
30	0.70
35	0.57
40	0.52
45	0.51
> 50	0.50

and Inman-Bamber et al. (2011, 2009). Due to lodging, the decline in RUE ranged from 30% to 50% in studies using APSIM-Sugar in Australia (Biggs et al., 2013; Inman-Bamber et al., 2006, 2004; Meier and Thorburn, 2016; Thorburn et al., 2011) and Brazil (Oliveira et al., 2016), where our maximum decline due to RGP in general was about 50%, consistent with the results reported above.

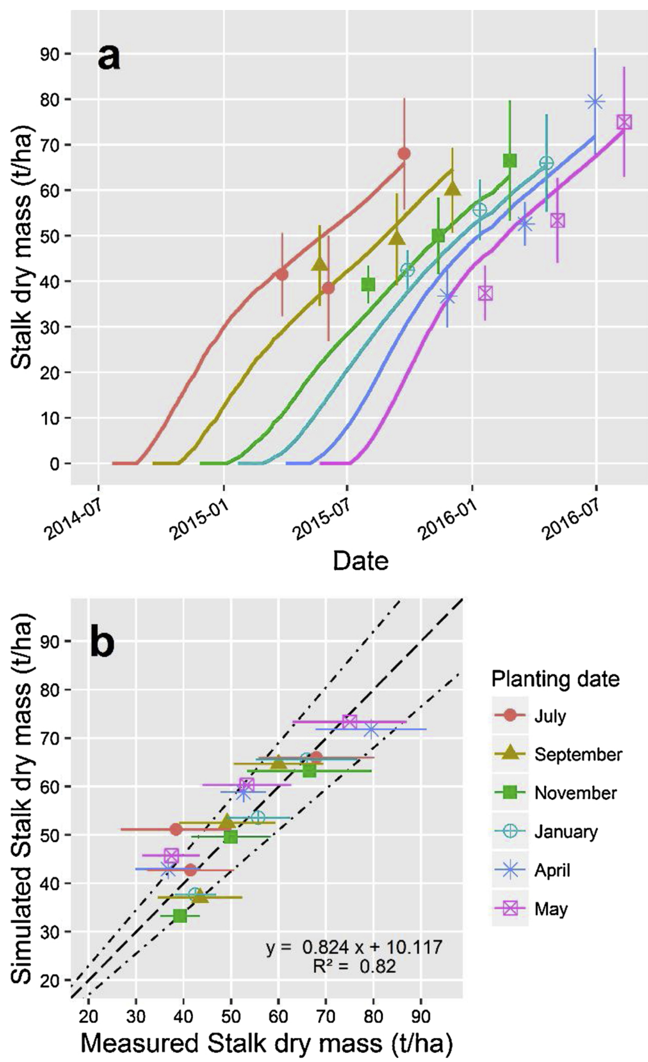

Fig. 8. Stalk dry mass measured (points plus bars) and simulated (lines) by APSIM-Sugar model after canopy parameters calibration and introduction of growth slowdown feature to account for the reduced growth phenomenon for Brazilian sugarcane varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter plot of simulated and measured values (b), where 1:1 line (dashed lines) and ± 15% deviation (dotted dashed lines) are shown.

The statistical indices for yields simulated with APSIM-Sugar for Gualadupe, using the RGP effect, cannot be compared directly to other studies in literature where lodging rules were applied in APSIM-Sugar (Biggs et al., 2013; Inman-Bamber et al., 2004; Meier and Thorburn, 2016; Oliveira et al., 2016; Thorburn et al., 2011) and in CANEGRO/CANESIM (Singels et al., 2008; Van Heerden et al., 2015) due to many reasons. First, the statistical indices for yields were not available (Biggs et al., 2013; Inman-Bamber et al., 2004; Van Heerden et al., 2015) or were not available for data where lodging played a role (Singels et al., 2008). Second, other site-specific changes in the models for reducing RUE were applied together with lodging, for instance waterlogging (Meier and Thorburn, 2016), making it difficult for comparisons. Lastly, because RGP was not the main focus in the studies that investigated lodging, except for the studies conducted by Inman-Bamber et al. (2004) and van Heerden et al. (2015). Despite the above considerations, RMSE for the studies above-mentioned ranged from 4.7 t/ha (Thorburn et al., 2011) to 19 t/ha (Meier and Thorburn, 2016) for cane yield, and from 3.5 to 9.3 t/ha (Singels et al., 2008) for stalk dry mass. In the present study, RMSE for stalk dry mass and cane yield were 5.6 t/ha and 18.7 t/ha, respectively, proving that the growth slowdown factors proposed to account for RGP was crucial to simulate sugarcane yield accurately under high input conditions in Brazil.

