University of São Paulo
'Luiz de Queiroz' College of Agriculture

Sugarcane variety trait modelling: evaluating and improving the APSIM-Sugar model for simulating crop performance under current and future climates across Brazil

Henrique Boriolo Dias

Thesis presented to obtain the degree of Doctor in Science.
Area: Agricultural Systems Engineering

Piracicaba
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versão revisada de acordo com a resolução CoPGr 6018 de 2011

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CONTENTS

RESUMO

Modelagem de variedades de cana-de-açúcar: avaliação e melhoria do modelo APSIM-*Sugar* para simular o desempenho da cultura sob condições climáticas atuais e futuras no Brasil

O Brasil é o maior produtor de cana-de-açúcar do mundo e os sistemas de produção no país são bastante complexos, apresentando apreciáveis variações espaciais e temporais de produtividade. Isso é resultado da intensa interação entre genótipo × ambiente × manejo (G × A × M) que afetam o desempenho da cultura. Além disso, prováveis mudanças nas condições climáticas são esperadas no futuro impondo desafios adicionais à produção de cana-de-açúcar. A modelagem de culturas baseada em processos biofísicos é cientificamente aceita como uma maneira de entender essas interações. Nesse contexto, este estudo teve como objetivo integrar conjuntos de dados de experimentos de campo com o modelo APSIM-*Sugar* para melhor entender as interações entre G × A × M em sistemas de produção brasileiros. A capacidade do modelo foi avaliada primeiramente com as configurações padrões e, em seguida, foram propostas modificações e parâmetros para predizer efetivamente as diferenças entre variedades (G). Com o APSIM-*Sugar* aprimorado, foi realizada uma projeção atualizada dos impactos de cenários climáticos futuros na cana-de-açúcar em diferentes regiões brasileiras. O conjunto de dados da cultura foram provenientes de grandes experimentos de campo realizados entre 2012 e 2017 em dois locais no Brasil tropical: Guadalupe, PI, e São Romão, MG, onde diversas variedades foram cultivadas em condições não limitantes (potenciais). Esses dados foram analisados e empregados para caracterizar os parâmetros varietais para uso no APSIM-*Sugar*. Mudanças foram necessárias para permitir que o modelo simulasse o desenvolvimento do dossel e a produtividade adequadamente. Os resultados mostraram que com essas modificações o modelo é capaz, embora ainda empiricamente, de considerar o efeito da idade da cultura no acúmulo de biomassa, processo conhecido como fenômeno de crescimento reduzido, para obter melhores estimações de produtividade em ambientes de alto rendimento, assim como ter a capacidade de distinguir variedades quando se atingem ganhos acima de ~ 150 t/ha (~ 40 t/ha em massa seca). Os resultados sugerem que as modificações e parâmetros propostos no APSIM-*Sugar* são plausíveis e são um passo importante para desvendar as interações G × A × M visando melhorar o desempenho do setor canavieiro. Outra etapa deste estudo, antes de se aplicar o APSIM-*Sugar*, foi avaliar conjuntos de dados climáticos em grade (NASA/POWER e outro desenvolvido no Brasil conhecido como 'XAVIER') como fontes alternativas de dados entrada no modelo. Os resultados indicaram que essas fontes devem ser empregadas com cautela quando o objetivo é simular a produtividade devido à baixa qualidade dos dados de chuva em grade, ao menos no Centro-Sul do Brasil. Por fim, foi realizada uma avaliação do impacto das mudanças climáticas na cultura da cana-de-açúcar por meio do APSIM-*Sugar*, considerando os novos recursos e parâmetros, em 10 localidades brasileiras, sendo seis em cultivo de sequeiro e quatro sob irrigação plena. Cinco modelos climáticos globais foram selecionados para representar classes básicas de mudanças climáticas: relativamente frio/úmido; frio/seco; mediano; quente/úmido; e quente/seco, para quatro cenários futuros. Essas séries climáticas foram usadas como entrada para simulações de sistemas típicos de cultivo. O conjunto de projeções futuras sugere que a produtividade de cana diminuirá em muitos casos para ambos os sistemas (sequeiro e irrigado), todavia, os cenários gerados pelos modelos climáticos apresentaram grande incerteza, o que faz com que essas projeções devam ser interpretadas com cautela.

Palavras-chave: *Saccharum* spp.; Modelagem de culturas agrícolas; Fenômeno de crescimento reduzido; Interceptação de radiação; Biomassa; Mudanças climáticas

ABSTRACT

Sugarcane variety trait modelling: evaluating and improving the APSIM-Sugar model for simulating crop performance under current and future climates across Brazil

Brazil is the largest sugarcane producer in the world and the production systems across the country are very complex with large spatial and temporal variations in yields. This is a result of large Genotype × Environment × Management (G × E × M) interactions that ultimately affect crop performance. Moreover, likely changes in the climate conditions are expected in the future imposing additional challenges to sugarcane production. Process-based crop modelling is scientifically accepted as a way to understand those interactions. Upon that, this thesis aimed to integrate field experiments datasets with the APSIM-Sugar model for better understanding the G × E × M interactions in Brazilian cropping systems. The capability of the model was first evaluated with default settings and then modifications and traits were proposed to effectively predict G (varieties) differences. With APSIM-Sugar upgraded, an up-to-date projection of future climate impacts on sugarcane yields across Brazil was performed. The sugarcane dataset came from large field experiments carried out between 2012 and 2017 at two tropical sites in Brazil: Guadalupe, in the state of Piauí (PI), and São Romão, in the state of Minas Gerais (MG), where several varieties were cultivated under non-limiting (potential) conditions. These data were analysed and employed to characterise variety traits for use in APSIM-Sugar. Substantial changes were required to enable the model to simulate canopy development and stalk yield appropriately. The outcomes from the modelling studies showed that the model is now able, although yet empirically, to account for ageing processes, known as the reduced growth phenomenon, to get better yield predictions in high yielding environments, as well as the ability to distinguish between varieties when it comes to yield gains above ~ 150 t/ha (~ 40 t/ha in dry mass). The findings suggest it is reasonable to hypothesise that the APSIM-Sugar modifications and traits are plausible and are an important step for unravelling G × E × M interactions to improve the performance of the sugarcane industry. Another step of this thesis, before applying APSIM-Sugar, was to evaluate gridded weather datasets (NASA/POWER and other developed for Brazil referred to 'XAVIER') as alternative climate inputs in the model. The results indicated these data sources should be employed with caution when the purpose is to simulate sugarcane yield because of the poor performance of gridded rainfall, at least for Center-South Brazil. Lastly, a climate change impact assessment was performed with APSIM-Sugar considering new features and traits for 10 Brazilian sites, being six under rainfed and four under fully-irrigated conditions. Five global climate models were selected to represent basic classes of climate changes: relatively cool/wet; cool/dry; middle; hot/wet; and hot/dry, for four future scenarios. These climate series were then used as input for simulations of typical cropping systems. The ensemble of future climate-crop model projections suggests that cane yields will mostly decline for both rainfed and fully-irrigated systems, however, the scenarios generated by climate models presented large uncertainty, requiring that these projections should be interpreted with caution.

Keywords: *Saccharum* spp.; Crop modelling; Reduced growth phenomenon; Radiation interception; Biomass; Climate change

1. Introduction

Sugarcane (*Saccharum* spp.), a large and perennial grass recognised as one of the world's most efficient crops in converting solar radiation into biomass, is grown in the tropics and subtropics around the world as a source of sugar, bioenergy (bioethanol and electricity) and others (for example, molasses, alcoholic beverages, and chemicals) (Moore et al., 2014; Sage et al., 2014). The crop is produced by nearly 100 countries and occupies roughly 26 M ha of land (FAO, 2019). The largest producer is Brazil, followed by India, China, and Thailand, which together produce more than two thirds (~ 69%) of the total world's cane (FAO, 2019).

In Brazil, the sugarcane crop is cultivated at about 10 M ha, mainly in the Center-Southern states of the country, where it is grown mainly under rainfed conditions (Fig. 1a; IBGE, 2020). The state of São Paulo has been historically the main sugarcane producer, accounting nowadays for roughly 55% of the cropping area, followed by Goiás, Minas Gerais, Mato Grosso do Sul and Paraná. The Northeast region is also a traditional growing area, in which sugarcane is grown at about 0.87 M ha, especially in the lands near to the coast. The Brazilian average sugarcane yield is about 75 t/ha but varies enormously among states and their subregions (Fig. 1b; IBGE, 2020). Despite that, yields were increasing until 2010, but since then it has been quite stagnated due to economical, crop management and other issues (Marin, 2016).

A wide variety of production systems have evolved across Brazil in response to local environments (climates and soils) as well as the availability of resources and genetic material. Traditional and evolving arrangements between farmers and millers and scales of production also influence the way the sugarcane crop is grown and delivered for processing. The range of genotypes (varieties), planting dates, crop ages, row spacings, irrigation methods, harvest methods, residue management, crop nutrition (especially nitrogen), pest and disease control methods, is very large. Moreover, sugarcane cultivation increased and is expected to increase in new environments where crop performance is likely to be different from the traditional growing regions (see the evolution of cultivation area in Fig. 1a). Consequently, there are large genotype × environment × management (G × E × M) interactions that affect crop growth, development, yield and quality (Inman-Bamber, 2014; Muchow et al., 1997) (see the inter-annual yield variability across Brazilian states as an example in Fig. 1b).

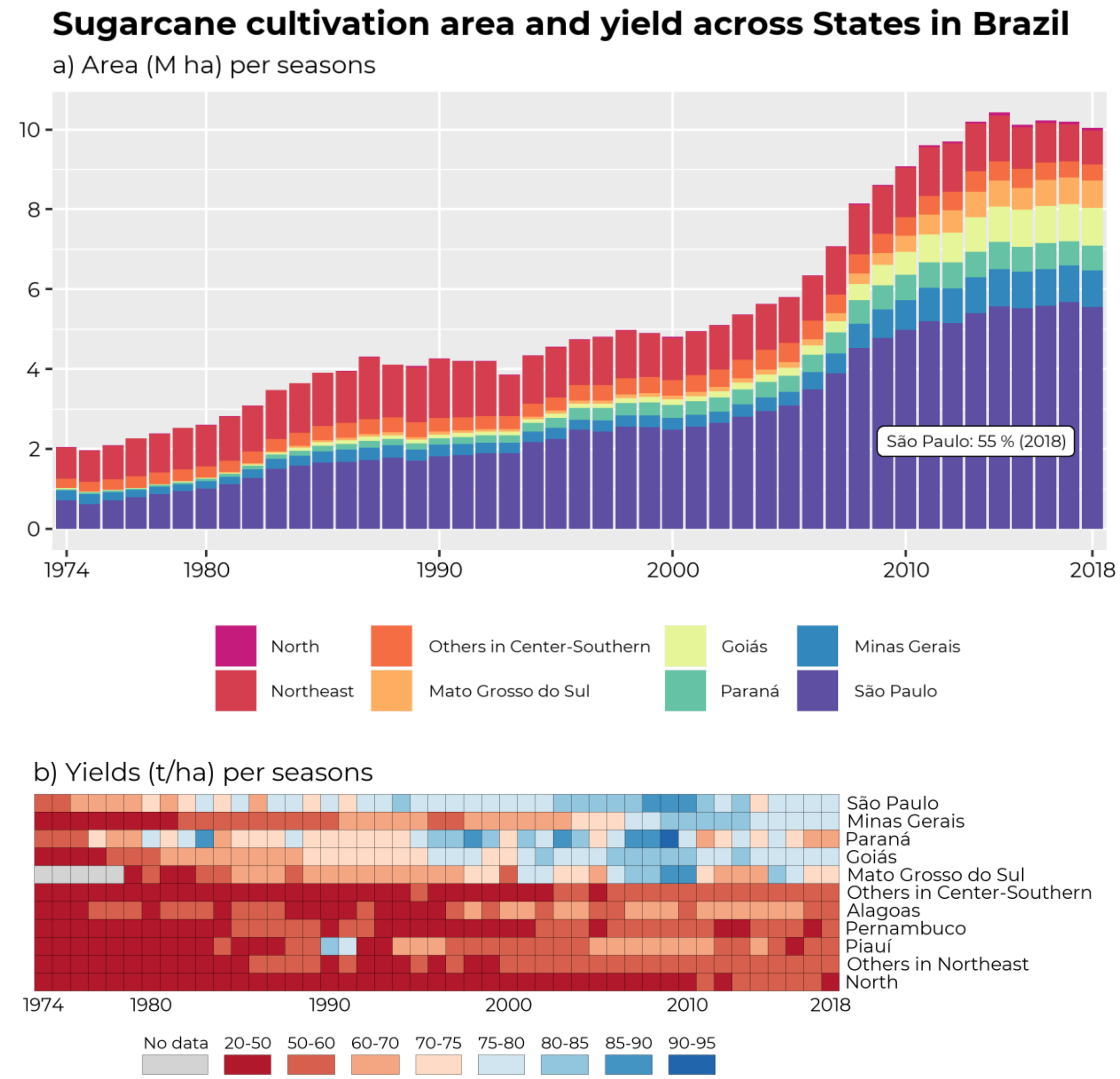

Fig. 1. Average sugarcane production area (a) and yields (b) from 1974 to 2018 across Brazilian states. Source of data: IBGE (2020).

In addition to the inter-annual climate variability, the climate change attributed mainly to anthropic greenhouse gases emissions has been projected by the Intergovernmental Panel on Climate Change (IPCC, 2014). Increments in global temperatures and weather extremes such as heat and cold waves, drought and flooding are likely to be more severe and more often, which will affect agriculture, livestock, forestry, and many other sectors of society and environment (IPCC, 2014). In this context, high-quality historical series of weather data, ground-measured or alternatives such as gridded weather sources, are crucial for reliable model applications such as impact assessments of future climate projections on crop production, as well as for the investigation of mitigation and adaptation strategies in agricultural production systems.

One way to have an overall understanding of the agricultural production systems, in other words, the interactions between G × E × M, is via mechanistic or process-based simulation modelling, in which the crops are important components (Holzworth et al., 2015; Jones et al., 2003; van Ittersum et al., 2003). The crop models embedded in agricultural systems modelling platforms are powerful tools that can be useful for several sectors, such as consulting, farmers, agro-industry, government and policymakers (Boote et al., 1996; Vos et al., 2007; Wallach, 2006). Sugarcane management in countries like Australia and South Africa has been significantly influenced by crop science research, both directly and indirectly, through crop models (Lisson et al., 2005). Comprehensive reviews and comparisons of the main crop models dedicated to, or adapted for, sugarcane can be found in Lisson et al. (2005), Singels (2014) and Dias and Inman-Bamber (2020). Among those currently dedicated to sugarcane, the South African CANEGRO model (Inman-Bamber, 1991; Jones and Singels, 2019; Singels et al., 2008) and the 'Sugar' module (Keating et al., 1999) in the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM-Sugar) (Holzworth et al., 2015) developed in Australia, are the most widely used around the world since when they were launched (Dias and Inman-Bamber, 2020). Sugarcane models have gained attention for research purposes since the last decade in Brazil (Dias and Inman-Bamber, 2020), but before their use and application, it is conceivable to evaluate them and be aware of their weakness and limitations though.

Historically, sugarcane models were developed based on existing knowledge of crop physiology. It soon became evident that the knowledge available to account for observations of crop growth, development, and yield, was incomplete and this led to an iterative process between field research and model building (Lisson et al., 2005) (see the timeline in Fig. 2 for the APSIM-Sugar model main events). Among the model's weakness, some were acknowledged such as crop ageing processes, sucrose accumulation, water relations (stress physiology and the interactions between various drought resistance mechanisms and water retention in stalks), root dynamics and its role in crop yield-building processes, nutrients, flowering, CO_2 and heat stress effects (Dias and Inman-Bamber, 2020; Inman-Bamber et al., 2012; Lisson et al., 2005; O'Leary, 2000; Singels, 2014). Some of those listed weakness such as water relations (Inman-Bamber et al., 2016; Jones and Singels, 2019), sucrose accumulation (Singels and Bezuidenhout, 2002; Singels and Inman-Bamber, 2011), and temperature (Jones and Singels, 2019) and CO_2 (Singels et al., 2014; Stokes et al., 2016) interactions were well or partially addressed in the past 15 years.

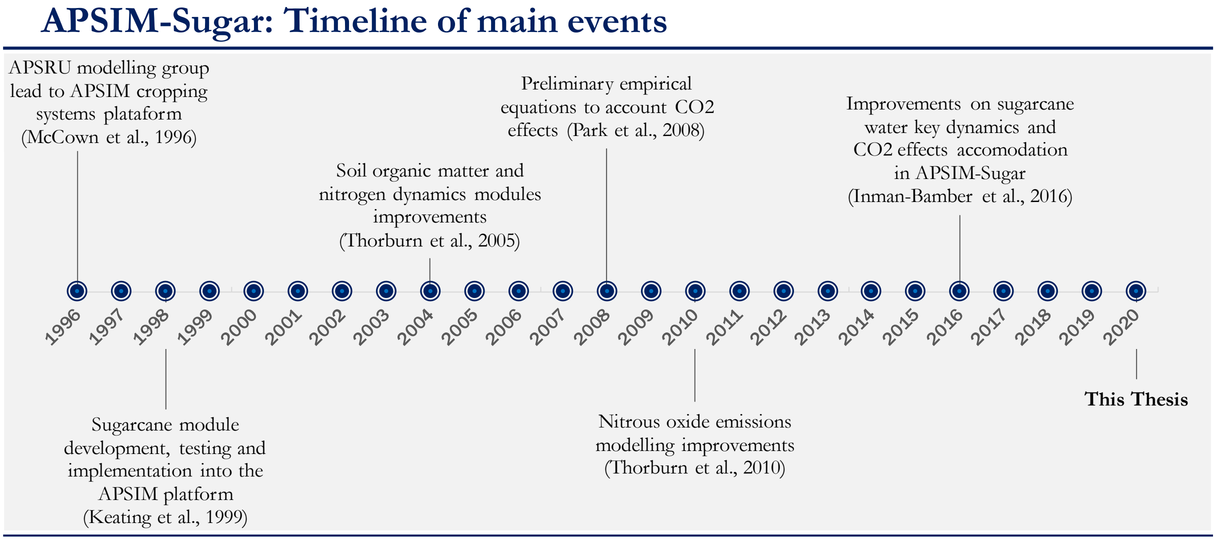

Fig. 2. Timeline of main events of the APSIM-Sugar model concerning modelling aspects. Adapted from Dias and Inman-Bamber (2020).

A particular topic of interest in sugarcane modelling is the reduced growth phenomenon (RGP), related to the crop ageing process (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 when crops are large; however, its exact cause is still unknown (Park et al., 2005; van Heerden et al., 2010). Moreover, RGP seems to be influenced partially by variety, which could explain differences in yields at least to some extent (Donaldson, 2009; Tejera et al., 2007) and, therefore, needs further investigation. Overestimations in cane yield are likely to occur if the RGP is not taken into account, which would likely envisage simulations results in sugarcane models' applications.

Application of crop models in breeding programs is likely to be one of the main avenues in sugarcane modelling from now on (Singels, 2014), however, the modellers have rarely looked at distinguishing varieties in the past though (Inman-Bamber et al., 2016). According to Inman-Bamber et al. (2016) characterising cane varieties is more challenging because it is more difficult to model vegetative growth in comparison to crops with reproductive processes, which are more predictable from climatic variables like temperature and photoperiod. Modelling G × E with CANEGRO were explored by Singels et al. (2010) by linking traits with quantitative trait loci (QTLs) data, and by Hoffman et al. (2018) by estimating traits from infrared gas analyser (IRGA) and leaf porometer measurements, and they found promising results for sugarcane breeding in South Africa. Inman-Bamber et al. (2016) enhanced the APSIM-Sugar model by accommodating key physiological mechanisms concerning traits affecting transpiration efficiency (TE) and water uptake by roots, but the model is yet to be tested for trait selection in commercially relevant genetic populations, in the context of Australian breeding. Indeed, Sexton et al. (2016) stated that most of the 14 genotypes in the APSIM-Sugar library are no longer commercially grown, which is also the case of the Brazilian context once varieties are continuously released and still need an extensive trait characterisation for modelling purposes.

Based on the rationale set out above, this thesis brings new field datasets and integrates them with process-based modelling towards a better understanding of G (varieties and harvesting age), E (especially in tropical regions), and to a lesser extent M (planting dates and row spacing), and their interactions for Brazilian cropping systems. Furthermore, it provides an up-to-date projection of future climate impacts on the crop at selected sites where the crop is, or is expected to be, important for sugarcane production. In this context, it was first hypothesised that the well-known APSIM-Sugar model would be capable of predicting crop performance and variety differences in high-yielding Brazilian environments. Secondly, before applying the model, gridded weather databases were evaluated in which it was hypothesised that they would provide reliable simulation results when compared to a carefully selected series of measured weather data. Lastly, this study had as a third hypothesis that the upgraded APSIM-Sugar model would be able to provide an updated climate change impact assessment across important sugarcane producing sites across Brazil.

1.1. Objectives

Based on the hypotheses previously presented, this study had as an overall objective to integrate field experiments datasets with the APSIM-Sugar model to better understand the G × E × M interactions in Brazilian cropping systems and to apply this model, after proper evaluation, for assessing the impacts of current and future climate scenarios on crop performance across the growing regions. The overall objective, in turn, can be subdivided into the following specific objectives:

I) to assess the sugarcane crop performance grown under non-limiting (potential) conditions in Guadalupe, PI, and evaluate the ability of APSIM-Sugar to predict it with a new feature to account for RGP;

II) to assess the canopy development and light interception by 27 sugarcane varieties grown at two Brazilian tropical sites (São Romão, MG, and Guadalupe, PI) under potential conditions and test the capability of APSIM-Sugar to distinguish them;

III) to assess the yield accumulation by nine sugarcane varieties grown at two Brazilian tropical sites (São Romão, MG, and Guadalupe, PI) under potential conditions and test the capability of APSIM-Sugar to distinguish them using variety-specific growth slowdown factors applied to RUE proposed in Objective I with traits from Objective 2;

IV) to evaluate the quality of gridded weather data from two different sources (NASA and XAVIER) and their impact on sugarcane crop performance when simulated by APSIM-Sugar at traditional sugarcane producing sites in Center-South Brazil, and;

V) to project sugarcane crop performance under likely changing climates in the main Brazilian producing regions with new features and traits for the most cultivated variety (RB867515).

Thesis Overview

A flow diagram of the studies developed to test the hypotheses of this study is presented in Fig. 3, which provides an overview of all chapters of the present thesis.

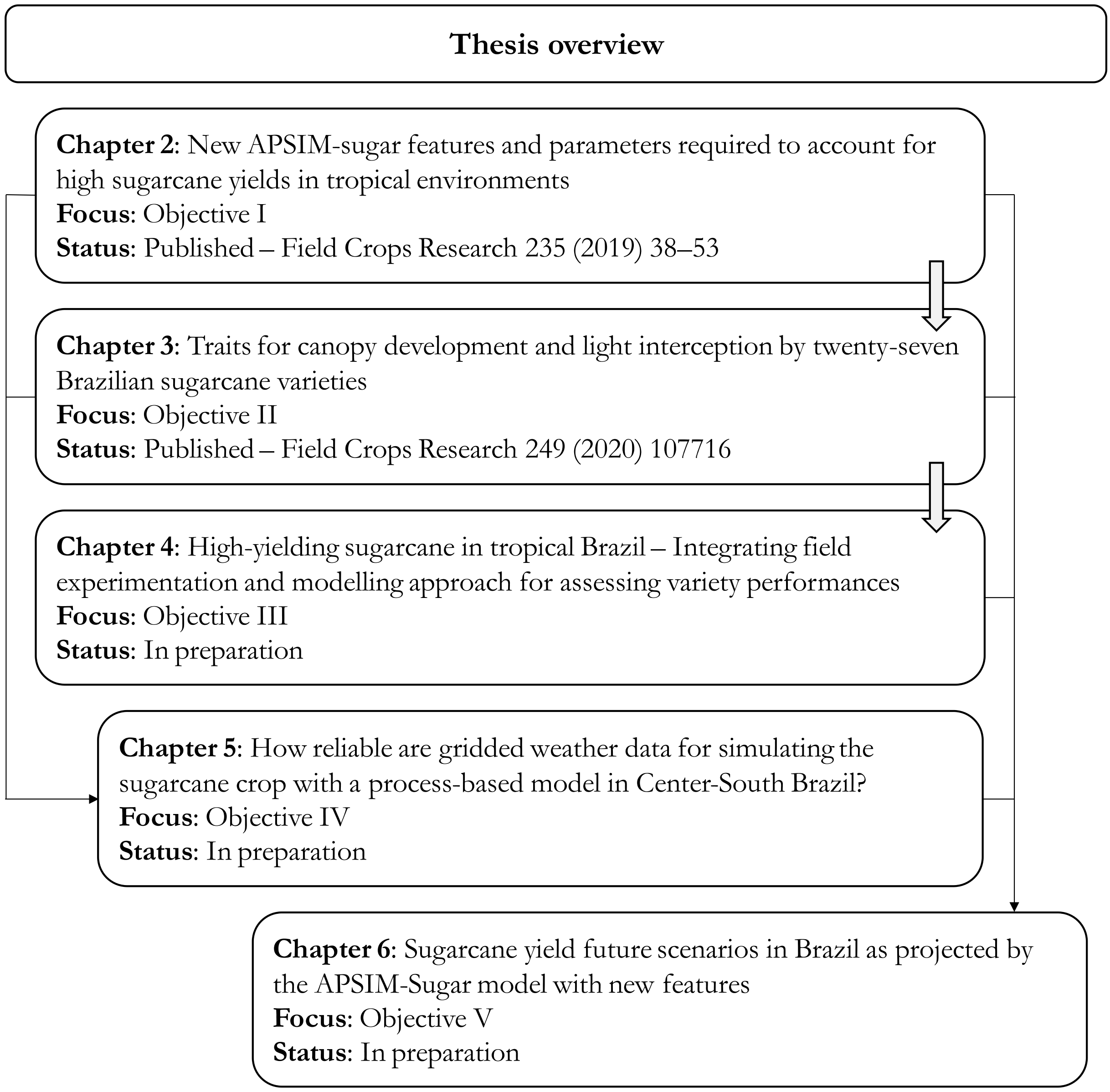

Fig. 3. Flow diagram of thesis' chapters.

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

Abstract

Sugarcane in field plot experiments in tropical Brazil (Guadalupe, Piauí State, 6.8°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 seven/eight 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.

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

2.1. Introduction

The traditional sugarcane industry in Brazil is based largely in the southern region (>19 ºS) and in the coastal area of Northeast region (6-10 ºS), mainly in the states of Alagoas, Paraíba and Pernambuco. Considerable expansion occurred in the mid 2000's mainly in Midwest (~15 ºS to 18 ºS), 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 program 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).

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Since land demand for sugarcane production in Brazil is expected to increase with 'RenovaBio', in-land tropical areas towards equator (~14 º to 2 ºS) 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 ºS), 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 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, 2019; 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, 2019; 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 favorable 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.

2.2. Material and methods

2.2.1. Field experiments

Six field experiments were carried out at the Agro-Industrial Complex of Terracal Company, in Guadalupe, state of Piauí, Brazil (6.8 ºS, 43.6 ºW, 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 2.2.1.1 and the experiments for in-site validation are described in Section 2.2.1.2. The weather conditions during the experiments are presented in Section 2.2.1.3.

2.2.1.1. 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 to 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 hours. 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 ºC d had accumulated, obtained by interpolation using the nearest measurements to this thermal time (TT), considering a base temperature of 9 ºC.

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.

2.2.1.2. Variety experiments for model validation

The modifications performed in the 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.

2.2.1.3. 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 ºC and were mostly greater than 30 ºC (Fig. 1a). Day-to-day variation in minimum temperature (Tmin) was also small (~5 ºC) 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 autumnal equinoxes (the site is 6.6 ºS) (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.

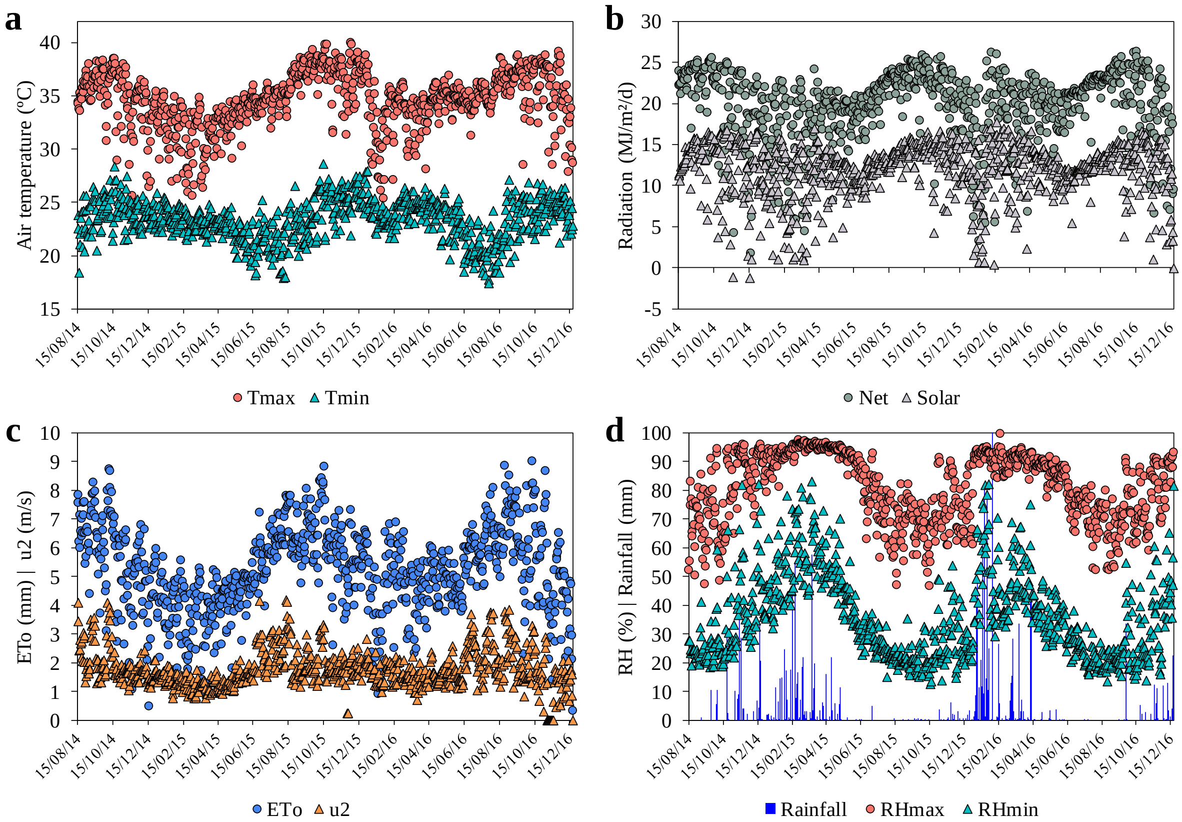

Fig. 1. Weather conditions during sugarcane field experiments, from August 2014 to December 2016. Maximum (Tmax) and minimum (Tmin) air temperatures (a), solar and net radiation (b), wind speed (u2) and reference evapotranspiration (ETo) (c) and, maximum (RHmax) and minimum (RHmin) relative humidity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

A climatic comparison between Guadalupe and two areas where sugarcane is grown in Brazil, a traditional sub-tropical (Piracicaba, São Paulo State, 22.7 ºS, 47.6 ºW and 546 m asml) and a semi-arid (Petrolina, Pernambuco State, 9.4 ºS, 40.5 ºW and 370 m asml), was performed. In addition, Ayr (Queensland Province, Australia, 19.6 ºS, 147.4 ºE 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 to 2016). Data from Floriano city (6.7 °S, 43.0 ºW 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 'Luiz de Queiroz' College of Agriculture (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).

2.2.2. 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.

2.2.2.1. Canopy and light interception

Canopy development is regulated by TT with a single base temperature (Tb = 9 ºC) 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/ºC d (*shoot_rate*), after a TT lag (*shoot_lag*) of 250 ºC d for plant crops and 100 ºC 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 (*extinction_coef,* referred as *k* hereafter) is set as 0.38 according to Muchow et al. (1994). Light competition is simulated to induce senescence once SRAD interception reaches 85%.

2.2.2.2. 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 to 1900 ºC 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.

2.2.2.3. 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, 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.

2.2.3. 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 soil 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.

2.2.3.1. 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 ºC d because the accumulated degree days at Guadalupe exceeded the default setting of 6000 ºC 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 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 light extinction coefficient increases with reduced row spacing (Flénet 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 to 18.1 ºC, much higher than the Tb adopted in APSIM-Sugar (9 ºC) and CANEGRO (10 ºC). The new version of CANEGRO now considers 16 ºC as Tb for this process (Jones and Singels, 2019). 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 ºC d; and iii) initial total plant leaf area (*initial_tpla*): 1,000, 1,250, 1,500, 1,750 and 2,000 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 ºC 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 to 302 ºC d over the range of *shoot_lag* values (50 and 250 ºC 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 16º C rather than 9º C (Inman-Bamber, 1994; Abraham 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 ºC d for the *shoot_lag* of 100 ºC 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.

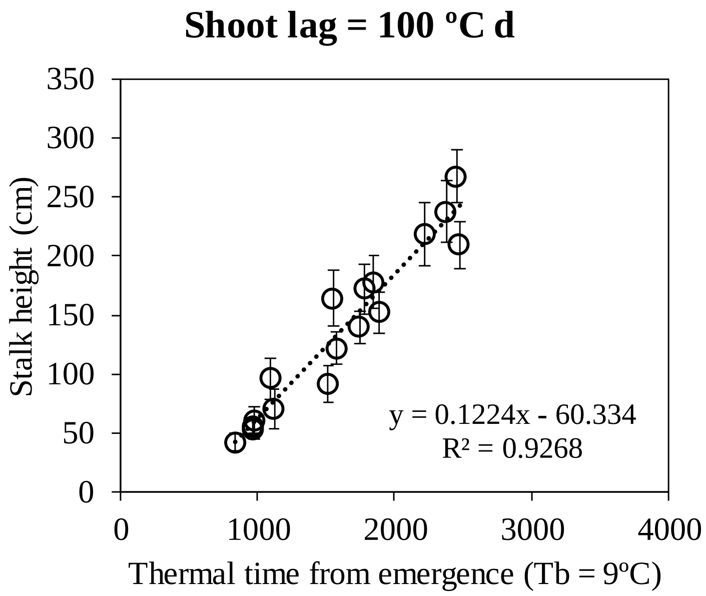

Fig. 2. Relationship between stalk height and thermal time from emergence using a *shoot_lag* coefficient of 100 ºC (base temperature of 9º C). The variety measurements were pooled.

2.2.3.2. 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:

$$y\_rue\_leaf\_no\_fact = 1 - A * \exp\ [-\exp\ (B - C * leaf\_no)] \quad (1)$$

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 equation 1: i) A: 0.40, 0.45, 0.50, 0.55 and 0.60; ii) B: 6, 7, 8, 9 and 10; 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.

2.2.3.3. 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 to 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:

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

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.

2.2.4. 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 ºS (tropical climate) to 29.5 ºS (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.

2.2.5. 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* environment (R CORE TEAM, 2018).

2.3. Results

2.3.1. Sugarcane performance in Guadalupe, PI, tropical Brazil

2.3.1.1. 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.

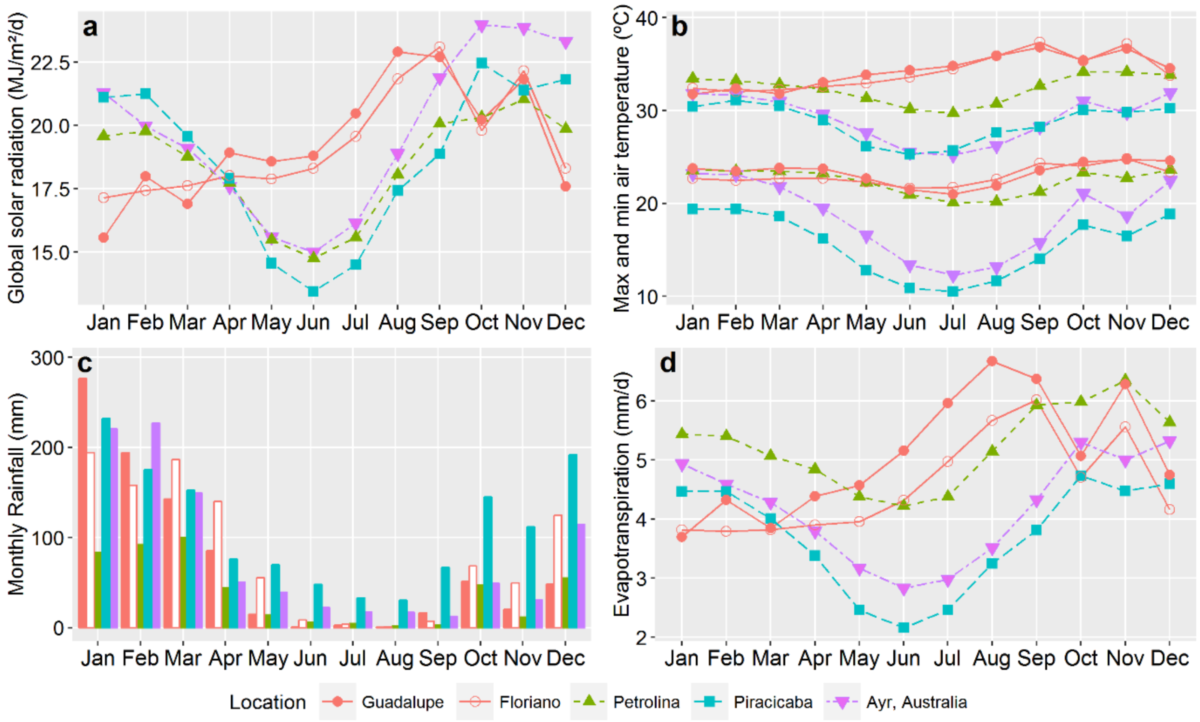

Fig. 3. Comparison between climatic conditions for Guadalupe, Floriano, Petrolina, Piracicaba (Brazil), and Ayr (Australia): monthly mean daily solar radiation (a), average minimum and maximum air temperature (b), monthly mean total rainfall (d) and monthly mean daily reference evapotranspiration (d).

2.3.1.2. ANOVA of PARi and yields

The ANOVA of PARi performed using data at TT = 1500 ºC d (Tb = 9 ºC) 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.

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 ºC d	DAP to reach PARi of 0.70	Planting date	PARi at 1500 ºC 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

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 ($p<0.001$).

Table 2

Analysis of variance based on a split-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%)

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			8.0 (p<0.001)				

[a] least significant difference

[b] *p-value* (5%)

2.3.2. 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.

2.3.2.1. 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, Fig. 5b). The TT for sprouting (*shoot_lag*) after planting was reduced from 250 to 100 ºC d for plant cane (Fig. 5c, Fig. 5d). It seems that TT change was plausible, since the minimum air temperature measured in the 30 days after planting was 18.7 ºC considering all planting dates for Guadalupe. The initial total plant leaf area was increased from 10 to 20 cm^2 (Fig. 5e, Fig. 5f).

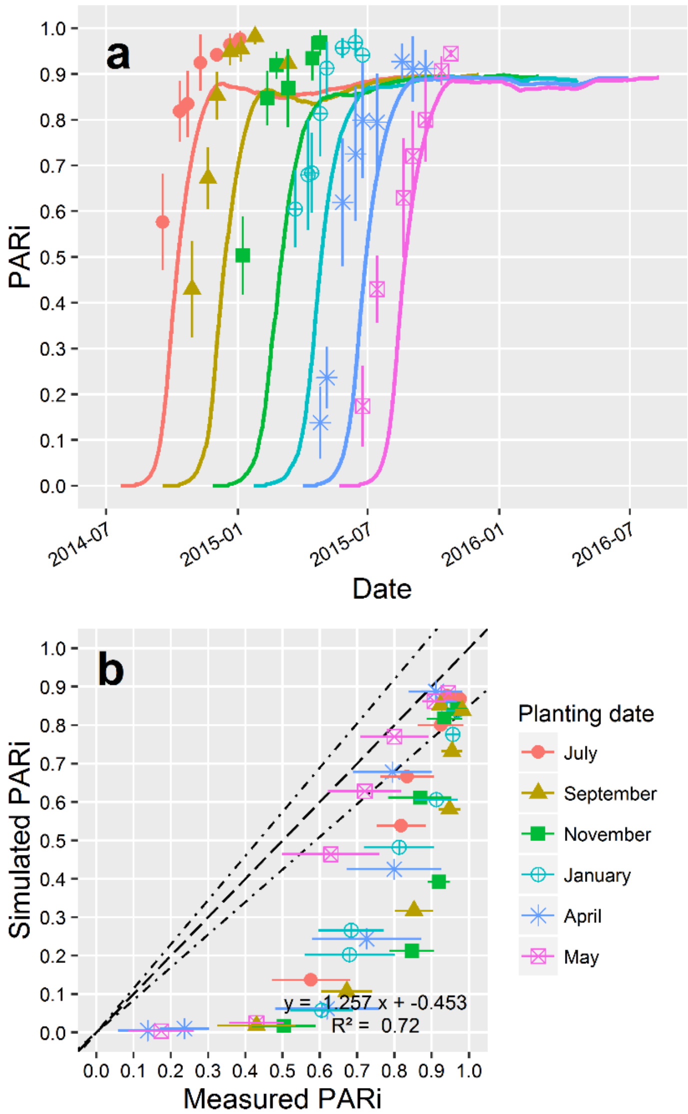

Fig. 4. Fractional photosynthetically active radiation interception (PARi) measured (points plus bars) and simulated (lines) by the APSIM-Sugar model using default settings of Q117 Australian sugarcane variety for the Brazilian varieties in different planting dates under high input conditions in tropical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

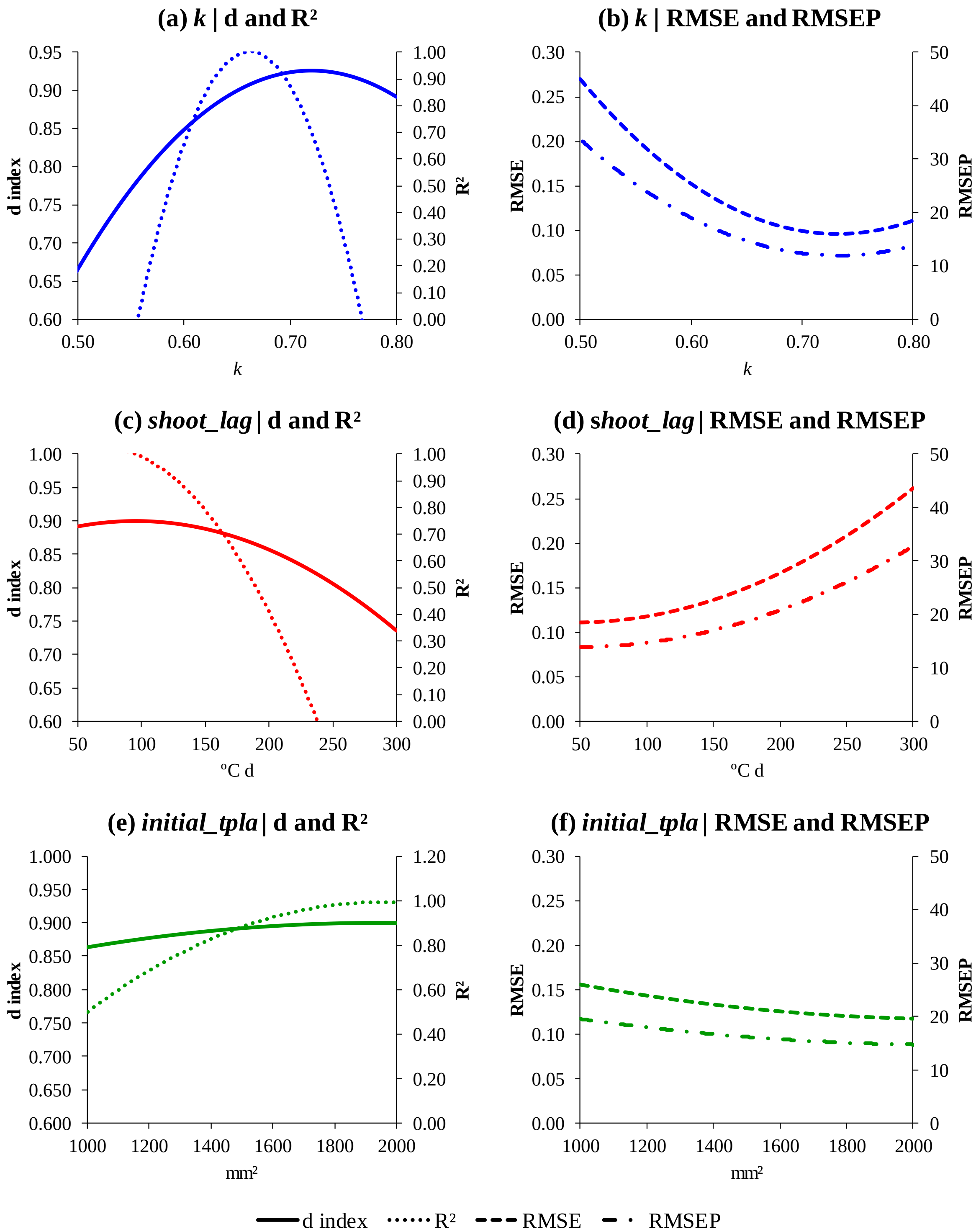

Fig. 5. Optimisation of *k* (a, b), *shoot_lag* (c, d) and *initial_tpla* (e, f) parameters in APSIM-Sugar for simulating sugarcane fractional photosynthetically active radiation interception, based on *d*, R^2 (a, c, e), RMSE and RMSEP (b, d, f) indices.

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 agreement, measured by *d*, reached 0.95, much higher than the prior 0.74. The RMSE was markedly reduced from 39%, for the default 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.

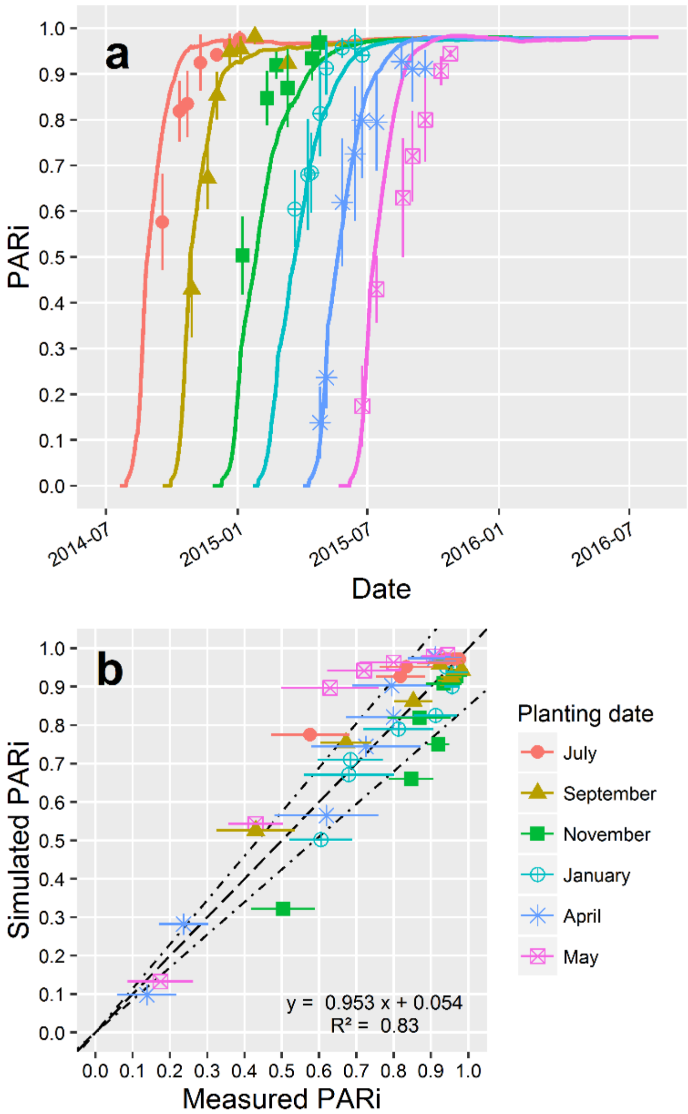

Fig. 6. Fractional photosynthetically active radiation interception (PARi) measured (points plus bars) and simulated (lines) by the APSIM-Sugar model after canopy parameters calibration for Brazilian sugarcane varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter 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

2.3.2.2. 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.

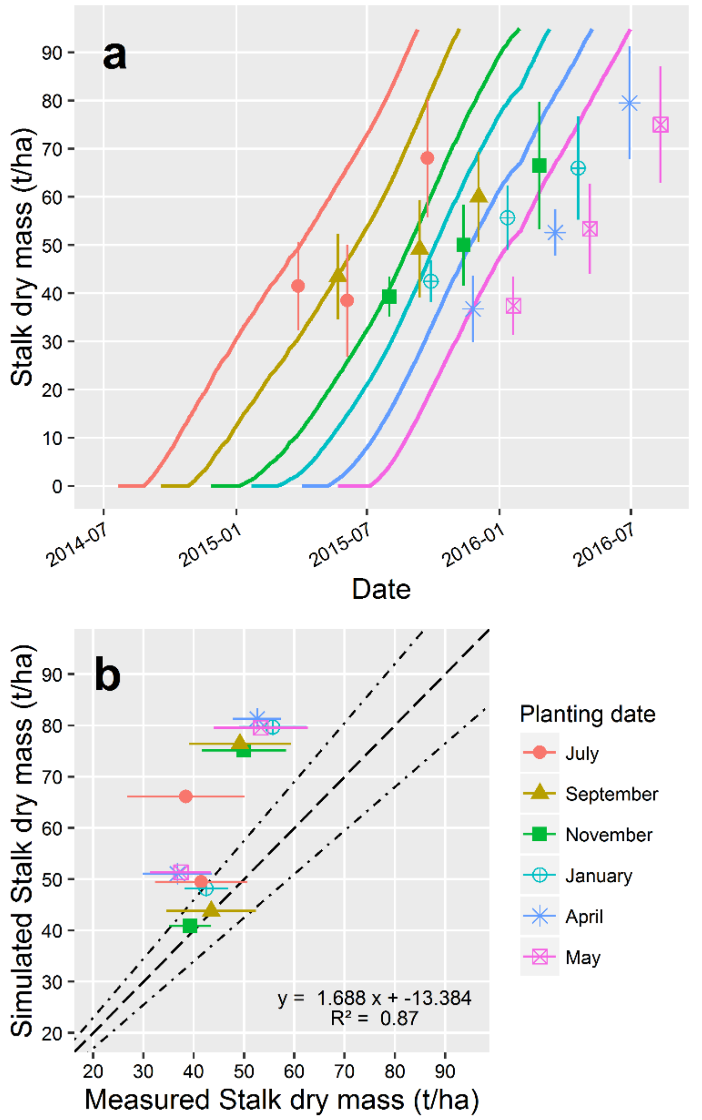

Fig. 7. Stalk dry mass measured (points plus bars) and simulated (lines) by the APSIM-Sugar model after canopy calibration for Brazilian sugarcane varieties in different planting dates under high input conditions in tropical Brazil (a). Scatter plot of simulated and measured values (b), where 1:1 line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

In order to account the RGP observed at Guadalupe experiment, we only used one option for reducing growth rate after seven/eight 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%.

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

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 ºC d (ranging from 3660 to 4350 ºC 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 to 0.82) with the calibration of such parameter, however the agreement (*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).

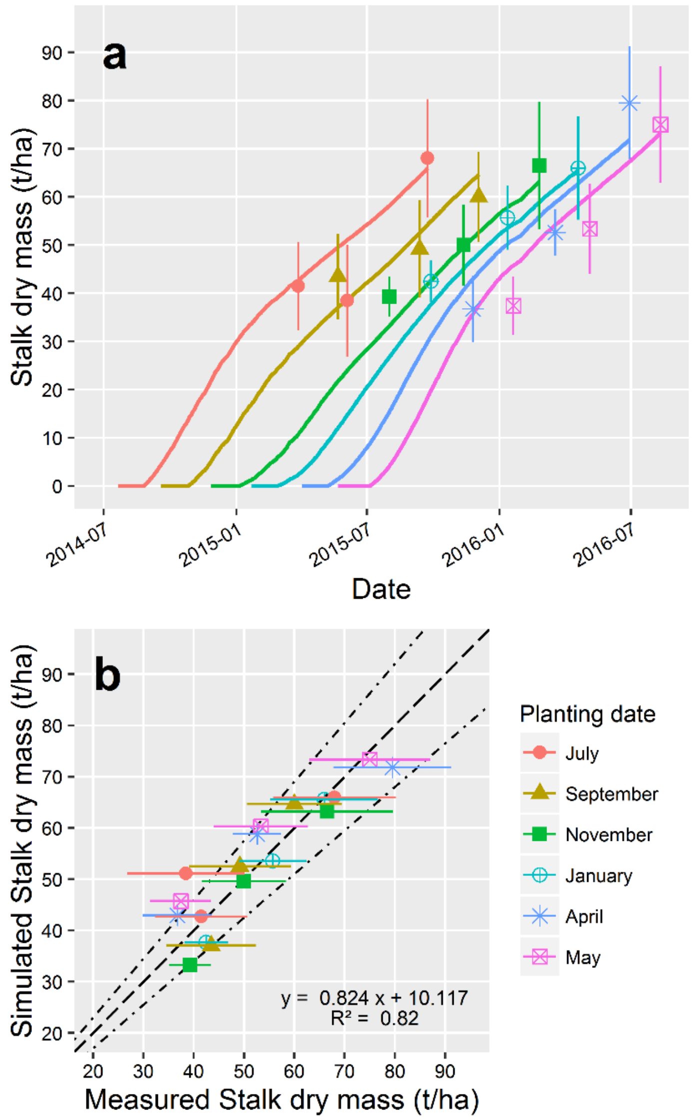

Fig. 8. Stalk dry mass measured (points plus bars) and simulated (lines) by the APSIM-Sugar model after canopy parameters calibration and introduction of growth slowdown feature to account for the reduced growth phenomenon for Brazilian sugarcane varieties in different planting dates under high input 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.

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

2.3.2.3. 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.

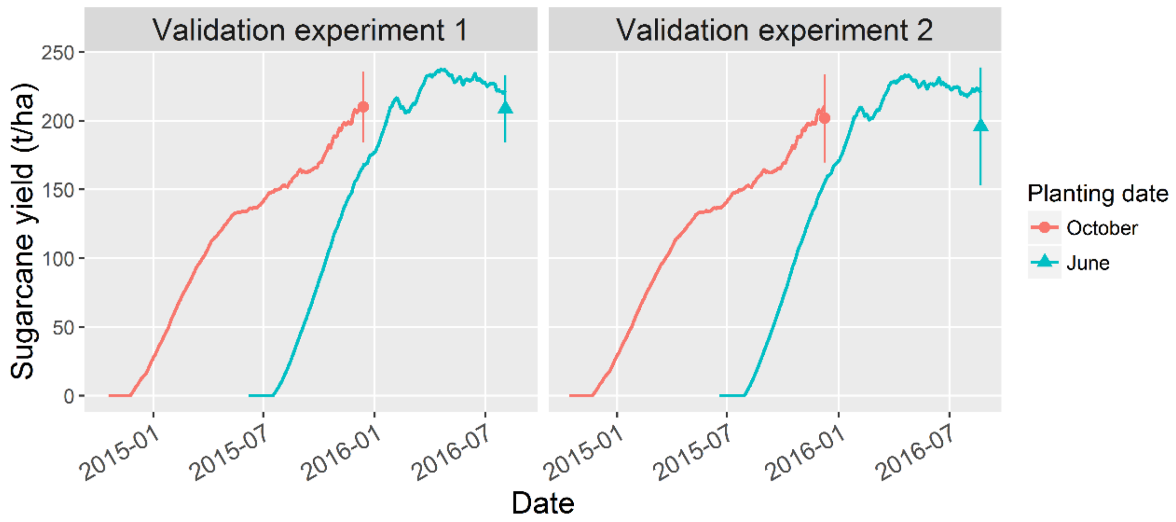

Fig. 9. Sugarcane yield measured (points plus bars) and simulated (lines) by the APSIM-Sugar model during validation with independent data under high input conditions in tropical Brazil.

2.3.2.4. 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 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).

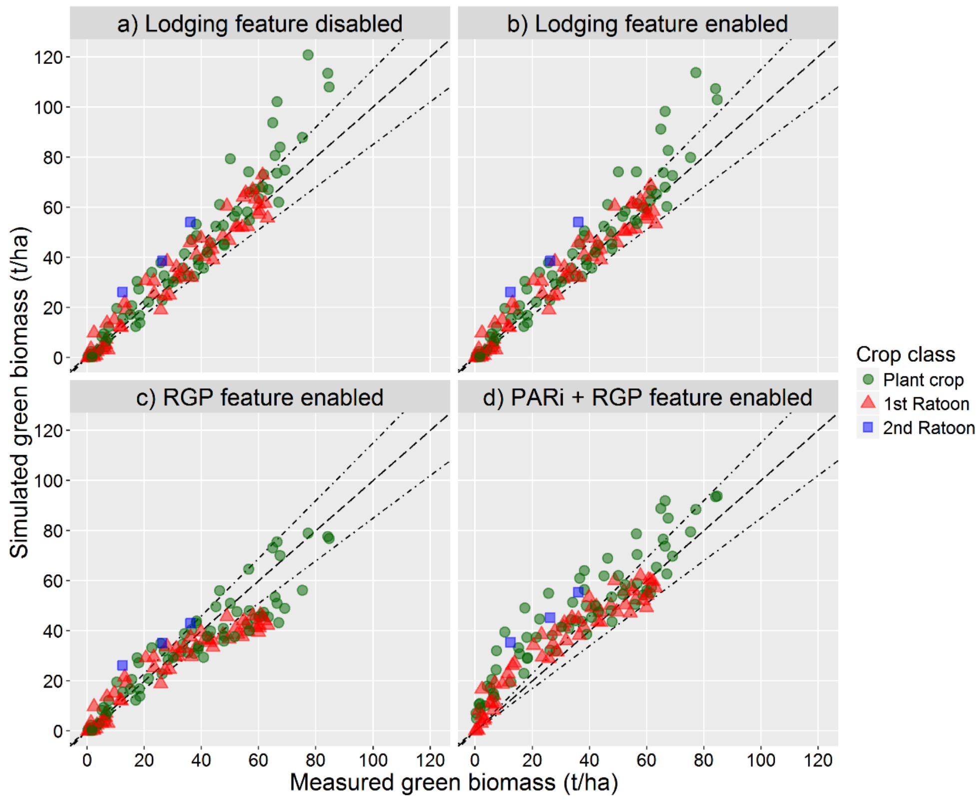

Fig. 10. Scatter plot of measured and simulated green biomass by APSIM-Sugar using Keating et al. (1999) dataset differentiated by crop class. (a) Lodging rules disabled; (b) Lodging rules enabled; (c) Growth slowdown feature to account for the reduced growth phenomenon (RGP) enabled; (d) Modifications 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

2.4. 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 ºS) (Inman-Bamber, 1994). For simulating cane growth, an additional TT of 250 ºC 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 ºC (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 ºS) 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 hot environments in Brazil (semi-arid and tropical, respectively).

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 21ºC 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 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, althouth recognising that it is difficult to measure in field experiments. 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 ºC d while a value of 250 ºC d appears in the default parameters of the APSIM-Sugar software. Brazilian varieties required a 60% reduction in TT, from 250 ºC d to 100 ºC 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 ºC for South African varieties, which is nearly twice the value (9 ºC) assumed for all expansive processes (cell division and expansion) in APSIM-Sugar (Keating et al., 1999). While Tb can be changed in the 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, 2019; 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 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) 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.

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, agreement 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 2.2.2.3), 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 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, 2019) 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 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, 2001; 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.

2.5. 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 seven/eight months and at about 4000 degree-days (Tb of 9 ºC).

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.

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Supplementary material

Table S1

Soil types and their main characteristics used in the simulations.

Soil layer (cm)	Horizon -	OM [a] %	pH_{H2O} [b] -	Clay	Silt	Sand	BD [c] (g/cm)	θ_{LL} [d]	θ_{DUL} [e]	θ_s [f]	K_L [g] per d^{-1}
				-------- (%) ---------				------ (cm^3/cm^{-3}) ------			
G × E × M experiment (calibration) and validation experiment 2: *Latossolo Amarelo distrófico* [h]											
0-10	A	0.69	4.9	24	5	70	1.71	0.14	0.29	0.42	0.15
10-30	BA	0.63	5.0	28	7	65	1.63	0.16	0.32	0.47	0.12
30-50	Bw	0.59	5.1	31	8	62	1.51	0.17	0.32	0.47	0.08
50-200	Bw	0.00	5.1	31	8	62	1.51	0.17	0.32	0.47	0.05
Validation experiment 1: *Neossolo Quartzarênico* [i]											
0-10	AP	1.80	5.0	10.4	5.3	84.3	1.62	0.07	0.16	0.44	0.15
10-30	CA	0.64	5.0	14.7	4.3	80.9	1.68	0.10	0.21	0.39	0.12
30-50	C1	0.53	5.0	17.4	5.0	77.6	1.66	0.11	0.23	0.37	0.08
50-200	C2	0.00	5.0	17.4	5.0	77.6	1.66	0.11	0.23	0.37	0.05

[a] Soil organic matter
[b] Actual values not used in the simulations to avoid nitrogen stress in the crop
[c] Soil bulk density
[d] Lower limit (-1500 kPa)
[e] Drained upper limit (-10 kPa)
[f] Saturated water content
[g] Root extraction constant
[h] Ferralsol in FAO classification system
[i] Arenosol in FAO classification system

Table S2

Crop management applied in the G × E × M experiment prior each planting month for model calibration.

Management	Planting month					
	July	September	November	January	April	May
Ploughing	18/06/2014	14/08/2014	20/10/2014	10/12/2014	26/11/2014	04/04/2015
Soil correction (2.8 t lime/ha)	19/06/2014	17/08/2014	22/10/2014	15/12/2014	30/11/2014	06/04/2014
Culm pieces harvesting	18/07/2014	15/09/2014	24/11/2015	19/01/2015	28/03/2015	19/05/2015
Fungicide Treatment (PrioriXtra®)	20/07/2014	16/09/2014	25/11/2015	21/01/2015	30/03/2015	21/05/2015
Ratoon stunting disease treatment [a]	20/07/2014	16/09/2014	25/11/2015	21/01/2015	30/03/2015	21/05/2015
'Seed' bed preparation	20/07/2014	16/09/2014	25/11/2015	21/01/2015	30/03/2015	21/05/2015
Initial fertiliser application in planting furrow [b]	20/07/2014	16/09/2014	25/11/5014	21/01/2015	30/03/2015	21/05/2015
Planting (~12 t/ha)	21/07/2014	17/09/2014	26/11/2014	22/01/2015	01/04/2015	22/05/2015

[a] Culm pieces for nursery heat treated (50 ºC for 2 hours)
[b] Nitrogen, phosphorus and potassium at 323, 100 and 345 kg/ha, respectively

Table S3

Crop management applied in the experiments prior planting for model validation. The same varieties used in the G × E × M experiment are marked in **bold**.

Management	Varieties			
	Experiment 1 RB845210, **RB867515**, **RB92579**, **RB931003**, RB947532, RB99395, RB012046, SP81-3250, **SP94-3206**, CTC2, IAC87-3396, VAT90212		Experiment 2 RB835486, RB855156, RB863129, RB931011, RB951541, RB957508, **RB961003**, RB966928, **RB98710**, RB012090, SP80-1816, IAC95-5000	
Ploughing	06/09/2014	27/04/2015	07/09/2014	28/04/2015
Soil correction (t lime/ha)	10/09/2014 (2.5)	05/04/2015 (2.7)	11/09/2014 (2.6)	06/05/2015 (2.4)
Culm pieces harvesting	14/10/2014	10/06/2015	13/10/2014	17/06/2015
Fungicide Treatment (PrioriXtra®)	15/10/2014	11/06/2015	14/10/2014	18/06/2015
Ratoon stunting disease treatment [a]	15/10/2014	11/06/2015	14/10/2014	18/06/2015
'Seed' bed preparation	15/10/2014	11/06/2015	14/10/2014	18/06/2015
Initial fertiliser application in planting furrow [b]	16/10/2014	12/06/2015	15/10/2014	19/06/2015
Planting (~12 t/ha)	16/10/2014	12/06/2015	15/10/2014	19/06/2015

[a] Culm pieces for nursery heat treated (50 ºC for 2 hours)
[b] Nitrogen, phosphorus and potassium at 323, 100 and 345 kg/ha, respectively

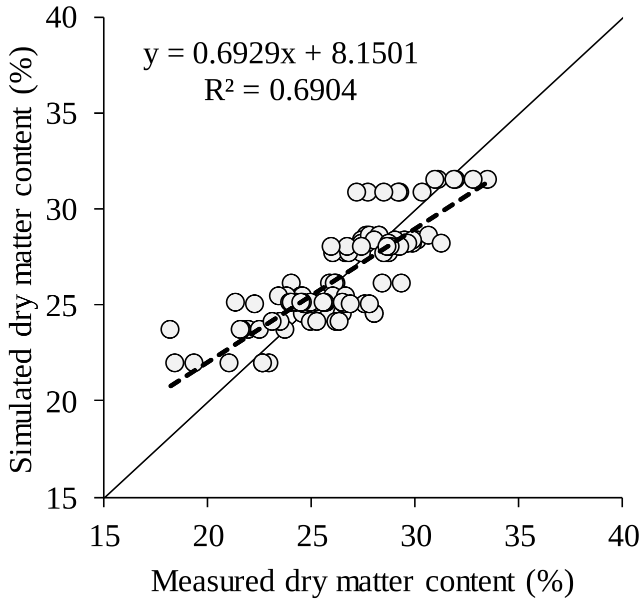

Fig. S1. Scatter plot of measured and simulated sugarcane dry matter content based on cumulated thermal time from planting and daily air temperature amplitude averaged over 20 days before sampling.

Table S4

Sub-set of experiments numbered as in Keating et al. (1999) that were used to test the new APSIM-Sugar slowdown feature to account the reduced growth phenomenon. The measurements included just green biomass (dry stalk + dry cabbage).

Dataset	Site	Latitude	Variety	Crop class	Treatment	Irrigation (mm)	n
1	Harwood, NSW, Australia	29.5 °S	Q117	Plant	None	1275	16
2	Ingham, QLD, Australia	18.4 °S	Q117	Plant	None	698	11
3	Ingham, QLD, Australia	18.4 °S	Q117	1st ratoon	None	662	11
5	Ayr, QLD, Australia	19.5 °S	Q96	Plant	None	3400	10
6	Ayr, QLD, Australia	19.5 °S	Q117	1st ratoon	None	4913	13
7	Pongola, KZN, S. Africa	27.5 °S	N14	Plant	None	725	5
8	Bundaberg, QLD, Australia	24.5 °S	CP51-21	1st ratoon	340 kg N/ha	479	7
8	Bundaberg, QLD, Australia	24.5 °S	CP51-21	2nd ratoon	170 kg N/ha	201	3
9	Bambaroo, QLD, Australia	18.4 °S	Q124	Plant	Fully irrigated	481	4
11	Grafton, NSW, Australia	29.5 °S	Q117	Plant	None	291	8
12	Pongola, KZN, S. Africa	27.5 °S	N14	1st ratoon	None	720	5
14	Ayr, QLD, Australia	19.5 °S	Q117	Plant	None	5496	11
14	Ayr, QLD, Australia	19.5 °S	Q117	1st ratoon	None	4333	12
15	Ingham, QLD, Australia	18.4 °S	Q117	Plant	None	788	4
16	Ingham, QLD, Australia	18.4 °S	Q117	Plant	268 kg N/ha	698	1
16	Ingham, QLD, Australia	18.4 °S	Q117	1st ratoon	774 kg N/ha	860	10

Table S5

Comparison between annual climatic conditions for Guadalupe (2015 only), Floriano, Petrolina, Piracicaba (Brazil), and Ayr (Australia).

Site	Coordinates and elevation	Period	Thermal time [a] (°C d/year)	ETo [b] (mm/year)	Rainfall (mm/year)
Guadalupe, PI	6.8 °S, 43.6 °W, and 170 m asml	2015	7224.6	1866.6	564.6
Floriano, PI	6.7 °S, 43.0 °W and 126 m asml	1994-2013	7141.1	1666.5	995.8
Petrolina, PE	9.4 °S, 40.5 °W and 370 m asml	1994-2013	6704.5	1910.8	460.7
Piracicaba, SP	22.7 °S, 47.6 °W and 546 m asml	1980-2016	4783.7	1346.6	1330.9
Ayr, QLD	19.6 °S, 147.4 °E and 17 asml	1980-2016	5323.6	1504.7	943.5

[a] Daily basis using 9 °C as base temperature;
[b] Reference evapotranspiration

Table S6

List of changes in Sugar.xml after model calibration and validation.

Parameters or coefficients	APSIM term	Q117 (default)	Brazilian genotype (6 varieties pooled)
Light extinction coefficient	*extinction_coef*	0.38	0.65
Thermal time from planting to sprouting	*shoot_lag*	250	100
Initial total plant leaf area	*initial_tpla*	1000	2000
Area of specific leaves	*leaf_size*	1500 55000 55000	5800 20000 36000 46000 51000 51400 50700 49300 43500
Numbered leaf from top of stalk	*leaf_size_no*	1 14 20	1 5 10 15 20 22 24 26 30
Thermal time from emergence to onset of stalk growth	*tt_emerg_to_begcane*	1900	493

3. Traits for canopy development and light interception by twenty-seven Brazilian sugarcane varieties

Abstract

Since new varieties are released continuously in the Brazilian sugarcane agro-industry, the understanding of their growth, development and yields are necessary. In Brazil, there is a lack of studies on sugarcane variety traits for canopy development and yields, especially those employed by the sugarcane modelling community. This paper assessed the canopy development and light interception by 27 sugarcane varieties grown at two tropical sites (São Romão, MG, and Guadalupe, PI) under non-limiting (potential) conditions in Brazil and tested the capability of the well-known APSIM-Sugar model to distinguish these varieties. Parameters for APSIM-Sugar canopy traits (leaf size, green leaf number, tillering and stalk emergence) and the light extinction coefficient were derived for each variety from field experiments and by calibration for the plant cane cycle. Trait parameters were then validated satisfactorily against independent datasets from the same two sites (first ratoon cycle of 27 varieties) and a row spacing experiment at São Romão (plant and ratoon for six varieties). A validation was also done using published experiments in other five sites across Brazil (four varieties). After APSIM-Sugar parameters were calibrated and validated, long-term simulations were run for each variety at the two sites. APSIM-Sugar outputs of thermal time to reach 50% of canopy closure were employed to group the varieties in terms of canopy formation by clustering analysis. The four major clusters corresponded with promotional information from breeding companies in Brazil about canopy formation. These findings suggest it is reasonable to hypothesise that the APSIM-Sugar parameters are plausible and are an important step for unravelling genetic × environment × management interactions to improve yields and quality in the Brazilian sugarcane agro-industry.

Keywords: *Saccharum* spp.; Crop modelling; APSIM; Canopy development; Photosynthetically active radiation; G × E × M interaction

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3.1. Introduction

The increase in sugarcane yield achieved in recent decades in Brazil is due to many factors, including genetic improvement and better crop management practises (Burnquist et al., 2010; Dal-Bianco et al., 2012; Pereira et al., 2012). The number of varieties released and adopted by the Brazilian sugarcane industry increased from 1977 to 2017 (Burnquist et al., 2010; Dal-Bianco et al., 2012; RIDESA, 2015) and will keep increasing due to the necessity to adapt to intensive mechanisation, changes in other management factors (M) and new environments (E), such as those in Cerrado Biome (Central-West region) and in-land tropical areas in the Northeast region. Therefore, understanding the genotype (G) component in a sugarcane production system is crucial for optimising yield from new varieties in changing production environments. The interactions between G, E and M affect sugarcane growth and development, consequently affecting radiation capture, yields and quality.

Compared to other C_4 plants, such as grasses and grain crops (maize and sorghum), the sugarcane canopy develops slowly (Allison et al., 2007; Inman-Bamber, 2014). Canopy development also differs substantially between varieties (Dias et al., 2019; Garside and Bell, 2009a; Inman-Bamber, 1994; Abraham Singels et al., 2005) and is affected by crop class and planting or ratooning date (Dias et al., 2019; Inman-Bamber, 1994; Abraham Singels et al., 2005), water stress (Inman-Bamber and Smith, 2005; Robertson et al., 1999a), planting density (Bell and Garside, 2005; Garside and Bell, 2009b), row spacing (Garside et al., 2009; Rossi Neto et al., 2018; Singels and Smit, 2009) and soil health (Garside and Bell, 2009b). Tactical decisions in sugarcane fields could be supported using process-based or crop simulation models as a tool. Singels et al. (2005) suggested, for example, that summer rather winter planting would help compensate for slow canopy development in varieties which otherwise have desirable traits. The rate of canopy development and radiation capture also affect decisions regarding the optimum age for harvesting (Bezuidenhout et al., 2002; Inman-Bamber, 1991), irrigation management (Inman-Bamber et al., 2007; Robertson et al., 1999b), and weed management (Inman-Bamber and Stead, 1990), all of which can be supported by crop models.

Crop models are able to estimate growth, development and yield for a set of G coefficients in a given environment (climate and soil) and under different managements (such as irrigation, fertilisation and row spacing) (Jeuffroy et al., 2006; Monteith, 1996), and can be used to develop and test scientific hypotheses. and as a tool for decision makers (Boote et al., 1996; Wallach, 2006a). Among some crop models dedicated to sugarcane, the most commonly used are CANEGRO (Inman-Bamber, 1991; Jones and Singels, 2019; Singels et al., 2008) and APSIM-Sugar (Holzworth et al., 2014; Keating et al., 1999; McCown et al., 1996). The basic processes simulated by current sugarcane models can be summarised as canopy development and radiation interception, biomass production and partitioning (Singels, 2014).

Plant processes of canopy formation such as sprouting, emergence, leaf and stalk appearance and elongation are strongly influenced by air temperature (Allison et al., 2007; Inman-Bamber, 1994; van Dillewijn, 1952), therefore, thermal time (TT, also known as or heat units or growing degree-days) is a common index used to drive phenology and growth in sugarcane models. Temperature, water and nitrogen stresses also affect canopy development and are currently included in sugarcane models´ algorithms (Singels, 2014). These processes govern the amount of light intercepted by the crop and have a direct impact on sugarcane yield (Inman-Bamber, 1994; Abraham Singels et al., 2005).

Light interception by the canopy in many crop models, including those dedicated to sugarcane (Singels, 2014), is simulated using Beer's Law approach (Monsi and Saeki et al., 1953 cited by Saeki, 1963). The exponential equation is driven by leaf area index (LAI) and the light extinction coefficient. Sugarcane models use photosynthetically active radiation (PAR) or solar radiation. Although there is some evidence in the literature that the light extinction coefficient is variety-specific (Araújo, 2016; De Silva and De Costa, 2012; Magalhães Filho, 2014; Park et al., 2005; Zhou et al., 2003), in sugarcane models such as CANEGRO and APSIM-Sugar it is a trait usually considered as constant instead. Therefore, an assessment of the impact of variety-specific light extinction coefficient would contribute to better understanding its impact on sugarcane models.

Crop models can be used to unravel G × E × M interactions in sugarcane by trait-modelling studies such as predicting genotype differences in regard to yield (Hoffman et al., 2018; Thorburn et al., 2014) and identification of desirable crop characteristics for water-limited environments (Inman-Bamber et al., 2012; Singels et al., 2016). Regarding genotype differences, Thorburn et al. (2014) evaluated the ability of the APSIM-Sugar model to predict dry cane yields for nine varieties distributed in seven countries by considering traits such as leaf size and biomass partitioning using evidences from field experiments. While these particular traits were important for leaf and stalk appearance in relation to thermal time (phenology), they offered only a small improvement in overall prediction of stalk dry mass. The authors hypothesised that either there is no crucial information in phenology data for stalk dry mass estimation or the model is not sensitive to these parameters. Under irrigated conditions in South Africa, Hoffman et al. (2018) found that CANEGRO was able to simulate stalk dry mass satisfactorily by changing the parameter related to the maximum radiation use efficiency for 14 genotypes from measurements of leaf level photosynthetic efficiency and stomatal conductance, providing trait information that could help to devise feasible targets for breeders. However, none of these mentioned studies investigated or detailed traits related to canopy development and light interception, a fundamental process for yield accumulation in the current sugarcane crop models and in nature.

Unfortunately, in Brazil, there is a lack of studies on sugarcane variety traits for canopy development and yields, especially those employed by the sugarcane modelling community. Even when considering the most common crop models dedicated to sugarcane, there are few studies that offer calibrations and adaptations for Brazilian varieties (see supplementary Table S1), which are likely to differ substantially from other varieties around the world that have been used in developing and improving the models. Further investigations of varietal differences are required for enhancing the knowledge of G × E × M interactions to improve these models and for their use in Brazil. The calibrations of Leal (2016) using the CANEGRO model for seven extensively measured varieties in a glasshouse experiment in southeastern Brazil provided valuable information about canopy and biomass traits but this work needs to be followed up by experiments under field conditions.

The aims of our study were to advance the understanding of G × E × M interactions for sugarcane production in regard to radiation capture for 27 Brazilian varieties under field conditions where water, nutrition, weeds, pests and diseases were non-limiting. We aimed to determine traits for canopy development from our field experiments and from the literature that would distinguish between the most common Brazilian varieties, for use with the APSIM-Sugar model. We then aimed to group the most commonly used Brazilian varieties according to their rate of canopy development and radiation capture in order to inform decisions about choice of variety and options for their management (planting dates, optimum age at harvest and irrigation, for example).

3.2. Material and methods

3.2.1. Field experiments

Field experiments were carried out at two sites of Agro-Industrial Complexes of Terracal Company to achieve potential yields. The experiments were conducted in São Romão, state of Minas Gerais (16.4 ºS, 45.1 ºW, and 500 m asml), and Guadalupe, state of Piauí (6.8 ºS, 43.6 ºW, and 170 m asml), both in Brazil. Table 1 provides details for each location, including the number of varieties in each experiment, starting and harvesting dates of each crop class, the average climatic conditions and total amount of irrigation applied during each crop cycle. Fig. 1 shows where the experiments (red diamonds) were located.

The statistical design was random blocks for the experiments with 12 varieties and a split-split-plot design for the experiments with 6 varieties harvested at different ages (at 8, 10.5, 12, 13.5 and 15 months-old at São Romão, and at 8, 11.5 and 15 months-old at Guadalupe), all with four replications. In total, 27 varieties were grown in the experiments, 21 being in common to both locations. The 21 in common were RB835054, RB845210, RB855156, RB867515, RB92579, RB931003, RB947532, RB951541, RB957508, RB961003, RB966928, RB98710, RB99395, RB012046, RB012090, SP80-1816, SP81-3250, SP94-3206, IACSP87-3396, IACSP95-5000 and CTC2. Varieties RB855453, RB855536 and VAT90212 were grown only in São Romão, whereas RB835486, RB863129 and RB931011 were grown only in Guadalupe. The varieties were chosen to represent a wide range of those common in the Brazilian cane industry (for example, RB867515 and RB92579, which are the most popular in Center-Southern and Northeast regions, respectively), those which are gaining importance (such as RB966928, the most widely planted last season), and recently released ones (for instance, RB012046 and RB012090). The variety characteristics we found so far were gathered from breeding catalogues.

The predominant soils at São Romão and Guadalupe were classified as Neossolo Quartzarênico (Arenosol, FAO soil classification system) and Latossolo Amarelo (Ferralsol, FAO soil classification system), respectively. Before planting, soil correction was done for each experiment based on in-site chemical analyses which indicated requirements of limestone application in the range of 2 to 3 t/ha. Sugarcane setts were treated with fungicide and heat (50º C for two hours) to prevent fungal and ratoon stunting diseases.

In-site automatic weather stations (Campbell Scientific, CS) for each location were used for monitoring the meteorological conditions. 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).

The row spacing differed between the two sites. In São Romão the rows were single and 1.5 m apart. In Guadalupe, dual rows were used with an alternate spacing of 0.9 m and 1.5 m (1.2 m mean). The difference in row spacing between the two sites was due the intention to use a crop arrangement suitable for field mechanisation in the commercial operation. The number of buds per meter at planting was about 18.

During the plantings in São Romão experiments, nitrogen, phosphorus and potassium (NPK) were applied at 44, 154, and 88 kg/ha, respectively. After planting or harvesting, adequate nutrient amounts were applied through a sub-surface drip system, each row with its own drip tube reticulation. In total, for plant canes it was applied around 261, 260 and 421 kg/ha of NPK, respectively, whereas for ratoons it was applied around 275, 100 and 300 kg/ha of NPK, respectively. Differently from São Romão, nutrient amounts in Guadalupe experiments were applied exclusively through the sub-surface drip system. Plant canes received around 323, 100 and 345 kg/ha of NPK, respectively. For the two experiments where ratoons were grown, it was applied around 209, 73 and 360 kg/ha of NPK, respectively.

At both sites, an array of 18 capacitance sensors showed that roots extracted water from the soil to at least 1.9 m depth. Irrigation was managed daily in all experiments through the reference evapotranspiration (ETo) and crop coefficient (Kc) approach and with tensiometers in four experiments (Table 1). The tensiometers and the capacitance sensors were used to ensure that water supply was not limited at any crop stage. ETo was determined by the Penman-Monteith method following the parameterisation presented by Allen et al. (1998). The Kc values were based on Inman-Bamber and McGlinchey (2003). A drying-off period of about 30 days prior the harvest was applied to avoid soil compaction rather than to increase sucrose levels in the stalks at harvesting.

Measurements in plant cane and first ratoon were taken in both sites for each plot, as described below:

- Stalk heights: the height above ground level of the dewlap (ligule) of the youngest fully expanded leaf of 20 stalks spaced at regular intervals, was recorded only while this was possible in upright cane;
- Stalk counts: stalks over a distance of 10 m for one cane row in each plot were counted while this was still possible in upright cane. The number of stalks was also measured at harvest;
- Green leaf counts: the number of green leaves per stalk was recorded on five large stalks per plot when crop was about 13 months-old for 14 varieties in São Romão.
- Fractional PARi: a ceptometer (Accupar LP80 model, Decagon Instruments) was employed to measure PARi while this was < 0.90 and the crop was not lodged. The measurements were taken on sunny days between 10 am and 2 pm in all plots in all experiments. 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, by holding the sensor horizontally well above the canopy, using a ladder.

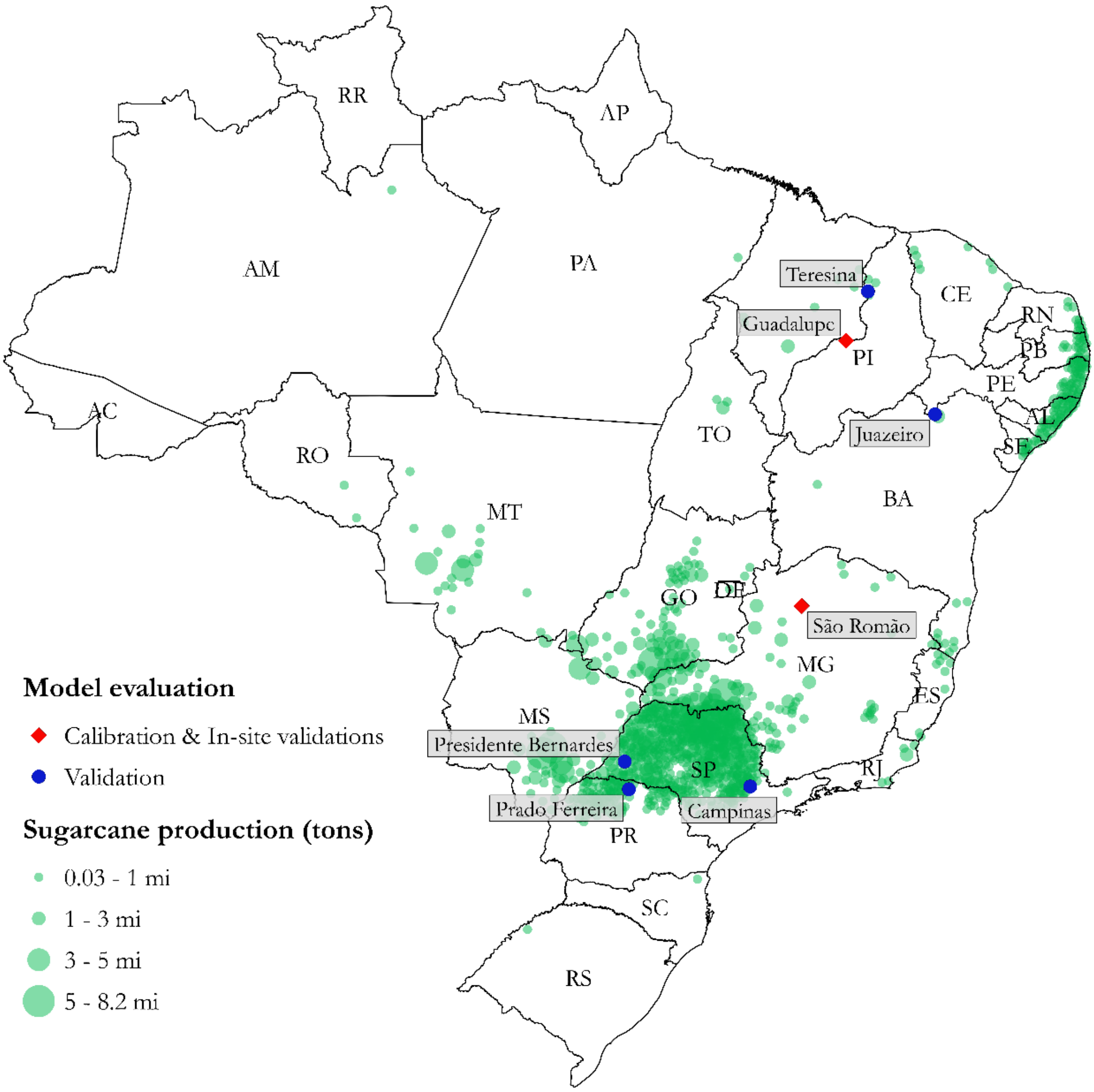

Fig. 1. Spatial distribution of the G × E × M experiments used for determining the sugarcane variety traits (red diamonds) and the published experiments employed in the validation phase (blue circles). Green circles represent the Brazilian municipalities where sugarcane production was higher than 30,000 tons in the 2017/2018 growing season (IBGE, 2018).

Table 1

Management and meteorological conditions of the experiments used in the trait modelling study for canopy development and light interception with the APSIM-Sugar model.

Site (row spacing)	Varieties	Crop Class	Crop start	Harvesting	Mean air temperature (ºC)	Rainfall (mm)	Irrigation (mm)	Solar radiation (MJ/m²/d)
São Romão, MG	12	Plant	2012/Dec	2014/Feb	25.2	1175	1844 [a]	8623
(single row 1.5 m)	12	1st Ratoon	2014/Feb	2015/Feb	24.9	931	1283 [a]	7384
	12	Plant	2012/Dec	2014/Feb	25.3	1203	1844 [a]	9118
	12	1st Ratoon	2014/Feb	2015/Feb	24.9	950	1332 [a]	7507
	12	Plant	2013/Aug	2014/Oct	24.7	1046	1750	8592
	12	Plant	2013/Jul	2014/Sep	24.6	1035	1502	8746
	12	1st Ratoon	2014/Sep	2015/Sep	25.1	891	1407	7079
	12	Plant	2014/Apr	2015/Jun	24.8	893	1518	8537
	12	1st Ratoon	2015/Jun	2016/Jun	25.7	852	1542	7647
	6	Plant	2013/Aug	2014/Nov	24.9	1356	1666	9813
	6	Plant	2013/Oct	2015/Jan	25.1	1495	1687	9849
	6	Plant	2013/Dec	2015/Mar	25.1	1544	1585	9789
	6	Plant	2014/Mar	2015/Jul	24.7	1052	1814	9277
	6	Plant	2014/May	2015/Aug	24.4	899	1858	9187
	6	Plant	2014/Jun	2015/Sep	24.7	896	1773	8871
Guadalupe, PI	12	Plant	2014/Oct	2015/Dec	28.7	768	2291	8189
(alternate 1.5 x 0.9 m)	12	1st Ratoon	2015/Dec	2016/Dec	29.1	1018	1246	7209
	12	Plant	2014/Oct	2015/Dec	28.7	768	2255	8113
	12	1st Ratoon	2015/Dec	2016/Dec	29.1	1012	1288	7248
	12	Plant	2015/Jun	2016/Aug	29.1	939	2613	8634
	12	Plant	2015/Jun	2016/Aug	29.1	938	2718	8739
	6	Plant	2014/Jul	2015/Sep	28.4	776	2235	8408
	6	Plant	2014/Sep	2015/Dec	28.8	794	2385	8618
	6	Plant	2014/Nov	2016/Feb	28.7	1309	2452	8666
	6	Plant	2015/Jan	2016/Apr	28.7	1430	2669	8687
	6	Plant	2015/Apr	2016/Jun	25.5	920	2843	8924
	6	Plant	2015/May	2016/Aug	25.2	853	2824	8847

[a] Based on tensiometer readings

3.2.1.1. Row spacing experiment in São Romão, MG

A row spacing experiment was carried out at São Romão and was used for validation of the trait parameters for PARi given that row spacing differed between the two sites. This experiment included both row spacings. The experiment was a split-plot design with four replications. Three row spacings (1.5 m single row; 1.4 + 0.4 m and 1.5 + 0.9 m alternate dual rows) were used as whole plots and six varieties (RB867515, RB92579, RB961003, RB966928, SP91-3250 and VAT90212) as sub-plots. The crop was planted in December 2012 and harvested in February 2014. The subsequent ratoon was harvested in February 2015. The same measurements described in item 2.1 were taken in this experiment.

3.2.1.2. Published experiments

Published experimental data for some varieties listed in Table 1 were gathered from literature and were also employed in the model validation, including rainfed sites, which are summarised in supplementary Table S2. . The location of the experiments is presented in Fig. 1 (blue circles). LAI measurements were available for those experiments, while at only two sites PARi measurements were available and, therefore, used in the validation stage. Soil physical properties were available and when needed, pedotransfer functions for Brazilian soils (Tomasella et al., 2000) were used to estimate their water limits for each soil layer. When absent, climate data required by APSIM-Sugar were compiled from freely available data from automatic weather stations close to experimental fields from National Institute of Meteorology (INMET), at national level, and from Agronomic Institute of Campinas (IAC), in the state of São Paulo.

3.2.2. APSIM-Sugar modelling

The APSIM-Sugar model (version 7.9 r4404), a crop module embedded in the APSIM platform (**A**gricultural **P**roduction **S**ystems **SIM**ulator) (Holzworth et al., 2014; McCown et al., 1996), was employed in this study. The model was built to simulate sugarcane canopy development and light interception, crop biomass and partitioning, cane and sucrose yields, water use and nitrogen uptakes. It runs on a daily time-step and has sugarcane performance influenced by genotype, climate (rainfall, air temperature and solar radiation), soil water, nitrogen and crop residues. Further details about this model can be found in Keating et al. (1999), Thorburn et al. (2005), Singels (2014), Inman-Bamber et al. (2016), Marin et al. (2015) and Dias et al. (2019).

The experiments in São Romão and Guadalupe were carried out under optimum conditions (aiming to achieve potential yield) with the intention of using APSIM-Sugar, also based on experiments under optimum or controlled conditions, for interpreting and extrapolating the results. The model was configured to represent the Brazilian experiments as close as possible (Dias et al., 2019). The pH values were set at 6 to ensure that the plants were not stressed by nitrification. Nitrogen was applied in order to avoid stresses in canopy development and biomass accumulation. Automatic irrigations were also used to avoid any water deficit. All stress factors were checked through the accumulation of stress days so that we could be sure that the simulations were run without water stress or nitrogen stress. APSIM-Sugar does not simulate balances of the other essential nutrients.

For published experiments, crop simulations were run with adequate amounts of water and nitrogen where the experiments were irrigated, and with adequate nitrogen and no irrigation where they were rainfed.

3.2.2.1. Trait determination

Varietal trait parameters available from the literature and from our field experiments were included in APSIM-Sugar before any calibration began. Unknown trait parameters were obtained by calibration, thus finding the best (optimum) values to explain observed PARi attributes for a given variety. Trait parameters that were based on literature, field measurements and optimisations are detailed in Sections 3.2.2.1.1, 3.2.2.1.2 and 3.2.2.1.3, respectively. The list of traits considered as variety-specific and those regarded as general between varieties for use in APSIM-Sugar modified in this study is presented in Table 2.

Table 2

Description of APSIM-Sugar considered as variety-specific and as general traits investigated in the study.

Traits description	APSIM term	Units
Varietal		
Area of each leaf	*leaf_size*	mm^2
Green leaf number	*green_leaf_no*	leaves
Expansion factor applied to leaf_size due to tillering	*tillerf_leaf_size*	unitless
Thermal time required from emergence to initial stalk growth	*tt_emerg_to_begcane*	°C d
General traits		
Initial total plant leaf area	*initial_tpla*	mm^2
Thermal time from planting to sprouting	*shoot_lag*	°C d
Light extinction coefficient (Beer's Law)[1]	*extinction_coef*	unitless

[1] Regarded as varietal in this study

3.2.2.1.1. Based on literature

Maximum area of successive leaves was regarded as the same for all Brazilian varieties because measurements of this trait were not taken in the São Romão or Guadalupe experiments. These values were based on measurements of seven Brazilian varieties in a glasshouse done by Leal (2016). The leaf sizes employed 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 1, 5, 10, 15, 20, 22, 24, 26 and 30 or older, respectively.

The thermal time from planting to sprouting was set as 100 ºC d (base temperature, Tb = 9 ºC) for a plant crop, based on model calibration and validation work for Brazilian varieties done by Dias et al. (2019) in Guadalupe, PI. For ratoons, this trait was set as 25% less (75 ºC d), based on the average difference between TT from planting and stalk elongation in plant crops, and TT between harvesting and stalk elongation in ratoon crops.

PARi was found to be sensitive to the initial total plant leaf area by Dias et al. (2019) and was set as 2000 mm^2 for Guadalupe experiments and it was kept as 1000 mm^2 for São Romão experiments. The change accounts partly for the difference observed between the two sites in the rate of sprouting, which was higher in Guadalupe.

3.2.2.1.2. Based on field measurements

Final stalk population, which is set as the plant population (*plants*) for each variety in the model, was determined from stalk counts when its number had stabilised, commonly after 1200 ºC d (Tb = 16º C) (Abraham Singels et al., 2005). Stalk counts when the plant crop was older than 12 months were excluded because suckers developed after crop had lodged. Tiller production and death profiles were determined from shoot counts taken during canopy development and at harvest. The APSIM-Sugar tillering factor (*tillerf_leaf_size*), which accounts for leaf area attributed to tillers, was applied to leaf stages 1, 9, 11, 13, 17, 25 and 40 because they represented best the inflection points of stalk dynamics for all varieties.

The TT from emergence to the onset of stalk growth was derived according Dias et al. (2019), which used a linear regression equation between stalk height and TT to identify the TT for beginning of stalk elongation, a trait value required for each variety in APSIM-Sugar.

The maximum number of green leaves per stalk is another trait for canopy development. As previously described, 14 varieties had measurements of green leaf number, while for the other 13 varieties the referred trait was regarded as the average of all measurements available to represent the Brazilian gene pool as far as possible.

3.2.2.1.3. Based on optimisation

The light extinction coefficient, which is used to derive PARi from LAI in Beer's law, had to be optimised for each one of the 27 varieties through calibration of the model because LAI measurements were not available. Light interception in APSIM-Sugar is based on solar radiation and not PAR. Bonhomme (2000) and Dias et al. (2019) pointed out that the light extinction coefficient for PAR differs from that for solar radiation and there is also evidence in literature that this trait is variety-specific (Araújo, 2016; De Silva and De Costa, 2012; Magalhães Filho, 2014; Park et al., 2005; Zhou et al., 2003). The light extinction coefficient is important for biomass and yield accumulation and can be successfully obtained from model calibrations (Dias et al., 2019; Sexton et al., 2016). Light extinction coefficients for PAR for international and Brazilian sugarcane varieties in the 0.40 to 0.88 range can be found in the literature (see supplementary Tables S3 and S4).

An optimisation procedure adopted by Inman-Bamber (1994) and Dias et al. (2019) was applied to find the best light extinction coefficient for each variety. Briefly, this coefficient was varied between 0.40 to 0.80 at regular intervals of 0.05 for each variety and the model was run. The coefficient that gave the smallest root mean squared error (RMSE) compared to measured PARi was adopted. The light extinction coefficient was optimised separately for São Romão and Guadalupe since the experiments had different row spacing, which is known to affect light interception (Garside and Bell, 2009b, 2009a; Singels and Smit, 2009). Stalk population is one of the traits affected by row spacing (Garside and Bell, 2009b, 2009a; Singels and Smit, 2009), however, the available data was insufficient to develop differences in tillering habits between row spacings for each variety. Indeed, tillering process is modelled as an empirical approach and our choice was to change the light extinction coefficient rather than the tillering factors for row spacing. In other crop modules in the APSIM platform, such as maize (Brown et al., 2016), sorghum (Hammer and Muchow, 1991; Whish et al., 2005) and millet (Van Oosterom et al., 2001), the light extinction coefficient varies according to row spacing and our approach is therefore consistent with APSIM modelling approach.

3.2.2.2. Model evaluation

Plant cane data for PARi from both field experiment sites (São Romão and Guadalupe) were employed to assess the capability of APSIM-Sugar to distinguish between varieties by including traits from the literature and field measurements. The performance of APSIM-Sugar was assessed by common statistical indices in crop modelling, such as coefficient of determination (R^2), RMSE and its percentage (RMSEP) and Willmott's '*d*' index (Wallach, 2006b). The graphics for visual analysis were created using the *ggplot2* package (Wickham, 2016) in the *R environment* (R CORE TEAM, 2018).

After the process described above, in-site validations of the model were performed using independent PARi data from first ratoon crops at both sites. PARi from both plant and first ratoon crops of the row spacing experiment at São Romão were employed as an independent in-site validation as well.

Another validation of APSIM-Sugar was also done by using data from the published literature for four varieties in other environments in Brazil, including sites from Southern region (colder than experimental sites used) where the crop is grown extensively under rainfed conditions.

The number of measurements used at each stage of model assessment can be found in supplementary Table S5.

3.2.3. Cluster analysis to group the varieties

In order to compare the Brazilian varieties, long-term APSIM-Sugar simulations were performed for sites near São Romão and Guadalupe experiments, using distinct traits for each variety as characterised in the study. Varieties were then grouped according PAR interception rate, using cluster analysis.

Simulations were performed under non-limiting conditions (without water and nitrogen stresses) between July 2007 and June 2018, the longest climate data available for both tropical sites. Climate data were compiled from the public automatic weather stations of National Institute of Meteorology (INMET) for São Romão, MG, and Floriano, PI (roughly 60 km from Guadalupe and at a similar altitude). A cropping system composed of 12-month old plant cane and four ratoons was started for each month of the year. The decline of vigour in successive ratoons (Dias and Sentelhas, 2017; Inman-Bamber et al., 2012; Ramburan et al., 2013) was not included in the simulations apart from the difference between plant and all ratoon crops regarding RUE and TT for sprouting, as required for APSIM-Sugar (Keating et al., 1999). The light extinction coefficients for the six varieties that were not common to both experimental sites, were derived based on the equation presented in Section 3.2.2.

PARi was simulated for each variety using variety-specific traits obtained from field measurements of PARi as described above. TT from APSIM-Sugar outputs were accumulated from the planting or ratooning dates of each simulation (starting months and years) for both locations. Varieties were grouped by the TT required for canopy development to reach the point at which PARi = 50%. Each of 27 varieties had 257 values that came from each combination of crop cycle (plant and ratoons), starting dates (month/year) and sites (Guadalupe and São Romão). A hierarchical clustering analysis was performed by Ward's method using the Euclidian distance (nearest neighbour) to group the varieties in terms of canopy development, using the package *dendextend* (Galili, 2015) in the *R environment*. The number of clusters was defined by analysing the *k-means* clustering graph for 1 to 'n' clusters, in which the total within groups' sum of squares (wss) method was used.

3.3. Results

3.3.1. Canopy traits based on field measurements

The canopy traits determined for 27 Brazilian varieties based on field measurements in São Romão and Guadalupe under non-limiting conditions are presented in Table 3. Final stalk population ranged from 7.7 to 11.1 stalks/m^2 (average 9.7 stalks/m^2). The gain and loss of tillers was as expected for sugarcane with maximum stalk population occurring mostly between leaf numbers 9 and 11 (Table 3). Tillers added to the population until this reached from 1.3 to 3.8 times the initial and final stalk population, depending on variety.

The TT from emergence to the beginning of stalk growth was also variable according variety (Table 3). Averaging all varieties, the Brazilian genotypes require about 485 ºC d to the onset of stalk growth. The minimum and maximum TT required were 338 and 673 ºC d, respectively. Maximum green leaf number trait was measured for 15 varieties and it ranged from 8.0 to 14.8 (Table 3). The average of all varieties was 11.7, which was used for the other 13 varieties for which no measurements were available.

Table 3

APSIM-Sugar canopy traits based on field measurements for 27 Brazilian sugarcane varieties grown under irrigated (potential) conditions in Tropical Brazil.

Variety	Stalks at harvest (*plants*)	*tillerf_leaf_size* (Leaf stages 1, 9, 11, 13, 17, 25 and 40)	*tt_emerg_to_begcane* (ºC d)	*green_leaf_no* (#)
RB867515	9.2	1.0 1.5 1.5 1.6 1.3 1.1 1.0	461	11.7
RB92579	9.9	1.0 1.4 1.7 1.6 1.2 1.1 1.0	468	11.2
RB931003	10.2	1.0 1.5 2.1 1.5 1.1 1.1 1.0	502	11.7
RB961003	8.4	1.0 1.3 1.2 1.2 1.0 1.0 1.0	466	11.7
RB966928	10.1	1.0 1.9 1.7 1.4 1.2 1.1 1.0	474	13.5
RB98710	10.3	1.0 3.7 3.0 1.4 1.2 1.2 1.0	486	11.4
SP81-3250	11.0	1.0 1.5 1.7 1.8 1.3 1.2 1.0	544	11.7
SP94-3206	7.7	1.0 2.3 1.9 1.8 1.4 1.2 1.0	370	11.7
VAT90212	8.2	1.0 1.2 1.3 1.4 1.3 1.2 1.0	673	11.3
RB835054	11.1	1.0 1.8 1.7 1.5 1.5 1.2 1.0	472	11.7
RB835486	9.5	1.0 3.0 2.9 2.3 1.8 1.4 1.0	515	11.7
RB845210	9.5	1.0 1.5 2.9 1.7 1.5 1.3 1.0	449	12.2
RB855156	9.9	1.0 2.4 1.6 1.5 1.5 1.2 1.0	495	11.7
RB855453	10.5	1.0 2.1 1.4 1.3 1.3 1.3 1.0	602	10.5
RB855536	9.3	1.0 2.7 1.8 1.6 1.6 1.5 1.0	644	10.5
RB863129	8.9	1.0 2.5 2.8 2.2 1.6 1.3 1.0	541	11.7
RB931011	11.1	1.0 2.1 2.7 2.2 1.7 1.3 1.0	490	11.7
RB947532	9.4	1.0 1.5 2.2 1.7 1.3 1.2 1.0	429	11.7
RB951541	10.1	1.0 2.5 2.5 2.2 1.8 1.3 1.0	377	11.7
RB957508	9.2	1.0 2.9 2.9 2.5 2.1 1.3 1.0	439	14.8
RB99395	10.3	1.0 1.5 2.9 1.8 1.4 1.2 1.0	338	8.0
RB012046	8.7	1.0 1.5 2.9 1.8 1.6 1.3 1.0	354	11.9
RB012090	11.1	1.0 3.2 3.0 2.5 1.9 1.3 1.0	574	12.5
SP80-1816	9.5	1.0 2.7 3.0 2.6 2.2 1.3 1.0	506	13.2
IACSP87-3396	9.0	1.0 2.3 1.9 1.6 1.5 1.2 1.0	486	11.6
IACSP95-5000	10.1	1.0 2.4 1.7 1.5 1.3 1.2 1.0	552	11.6
CTC2	10.3	1.0 1.5 3.1 1.9 1.3 1.2 1.0	380	11.7

3.3.2. APSIM-Sugar performance with variety traits

After the inclusion of traits gathered from the literature and those determined with field measurements (Table 3), the light extinction coefficient was optimised for plant cane for each variety and experimental site to achieve the best performance of APSIM-Sugar to predict PARi. The optimised extinction coefficients are presented in Table 4. The values found for all varieties ranged from 0.45 to 0.59 in São Romão (single row spacing) and from 0.55 to 0.77 in Guadalupe (alternate row spacing). The relationship between the extinction coefficients found in both sites was highly significant ($y = 1.257 x + 0.01$, $R^2 = 0.71$, *p-value* < 0.001, $n = 21$). This relationship means that regardless of the site and row spacing, varieties had a conservative performance in terms of radiation capture.

Table 4

Light extinction coefficient optimised in APSIM-Sugar for 27 Brazilian sugarcane varieties grown under irrigated conditions in two sites in Brazil with different row spacings.

Variety	São Romão, MG (single row 1.5 m)	Guadalupe (alternate 1.5 x 0.9 m)
RB867515	0.52	0.65
RB92579	0.48	0.64
RB931003	0.49	0.62
RB961003	0.47	0.64
RB966928	0.52	0.66
RB98710	0.49	0.59
SP81-3250	0.50	0.60
SP94-3206	0.55	0.72
VAT90212	0.46	-
RB835054	0.49	0.61
RB835486	-	0.61
RB845210	0.50	0.65
RB855156	0.47	0.63
RB855453	0.45	-
RB855536	0.48	-
RB863129	-	0.60
RB931011	-	0.58
RB947532	0.50	0.63
RB951541	0.53	0.66
RB957508	0.50	0.64
RB99395	0.59	0.77
RB012046	0.55	0.72
RB012090	0.45	0.55
SP80-1816	0.55	0.64
IACSP87-3396	0.53	0.67
IACSP95-5000	0.50	0.61
CTC2	0.52	0.70

A summary of performance of APSIM-Sugar to simulate PARi for plant cane for each variety and experimental site is presented in Table 5. The precision given by R^2 varied between 0.37 and 0.97 in São Romão (single row spacing) and 0.59 and 0.88 and in Guadalupe (alternate row spacing). Model agreement (*d*) was more similar between locations, and ranged from 0.38 to 0.93. The errors, represented by RMSEP, varied between 13 % and 62 % in São Romão and 16 % and 27 % in Guadalupe. APSIM-Sugar performed better for most of the varieties in Guadalupe than São Romão. Overall, PARi for both datasets was well simulated, R^2, *d* and RMSEP were 0.57, 0.86 and 22.1 %, respectively.

Table 5

Performance of APSIM-Sugar to simulate plant cane photosynthetically active radiation interception (PARi) during calibration process for 27 Brazilian sugarcane varieties grown in two sites in Brazil.