The growth slowdown feature proved to be credible to account high levels of biomass in tropical and sub-tropical environments in Australia (Fig. 10), where lodging interfered in crop performance and possibly in other RGP contributors as well. The validation with this dataset can also be viewed as a verification of models' stability, since RGP feature did not changed substantially the precision, accuracy and error of the estimates (Table 7). The worst statistical performance (Table 7) were for simulations with canopy parameters for Brazilian varieties applied together with the RGP feature (Fig. 10d), suggesting that these parameters are not broadly applicable for all varieties or Brazilian varieties may gain biomass more rapidly than the varieties in the Keating et al. (1999) dataset (mainly Australian and South African). Nonetheless, by the time the crops were ready for harvesting the predictions with all the Brazilian parameters were good (MAE = 7.2 t/ha) and did not suffer as much from the large over-estimates of biomass yield without these new parameters. The underestimation of first ratoon green biomass when RGP feature was applied (Fig. 10c) suggests that our growth slowdown coefficients need to be further tested for ratoons in APSIM-Sugar, since the model already applies a decline in RUE for this crop class (from 1.8 to 1.65 g/MJ, Keating et al., 1999).

Lodging rules need to be developed for the conditions of Guadalupe before this option can be used reliably in APSIM-Sugar, once wind speed, rainfall, variety and total above-ground biomass play their expected roles (Singh et al., 2002; Van Heerden et al., 2010). The modelling approaches for lodging of Inman-Bamber et al. (2004), Thorburn et al. (2011) and Van Heerden et al. (2015) could be tested in future studies and added to a list of improvements required by APSIM-Sugar to improve its performance. In APSIM-Sugar, lodging can trigger a reduction in RUE, stalk population and other processes (see Section 2.2.3), but these effects cannot be reversed once the trigger has been invoked. In practice, the effect of lodging on RUE may be more complex because geotropism leads to a recovery of the canopy and erect growth followed by further lodging events, which was the case of the experiments at Guadalupe. Moreover, Park et al. (2005) showed that lodging

Table 6
Performance of APSIM-Sugar to simulate sugarcane stalk dry and fresh mass after introduction of growth slowdown feature to account for the reduced growth phenomenon (RGP) under high input conditions in tropical Brazil.

Index	Stalk dry mass		Stalk fresh mass
	RGP feature disabled	RGP feature enabled	RGP feature enabled
Simulated mean (t/ha)	76.12	53.84	198.51
Measured mean (t/ha)	53.07	53.07	202.73
a	−13.05	10.26	16.82
b	1.68	0.82	0.90
R^2	0.86	0.82	0.69
RMSE (t/ha)	26.22	5.64	18.70
RMSEP (%)	49.40	10.63	9.23
d	0.64	0.95	0.90