Variety	R^2			*d*			RMSEP (%)		
	São Romão, MG	Guadalupe, PI	Both	São Romão, MG	Guadalupe, PI	Both	São Romão, MG	Guadalupe, PI	Both
RB867515	0.51	0.77	0.64	0.83	0.92	0.89	24.3	16.5	19.8
RB92579	0.59	0.78	0.67	0.84	0.93	0.90	24.1	16.2	19.5
RB931003	0.51	0.76	0.54	0.38	0.91	0.83	62.2	17.8	24.1
RB961003	0.77	0.82	0.74	0.93	0.93	0.92	29.5	17.4	21.4
RB966928	0.46	0.76	0.50	0.80	0.82	0.83	26.9	19.1	24.8
RB98710	0.97	0.83	0.68	0.93	0.93	0.91	15.8	15.9	15.9
SP81-3250	0.54	0.63	0.49	0.79	0.76	0.80	25.7	25.0	25.5
SP94-3206	0.71	0.82	0.61	0.77	0.91	0.88	21.3	17.1	17.8
VAT90212	0.40	-	-	0.71	-	-	29.8	-	-
RB835054	0.45	0.88	0.58	0.68	0.86	0.86	20.8	20.9	20.9
RB835486	-	0.67	-	-	0.77	-	-	23.1	-
RB845210	0.87	0.72	0.50	0.75	0.80	0.78	28.7	23.7	25.7
RB855156	0.62	0.59	0.49	0.78	0.74	0.83	18.7	27.3	24.8
RB855453	0.37	-	-	0.51	-	-	25.9	-	-
RB855536	0.54	-	-	0.70	-	-	21.5	-	-
RB863129	-	0.78	-	-	0.81	-	-	20.5	-
RB931011	-	0.75	-	-	0.83	-	-	21.0	-
RB947532	0.72	0.79	0.49	0.58	0.84	0.77	45.9	21.1	30.4
RB951541	0.86	0.73	0.53	0.73	0.83	0.81	32.4	19.7	24.3
RB957508	0.83	0.73	0.61	0.88	0.84	0.87	21.7	19.8	20.6
RB99395	0.68	0.81	0.50	0.72	0.83	0.77	26.3	18.5	21.7
RB012046	0.90	0.73	0.61	0.89	0.82	0.85	18.9	21.7	20.9
RB012090	0.62	0.85	0.49	0.46	0.82	0.70	49.2	21.6	32.5
SP80-1816	0.68	0.74	0.50	0.68	0.82	0.73	30.6	20.5	24.7
IACSP87-3396	0.79	0.74	0.52	0.88	0.80	0.83	14.1	20.4	18.0
IACSP95-5000	0.60	0.70	0.54	0.89	0.78	0.84	13.0	21.7	18.8
CTC2	0.88	0.78	0.63	0.84	0.83	0.85	24.4	20.7	22.2
Overall	0.54	0.54	0.57	0.84	0.85	0.86	26.9	18.9	22.1

3.3.2.1. In-site validations with ratoon crops

The statistics for in-site validations of APSIM-Sugar with first ratoon data for each variety in both experimental sites are presented in Table 6. As in plant crop class, the model performed better in Guadalupe (alternate row spacing) than in São Romão (single row spacing). The prediction skill for PARi was better for the validation (ratoon crop) than for the calibration (plant crop), an unexpected but pleasing result. When all ratoon crop data available for validation were considered, R^2, *d* and RMSEP were 0.72, 0.92 and 16.7 %, respectively.

Table 6

Performance of APSIM-Sugar to simulate first ratoon photosynthetically active radiation interception (PARi) during validation process for 27 Brazilian sugarcane varieties grown in two sites in Brazil.

Variety	R^2			*d*			RMSEP (%)		
	São Romão, MG	Guadalupe, PI	Both	São Romão, MG	Guadalupe, PI	Both	São Romão, MG	Guadalupe, PI	Both
RB867515	0.93	0.91	0.91	0.97	0.98	0.97	11.4	8.1	10.4
RB92579	0.81	0.98	0.91	0.97	1.00	0.97	12.4	3.5	10.2
RB931003	0.79	0.92	0.70	0.86	0.98	0.91	16.8	9.5	15.2
RB961003	0.46	0.96	0.40	0.77	0.99	0.76	34.2	9.3	31.6
RB966928	0.93	0.95	0.90	0.96	0.99	0.97	12.1	4.4	10.7
RB98710	0.95	0.95	0.92	0.96	0.99	0.97	9.1	6.2	8.7
SP81-3250	0.87	0.92	0.81	0.92	0.98	0.94	16.3	7.7	14.1
SP94-3206	0.83	0.82	0.79	0.93	0.93	0.94	16.0	14.5	15.5
VAT90212	0.73	-	-	0.82	-	-	26.0	-	-
RB835054	0.83	0.93	0.85	0.92	0.97	0.93	20.5	12.1	18.1
RB835486	-	0.98	-	-	0.99	-	-	5.4	-
RB845210	0.80	0.93	0.76	0.87	0.97	0.91	16.8	9.0	15.2
RB855156	0.82	0.93	0.91	0.98	0.96	0.97	11.8	12.5	12.0
RB855453	0.82	-	-	0.85	-	-	25.0	-	-
RB855536	0.87	-	-	0.90	-	-	17.7	-	-
RB863129	-	0.99	-	-	0.99	-	-	6.2	-
RB931011	-	0.90	-	-	0.97	-	-	12.3	-
RB947532	0.61	0.93	0.53	0.81	0.97	0.85	27.0	11.1	23.3
RB951541	0.79	0.93	0.67	0.86	0.98	0.90	19.5	7.9	18.0
RB957508	0.63	0.99	0.57	0.81	1.00	0.86	23.1	1.6	20.8
RB99395	0.52	0.92	0.70	0.75	0.97	0.85	20.9	8.2	18.5
RB012046	0.93	0.96	0.88	0.95	0.98	0.96	11.8	7.0	10.7
RB012090	0.72	0.84	0.69	0.89	0.95	0.91	16.8	13.2	16.1
SP80-1816	0.93	0.86	0.81	0.93	0.92	0.93	10.9	11.3	11.0
IACSP87-3396	0.96	0.97	0.86	0.94	0.99	0.96	14.1	5.5	11.8
IACSP95-5000	0.89	0.92	0.89	0.93	0.98	0.94	15.8	7.8	14.3
CTC2	0.46	0.94	0.60	0.72	0.99	0.83	23.2	6.5	20.2
Overall	0.66	0.91	0.72	0.90	0.98	0.92	18.7	8.9	16.7

3.3.2.2. In-site validation with a row spacing experiment

The optimised extinction coefficients for six varieties in the alternate row spacing at Guadalupe were tested against PARi determined in the row spacing experiment at São Romão. Simulated and measured PARi for each variety and crop class (plant, R0, and first ratoon, R1) are presented in Fig. 2. APSIM-Sugar captured differences in PARi between crop class, varieties and row spacing reasonably well apart from the plant crop of variety VAT90212, and first ratoon of variety RB961003, both in a single row configuration.

Statistical indexes of model performance for the simulation of this experiment (R2 = 0.72; *d* = 0.91; RMSEP = 17.0 %; also see Supplementary Table S6), were of the same magnitude as those presented in Tables 5 and 6 for the two large serial harvesting experiments.

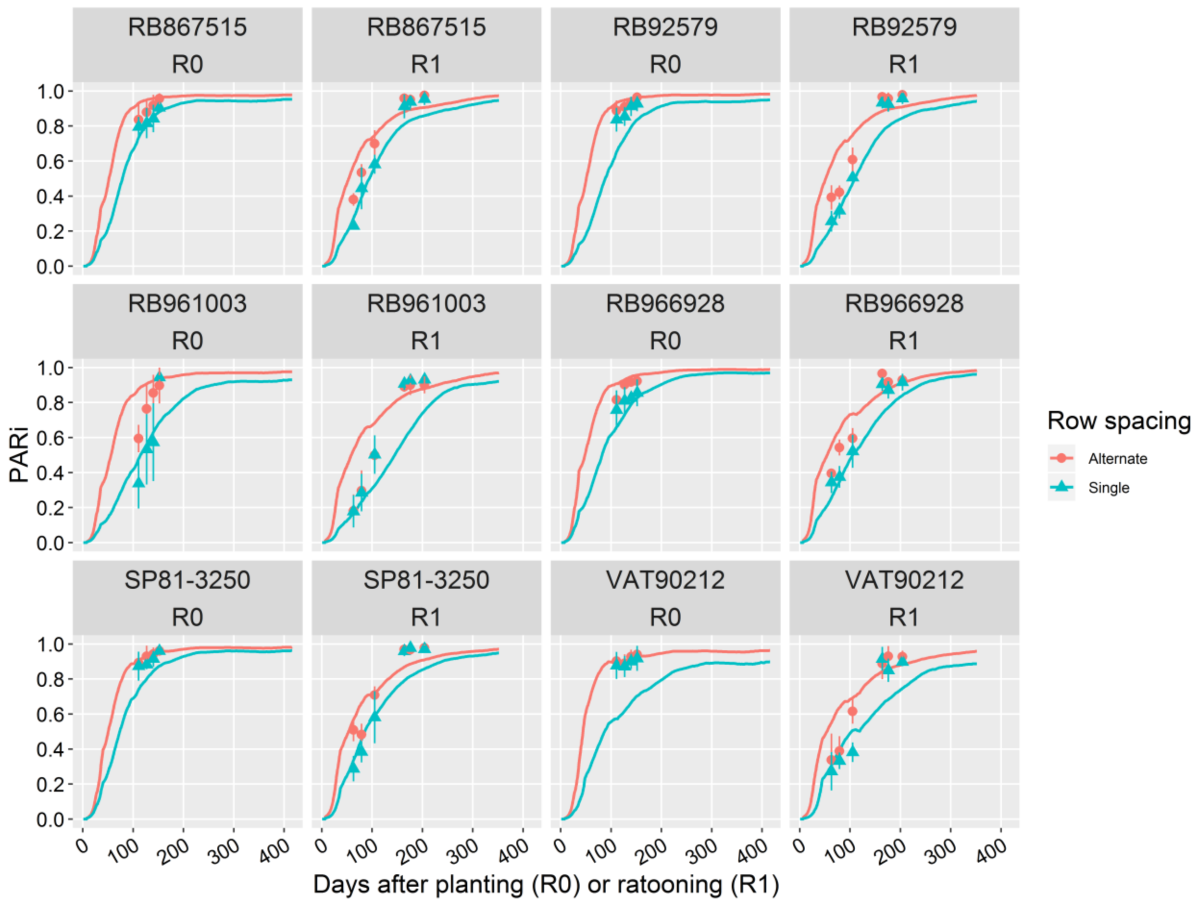

Fig. 2. Fractional photosynthetically active radiation interception (PARi) measured (points plus bars) and simulated (lines) by the APSIM-Sugar model during in-site validation process for six Brazilian sugarcane varieties grown in two row spacings (single and alternate) in São Romão, MG, Brazil under irrigated conditions. R0 = plant crop and R1 = first ratoon.

3.3.2.3. Validation with published experiments

APSIM-Sugar canopy traits for varieties RB855156, RB867515, RB92579 and IACSP95-5000 were validated for some sites across Brazil under rainfed and irrigated conditions. Simulations are presented in Fig. 3a for LAI and in Fig. 3b for PARi. Both crop variables were predicted well by APSIM-Sugar, with the exception of early LAI measurements under rainfed conditions in Presidente Bernardes, São Paulo state (Supplementary Table S2). The later measurements for irrigated experiments (Juazeiro, Teresina and Campinas; Supplementary Table S2) were affected by lodging. No lodging options were included in the simulations.

The statistical indices for all validation measurements available from the literature were R2 = 0.46, *d* = 0.79 and RMSEP = 27.3 % for LAI, and for PARi these indices were R2 = 0.57, *d* = 0.85 and RMSEP = 9.9 %. The agreement between simulated and observed results over seven distinct climate zones and soil types in Brazil, provide confidence in the robustness of the parameters used in these simulations.

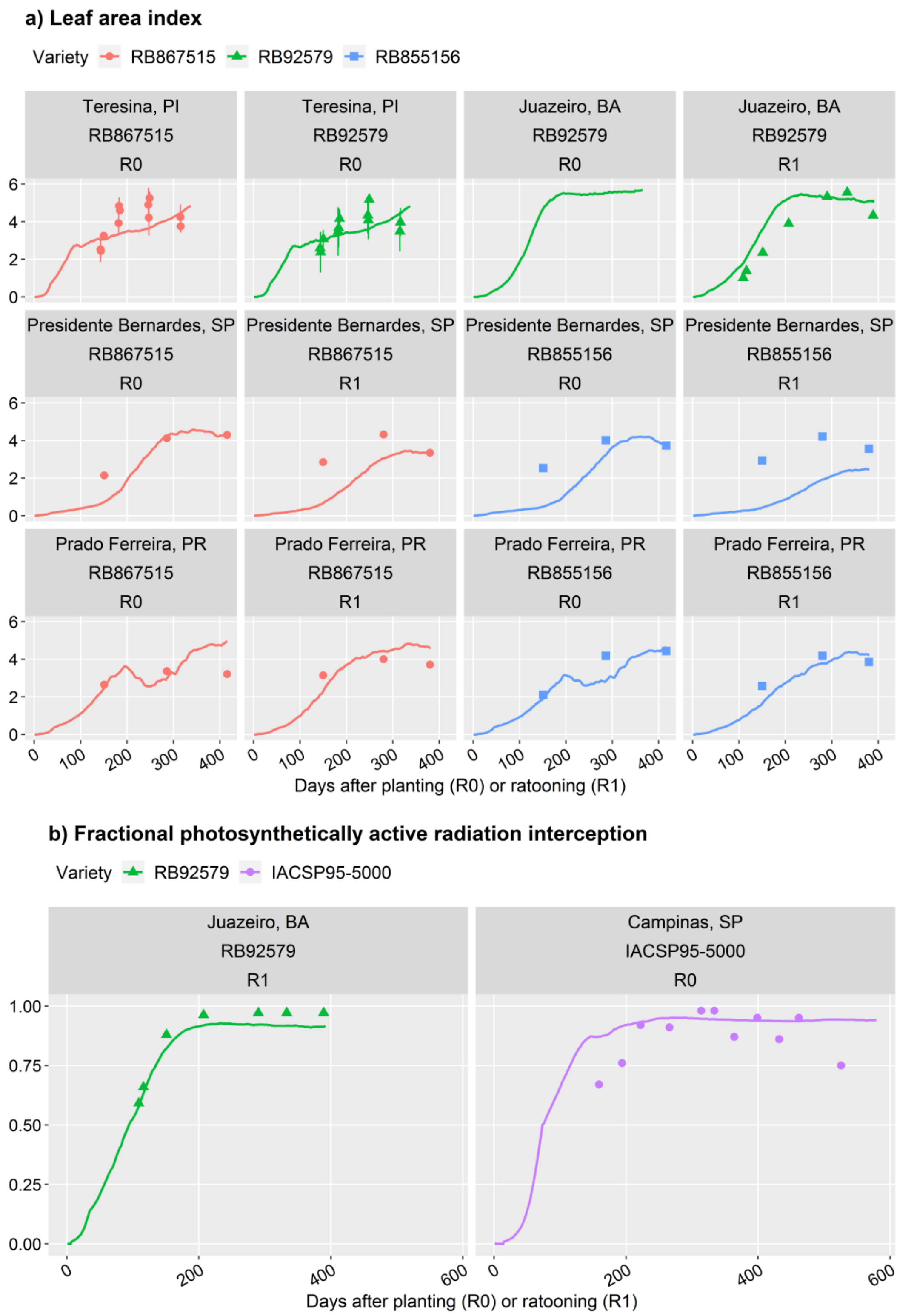

Fig. 3. a) Leaf area index (LAI) and b) fractional photosynthetically active radiation interception (PARi), measured (points) and simulated (lines) by the APSIM-Sugar model during a validation process for Brazilian sugarcane varieties grown in five environments in Brazil. R0 = plant crop and R1 = first ratoon. Details of these locations can be found in Supplementary Table S2.

3.3.3. Cluster Analysis

The relationship between the average TT to reach PARi of 50% for the 27 varieties when sugarcane crop was simulated for a long-term period in São Romão and Guadalupe is presented in Fig. 4. Varieties performed consistently in terms of light interception across both experimental sites under high-inputs conditions, which can be proved by the significant *p-value* (<0.001) found in the regression equation.

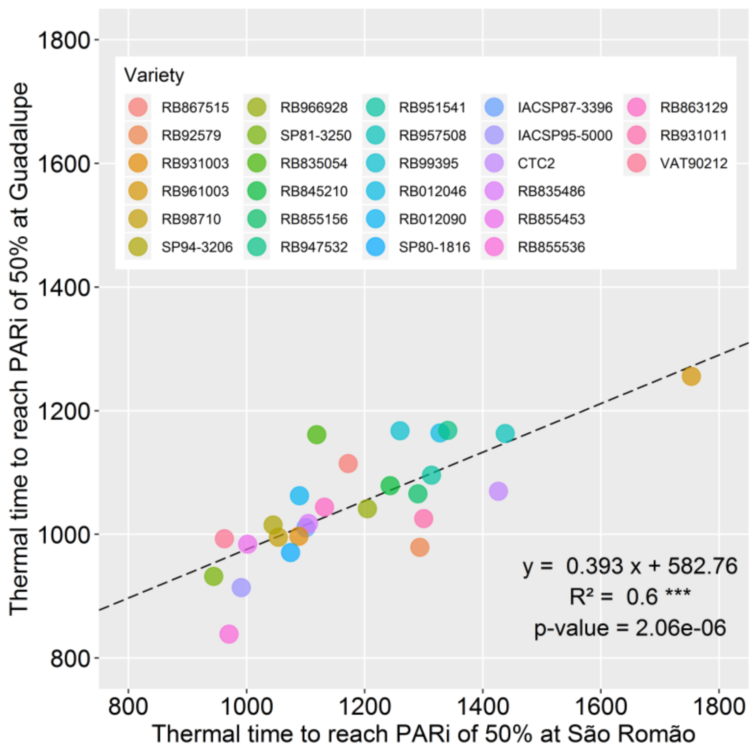

Fig. 4. Relationship between APSIM-Sugar thermal time to sugarcane varieties intercept 50% of the photosynthetically active radiation (PARi) at two irrigated sites in Brazil.

By analysing the wss generated by the *k-means* clusterings, the number of clusters found was four (supplementary Fig. S1). The dendrogram resulting from the hierarchical clustering analysis of APSIM TT required for canopy development to reach the point at which PARi = 50%, is presented in Fig. 5, where the varieties located from the top to the bottom represent the slower to the faster ones, respectively, in terms of canopy development. The fastest varieties were RB855536, IACSP95-5000 and SP81-3250, while the slowest ones were RB947532, RB012046, RB957508 and RB961003. The other 20 varieties were moderate regarding to canopy formation and were grouped in two groups of 12 and 8 members.

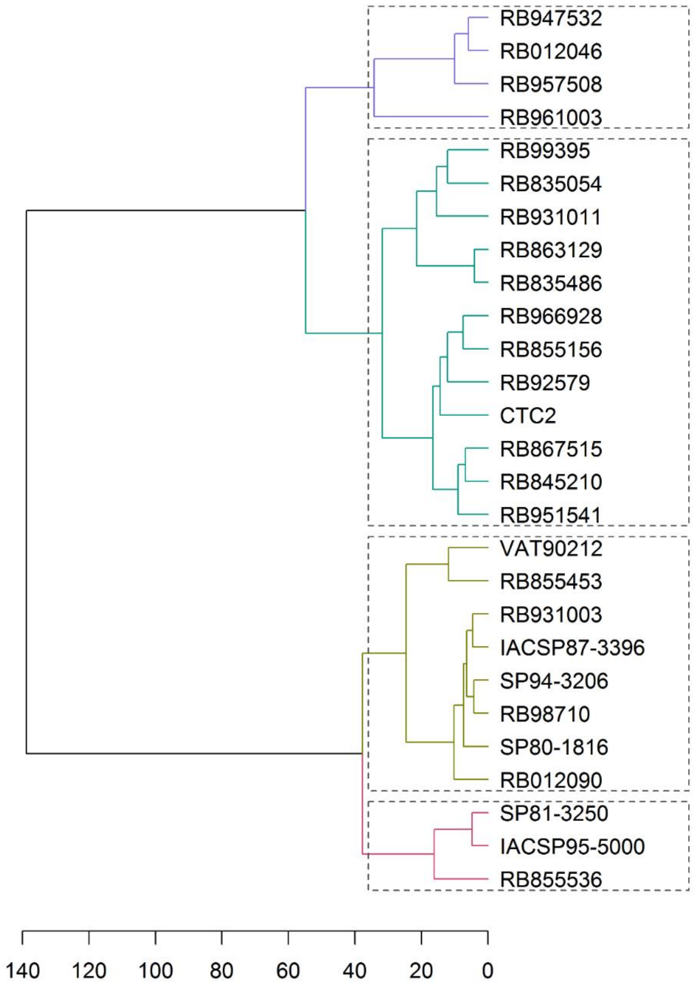

Fig. 5. Dendrogram obtained through hierarchical clustering analysis of thermal time required to intercept 50% of the photosynthetically active radiation (PARi) obtained through long-term APSIM-Sugar simulations for each variety at two Brazilian sites and 12 starting dates (corresponding to months of the year), using the nearest neighbour method.

3.4. Discussion

This paper provides trait values regarding canopy development and light interception that could be useful for crop modellers, breeders, physiologists, crop scientists, industry and growers involved with sugarcane. Currently, the latest version of APSIM-Sugar comes with 14 varieties, none of which are Brazilian. We have provided canopy trait parameters for an additional 27 varieties for APSIM's users. In addition, these trait values could be used for providing reliable ranges for Bayesian statistical techniques of model calibration (Sexton et al., 2016) and design ideotypes for target environments (Inman-Bamber et al., 2012; Singels, 2014; Tao et al., 2017).

Stalk dynamics, including the gain and loss of tillers, is highly variable between varieties across environments and crop management options (Bell and Garside, 2005; Dias et al., 2019; Garside et al., 2009; Garside and Bell, 2009b, 2009a; Inman-Bamber, 1994; Rossi Neto et al., 2018; Abraham Singels et al., 2005; Singels and Smit, 2009). The established stalk population at harvest (base population) for Brazilian varieties ranged from 7.7 to 11.0 stalk/m^2 (Table 3). The same trait ranged from 5.6 to 10.9 stalks/m^2 for Australian varieties grown in two sites under different crop managements (Bell and Garside, 2005). On the other hand, a South African variety NCo376 achieved between 11.9 to 22.0 stalk/m^2 when planted at 2.70 and 0.64 m apart, respectively (Abraham Singels et al., 2005). Peak stalk populations from tillering were 1.3-3.8 times the base population for Brazilian varieties (Table 3), which is similar to the range (1.1-3.9) found by Bell and Garside (2005) for Australian varieties and cropping systems.

The onset of stalk growth, which is determined by the accumulated TT from crop emergence, was much lower for Brazilian varieties than for the 14 varieties currently available in APSIM-Sugar. Using APSIM's approach to derive TT, Brazilian varieties required between 337 ºC d to 673 ºC d before stalks started growing, whereas the 14 current APSIM varieties require between 1200 ºC d to 1900 ºC d. By calibrating APSIM-Sugar parameters in cropping systems in Brazil, Marin et al. (2015) and Dias and Sentelhas (2017) also had to reduce this parameter to improve cane yield simulations. These results suggest either that Brazilian varieties are faster for starting stalk growth or that base temperature used in APSIM-Sugar, and/or TT approach are unsuitable for this process. Stalk-related processes requires a Tb around 16º C (Inman-Bamber, 1994; Abraham Singels et al., 2005) rather than 9 ºC assumed for all plant processes in APSIM-Sugar (Keating et al., 1999). The simplification used by Keating et al. (1999) would not work for a wide range of climates without adjustments of the discussed parameter. Furthermore, a glasshouse study of Smit and Singels (2007) has found evidences of variety differences in terms of base temperature for stalk elongation rate, which can also contribute to the variation in the values determined in our results. Results from Jones et al. (2019) indicate that high-intensity solar radiation during the sugarcane tillering phase appears to hasten the beginning of stalk growth. This effect of radiation may partly explain the early start of stalk elongation in the environments where our experiments were carried out.

By including all variety traits (Table 3) and optimising the light extinction coefficient for each experimental site (Table 4) it was possible to distinguish PARi between sugarcane Brazilian varieties by using the APSIM-Sugar model, for both plant cane (Table 5) and first ratoon (Table 6), as far as a crop model performance is concerned. There are few Brazilian varieties with light extinction coefficient determined in literature (Supplementary material Table S1) and its variability is notable, which can be associated to the methods of determination. The light extinction coefficients found in this study varied from 0.45 to 0.77 and literature shows that a range of 0.40 to 0.88.

The light extinction coefficient represents ultimately the ability of a canopy to intercept radiation, and its variation is related to morphological and physiological characteristics of the crop

(Campbell and Norman, 1998; Nobel et al., 1993). Canopy architecture, considering leaf size, number, and distribution, and growth habit dictates the microenvironment surrounding leaves, having a great influence on the exchange of mass and energy between plants and their environment (Campbell and Norman, 1998; Nobel et al., 1993). Brazilian sugarcane varieties from the 'IACSP' gene pool, are known to have differences in leaf size and angle, affecting yields differently (Magalhães Filho, 2014; Marchiori et al., 2010).

APSIM-Sugar also predicted well the light interception pattern for the validation row experiment in São Romão (Fig. 2), even though the faster canopy closure in an alternate row spacing was a bit over predicted in some cases. Canopy development and light interception change with crop arrangement and narrower row spacings intercept more radiation in the first months after planting or harvesting (Garside and Bell, 2009b; Singels and Smit, 2009). PARi measurements were not available early in the development of the plant crop of the row spacing experiment but they were available for the ratoon crop where PARi varied between treatments at this stage. Singels et al. (2005) found that PARi increased with a reduction in row spacing when measured between the rows but not when measured within the row, for an unstressed first ratoon of variety NCo376 grown in South Africa was higher between cane rows, however, within rows there was no difference. Lodging was observed in all varieties in our experiments and this could have affected the stalk population of ratoon crops (Garside and Bell, 2009b, 2009a; Singh et al., 2002), making the differences less predictable for the varieties in ratoon crops. There is some evidence that the response to row spacing is also variety-dependent (Garside and Bell, 2009a), which could explain why varieties RB867515 and RB966928 seemed to intercept more PARi in the alternate row spacing.

The light extinction coefficient based on solar radiation in C_4-plant modules in APSIM changes according modifications of single row spacings. For instance, in the maize module (Brown et al., 2016), the extinction coefficient is 0.40, 0.50 and 0.70 for row spacings of 1.0 m, 0.5 m and 0.2 m, respectively. In the sorghum module (Hammer and Muchow, 1991; Whish et al., 2005), the light extinction coefficient increases 75% (from 0.40 to 0.70) when row spacing decreases from 0.5 m to 0.2 m. In the case of the millet module (Van Oosterom et al., 2001), the light extinction coefficient is 0.37, 0.61 and 0.79 for row spacing of 1.50 m, 0.75 m and 0.20 m, respectively. In our case, we found that light extinction coefficient increased about 26% between single 1.5 m and alternate 1.5 m x 0.9 m row spacings when all varieties were considered (Table 4).

Light extinction coefficients based on PARi for sugarcane variety RB98710 grown under irrigation in Rio Largo, AL (9.5 ºS), were 0.48 and 0.51 respectively for a single 1.0 m row arrangement and an alternate (1.4 m x 0.6 m) arrangement (Ferreira Junior et al., 2015). The extinction coefficients for the same variety through optimisation found in our study were 0.49 and 0.59 for single 1.5 m and alternate 1.5 m x 0.9 m row spacings, respectively. In our experiments, the row spacing was decreased and also rearranged, which can help to explain the higher increment in light extinction coefficient between the row spacings.

In the sugarcane modelling community the prediction of LAI is more often assessed than PARi and presents variable predictions skills (see references in supplementary Table S1). The validation of APSIM-Sugar capability to predict LAI for three important Brazilian varieties (Fig. 2a) in four sites across Brazil for both, plant cane and a first ratoon, suggests that our trait parameters for these varieties are widely applicable. Besides its agronomic importance for yield, LAI is also important for determining water requirements for sugarcane which can be estimated with old and new APSIM features (Inman-Bamber et al., 2016; Keating et al., 1999) or by models using the Penman-Monteith approach (Allen et al., 1998). LAI also has an important role in the impact of CO_2 on sugarcane water relations under climate change impact studies (Everingham et al., 2015; Stokes et al., 2016). Varietal differences in canopy development and LAI are therefore important for a number of reasons.

Canopy development was consistently faster in Guadalupe than in São Romão (Fig. 4), which may be associated with the E × M interaction. High yields in Guadalupe were explained by high, but not excessive temperatures, which favour radiation capture (Dias et al., 2019). The narrower row spacing in an alternate design also favours a faster canopy development (Garside and Bell, 2009b; Singels and Smit, 2009), explaining the better radiation capture for all varieties in Guadalupe.

Sugarcane varieties and unselected clones presented little G × M variation in terms of biomass accumulation across different climatic and irrigated environments in Australia (Basnayake et al., 2012) and in China (Liu et al., 2016). Our results in terms of canopy development using APSIM-Sugar simulations suggest that Brazilian varieties perform consistently (low G × E × M) across the two environments and row spacing arrangements of our experiments.

The clustering analysis aggregated the 27 varieties into four major groups regarding canopy development. By gathering some variety information from catalogues of breeding institutions in Brazil (CTC, 2019; RIDESA, 2015), it was possible to verify if the modelling results of APSIM-Sugar in terms of canopy development agreed at least to some extent. Most of the varieties from what the information available were categorised as ‘good’ or ‘regular’ regarding canopy formation, which comprised basically the two intermediate clusters (Fig. 5). According to the breeding companies’ information, the varieties SP80-1816, IACSP95-5000 and RB855536 were categorised as ‘very good’ or ‘excellent’ in terms of canopy formation. Two of these varieties appeared in the fastest group of clusters and the other in the next fastest group of Fig. 4. There was no information available from breeders for varieties in the slowest group of clusters possibly because they have only recently been released. Canopy formation of variety RB835054 was categorised as 'poor' by the breeders, consistent with its classification in the cluster analysis, very close to the slow group (Fig. 5). The close correspondence between simulated canopy development and information from breeders adds credence to the reliability of the trait parameters derived for these varieties. It is worth to mention that the information of breeding catalogues come mostly from sugarcane trials across several rainfed environments in Brazil, cultivated under different soil and climate conditions. This information is qualitative and while ours is quantitative.

The effects on yield of canopy development and consequently light interception, will depend on the duration from planting to harvest. For example, the South African variety N12 develops its canopy much slower than NCo376 (Inman-Bamber, 1994), but yields as much as the faster one if grown in a longer crop cycle (Inman-Bamber, 1985). Depending on the harvest window and how mature the crop is, varieties with faster canopy development could be harvested earlier. This benefit could be assessed through simulation studies using crop models that account for these G × E × M interactions, therefore, helping to improve yield through better planning of the planting and harvesting schedule for a given sugarcane farm or agro-industry.

The trait parameters for canopy development and light interception could be improved with more information about sub-traits such as leaf area profiles and phyllocron intervals which are likely to differ between varieties (Inman-Bamber, 2014).

3.5. Conclusions

APSIM-Sugar is able to distinguish satisfactorily between varieties in terms of PARi by including specific canopy traits and changing the light extinction coefficient in two tropical environments in Brazil under high input conditions for both, plant (optimisation process) and ratoons (validation process) crops. The validation with published experimental data in colder and rainfed environments for some varieties showed that modifications in the model were satisfactory and broadly applicable.

Long-term simulations using APSIM-Sugar with variety-specific traits and clustering analysis allowed for the grouping of Brazilian varieties in terms of light interception over a wide set of G × E × M interactions. Four groups of varieties were found and these aligned well with groups based on descriptive information from breeding companies. Our trait parameters are quantitative rather than qualitative and can now be used in G × E × M studies to inform decisions where canopy development plays an important role. Traits for canopy development can also be assessed in future trait modelling studies by comparisons of the 27 Brazilian varieties with the other international varieties now in the APSIM-Sugar genotype library.

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Supplementary Material

Table S1

Sugarcane models' calibrations found in literature for Brazilian varieties and its main methods for trait determination.

Model	Variety	Traits determination	Validation	Reference
APSIM-Sugar	SP80-1842	Expertise	No	Costa et al. (2014)
APSIM-Sugar	RB867515	Field meas./Expertise	No	Marin et al. (2015)
APSIM-Sugar	Not specified	Default Q117	No	Oliveira et al. (2016)
APSIM-Sugar	Not distinguished	Expertise	Yes	Dias and Sentelhas (2017) [c]
CANEGRO [a]	RB72454	GLUE [b]	Embedded on cross-validation	Marin et al. (2011)
CANEGRO	SP83-2847	GLUE	Embedded on cross-validation	Marin et al. (2011)
CANEGRO	RB92579	Field meas./Expertise	No	Silva (2012)
CANEGRO	RB835486	GLUE	Yes	Nassif et al. (2012)[c]
CANEGRO	RB867515	GLUE	Yes	Nassif et al. (2012) [c]
CANEGRO	CTC 4	GLUE	Yes	Nassif et al. (2012) [c]
CANEGRO	CTC 7	GLUE	Yes	Nassif et al. (2012) [c]
CANEGRO	CTC 20	GLUE	Yes	Nassif et al. (2012) [c]
CANEGRO	RB867515	Field meas./Expertise	No	Marin et al. (2015)
CANEGRO	Not distinguished	Expertise	No	Vianna and Sentelhas (2016) [c]
CANEGRO	RB92579	Expertise	No	Barros et al. (2016)
CANEGRO	RB93509	Expertise	No	Barros et al. (2016)
CANEGRO	RB931530	Expertise	No	Barros et al. (2016)
CANEGRO	SP79-1011	Expertise	No	Barros et al. (2016)
CANEGRO	CTC15	Field meas./Expertise	No	Leal (2016)
CANEGRO	CTC17	Field meas./Expertise	No	Leal (2016)
CANEGRO	RB867515	Field meas./Expertise	No	Leal (2016)
CANEGRO	RB92579	Field meas./Expertise	No	Leal (2016)
CANEGRO	RB931011	Field meas./Expertise	No	Leal (2016)
CANEGRO	RB966928	Field meas./Expertise	No	Leal (2016)
CANEGRO	IACSP95-5000	Field meas./Expertise	No	Leal (2016)
CANEGRO	Not distinguished	Expertise	Yes	Dias and Sentelhas (2017) [c]
CANEGRO	RB93509	Expertise	No	Carvalho et al. (2018)
MOSICAS	RB72454	Field meas./Expertise	No	Suguitani (2006)
MOSICAS	SP83-2847	Field meas./Expertise	No	Suguitani (2006)

[a] Embedded in the DSSAT agricultural system modelling platform
[b] Generalized likelihood uncertainty estimation tool in DSSAT
[c] Leaf area index not included

Table S2

Sources of experimental data from literature used for model validation and their main information regarding to genotype (variety), environment and crop management.

Site	Latitude (º S)	Soil classification	Source of climate data [a]	Row spacing (m)	Variety	Crop Class	Crop Start	Harvesting	Measurements [b]	Reference
Teresina, PI	5.0	*Argissolo Vermelho-Amarelo* [c]	INMET, in-site rainfall	1.5 x 0.5	RB867515	Plant	2015/Oct	2016/Sep	LAI	Andrade Júnior et al. (2018)
				1.5 x 0.5	RB92579	Plant	2015/Oct	2016/Sep	LAI	
Juazeiro, BA	9.5	*Vertissolo* [d]	INMET	1.5	RB92579	Ratoon 1	2007/May	2008/Jun	LAI, PARi	Silva (2009)
Campinas, SP	22.9	*Latossolo Vermelho* [e]	IAC	1.5	IACSP95-5000	Plant	2010/May	2008/Oct	PARi	Magalhães Filho (2014); Silva (2014)
Presidente Bernardes, SP	22.3	*Argissolo Vermelho* [c]	IAC, INMET	1.5	RB867515	Plant	2014/Mar	2015/May	LAI	Barbosa (2017)
						Ratoon 1	2015/May	2016/Jun	LAI	
				1.5	RB855156	Plant	2014/Mar	2015/May	LAI	
						Ratoon 1	2015/May	2016/Jun	LAI	
Prado Ferreira, PR	23.0	*Nitossolo Vermelho* [f]	Xavier et al. (2015)	1.5	RB867515	Plant	2014/Mar	2015/May	LAI	
						Ratoon 1	2015/May	2016/Jun	LAI	
				1.5	RB855156	Plant	2014/Mar	2015/May	LAI	
						Ratoon 1	2015/May	2016/Jun	LAI	

[a] INMET = National Institute of Meteorology; IAC = Agronomic Institute of Campinas.
[b] LAI = leaf area index; PARi = fractional photosynthetically active radiation interception
[c] Acrisols in FAO soil classification system
[d] Vertisol in FAO soil classification system
[e] Ferralsol in FAO soil classification system
[f] Nitossol in FAO soil classification system

Table S3

Values of the light extinction coefficient based on photosynthetically active radiation and solar radiation found for international varieties in literature.

Site	Country	Variety	Crop cycle	Experiment issue (s)	Based on PAR [a]	Based on SRAD [b]	Row spacing (m)	CS [c]	Reference
Mount Edgecombe	South Africa	NCo376	Plant	Modelling	0.58 to 0.86	-	Mostly 1.2	I	Inman-Bamber (1991)
Ayr	Australia	Q117	Plant	Fumigation	-	0.44	1.5	I	Muchow et al. (1994a)
Macknade	Australia	Q117	Plant	Fumigation	-	0.40	1.5	I	Muchow et al. (1994a)
Macknade	Australia	Q138	Plant	Fumigation	-	0.40	1.5	I	Muchow et al. (1994a)
Ayr	Australia	Q96	Plant	Growth analysis	-	0.38	1.5	I	Muchow et al. (1994b)
Several	Australia	Several	Plant	Reducing growth phenomenon	-	0.37-0.40	Mostly 1.5	I	Park et al. (2005)
Several	Australia	Several	Ratoons (mostly R1)	Reducing growth phenomenon	-	0.37-0.53	Mostly 1.5	I	Park et al. (2005)
Kunia	Hawaii	H73-6110	Plant	Growth analysis	-	0.40	1.5	I	Muchow et al. (1997)
Kunia	Hawaii	H78-7234	Plant	Growth analysis	-	0.40	1.5	I	Muchow et al. (1997)
Maui	Hawaii	H65-7052	Plant	Growth analysis	0.53	-	1.82 x 0.91	I	Meki et al. (2015)
Chiredzi	Zimbabwe	ZN6	Plant	Modelling	0.43-0.67	-	Not specified	I	Zhou et al. (2003)
Chiredzi	Zimbabwe	ZN7	Plant	Modelling	0.42-0.70	-	Not specified	I	Zhou et al. (2003)
Chiredzi	Zimbabwe	N14	Plant	Modelling	0.41-0.60	-	Not specified	I	Zhou et al. (2003)
Chiredzi	Zimbabwe	NCo376	Plant	Modelling	0.43-0.70	-	Not specified	I	Zhou et al. (2003)
Uda Walawe	Sri Lanka	Several	Plant	Growth analysis	-	0.22-0.28	Not specified	I	De Silva and De Costa (2012)
Uda Walawe	Sri Lanka	Several	Plant	Growth analysis	-	0.31-0.47	Not specified	R	De Silva and De Costa (2012)
San Luis Potosi	Mexico	CP72-2086	Plant	Modelling	0.69	-	1.2 to 1.4	R	Baez-Gonzalez et al. (2018)

[a] Photosynthetically active radiation
[b] Solar radiation
[c] CS = Cropping system; I = Irrigated; R = Rainfed

Table S4

Values of the light extinction coefficient based on photosynthetically active radiation and solar radiation found for Brazilian varieties in literature.

Site	Country	Variety	Crop cycle	Experiment issue (s)	Based on PAR [a]	Based on SRAD [b]	Row spacing (m)	CS [c]	Reference
Piracicaba, SP	Brazil	NA56-79	Plant	Modelling	0.88	0.52	1.4	R	Machado (1981)
Piracicaba, SP	Brazil	RB855156	Plant	Growth and Quality analysis	0.58	-	1.4	R	Scarpari and Beauclair (2008)
Piracicaba, SP	Brazil	SP80-3280	Plant	Growth and Quality analysis	0.48	-	1.4	R	Scarpari and Beaclair (2008)
Juazeiro, BA	Brazil	RB92579	R1	Growth analysis	0.72	-	1.5	I	Silva (2009)
São Paulo State	Brazil	SP83-2847	Plant/R1	Modelling	0.73	-	1.4 to 1.5	I/R	Marin and Jones (2014)
Campinas	Brazil	IACSP95-5000	Plant	Physiology	0.45	-	1.5	I	Magalhães Filho (2014)
Campinas	Brazil	IACSP94-2101	Plant	Physiology	0.50	-	1.5	I	Magalhães Filho (2014)
Campinas	Brazil	SP79-1011	Plant	Physiology	0.53	-	1.5	I	Magalhães Filho (2014)
Campinas	Brazil	IACSP94-2094	Plant	Physiology	0.40	-	1.5	I	Magalhães Filho (2014)
Rio Largo, AL	Brazil	RB98710	Plant	Irrigation and row spacing	0.48	-	1	I	Ferreira Junior et al. (2015)
Rio Largo, AL	Brazil	RB98710	Plant	Irrigation and row spacing	0.51	-	1.4 x 0.6	I	Ferreira-Junior et al. (2015)
Pelotas, RS	Brazil	RB867515	Plant	Growth analysis	-	0.70	1.4	R	Araújo (2016)
Pelotas, RS	Brazil	RB966928	Plant	Growth analysis	-	0.75	1.4	R	Araújo (2016)
Pelotas, RS	Brazil	RB855156	Plant	Growth analysis	-	0.66	1.4	R	Araújo (2016)
Pelotas, RS	Brazil	RB92579	Plant	Growth analysis	-	0.62	1.4	R	Araújo (2016)
Piracicaba, SP	Brazil	RB867515/RB966928	Plant/R1	Growth analysis - Monoculture	0.74	-	1.4	I	Grubert (2018)
Piracicaba, SP	Brazil	RB867515/RB966928	Plant/R1	Growth analysis - Canola between rows	0.71	-	1.4	I	Grubert (2018)
Piracicaba, SP	Brazil	RB867515	Plant/R1/ R2	Modelling	0.59	-	1.4 to 1.5	I/R	Vianna (2018)
Guadalupe, PI	Brazil	6 varieties pooled	Plant	Modelling	0.65	-	1.5 x 0.9	I	Dias et al. (2019)

[a] Photosynthetically active radiation
[b] Solar radiation
[c] CS = Cropping system; I = Irrigated; R = Rainfed

Table S5

Number of measurements employed in the APSIM-Sugar modelling during calibration (plant crop) and validation (first ratoon) processes for both sites, São Romão, MG, and Guadalupe, PI.

Variety	Plant crop (calibration)			First Ratoon (validation)		
	São Romão, MG	Guadalupe, PI	Both	São Romão, MG	Guadalupe, PI	Both
RB867515	46	55	101	11	6	17
RB92579	46	57	103	11	6	17
RB931003	9	57	66	12	6	18
RB961003	43	57	100	12	4	16
RB966928	46	13	59	11	4	15
RB98710	10	55	65	12	4	16
SP81-3250	46	12	58	11	6	17
SP94-3206	12	53	65	11	6	17
VAT90212	46	-	-	11	-	-
RB835054	12	12	24	11	6	17
RB835486	-	12	-	-	4	-
RB845210	10	12	22	12	6	18
RB855156	9	11	20	11	4	15
RB855453	13	-	-	11	-	-
RB855536	12	-	-	11	-	-
RB863129	-	13	-	-	4	-
RB931011	-	13	-	-	4	-
RB947532	10	13	23	12	6	18
RB951541	10	13	23	12	4	16
RB957508	10	13	23	12	4	16
RB99395	10	13	23	12	6	18
RB012046	10	13	23	12	6	18
RB012090	10	13	23	12	4	16
SP80-1816	10	12	22	12	4	16
IACSP87-3396	12	12	24	11	6	17
IACSP95-5000	12	13	25	11	4	15
CTC2	10	12	22	12	6	18
Overall	464	559	1023	276	120	396

Table S6

Performance of APSIM-Sugar to predict fractional photosynthetically active radiation interception (PARi) for six varieties grown in two row spacings in São Romão, MG.

Variety	R^2	*d*	RMSEP (%)
RB867515	0.87	0.96	10.34
RB92579	0.79	0.93	15.02
RB961003	0.53	0.84	29.26
RB966928	0.82	0.95	11.53
SP81-3250	0.88	0.94	11.38
VAT90212	0.61	0.85	21.54
Single row 1.5 m	0.86	0.92	18.67
Alternate rows 1.5 x 0.9 m	0.87	0.88	15.38
Overall	0.72	0.91	16.98

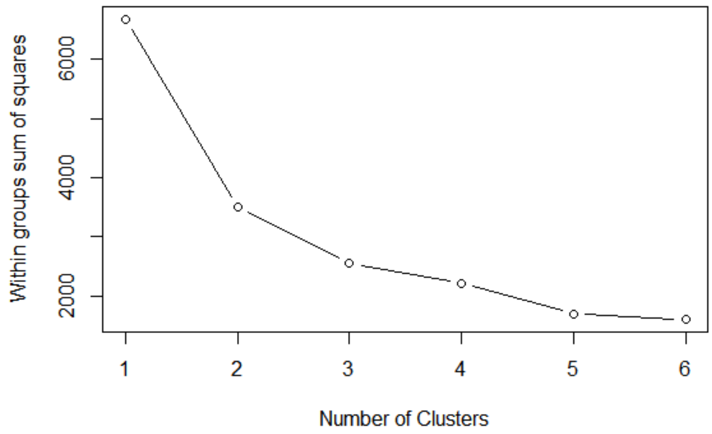

Fig. S1. Within groups sum of squares from *k-means* clustering of thermal time required for varieties canopy development to reach the point at which photosynthetically active radiation (PARi) is 50% obtained through long-term APSIM-Sugar simulations for each variety at two Brazilian sites and 12 starting dates (corresponding to months of the year)

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4. High-yielding sugarcane in tropical Brazil – Integrating field experimentation and modelling approach for assessing variety performances

Abstract

Aiming to gain understanding on yield accumulation by elite varieties in Brazil, a dataset from large field experiments carried out in tropical sites in Brazil (Guadalupe, 6.8 ºS; São Romão, 16.4 ºS) were integrated with the APSIM-Sugar model with recently determined traits and a new feature to account for growth slowdown (reduced growth phenomenon) in highly favourable environments. By doing that, we also aimed to improve APSIM-Sugar ability for the purpose of applying the model by the end-users. Yield levels achieved in both environments were high as far as cane yield is concerned, but temperatures are more favourable for canopy development and stalk formation at Guadalupe than at São Romão. Variety RB961003 produced remarkable yields at both environments. Even though it did not differ statistically from the other varieties at São Romão, its ability to keep increasing mass of stalks was evident. The most cultivated varieties, RB867515 in Center-Southern Brazil and RB92579 in Northeast region, considered as stable and high-yielding genotypes in several Brazilian environments, were ranked well in both experiments concerning crop performance. RB98710 had the poorest performance compared with the other varieties at Guadalupe, which was caused by a severe growth slowdown and lower biomass partitioning to stalks in comparison to other varieties. APSIM-Sugar was able to predict cane yields accurately in both experiments as well as the differences among varieties when specific slowdown reducing factors were invoked. Differences in growth slowdown factors between varieties RB867515 and RB961003 at leaf stages #30, #40 and #50 were consistent at both sites, showing that RB961003 is better for maintaining growth rates when yields are high and crops are likely to lodge. The outcomes from the modelling study showed that the model is now better able, even though yet empirically, to account for ageing processes to get reliable yield predictions in favourable environments, as well as the ability to distinguish between varieties when it comes to yield gains above ~150 t/ha (~40 t/ha in dry mass). Possible implications of the findings of this study for management at irrigated sites are also discussed.

Keywords: *Saccharum* spp.; Biomass; Reduced growth phenomenon; Potential yield; APSIM; Traits

4.1. Introduction

Brazil is the largest sugarcane producer around the world and the crop is used as a raw material for sugar, biofuel (ethanol) and bioelectricity production (FAO, 2019; Leal et al., 2013; Waclawovsky et al., 2010). The Brazilian government is adopting measures through the 'RenovaBio' program to stimulate the production and use of biofuels, including ethanol, aiming to reduce greenhouse gas emissions (Brazil, 2015; Grassi and Pereira, 2019; MME, 2017). The incentives for biofuels consumption will mainly require, from the agricultural perspective, increments in yields. Therefore, understanding how sugarcane will perform in new environments to where the crop is expanding is a fundamental step to achieve sustainable production.

Dias et al. (2019) recently analysed new field data for understanding genotype × environment × crop management (G × E × M) interactions using a modelling approach to account for high cane yields obtained under full irrigation and high temperatures in Guadalupe, Piauí State, Brazil. Cane yield started to differentiate between varieties from 7-8 months-old onwards, which was attributed to varietal differences in the reduced growth phenomenon (RGP). Evidence for the RGP was presented by Park et al. (2005) in a comprehensive study of yield accumulation in the Australian sugar industry. RGP was also recognised earlier at least indirectly by authors such as Rostron (1974), Lonsdale and Gosnell (1976), Thompson (1978), Inman-Bamber and Thompson (1989) and Muchow et al. (1994). This phenomenon results in reduced radiation use efficiency (RUE, Monteith, 1972; Sinclair and Muchow, 1999), usually under highly favourable environments where lodging is often observed. However, RGP was also observed in some crops which remained erect, raising the possibility that other factors such as an irreversible decline in leaf nitrogen content with age, respiration when crops were large, and feedback inhibition of photosynthesis by high sucrose content in mature internodes, could be involved (Park et al., 2005; van Heerden et al., 2010). Nevertheless, the factors that are advocated to contribute to growth slowdown were not considered as conclusive yet.

Maximum RUE in APSIM-Sugar is assumed to be constant over the growing season and has historically been used in this way, with few exceptions where site-specific lodging rules were applied to better simulate irrigated yields in Australia (Biggs et al., 2013; Meier and Thorburn, 2016; Thorburn et al., 2017). Aiming to deal with this phenomenon through crop modelling, Dias et al. (2019) introduced a new feature in the APSIM-Sugar model (version 7.9 r4404 and later), which allows RUE to be modified by leaf stage as a catchall for all RGP factors aiming to avoid excessive prediction of high yields. The slowdown coefficients proposed were regarded as appropriate at least for the Brazilian gene pool because they explained yield accumulation measured in experiments independent of those used to develop the coefficients. Furthermore, they also accounted reasonably well for yields of the original dataset (mainly Australian) used for model development (Keating et al., 1999). The feature did not change the performance Keating's model version substantially because his yields were generally not as high as they were in Northeast Brazil. Nonetheless, the feature helped to correct simulated yields above 150 t/ha where observed yields were not as high. The authors suggested that the new feature in APSIM-Sugar should be used in situations where simulated yields are likely to exceed 150 t/ha (~ 40 t/ha in dry mass basis). This recommendation could depend on variety because RGP seems to be influenced partially by variety (Donaldson et al., 2008; Tejera et al., 2007; van Heerden et al., 2010), which could explain differences in cane yields in high yielding (above 150 t/ha) environments.

This study aimed to assess RGP for Brazilian sugarcane varieties when grown under high-yielding (potential) conditions by integrating field data from serial harvesting experiments in two tropical environments with crop modelling using the APSIM-Sugar model. The goal was to improve the simulation capability of APSIM-Sugar for the purposes of potential yield estimation, irrigation impact and scheduling analysis, yield gap analysis, improved choice of variety and planting and harvesting date options, impact of climate change, amongst other uses of the model.

4.2. Material and methods

In this study, the sugarcane yield dataset from Dias et al. (2019) was used together with more field data from another tropical environment in Brazil (São Romão, Minas Gerais State) towards understanding how sugarcane varieties perform in terms of yield accumulation and growth slowdown in high-yielding (potential) conditions. The experiments were designed to gain knowledge of the G × E × M interaction in tropical Brazil concerning biomass and sugar production rather than to fully unravel the factors underlying the RGP itself. These datasets were integrated with modelling to further knowledge of variety distinctions and to allow for extrapolation of the data to other environments.

4.2.1. Field Experiments

Several field experiments were carried out at two areas of Agro-Industrial Complexes of Terracal Company to achieve potential yield and aiming to gain knowledge of the G × E × M interactions in tropical Brazil. The experiments were conducted in Guadalupe, state of Piauí (6.8 ºS, 43.6 ºW, and 170 m asml), and São Romão, state of Minas Gerais (16.4 ºS, 45.1 ºW, and 500 m asml), both in the Central-North region of Brazil. The predominant soils at Guadalupe and São Romão were classified, according to FAO soil classification system, as Ferralsol (*Latossolo Amarelo* in the Brazilian system) and Arenosol (*Neossolo Quartzarênico*), respectively. Further information about soils properties can be found in supplementary Table S1. The experiments and their management were described previously in Dias et al. (2019) (at Guadalupe) and in Dias et al. (2020) (both sites), in which the feature to account for RGP in APSIM-Sugar was introduced and variety-specific traits for 27 Brazilian varieties regarding canopy formation and light interception were determined, respectively. The main features of the experiments are briefly described here. The experiments employed for statistical and modelling are described in Section 4.2.1.1 and those for model validation are described in Section 4.2.1.2.

4.2.1.1. G × E × M experiments

The experiments were designed to investigate the variety × planting date × harvest age interaction. Both experiments were installed in a randomised blocks design with a split-split-plot arrangement, with four replications. Three factors were considered: planting dates (main plot with six levels); varieties (subplot with six levels); and crop ages at harvesting (sub-sub plots with three or five levels).

At São Romão, sugarcane was planted in August, October and December of 2013, and in March, May and June of 2014. The planted varieties were RB867515, RB92579, RB961003, RB966928, SP81-3250 and VAT90212. The harvesting ages were around 8, 10, 12, 13.5 and 15 months after planting. At Guadalupe, sugarcane was planted in July, September and November of 2014, and in January, April and May of 2015. The varieties were RB867515, RB92579, RB931003, RB961003, RB98710 and SP94-3206. The harvests in Guadalupe occurred at about 8, 11.5 and 15-months-old. Varieties RB867515, RB92579 and RB961003, and harvesting ages at 8, ~12, and 15 months, were thus common between sites. The varieties were chosen to represent a range of those commonly used in the Brazilian sugarcane industry, such as RB867515 and RB92579, which are the most cultivated in Southern and Northeast regions, respectively, and those that are gaining importance, like RB966928, the most widely variety planted in 2018-19 growing season, and RB931003 and RB961003 which are well-adapted to tropical areas. A brief comparison of the varieties used in this study, considering the breeding companies' catalogues, can be found in a supplementary table in Dias et al. (2020).

Actual measurements of (aboveground) biomass components were taken when crops were 7 to 16 months old, following the recommendations of Muchow et al. (1993) and Robertson et al. (1996). Since three varieties were common for both experimental sites, there was a total of nine varieties which provided measurements of dry biomass accumulation and other yield components.

Larger net plot- and border-areas were required for later harvests because of the increased length of cane stalks. Within 2 months after planting, pegs were inserted firmly to demarcate the sub-sub plot (harvest age) areas. A rope was tied between pegs to ensure that the crop rooted in the sub-sub plot area was harvested and nothing else. This was essential for a given crop that lodged as early as 5/6 months. Starting from one of the pegs, 15 contiguous stalks in the sub-sub plot area were cut at the base and set aside. All remaining stalks in the demarcated area were then cut and weighed with the green and dead leaves attached. Green leaf blades and dead leaves were removed and weighed. Green leaf sheaths including stalk tissue above the fourth node from the top of the stalk were removed and weighed. The remaining millable cane stalk was weighed.

Sub-samples of plant components were weighed and properly dried in a forced draft oven at the laboratory to determine the dry matter content, and thereby stalk dry matter yield and yield other dry components. At São Romão, no measurements were taken at 8 months in plots planted in March, and at 13.5 months in plots planted in October, due to operational difficulties.

4.2.1.1.1. Meteorological conditions during the experiments

In-site automatic weather stations (Campbell Scientific, CS) for each site were used for monitoring the meteorological conditions. The weather stations 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 relative humidity sensor (CS215 model). Table 1 presents the details for each experiment, concerning the planting and harvesting dates, as well as the summary of the meteorological conditions and total irrigation applied throughout the growing seasons, which are also presented in Fig. 1 on a daily scale.

At Guadalupe, daily maximum temperature increased from April to October each year with little day-to-day variation. Maximum temperatures never exceeded 40 °C and were mostly greater than 30 °C. Day-to-day variation in minimum temperature was also small (~ 5 °C) around a seasonal pattern with lowest values (never < 17 ºC) mid-year and highest values between October and January. On average, mean temperatures fluctuated between 25 and 29 ºC across planting dates. Solar radiation exceeded 25 $MJ/m^2/d$ between September and November, but also in February 2016, with little variation in the total amount for the 15-month growth cycle, across planting dates (~8692 ± 181 MJ/m^2). Wind speeds extrapolated to a 2-m height often exceeded 2 m/s between July and October each year, coinciding with low relative humidity. Rainfall occurred mainly in the spring and summer in 2014/2015, when it was well distributed with only two events higher than 50 mm/d. In 2015/2016 rain fell mainly during January and February with three events higher than 70 mm/d. Cumulated in-crop rainfall exceeded 1000 mm only for November (spring 2014) and January plantings (summer 2015).

At São Romão mean air temperature averaged 25 ± 0.3 ºC across planting dates, considerably lower than at Guadalupe. Day-to-day and annual variation in minimum temperature was more pronounced at São Romão than at Guadalupe as may be expected by the latitudinal and altitudinal differences. Temperatures were as low as 10 ºC on seven occasions at São Romão. Solar radiation approached 30 $MJ/m^2/d$ between October and February, with some variation in terms of the total incoming radiation across planting dates (~ 9464 ± 410 MJ/m^2), which was mostly above 9000 MJ/m^2 and higher than Guadalupe for all plantings. Wind speed was similar between sites apart from the very windy conditions (>3.5 m/s) experienced at Guadalupe on several occasions. In-crop rainfall was higher than 895 mm for all planting date treatments at São Romão, and averaged 1207 mm (~ 20% more than Guadalupe).

The total irrigation applied in the experiments depended on the interactions between the environment (weather and soil conditions) and sugarcane growth phases. Water requirement to keep sugarcane free of stress throughout its growing period ranged from 2235 to 2843 mm at Guadalupe, and from 1585 to 1858 mm at São Romão.

Table 1

Experimental details regarding management and meteorological conditions during the sugarcane crop cycles for each planting date in Guadalupe, PI, and São Romão, MG, in Brazil.

Site	Crop start	Harvesting	Mean air temperature (ºC)	Total Rainfall (mm)	Total Irrigation (mm)	Total solar radiation (MJ/m^2 cycle)
Guadalupe, PI	2014/Jul	2015/Sep	28.4	776	2235	8408
	2014/Sep	2015/Dec	28.8	794	2385	8618
	2014/Nov	2016/Feb	28.7	1309	2452	8666
	2015/Jan	2016/Apr	28.7	1430	2669	8687
	2015/Apr	2016/Jun	25.5	920	2843	8924
	2015/May	2016/Aug	25.2	853	2824	8847
São Romão, MG	2013/Aug	2014/Nov	24.9	1356	1666	9813
	2013/Oct	2015/Jan	25.1	1495	1687	9849
	2013/Dec	2015/Mar	25.1	1544	1585	9789
	2014/Mar	2015/Jul	24.7	1052	1814	9277
	2014/May	2015/Aug	24.4	899	1858	9187
	2014/Jun	2015/Sep	24.7	896	1773	8871

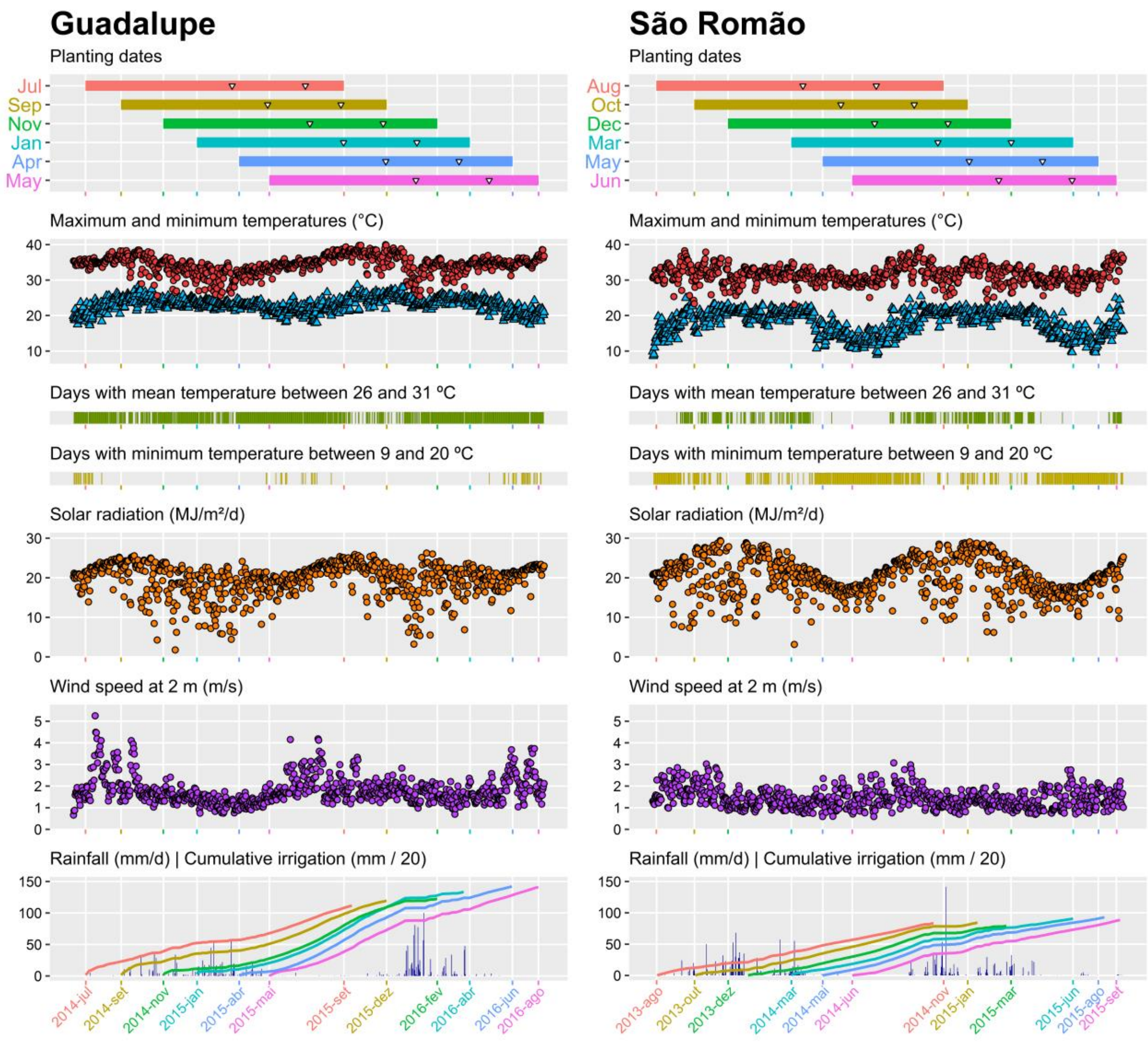

Fig. 1. Daily weather conditions and accumulated irrigation during sugarcane field experiments in Guadalupe, PI, and São Romão, MG, in Brazil. The symbol ▽ indicates harvests at 8 and 12 months.

4.2.1.2. Variety experiments for model validation

The modifications to the model were validated with independent data from several field experiments at the São Romão and Guadalupe sites, carried out with a total of 27 varieties of which nine were in common with those used in the G × E × M experiments. The validation experiments were designed as random blocks with four replications for the purpose of testing the suitability of Brazilian for new production enterprises. Cane yield (or stalk fresh mass) for each plot was measured at harvest when the plant and ratoons were about 14 and 12 months old, respectively. Results of only nine varieties in the variety experiments were used for validation because they were the only ones used in the G × E × M experiments and the only varieties for which dry matter content estimates were possible. Further details can be found in Dias et al. (2020).

At Guadalupe, there were four validation experiments, each one with 12 varieties, two planted in October 2014 and two in June 2015 that were harvested and ratooned in 2015 and 2016, providing yields determined on six occasions, which were used in model validation. For the São Romão environment, experiments with 12 varieties were conducted from the end of 2012 to 2016 from four planting dates. An experiment planted in December 2012 included four crop cycles (plant crop and three ratoons), in which in the first cycle yield was also measured before the final harvest (~ 14 months) on two occasions (at ~ 8 and ~ 12 months). An experiment planted in August 2013 provided plant crop yield at harvesting, whereas another planted in April 2014 presented yields at harvesting for the plant crop and the subsequent ratoon. A plant crop and two subsequent ratoons of variety RB961003 were grown in crop experiment started July 2014.

4.2.2. Data analysis of G × E × M experiments

4.2.2.1. Statistics

The yield components (stalk dry mass, cane yield, individual stalk – dry – weight and stalk population at harvest) were interpolated to estimate their values 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.

Firstly, an analysis of variance was conducted using the *lm* function in R *environment* (R CORE TEAM, 2018) for yield components for the three common varieties (RB867515, RB92579, RB961003) and harvest ages (8, 12 and 15 months) to analyse the site × variety × age interaction and verify whether varieties were consistent regarding growth slow-down across the two sites in Brazil. Two planting dates, one at each experimental site, were not included at this stage because the March planting date at São Romão was not sampled at 8 months and the July planting at Guadalupe flowered severely at 11.5 months. Flowering was mild for other planting dates.

Analyses of variance was then performed for each yield component for each site separately, based on a split-plot design with planting date as the whole plot treatment and varieties as the sub-plot treatment. Harvest ages, in this case, were analysed independently of the other treatment effects. Treatment effects were regarded as significant when *p-value* < 0.05. The least significant difference (LSD) *post-hoc* test at the 0.05 level of significance was then used to determine which treatment effects differed from each other in cases where variety and planting dates effects were significant at a given harvest age.

4.2.2.2. Modelling

The APSIM-Sugar model (version 7.9 r4404), which is a crop module embedded in the APSIM platform (**A**gricultural **P**roduction **S**ystems **SIM**ulator) (Holzworth et al., 2015; McCown et al., 1996) (Holzworth et al., 2014; McCown et al., 1996) was employed in this study for assessing sugarcane variety performance. The model was built to simulate sugarcane canopy development and light interception, crop biomass, cane and sucrose yield, water use and nitrogen uptake and partitioning. It runs on a daily time-step and genotype, climate (rainfall, air temperature and solar radiation), soil water, nitrogen and crop residues affect sugarcane performance. Further details of this model can be found in Keating et al. (1999), Thorburn et al. (2005), Singels (2014), Inman-Bamber et al. (2016), Marin et al. (2015) and Dias et al. (2019).

The simulations were run to represent the sugarcane crop under non-limiting conditions, as occurred in the field experiments. The soil pH was set at 6 to ensure that the plants were not stressed by nitrification. In the simulations, nitrogen was applied to avoid stresses in canopy development and biomass accumulation. Irrigation was simulated in APSIM always when necessary in order to avoid any water stress. All stress factors were checked through the accumulation of stress days following Inman-Bamber et al. (2016).

Canopy (leaf size, green leaf number, tillering and stalk emergence) and radiation capture (extinction coefficient for photosynthetically active radiation interception) traits for each variety were obtained from Dias et al. (2020), which were based on several field experiments, including those employed in this this study. The variety traits can be found in Supplementary Tables S2 and S3. Overall, the APSIM-Sugar model predicted the photosynthetically active radiation interception satisfactorily for the nine varieties included in the present study (see Supplementary Table S4).

Stalk fraction for APSIM-Sugar (*cane_fraction*) was determined as the slope of the regression equation between stalks dry mass and dry biomass which included mature and immature stalks (cabbage), green leaf sheaths, green leaves and dry leaves attached (Cheeroo-Nayamuth et al., 2000). Following Evensen et al. (1997), Muchow et al. (1997) and Robertson et al. (1996), the total biomass was increased by 15% to consider the crop residues unrecovered during the growing season. The intercept, which represents the biomass produced before stalk elongation, was set as 10.9 t/ha which was obtained from Singels and Smit (2009) for a South African cultivar arranged (row spacing) at 1.3 m apart, similar to what was used in our field experiments.

The RGP feature in APSIM-Sugar is driven by leaf stage, in other words, the physiological age, and is used to decrease RUE. This feature, while not explained on the APSIM website can be invoked using a Sugar.xml file which is also not explained officially as yet but can be inserted in the user interface where no option to do this seems available. The feature was invoked to deal with the observed reduction in cane yield accumulation. Slowdown factors (RGP_F, *y_rue_leaf_no_fact*) applied to RUE for each leaf stage (*leaf_no*) were derived using the Gompertz equation, in which 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 (Dias et al., 2019). The RGP_F used in APSIM were determined for each growth stage, which was defined according to the leaf number: #10, #20, #30, #40 and #50.

Lodging, one of the causes of RGP, is influenced by G and E (Amaya et al., 1996; Berding and Hurney, 2005; Carlin et al., 2008; Singh et al., 2002; Singkham et al., 2016; van Heerden et al., 2015). RGP itself also seems to be influenced by G and E (Donaldson et al., 2008; Park et al., 2005; Tejera et al., 2007; van Heerden et al., 2010). Therefore, RGP_F were calibrated for each variety by running 539 simulations for each of the 72 (2 x 6 x 6) combinations of environment, planting date and variety. For each treatment combination, growth slowdown values were derived from all factorial combinations of the A, B and C coefficients in the Gompertz equation [*y_rue_leaf_no_fact* = 1 – A × exp (– exp (B – C × *leaf_no*))], following Dias et al. (2019) where A was varied between 0.35 and 0.65 in increments of 0.05, B between 5.5 and 8.5 in increments of 0.5 and C between 0.20 and 0.30 in increments of 0.01 (7 x 7 x 11 = 539). The Gompertz coefficients that provided the best fit between observed and simulated yield for each treatment yield where then used and the rest discarded. The graphics for visual analysis in all the modelling steps were created using the *ggplot2* package (Wickham, 2016) in the *R environment* (R CORE TEAM, 2018).

4.2.2.2.1. RUE slowdown factors (RGP_F) determination and comparison

The performance of APSIM-Sugar in predicting stalk dry mass was assessed by common statistical indices in crop modelling, such as coefficient of determination (R^2), root mean squared error (RMSE) and its percentage (RMSEP) and Willmott's '*d*' index (Wallach, 2006). An alternative index called 'C' was also used, which is calculated as $\sqrt{R^2} \times d$ (Camargo and Sentelhas, 1997). The best combination was found by minimising model errors, which is a common approach in crop modelling (Seidel et al., 2018). In our study the lowest RMSE was used to define optimum Gompertz and hence RGP_F coefficients. Actual harvesting dates and yields were used instead of the normalised ones employed in Section 4.2.2.1.

4.2.2.2.2. Simulations for model validation

Cane yield for the experiments described in Section 4.2.1.2. were used to verify the model variety traits at Guadalupe and São Romão. Physiological parameters were left as they were for the G × E × M experiments including RGP_F values apart from the need to use means across planting dates. RGP_F values were thus specific to each variety and experimental site but not for the different planting and ratooning dates of the validation experiments. The stalk water content dynamic simulated by APSIM-Sugar was recognised to be inappropriate by Dias et al. (2019) and they employed an empirical equation based on daily air temperature amplitude averaged over 20 days before measurements (ampd20) and cumulated daily thermal time (TT) to account for the dry matter content (DMC) as follows: $DMC = 17.854 + ampd20 \times (TT/1000) \times 0.115$. This equation was coupled with stalk dry mass simulated by the model to get cane yield in both locations, even though it was developed for Guadalupe conditions.

4.3. Results

4.3.1. Statistical analysis

4.3.1.1. Analysing variety growth slowdown across environments

The analysis of variance to verify if there is evidence of differences in growth slowdown across the two experimental sites is presented in Table 2. The site × variety × harvest age interaction was not significant for any yield components. By contrast, age effects and the site × variety interaction were mostly highly significant. The site × age effect was only significant for individual stalk dry mass. Stalk number, on the other hand, was the only exception in terms of significance for the site effect and variety × age interaction. There is evidence for significant variety differences for all components with the exception of stalk dry mass.

The variety × age interaction was significant for all mass components but the site × variety × age interaction was not significant for any mass component (*p-values* 0.43-0.87; Table 2), as well as stalk number (*p-value* = 0.96). Varietal differences in growth slowdown with age were therefore consistent across the two environments in tropical Brazil.

Table 2

Analysis of variance for site × variety × age interaction for sugarcane yield components for common varieties (RB867515, RB92579, RB961003) and harvest ages (8, 12 and 15 months) between experimental sites. Symbols: * (*p-value* < 0.05), ** (*p-value* < 0.01), *** (*p-value* < 0.001), and ns (not significant).

Effect	Stalk dry mass	Cane yield	Individual stalk dry mass	Stalks/m²
Site	< 0.001 ***	< 0.001 ***	< 0.001 ***	0.44 ns
Variety	0.27 ns	< 0.01 **	< 0.001 ***	< 0.001 ***
Age	< 0.001 ***	< 0.001 ***	< 0.001 ***	< 0.001 ***
Site × Variety	< 0.01 **	< 0.001 ***	< 0.05 *	< 0.01 **
Site × Age	0.16 ns	0.95 ns	< 0.05 *	0.35 ns
Variety × Age	< 0.05 *	< 0.05 *	< 0.01 **	0.75 ns
Site × Variety × Age	0.43 ns	0.87 ns	0.44 ns	0.96 ns

4.3.1.2. Guadalupe

A summary of the statistics concerning planting dates and varieties separately for sugarcane yield components at Guadalupe experiment is presented in Table 3. Stalk dry mass at 8 months was similar (~ 40 t/ha) for all planting dates. For cane yield (fresh basis), the November planting yielded only 147 t/ha at this stage, significantly less than for the other planting dates. At 11.5 and 15 months, stalk dry mass differed between planting dates, the autumn ones (April and May) being the most productive (79.9 and 76.6 t/ha at 15 months, respectively). Cane yields differed substantially at 15 months with the April planting yielding as high as 260 t/ha and the September planting as low as 212 t/ha. Yields at 15 months for the other planting dates were similar, averaging ~ 243 t/ha.

Varieties differed consistently for stalk dry mass at 11.5 and 15 months and cane yield at all ages, with RB98710 being the least productive. At 15 months varieties RB961003 and RB931003 were not significantly different in regard to stalk dry mass whereas the cane yield for RB961003 was higher than all the other varieties at this age. The average cane yield for RB961003 across all planting dates was 230 t/ha at 11.5 months and 231 t/ha at 15 months.

The interaction between varieties and planting dates was significant at 11.5 months for both stalk dry mass and cane yield (see Table S5). The highest dry stalk yield was obtained with RB961003 and RB931003, partly due to superior performance when planted in April and May (data not shown). Yields exceeding 310 t/ha were obtained with RB961003 planted in April and November when harvested with 15 months (data not shown).

Individual stalk (dry) weight and stalk number were, in general, inversely proportional as may be expected. For instance, at 8 months stalks for the crop planted in July were significantly heavier than for the May and January planting (0.43 *versus* 0.32 kg), but the opposite was true for stalk numbers (9.3 *versus* 12.0 and 12.9 per m^2). Conversely, at 15 months, varieties starting in July had seven stalks/m^2 more than those starting in May and January, but with the stalks weighing less (0.49 *versus* 0.85 and 0.63 kg). Despite that, there was no interaction between planting date and varieties for individual stalk weight, suggesting that it is a reasonably stable trait for the Brazilian varieties assessed. Similar to cane yield, varieties differed consistently in stalk weight, which was substantially lower for RB98710 than for RB961003 and RB931003, at all three harvest ages. Varieties RB867515, RB92579 and SP94-3206 ranked between them for stalk weight.

Table 3

Mean comparison after an analysis of variance based on a split-plot design with planting date as whole plot treatment and sugarcane varieties as sub-plot treatment for stalk dry mass, cane yield, individual stalk dry mass and stalk number for sugarcane varieties harvested 8, 11.5 and 15 months-old in Guadalupe, PI, Brazil.

Crop variable	Factor	Level	Crop age (months)		
			8	11.5	15
Stalk dry mass (t/ha)	Planting date	July	40.4 ns	42.3 d	72.3 bc
		September	43.0 ns	47.9 c	62.1 d
		November	38.7 ns	50.0 bc	66.7 cd
		January	41.5 ns	54.9 a	66.4 cd
		April	37.7 ns	52.4 ab	79.9 a
		May	37.5 ns	53.5 ab	76.6 ab
	Variety	RB867515	40.0 ns	50.8 ab	70.0 c
		RB92579	40.0 ns	48.4 b	72.2 bc
		RB931003	42.4 ns	54.8 a	75.5 ab
		RB961003	38.8 ns	54.2 a	80.1 a
		RB98710	37.0 ns	42.1 c	58.7 d
		SP94-3206	40.7 ns	50.7 ab	67.6 c
Cane yield (t/ha)	Planting date	July	180.0 a	216.3 a	252.7 ab
		September	177.3 a	168.6 c	211.7 c
		November	146.6 b	187.8 b	243.9 ab
		January	167.1 a	212.9 a	237.9 b
		April	175.3 a	210.9 a	259.6 a
		May	177.8 a	218.0 a	238.7 b
	Variety	RB867515	168.6 b	208.4 b	239.3 bc
		RB92579	173.9 ab	193.2 c	247.5 b
		RB931003	171.3 b	205.3 bc	246.9 b
		RB961003	184.0 a	229.8 a	281.1 a
		RB98710	156.7 c	174.1 d	202.2 d
		SP94-3206	169.5 b	203.8 bc	227.6 c
Individual stalk dry weight (kg)	Planting date	July	0.43 a	0.46 ns	0.49 d
		September	0.39 a	0.47 ns	0.65 c
		November	0.38 ab	0.52 ns	0.66 c
		January	0.32 b	0.59 ns	0.63 c
		April	0.40 a	0.53 ns	0.74 b
		May	0.32 b	0.51 ns	0.85 a
	Variety	RB867515	0.39 bc	0.51 bc	0.65 cd
		RB92579	0.35 c	0.48 c	0.62 de
		RB931003	0.39 ab	0.54 ab	0.71 b
		RB961003	0.37 bc	0.58 a	0.77 a
		RB98710	0.30 d	0.41 d	0.57 e
		SP94-3206	0.43 a	0.57 a	0.69 bc
Stalks/m²	Planting date	July	9.3 c	10.3 ns	16.2 a
		September	11.4 ab	10.6 ns	10.2 b
		November	10.3 bc	9.8 ns	10.2 b
		January	12.9 a	9.8 ns	10.6 b
		April	9.8 bc	9.8 ns	11.0 b
		May	12.0 a	10.5 ns	9.1 c
	Variety	RB867515	10.7 c	10.3 a	11.4 ns
		RB92579	11.4 b	10.6 a	12.1 ns
		RB931003	10.9 bc	10.4 a	11.2 ns
		RB961003	10.7 c	10.0 a	11.1 ns
		RB98710	12.3 a	10.4 a	10.9 ns
		SP94-3206	9.6 d	9.0 b	10.5 ns

4.3.1.3. São Romão

A summary of the statistics concerning planting dates and varieties for sugarcane yield components at São Romão experiment is presented in Table 4. Unlike the Guadalupe experiment, stalk dry mass and cane yield significantly different across planting dates for all harvest ages. Stalk dry mass of the crops planted in August, October and May was at least 30.4 t/ha when varieties were 8-months old. June was generally the least productive planting date until 15 months of harvesting, which produced a remarkable 72.2 t/ha (238 t cane/ha). Together with December (63.3 t/ha), these were the most productive planting dates in terms of stalk dry mass at 15 months. As at the Guadalupe experiment, lodging occurred at São Romão for all planting dates at some point and to some extent, whereas flowering was observed for some varieties in March, August and October planting dates, which probably caused some seasonal cane yield variations.

Varieties differed regarding stalk dry mass at 8 and 10 months, but not for later harvests. RB966928 yielded almost 10 t/ha more than RB961003 (25.4 t/ha) at 8 months. With the exception of RB961003, all the other varieties were more productive than VAT90212 (31.6 t/ha) at 10 months. Mean yields at 15 months were 56.8 t/ha for stalk dry mass and 213 t/ha for cane yield and did not differ significantly between varieties. Similar to the Guadalupe experiment, variety RB961003 was one of the highest yielding ones when harvested after 8 months, approaching in the final harvesting, 218 t/ha in terms of cane yield across planting dates.

The interactions between varieties and planting dates for each harvest age were mainly not significant for yields (both dry and fresh mass), with exception of cane yield at the 12-month and stalk dry mass at 10 month which approached significance (see Table S5; *p-value* = 0.07). Variety RB966928 seemed to benefit from March and August planting dates at the referred age for which stalk dry mass reached at least 46.7 t/ha, but not from a June planting, which resulted in less than half of that yield (21.6 t/ha) (data not shown).

The compensation effect of individual stalk weight and stalk number across planting dates was not as clear for São Romão as it was for the Guadalupe experiment. Again, lodging probably played an important role in this compensation. The compensatory capacity was more evident across varieties than across sites. Especially at 15-month harvest age, varieties RB961003 and RB867515 had fewer stalks/m^2 (9.8 and 10.4 respectively) than almost all varieties, but usually had heavier stalks, weighing 0.59 and 0.55 kg respectively. RB867515 ranked highly in regard to individual stalk mass at all the harvest ages (Table 4).

Table 4

Mean comparison after an analysis of variance based on a split-plot design with planting date as whole plot treatment and sugarcane varieties as sub-plot treatment for stalk dry mass, cane yield, individual stalk dry mass and stalk number for sugarcane varieties harvested 8, 11.5 and 15 months-old in São Romão, MG, Brazil.

Crop variable	Factor	Level	Crop age (months)				
			8	10	12	13.5	15
Stalk dry mass (t/ha)	Planting date	August	32.8 ab	43.7 a	50.2 a	56.1 ab	51.8 c
		October	33.5 a	39.4 b	46.3 ab		48.4 c
		December	25.9 d	38.3 b	49.5 a	49.6 bc	63.3 b
		March		43.0 a	42.4 ab	58.9 a	50.6 c
		May	30.4 bc	30.2 c	38.9 b	44.8 c	48.9 c
		June	28.1 cd	22.4 d	42.5 ab	35.2 d	72.2 a
	Variety	RB867515	30.4 b	38.1 a	44.1 ns	49.3 ns	57.0 ns
		RB92579	31.6 ab	37.4 a	43.6 ns	49.7 ns	56.8 ns
		RB961003	25.4 c	35.0 ab	46.1 ns	50.2 ns	56.0 ns
		RB966928	35.0 a	38.1 a	46.5 ns	48.7 ns	53.8 ns
		SP81-3250	29.2 b	36.7 a	47.9 ns	46.5 ns	56.1 ns
		VAT90212	29.2 b	31.6 b	41.7 ns	48.9 ns	55.5 ns
Cane yield (t/ha)	Planting date	August	137.6 a	165.8 b	177.4 ns	175.2 ns	176.1 b
		October	134.8 a	144.3 cd	154.0 ns		185.7 b
		December	101.2 b	133.3 d	181.7 ns	174.8 ns	225.5 a
		March		187.1 a	179.7 ns	224.2 ns	226.3 a
		May	141.3 a	147.8 bcd	169.1 ns	203.1 ns	224.1 a
		June	146.7 a	160.7 bc	168.2 ns	175.0 ns	238.4 a
	Variety	RB867515	141.3 a	161.4 ab	172.8 ab	183.9 bc	214.0 ns
		RB92579	144.2 a	166.2 a	180.4 a	201.5 ab	218.2 ns
		RB961003	119.5 b	164.8 a	182.7 a	208.6 a	218.5 ns
		RB966928	141.0 a	153.4 abc	165.1 b	184.7 bc	206.3 ns
		SP81-3250	124.2 b	148.1 bc	168.5 ab	171.8 c	204.4 ns
		VAT90212	123.7 b	145.2 c	160.7 b	192.3 ab	214.6 ns
Individual stalk dry weight (kg)	Planting date	August	0.31 a	0.41 a	0.54 a	0.53 a	0.49 b
		October	0.34 a	0.36 b	0.43 b		0.49 b
		December	0.25 b	0.34 b	0.43 b	0.43 b	0.55 ab
		March		0.36 b	0.38 b	0.54 a	0.52 b
		May	0.24 b	0.29 c	0.38 b	0.41 bc	0.46 b
		June	0.24 b	0.22 d	0.45 b	0.35 c	0.62 a
	Variety	RB867515	0.29 b	0.38 a	0.44 a	0.47 a	0.55 ab
		RB92579	0.25 cd	0.32 b	0.40 b	0.43 ab	0.50 b
		RB961003	0.25 d	0.33 b	0.46 a	0.47 a	0.59 a
		RB966928	0.33 a	0.33 b	0.45 a	0.45 ab	0.50 b
		SP81-3250	0.24 d	0.31 b	0.43 ab	0.41 b	0.49 b
		VAT90212	0.28 bc	0.32 b	0.44 a	0.47 a	0.49 b
Stalks/m²	Planting date	August	10.7 bc	10.9 b	9.4 c	10.5 ns	10.2 cd
		October	10.4 c	10.9 b	10.5 ab		11.3 abc
		December	9.6 c	10.5 b	11.1 a	11.8 ns	11.5 ab
		March		12.3 a	11.1 a	10.9 ns	9.6 d
		May	12.4 ab	10.1 b	10.0 bc	10.6 ns	10.7 bcd
		June	12.5 a	10.1 b	9.5 c	10.3 ns	12.2 a
	Variety	RB867515	10.6 b	10.0 c	9.9 bc	10.4 ns	10.4 bc
		RB92579	12.4 a	11.5 a	10.9 a	11.5 ns	11.3 a
		RB961003	10.5 b	10.6 bc	10.1 bc	10.5 ns	9.8 c
		RB966928	10.6 b	11.2 ab	10.3 ab	10.7 ns	11.2 ab
		SP81-3250	12.4 a	11.6 a	11.0 a	11.5 ns	11.5 a
		VAT90212	10.2 b	9.9 c	9.4 c	10.3 ns	11.3 a

4.3.2. Use of APSIM-Sugar to distinguish between varieties

4.3.2.1. Stalk fraction

The stalk fraction obtained from the data for the varieties ranged from 0.65 for (RB98710) to 0.77 for (RB966928 and VAT90212) (Table 5). These fractions were used in modelling with the APSIM-Sugar model (*cane_fraction* parameter) before the optimisation of RGP_F. The most cultivated varieties in Southern (RB867515) and Northeast (RB92579) Brazil had a similar proportion (0.72 and 0.71, respectively) of stalks in the biomass.

Table 5

Stalk fraction in aboveground biomass for the nine Brazilian varieties grown under high input conditions at two tropical sites in Brazil (São Romão, MG and Guadalupe, PI).

Variety	Stalk fraction (*cane_fraction*)
RB867515	0.72
RB92579	0.71
RB931003	0.72
RB961003	0.75
RB966928	0.77
RB98710	0.65
SP81-3250	0.73
SP94-3206	0.71
VAT90212	0.77

4.3.2.2. Growth slowdown comparisons

APSIM-Sugar simulations results are depicted in Figs. 2 and 3 for Guadalupe and São Romão experiments, respectively. The Gompertz terms used to derive RGP_F to account for the observed growth reduction for each combination of site × variety × planting date and statistical indices for stalk dry mass can be found in Supplementary Tables S6 and S7, respectively. Medians (and ranges) for A, B and C terms were 0.50 (0.35-0.65), 7.0 (5.5-8.5) and 0.26 (0.20-0.30), respectively. The precision for simulated yield given by R^2 varied between 0.17 and 1.00 (median = 0.89), whereas the agreement given by the *d* varied between 0.51 and 1.00 (median = 0.95). The errors given by the RMSE ranged from 1.1 to 13.9 t/ha (median = 4.2 t/ha), resulting in a median of RMSEP of less than 10%.

For the Guadalupe experiment (Fig. 2), variety RB961003 required the least adjustment for growth slowdown. This was usually the most vigorous and best-performing variety in the experiment. RB98710 was the weakest variety and required the most adjustment to RUE starting as early as 6-7 months for some planting dates. The other varieties were intermediate in terms of RGP_F. Stalk dry mass simulated by APSIM-Sugar mostly fell in the range of measurements given by the standard deviation (bars), with the main exceptions of measurements at 11.5 months in July. These results mesh well with the data analysis presented in Section 4.3.1.

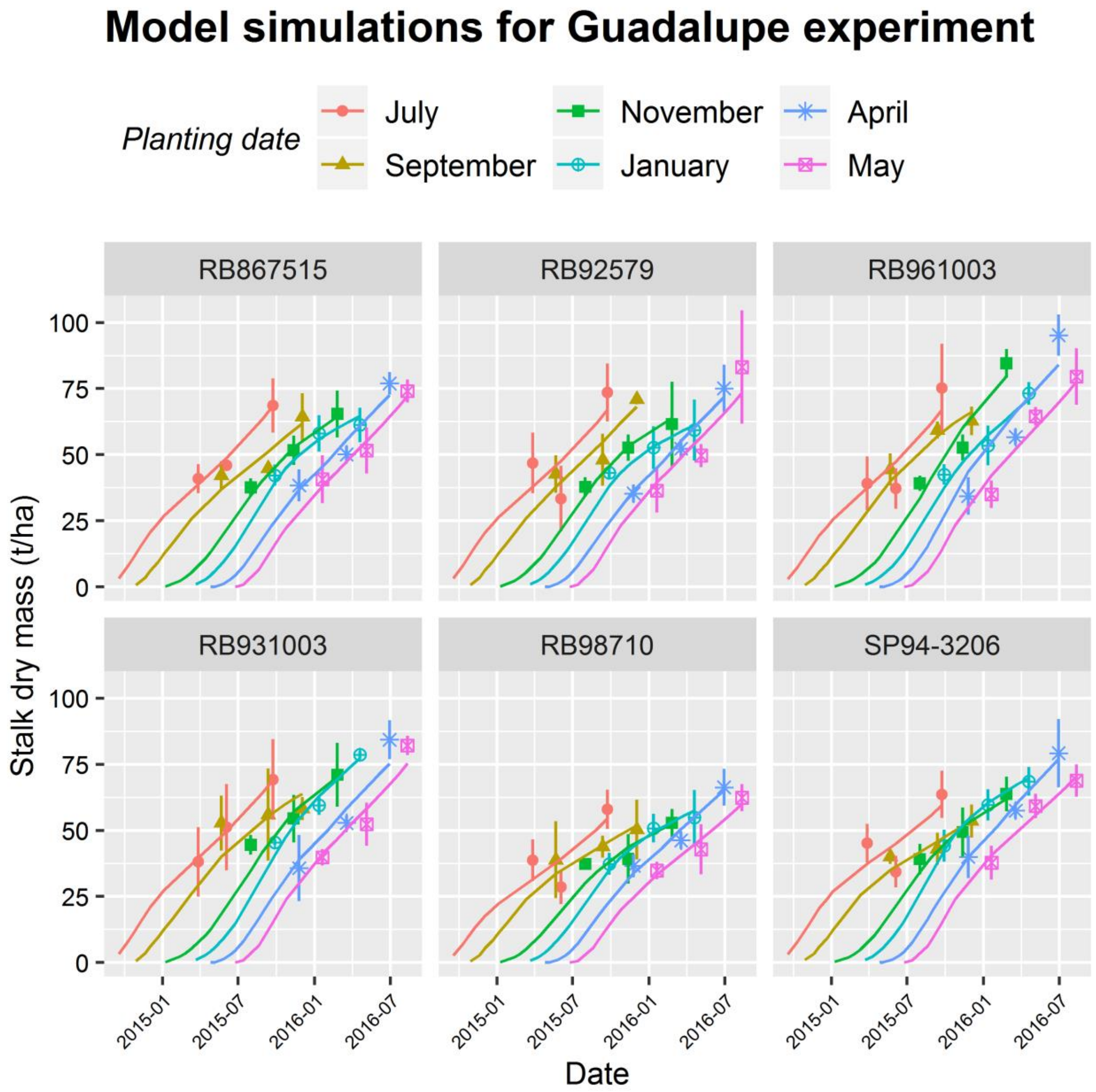

Fig. 2. Stalk dry mass measured (points plus bars) and simulated (lines) by the APSIM-Sugar model for Brazilian sugarcane varieties in different planting dates under in Guadalupe, PI, Brazil.

For São Romão experiment (Fig. 3), variety RB961003 also required the least adjustment for growth slowdown. RB966928 exhibited similar early levels of growth of RB961003, but RB867515, SP81-3250 and VAT90212 required early adjustments in the RGP_F. All varieties presented a similar reduction in RUE when approaching the final harvest. As at Guadalupe, stalk dry mass at São Romão simulated by APSIM-Sugar mostly fell in the range of measurements given by the standard deviation (bars), but the model failed to predict the variability and the high yields in June. Crops starting in December required the least adjustment to account for growth slowdown in the model. These results also reasonably agree with the data analysis presented in Section 4.3.1.

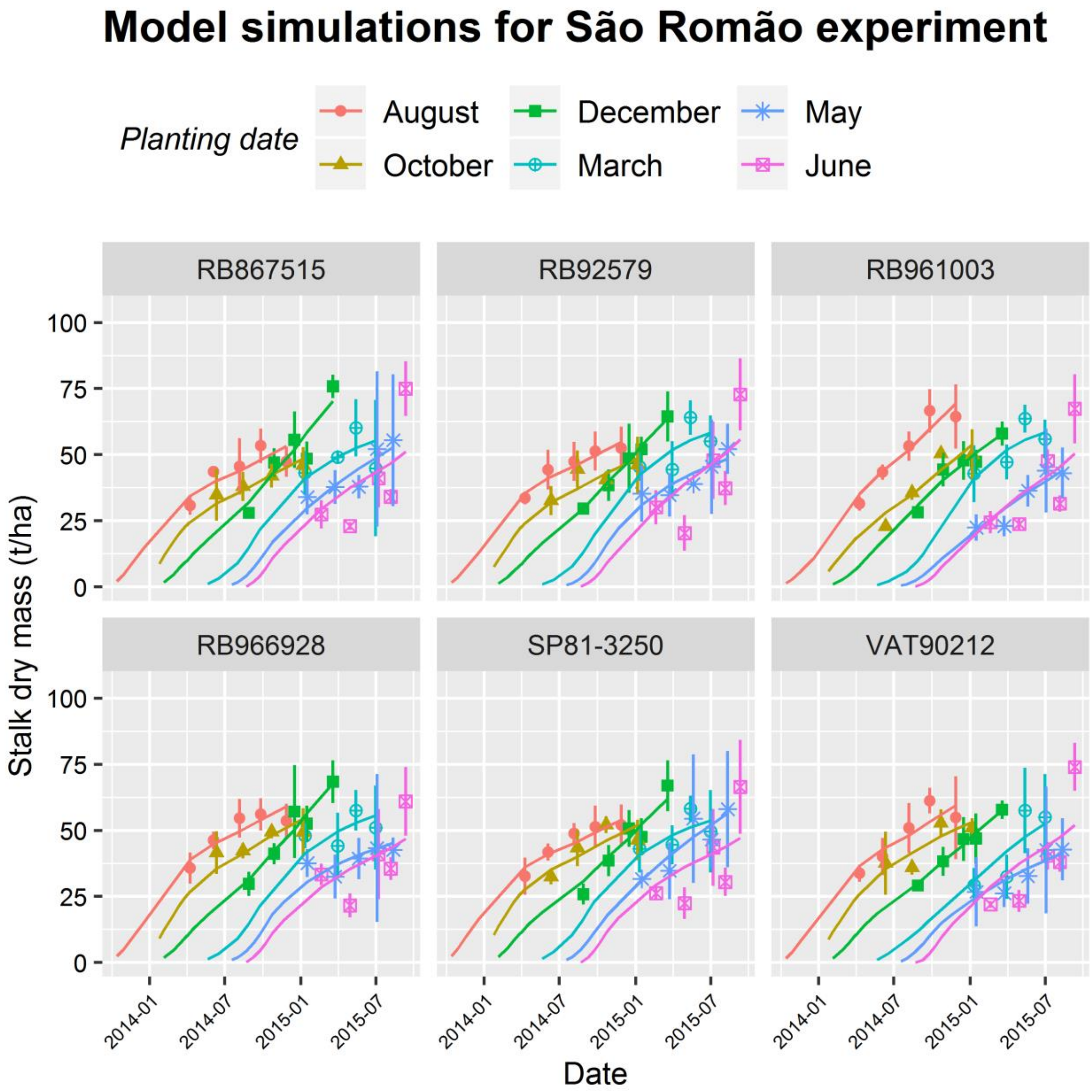

Fig. 3. Stalk dry mass measured (points plus bars) and simulated (lines) by the APSIM-Sugar model for Brazilian sugarcane varieties in different planting dates under in São Romão, MG, Brazil.

RGP_F means across the six planting dates and their standard errors for each variety and leaf stage are presented in Fig. 4. This analysis was employed to compare the nine varieties even though only three were common to both sites. The analysis included all treatments that had $R^2 > 0.56$ and $C > 0.53$, which resulted in the omission of eight of the 72 treatment combinations (see supplementary Fig. S1).

For leaf #10, RGP_F was 1.0 (RUE unchanged) for all treatments (data not shown). For leaf #20, RGP_F was close to 1.0 for all varieties at Guadalupe except for RB98710 where RGP_F was 0.9, significantly lower (given by the standard error of the mean) than the other varieties. RGP_F was reduced slightly for all varieties at São Romão at this stage, with SP81-3250 and VAT90212 growing slower than RB92579, RB966928 and RB961003 for which RGP_F was still around 0.9. The difference in early growth slowdown between SP81-3250 and VAT90212 *versus* RB966928 reached significance.

For leaf #30, RGP_F declined significantly below 0.9 for all treatments apart from RB931003 and RB961003 at Guadalupe. Growth at this stage was most vigorous for RB961003 in both environments. Growth for RB867515 and SP81-3250 at São Romão had now fallen to about 60% of their growth rate when leaf stage was < #10. RB867515 was also the slowest of the three varieties common to both environments; significantly, slower than RB961003 at Guadalupe at least, which was still growing within a standard error of 90% of the maximum rate at both environments.

When growth stage reached leaf #40, RGP_F was below 80% for all treatments apart from RB961003 at Guadalupe, and as low as 45% for RB966928 at São Romão. Differences between the three varieties common to both environments were as before with RB961003 growing more vigorously in both environments and RB867515 the slowest (and RB92579 in between). Growth of RB931003 at this stage had fallen significantly behind RB961003 at Guadalupe but was still growing vigorously than the other four varieties at this environment. At São Romão, VAT90212 occupied a similar position to RB931003 at Guadalupe, that is, slower than RB961003 and faster than RB92579.

At growth stage leaf #50, differences between varieties were less pronounced than before. RB931003 and RB961003 were growing most vigorously at Guadalupe and VAT90212 at São Romão. The differences between varieties were not significant mostly, apart from the superior growth of RB961003 and RB931003 over RB98710 and SP94-3206 at Guadalupe. By growth stage at leaf #60 varietal differences were similar to the those at leaf #50 (data not shown).

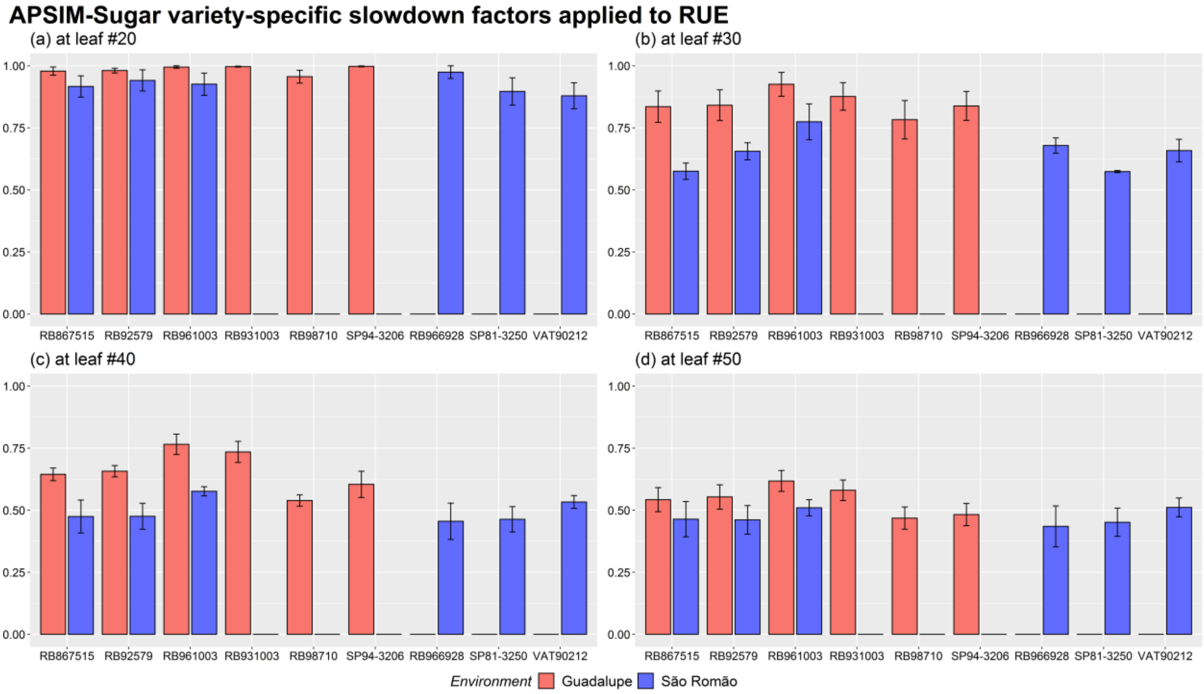

Fig. 4. APSIM-Sugar variety-specific growth slowdown factors applied to RUE at different leaf stages (#20, #30, #40 and #50) for two tropical environments in Brazil. The bars are the standard error of the mean factors considering the planting dates of the experiments.

4.3.2.3. In-site validations with other planting dates and crop cycles

The validation of APSIM-Sugar with the RGP_F applied to RUE for Brazilian sugarcane varieties was performed with data from several independent experiments presented in Fig. 5 at Guadalupe and in Fig. 6 at São Romão. The shaded grey area represents the range of simulated yields using RGP_F values obtained from Gompertz coefficients (A, B and C, see Figs. 2 and 3) optimised for each of the six planting dates of the G × E × M (calibration) experiments. RGP_F values were unique for each variety and site but were the same for each validation experiment regardless of their starting date. The coloured line is the average of the six simulated yield accumulation curves.

At Guadalupe, final simulated cane yields were within the standard error of the measured cane yields for 16 of the 18 validation tests. The two exceptions were the overestimation of yield for RB98710 planted in June and for the first ratoon of variety RB867515 in the experiment planted in October (Fig. 5). At São Romão where more measurements were available for validation including some taken before the final harvest, APSIM-Sugar underestimated yields observed for RB8767515 planted December and for RB92579 ratooning after harvesting the crop planted in April (Fig. 6a). The model over-estimated yields for the third ratoons of varieties RB966928, SP81-3250 and VAT90212 in the São Romão validation experiments (Fig. 6a). APSIM-Sugar predictions for variety RB961003 at São Romão were tested against two additional experiments, planted in

December followed by three ratoons and in July followed by two ratoons (Fig. 6b). Plant cane yields were underestimated at the final harvest for both planting dates but were mostly simulated within the standard error of the measured values. Yields of the first and second ratoons for both planting dates were underestimated, especially the second ratoon. Cane yield for the third ratoon was very well captured by APSIM-Sugar. The simulations were therefore valid for 35 out of 42 cases at São Romão and for 51 out of 60 across both sites.

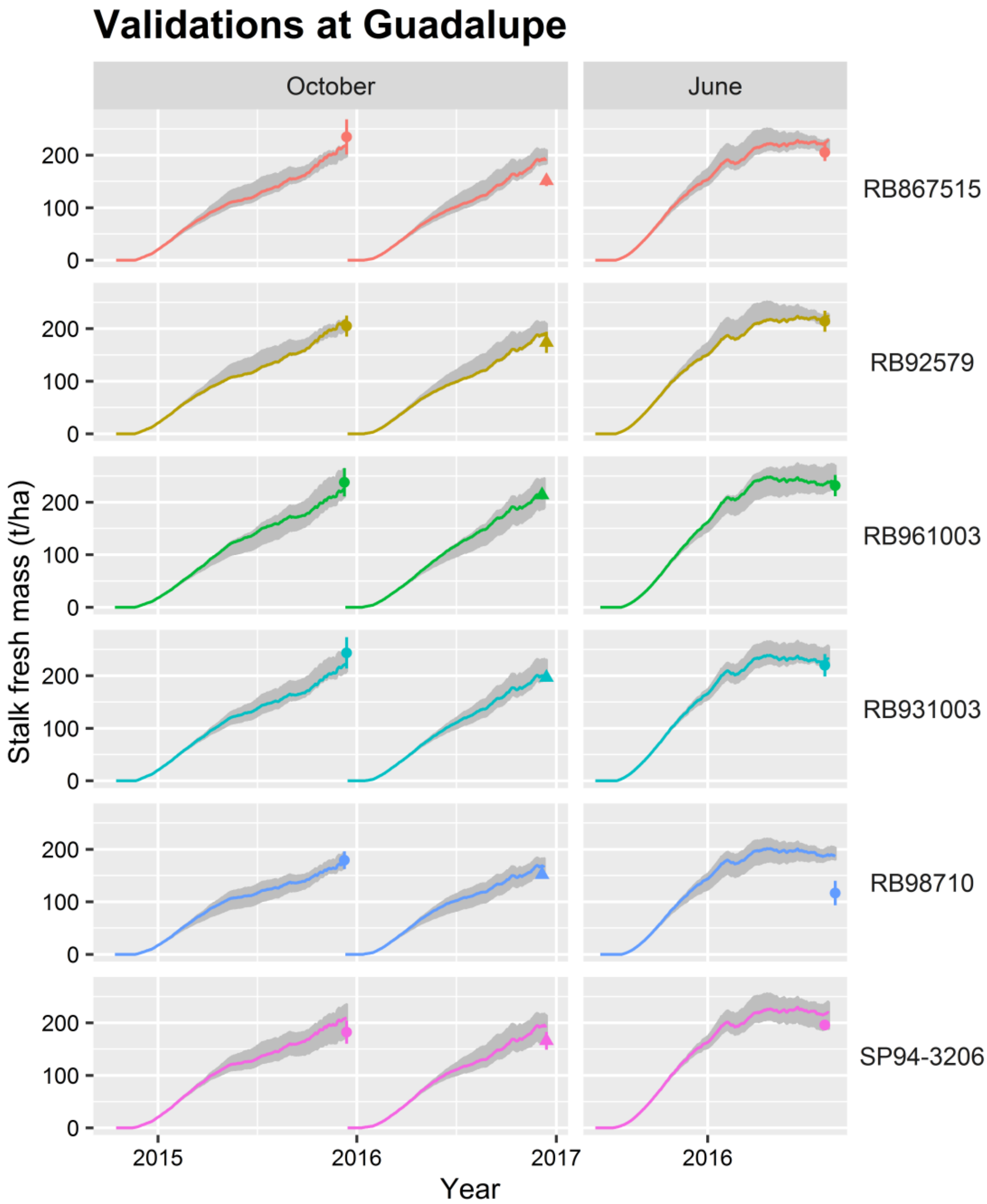

Fig. 5. Stalk dry mass measured (points plus bars) and simulated (coloured lines and shaded areas) by the APSIM-Sugar model during validation with independent data for Brazilian sugarcane varieties (horizontal facets) started at different planting dates (vertical facets) under Guadalupe, PI, conditions. The shaded grey area represents all the simulated values considering the optimised six RGP_F for each variety, while the coloured line is the average values. ○ = plant cane and Δ = ratoons.