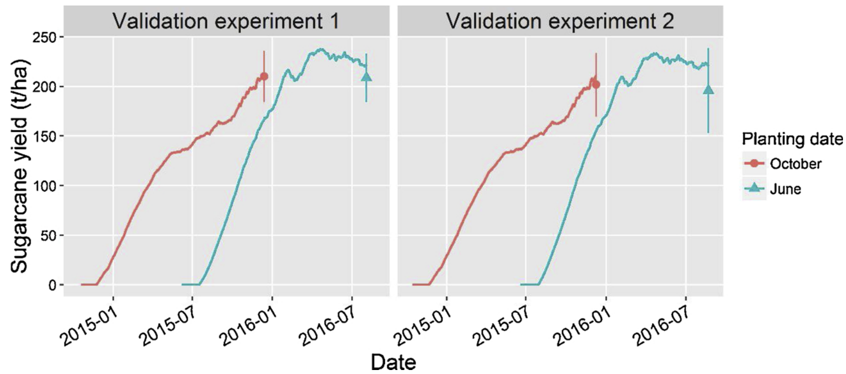

Fig. 9. Sugarcane yield measured (points plus bars) and simulated (lines) by APSIM-Sugar model during validation with independent data under high input conditions in tropical Brazil.

does not always have a marked negative effect on RUE. We suggest that lodging processes that were included in the original version of APSIM should not be used with our new RGP feature because it would amount to double accounting and lead to an underestimation of biomass gain.

Other factors such, reduced nitrogen leaf content, negative feedback of sucrose accumulation on photosynthesis, and increasing maintenance respiration during development and maturation (sucrose accumulation) can be related to RGP, nonetheless, there is little conclusive evidence to help accommodate these processes in the simulation of large sugarcane crops. An interesting finding of van Heerden et al. (2010), based on Donaldson et al. (2008), was that in South Africa, the well-watered and managed crops that started in the summer (December) presented lower yields than those started in the winter (July). In the summer crops, the slowdown commenced in the spring due low temperatures, but persisted after temperatures rose again. These authors suggested that maintenance respiration required by the higher biomass of summer crops in high temperatures was a limiting factor for increasing sugarcane yield. It is expected that the slowdown factors that we used will capture this constraint, at least to some extent, because summer crops develop their canopy rapidly and achieve the leaf number associated with the onset of RGP, relatively early.

Reduced RUE may well arise from increased respiration when large amounts of metabolically active sugars have accumulated. The new version of CANEGRO (Jones and Singels, 2018) and QCANE (Liu and Bull, 2001) both simulate respiration of plant components driven by temperature. Jones and Singels (2018) tested zero maintenance respiration in their simulations and found that it did not lead to improvements in biomass prediction and suggested that the respiration of components should be included in CANEGRO. The respiration of sugars that was included in the recent up-grade of the APSIM-Sugar module (Inman-Bamber et al., 2016), are yet to be tested and reported. Respiration warrants careful consideration before using this feature as an effective RUE slowdown process in APSIM-Sugar. The respiration of sugars is probably captured to some extent in the slowdown factors proposed.

Based on the experimental data from the present study and modelling results, RUE seemed to be highly conserved in elite sugarcane varieties. RUE = 1.8 g/MJ accounted well for stalk dry mass at about 8