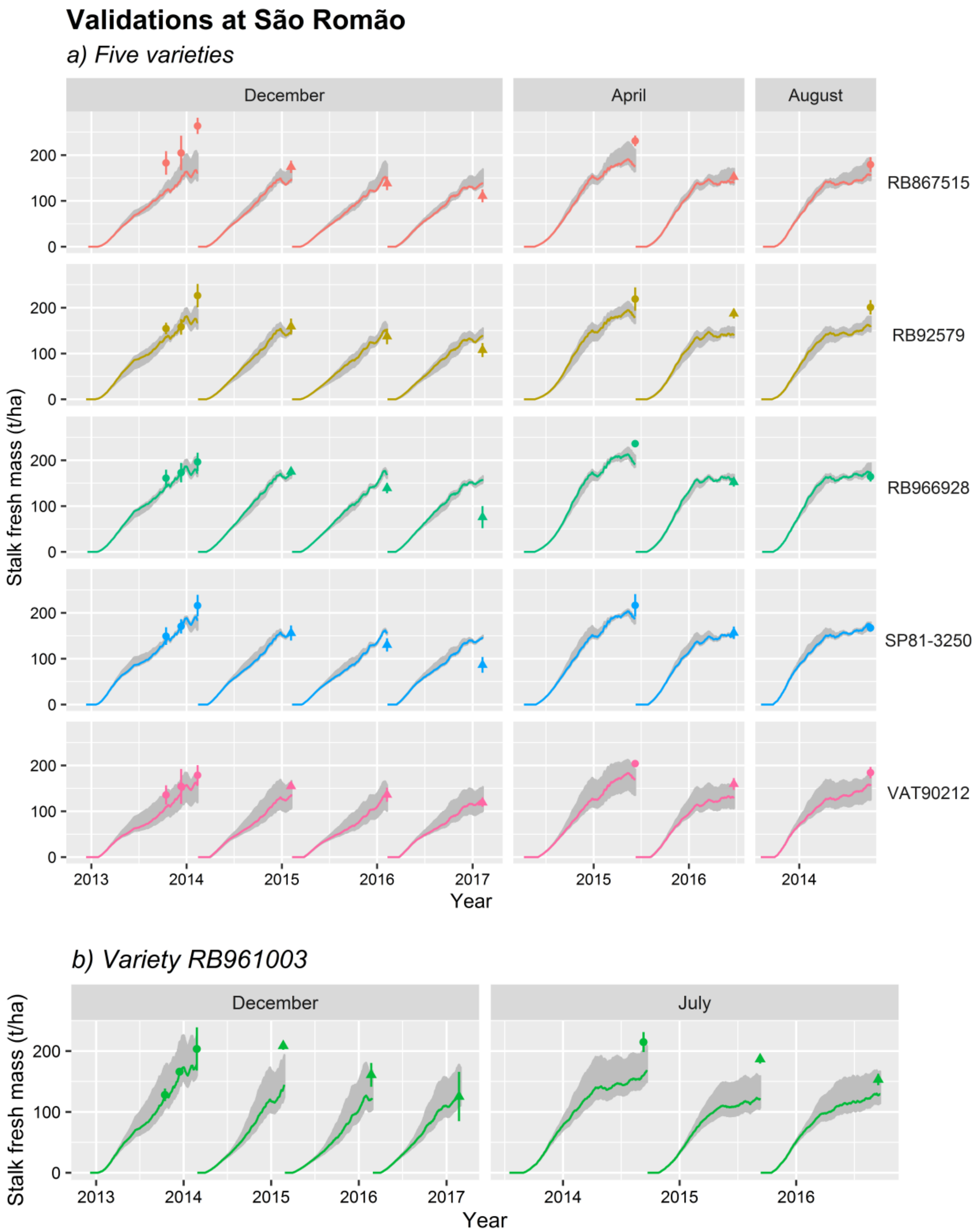

Fig. 6. Stalk dry mass measured (points plus bars) and simulated (coloured lines and shaded areas) by the APSIM-Sugar model during validation with independent data for Brazilian sugarcane varieties (a) RB867515, RB92579, RB966928, SP81-3250, VAT90212 (horizontal facets) and (b) RB961003 started at different planting dates (vertical facets) under São Romão, MG, conditions. The shaded grey area represents all the simulated values considering the optimised six RGP_F for each variety, while the coloured line is the average values. ○ = plant cane and Δ = ratoons.

4.4. Discussion

The results of the two experiments analysed are challenging and promising because the yields achieved in the field trials at both tropical sites were remarkably high as far cane yield is concerned, especially at Guadalupe and it could bring new insights for sugarcane crop improvement, in terms of both biological and environmental limits for yield and modelling aspects. The field data obtained in these large experiments with such high yielding crops are rare in sugarcane literature possibly because yields of heavily lodged crops such as these are hard to obtain. The strict discipline required of field workers for harvesting only stalks rooted in the clearly demarcated area was essential for obtaining these results.

Taking into account all planting dates and varieties, Guadalupe is a better production environment for sugarcane than São Romão when crop is grown under high-input conditions (Tables 2-4). Cane yield in the Guadalupe environment for most planting dates was well above 150 t/ha at 8 months (Table 3, Fig. 2). This yield would be regarded as a good yield for 12-month crops in many irrigated production areas around the world (Evensen et al., 1997; Muchow et al., 1994; Singh et al., 2002; van Heerden et al., 2015). Yields exceeding 200 t/ha at about 12 months, were obtained for almost all planting dates at Guadalupe. Dias et al. (2019) attributed the high yields achieved in the Guadalupe environment to the high, but not excessive temperatures, resulting in a more efficient radiation capture. Considering the optimum mean daily temperature for internode elongation to be between 26 and 31°C (Inman-Bamber et al., 2010), most of the days in Guadalupe environment can be regarded as thermally favourable (Fig. 1) not only for radiation capture but also stalk elongation. In the São Romão experiment, there were fewer favourable days for internode elongation than at Guadalupe.

The growth slowdown can be partly attributed to lodging experienced in most of the plots at both experiments. Lodging is considered a random, chaotic event (Amaya et al., 1996; Berding and Hurney, 2005) and yield reductions after lodging should be expected on occasions when lodging causes damage to the crop in the form of stool tipping, stalk breakage and/or smothering (Singh et al., 2002; van Heerden et al., 2015). In this context, it is difficult to determine the best planting dates for both environments. Furthermore, the water content in stalks is highly variable and is hard to predict across harvest ages, and it increases the complexity in analysing seasonal effects. Stalk fresh mass affects cane harvesting and transporting costs and is important for industry operational efficiency. Another aspect worth to mention is that Garside and Bell (2009) showed that there is a compensatory capacity in sugarcane to manipulate stalk number and individual stalk mass across a range of row configurations, planting densities and locations, resulting in similar yields. In the present study, this capacity was also verified in many cases across planting dates and varieties in both experiments, even though crops lodged. Despite that, the early planting at Guadalupe (April and May) (Fig. 2, Table 3) and December and June planting dates at São Romão seemed to be better than other dates for (dry) biomass accumulation (Fig. 3, Table 4).

The crops lodged well before 12 months and it was surprising that cane yield continued to accumulate as rapidly after 12 months as before, therefore, it is necessary to understand sugarcane yield gains in lodged crops in which RGP (not just lodging) is operating. Park et al. (2005) analysed 34 experiments across Australia and found that growth slowdown and, or lodging occurred in 16 of them. There were cases where growth rates were decreased even without lodging and vice-versa. In this context, we suggest that initial RUE should not be varied in APSIM-Sugar simulations because photosynthesis of elite varieties tends to be similar and high in young leaves of young crops particularly in the morning before feedback within the leaf becomes limiting (Inman-Bamber et al., 2011). The Gompertz function reflects a gradual decline in RUE with physiological age and then a stable but reduced growth rate thereafter. This is a reasonable assumption if lodging is the main cause of RGP but other functions could be explored if other limiting factors continue to affect RUE during the presumed stable period.

The ALMANAC model has been adapted and parameterised to simulate a 2-year growth cycle sugarcane in Hawaii by Meki et al. (2015), but substantial changes for reducing the efficiency of radiation interception and RUE were required to enable site-specific reliable simulations. The new version of CANEGRO (Jones and Singels, 2019) has not been tested for nitrogen dynamics as has APSIM-Sugar, but its capability for simulating respiration has been improved. However, variety distinctions when it comes to yield gains above ~ 150 t/ha might still need some attention once the model is used as intended in the South African breeding program (Hoffman et al., 2018).

The APSIM-Sugar model was able to distinguish between varieties for simulating stalk dry mass accumulation by keeping initial RUE constant (1.80 g/MJ for plant crops and 1.65 g/MJ for ratoons) across varieties and using variety-specific traits for canopy development and light interception (Dias et al., 2020) and adding the recent RGP feature (Figs. 2 and 3), now shown to be variety dependent too. RGP_F was the only parameter that was calibrated (optimised) in order to explain the yields observed in the two large G × E × M experiments. Parameters for all other yield building processes were as found in past versions of the model or from recent publications from Brazil. The RGP_F parameters and all other parameters were shown to be robust across independent validation experiments and ratoons. Generalized RGP_F values were shown by Dias et al. (2019) also account for yields used in the original development of the model (Keating et al., 1999).

Model performance was reasonably good for predicting stalk dry mass, in which RMSEs were lower than 11 and 14 t/ha for Guadalupe and São Romão, respectively, but mostly below 7 t/ha (supplementary Fig. S2). RMSE for APSIM-Sugar's dataset used for model building/development (Keating et al., 1999) was 9.6 t/ha for stalk dry mass, but when considering the final harvest, it increased to 12.3 t/ha (APSIM, 2020). A broader validation done by Thorburn et al. (2014) using an international dataset resulted in a RMSE of 18.9 t/ha, even when variety-specific phenology parameters were included.

The dynamic of dry mass accumulation for some varieties for July planting at Guadalupe Fig. 2) and for March at São Romão (Fig. 3) was not well captured by APSIM-Sugar. This could be attributed to two aspects. Firstly, flowering was observed in some plots at around 9 months at Guadalupe and around 12 months for March planting at São Romão. Flowering is a well-known process that usually slows sugarcane growth (Berding and Hurney, 2005; Moore and Berding, 2014), therefore, it is not surprising the lack of model capability to predict stalk dry mass because APSIM-Sugar does not simulate this plant process yet. Secondly, suckers were observed in almost all plots during samplings at 11.5 months in the July planting at Guadalupe, mostly for variety RB98710. Suckers decrease cane quality mostly (Berding et al., 2005; Bonnett et al., 2001), but may also have influenced growth slowdown. As far as we know, the development and the effect of suckers is not currently simulated by any sugarcane model, despite the studies of Bonnett et al. (2001) and Berding et al. (2005) which elucidated the role of the environment and management on suckering.

Sugarcane yield is influenced by the amount of radiation intercepted and biomass accumulated, and also the amount of mass partitioned to harvestable parts (Inman-Bamber et al., 2002; Singels et al., 2005). Stalk fraction for Brazilian varieties falls in the range found for international and local varieties, ranging from 0.63 to 0.86 (Cheeroo-Nayamuth et al., 2000; Evensen et al., 1997; Robertson et al., 1996; Singels et al., 2005; Singels et al., 2008) and 0.60 to 0.83 (Araújo, 2016; Barbosa, 2017; Silva, 2009; Suguitani, 2006), respectively. The differences are likely to be due to genotypes, crop ages, cropping systems (rainfed *versus* irrigated, row spacing, etc) and meteorological conditions during crop growth, all influencing biomass partitioning, as well as differences in the methodology of biomass components determination (for example, different levels of senesced leaves recovery).

This study showed that varieties differ concerning growth slowdown after 6-8 months when yields were about 30-40 t/ha. The study also provided more traits for those interested in sugarcane research, such as crop modellers, breeders, physiologists, crop scientists, industry and farmers. Traits for yield formation (stalk fraction and growth slowdown) can also be assessed in future trait modelling studies by comparisons of the nine Brazilian varieties with the other international varieties currently in the APSIM-Sugar genotype library.

4.4.1. Possible reasons for varietal differences with ageing

The variety × age interaction was significant for all mass components but the site × variety × age interaction was not significant for any mass component (Table 2). Varietal differences in growth slowdown with age were therefore consistent across the two environments in tropical Brazil suggesting that RGP is an important reasonably stable varietal trait for high-yielding environments.

Differences in RGP_F between varieties RB867515 and RB961003 at leaf stages #30 and #40 in both environments were consistent, suggesting that RB961003 is better at maintaining growth rates when yields are high and crops are likely to lodge (Fig. 4). The RGP_F agreed reasonably well with the individual stalk dry mass dynamics of the varieties (Tables 3 and 4). However, the reduction degree on RUE at São Romão was more severe than at Guadalupe if we compare the three common varieties (Fig. 4). On average, RUE was decreased around 8, 30, 35 and 17% more at São Romão than at Guadalupe at leaf stages #20, #30, #40 and #50, respectively. We expected the slowdown degree would be similar across sites and it may indicate the lack of APSIM-Sugar's capability to deal with the environmental effects. The reasons for that are unclear and we do not have an explanation for it yet. In this context, we suggest that different RGP_F values be used for each variety obtained as the average RGP_F for both sites and all planting dates (these values can be found in Table S8, supplementary material), until this uncertainty is tackled. Regardless of the differences in growth slowdown across sites, the results agree that the most popular varieties RB867515 and RB92579 are stable and high-yielding genotypes because they were ranked well in both experiments (Tables 3 and 4) similar to what has been observed other Brazilian environments (Andrade Junior et al., 2017; RIDESA, 2015).

RB961003 usually had the highest cane yield among all varieties, which averaged at 12 months around 183 and 230 t/ha, and at 15 months approached 219 and 281 t/ha at São Romão and Guadalupe, respectively. These are remarkable yields by any measure. We hypothesise that growth slowdown after 6-8 months distinguished varieties regarding yields and it could be related to differences in canopy development, variety ability to maintain growth (dry mass gain) over a long thermal time when massive yields have accumulated (even for lodged crops), as well as the partitioning of biomass to stalks.

RB961003 is known to develop its canopy, and thus capture radiation, slower than other Brazilian varieties at the environments where the experiments were carried out (Dias et al., 2020, 2019), which could decrease the propensity to lodging and delay excessive crop respiration. Differences in yields occurred mainly after crop grew for around 6-8 months. RB961003 kept increasing stalk mass in both environments compared to RB98710 and SP94-3206 at Guadalupe. From 12 months onwards, at both experimental sites, RB961003 had heavier stalks than most of the varieties (Tables 3 and 4). Tejera et al. (2007) found that differences in yields of variety Ja60-5 compared to POJ2878 and B63118 grown in Cuba (22 ºN, ~ 24.5 ºC) started to differentiate around 10 months when stalk mass gain for Ja60-5 was higher than the others varieties. It was shown that Ja60-5 reduced carbon partitioned to foliar respiration and allowed light to penetrate into the canopy reaching lower leaves, both contributing to keeping high levels of biomass accumulation. High light penetration at the bottom canopy portion of Brazilian variety IACSP95-3028 was claimed to be responsible for a higher biomass accumulation compared to IACSP93-2060 grown in Ribeirão Preto, SP (21 ºS, ~ 23.0 ºC) by Marchiori et al. (2010). Moreover, RB961003 also allocated high amounts of biomass to stalks (0.75), only less than RB966928 and VAT90212 (0.77) (Table 5). Similar physiological analyses used by Tejera et al. (2007) and Marchiori et al. (2010) would help to unravel the processes underlying variety differences, and therefore, traits for breeding selection and crop models improvement.

Basnayake et al. (2012) investigated the G × E interaction on cane yield using 89 varieties and introgression clones at one site and 40 of these at another site over a plant and two ratoons under different levels of irrigation. The G × E interaction for this Australian gene pool was small and the genetic correlation was high across environments and water stress treatments. A similar study performed by Liu et al. (2016) confirmed the high genetic correlation across environments and irrigation treatments in China leading to the conclusion that selection trials need not be conducted under very specific conditions relating to the target environment. However, yields in all these environments were considerably lower than those found to invoke RGP in our experiments. It may be necessary for breeders to test their varieties under conditions where yields exceed 200 t/ha when sugarcane enterprises start expanding into high yielding environments such as those in our study.

RB98710 was the weakest variety at Guadalupe experiment, averaging 58.7 t/ha of stalk dry mass (202 t/ha on fresh basis) only at the final harvest (15-month), and a good yield nevertheless. RB98710 was grown under irrigated conditions and also performed poorer (129 t/ha) compared to other varieties after three successive harvests at around 12 months in Teresina, PI (5º S), a similar environment of Guadalupe (Andrade Junior et al., 2017). It thus led Andrade Junior et al. (2017) to recommend avoiding the use of variety RB98710 at Teresina conditions. This somehow challenges the idea of the conservative behaviour of RUE for elite varieties when the crop is young previously pointed out Dias et al. (2019). In addition to its expressive growth slowdown shortly before 8 months, RB98710 also partitioned much less mass to stalks (0.65) compared to other four varieties (0.71-0.77) (Table 5), which helped to elucidate the significant low yields achieved (Table 3).

4.4.2. Implications for crop management in irrigated areas in tropical environments

RB966928 yielded as much as 35 t/ha of stalk dry mass on average across planting dates when harvested at 8 months in São Romão experiment (Table 4), which correspond to an increment of 4.4 t/ha/month. This is a variety recommended for the beginning of harvesting season (RIDESA, 2015) and has been the most planted one in Central-Southern Brazilian producing areas. Early harvesting (when the crop is younger than 12 months old) would rather be an option to be explored in commercial fields, mainly where ethanol production is also produced from bagasse and straw and not only from sugarcane juice, arguably to increase due to interest on advanced biofuels production (Grassi and Pereira, 2019; Leal et al., 2013).

In high-yielding environments such as those analysed in this study should pursue crop erectness, which is likely to avoid yield losses but certain avoid particularly decreases in cane quality (Berding and Hurney, 2005). Options like early harvesting for some varieties as pointed out previously, choice of varieties with erect habit, managing irrigation to control crop size (Inman-Bamber et al., 2004) and increasing the anchorage of the plant through a combination of planting depth and row mounding (Berding and Hurney, 2005) are encouraged.

Good estimates of growth (yield) increments over sustained periods of development would allow the industry to better exploit the long growth cycle and reduced the need for intervention (replanting, ratooning) of the sugarcane crop provided the best varieties are used for long harvest cycles. Hawaiian farmers in the past used to grow sugarcane for ~ 2 years before harvest (Evensen et al., 1997), and this practice is now regarded again as an option in terms of biomass for ethanol production (Anderson et al., 2015). Another implication could be the variety prioritisation in fields where the crop is left to be harvested in the next season due to climate and/or industry processing capacity constraints (popularly known as 'cana bisada' in Brazilian industry), which is commonly reported across producing regions (CONAB, 2020).

From our perspective, the slowdown feature in APSIM-Sugar has advanced the understanding of G × E × M interactions for yield accumulation in sugarcane varieties. The model is now better able to be used towards improving yields through better choices of varieties, planting date and harvest ages by users, however, the sucrose dynamics simulation is yet to be evaluated and perhaps improved. As far as we know, APSIM-Sugar's ability to predict sucrose content in stalk has not been extensively assessed since its development, although some investigations were carried out by O'Leary (2000) and Inman-Bamber et al. (2002). Simulation of sucrose content is still problematic in sugarcane models (Lisson et al., 2005; O'Leary, 2000). Mechanistic approaches proposed by Singels and Bezuidenhout (2002) (currently used in CANEGRO) and Singels and Inman-Bamber (2011) to simulate sucrose dynamics in sugarcane accounting for G × E interaction have only been partially successful.

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Supplementary Material

Table S1

Soil types and their main characteristics used in the simulations.

Soil layer (cm)	Horizon -	OM [a] %	pH_{H2O} [b] -	Clay	Silt (%)	Sand	BD [c] (g/cm)	θ_{LL} [d]	θ_{DUL} [e] (cm^3/cm^{-3})	θ_s [f]	K_L [g] per d^{-1}
Guadalupe, PI: *Latossolo Amarelo distrófico* [h] (Dias et al., 2019)											
0-10	A	0.69	4.9	24	5	70	1.71	0.14	0.29	0.42	0.15
10-30	BA	0.63	5.0	28	7	65	1.63	0.16	0.32	0.47	0.12
30-50	Bw	0.59	5.1	31	8	62	1.51	0.17	0.32	0.47	0.08
50-200	Bw	0.00	5.1	31	8	62	1.51	0.17	0.32	0.47	0.05
São Romão, MG: *Neossolo Quartzarênico* [i] (Dias et al., 2020)											
0-10	AP	0.69	5.5	11	1	87	1.71	0.05	0.19	0.43	0.15
10-30	CA	0.62	4.9	12	1	87	1.71	0.05	0.17	0.42	0.12
30-50	C1	0.51	4.5	13	1	86	1.70	0.05	0.18	0.41	0.08
50-200	C2	0.00	4.5	13	1	86	1.70	0.05	0.18	0.41	0.05

[a] Soil organic matter; [b] Actual values not used in the simulations to avoid nitrogen stress in the crop; [c] Soil bulk density; [d] Lower limit (-1500 kPa); [e] Drained upper limit (-10 kPa); [f] Saturated water content; [g] Root extraction constant; [h] Ferralsol in FAO classification system; [i] Arenosol in FAO classification system

Table S2

APSIM-Sugar canopy traits based on field measurements for nine Brazilian sugarcane varieties grown under irrigated (potential) conditions at two sites in tropical Brazil. Source and further details: Dias et al. (2020).

Variety	*plants* (# stalks at harvest)	*tillerf_leaf_size* [a] (unitless)	*tt_emerg_to_begcane* [b] (ºC d)	*green_leaf_no* (# leaves)
RB867515	9.2	1.0 1.5 1.5 1.6 1.3 1.1 1.0	461.5	11.7
RB92579	9.9	1.0 1.4 1.7 1.6 1.2 1.1 1.0	467.9	11.2
RB931003	10.2	1.0 1.5 2.1 1.5 1.1 1.1 1.0	501.5	11.7
RB961003	8.4	1.0 1.3 1.2 1.2 1.0 1.0 1.0	466.3	11.7
RB966928	10.1	1.0 1.9 1.7 1.4 1.2 1.1 1.0	473.6	13.5
RB98710	10.3	1.0 3.7 3.0 1.4 1.2 1.2 1.0	485.6	11.4
SP81-3250	11.0	1.0 1.5 1.7 1.8 1.3 1.2 1.0	543.7	11.7
SP94-3206	7.7	1.0 2.3 1.9 1.8 1.4 1.2 1.0	370.2	11.7
VAT90212	8.2	1.0 1.2 1.3 1.4 1.3 1.2 1.0	672.7	11.3

[a] Applied to leaf stages 1, 9, 11, 13, 17, 25 and 40
[b] APSIM thermal time from emergence (plant) and sprouting (ratoons) (*shoot_lag*) were 100 and 75 ºC d, respectively.

Table S3

Light extinction coefficient optimised in APSIM-Sugar for nine Brazilian sugarcane varieties grown under irrigated (potential) conditions at two sites in tropical Brazil. Source and further details: Dias et al. (2020).

Variety	*extinction_coef* (unitless)	
	Guadalupe (combined rows 1.5 x 0.9 m)	São Romão, MG (single rows 1.5 m)
RB867515	0.65	0.52
RB92579	0.64	0.48
RB931003	0.62	0.49
RB961003	0.64	0.47
RB966928	0.66	0.52
RB98710	0.59	0.49
SP81-3250	0.60	0.50
SP94-3206	0.72	0.55
VAT90212	-	0.46

Table S4

Performance of APSIM-Sugar to simulate photosynthetically active radiation interception (PARi) for nine Brazilian sugarcane varieties grown at two sites in tropical Brazil. Model evaluation with published experiments presented were R^2 = 0.46, d = 0.79 and RMSEP = 27.3 % for leaf area index (LAI), and for PARi these indices were R^2 = 0.57, d = 0.85 and RMSEP = 9.9 %. Source: Dias et al. (2020).

Variety	R^2		d		RMSEP (%)	
	Guadalupe	São Romão	Guadalupe	São Romão	Guadalupe	São Romão
Calibration						
RB867515	0.77	0.51	0.92	0.83	16.5	24.3
RB92579	0.78	0.59	0.93	0.84	16.2	24.1
RB931003	0.76	0.51	0.91	0.38	17.8	62.2
RB961003	0.82	0.77	0.93	0.93	17.4	29.5
RB966928	0.76	0.46	0.82	0.80	19.1	26.9
RB98710	0.83	0.97	0.93	0.93	15.9	15.8
SP81-3250	0.63	0.54	0.76	0.79	25.0	25.7
SP94-3206	0.82	0.71	0.91	0.77	17.1	21.3
VAT90212	-	0.40	-	0.71	-	29.8
In-site validation						
RB867515	0.91	0.93	0.98	0.97	8.1	11.4
RB92579	0.98	0.81	1.00	0.97	3.5	12.4
RB931003	0.92	0.79	0.98	0.86	9.5	16.8
RB961003	0.96	0.46	0.99	0.77	9.3	34.2
RB966928	0.95	0.93	0.99	0.96	4.4	12.1
RB98710	0.95	0.95	0.99	0.96	6.2	9.1
SP81-3250	0.92	0.87	0.98	0.92	7.7	16.3
SP94-3206	0.82	0.83	0.93	0.93	14.5	16.0
VAT90212	-	0.73	-	0.82	-	26.0
In-site validation with a row spacing experiment						
RB867515	-	0.87	-	0.96	-	10.34
RB92579	-	0.79	-	0.93	-	15.02
RB961003	-	0.53	-	0.84	-	29.26
RB966928	-	0.82	-	0.95	-	11.53
SP81-3250	-	0.88	-	0.94	-	11.38
VAT90212	-	0.61	-	0.85	-	21.54

Table S5

Analysis of variance based on a split-plot design with planting date as whole plot treatment and sugarcane varieties as sub-plot treatment for stalk dry mass, cane yield, individual stalk dry mass and stalk number for sugarcane varieties harvested 8, 11.5 and 15 months-old in Guadalupe, PI, and São Romão, MG, tropical Brazil. Symbols: * (*p-value* < 0.05), ** (*p-value* < 0.01), *** (*p-value* < 0.001), and ns (not significant).

Site	Crop variable	Source of variation	Crop age (months)				
Guadalupe, PI			*8*	*11.5*	*15*		
	Stalk dry mass (t/ha)	Planting date (P)	ns	***	***		
		Variety (V)	ns	***	***		
		P x V	ns	*	ns		
	Cane yield (t/ha)	Planting date (P)	***	***	***		
		Variety (V)	***	***	***		
		P x V	ns	*	ns		
	Individual stalk dry weight (kg)	Planting date (P)	*	ns	***		
		Variety (V)	***	***	***		
		P x V	ns	ns	ns		
	Stalks/m²	Planting date (P)	**	ns	***		
		Variety (V)	***	**	ns		
		P x V	ns	*	*		
São Romão, MG			*8*	*10*	*12*	*13.5*	*15*
	Stalk dry mass (t/ha)	Planting date (P)	***	***	*	**	***
		Variety (V)	***	**	ns	ns	ns
		P x V	ns	ns	ns	ns	ns
	Cane yield (t/ha)	Planting date (P)	***	***	ns	ns	***
		Variety (V)	**	*	*	**	ns
		P x V	ns	ns	*	ns	ns
	Individual stalk dry weight (kg)	Planting date (P)	***	***	**	***	*
		Variety (V)	***	***	*	*	**
		P x V	ns	***	*	ns	ns
	Stalks/m²	Planting date (P)	*	**	**	ns	**
		Variety (V)	***	***	**	ns	***
		P x V	ns	***	**	ns	ns

Table S6

Performance of APSIM-Sugar to simulate stalk dry mass for sugarcane varieties grown at different planting dates under high input conditions in Guadalupe, PI, tropical Brazil. Gompertz terms used to derive the growth slowdown factors to account for the reduced growth phenomenon (RGP) are shown.

Variety	Planting date	Gompertz terms			Model evaluation statistical indices					n
		A	B	C	R^2	*d*	C	RMSE (t/ha)	RMSEP (%)	
RB867515	July	0.35	7.0	0.29	0.97	0.99	0.98	2.0	3.9	3
	September	0.55	8.5	0.26	0.77	0.94	0.82	4.9	9.8	3
	November	0.60	8.5	0.22	0.99	0.99	0.99	2.0	3.8	3
	January	0.65	8.0	0.21	0.96	0.98	0.96	2.8	5.2	3
	April	0.35	7.0	0.29	0.94	0.98	0.95	4.2	7.6	3
	May	0.35	6.0	0.29	0.96	0.99	0.97	2.7	4.9	3
RB92579	July	0.35	7.0	0.30	0.61	0.85	0.67	10.4	20.3	3
	September	0.45	8.5	0.26	0.84	0.96	0.88	5.1	9.4	3
	November	0.65	8.0	0.20	1.00	0.99	0.99	2.3	4.6	3
	January	0.65	8.5	0.23	1.00	0.96	0.96	3.0	5.9	3
	April	0.35	5.5	0.24	0.99	0.99	0.99	2.6	4.8	3
	May	0.35	5.5	0.24	0.94	0.95	0.93	7.1	12.6	3
RB961003	July	0.35	5.5	0.23	0.86	0.93	0.87	7.6	15.1	3
	September	0.65	8.5	0.21	0.97	0.97	0.95	3.5	6.3	3
	November	0.35	8.5	0.20	0.90	0.97	0.92	6.1	10.4	3
	January	0.45	8.5	0.23	0.93	0.98	0.94	3.9	6.9	3
	April	0.35	7.5	0.20	0.95	0.94	0.92	10.1	16.2	3
	May	0.35	6.0	0.21	0.97	0.98	0.96	5.0	8.3	3
RB931003	July	0.35	7.0	0.27	0.99	1.00	0.99	1.3	2.4	3
	September	0.65	8.5	0.22	1.00	0.58	0.58	8.0	14.4	3
	November	0.60	8.5	0.20	0.91	0.95	0.91	5.9	10.3	3
	January	0.45	8.5	0.21	0.95	0.98	0.96	3.6	5.8	3
	April	0.35	5.5	0.21	0.96	0.97	0.94	6.5	11.2	3
	May	0.35	6.5	0.26	0.95	0.97	0.95	5.3	9.1	3
RB98710	July	0.45	6.0	0.29	0.60	0.86	0.67	7.7	18.4	3
	September	0.65	8.5	0.26	0.97	0.93	0.92	3.1	7.1	3
	November	0.65	8.0	0.23	0.74	0.90	0.78	4.9	11.3	3
	January	0.65	7.5	0.21	0.98	0.98	0.97	2.1	4.4	3
	April	0.40	7.0	0.29	0.94	0.99	0.96	3.0	6.1	3
	May	0.45	5.5	0.26	0.94	0.98	0.96	2.7	5.9	3
SP94-3206	July	0.50	8.0	0.30	0.57	0.84	0.64	7.9	16.6	3
	September	0.65	8.5	0.27	0.85	0.94	0.87	3.2	7.1	3
	November	0.65	8.5	0.22	0.94	0.98	0.95	3.2	6.4	3
	January	0.65	8.0	0.20	1.00	1.00	1.00	1.4	2.5	3
	April	0.35	5.5	0.20	0.99	1.00	0.99	1.8	3.0	3
	May	0.45	5.5	0.21	0.96	0.99	0.97	2.7	4.9	3

Table S7

Performance of APSIM-Sugar to simulate stalk dry mass for sugarcane varieties grown at different planting dates under high input conditions in São Romão, MG, tropical Brazil. Gompertz terms used to derive the growth slowdown factors to account for the reduced growth phenomenon (RGP) are shown.

Variety	Planting date	Gompertz terms			Model evaluation statistical indices					n
		A	B	C	R^2	*d*	C	RMSE (t/ha)	RMSEP (%)	
RB867515	August	0.65	5.5	0.21	0.66	0.89	0.72	4.4	9.9	5
	October	0.65	7.5	0.29	1.00	0.96	0.96	2.2	5.4	5
	December	0.35	5.5	0.29	0.86	0.96	0.89	5.9	11.5	5
	March	0.65	8.5	0.28	0.17	0.66	0.27	6.6	13.3	4
	May	0.50	6.0	0.29	0.79	0.94	0.83	4.0	9.3	5
	June	0.50	5.5	0.30	0.56	0.70	0.53	13.9	34.5	5
RB92579	August	0.65	8.5	0.28	0.90	0.97	0.92	2.2	4.9	5
	October	0.65	8.5	0.30	0.58	0.87	0.66	4.2	10.2	5
	December	0.40	5.5	0.25	0.99	1.00	0.99	1.1	2.3	5
	March	0.65	7.0	0.21	0.43	0.77	0.50	6.1	11.7	4
	May	0.60	8.0	0.30	0.72	0.92	0.78	3.5	8.5	5
	June	0.40	5.5	0.30	0.58	0.77	0.58	12.8	30.6	5
RB961003	August	0.45	6.5	0.20	0.90	0.97	0.92	4.1	8.0	5
	October	0.50	5.5	0.21	0.85	0.95	0.88	4.5	11.3	5
	December	0.55	7.0	0.22	0.92	0.98	0.94	2.7	5.9	5
	March	0.65	8.5	0.23	0.64	0.88	0.70	4.8	9.2	4
	May	0.45	5.5	0.29	0.87	0.96	0.89	3.5	10.3	5
	June	0.40	5.5	0.30	0.61	0.80	0.62	11.2	28.7	5
RB966928	August	0.65	8.0	0.27	0.75	0.93	0.80	3.8	7.7	5
	October	0.65	8.0	0.28	0.84	0.86	0.79	4.0	8.9	5
	December	0.40	6.5	0.30	0.93	0.98	0.94	3.6	7.3	5
	March	0.65	8.5	0.28	0.20	0.61	0.27	5.4	10.8	4
	May	0.65	7.0	0.29	0.43	0.77	0.51	4.0	10.1	5
	June	0.55	5.5	0.30	0.46	0.71	0.49	9.7	25.3	5
SP81-3250	August	0.65	5.5	0.21	0.88	0.96	0.90	2.6	5.7	5
	October	0.65	7.5	0.28	0.60	0.87	0.67	4.6	10.6	5
	December	0.45	5.5	0.28	0.94	0.97	0.94	4.2	9.2	5
	March	0.65	8.0	0.28	0.43	0.78	0.51	4.6	9.4	4
	May	0.45	5.5	0.29	0.79	0.93	0.83	4.8	10.7	5
	June	0.55	5.5	0.30	0.55	0.68	0.51	12.2	32.4	5
VAT90212	August	0.55	6.5	0.22	0.79	0.93	0.83	4.6	9.7	5
	October	0.65	6.5	0.21	0.73	0.92	0.78	4.0	9.0	5
	December	0.45	7.0	0.29	0.98	0.99	0.98	1.4	3.3	5
	March	0.40	5.5	0.30	0.75	0.87	0.75	7.2	16.4	4
	May	0.50	5.5	0.30	0.81	0.94	0.84	3.2	9.5	5
	June	0.40	5.5	0.30	0.72	0.76	0.65	12.8	32.4	5

Table S8

Variety-specific means of APSIM-Sugar growth slowdown factors applied to radiation use efficiency at distinct sugarcane growth stages defined by the number of fully emerged leaves on primary stalks.

Variety	APSIM-Sugar growth slowdown factors applied to radiation use efficiency according to leaf number									
	1	15	20	25	30	35	40	45	50	> 60
RB867515	1.00	1.00	0.94	0.83	0.72	0.63	0.55	0.51	0.50	0.49
RB92579	1.00	1.00	0.97	0.89	0.77	0.65	0.57	0.52	0.50	0.49
RB961003	1.00	1.00	0.96	0.91	0.85	0.77	0.67	0.60	0.56	0.54
RB931003	1.00	1.00	1.00	0.95	0.88	0.83	0.73	0.64	0.58	0.55
RB98710	1.00	1.00	0.96	0.86	0.78	0.65	0.54	0.49	0.47	0.46
SP94-3206	1.00	1.00	1.00	0.95	0.84	0.72	0.60	0.52	0.48	0.46
RB966928	1.00	0.99	0.93	0.81	0.62	0.48	0.43	0.41	0.41	0.41
SP81-3250	1.00	0.99	0.88	0.74	0.57	0.48	0.45	0.44	0.43	0.43
VAT90212	1.00	0.99	0.88	0.77	0.66	0.57	0.53	0.52	0.51	0.51

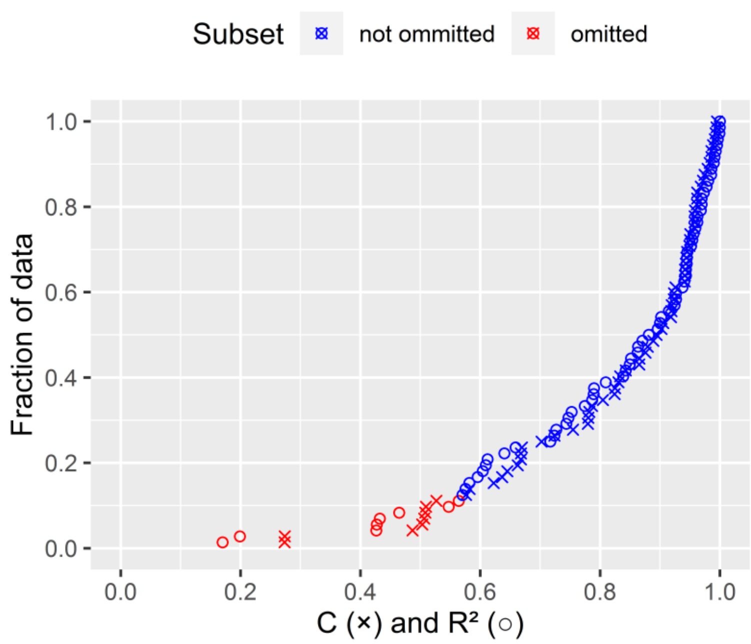

Fig. S1. Subset of the slowdown factors profiles based on C and R^2 indices.

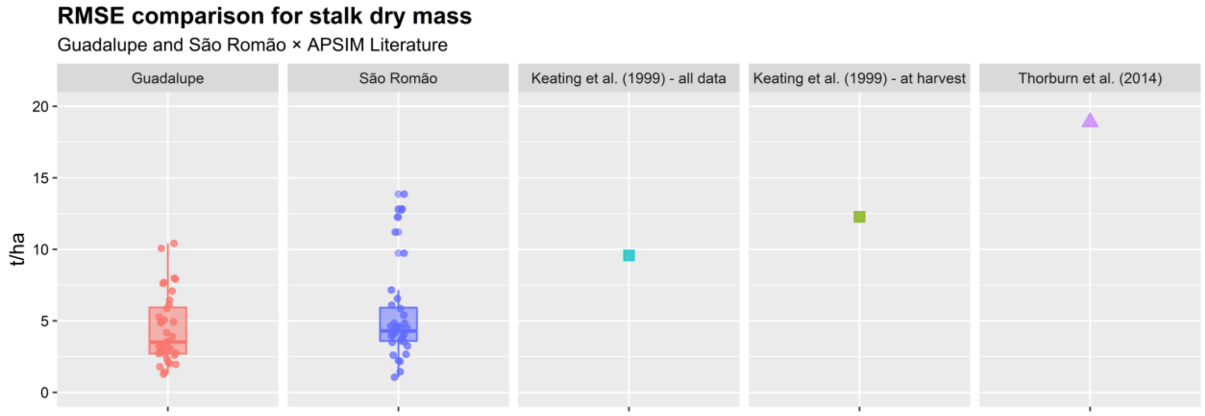

Fig. S2. Comparison of root mean squared errors (RMSE) between Guadalupe (from Table S5) and São Romão (from Table S6) *versus* other studies with APSIM found in the literature (APSIM, 2020; Keating et al., 1999; Thorburn et al., 2014).

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5. How reliable are gridded weather data for simulating the sugarcane crop with a process-based model in Center-South Brazil?

Abstract

High quality measured weather data (MWD) are essential for long-term and in-season crop modelling applications. When MWD is not available, one alternative for crop simulation is to employ gridded weather data (GWD), which needs to be evaluated a priori. Therefore, this study aimed to evaluate the quality of weather data from two GWD sources (NASA and XAVIER) in Center-South Brazil and to assess the impact these two sources have on simulating sugarcane crop performance within the APSIM-Sugar model at traditional sites where sugarcane is grown in Center-South Brazil. Finally, this study evaluated the impact of replacing GWD rainfall by measured data on sugarcane simulations. A common sugarcane cropping system was repeatedly simulated between 1997 and 2015 for different combinations of climate inputs. Both NASA and XAVIER seem to be reliable for applications that only require temperature and solar radiation for predictions, such as crop phenology and potential yield, nonetheless, GWD should be used with caution for applications that depend on accurate estimation of crop water balance, canopy development, and biomass accumulation, at least with crop models that run at a daily time-step. The replacement of gridded rainfall with measured rainfall was pivotal for improving sugarcane simulations, as observed for cane yield, by increasing both agreement (NASA: d from 0.67 to 0.90; XAVIER: *d* from 0.73 to 0.93) and R^2 (NASA: from 0.35 to 0.76; XAVIER: from 0.43 to 0.79), and reducing root mean square errors (RMSE) from 32.8 to 16.3 t/ha when simulated with other variables of NASA data, and from 27.9 to 12.7 t/ha when having XAVIER data as input. Therefore, using GWD from NASA and XAVIER it is recommended to replace gridded rainfall by measured values, whenever possible, to improve sugarcane simulations in Center-South Brazil.

Keywords: *Saccharum* spp.; Climate variability; Crop yield; Crop models; APSIM-Sugar; NASA/POWER

5.1. Introduction

Inter and intra-seasonal climate variability have a huge influence on crop yield and quality (Hoogenboom, 2000; Ray et al., 2015; Sivakumar, 2006), making measured weather data (MWD) from ground weather stations essential for better planning agriculture under current and future climates (Grassini et al., 2015; Ramirez-Villegas and Challinor, 2012). Measured climate data are often used as a 'baseline' and computed with climate modelled outputs under to generate climate change projections for a given site (Rosenzweig et al., 2013; Ruane and McDermid, 2017). The most common way to project the impacts of different climates, soils and management practises on agriculture is through the crop simulation models (Boote et al., 1996; Bouman et al., 1996; Hoogenboom, 2000), which are often developed, tested and improved by using high-quality weather and crop data from field experiments (Kersebaum et al., 2015; White et al., 2013). However, crop models present uncertainties related to models´ structure, parameters, and input variables, which include weather data (Aggarwal, 1995; Monod et al., 2006). Hence, high quality temporal and spatial weather data from ground stations are required for reliable crop simulations (Grassini et al., 2015; van Ittersum et al., 2013; Van Wart et al., 2013b).

Lack and/or poor quality MWD are very common in many agricultural areas around the world (Ramirez-Villegas and Challinor, 2012), including high-yield ones in developed countries, such as some states at the US Corn Belt (Mourtzinis et al., 2017). In Brazil, the largest weather station network belongs to the National Institute of Meteorology (INMET, http://www.inmet.gov.br). A spatial view of the INMET´s weather stations network, including automatic and conventional ones, is presented in Fig. S1 (Supplementary material). The automatic weather stations managed by INMET are increasing and it is the main source of real-time data nowadays; however, conventional stations remain as the main source of long-term series. The number of stations and the area of coverage per station for each Brazilian state and region are listed in Table S1 (Supplementary Material). In addition to INMET, the National Water Agency (ANA, 2020) has a rainfall network with about 2767 stations, being the main source of rainfall historical series in Brazil, with the oldest station measuring data since 1855. Despite this appreciable network, some of the weather and rainfall stations are unreliable or inactive.

Currently, INMET operates 565 automatic and 201 conventional weather stations. The area covered by each weather station varies between states (Table S1, Supplementary Material). Average coverage for the six states that contribute the most to Brazilian gross national product in terms of agriculture (Rio Grande do Sul, RS; São Paulo, SP; Paraná, PR; Minas Gerais, MG; Mato Grosso, MT; and Goiás, GO) ranges from 4,964 km^2 per station in SP to 20,075 km^2 per station in MT (IBGE, 2020). Nonetheless, considering only weather stations with more than 15 years of daily data at the same six states (total of 118), the average coverage is of 26,659 km^2 per station, more than twice of the same metric in the US Corn Belt (Mourtzinis et al., 2017). Thus, it is clear that there is a need to increase the number of weather stations in the main agricultural areas in Brazil, as weather data are essential for agricultural planning and climatic risk management. As the investments for this is large and will require efforts from different governmental agencies, an alternative approach to solving such a problem is by adopting gridded weather data (GWD).

GWD, are typically generated from the interpolation of data from different sources, such as ground weather stations, remotely sensed surface data from satellites or global circulation models at the desired temporal and spatial scales (Ruane et al., 2015; Van Wart et al., 2013a; Xavier et al., 2016). These data can be used to fill, replace, or generate synthetic climate data series, and are particularly useful for running crop simulations models (Van Wart et al., 2013a). Daily global GWD can be freely downloaded through websites from different research institutes like National Center for Environmental Prediction (NCEP; https://www.ncep.noaa.gov/), European Centre for Medium-Range Weather Forecasts Re-analysis (ERA; https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), and National Aeronautics and Space Administration/Prediction of World Wide Energy Resources (hereafter called NASA; http://power.larc.nasa.gov). Specifically for Brazil, a recent and promising GWD source from interpolated MWD was made available by Xavier et al. (2016) (hereafter called XAVIER; https://utexas.app.box.com/v/Xavier-etal-IJOC-DATA).

NASA (at 1º x 1º spatial resolution) and XAVIER (at 0.25º x 0.25º spatial resolution) seasonal weather data and their impacts on crop yield simulations were assessed recently in Brazil (Battisti et al., 2019; Bender and Sentelhas, 2018; Duarte and Sentelhas, 2020; Monteiro et al., 2018; Valeriano et al., 2018). A common issue was the poor performance of rainfall predictions, even when data were aggregated at a 10-day scale, affecting negatively crop yield simulations in many sites assessed by Monteiro et al. (2018) and Battisti et al. (2019). Furthermore, NASA database has recently been released at 0.5º x 0.5º grid cell (Stackhouse et al., 2018) and the quality of these data needs to be re-evaluated for Brazilian conditions, mainly for crop modelling applications.

Sugarcane is a very important crop in Brazil, that produces sugar, bioethanol, and bioelectricity (Cardoso et al., 2019). This crop is cultivated in about 10 mi ha, mainly concentrated in Center-South areas that comprise the Center-West, Southeast and South regions (IBGE, see Fig. 1), where climate has a substantial influence on yield (Dias and Sentelhas, 2018b; Marin et al., 2016; Monteiro and Sentelhas, 2017) and quality (Cardozo and Sentelhas, 2013; Scarpari and Beauclair, 2004). The sugarcane agro-industry has a considerable potential to offset greenhouse gases emissions (Börjesson, 2009), considering its feasibility to produce renewable energy; therefore it is likely cultivated area of this crop will keep increasing to support the Brazilian government's commitment to the Paris Agreement to mitigate greenhouse gases emissions (Brazil, 2015). Thus, high-quality climate databases are required to run sugarcane simulation models for assessing the impacts of sugarcane production on economic, environmental, and social aspects (Cardoso et al., 2019; Dias and Sentelhas, 2018b; Jaiswal et al., 2017).

Hereupon, the first aim of the present study was to evaluate the quality of two GWD sources (NASA and XAVIER) in Center-South Brazil and to assess the impact these datasets have on sugarcane simulations. This investigation was conducted using a well-validated crop simulation model (the 'Sugar' module embedded in the **A**gricultural **Production S**ystems s**IM**ulator platform, hereafter called 'APSIM-Sugar') for key sugarcane growing regions in Brazil. As a second aim, this study also evaluated how replacing interpolated (gridded) rainfall with measured rainfall data affected the sugarcane simulations, considering that such data is available from ANA network, which is larger and more spread out than the INMET weather stations.

5.2. Material and Methods

5.2.1. Study sites, weather and soil data

MWD were gathered from four sites in Center-South Brazil (Fig. 1). These sites were chosen because they represent important sugarcane cultivation areas in the above-mentioned region, which have distinct climatic conditions and automatic weather stations of high quality and with long-term data. Another important aspect is that XAVIER database did not employ the data from these weather stations for generating its GWD, which could perhaps favour this dataset in terms of quality for crop simulations.

MWD were retrieved from the automatic weather stations managed by the 'Luiz de Queiroz' College of Agriculture (ESALQ/USP) in Piracicaba, SP (22.71 ºS, 47.63 ºW, 546 m asml), São Paulo State University (UNESP) in Jaboticabal, SP (21.23 ºS, 48.29 ºW, 615 m asml), and Ilha Solteira, SP (20.42 ºS, 51.35 ºW, 337 m asml), and by Brazilian Agricultural Research Corporation (EMBRAPA) in Dourados, MS (22.28 ºS, 54.82 ºW, 408 m asml). Data from 1997 to 2018 were organised and few missing values were filled with data from conventional weather stations located next to these sites (the worst case was less than 0.4% for solar radiation at Piracicaba).

Despite having similar climate patterns (hot and wet summer; relatively cold and dry winter), these locations differ in terms of Koppen's climate classification (Alvares et al., 2013). Piracicaba, Jaboticabal, Ilha Solteira, and Dourados are classified, respectively, as Cfa (Humid subtropical climate, without a dry season and with hot summer), Cwa (Humid subtropical climate with a dry winter and hot summer), Aw (Tropical climate with a dry winter), and Am (Tropical monsoon climate). These climates are quite common across Brazilian environments (Alvares et al., 2013). A comparison of the climate conditions between the four sites can be found in Fig. S2 (Supplementary Material). Dourados is the wettest one among the four sites, with an annual rainfall of 1422 mm, while Ilha Solteira is the driest one, with roughly 1362 mm. Ilha Solteira is also the warmest place, with an annual mean air temperature slightly higher than 25 °C. Piracicaba, on the other hand, has the coldest minimum air temperatures, especially during winter, averaging around 12 °C between May and August. Jaboticabal has an intermediate climate among all the sites.

Site-specific soil properties, required to run APSIM-Sugar, were retrieved from published experiments at the same locations, which represent common soil classes in the growing regions assessed. Further information about the soils can be found in Table S2 (Supplementary Material).

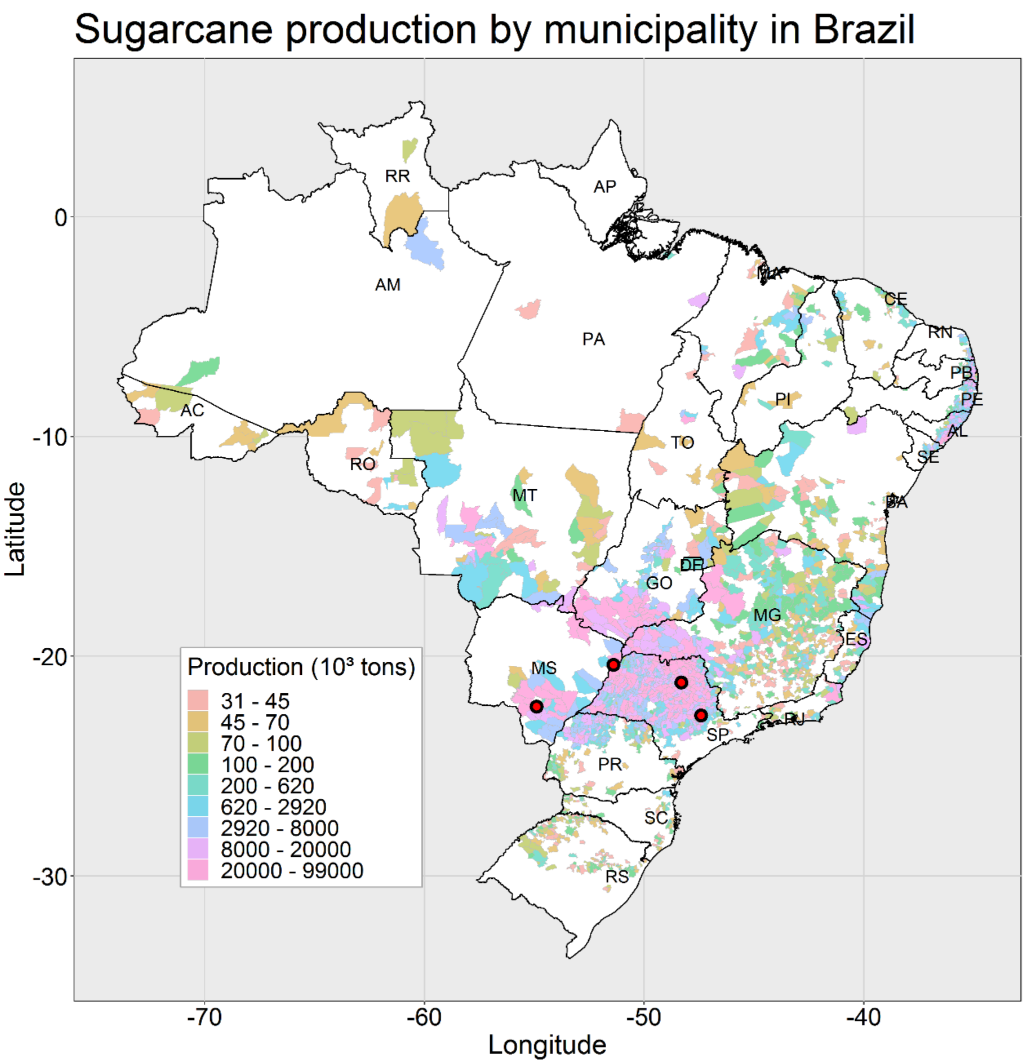

Fig. 1. Sites (red circles) with automatic weather stations employed in the present study. The coloured areas represent the municipalities where sugarcane production was higher than 30 thousand tons in the 2017-18 growing season (IBGE, 2020).

5.2.2. Gridded weather data (GWD) sources sources

Two freely available GWD were evaluated. The first one was the NASA database, which is derived from many sources such as satellites, radar imagery, land and ocean observations, meteorological probes, and meteorological balloons (Stackhouse et al., 2018). The climate data dedicated to the agro-climatology community were employed, which the most recent release is offered globally at a horizontal resolution of 0.5º x 0.5º (latitude, longitude) grid cell. Daily weather data are available from 1983 to near present, except for rainfall, which are available from 1997. Further details can be found in Stackhouse et al. (2018) and the NASA website (http://power.larc.nasa.gov)

The second GWD source was developed by Xavier et al. (2016). Daily weather variables from INMET's automatic and conventional weather stations plus rainfall from ANA network were interpolated, basically, by two methods (inverse distance weighting and angular distance weighting) depending on the weather variable. The grid cells of this GWD have a horizontal resolution of 0.25º x 0.25º (latitude, longitude). The most recent update provides daily weather data from 1980 to July 2017, except for rainfall, which are available until the end of 2015. Further details can be found in Xavier et al. (2016).

We did the comparisons and simulations for the period between 1997 and 2015 to keep the same climate series for both GWD. It was chosen not to downscale the NASA or upscale XAVIER grids because the purpose of this paper is to evaluate the data as they are available for end-users.

5.2.3. Crop model simulations

The crop model employed for sugarcane simulations was the well-known APSIM-Sugar model (Inman-Bamber et al., 2016; Keating et al., 1999; Thorburn et al., 2005) version 7.9 r4404. This is a process-based deterministic model that runs in daily time-step, capable of simulating plant, soil, climate, and crop management interactions (Holzworth et al., 2014). The parameters and coefficients for sugarcane crop were obtained from Dias et al. (2020), who calibrated and validated the model for several Brazilian varieties. The most popular one is the variety RB867515, which was chosen to represent the sugarcane fields of the assessed regions. The calibrated trait parameters for RB867515 as well as the statistical performance of APSIM-Sugar can be found in Tables S3 and S4 (Supplementary Material).

The APSIM-Sugar model was set up to simulate a typical crop cycle in the four sites. A 15-month-old plant cane was planted on 15th February and harvested in May of next year and followed by four 13-month-old ratoon crops. The decline of vigour in successive ratoons (Dias and Sentelhas, 2017; Inman-Bamber et al., 2012; Ramburan et al., 2013) was not included in the simulations apart from the difference between plant and all ratoons crops included in APSIM-Sugar regarding radiation use efficiency and thermal time required for sprouting. A green cane trash blanket system was simulated without any crop residue removal, which is common in the sugarcane farmers of the studied regions in Brazil. Nitrogen was applied in order to avoid stress, which was checked to confirm it throughout the crop cycle in all the simulations. The reason for not allowing possible nitrogen stress in the crop was that as far as we know APSIM-Sugar has not been tested properly in Brazilian cropping systems in terms of nitrogen dynamics, with proper experimental field data including varieties, soils, climates, and management practises. The effect of residues left in the soil after harvest, on the other hand, was evaluated before (Costa, 2017; Oliveira et al., 2016). The residue and water balances in the model were continued (not re-initiated) for the entire simulation period (Basso et al., 2015).

Daily weather variables required to run APSIM-Sugar are rainfall, solar radiation, and maximum (Tmax) and minimum (Tmin) air temperatures. The model was run for each site with MWD and GWD (NASA and XAVIER). In the second round of simulations with APSIM-Sugar, gridded rainfall from the two databases were replaced by the measured values. Thus, five sequential APSIM-Sugar outputs for each location were generated, corresponding to each climate input. The period of simulations started in 1997 and ended in 2015, totalling 16 growing seasons or harvests.

5.2.4. Evaluation of GWD performance and its impact on sugarcane simulations

The daily climatic variables (rainfall, solar radiation, Tmax, and Tmin) from GWD were compared to MWD for each site. Rainfall was also evaluated in a 10-day and monthly periods, as well as its accumulation during sugarcane growing season. Rainfall, solar radiation, and thermal time (or degree-days, from three-hourly air temperatures interpolated by APSIM from the daily Tmax and Tmin using 9 ºC as base temperature) accumulated since planting or ratooning were also analysed.

The outputs from APSIM-Sugar (model terms are shown in *italic* for precision) obtained from simulations with MWD, GWD sets, and those derived from the measured rainfall with other variables from GWD sets were compared, as follows:

- Canopy development: total number of leaves, days to reach 50% of photosynthetically active radiation interception (PARi, *cover_green*) and maximum leaf area index (LAI, *lai* in APSIM term) achieved during crop season;
- Water-related: cumulative crop water uptake (*cep*) and cumulative water stress-days that was based on the accumulation of soil water stress factor for photosynthesis (1-*swdef_photo*) throughout the crop cycle (Basnayake et al., 2012) and;
- Biomass accumulation: aboveground biomass (dry stalks and cabbages) and sugarcane yield (fresh basis), derived from stalk dry mass (*cane_wt*) assuming a constant dry matter content of 0.30 at harvest (Fageria et al., 2010; Inman-Bamber, 2004).

For a given weather or crop performance output, common statistical indices such as 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 those variables estimated with GWDs solely or GWDs with measured rainfall and MWD. Visual analysis and graphics were performed using *ggplot2* package (Wickham, 2016) in the R *environment* (R CORE TEAM, 2018).

5.3. Results

5.3.1. Comparison of seasonal weather data

A summary of the performance of weather variables from MWD and GWD sources are presented in Tables 1 to 3. Tmax has a satisfactory performance (d = 0.86-0.97; R^2 = 0.55-0.90) for both GWD sets across all sites. The error from XAVIER (overall RMSEP = 5.2%) was lower than NASA (overall RMSEP = 8.6%) (Table 1). Similarly, Tmin also has a satisfactory performance but with the R^2 and RMSE slightly higher (Table 1). The performance of both GWDs for solar radiation was nearly the same (d > 0.91; R^2 > 0.70) for all sites (Table 1), with RMSEP always below 17%, except at Dourados where it was higher than 20%.

Daily rainfall was the only weather variable that had poor performance (Table 2), which is common in climate modelling. When aggregated at 10-day and monthly scales, the performance of both GWD sets was enhanced, especially for XAVIER. Overall RMSEP for XAVIER's 10-day rainfall was 54.8% compared to 224.9% for daily rainfall. For the monthly scale, the overall RMSEP was even lower, reaching 32.6%.

Despite the poor performance of daily rainfall from both GWD sets, the accumulated rainfall values along the sugarcane crop cycle were similar (Table 3), with d ranging from 0.97 to

0.98, R^2 from 0.89 and 0.93, and acceptable errors, with RMSE lower than 189.9 mm/cycle. Given the satisfactory performance of daily values of Tmax, Tmin and solar radiation obtained by both GWD (Table 1), the statistical performances of the accumulated solar radiation and thermal time during crop cycle were also good enough (Table 3).

Table 1

Statistical analysis for the comparison between measured (MWD) and two gridded (NASA and XAVIER) weather data for daily maximum (Tmax) and minimum (Tmin) air temperatures, and solar radiation for four sites in Center-South Brazil. Average values, coefficient of determination (R^2), agreement coefficient (*d*), root mean square error (RMSE) and its percentage RMSEP are presented.

Site	Weather variable	Average MWD	NASA					XAVIER				
			Average	R^2	*d*	RMSE	RMSEP	Average	R^2	*d*	RMSE	RMSEP
Piracicaba	Tmax (ºC)	28.7	27.5	0.66	0.87	2.6	9.1	27.6	0.87	0.94	1.8	6.3
	Tmin (ºC)	16.0	15.9	0.90	0.97	1.3	8.0	16.1	0.94	0.98	1.1	6.6
	Solar radiation (MJ/m²/d)	18.0	18.2	0.81	0.95	2.8	15.4	16.8	0.81	0.93	3.0	16.6
Jaboticabal	Tmax (ºC)	29.0	29.4	0.55	0.86	2.5	8.5	29.3	0.90	0.97	1.1	3.8
	Tmin (ºC)	17.1	17.5	0.85	0.96	1.4	8.2	17.0	0.92	0.98	1.0	5.7
	Solar radiation (MJ/m²/d)	20.0	18.8	0.76	0.92	3.1	15.4	17.8	0.85	0.92	3.1	15.7
Ilha Solteira	Tmax (ºC)	31.3	30.0	0.64	0.86	2.7	8.5	31.1	0.86	0.96	1.5	4.7
	Tmin (ºC)	19.5	19.9	0.75	0.93	1.9	9.9	19.1	0.82	0.95	1.5	7.9
	Solar radiation (MJ/m²/d)	18.9	19.0	0.77	0.94	2.9	15.2	18.7	0.76	0.93	2.9	15.4
Dourados	Tmax (ºC)	29.7	29.9	0.76	0.93	2.4	8.0	29.0	0.88	0.96	1.8	5.9
	Tmin (ºC)	17.5	17.7	0.87	0.96	1.7	9.6	17.7	0.90	0.97	1.4	8.1
	Solar radiation (MJ/m²/d)	17.7	18.1	0.71	0.91	3.8	21.4	17.8	0.70	0.91	3.7	21.0
Overall	Tmax (ºC)	29.7	29.2	0.65	0.89	2.5	8.6	29.2	0.87	0.96	1.6	5.2
	Tmin (ºC)	17.5	17.7	0.85	0.96	1.6	9.1	17.5	0.90	0.97	1.3	7.2
	Solar radiation (MJ/m²/d)	18.7	18.5	0.75	0.93	3.1	16.8	17.8	0.76	0.92	3.2	17.1

Table 2

Statistical analysis for the comparison between measured (MWD) and two gridded (NASA and XAVIER) weather data for rainfall at different time-scales (daily, 10-day and monthly) at four sites in Center-South Brazil. Average values, coefficient of determination (R^2); agreement coefficient (*d*); root mean square error (RMSE) and its percentage RMSEP are presented.

Site	Weather variable	Average MWD	NASA					XAVIER				
			Average	R^2	*d*	RMSE	RMSEP	Average	R^2	*d*	RMSE	RMSEP
Piracicaba	Daily rainfall (mm)	3.4	3.6	0.42	0.76	6.8	201.0	3.7	0.23	0.66	8.4	245.4
	10-day rainfall (mm)	34.6	37.0	0.72	0.92	20.6	59.7	37.2	0.78	0.94	18.6	53.9
	Monthly rainfall (mm)	103.7	111.2	0.82	0.95	37.7	36.3	111.6	0.87	0.96	32.9	31.7
Jaboticabal	Daily rainfall (mm)	3.8	3.5	0.15	0.56	9.8	257.6	3.8	0.65	0.87	6.2	163.5
	10-day rainfall (mm)	38.7	35.2	0.66	0.88	28.2	73.0	38.2	0.84	0.95	19.2	49.6
	Monthly rainfall (mm)	116.0	106.1	0.77	0.92	55.6	47.9	114.7	0.91	0.97	34.4	29.6
Ilha Solteira	Daily rainfall (mm)	3.7	3.5	0.28	0.67	8.8	235.3	3.5	0.25	0.66	9.1	244.9
	10-day rainfall (mm)	37.8	35.9	0.64	0.88	27.2	71.9	35.9	0.75	0.92	22.6	59.7
	Monthly rainfall (mm)	113.5	107.9	0.79	0.94	47.9	42.1	107.7	0.85	0.95	40.2	35.4
Dourados	Daily rainfall (mm)	3.9	3.9	0.35	0.73	8.8	223.5	4.1	0.29	0.69	9.4	239.5
	10-day rainfall (mm)	39.7	39.6	0.65	0.89	25.0	62.9	42.0	0.73	0.92	22.0	55.5
	Monthly rainfall (mm)	118.2	119.8	0.70	0.91	46.0	38.9	126.1	0.79	0.94	39.1	33.1
Overall	Daily rainfall (mm)	3.7	3.6	0.29	0.68	8.6	232.1	3.8	0.34	0.73	8.4	224.9
	10-day rainfall (mm)	37.6	36.9	0.66	0.89	25.5	67.6	38.3	0.78	0.93	20.6	54.8
	Monthly rainfall (mm)	112.6	111.3	0.77	0.93	47.3	42.0	115.0	0.86	0.96	36.7	32.6

Table 3

Statistical analysis for the comparison between measured (MWD) and two gridded (NASA and XAVIER) weather data for accumulated rainfall, solar radiation and APSIM-Sugar's thermal time throughout the sugarcane crop cycle for four sites in Center-South Brazil. Average values, coefficient of determination (R^2); agreement coefficient (*d*); root mean square error (RMSE) and its percentage RMSEP are presented.

Site	Weather variable	Average MWD	NASA					XAVIER				
			Average	R^2	*d*	RMSE	RMSEP	Average	R^2	*d*	RMSE	RMSEP
Piracicaba	Rainfall (mm/cycle)	1328.2	1417.6	0.53	0.82	188.3	14.2	1428.2	0.72	0.87	158.8	12.0
	Solar radiation (MJ/m²/cycle)	7263.4	7391.3	0.33	0.74	589.8	8.1	6815.7	0.64	0.79	605.7	8.3
	Thermal time (ºC d/cycle)	5294.2	5057.0	0.90	0.88	268.0	5.1	5125.6	0.88	0.91	218.4	4.1
Jaboticabal	Rainfall (mm/cycle)	1481.1	1373.3	0.59	0.83	193.7	13.1	1492.9	0.84	0.96	100.8	6.8
	Solar radiation (MJ/m²/cycle)	8125.1	7638.6	0.93	0.83	509.6	6.3	7201.1	0.92	0.58	938.8	11.6
	Thermal time (ºC d/cycle)	5610.6	5693.9	0.93	0.97	131.0	2.3	5638.2	0.99	1.00	53.7	1.0
Ilha Solteira	Rainfall (mm/cycle)	1461.3	1391.2	0.30	0.72	209.3	14.3	1387.9	0.52	0.81	158.8	10.9
	Solar radiation (MJ/m²/cycle)	7657.2	7700.8	0.76	0.93	315.6	4.1	7570.5	0.80	0.94	295.1	3.9
	Thermal time (ºC d/cycle)	6350.1	6272.9	0.92	0.97	167.0	2.6	6284.0	0.94	0.98	141.6	2.2
Dourados	Rainfall (mm/cycle)	1524.5	1547.6	0.54	0.84	211.0	13.8	1636.0	0.74	0.89	180.9	11.9
	Solar radiation (MJ/m²/cycle)	7233.4	7296.0	0.40	0.74	638.5	8.8	7201.7	0.57	0.82	548.3	7.6
	Thermal time (ºC d/cycle)	5640.9	5758.8	0.90	0.95	165.8	2.9	5682.0	0.83	0.95	173.4	3.1
Overall	Rainfall (mm/cycle)	1448.8	1432.4	0.46	0.82	200.8	13.9	1486.2	0.68	0.90	152.7	10.5
	Solar radiation (MJ/m²/cycle)	7569.8	7506.7	0.54	0.83	527.9	7.0	7197.2	0.55	0.80	639.5	8.4
	Thermal time (ºC d/cycle)	5724.0	5695.6	0.89	0.97	189.9	3.3	5682.5	0.93	0.98	158.7	2.8

5.3.2. Comparison of APSIM-Sugar simulations outputs simulated with measured and gridded weather data

Canopy development, water relations, and biomass accumulation outputs from APSIM-Sugar were used to test the ability of the GWD sources and GWD sources with measured rainfall to reproduce the same outputs when estimated with MWD. Overall statistics considering all sites for sugarcane crop outputs from APSIM-Sugar simulated with the MWD and the GWD sets are present in Table 4. Specific statistics for each site can be found in Tables S5 and S6 (Supplementary Material). Given the good agreement between GWD and MWD for air temperature and, consequently, thermal time, the total number of sugarcane leaves were similar when simulated by both weather databases. The use of measured rainfall did not have a strong influence on that, since the leaf appearance rate in APSIM-Sugar basically depends on air temperature (Keating et al., 1999). On the other hand, LAI and PARi changed when measured rainfall was replaced by gridded data.

The poor performance of crop outputs when using GWD solely was enhanced when measured rainfall was used in the simulations (Table 4 and Figs. 2-5). Measured rainfall also improved PARi simulations for all sites (Fig. 2). The inclusion of measured rainfall in NASA climate database improved the estimation of maximum LAI, increasing *d* from 0.64 to 0.85 and R^2 from 0.35 to 0.58, and decreasing RMSEP from 25.8% to 17.1%. Similarly, when measured rainfall data were combined with the other variables from XAVIER climate database, maximum LAI had an improved *d* from 0.75 to 0.86, and R^2 enhanced from 0.39 to 0.56. Consequently, RMSEP was reduced to 15.0%, compared to 22.0% when maximum LAI was simulated with gridded rainfall.

It is well known that water in the soil-plant-atmosphere *continuum* plays a major role in crop water use and biomass accumulation. On average, the total water uptake at the end of the sugarcane cycle was 90 mm and 127 mm higher when APSIM-Sugar was run with NASA and XAVIER climate data, respectively, than when simulated with MWD (695 mm/cycle) (Table 4). Despite the reasonable performance for sugarcane water uptake, a RMSEP around 30% was found for the simulations with both GWD sets. Another aspect of high relevance was observed at the daily scale for the cumulative water stress-days throughout the sugarcane cycle (Fig. 3), which was poorly reproduced when run with GWD, with an exception at Ilha Solteira, the hottest assessed site (Tables 1 and 3). The use of measured rainfall together with gridded solar radiation and air temperatures brought substantial improvements for all sites, but still with high errors for this water stress-related variable (RMSEP = 41%).

Similar to what was observed for other crop variables, the biomass accumulation had a poor to reasonable performance (*d* ranging from 0.65 to 0.73 and $R^2 < 0.43$) and high errors

(RMSEP > 29.8%) when simulated with GWD (Table 4). Replacing gridded rainfall by measured data in both GWD sets resulted in substantial improvements in the sugarcane aboveground biomass and yield estimates, which is depicted in Fig. 4 for sugarcane yield in all assessed sites. The probability curves throughout the sugarcane cycle derived from APSIM-Sugar long-term outputs simulated with MWD and GWD (Fig. 4) were better overlapped after replacing gridded by measured rainfall.

The improvements offered by replacing rainfall can also be seen in the scatter plots of simulated yields in Fig. 5. The data dispersion was higher when APSIM-Sugar was run only with GWD. Even though when measured rainfall data were used at Piracicaba for both GWD sets, and at Ilha Solteira for NASA, simulations still exhibited consistent overestimation when compared to yields simulated with MWD.

Generally, XAVIER performed better than NASA for all seasonal weather data (Tables 1-3), which culminated in a better performance of the simulations of crop variables (Table 4), regardless of the inclusion of measured rainfall. Considering the simulations with measured rainfall combined with other weather variables from GWDs, sugarcane yield simulated by APSIM-Sugar with XAVIER data outperformed slightly the simulations with NASA data in terms of performance, with *d* of 0.93 *vs* 0.90, R^2 of 0.79 *vs* 0.76, and RMSE of 12.7 t/ha *vs* 16.3 t/ha, corresponding to a RMSEP of 13.6 % *vs* 17.5 % (Table 4).

Table 4

Statistical analysis for the comparison between measured (MWD) and two gridded weather data (NASA and XAVIER) with and without measured rainfall replacement for sugarcane crop performance APSIM-Sugar's outputs at four sites in Center-South Brazil. Average values, coefficient of determination (R^2); agreement coefficient (*d*); root mean square error (RMSE) and its percentage RMSEP are presented.

GWD	Crop performance variable	Average MWD	Gridded rainfall					Measured rainfall				
			Average GWD	R^2	*d*	RMSE	RMSEP	Average GWD	R^2	*d*	RMSE	RMSEP
NASA	Total number of leaves	49	49	0.83	0.95	1	3.1	49	0.89	0.97	1	2.5
	Days to reach PARi of 0.50	121	104	0.29	0.72	52	43.1	111	0.75	0.92	30	24.5
	Maximum LAI	3.1	3.6	0.35	0.69	0.8	25.8	3.4	0.58	0.84	0.5	17.1
	Water uptake (mm/cycle)	695	785	0.22	0.67	209	30.0	685	0.79	0.94	84	12.1
	Water stress-days	68	35	0.05	0.47	50	73.7	52	0.59	0.79	28	41.0
	Aboveground biomass (t/ha)	31.1	38.8	0.32	0.65	11.2	35.9	34.7	0.74	0.88	5.6	18.1
	Sugarcane yield (t/ha)	93.5	115.6	0.35	0.67	32.8	35.1	103.4	0.76	0.90	16.3	17.5
XAVIER	Total number of leaves	49	49	0.92	0.98	1	2.2	48	0.91	0.97	1	2.4
	Days to reach PARi of 0.50	121	105	0.42	0.75	45	37.3	115	0.65	0.89	34	28.0
	Maximum LAI	3.1	3.4	0.39	0.75	0.7	22.0	3.1	0.56	0.86	0.5	15.0
	Water uptake (mm/cycle)	695	822	0.37	0.70	196	28.3	701	0.88	0.97	63	9.1
	Water stress-days	68	30	0.09	0.50	53	77.9	50	0.64	0.82	28	41.0
	Aboveground biomass (t/ha)	31.1	37.5	0.42	0.72	9.3	30.0	32.6	0.78	0.93	4.3	13.7
	Sugarcane yield (t/ha)	93.5	112.2	0.43	0.73	27.9	29.8	97.5	0.79	0.93	12.7	13.6

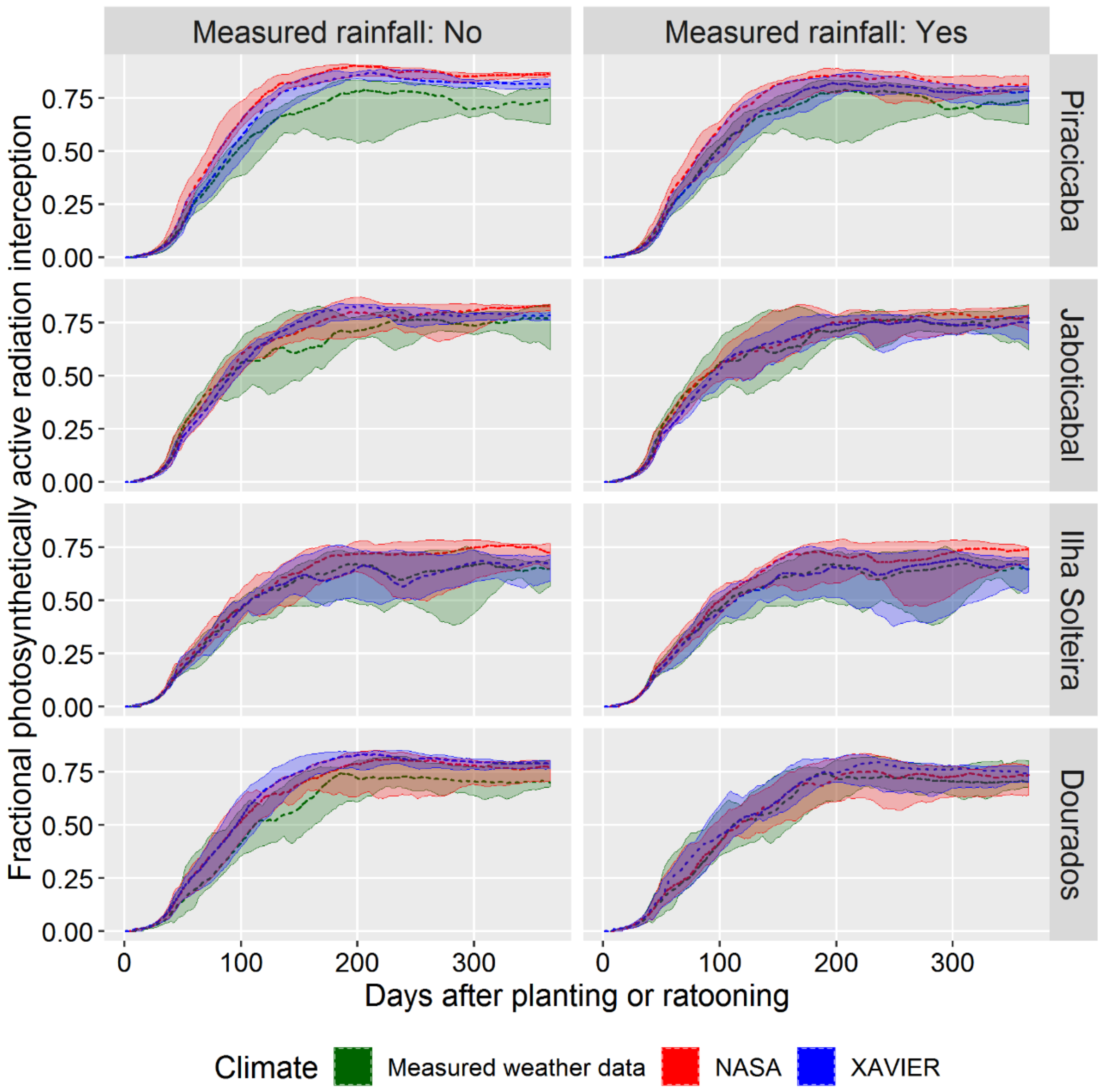

Fig. 2. Long-term sugarcane fractional photosynthetically active radiation interception simulated by APSIM-Sugar with measured (green) and gridded weather data from NASA (red) and XAVIER (blue) with and without measured rainfall replacement in four sites in Center-South Brazil. Dashed lines represent medians and continuous lines represent 25% and 75% percentiles.

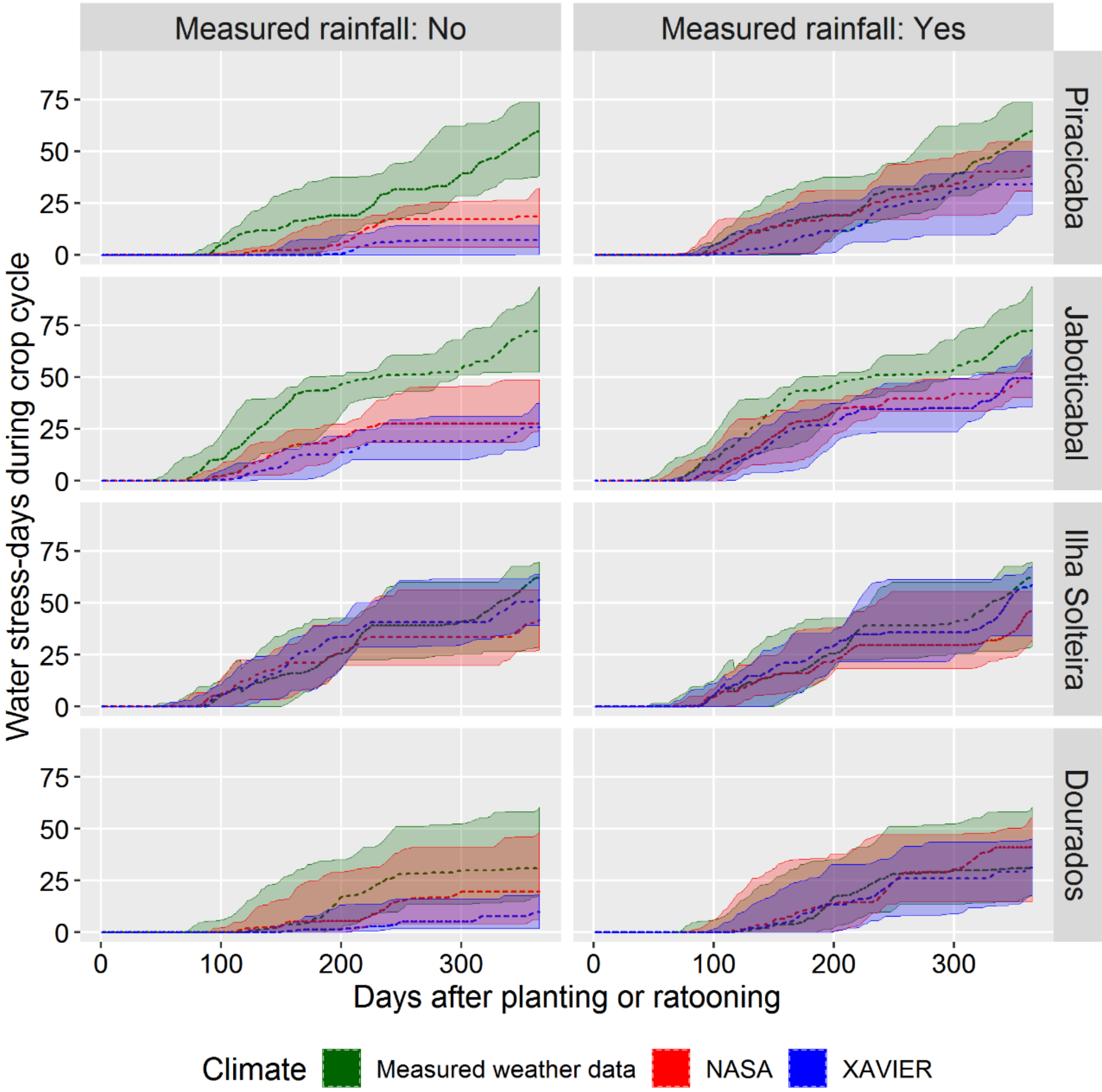

Fig. 3. Cumulative water stress-days for sugarcane simulated by APSIM-Sugar with measured (green) and gridded weather data from NASA (red) and XAVIER (blue) with and without measured rainfall replacement in four sites in Center-South Brazil. Dashed lines represent medians and continuous lines represent 25% and 75% percentiles.

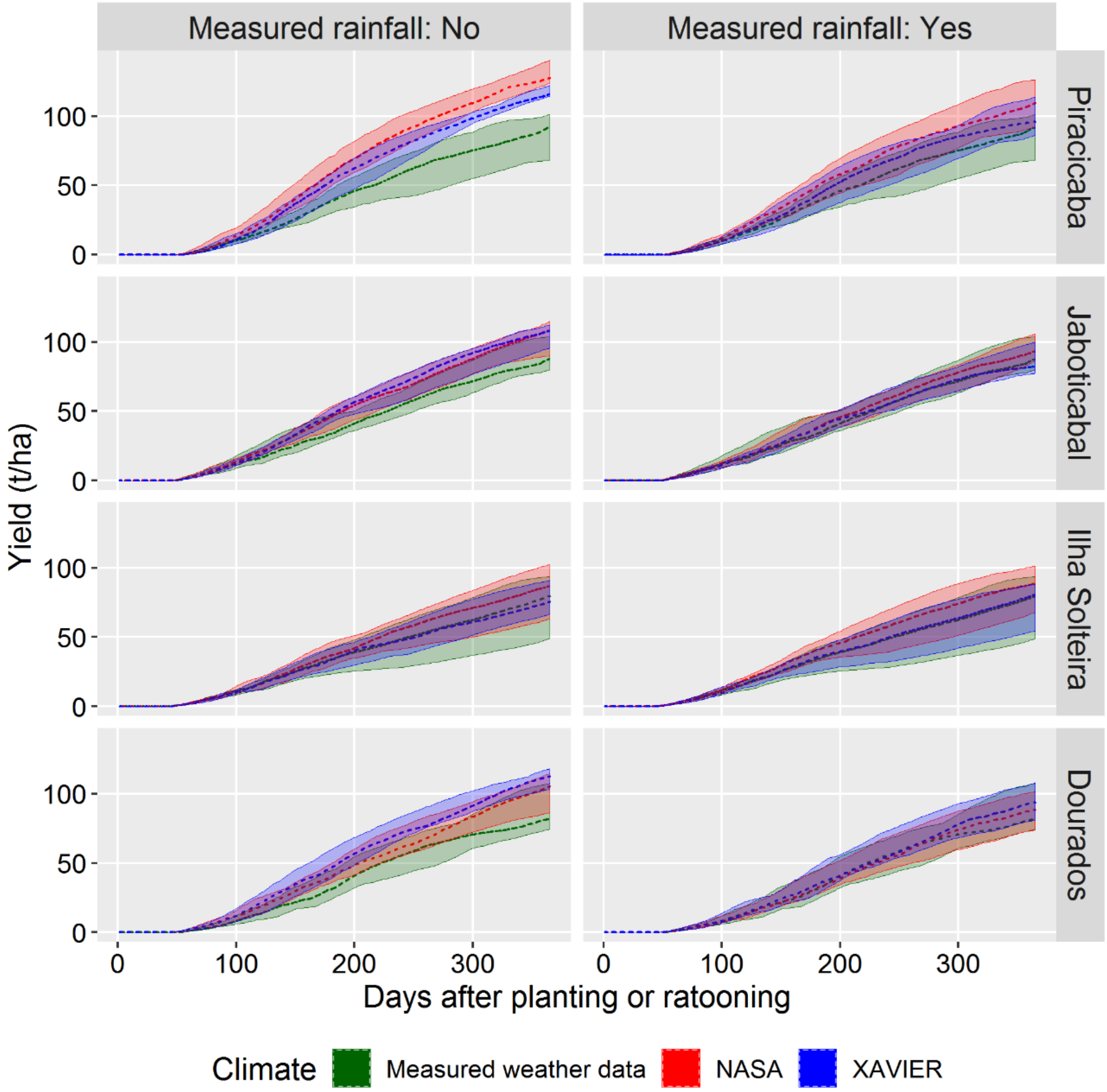

Fig. 4. Sugarcane yields simulated by APSIM-Sugar with measured (green) and gridded weather data from NASA (red) and XAVIER (blue) with and without measured rainfall replacement in four sites in Center-South Brazil. Dashed lines represent medians and continuous lines represent 25% and 75% percentiles.

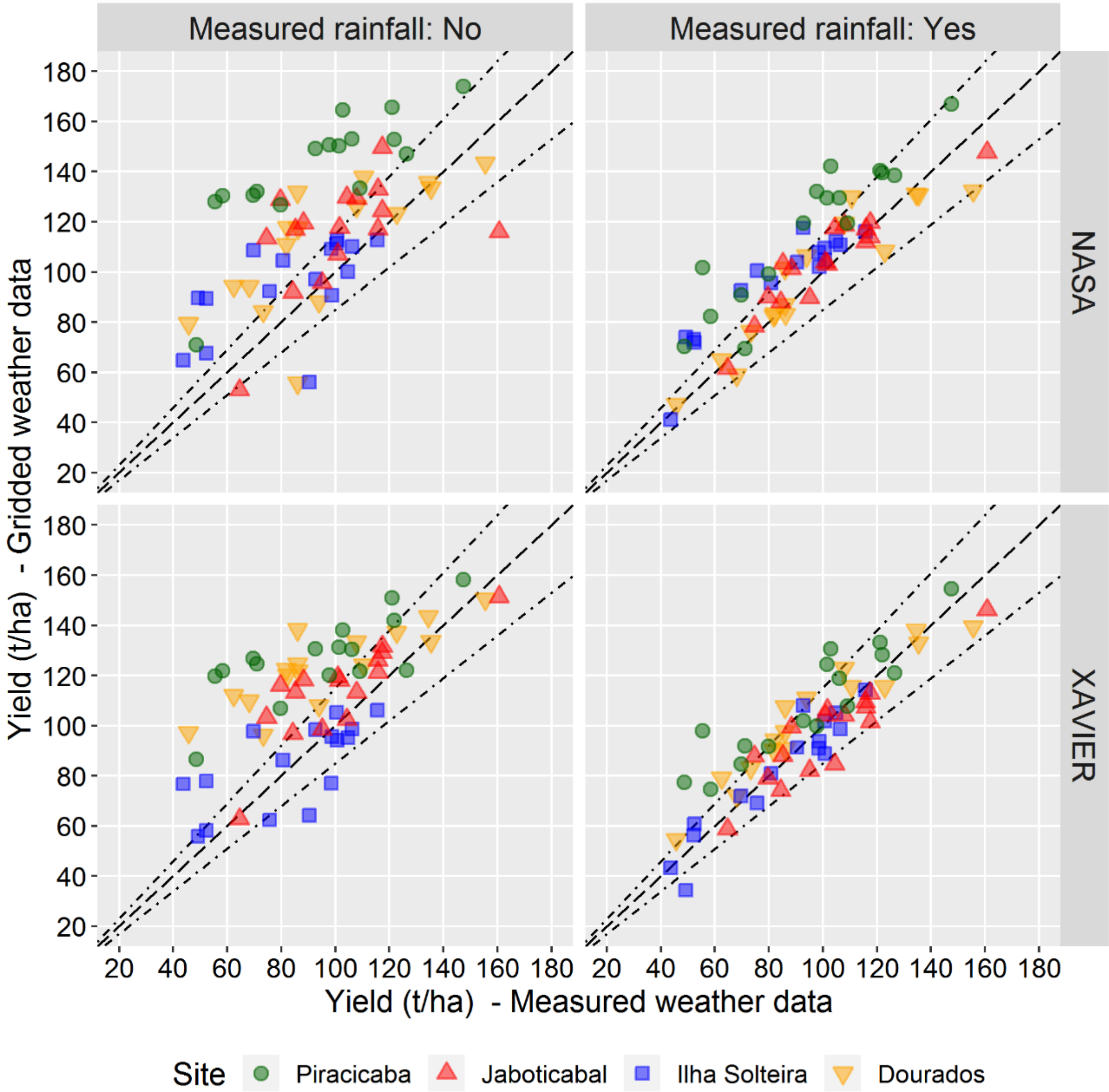

Fig. 5. Relationship between yields simulated by APSIM-Sugar with measured and gridded weather data (NASA and XAVIER) with and without measured rainfall replacement in four sites in Center-South Brazil. The dashed line represents the 1:1 line and dotted lines ±15% deviations.

5.4. Discussion

Daily air maximum and minimum temperatures, accumulated thermal time during the sugarcane cycle, and solar radiation (daily and accumulated) data from XAVIER and NASA presented a satisfactory performance compared to MWD at the four assessed sugarcane growing regions (Tables 1 and 3). The satisfactory quality of solar radiation and temperature data of GWD has been shown in many studies in Brazil (Battisti et al., 2019; Bender and Sentelhas, 2018; Duarte and Sentelhas, 2020; Monteiro et al., 2018; Valeriano et al., 2018) and around the world (Bai et al., 2010; Mourtzinis et al., 2017; Ojeda et al., 2017; Van Wart et al., 2013a; White et al., 2011). It is not surprising that key phenological stages of annual crops were well simulated with GWD in thermal time-dependent crop models (Battisti et al., 2019; Mourtzinis et al., 2017; van Bussel et al., 2011), similar to what was found in this study for the total number of sugarcane leaves, which is an important canopy development state variable of the APSIM-Sugar model (Table 4).

Potential yield, consequently, is usually well simulated using GWD for annual crops (Battisti et al., 2019; Van Wart et al., 2013a), however, it depends on the regional environment characteristics (Bai et al., 2010; Ojeda et al., 2020; Van Wart et al., 2013a). Monteiro et al. (2018) showed that sugarcane potential yield predicted by a generic FAO-AEZ model when using NASA GWD (1º x 1º grid cell) presented low errors (RMSE < 30 t/ha) in the majority of Brazilian territory (1 ºN to 25 ºS). Despite not evaluating potential yield, we hypothesise that this crop performance variable would be well simulated by APSIM-Sugar using NASA (here at a 0.5º x 0.5º grid cell) or XAVIER, since the main drivers of sugarcane yield-building processes when water is not limiting, like solar radiation and air temperature (Inman-Bamber, 2014; Muchow et al., 1997), presented a satisfactory performance compared to MWD (Tables 1 and 3).

By contrast, rainfall performance at a daily scale from both GWD analysed here was poor. It affected negatively sugarcane yield simulations in all sites (Table 4, Figs. 4 and 5). Sexton et al. (2017) showed that water-related trait parameters, such as transpiration efficiency coefficient and root conductance in APSIM-Sugar are quite sensitive for biomass accumulation under water-limited conditions regardless of soil characteristics. Therefore, it is crucial to have high-quality rainfall data for reliable sugarcane crop simulations.

Rainfall accumulated for 10-day and monthly offered an improvement in the performance of both GWD (Table 2). Based on that, the uncertainty that gridded rainfall can generate in the simulations obtained from other mechanistic, such as Century for soil organic matter dynamics (Galdos et al., 2010; Silva-Olaya et al., 2017), or statistical models, such as for cane quality (Cardozo et al., 2015; Kingston, 2002), that use accumulated rainfall could be lower than what was found in the present study.

The main finding of the present study is that assessed GWD (NASA and XAVIER) are still not reliable for sugarcane simulations in Center-South Brazil (Table 4, Figs. 2 to 5), assuming that simulations using GWD should provide similar errors to those obtained with a well-tested model using MWD. Dias and Sentelhas (2017) and Dias et al. (2019) found RMSEs between 15 and 19 t/ha using APSIM-Sugar for a wide range of cropping systems in Brazil, which are lower than RMSEs obtained in this study (higher than 27 t/ha) when sugarcane yield was simulated with GWD. Hence, outcomes from studies based on GWD to assess the impact of climate on sugarcane crop using mechanistic crop models may also have a certain degree of uncertainty (for instance in Jaiswal et al., 2017), as previously shown for annual crops worldwide (Mourtzinis et al., 2017; Van Wart et al., 2013a).

Other issues such as topography (Ojeda et al., 2020; White et al., 2011) and aggregation of soil and climate data (Hoffmann et al., 2016; Ojeda et al., 2020) are also recognized as sources of uncertainties and should be evaluated before simulating sugarcane and other crops performances in a spatial scale in countries with continental dimensions, like Brazil.

The other main finding of the present study is that GWD from NASA or interpolated from ground weather stations (XAVIER) together with measured rainfall offers a better alternative for sugarcane simulations using a well-evaluated crop model (Table 4, Figs. 2 to 5). Even considering that the replacement of measured rainfall would bring unexpected inconsistencies in the weather that the sugarcane is experiencing though, perhaps creating somewhat unrealistic conditions, mainly for solar radiation and temperatures, which will affect the crop model, the crop growth and yield simulations were substantially improved by adopting such strategy. Since ANA database is an open-source of measured rainfall data across Brazil, with more than 2,700 stations, and, therefore, it could be easily employed for crop simulation purposes.

Another important aspect related to precise weather databases is the utility that they have as 'baseline' data for generating climate change scenarios, which are used for simulating the performance of different crops in the future (Rosenzweig et al., 2013; Ruane and McDermid, 2017). It does not reduce, however, the need for increasing the number of high-quality weather stations and free access to existing ones. Efforts on this matter from the government and private sector are required to improve the quality of weather data to subsidise studies about the impact of climate variability and change on the sugarcane agro-industry, but also for other agricultural, forestry and livestock sectors.

5.5. Conclusions

Climate data from GWD sources (NASA and XAVIER), with the exception of rainfall, have satisfactory performance compared to MWD at Center-South sites in Brazil. The poor performance of rainfall from GWDs made rainfed sugarcane simulations with the APSIM-Sugar model uncertain, therefore, not reliable for crop model applications to date. Thus, it is recommended to replace gridded rainfall for measured data, whenever possible, in order to improve sugarcane simulations (at least with APSIM-Sugar) for Center-South Brazilian environments where this crop is mostly cultivated.

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Supplementary Material

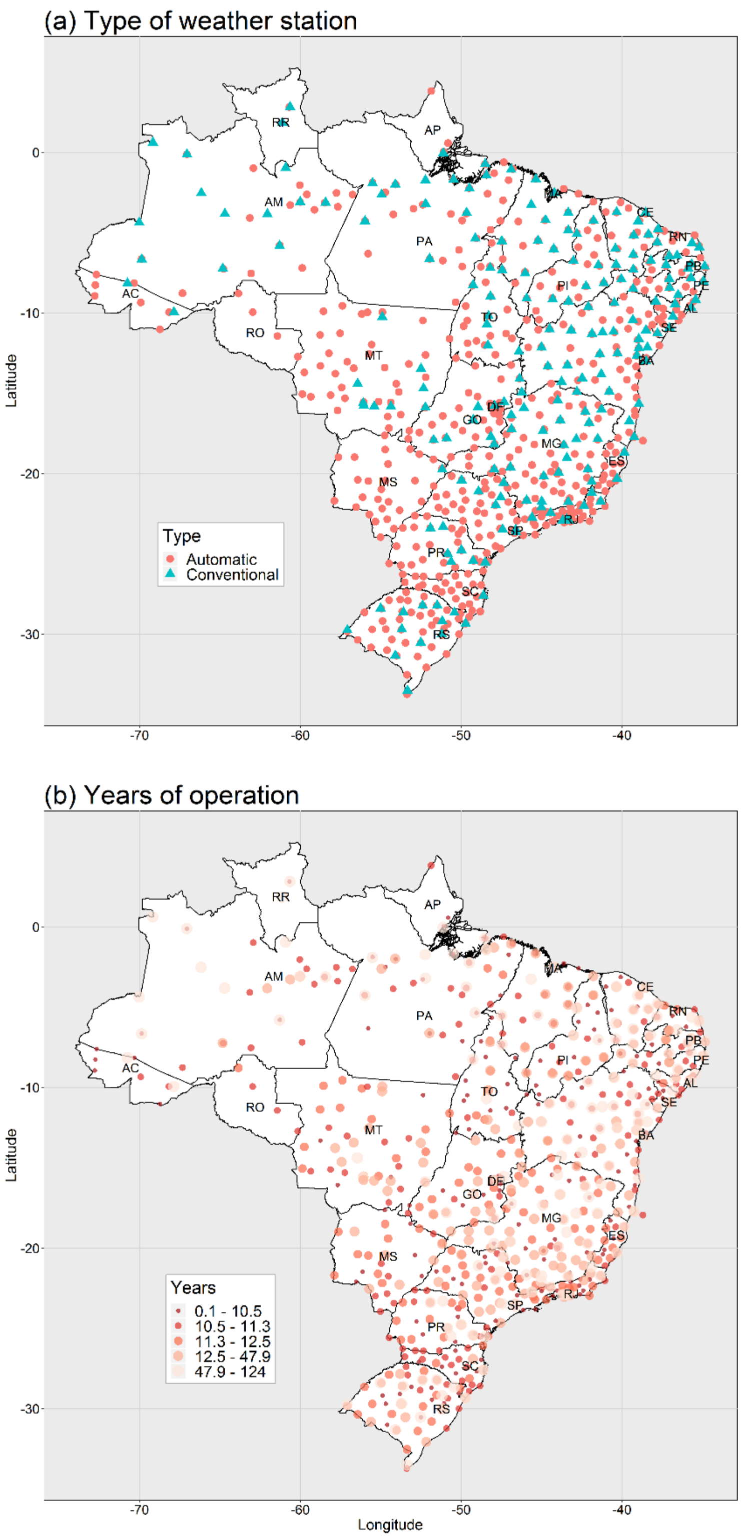

Fig. S1. Spatial distribution of type (a) and years of operation since installation (b) of weather stations from National Institute of Meteorology (INMET) in Brazil.

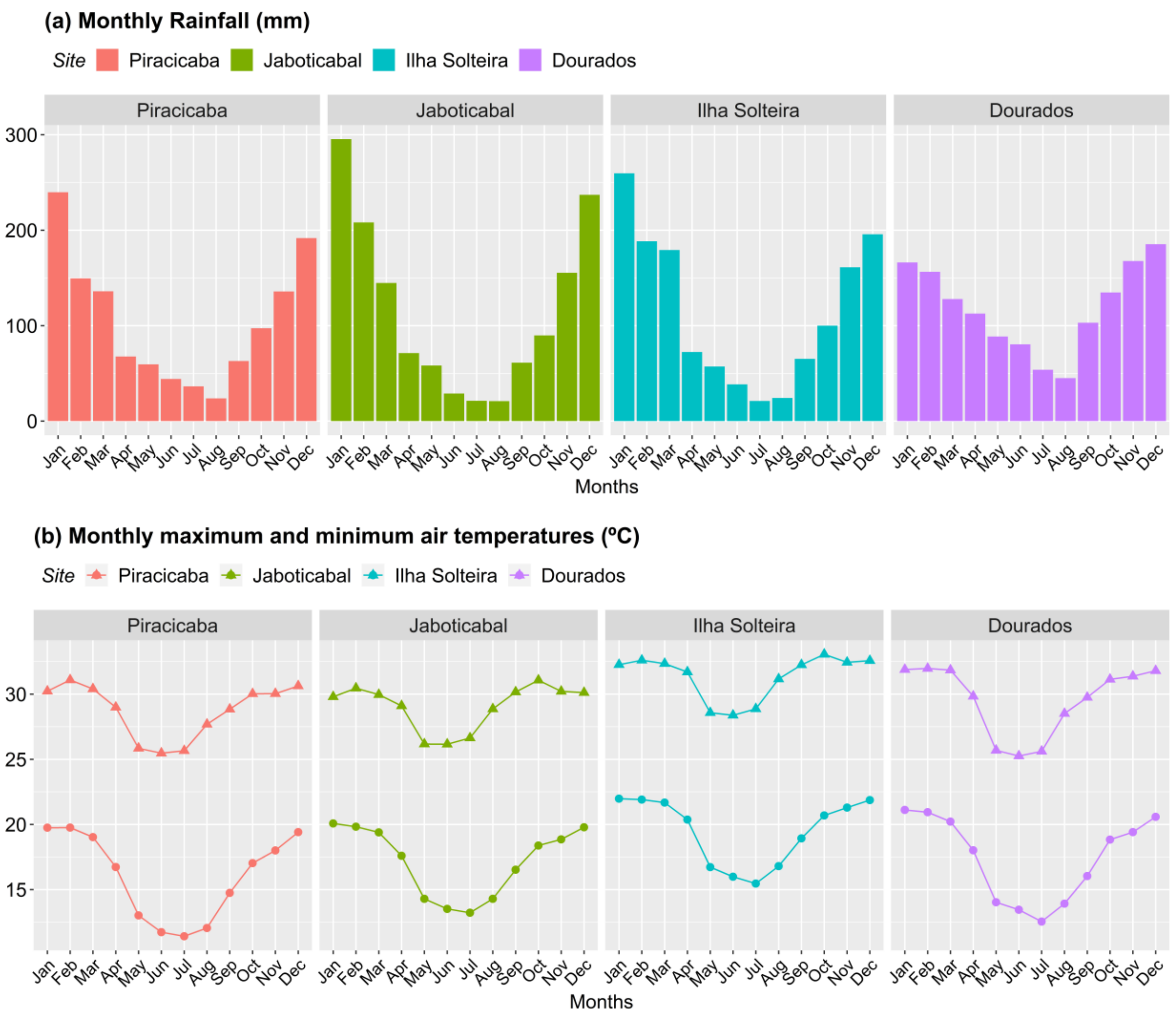

Fig. S2. Climatic conditions of Piracicaba, SP, Jaboticabal, SP, Ilha Solteira, SP, and Dourados, MS: monthly mean total rainfall (a) and average minimum and maximum air temperatures (b).

Table S1

Number and average area covered by per station (automatic or conventional types) of the National Institute of Meteorology (INMET) for each Brazilian region and their states.

Regions and States	Area (km²)	Number of weather stations			Area covered by weather stations (km²/station)		
		Automatic	Conventional	Total	Automatic	Conventional	Total
North Region	3,853,677	83	38	121	46,430	101,413	31,849
Acre (AC)	164,123	7	2	9	23,446	82,062	18,236
Amazonas (AM)	1,559,159	18	12	30	86,620	129,930	51,972
Amapá (AP)	142,829	3	1	4	47,610	142,829	35,707
Pará (PA)	1,247,955	30	15	45	41,598	83,197	27,732
Rondônia (RO)	237,591	4	-	4	59,398	-	59,398
Roraima (RR)	224,301	1	2	3	224,301	112,150	74,767
Tocantins (TO)	277,721	20	6	26	13,886	46,287	10,682
Northeast Region	1,554,570	146	80	226	10,648	19,432	6,879
Alagoas (AL)	27,779	7	4	11	3,968	6,945	2,525
Bahia (BA)	564,733	48	25	73	11,765	22,589	7,736
Ceará (CE)	148,920	16	10	26	9,308	14,892	5,728
Maranhão (MA)	331,937	16	12	28	20,746	27,661	11,855
Paraíba (PB)	56,585	9	6	15	6,287	9,431	3,772
Pernambuco (PE)	98,312	14	7	21	7,022	14,045	4,682
Piauí (PI)	251,578	21	8	29	11,980	31,447	8,675
Rio Grande do Norte (RN)	52,811	8	5	13	6,601	10,562	4,062
Sergipe (SE)	21,915	7	3	10	3,131	7,305	2,192
Central-West Region	1,606,404	96	19	115	16,733	84,548	13,969
Distrito Federal (DF)	5,780	4	1	5	1,445	5,780	1,156
Goiás (GO)	340,112	27	9	36	12,597	37,790	9,448
Mato Grosso do Sul (MS)	357,146	28	1	29	12,755	357,146	12,315
Mato Grosso (MT)	903,366	37	8	45	24,415	112,921	20,075
Southeast Region	924,620	173	50	223	6,497	22,479	5,040
Espírito Santo (ES)	46,096	13	2	15	3,546	23,048	3,073
Minas Gerais (MG)	586,522	67	25	92	8,754	23,461	6,375
Rio de Janeiro (RJ)	43,780	26	7	33	1,684	6,254	1,327
São Paulo (SP)	248,222	41	9	50	6,054	27,580	4,964
South Region	576,774	67	14	81	5,634	26,962	4,660
Paraná (PR)	199,308	26	7	33	7,666	28,473	6,040
Rio Grande do Sul (RS)	281,730	43	13	56	6,552	21,672	5,031
Santa Catarina (SC)	95,736	24	1	25	3,989	95,736	3,829
Overall	8,516,045	565	201	766	15,073	42,368	11,118

Table S2

Site-specific soil properties employed in the simulations.

Soil layer (cm)	Horizon -	OC [a] %	pH_{H2O} [b] -	Clay	Silt -------- (%) ---------	Sand	BD [c] (g cm^{-3})	θ_{LL} [d]	θ_{DUL} [e] ------ (cm3 cm-3) ------	θs [f]	K_L [g] per d^{-1}
Piracicaba, SP | Latossolo Vermelho-Amarelo (Laclau and Laclau, 2009) | Ferralsol [h]											
0-20	Ap	0.8	4.0	54	7	39	1.37	0.242	0.355	0.483	0.12
20-40	AB	0.6	4.1	57	7	36	1.35	0.249	0.363	0.491	0.09
40-60	Bw1	0.37	4.1	54	5	41	1.15	0.247	0.365	0.566	0.07
60-100	Bw2	0.23	4.5	59	6	35	1.13	0.261	0.378	0.574	0.06
100-200	Bw3	0.1	4.7	45	22	33	1.12	0.263	0.398	0.577	0.04
200-300	Bw4	0.27	5.1	48	19	33	1.10	0.267	0.397	0.585	0.02
Jaboticabal, SP | Latossolo Vermelho (Otto, 2012) | Ferralsol [h]											
0-15	Ap	1.34	6.3	29	5	66	1.31	0.165	0.277	0.508	0.12
15-37	A2	0.93	6.0	30	5	65	1.46	0.162	0.276	0.449	0.09
37-56	BA	0.64	5.1	35	5	60	1.39	0.181	0.297	0.475	0.08
56-96	Bw1	0.47	5.6	37	5	58	1.21	0.196	0.311	0.544	0.06
96-150	Bw2	0.41	5.9	37	5	58	1.24	0.196	0.312	0.531	0.04
Ilha Solteira, SP | Argissolo Vermelho (Gioia, 2011) | Acrisol or Alisol [h]											
0-33	Ap	0.38	4.5	16	12	73	1.56	0.123	0.235	0.400	0.10
33-63	BA	0.23	4.5	34	12	54	1.58	0.186	0.272	0.350	0.07
63-124	Bt1	0.11	4.2	35	8	57	1.5	0.182	0.270	0.370	0.05
124-164	Bt2	0.07	4.2	37	7	56	1.44	0.192	0.297	0.430	0.04
164-200	Bt3	0.11	4.2	39	7	54	1.49	0.194	0.296	0.410	0.03
Dourados, MS | Latossolo Vermelho (Amaral et al., 2000) | Ferralsol [h]											
0-18	A	0.97	5.2	62	16	22	1.22	0.285	0.422	0.590	0.12
18-67	AB	0.81	5.2	69	11	20	1.02	0.295	0.41	0.640	0.09
67-71	B	0.59	5.2	67	13	20	1.09	0.293	0.416	0.620	0.07
71-145	Bw1	0.42	5.5	67	13	20	1.09	0.293	0.416	0.620	0.05
145-260	Bw2	0.18	5.7	69	11	20	1.06	0.293	0.412	0.630	0.02
260-320	Bw3	0.02	5.7	74	7	19	1.06	0.290	0.406	0.630	0.01

[a] Soil organic carbon; [b] Actual values not used in the simulations to avoid nitrogen stress in the crop. pH values were set as 6; [c] Soil bulk density; [d] Lower limit (-1500 kPa); [e] Drained upper limit (-10 kPa); [f] Saturated water content; [g] Root extraction constant: calculated using the exponential functions as in Battisti and Sentelhas (2017) with the exponential geotropism constant as 3.5 for a deep soil (Laclau and Laclau, 2009). The first 20 cm was considered as 0.10-0.12. The values are similar to those presented by Robertson et al. (1999) and Inman-Bamber et al. (2000); [h] FAO classification system

Table S3

APSIM-Sugar parameters or coefficients for variety RB867515 used in the simulations.