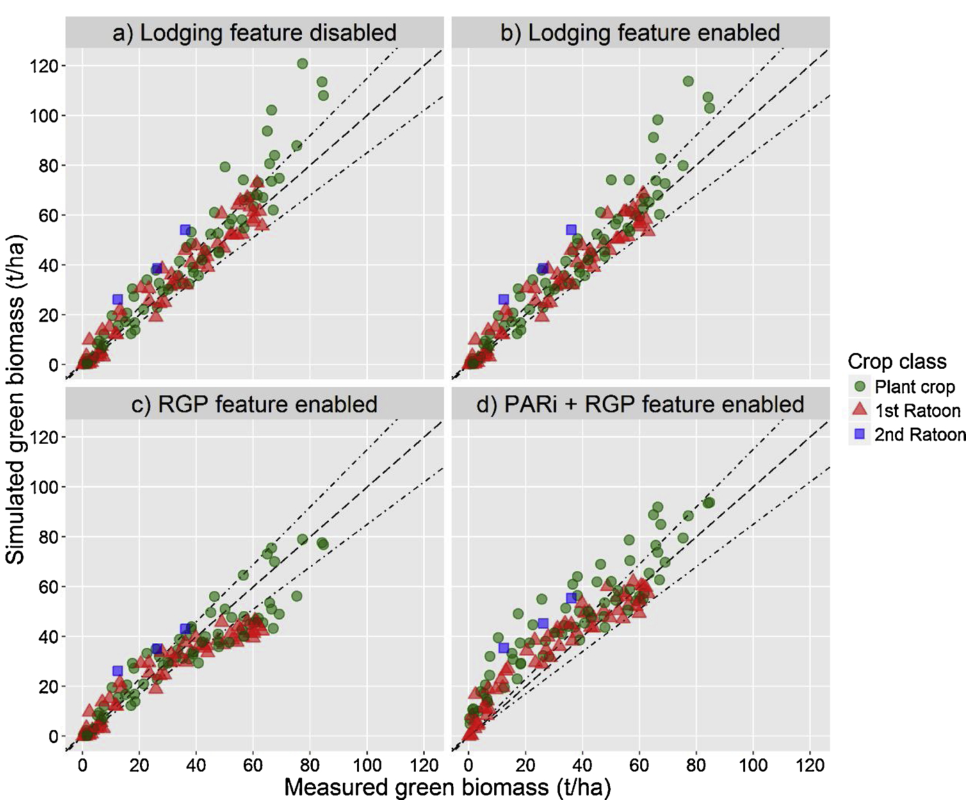

Fig. 10. Scatter plot of measured and simulated green biomass by APSIM-Sugar using Keating et al. (1999) dataset differentiated by crop class. (a) Lodging rules disabled; (b) Lodging rules enabled; (c) Growth slowdown feature to account for the reduced growth phenomenon (RGP) enabled; (d) Modifications in canopy parameters for photosynthetically active radiation interception (PARi) plus RGP feature enabled. The lines 1:1 (dashed lines) and ± 15% deviation (dotted dashed lines) are also shown.

Table 7
Performance of APSIM-Sugar to simulate green biomass using Keating et al. (1999) dataset with lodging feature disabled and enabled, with growth slowdown feature to account for the reduced growth phenomenon (RGP) enabled, and with modifications in canopy parameters for photosynthetically active radiation interception (PARi) plus RGP feature enabled.

Index	Lodging feature disabled	Lodging feature enabled	RGP feature enabled	PARi + RGP feature
Simulated mean (t/ha)	38.31	37.25	30.58	41.79
Measured mean (t/ha)	33.92	33.92	33.92	33.92
a	−0.61	0.36	4.33	11.38
b	1.15	1.09	0.77	0.90
R^2	0.92	0.92	0.87	0.86
RMSE (t/ha)	9.4	8.2	9.1	11.6
RMSEP (%)	27.84	24.31	26.70	34.32
d	0.96	0.97	0.95	0.93
MAE (t/ha)	6.11	5.42	6.95	9.22
MAE for yield > 50 t/ha[a]	10.52	8.28	13.30	7.17

[a] Total number of measurements after sub-set: 38.

months in our experiment regardless of planting date (Fig. 8) and it is also applied to all the varieties and climatic conditions around the world (including Australia, South Africa, Swaziland and Hawaii) in Keating et al. (1999). The empirical RGP coefficients used to account for stalk dry mass at 11.5 and 15 months were also found to be valid for stalk dry mass in four independent experiments at the same site. The RGP feature and parameters were also shown to be reliable when simulating experiments used to build APSIM-Sugar (Fig. 10). We advocate that these RGP coefficients (Table 5) could be used in APSIM-Sugar for well managed irrigated sugarcane until more certainty could be obtained regarding the large number of factors and processes that could contribute to RGP.