Parameters or coefficients	APSIM term	Q117 (default)	RB867515 (Dias et al., 2020)
Light extinction coefficient	*extinction_coef*	0.38	0.52
Thermal time from planting to sprouting	*shoot_lag*	250	100
Thermal time from ratooning to sprouting	*shoot_lag*	100	75
Area of specific leaves	*leaf_size*	1500 55000 55000	5800 20000 36000 46000 51000 51400 50700 49300 43500
Numbered leaf from top of stalk	*leaf_size_no*	1 14 20	1 5 10 15 20 22 24 26 30
Number of green leaves	*green_leaf_no*	13	11.7
Thermal time from emergence to onset of stalk growth	*tt_emerg_to_begcane*	1900	461.5
Expansion factor for *leaf_size*. Represents the effect of tillering on the leaf profile	*tillerf leaf size*	1.0 1.5 1.5 1.0 1.0	1.00 1.51 1.53 1.56 1.26 1.07 1.00
Numbered leaf from top of stalk	*tillerf leaf size no*	1 6 10 12 26	1 9 11 13 17 25 40

Table S4

Statistics of model performance for variety RB867515 (Dias et al., 2020).

Index	Stage			
	Calibration with plant data [a]	In-site validation with first ratoon [a]	In-site validation with plant and first ratoon [a]	Validation with published experiments [b]
n	101	17	20	23
R^2	0.64	0.91	0.87	0.40
d	0.89	0.97	0.96	0.75
RMSEP (%)	19.8	10.4	10.3	23.8

[a] Fractional photosynthetically active radiation interception; [b] Leaf area index

Table S5

Statistical analysis for the comparison between measured (MWD) and NASA gridded weather data with and without measured rainfall replacement for sugarcane crop performance APSIM-Sugar's outputs at four sites in Center-South Brazil. Average values, coefficient of determination (R^2), agreement coefficient (*d*), root mean square error (RMSE) and its percentage (RMSEP) are presented.

Site	Crop performance variable	Average MWD	Gridded rainfall					Measured rainfall				
			Average NASA	R^2	*d*	RMSE	RMSEP	Average	R^2	*d*	RMSE	RMSEP
Piracicaba	Total number of leaves	46	44	0.88	0.85	2	3.8	44	0.88	0.84	2	4.0
	Days to reach PARi of 0.50	117	86	0.25	0.62	55	46.5	102	0.72	0.89	32	27.0
	Maximum LAI	3.2	4.4	0.30	0.48	1.3	41.4	3.9	0.57	0.63	0.9	27.2
	Water uptake (mm/cycle)	691	924	0.45	0.61	270	39.1	732	0.80	0.93	93	13.4
	Stress-days	73	21	0.12	0.43	62	84.5	53	0.68	0.79	29	39.5
	Aboveground biomass (t/ha)	31.4	47.5	0.62	0.54	17.1	54.2	39.4	0.85	0.80	8.8	27.9
	Sugarcane yield (t/ha)	94.3	141.3	0.63	0.57	49.9	53.0	117.0	0.85	0.82	25.3	26.8
Jaboticabal	Total number of leaves	48	48	0.31	0.75	2	3.8	49	0.90	0.96	1	1.7
	Days to reach PARi of 0.50	105	99	0.17	0.69	45	42.9	99	0.59	0.86	27	26.2
	Maximum LAI	3.5	3.6	0.37	0.77	0.4	12.0	3.5	0.86	0.96	0.2	4.7
	Water uptake (mm/cycle)	698	786	0.18	0.61	176	25.1	690	0.85	0.94	63	9.0
	Stress-days	89	41	0.12	0.48	59	65.5	60	0.80	0.73	34	38.2
	Aboveground biomass (t/ha)	33.7	38.9	0.22	0.63	8.9	26.3	35.0	0.86	0.95	3.1	9.1
	Sugarcane yield (t/ha)	100.8	115.2	0.24	0.65	26.1	25.9	104.1	0.87	0.96	8.6	8.5
Ilha Solteira	Total number of leaves	53	53	0.89	0.96	1	2.1	52	0.91	0.96	1	2.0
	Days to reach PARi of 0.50	142	133	0.36	0.76	64	45.2	124	0.85	0.95	34	24.0
	Maximum LAI	2.6	2.9	0.22	0.62	0.6	23.4	2.9	0.62	0.78	0.5	18.7
	Water uptake (mm/cycle)	660	585	0.26	0.63	174	26.3	599	0.80	0.88	108	16.3
	Stress-days	60	48	0.14	0.60	29	48.4	47	0.47	0.76	23	38.7
	Aboveground biomass (t/ha)	27.7	31.9	0.29	0.67	7.4	26.6	32.2	0.82	0.85	5.4	19.4
	Sugarcane yield (t/ha)	83.2	94.8	0.35	0.71	22.0	26.5	95.9	0.84	0.88	15.6	18.7
Dourados	Total number of leaves	48	49	0.86	0.93	1	2.3	49	0.84	0.93	1	2.1
	Days to reach PARi of 0.50	120	97	0.23	0.58	42	35.2	120	0.64	0.89	25	20.5
	Maximum LAI	3.1	3.3	0.54	0.84	0.5	17.2	3.1	0.77	0.93	0.3	10.9
	Water uptake (mm/cycle)	731	846	0.37	0.72	201	27.5	719	0.90	0.97	65	8.8
	Stress-days	50	30	0.00	0.43	45	89.4	47	0.50	0.84	24	48.4
	Aboveground biomass (t/ha)	31.8	36.9	0.49	0.77	8.7	27.3	32.1	0.87	0.96	3.5	11.1
	Sugarcane yield (t/ha)	95.7	110.9	0.52	0.78	25.4	26.6	96.4	0.87	0.96	10.6	11.1

Table S6

Statistical analysis for the comparison between measured (MWD) and XAVIER gridded weather data with and without measured rainfall replacement for sugarcane crop performance APSIM-Sugar's outputs at four sites in Center-South Brazil. Average values, coefficient of determination (R^2), agreement coefficient *(d)*, root mean square error (RMSE) and its percentage (RMSEP) are presented.

Site	Crop performance variable	Average MWD	Gridded rainfall					Measured rainfall				
			Average XAVIER	R^2	*d*	RMSE	RMSEP	Average	R^2	*d*	RMSE	RMSEP
Piracicaba	Total number of leaves	46	45	0.83	0.88	1	3.1	45	0.62	0.81	2	4.1
	Days to reach PARi of 0.50	117	97	0.22	0.57	50	42.5	102	0.50	0.69	41	35.2
	Maximum LAI	3.2	4.0	0.29	0.55	1.0	31.8	3.6	0.46	0.73	0.6	20.3
	Water uptake (mm/cycle)	691	879	0.39	0.61	238	34.4	730	0.85	0.93	86	12.5
	Stress-days	73	12	0.11	0.41	69	95.2	42	0.53	0.68	40	54.5
	Aboveground biomass (t/ha)	31.4	42.7	0.54	0.59	12.9	41.1	36.4	0.81	0.85	6.5	20.6
	Sugarcane yield (t/ha)	94.3	127.1	0.55	0.61	37.8	40.1	108.8	0.83	0.86	18.7	19.9
Jaboticabal	Total number of leaves	48	48	0.98	0.99	0	0.7	48	0.98	0.99	0	0.7
	Days to reach PARi of 0.50	105	97	0.21	0.67	38	36.7	108	0.32	0.75	36	34.1
	Maximum LAI	3.5	3.4	0.44	0.81	0.4	10.3	3.1	0.83	0.75	0.5	13.8
	Water uptake (mm/cycle)	698	842	0.57	0.72	176	25.2	697	0.89	0.96	51	7.4
	Stress-days	89	36	0.29	0.51	61	68.4	62	0.83	0.80	31	34.9
	Aboveground biomass (t/ha)	33.7	38.0	0.70	0.83	5.9	17.4	32.3	0.85	0.94	3.2	9.4
	Sugarcane yield (t/ha)	100.8	113.9	0.68	0.83	18.1	17.9	96.6	0.83	0.94	10.1	10.1
Ilha Solteira	Total number of leaves	53	53	0.92	0.97	1	1.7	53	0.91	0.97	1	1.9
	Days to reach PARi of 0.50	142	129	0.57	0.83	51	36.2	144	0.92	0.98	24	17.1
	Maximum LAI	2.6	2.6	0.40	0.76	0.4	16.3	2.5	0.75	0.93	0.3	10.4
	Water uptake (mm/cycle)	660	655	0.45	0.79	136	20.6	634	0.92	0.97	59	8.9
	Stress-days	60	59	0.26	0.67	23	39.3	57	0.87	0.96	10	16.9
	Aboveground biomass (t/ha)	27.7	28.2	0.44	0.79	5.3	19.0	27.3	0.89	0.97	2.4	8.7
	Sugarcane yield (t/ha)	83.2	84.4	0.47	0.81	16.4	19.8	81.9	0.90	0.97	7.4	8.9
Dourados	Total number of leaves	48	49	0.76	0.92	1	2.4	48	0.81	0.95	1	1.9
	Days to reach PARi of 0.50	120	98	0.35	0.62	39	32.5	108	0.48	0.73	32	26.4
	Maximum LAI	3.1	3.6	0.48	0.70	0.7	23.4	3.2	0.74	0.91	0.4	11.9
	Water uptake (mm/cycle)	731	912	0.70	0.67	220	30.1	742	0.96	0.98	48	6.6
	Stress-days	50	15	0.14	0.52	46	92.0	40	0.64	0.86	21	42.8
	Aboveground biomass (t/ha)	31.8	40.9	0.69	0.66	11.0	34.6	34.2	0.92	0.95	3.9	12.4
	Sugarcane yield (t/ha)	95.7	123.3	0.71	0.66	32.9	34.4	102.8	0.91	0.95	11.7	12.2

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6. Sugarcane yield future scenarios in Brazil as projected by the APSIM-Sugar model with new features

Abstract

Crop models can be used to assess the impacts of climate variability and change on sugarcane. Among the common models used for such purpose, APSIM-Sugar has been recently upgraded to simulate sugarcane in Brazil and to cater for climate impacts under water-limited environments. In this context, the first objective was to evaluate recently proposed features and with recently determined traits for the most cultivated variety under water-limited conditions. Then, these model settings were used to project crop performance under likely changing climates in important producing regions. The results for stalk mass predictions for four published experiments across Brazil for the standard settings were good, but the modifications further increased R^2 from 0.81 to 0.96, and the *d* index from 0.94 to 0.99, and reduced RMSE from 8.5 to 3.8 t/ha using serial measurements. The predictions for the final harvest were also enhanced, with RMSE dropping from 10.6 to 3.4 t/ha. Future climate projections (until 2099), considering two emission scenarios (RCP4.5 and RCP8.5), were derived based on a recent proposed subset approach of five climate models (GCMs) from CMIP5. The subset aimed to capture the full ensemble of temperature and rainfall changes considering basic classes of climate changes (relatively cool/wet, cool/dry, middle, hot/wet, and hot/dry). A typical system with 12-month old crops was simulated. The ensemble of future projections indicated that cane yields will decline compared to the average simulations (1980-2009) for rainfed sites, mainly due to increased water stress. Yields at fully-irrigated sites are projected to decline too, but slightly. However, the expected changes were highly variable between GCMs with the End-of-Century period presenting large uncertainty, thus these projections should be interpreted with caution. While providing an up-to-date projection of future climate change in sugarcane in Brazil, this study also raised some possible shortcomings in APSIM-Sugar to be further investigated.

Keywords: *Saccharum* spp.; Crop modelling; Climate variability; Climate change; Reduced growth phenomenon

6.1. Introduction

Climate and its variability affect crop growth, development and yield (Hoogenboom, 2000; Ray et al., 2015), thus impacting food, fibre and bioenergy production worldwide. Temporal and spatial climate variability accounts for roughly a third of global production variability of the four main crops (Ray et al., 2015), but in some cases, it can reach up to 80% (Hoogenboom, 2000; Ray et al., 2015). Expected changes in global climate projected by the Intergovernmental Panel on Climate Change (IPCC), induced mostly by human activities, add extra challenges for agricultural production security around the world (IPCC, 2014). Among the bioenergy crops, sugarcane in addition to its role as the main crop for sugar production worldwide, an important source of bioethanol and bioelectricity for many countries, especially for those in tropical and sub-tropical climates zones.

Sugarcane has been grown in Brazil since the colonial period and is still a very important source of income for the country's economy, considering both sugar and bioenergy (Cardoso et al., 2019). Brazil is currently is the largest sugarcane producer around the world, which ranks the country as the second largest sugar and bioethanol producer, and the largest sugar exporter, in the world (ISO, 2020; RFA, 2020). The crop is cultivated at about 10 mi ha, mainly in Center-Southern regions under rainfed conditions (IBGE, 2018). The harvest occurs during the dry season of the year usually when the crop is 12 months old. The long cycle and the harvest during 8 to 10 months per year make inter-annual and intra-seasonal climate variability of high importance for defining sugarcane yield (Cardozo and Sentelhas, 2013; Dias and Sentelhas, 2018b; Inman-Bamber, 2014; Muchow et al., 1997b). Further expansion of the sugarcane fields in tropical areas towards the equator (~14 to 2 °S), such as those in the north and northeast Brazil, will likely increase due to government incentives given by the 'RenovaBio' program (MME, 2017). This program aims to reduce greenhouse gas emissions by increasing biofuel use in the National energy matrix. Therefore, understanding how sugarcane crop will perform in these traditional and new environments is crucial for its sustainable production in both current and future climates.

The impacts of climate variability and change are already being detected around the world. Linnenluecke et al. (2020) argued that climate change has already impacted the Australian sugarcane industry between 1964 and 2012 based on an econometric modelling approach. Their results suggested that increases in atmospheric CO_2 concentration (from a mathematical and not a plant physiology perspective) have had a significant negative impact on sugarcane production after 1995, which contrasts with an earlier positive effect before 1995. Projections of climate change impacts on sugarcane are arguably better when carried out by process-based crop models instead of statistical approaches because they capture most of the important biophysical interactions affecting crop yields (Lobell and Asseng, 2017). Among the several models available for sugarcane, the DSSAT/CANEGRO (Inman-Bamber, 1991; Jones and Singels, 2019; Singels et al., 2008) and the APSIM-Sugar (Holzworth et al., 2015; Keating et al., 2003, 1999) models are the most commonly applied. A summary of the climate change studies with these process-based models and others can be seen in the literature compilation done by Linnenluecke et al. (2018), which in general projected a positive impact on cane yields in some producing countries, including Brazil.

The majority of the studies reported by Linnenluecke et al. (2018) were conducted with CANEGRO and APSIM-Sugar, however, both models have been recently upgraded with new features to improve sugarcane simulation, which makes it necessary for more studies about their performance and the impacts of climate change on the crop employing the new versions. Jones and Singels (2019) recently proposed improvements to CANEGRO regarding deficiencies found in the model in previous studies, such as in key plant processes influenced by changing climate variables, especially temperature. The new version of CANEGRO model is yet to be tested for Brazilian varieties, environments and cropping systems.

For APSIM-Sugar, Inman-Bamber et al. (2016) enhanced the model's capability to simulate water-related physiological processes aiming to support crop improvement in breeding programs and to better distinguish between varieties in the algorithms, including the response of transpiration efficiency (TE) to water stress and CO_2 concentration. As far as we know, the response of sugarcane crop to CO_2 is yet to be verified through free-air CO_2 enrichment experiments (FACE). Dias et al. (2019) proposed a new feature of the enhance model to deal with growth slowdown that was observed when the crop was about 8 months old and stalk dry mass yields were about ~ 40 t/ha (cane yield of ~ 150 t/ha). This feature was regarded as reliable and necessary for simulations in environments and seasons where yields exceeding 150 t/ha are expected. Traits for several Brazilian sugarcane varieties grown under full-irrigation have been recently determined with regard to canopy development and light interception (Dias et al., 2020) as well as growth slowdown (Dias et al., 2019). The growth slowdown feature still requires evaluation for reliability under rainfed cropping systems where yields may be relatively low even in crops older than 8 months.

Considering the recent advances in the APSIM-Sugar model and the importance of an up-to-date climate change impact assessment on sugarcane in Brazil, this study aimed to evaluate the recently proposed model features and traits in rainfed cropping systems and then apply these model settings to project climate change impacts on yields in traditional regions and others where new sugarcane production systems are expected to develop.

6.2. Material and methods

6.2.1. APSIM-Sugar evaluation

Stalk dry mass measurements for plant and ratoon crops from four rainfed field experiments previously published (21 observations, see Table 1 for details and references) were used to evaluate the model with its recent features and traits. All observation were for the variety RB867515 or its parent RB72454. The trait parameters regarding canopy development, light interception and growth slowdown used in the model were for variety RB867515 as recommended by Dias et al. (2019, 2020). All other parameters remained unchanged from the version 7.9 r4404 of the sugar module that was used. Details of these traits and other parameters used in the evaluation can be found in Table S1 and S2 (Supplementary material), respectively.

Table 1

Sources of experimental data from literature used for model evaluation and their main information regarding soil, climate and crop management.

Site	Latitude (° S)	Longitude (° W)	Altitude (m)	Soil classification	Source of climate data [a]	Reference
Piracicaba, SP* (SPPI)	22.43	47.25	570	*Latossolo Vermelho-Amarelo* [b]	ESALQ/USP	Suguitani (2006); Laclau and Laclau (2009)
Coruripe, AL (ALCO)	10.12	36.30	16	*Argissolo Vermelho Fragipânico* [c]	ANA, Xavier et al. (2015)	Silva (2007)
Presidente Bernardes, SP (SPPB)	22.28	51.68	400	*Argissolo Vermelho* [c]	CIIAGRO, INMET	Barbosa (2017)
Prado Ferreira, PR (PRPF)	23.00	51.46	530	*Nitossolo Vermelho* [d]	Xavier et al. (2015)	

* The variety grown in the Piracicaba experiment was RB72454, which is a progenitor of RB867515, therefore, it is reasonable to assume that many traits would behave similarly between them and we included the measurements in the model evaluation.

[a] ESALQ/USP = 'Luiz de Queiroz' College of Agriculture, University of São Paulo; ANA = National Water Agency; INMET = National Institute of Meteorology; IAC = Agronomic Institute of Campinas

[b] Ferralsol in FAO soil classification system

[c] Acrisols in FAO soil classification system

[d] Nitossol in FAO soil classification system

The TE response to water stress and CO_2 feature in the model proposed by Inman-Bamber et al. (2016) was turned on, in which the intrinsic water use efficiency or transpiration efficiency coefficient (TEC) is modified. The CO_2 effect follows Park (2008) and Webster et al. (2009). The following equation was employed:

$$\mathrm{TEC} = \min\left\{12.4; \left[8.7 \times \left(1 + (1 - \mathrm{WSD}_{\mathrm{ratio}}) \times \frac{43}{100 - 31}\right)\right]\right\} \times \left(1 + \frac{[\mathrm{CO_2}] - 350}{100} \times 0.08\right) \quad (1)$$

where TEC is the transpiration efficiency coefficient, and the 'base' value employed was 8.7 g kPa kg^{-1} after Inman-Bamber and McGlinchey (2003); WSD is the water supply/demand ratio, used to penalise crop expansion and photosynthesis in the model and; $[CO_2]$ is the atmospheric CO_2 concentration.

The results of the APSIM-Sugar with the new features and traits for RB867515 were compared with those from the original trait parameters for the standard Australian variety Q117 (Keating et al., 1999) in order to test the advantages of using the model for Brazilian conditions. All the observations from the field experiments were used. Standard statistical indices were used during model evaluation, such as coefficient of determination (R^2), mean absolute error (MAE), root mean square error (RMSE) and its percentage (RMSEP), and Willmott's '*d*' index (Wallach, 2006; Willmott et al., 1985), as follows:

$$\mathrm{MAE} = \frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} \left(\left| \mathrm{Est}_i - \mathrm{Obs}_i \right| \right) \tag{2}$$

$$\mathrm{MAPE} = \left[\frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} \left(\frac{\left| \mathrm{Est}_i - \mathrm{Obs}_i \right|}{\mathrm{Obs}_i} \right) \right] \times 100 \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}} \times \sum_{i=1}^{\mathrm{n}} \left(\mathrm{Est}_i - \mathrm{Obs}_i \right)^2} \tag{4}$$

$$\mathrm{RMSEP} = \frac{\mathrm{RMSE}}{\mathrm{Obs_m}} \times 100 \tag{5}$$

$$d = 1 - \frac{\sum_{i=1}^{\mathrm{n}} \left(\mathrm{Est}_i - \mathrm{Obs}_i \right)^2}{\sum_{i=1}^{\mathrm{n}} \left(\left| \mathrm{Est}_i - \mathrm{Obs_m} \right| + \left| \mathrm{Obs}_i - \mathrm{Obs_m} \right| \right)^2} \tag{6}$$

where Est_i and Obs_i are the estimated and observed sugarcane stalk dry mass, in t/ha, respectively; Est_m and Obs_m are the averages of estimated and observed sugarcane stalk dry mass, in t/ha, respectively; and n is the number of observations.

6.2.2. Crop simulations

6.2.2.1. Study sites

Traditional sites where sugarcane crop is grown under rainfed and irrigated conditions, as well as others to where this crop is expanding, were selected for simulations. Table 2 summarises information of these sites regarding its code identification, geographical coordinates, as well as the climate and soil data sources, which were gathered from public and/or published sources (see Fig. 1 for a spatial view). Climate characterisation and soil properties for each site can be found in Figs. S1 and S2 (Supplementary material), respectively.

Table 2

Brazilian sites used to simulate the climate change impacts on the sugarcane crop, with APSIM-Sugar, and their respective IDs, geographic coordinates, altitude, climate classification and sources of data.

Site	ID	Latitude (º S)	Longitude (º W)	Altitude (m)	Source of climate data [a]	Koppen's climate [b]	Source of soil data
Piracicaba, SP	SPPI	-22.71	-47.42	546	ESALQ (USP)	Cfa	Laclau and Laclau (2009)
Jaboticabal, SP	SPJB	-21.23	-48.28	615	UNESP	Cwa	Otto (2012)
Ilha Solteira, SP	SPIS	-20.42	-51.35	337	UNESP	Aw	Gioia (2011)
Dourados, MS	MSDO	-22.28	-54.92	408	EMBRAPA, INMET	Am	Amaral et al. (2000)
Maringá, PR	PRMA	-23.40	-51.91	542	INMET	Cfa	Romero et al. (2012) [c]
Capinópolis, MG	MGCA	-18.71	-49.55	621	INMET	Aw	Romero et al. (2012) [c]
Januária, MG	MGJA	-15.45	-44.00	474	INMET	Aw	Dias et al. (2020)
Petrolina, PE	PITE	-5.36	-42.81	74	INMET	BSh	Romero et al. (2012) [c]
Teresina, PI	PEPE	-9.36	-40.46	370	INMET	Aw	Dias et al. (2019)
Maceió, AL	ALMA	-9.66	-35.70	64	INMET	Am	Maia and Ribeiro (2004)

[a] ESALQ/USP = 'Luiz de Queiroz' College of Agriculture, University of São Paulo; UNESP = São Paulo State University; EMBRAPA = Brazilian Agricultural Research Corporation; INMET = National Institute of Meteorology

[b] Alvares et al. (2013)

[c] Soi water limits (lower limit, drained upper and saturated limits) derived based on the pedotransfer functions for Brazilian soils developed by Tomasella et al. (2000).

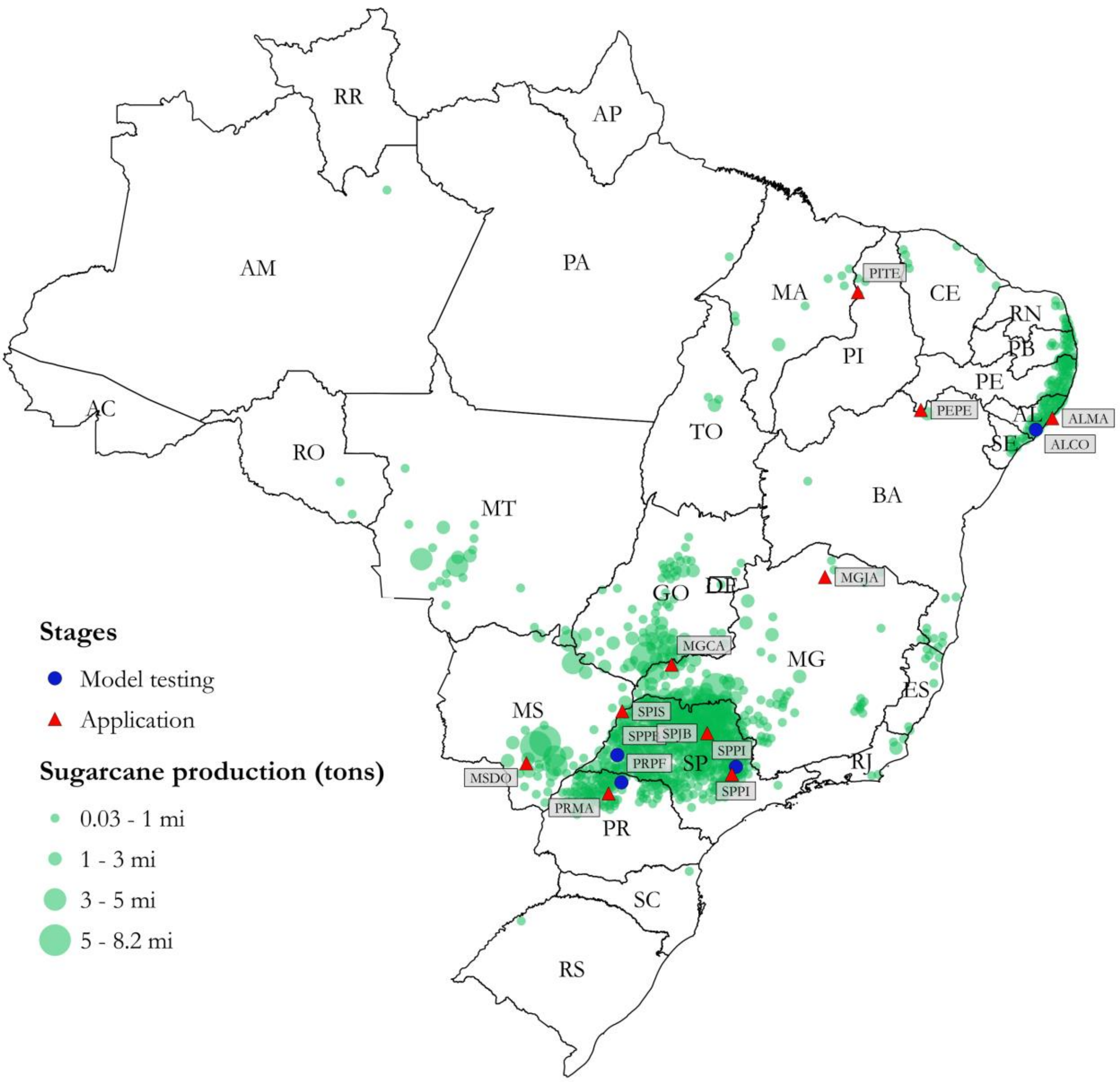

Fig. 1. Spatial distribution of the sites where the climate change study was performed (red triangles) and the location of four published field experiments used to validate the model (blue dots). Green circles represent the Brazilian municipalities where sugarcane production was higher than 30,000 tons in the 2017/2018 growing season (IBGE, 2018). The site codes can be found in Tables 1 and 2.

A schematic representation of the crop simulations after APSIM-Sugar evaluation is depicted in Fig. 2. Each step is detailed next in the subsequent sub-sections.

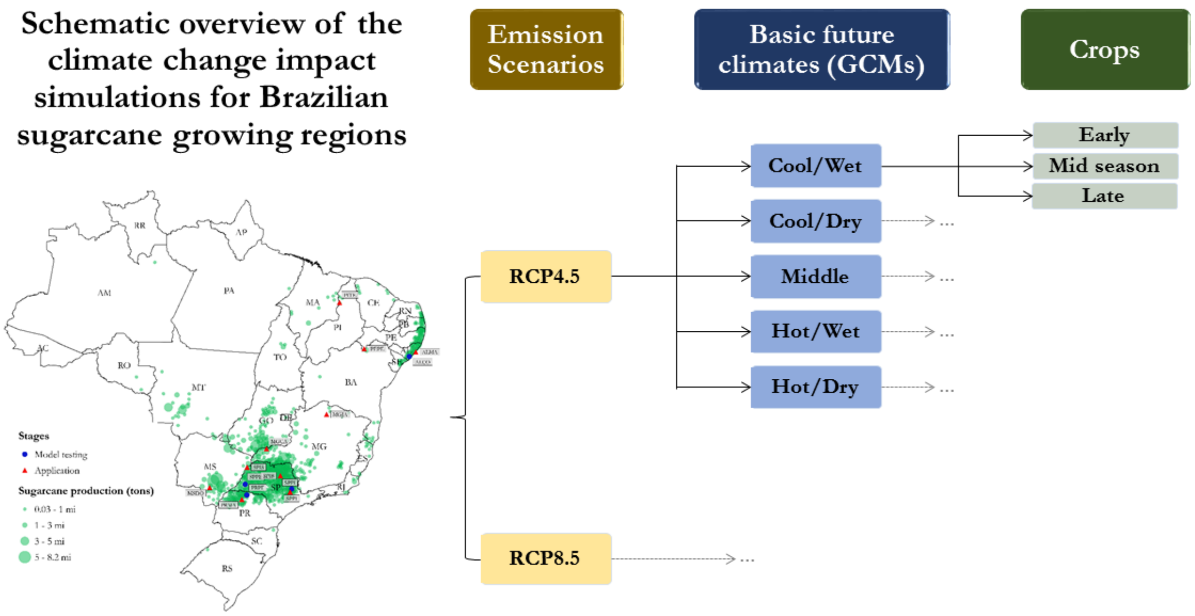

Fig. 2. Schematic overview of the climate change impact simulations for Brazilian sugarcane growing regions.

6.2.2.2. Climate change projections

The strategy used to generate future climate scenarios was based on the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig et al., 2016, 2013). The climate change impact studies for sugarcane in Brazil were mostly carried out with the global climate models (GCMs) from early phases of the Coupled Model Intercomparison Project (CMIP), which is currently available for its fifth phase (Taylor et al., 2012). The projections of 29 GMCs from CMIP5 were downscaled using the Delta change method (Wilby et al., 2004), whereby the observed (baseline, 1980-2009) daily time series is adjusted to impose monthly rainfall and temperature changes (the difference between a GCM's future and baseline period). Two Representative Concentration Pathways (RCPs; Moss et al., 2010), 4.5 and 8.5 (the extreme or 'business as usual' scenario) were considered for two time-periods, Mid-Century (2040-2069) and End-of-Century (2070-2099). Increments in atmospheric CO_2 concentration until 2100 for each RCP were based on Moss et al. (2010). Average [CO_2] levels are projected to rise around 499 and 571 ppm for RCP4.5 and RCP8.5 in the central year for Mid-Century, and around 532 and 801 ppm for End-of-Century, respectively. The median was used to aggregate the long-term projections from each combination of site × period × RCP and the changes were in relation to the baseline or historical period.

A sub-setting of five GCMs was then applied following the methodology of Ruane and McDermid (2017), which groups those GCMs that present probability of basic classes of climate changes (relatively cool/wet, cool/dry, middle, hot/wet, and hot/dry) for each location. The five site-specific GMCs for each location were then used to run the APSIM-Sugar model simulations, which some information about them can be found in Table S3 (Supplementary material).

6.2.2.3. Cropping systems

Typical 12-month old plant cane starting from planting or ratooning in April, July and October, were simulated in the APSIM-Sugar module with the traits for variety RB867515 to mimic early, middle and late harvests during a regular season in Brazil, respectively. The only exception was at Maceió in the east of Northeast region, where the rainy season is the opposite of the other sites. For this location, the simulations started in November, February and April to represent early, middle and late plant cane cycles, respectively. The planting depth adopted was 15 cm. The time limit for emergence was removed but the thermal time or the cumulative stress limits, which can also lead to crop failure during the initial phases were retained. Nitrogen was applied to avoid any deficiency and simulations were continuous (no resetting) from 1980 to 2100 (Basso et al., 2015) with residues left in the soil after harvesting, a common practise in many Brazilian cropping systems. Automatic full-irrigation option in the model was adopted at Januária, Teresina, Petrolina and Maceió. No irrigation was simulated at the other sites.

Plant cane and five subsequent ratoons were simulated, which is consistent with the common cropping systems in Brazil. The decline of vigour in successive ratoons (Dias and Sentelhas, 2017; Inman-Bamber et al., 2012; Ramburan et al., 2013) was not included in the simulations apart from the difference between plant and all ratoon crops regarding RUE and thermal time for sprouting, as required for APSIM-Sugar (Keating et al., 1999). Crop yields (fresh basis) were derived from stalk dry mass outputs assuming a constant dry matter content of 0.30 at harvest (Fageria et al., 2010; Inman-Bamber, 2004).

The median yield was used to aggregate the long-term simulated projections from each combination of site × period × RCP and the changes were in relation to the baseline or historical period. The ensemble of the simulation outputs considering all the five GCM was also analysed.

The graphics for visual analysis were created using the *ggplot2* package (Wickham, 2016) in the R *environment* (R CORE TEAM, 2018).

6.3. Results

6.3.1. APSIM-Sugar's performance for estimating stalk dry mass

APSIM-Sugar had a good performance for estimating sugarcane stalk dry mass under rainfed conditions in different Brazilian environments after including specific traits for variety

RB867515 and the features for TE and growth slowdown when compared to the standard version of the model with the traits for Australian variety Q117 (Fig. 3 and Table 3). With standard (default) settings, APSIM-Sugar predicted stalk dry mass reasonably well except for experiments at Piracicaba and Coruripe, where yields from the last two samples were underestimated and at Presidente Bernardes, where the model overestimated yield mainly from the last sample. Statistical indices for the standard settings showed that the model slightly underestimated stalk dry mass (ME = -1.3 t/ha), but accounted for 81% of the observed variation, with a good agreement (*d* = 0.94), and MAE and RMSE less than 7 t/ha and 10 t/ha, respectively. However, at harvest the statistical indices and errors were worsened (R^2 = 0.71; *d* = 0.88; MAE = 9.4 t/ha; RMSE = 10.6 t/ha). After the inclusion of specific traits for RB867515, APSIM-Sugar's performance was improved, especially for yield values at harvest, with R^2 and *d* index enhanced by 33% and 12%, respectively, and MAE and RMSE reduced by 68%. RMSEP reached 18% and 9%, respectively, for the values measured throughout the cane cycle and at harvest. Despite the appreciable improvements brought by the specific traits for the Brazilian variety and new model´s features, APSIM-Sugar estimates at Coruripe remained poor when the crop was young.

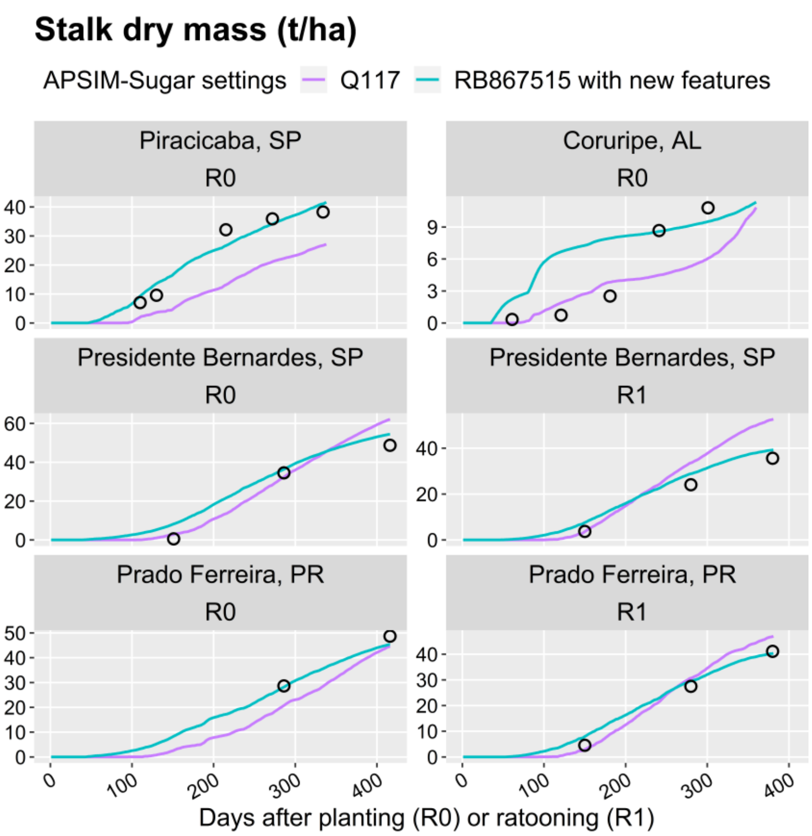

Fig. 3. Stalk dry mas measured (empty circles) and simulated (lines) by the APSIM-Sugar model with traits for variety RB867515 and features for transpiration efficiency and growth slowdown (green line), compared to the simulations with the traits for the standard variety Q117 (purple line), for rainfed experiments in Brazil. R0 = plant crop and R1 = first ratoon. Note that the y-axes have different values.

Table 3

Performance of APSIM-Sugar to simulate sugarcane stalk dry mass throughout crop season (n = 21) and at harvest (n = 6) with traits for variety RB867515 and features for transpiration efficiency and growth slowdown, compared to simulations with the traits for the standard variety Q117, for the four rainfed experiments in Brazil.

Index	Q117		RB867515 with new features	
	season	at harvest	season	at harvest
R^2	0.81	0.71	0.96	0.95
d	0.94	0.88	0.99	0.98
ME (t/ha)	-1.32	2.64	2.00	1.14
MAE (t/ha)	6.43	9.41	3.26	2.94
RMSE (t/ha)	8.48	10.59	3.82	3.35

6.3.2. Future climate change projections

Projected changes in monthly mean air temperature and rainfall for each site and RCP (4.5 and 8.5) from 29 GCMs are depicted in Figs. 4 and 5, respectively. As expected, RCP8.5 projects warmer climates than RCP4.5, but both agree that the spring months (around September to December) will be the warmest ones for all future periods considered (Fig. 4). Considering the period of 2040-2069, some months in the spring at Jaboticabal, Ilha Solteira, Dourados, Jaíba and Capinópolis may face changes around 3 to 4 ºC in the high emission scenario. This level of warming is only projected in September at Ilha Solteira and October at Capinópolis in the End-of-Century period under RCP4.5. Among the sites assessed, Maceió (northeast shore) is the one where temperature increments are projected to be lower. For the End-of-Century period (2070-2099), GCMs are projecting that all sites are likely to face increments in temperature between 3 and 4 ºC at least. The uncertainty for the temperature changes among GCMs can be found in Supplementary Fig. S3.

The projected scenarios exhibit different changes in monthly rainfall across sites and months (Fig. 5), but there is a high uncertainty among all the 29 GCMs for long-term changes (see supplementary Fig. S4). Both RCPs agree reasonably well in regard to the patterns of change whether increasing or decreasing amounts of rain. Maceió, the most distinguishable site amongst all, may face appreciable reductions of rain in the wet season (May to August). Conversely, Southern sites (Maringá, Dourados, Ilha Solteira, Piracicaba and Jaboticabal) are expected to receive slightly higher amounts of annual rainfall. The wet and dry seasons in Jaíba are projected to be intensified, but with a similar amount of total rainfall for the year. At in-land sites in the Northeast region (Teresina and Petrolina), projections suggest that annual rainfall will be slightly reduced but with summer months receiving more rain according to the ensemble of the GCMs.

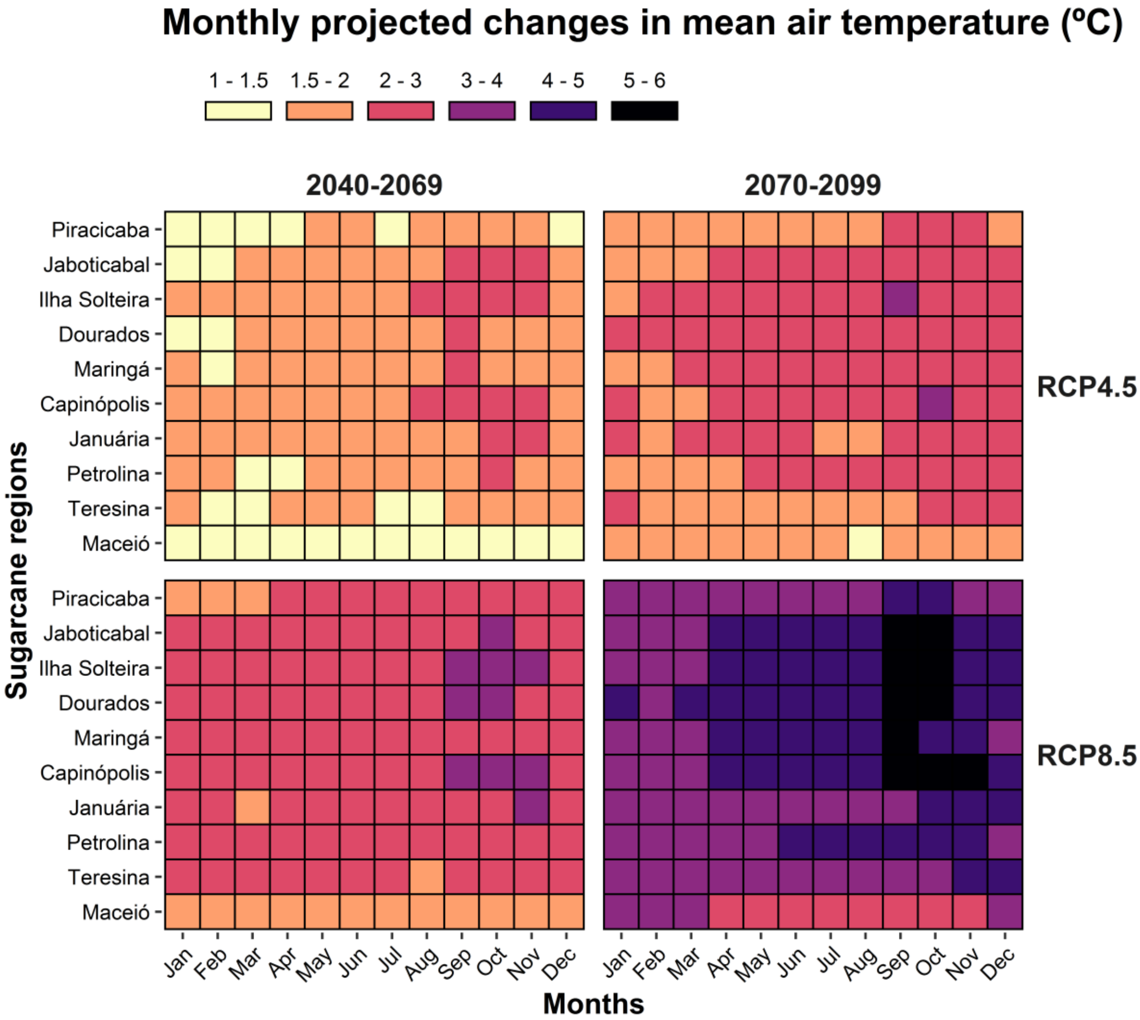

Fig. 4. Projected monthly changes in mean air temperature (ºC) from the median of 29 global climate models (GCMs), for 10 sites representing sugarcane regions in Brazil, for Mid-Century (2040–2069) and End-of-Century (2070–2099) periods, under intermediate (RCP4.5) and high (RCP8.5) greenhouse gases emission scenarios, considering the historical period as 1980–2009 as the baseline.

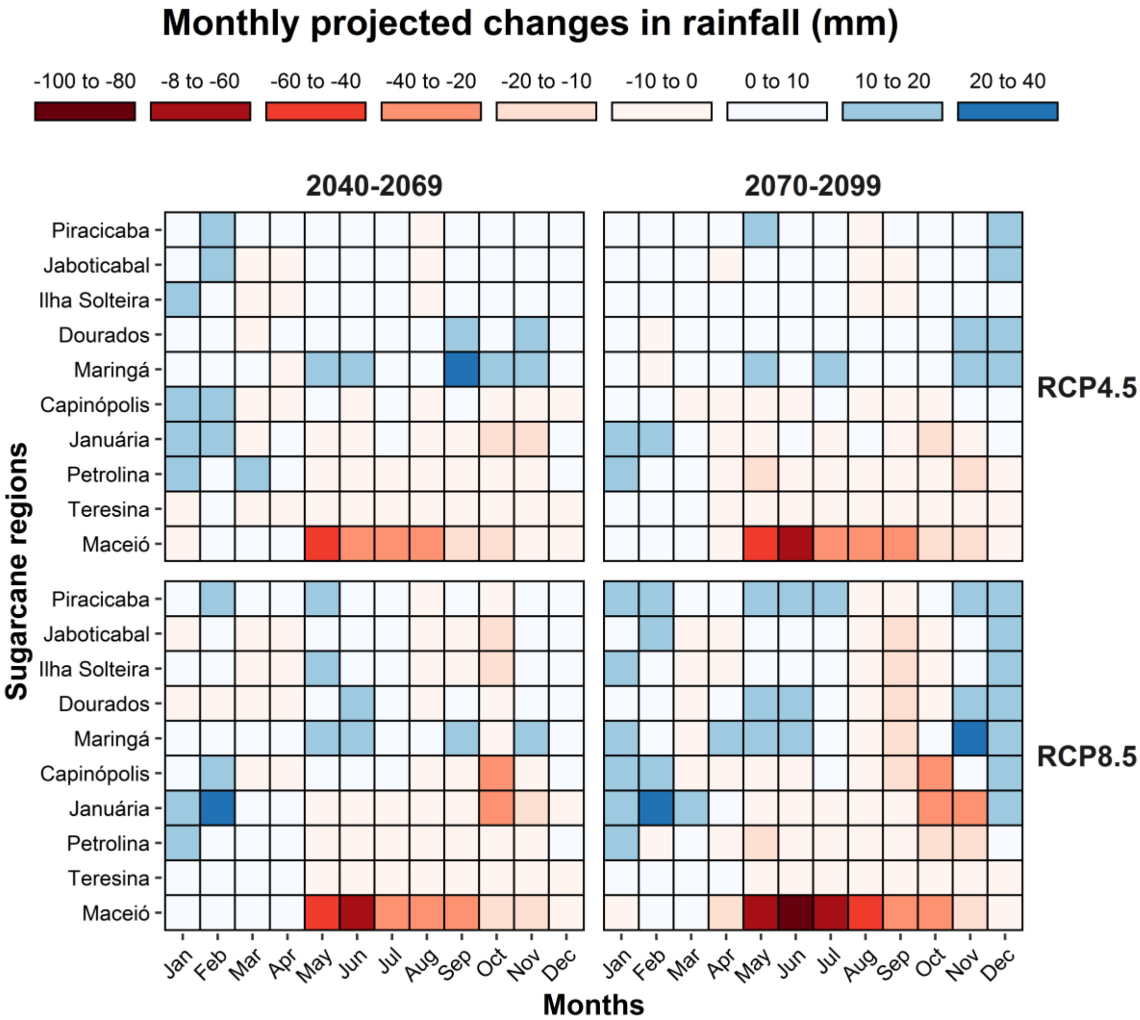

Fig. 5. Projected monthly changes in rainfall (mm) from the average of 29 global climate models (GCMs), for 10 sites representing sugarcane regions in Brazil, for Mid-Century (2040–2069) and End-of-Century (2070–2099) periods, under intermediate (RCP4.5) and high (RCP8.5) greenhouse gases emission scenarios, considering the historical period as 1980–2009 as the baseline.

6.3.3. Projected impacts of climate future scenarios on sugarcane yields

6.3.3.1. Rainfed sites

The effect on sugarcane yield projected for future climates from the five GCMs for two time-periods and RCPs are presented in Tables 4 and 5, in which the results for the three starting dates were pooled. Simulations of past (historical) yields (1980-2009) ranged from 94 to 145 t/ha across the sites. The impact of warming at all sites will be variable depending on the relative temperature and rainfall changes projected by the GCMs for each RCP, as well as the future period considered (Mid-Century or End-of-Century). In most of the projected scenarios for a relatively cool/wet climate yields will be positively impacted in the sites of the state of São Paulo and Dourados, with the exception at Jaboticabal in the End-of-Century period for both RCPs, where cane yields will be kept much the same as the baseline historical scenario (-1.6% to -1.7% decreases). The cool/dry climate at Capinópolis will be more favourable for sugarcane production than the cool/wet one, which could be attributed to the relatively small changes in climate projected by both groups of GCMs selected for each location (Table S3, relative changes not shown). Changes in rainfall will be small for these GCMs and the cool/dry climate will be relatively 'less warm' than the cool/wet one, which might contribute to reducing crop evapotranspiration throughout crop cycles.

On the other hand, a future hot/dry climate will negatively impact cane yields in all simulated conditions, ranging from -11% to -49.2%. The worst projected decrease at Dourados for the RCP8.5 in the End-of-Century period approaches half of the historical yields (a decrease of ~ 58 t/ha) (Table 5). The impacts of other basic classes of climate change were variable depending on the combinations of environment, time-periods and RCPs, thus quite uncertain.

The ensemble of all GCMs used to represent the five basic future climates usually projected negative impacts on cane yields, however, for the RCP8.5 emission scenario, the decreases achieved -10% or less mainly for the End-of-Century period (Tables 4 and 5). Among all sites assessed, Piracicaba will be the least affected by climate change when coupling future climate-crop modelling simulations, which can be attributed to the positive changes when increments in rainfall are likely to occur (future scenarios with a 'wet' climate; Table 4).

Table 4

Projected relative changes (Δ, %) of simulated sugarcane yields in 2040-2069 and 2070-2099 under RCP4.5 and RCP8.5 compared to historical (baseline, 1980–2009) according to five basic class of climate change and their ensemble, at three rainfed sites in the state of São Paulo, Brazil.

Site	Historical (1980-2009)	Basic class of climate change	2040-2069				2070-2099			
			RCP4.5	Δ (%)	RCP8.5	Δ (%)	RCP4.5	Δ (%)	RCP8.5	Δ (%)
Piracicaba, SP	123.4	Cool & Wet	135.8	10.1	135.8	10.1	132.8	7.6	132.8	7.7
		Cool & Dry	112.2	-9.0	106.1	-14.0	116.8	-5.3	95.2	-22.8
		Middle	126.8	2.8	121.8	-1.2	121.7	-1.3	120.0	-2.7
		Hot & Wet	134.7	9.2	130.5	5.8	134.4	8.9	126.4	2.4
		Hot & Dry	93.2	-24.5	84.8	-31.2	83.4	-32.4	73.1	-40.7
		Ensemble	*123.6*	*0.2*	*120.2*	*-2.5*	*121.0*	*-1.9*	*113.4*	*-8.1*
Jaboticabal, SP	113.4	Cool & Wet	116.3	2.5	114.5	1.0	111.6	-1.6	111.5	-1.7
		Cool & Dry	92.1	-18.8	77.2	-32.0	88.6	-21.8	69.3	-38.9
		Middle	105.6	-6.9	108.8	-4.0	106.7	-5.9	110.6	-2.5
		Hot & Wet	108.5	-4.3	110.6	-2.5	107.7	-5.0	109.6	-3.3
		Hot & Dry	84.8	-25.2	71.6	-36.8	77.1	-32.0	64.1	-43.5
		Ensemble	*102.4*	*-9.7*	*99.6*	*-12.2*	*99.8*	*-12.0*	*96.2*	*-15.1*
Ilha Solteira, SP	94.0	Cool & Wet	104.8	11.5	102.0	8.6	105.8	12.6	101.2	7.7
		Cool & Dry	84.2	-10.4	65.4	-30.4	85.5	-9.0	51.7	-45.0
		Middle	91.9	-2.2	91.7	-2.4	89.9	-4.3	100.6	7.0
		Hot & Wet	89.2	-5.1	87.4	-6.9	86.8	-7.6	87.6	-6.7
		Hot & Dry	62.5	-33.5	49.3	-47.6	60.5	-35.7	48.8	-48.1
		Ensemble	*86.2*	*-8.2*	*79.7*	*-15.2*	*85.0*	*-9.5*	*78.0*	*-17.0*

Table 5

Projected relative changes (Δ, %) of simulated sugarcane yields in 2040-2069 and 2070-2099 under RCP4.5 and RCP8.5 compared to historical (baseline, 1980–2009) according to five basic class of climate change and their ensemble, at three rainfed sites in the states of Mato Grosso do Sul (MS), Paraná (PR) and Minas Gerais (MG), Brazil.