Better modelling of RGP will probably reduce the uncertainties in sugarcane simulations. For example, the drying-off days to increase sucrose yield in irrigated sugarcane estimated in Brazil (Dias and Sentelhas, 2018a), South Africa (Donaldson and Bezuidenhout, 2000) and Australia (Robertson et al., 1999) with APSIM-Sugar and CANEGRO models would be improved, since they used relative stalk dry mass as a trigger to withhold water before harvest. Several sugarcane yield gap analyses performed with crop models in Brazil (Dias and Sentelhas, 2018b; Marin et al., 2016; Monteiro and Sentelhas, 2017) and other countries (Cheeroo-Nayamuth et al., 2000; Jones and Singels, 2015; Van den Berg and Singels, 2013; Zu et al., 2018) did not take into account the RGP in the simulations. Thus, there is a possible underestimation of the efficiencies of sugarcane industries, which may be performing closer to the optimum than the simulations show in these studies.

The uncertainty about the RGP effect on sugarcane simulations is also valid for climate change studies performed in Brazil (Carvalho et al., 2015; Jaiswal et al., 2017; Marin et al., 2013; Singels et al., 2014) and around the world (Baez-Gonzalez et al., 2018; Cheeroo-Nayamuth and Nayamuth, 2012; Jones et al., 2015; Knox et al., 2010; Ruan et al., 2018; Singels et al., 2014), where the majority of these studies suggested an increment in sugarcane yields, which can be exaggerated without considering the discussed crop constraint. As far as we know, climate change impacts assessed in Australian sugarcane regions performed by Biggs et al. (2013) and Everingham et al. (2015) were the only studies that considered lodging as one of the causes of RGP explicitly in the crop model simulations.

Water demand in APSIM-Sugar is related to biomass accumulation, therefore, unrealistic estimates of biomass gain in large crops could also lead to an overestimation of irrigation water requirements (Inman-Bamber et al., 2016). The features proposed here have not been tested under rainfed conditions in hot environments and, or years, where the production of leaves is faster and slowdown would commence when crop is not large.

The assessment and modelling of a high yield area in a tropical region is now covered at least to some extent in order to gain understanding of sugarcane crop performance for areas of expansion of sugarcane industry. An assessment of each factor that could be related to RGP still needs to be further investigated. Modelling variety differences and sucrose dynamics in these areas would also provide a valuable tool to help increasing sugar and bioenergy production in Brazil.

5. Conclusions

The high yields achieved in Guadalupe, tropical Brazil, were explained by high, but not excessive air temperatures, resulting in a more efficient capture of PAR. PARi and yields were increased further by planting earlier rather than later in the year. The onset RGP seems to be consistent at about 7–8 months and at about 4000 degree-days (Tb of 9 °C).

APSIM-Sugar simulated PARi satisfactorily after several modifications in canopy and light interception parameters. We suggest that these modifications be tested for other regions and varieties in future studies, since they seem to be genotype and management dependent.

Initial RUE for elite Australian and Brazilian varieties appears to be similar since the default RUE in APSIM-Sugar for plant crops (1.8 g/MJ) accounted for stalk dry mass up to 40 t/ha (150 t/ha on fresh basis) in Brazil. The growth slowdown feature in APSIM-Sugar and our empirical coefficients accounted for stalk dry mass accumulation when it exceeded 40 t/ha. The validation using the dataset of Keating et al. (1999) showed that such coefficients could be employed in different sugarcane regions under high input conditions. Simulation studies involving irrigation, yield gap analysis and climate change in environments where stalk dry mass is likely to exceed 40 t/ha should include the RGP proposed here. APSIM-Sugar and the growth slowdown feature with our empirical coefficients would be an option for doing this until more is known about the RGP.

Acknowledgements

The authors are grateful to Terracal Alimentos e Bioenergia for permission to use their data for this publication. Special thanks also go to the field and laboratory staff Alberto Brandão, Saulo Almeida Costa, Jorge Osório, José Alves and Lucas Dias for their high standard of work.

The first author is thankful to the São Paulo Research Foundation (FAPESP) for the scholarships (grant#2017/24424-5 and grant#2016/11170-2). The fourth author is thankful to Brazilian Research and Development Council (CNPq) for his fellowship (Level 1A). We also would like to express our gratitude to the Co-Editor-in-Chief and to the two anonymous reviewers for helpful comments and suggestions that improved the earlier versions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2019.02.002.

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