Site	Historical (1980-2009)	Basic class of climate change	2040-2069				2070-2099			
			RCP4.5	Δ (%)	RCP8.5	Δ (%)	RCP4.5	Δ (%)	RCP8.5	Δ (%)
Dourados, MS	109.8	Cool & Wet	123.1	12.1	112.6	2.6	118.7	8.1	114.1	3.9
		Cool & Dry	87.3	-20.4	76.9	-30.0	96.1	-12.5	63.0	-42.6
		Middle	105.4	-4.0	113.8	3.6	105.7	-3.7	106.2	-3.3
		Hot & Wet	117.3	6.8	113.2	3.1	111.1	1.2	108.5	-1.1
		Hot & Dry	93.1	-21.4	72.6	-38.7	77.2	-34.9	60.1	-49.2
		Ensemble	*106.7*	*-7.3*	*101.4*	*-12.0*	*103.0*	*-10.5*	*96.4*	*-16.2*
Maringá, PR	144.9	Cool & Wet	142.8	-1.4	139.8	-3.5	137.9	-4.8	130.3	-10.1
		Cool & Dry	140.6	-2.9	136.5	-5.8	138.5	-4.4	128.6	-11.2
		Middle	137.0	-5.4	130.3	-10.1	133.6	-7.8	123.7	-14.6
		Hot & Wet	139.0	-4.1	132.7	-8.4	132.6	-8.5	121.7	-16.0
		Hot & Dry	128.9	-11.0	124.1	-14.4	121.3	-16.3	114.9	-20.7
		Ensemble	*137.2*	*-5.3*	*132.5*	*-8.5*	*133.1*	*-8.1*	*124.0*	*-14.4*
Capinópolis, MG	113.3	Cool & Wet	111.7	-1.4	111.6	-1.4	109.5	-3.3	113.4	0.1
		Cool & Dry	122.3	8.0	116.7	3.0	121.3	7.1	120.9	6.7
		Middle	102.0	-9.9	99.5	-12.1	106.2	-6.2	104.6	-7.6
		Hot & Wet	104.7	-7.5	103.1	-8.9	105.1	-7.2	109.4	-3.4
		Hot & Dry	74.9	-33.9	76.6	-32.4	69.6	-38.6	69.8	-38.3
		Ensemble	*105.3*	*-7.0*	*103.5*	*-8.6*	*104.7*	*-7.6*	*106.6*	*-5.9*

The rainfed sites in Southern Brazil have a similar climate pattern, with a hot and wet summer, and relatively cool and dry winter, thus, sugarcane growth faces different meteorological conditions across different plantings and ratooning dates. Fig. 6 provides an in-depth look at the profile of the water deficit factor applied to photosynthesis in APSIM-Sugar at different starting dates in the current (black lines) and future climates scenarios (coloured ranges) at the End-of-Century period for these water-limited environments. The water stress patterns are variable with respect to the duration, intensity, phenological timing, and therefore physiological effects.

Early plantings and the subsequent ratoons are mostly affected by drought between 100 and 250 days after crop start (DAS). The less favourable environments for early plants are at Ilha Solteira, Jaboticabal and Capinópolis. The most favourable one is at Maringá, not only because of the reasonable rainfall volume and distribution but also because of the quality of the deep and well-structured soils found in this region. Piracicaba and Dourados are intermediate in terms of the water stress pattern. Advancing the planting and ratooning periods towards the winter (representing a 'Middle' crop), water stress is less intensive because of the lower temperatures as well as the smaller crop size, demanding less water for cane growth. The limiting effect of water on cane phenology and biomass accumulation starts sooner for the Middle crop (50-200 DAS) than for the Early planting. The Late planting and ratooning date have favourable conditions in terms of water supply, however, there is a severe terminal water stress after about 200 DAS towards the harvest. Moderate stress at the end of crop cycle is often desirable for sucrose accumulation, nevertheless, intense water stress at this moment can dehydrate the stalks, which is unfavourable for processing them in the industry. The high climate variability at Dourados, especially during the transition between summer and autumn, can influence strongly the yield-building processes for the Late crops between 50 and 200 DAS, even though the average monthly rainfall is around 100 mm until April (Fig. S2a, supplementary material). The simulated historical yields presented in Tables 4 and 5 mesh well with the water stress patterns depicted in Fig. 6.

The projected water stress profiles for the same combination of environment and crop start dates for the End-of-Century period for both RCPs (Fig. 6) revealed that the patterns may be similar in future, but largely intensified for a relatively hot/dry climate, especially for RCP8.5 (lower lines). A warmer and drier summer in these environments will likely impact cane cultivation severely, even during the first 50 DAS for the Late planting and ratooning. It seems that the combination of likely increments in rainfall (Fig. 5) with a deep and well-structured soil in Maringá will alleviate the impacts of warming to some extent.

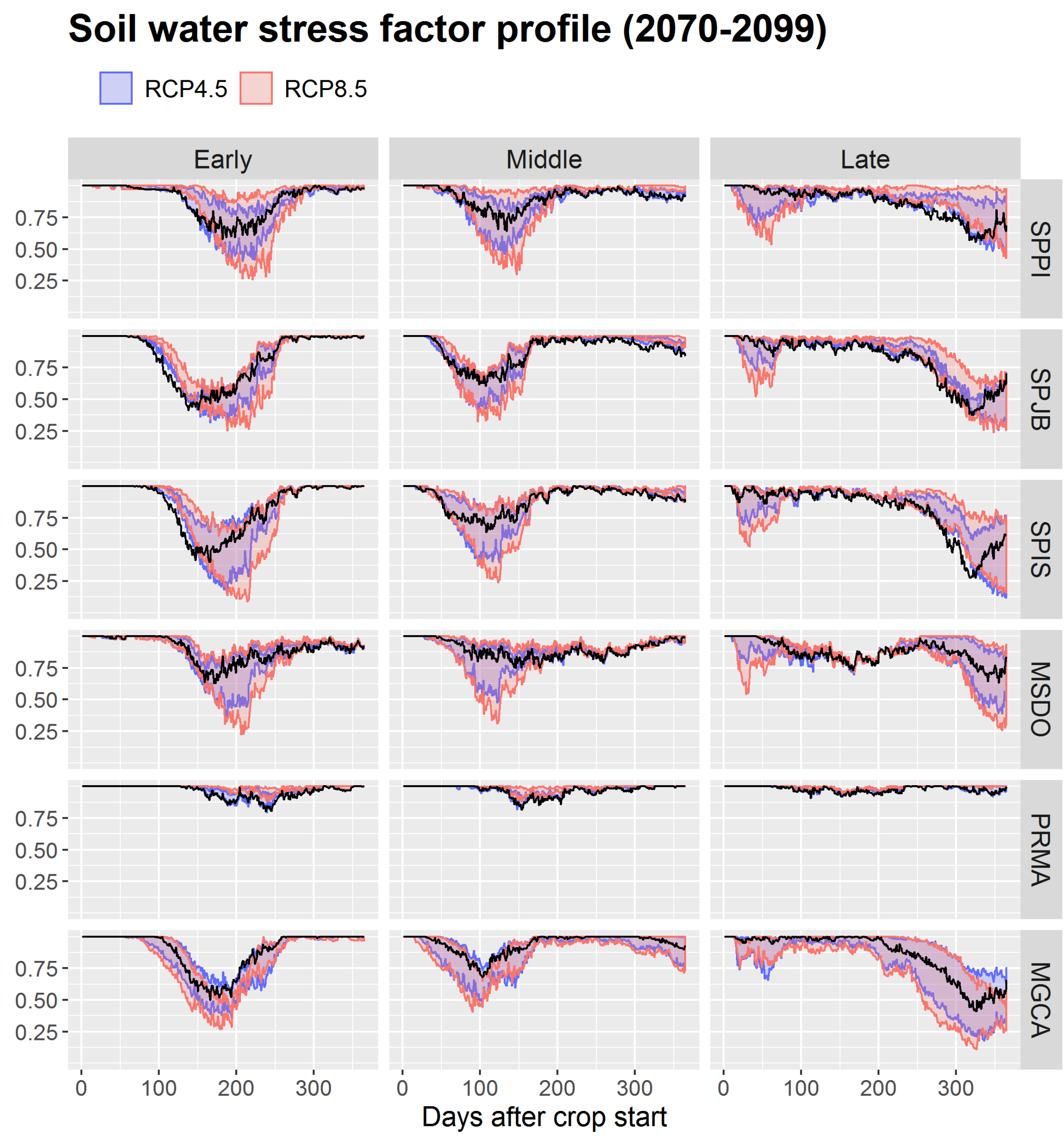

Fig. 6. Historical (black lines) and projected (coloured ranges) soil water stress factor profile throughout crop cycles (early, middle and late canes) for the End-of-Century (2070–2099) period, under intermediate (RCP4.5) and high (RCP8.5) greenhouse gases emission scenarios in rainfed sugarcane areas in Brazil, as estimated by APSIM-Sugar. The ranges for each RCP represent the values for the two different projected future climates (relatively cool/dry, upper lines; relatively hot/wet, lower lines) selected according to Section 6.2.2.2.

6.3.3.2. Irrigated sites

The results for fully-irrigated sites according to simulations with the combinations of the basic future climates from the GCMs projections, time-periods and RCPs are presented in Table 6. As for the rainfed sites, the results for three starting dates were pooled. Simulated historical cane yields ranged from 185 to 269 t/ha. Projected impacts of climate change were slightly negative for all sites regardless of the scenario, especially at Maceió where the worst reduction simulated was around 22% for a hot/wet climate in the End-of-Century period for RCP8.5. Petrolina and Teresina, the locations with the highest yields, will likely be less impacted by changing climates according to the simulations, with changes within 5% of the baseline yields. At Januária, the yield variation is expected to be intermediate relative to the aforementioned sites. As a consequence of such negative impacts of the scenarios assessed, the ensembles of all GCMs used to represent the five basic future climate scenarios are projecting negative impacts on irrigated cane yields, but only a few of them are as low as -10% (maximum reduction at Maceió in the End-of-Century period for RCP8.5).

Table 6

Projected relative changes (Δ, %) of simulated sugarcane yields in 2040-2069 and 2070-2099 under RCP4.5 and RCP8.5 compared to historical (baseline, 1980–2009) according to five basic class of climate change and their ensemble, at four fully-irrigated sites in the states of Minas Gerais (MG), Pernambuco (PE), Piauí (PI) and Alagoas (AL), Brazil.

Site	Historical (1980-2009)	Basic class of climate change	2040-2069				2070-2099			
			RCP4.5	Δ (%)	RCP8.5	Δ (%)	RCP4.5	Δ (%)	RCP8.5	Δ (%)
Januária, MG	175.0	Cool & Wet	164.8	-5.8	161.6	-7.7	160.5	-8.3	155.0	-11.4
		Cool & Dry	164.5	-6.0	160.3	-8.4	164.6	-5.9	155.3	-11.3
		Middle	163.0	-6.9	160.1	-8.5	159.7	-8.7	155.6	-11.1
		Hot & Wet	161.8	-7.6	160.1	-8.5	159.0	-9.2	156.2	-10.8
		Hot & Dry	161.7	-7.6	158.4	-9.5	158.4	-9.5	156.2	-10.8
		Ensemble	*163.3*	*-6.7*	*160.2*	*-8.4*	*160.4*	*-8.3*	*155.9*	*-10.9*
Petrolina, PE	224.0	Cool & Wet	217.6	-2.8	214.9	-4.0	214.7	-4.1	210.4	-6.0
		Cool & Dry	217.5	-2.9	215.3	-3.9	216.0	-3.6	212.8	-5.0
		Middle	215.5	-3.8	214.7	-4.1	214.9	-4.1	213.0	-4.9
		Hot & Wet	214.5	-4.2	212.2	-5.2	211.6	-5.5	211.3	-5.6
		Hot & Dry	215.1	-3.9	213.5	-4.7	213.6	-4.6	212.6	-5.1
		Ensemble	*216.4*	*-3.4*	*214.5*	*-4.2*	*214.7*	*-4.1*	*212.1*	*-5.3*
Teresina, PI	215.3	Cool & Wet	212.1	-1.5	210.7	-2.2	212.4	-1.4	210.8	-2.1
		Cool & Dry	210.8	-2.1	211.2	-1.9	211.4	-1.8	211.3	-1.9
		Middle	210.5	-2.2	210.6	-2.2	211.0	-2.0	212.2	-1.5
		Hot & Wet	209.2	-2.8	208.0	-3.4	208.9	-3.0	209.0	-2.9
		Hot & Dry	211.6	-1.7	212.1	-1.5	212.5	-1.3	217.3	0.9
		Ensemble	*210.5*	*-2.2*	*210.9*	*-2.1*	*211.2*	*-1.9*	*212.1*	*-1.5*
Maceió, AL	154.3	Cool & Wet	147.9	-4.1	144.9	-6.1	146.5	-5.0	139.2	-9.8
		Cool & Dry	144.3	-6.5	140.4	-9.0	141.9	-8.1	131.5	-14.8
		Middle	141.7	-8.1	136.8	-11.3	139.8	-9.4	129.1	-16.3
		Hot & Wet	138.9	-10.0	132.6	-14.1	133.6	-13.4	120.0	-22.2
		Hot & Dry	139.9	-9.3	134.8	-12.6	138.6	-10.2	129.1	-16.3
		Ensemble	*142.3*	*-7.7*	*137.5*	*-10.9*	*139.8*	*-9.4*	*130.0*	*-15.7*

6.4. Discussion

Recent research into trait parameters for Brazilian varieties and new model features improved the capability of the APSIM-Sugar module to represent sugarcane performance under rainfed conditions in field experiments in Brazil, at least for the most cultivated variety (RB867515) (Fig. 3). The RMSE of 3.8 t/ha (Table 3) for the serial stalk dry mass measurements fell within the range (1.1 to 34.2 t/ha, averaging ~ 8.9 t/ha) reported in the literature with APSIM-Sugar, CANEGRO and other crop models (see Fig. S5 in the supplementary material). Whilst it is difficult to compare crop models' performance given the differences in models' structures, versions, and calibration approaches, as well as experimental datasets, it seems that the results reported here demonstrate that APSIM-Sugar had a satisfactory performance for simulating sugarcane crop. Moreover, Dias et al. (2019) argued that the feature to account for cane growth slowdown avoided overestimation in cane yields in irrigated conditions and it appears to have worked reasonably well in capturing yields at harvest for rainfed experiments as well. Despite having a lower number of measurements, the RMSE of 3.3 t/ha found in our study (Table 3) compares favourably with the value reported for the original dataset (9.6 t/ha) used in the development of APSIM-Sugar (APSIM, 2020; Keating et al., 1999).

The projections of climate change impacts on cane yields in different Brazilian carefully selected environments have now been updated with the new APSIM-Sugar modifications and traits employed in the climate-crop modelling simulations. Such projections are highly uncertain for rainfed sites considering the five possible basic climates (relatively cool/wet, cool/dry, middle, hot/wet, and hot/dry) they may face in the future, but in general, the results showed that sugarcane crop will face mostly a negative outcome (Tables 4 and 5). Water stress was the main driver of sugarcane yield losses in Brazil under future climate scenarios, which was caused by the increments in water demand induced by higher temperatures and vapour pressure deficit, especially for drier scenarios, where rainfall will decrease (Figs. 4 to 6).

The soil water stress factor profiles depicted in Fig. 6 also serve as a general characterisation of the environments for traditional water-limited sites where the sugarcane crop is grown in Southern Brazil. It showed how the water stress pattern varies across planting and ratooning dates, and that droughts are likely to be more severe in future climates, except for Maringá, where there is a well-structured soil and a rainfall increase will offset the effects of increasing temperatures on water deficit. This kind of characterisation could be further explored to interpret variety performance and infer adaptation options to specific environments (Chapman et al., 2002; Singels, 2014).

While it is difficult to make comparisons between this study and those from literature, given differences in environments, varieties, managements, crop models and their versions and settings, as well as different approaches to derive the future climates (RCPs, number and version of the GCMs projections), many other simulation studies have projected a positive impact of climate change on sugarcane yield worldwide, as reported in the literature compilation done by Linnenluecke et al. (2018). There are some studies with the standard version of APSIM-Sugar in Australia (Biggs et al., 2013; Park, 2008; Webster et al., 2009), China (Ruan et al., 2018) and Brazil (Marin, 2014), which usually projected a positive outcome for cane yield under future climate scenarios. The exceptions occurred usually when nitrogen management and extreme reductions in rainfall were expected. In the Brazilian study (Marin, 2014), nitrogen simulations were included, adding another source of variation to the results. To the best of our knowledge, APSIM-Sugar has not been validated for Brazilian environments and cropping systems with respect to nitrogen dynamics, which are known to possess a relatively high use efficiency in the sugarcane production (Franco et al., 2011; Otto et al., 2016; Robinson et al., 2014; Thorburn et al., 2017). Even considering the possible uncertainty concerning nitrogen dynamics, Marin (2014) found higher (historical) yields than those presented in Tables 4 and 5 for some nearby sites, even though we avoided nitrogen stress. For example, the cane yield simulated at Jaboticabal was 113.4 t/ha, while Marin (2014) reported 139.3 t/ha (average of two starting dates) for Catanduva, a nearby region with a similar climate and soil. The differences can be attributed largely to the effect of ageing by using the RGP factors, slowing down the biomass accumulation and, consequently, affecting yields in our simulations (Dias et al., 2019).

The slowdown feature used in our simulations is a catchall for a number of factors such as lodging, respiration and feedback inhibition of photosynthesis by stored sucrose, which could be responsible for reduced biomass accumulation with age in sugarcane (Dias et al., 2019; Park et al., 2005; van Heerden et al., 2010). These factors are likely to be coupled with phenology, perhaps not in the exact mathematical sense as is assumed in the model. Studies that ignore growth slowdown are likely to overestimate benefits of increased temperature that hastens crop development. A difference in mean annual temperature of 3.8 ºC between two irrigation schemes in Australia did not result in the increase in sucrose yield predicted by Muchow et al. (1997) using APSIM-Sugar without the growth slowdown feature. In one study actual yields departed from predicted yields after 35 t/ha of crop biomass had been produced at which point RUE had to be reduced by 40% (Inman-Bamber et al., 2006) which is similar to the growth slowdown extent for RB867515 in our study.

A common assumption among the studies with APSIM-Sugar is that RUE and TEC would increase by 1.43% and 8% for every 100 ppm increase in CO_2 concentration, respectively. There is evidence that TEC is enhanced when sugarcane grows under higher [CO_2], however, the effects on RUE lack of evidence. Results from Stokes et al. (2016) found no difference in sugarcane photosynthesis or biomass yield at elevated [CO_2] when plants were watered on demand, suggesting that the reported increments in biomass were due to water-related processes. Moreover, FACE experiments have shown positive impacts on yields of C_4 crops such as maize and sorghum only under water-limited conditions (Kimball, 2016). The responses of crops submitted to FACE experiments are now challenged because oscillating and irregular fluctuating elevated [CO_2] that happen in these experiments are likely to underestimate the benefits of CO_2 enrichment (Allen et al., 2020). The positive CO_2 effect on RUE, one of the most sensitive parameters in the APSIM-Sugar model (Sexton et al., 2017), certainly helped to minimise the likely impacts of future climate changes on previous impacts assessments. The CO_2 fertilisation effect on RUE was removed in the most recent version of CANEGRO (Jones and Singels, 2019) until future studies bring new evidence on this matter. Based on the available evidence we also assumed that RUE would not increase with rising atmospheric CO_2.

For the fully irrigated sites, the simulations under the future climates indicate that sugarcane yields will decrease, but in most of the cases by less than 10% (Table 6). The yield decreases at Maceió (Northeast shore) should be analysed with caution because the decreases in rainfall (Fig. 5) are also likely associated with increases of solar radiation. Solar radiation was kept as in the historical record and this is a source of uncertainty too. In a few cases, cane yields will not change or may increase slightly. Earlier onset of growth slowdown was the main reason for predictions of decreased yield in irrigated regions. The slowdown is driven by phenology defined by leaf number (Dias et al., 2019), which is predominantly temperature-dependent (Keating et al., 1999).

Jones and Singels (2019) made improvements in CANEGRO regarding temperature effects, but in other sugarcane models, this topic has received little attention. Similarly to APSIM-Sugar, the last and upgraded version of CANEGRO still considers a wide range of optimum temperatures for its RUE related-parameter (20-40ºC), even after the recent improvements. Field-based RUEs for well-watered experiments from Donaldson (2009) and Jones et al. (2019) indicated that this trait seems to be well-correlated with air temperature, and the values found were higher for the warmer growing seasons within the range between 18 and 25 ºC. Upon that, further studies regarding the effects of temperature for the main sugarcane yield-building processes in terms of physiology and modelling perspectives are warranted. Heat stress physiology is a topic that has received little attention in sugarcane research (Inman-Bamber et al., 2011; Lakshmanan and Robinson, 2014). Sugarcane is adapted to warm climates, but air temperatures above 40 ºC affect sett germination and shoot emergence, leaf phenology and increase plant respiration (Bonnett et al., 2006; Jones and Singels, 2019; Lakshmanan and Robinson, 2014), all of which affect yields. Temperature response functions in wheat and maize process-based models have been recently revised and improved for predicting yields in changing climates in the APSIM and DSSAT agricultural systems platforms (Wang et al., 2017, 2018). In the case of APSIM, RUE for both crops was considered optimum over quite a broad, range of temperatures. The linear functions used to determine RUE were replaced for non-linear functions with a narrower range for optimum temperatures to better simulate yields under rising temperature projections.

Despite the possible model shortcomings raised, it is necessary to better prepare the sugarcane production systems for risks imposed by the future climates. Keating et al. (2003) argued that continuous efforts towards better managing the current agricultural systems taking into account the historical climate variability will remain as a pivotal aspect of any climate change adaptation. Indeed, a simulation study with maize in southern Africa carried out by Corbeels et al. (2018) showed that the uncertainty of the projections across GCMs were larger than expected crop responses to most management-level interventions or adaptations assessed. The authors argued that crop modellers should be cautious when informing future crop management adaptation strategies based on climate-crop model simulation studies, supporting the idea of the better adapted the agricultural systems nowadays, the less impact in future climates they will suffer. Exploring genetic improvements (for example, for drought resistance; Basnayake et al., 2012; Inman-Bamber et al., 2012) and management adaptation (for example, deeper soil preparation; Scarpare et al., 2019) options for sugarcane are, therefore, of high priority across producing countries towards sustainable sugarcane production (Linnenluecke et al., 2018).

6.5. Conclusions

Recent APSIM-Sugar features and traits improved the capability of the model to simulate crop performance under rainfed field experiments in Brazil, at least for the most cultivated variety RB867515. RMSE for stalk dry mass was reduced from 8.5 to 3.8 t/ha using serial measurements, and from 10.6 to 3.4 t/ha at harvest, which makes the recent modifications comparable with studies with APSIM-Sugar and other models in the literature.

The ensemble of future projections suggests that sugarcane yields will mostly decline for both rainfed and fully-irrigated sites. The expected changes are highly variable between GCMs, nevertheless, presenting large uncertainty. Therefore, climate change projections for Brazilian environments and their impact on sugarcane crop should be interpreted with caution. Moreover, possible shortcomings in APSIM-Sugar were pointed to be further investigated aiming to get more realistic simulations of crop performance, such as the response temperature function for RUE and the effectiveness of the growth slowdown feature under excessive warming scenarios.

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Supplementary Material

Table S1

Parameters of APSIM-Sugar for varieties Q117 and RB867515.

Parameters or coefficients	APSIM term	Q117 (default)	RB867515 (Dias et al. 2020; Chapter 4)
Light extinction coefficient	*extinction_coef*	0.38	0.52
Thermal time from planting to sprouting	*shoot_lag*	250	100
Thermal time from ratooning to sprouting	*shoot_lag*	100	75
Area of specific leaves	*leaf_size*	1500 55000 55000	5800 20000 36000 46000 51000 51400 50700 49300 43500
Numbered leaf from top of stalk	*leaf_size_no*	1 14 20	1 5 10 15 20 22 24 26 30
Number of green leaves	*green_leaf_no*	13	11.7
Thermal time from emergence to the onset of stalk growth	*tt_emerg_to_begcane*	1900	461.5
Expansion factor for *leaf_size*. Represents the effect of tillering on the leaf profile	*tiller_leaf_size*	1.0 1.5 1.5 1.0 1.0	1.00 1.51 1.53 1.56 1.26 1.07 1.00
Numbered leaf from top of stalk	*tillerf_leaf_size_no*	1 6 10 12 26	1 9 11 13 17 25 40
Growth slowdown factors applied to RUE	*y_rue_leaf_no_fact*	Not invoked	1 1 0.94 0.83 0.72 0.63 0.55 0.51 0.50
Numbered leaf from top of stalk	*x_leaf_no*	Not invoked	1 15 20 25 30 35 40 45 50

Table S2

Statistics of the performance of APSIM-Sugar with traits calibrated for variety RB867515.

Index/Error	Dias et al. (2020)		Chapter 4
	Fractional photosynthetically active radiation interception	Leaf area index	Stalk dry mass
R^2	0.64 - 0.91	0.40	0.56 - 1.00
d	0.89 - 0.96	0.75	0.70 - 0.99
RMSEP (%)	10.3 - 19.8	23.8	3.78 - 34.5

Table S3

Summary of the percentage of the 29 global climate models (GCMs) classified considering the probability of basic classes of climate changes (relatively cool/wet, cool/dry, middle, hot/wet, and hot/dry) according to Ruane and McDermid (2017)´s method for each site. Classifications for two timeframes (Mid-Century and End-of-Century) and emission scenarios (RCP4.5 and RCP8.5) were used. The subsetted GCMs to each basic class of climate changes used in APSIM-Sugar simulations are shown. Further information about the 29 GCMs can be found in Ruane and McDermid (2017).

Site	% GCMs classified as					Selected GCMs				
	cool/wet	cool/dry	middle	hot/wet	hot/dry	cool/wet	cool/dry	middle	hot/wet	hot/dry
Piracicaba, SP	17	21	20	24	18	MIROC5	GFDL-ESM2	CESM1-BGC	HadGEM2-AO	GFDL-CM3
Jaboticabal, SP	22	21	15	23	19	CNRM-CM5	GGFDL-ESM2M	GISS-E2-R	ACCESS1-0	GFDL-CM3
Ilha Solteira, SP	21	19	13	22	25	MIROC5	GFDL-ESM2	GISS-E2-R	CMCC-CMS	GFDL-CM3
Dourados, MS	20	16	23	20	21	MIROC5	GGFDL-ESM2M	BNU-ESM	ACCESS1-0	GFDL-CM3
Maringá, PR	21	18	18	22	22	MIROC5	inmcm4	CESM1-BGC	ACCESS1-0	CSIRO-Mk3-6-0
Capinópolis, MG	21	22	12	23	22	CNRM-CM5	MRI-CGCM3	GISS-E2-R	CMCC-CMS	CanESM2
Januária, MG	19	24	14	24	19	CNRM-CM5	CCSM4	GISS-E2-R	HadGEM2-ES	GFDL-CM3
Petrolina, PE	16	16	29	21	18	CNRM-CM5	NorESM1-M	MIROC5	HadGEM2-ES	GFDL-CM3
Teresina, PI	22	5	41	9	22	FGOALS-g2	IPSL-CM5B-LR	MPI-ESM-MR	IPSL-CM5A-MR	CanESM2
Maceió, AL	17	19	17	28	18	inmcm4	MRI-CGCM3	GISS-E2-R	IPSL-CM5A-MR	CanESM2

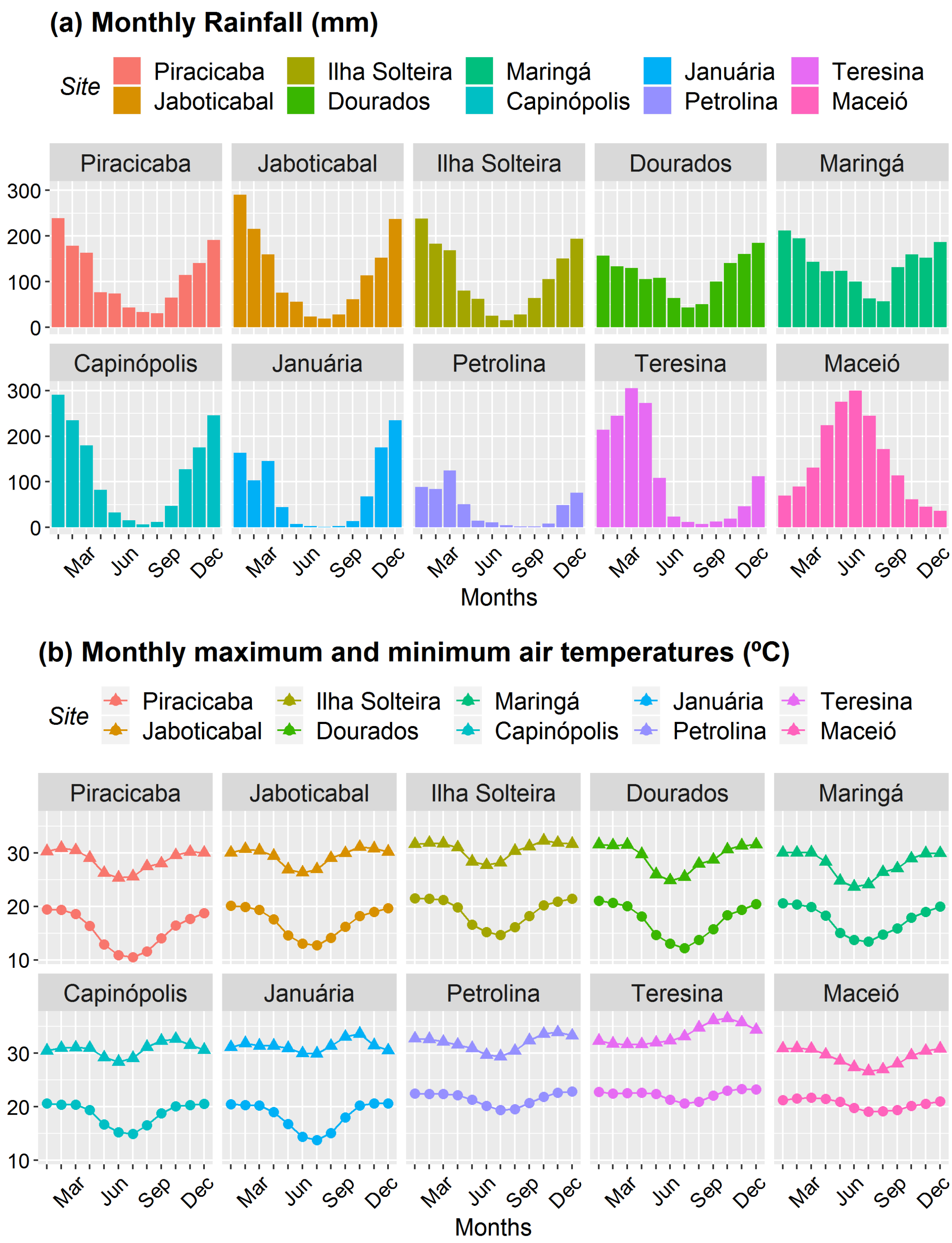

Fig. S1. Climatic conditions at Piracicaba, SP, Jaboticabal, SP, Ilha Solteira, SP, Dourados, MS, Maringá, PR, Capinópolis, MG, Januária, MG, Petrolina, PE, Teresina, PI, and Maceió, AL: monthly mean total rainfall (a) and average minimum and maximum air temperatures (b).

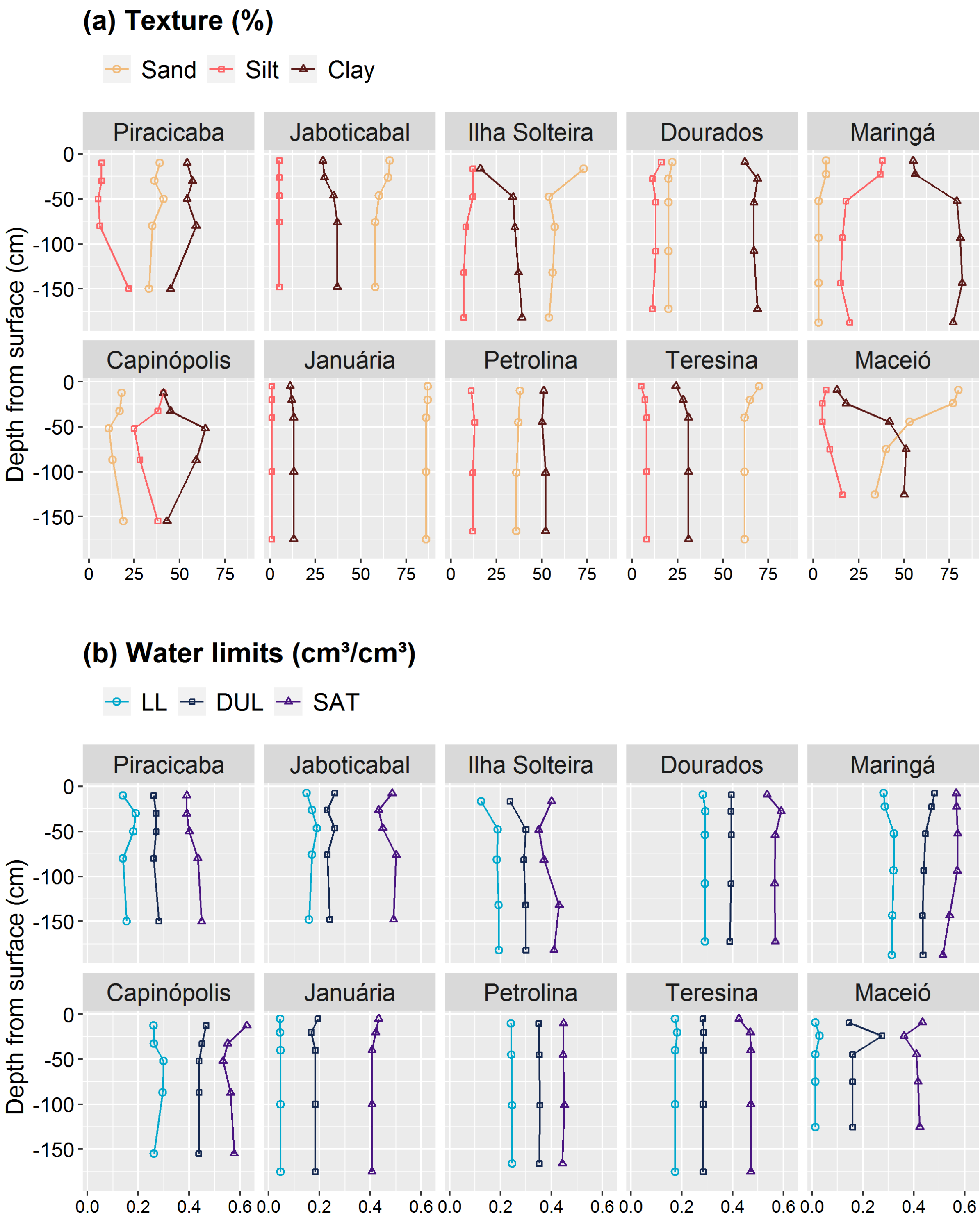

Fig. S2. Soil properties at Piracicaba, SP, Jaboticabal, SP, Ilha Solteira, SP, Dourados, MS, Maringá, PR, Capinópolis, MG, Januária, MG, Petrolina, PE, Teresina, PI, and Maceió, AL: texture (a) and water limits (b) LL, DUL and SAT are the lower, drained upper and saturated water limits, respectively. Simulations at Maceió considered the maximum soil depth at 59 cm due to physical constraints.

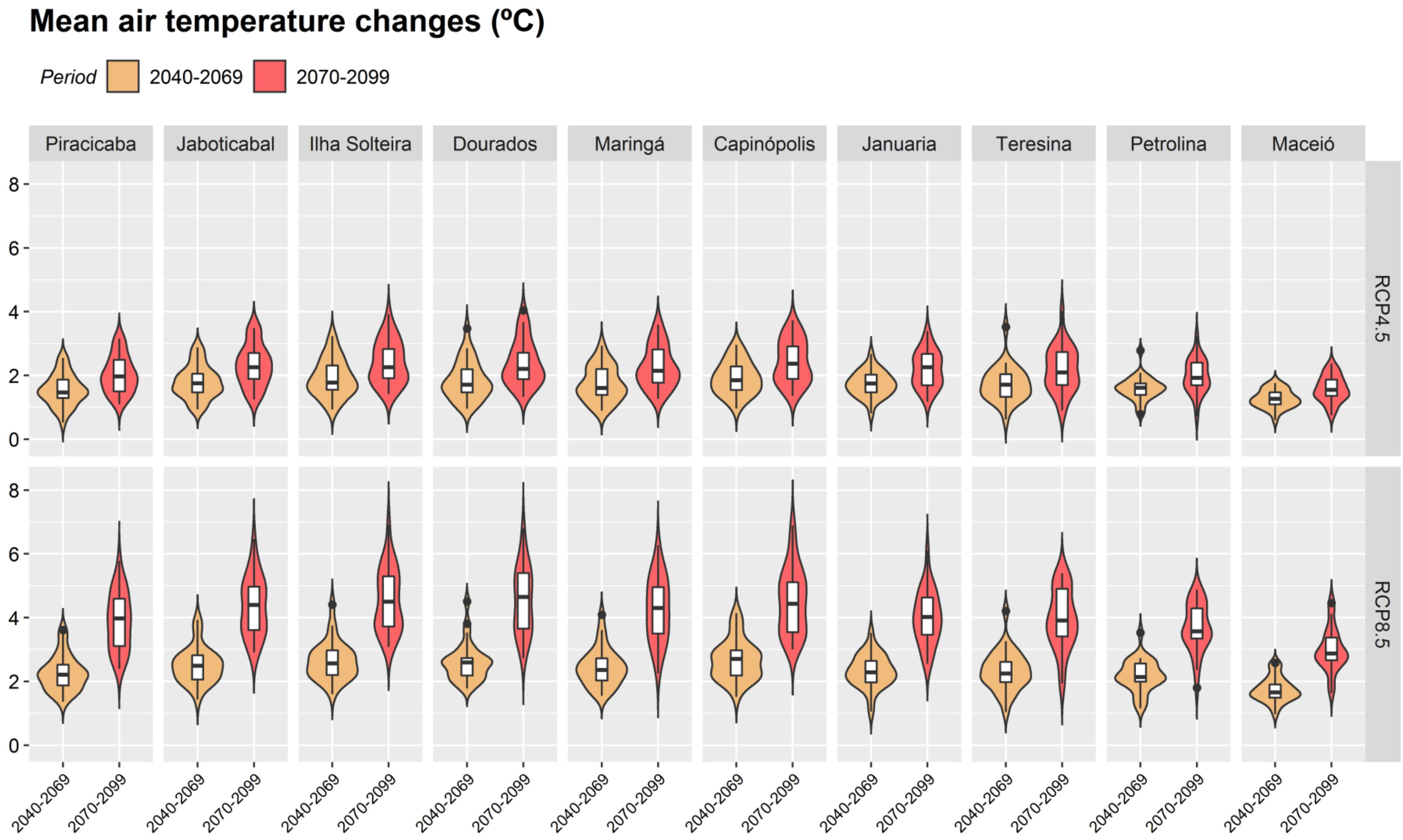

Fig. S3. Frequency distributions and boxplots of absolute mean air temperature changes for the 29 GCMs during the future periods 2040-2069 and 2018-2099 under climate scenarios RCP4.5 and RCP8.5 at the 10 study sites in Brazil. Upper and lower edges of boxes indicate 75th and 25th percentiles, horizontal line within box indicates median, whiskers below and above the box indicate the 10th and 90th percentiles.

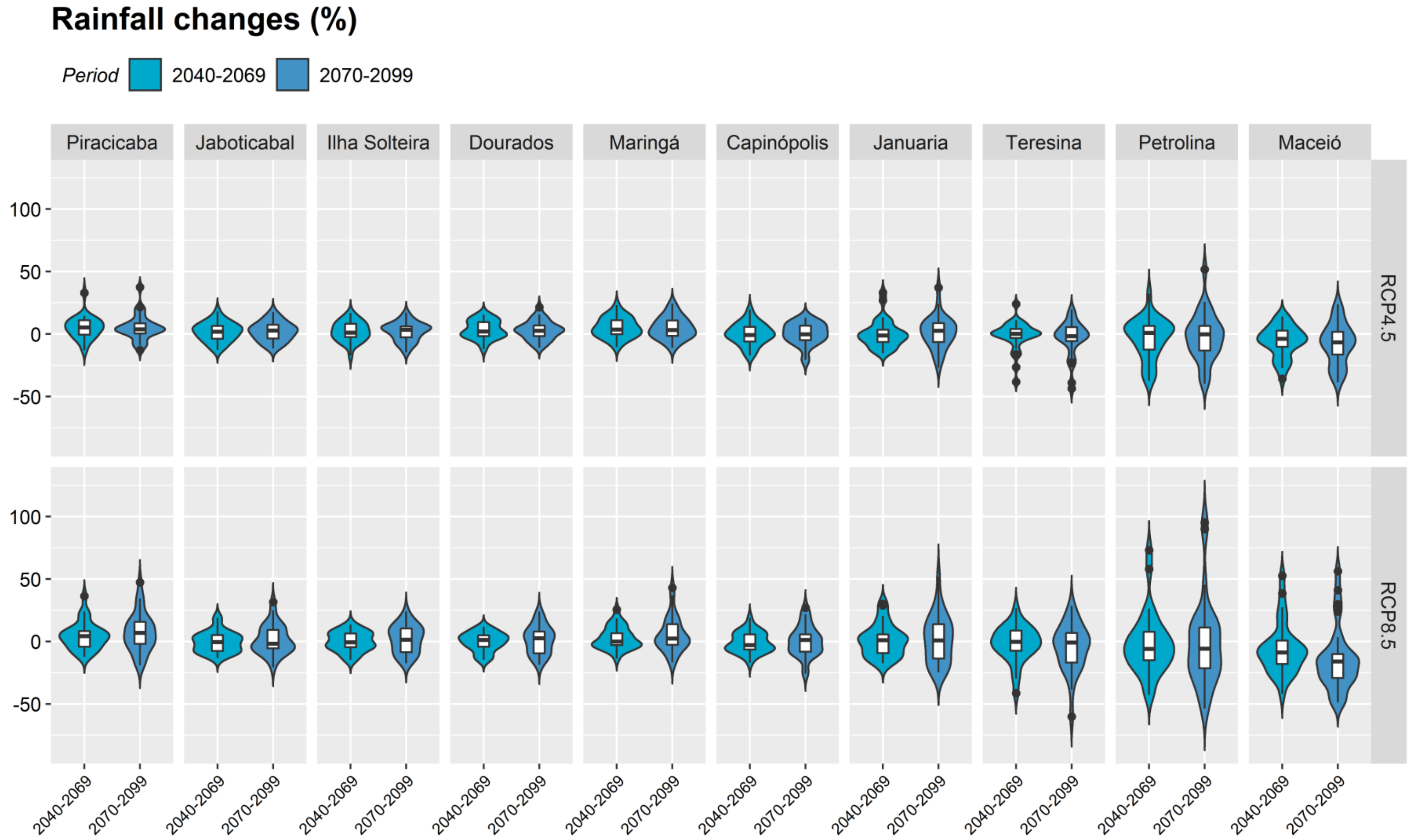

Fig. S4. Frequency distributions and boxplots of relative rainfall changes for the 29 GCMs during the future periods 2040-2069 and 2018-2099 under climate scenarios RCP4.5 and RCP8.5 at the 10 study sites in Brazil. Upper and lower edges of boxes indicate 75th and 25th percentiles, horizontal line within box indicates median, whiskers below and above the box indicate the 10th and 90th percentiles.

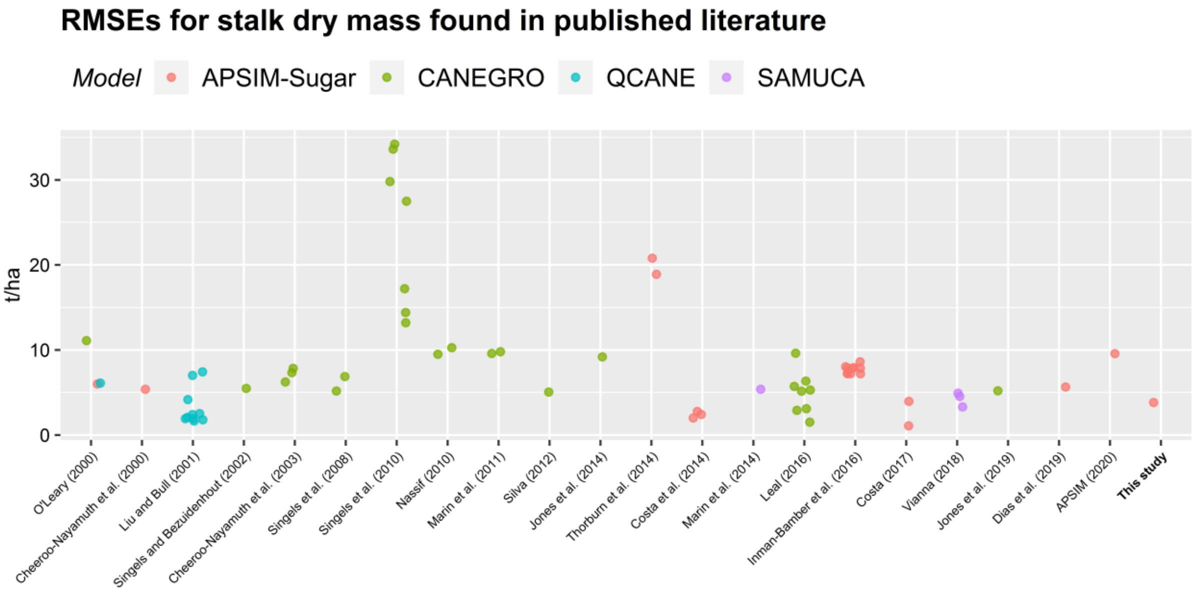

Fig. S5. Root mean squared errors (RMSEs) for stalk dry mass (t/ha) found in sugarcane modelling published literature and their references.

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7. Concluding remarks

Interactions between variety, environment and management are of high importance in agricultural production systems and the use of process-based simulation models as an effective tool for investigating and understanding these interactions without carrying laborious and expensive field experiments are valuable. This thesis analysed a unique field dataset in which a large number of sugarcane varieties grown under high input conditions developed their canopy quite fast and achieved outstanding high yields in new environments in tropical regions. The dataset employed in is thesis and others from literature were integrated with the APSIM-Sugar model to evaluated the model's capability towards reliable simulations of the sugarcane crop in different Brazilian producing regions. APSIM-Sugar has now a credible way, even though yet empirical, to account for ageing processes (known as the reduced growth phenomenon) to get better yield predictions in high yielding environments, as well as the possibility to distinguish between varieties when yields achieved are above ~ 150 t/ha (~ 40 t/ha in dry mass basis). Traits for 27 Brazilian varieties were determined as far as possible based on field data, existing literature and model optimisations, incrementing substantially the options available in the APSIM-Sugar genotype library. The features and traits were further evaluated with the original dataset used for model building and existing field data from literature. It is reasonable to say that APSIM-Sugar traits are plausible and are an important step for unravelling genetic × environment × management interactions to improve yields and quality in the Brazilian sugarcane industry. We believe that APSIM-Sugar was improved for the purpose of potential yield estimation, yield gap analysis, improved choice of variety and planting and harvesting date options, impact of climate change, amongst other uses of the model. Codes (*.xml* format) for those varieties are made available in Appendix A.

This study also provides two other important findings for sugarcane modelling applications with APSIM-Sugar, which could perhaps be extended to other crop models and simulation studies. First, researchers and end users should be cautious when using gridded weather datasets, especially in the context of decision-making because of the poor performance of gridded rainfall data. It is recommended to replace gridded rainfall data for measured values as far as possible as a mean to improve sugarcane simulations at least for similar environments where the study was taken place (Center-South Brazil). Secondly, the ensemble of future climate-crop model projections suggests that cane yields will decline for both rainfed and fully-irrigated sites assessed, however, the scenarios generated by climate models presented large uncertainty, thus these projections for Brazilian environments should be interpreted with caution. Despite well tested in Brazilian cropping systems under potential and water-limited environments, possible shortcomings in were raised for further investigated aiming to get more realistic simulations of the crop performance with APSIM-Sugar, such as the response temperature function for radiation use efficiency and the effectiveness of the growth slowdown feature under excessive warming scenarios.

It is suggested that continuous physiology experimentation and modelling efforts are needed to fill the knowledge gaps in these sugarcane research areas as pointed out in the introductory chapter. Collaboration between research groups worldwide might speed up this process. Despite their weaknesses, sugarcane models can be powerful tools to understand and propose management and adaptive actions to mitigate losses or increase yields under current and, perhaps, future climatic conditions. However, sugarcane crop modellers and users should be cautious when informing future crop management adaptation strategies based on climate-crop model simulation studies, which reinforces, at least to some extent, the argument of better adapting the current agricultural systems to cope with the existing and known climate variability.

Appendices

Appendix A. Modifications performed in the APSIM-Sugar xml file for Brazilian sugarcane varieties parameterised for the genotypes, environments and crop management in the thesis.

Important notes:

- The light extinction coefficients (*extinction_coef*) and the growth slowdown factors applied to radiation use efficiency (*y_rue_leaf_no_fact*) are variety-specific, therefore, a *Sugar.xml* file for each variety is needed in the modified version of the APSIM Classic;
- Row spacing is accounted for by the two options of extinction coefficients;
- Growth slowdown factors and stalk fraction (*cane_fraction*) differ for the first nine varieties (those with extensive measurements), whereas for the other 21 it is the median of them;
- The parameters are the same for plant and ratoon crops, except for the thermal time for sprouting (*shoot_lag*);
- Final stalk population is set as the plant base population (*plants*) for each variety in the operations in APSIM's shell (the values can be found in Table 3 of Chapter 3);
- The lodging option should be disabled when growth slowdown factors are invoked;
- The changes proposed by N. G. Inman-Bamber et al. (2016, Field Crop. Research 196) should also be enabled. These changes and the growth slowdown feature introduced in the thesis are referred as a modified version of the APSIM-Sugar Classic and are yet to be approved for official release.

```
<!-- "General" for all varieties -->
     <initial_tpla units="mm^2" description="initial total plant leaf area">2000</initial_tpla>
! or 1000 for a regular crop emergence
! plant cane
     <shoot_lag units="oC" description="time lag before linear coleoptile">100</shoot_lag>
! ratoons
     <shoot_lag units="oC" description="time lag before linear coleoptile">75</shoot_lag>
! based on D.P.V. Leal (2016, ESALQ PhD Thesis, 10.11606/T.11.2016.tde-26092016-145237)
     <leaf_size>  5800 20000 36000 46400 51000 51400  50700 49300  </leaf_size>
     <leaf_size_no>  1 5    10    15    20    22    24    26  </leaf_size_no>

<!-- Variety RB867515 -->
   <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
   <y_rue_leaf_no_fact>  1 1 0.94 0.83 0.72 0.63 0.55 0.51 0.5 0.49   </y_rue_leaf_no_fact>
     <extinction_coef>0.52</extinction_coef>    <!-- single row 1.5 m -->
     <extinction_coef>0.65</extinction_coef>    <!-- alternate 1.5×0.9 m-->
     <cane_fraction>0.72</cane_fraction>
     <tt_emerg_to_begcane>461.5</tt_emerg_to_begcane>
     <green_leaf_no>11.7</green_leaf_no>
     <tillerf_leaf_size>     1    1.51  1.53  1.56  1.26  1.07  1  </tillerf_leaf_size>
     <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```

```
<!-- Variety RB92579 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.97 0.89 0.77 0.65 0.57 0.52 0.5 0.49   </y_rue_leaf_no_fact>
    <extinction_coef>0.48</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.64</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.71</cane_fraction>
    <tt_emerg_to_begcane>467.9</tt_emerg_to_begcane>
    <green_leaf_no>11.2</green_leaf_no>
    <tillerf_leaf_size>     1    1.44  1.70  1.61  1.18  1.05  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB931003 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.91 0.85 0.77 0.67 0.6 0.56 0.54   </y_rue_leaf_no_fact>
    <extinction_coef>0.49</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.62</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>501.5</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    1.50  2.11  1.45  1.12  1.11  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB961003 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 1 0.95 0.88 0.83 0.73 0.64 0.58 0.55   </y_rue_leaf_no_fact>
    <extinction_coef>0.47</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.64</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.75</cane_fraction>
    <tt_emerg_to_begcane>466.3</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    1.32  1.23  1.18  1.00  1.00  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB98710 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 1 0.95 0.84 0.72 0.6 0.52 0.48 0.46   </y_rue_leaf_no_fact>
    <extinction_coef>0.49</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.59</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.65</cane_fraction>
    <tt_emerg_to_begcane>485.6</tt_emerg_to_begcane>
    <green_leaf_no>11.4</green_leaf_no>
    <tillerf_leaf_size>     1    3.71  3.01  1.37  1.23  1.21  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety SP94-3206 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 0.99 0.88 0.74 0.57 0.48 0.45 0.44 0.43 0.43   </y_rue_leaf_no_fact>
    <extinction_coef>0.55</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.72</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.71</cane_fraction>
    <tt_emerg_to_begcane>370.2</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    2.29  1.94  1.79  1.36  1.18  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB966928 -->
  <x_leaf_no>        1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.78 0.65 0.54 0.49 0.47 0.46   </y_rue_leaf_no_fact>
    <extinction_coef>0.52</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.66</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.77</cane_fraction>
    <tt_emerg_to_begcane>473.6</tt_emerg_to_begcane>
    <green_leaf_no>13.5</green_leaf_no>
    <tillerf_leaf_size>     1    1.93  1.73  1.45  1.21  1.11  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```

```xml
<!-- Variety SP81-3250 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 0.99 0.93 0.81 0.62 0.48 0.43 0.41 0.41 0.41   </y_rue_leaf_no_fact>
   <extinction_coef>0.50</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.60</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.73</cane_fraction>
   <tt_emerg_to_begcane>543.7</tt_emerg_to_begcane>
   <green_leaf_no>11.7</green_leaf_no>
   <tillerf_leaf_size>     1    1.54  1.75  1.78  1.30  1.18  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety VAT90212 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 0.99 0.88 0.77 0.66 0.57 0.53 0.52 0.51 0.51   </y_rue_leaf_no_fact>
   <extinction_coef>0.46</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.59</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.77</cane_fraction>
   <tt_emerg_to_begcane>672.7</tt_emerg_to_begcane>
   <green_leaf_no>11.3</green_leaf_no>
   <tillerf_leaf_size>     1    1.23  1.28  1.41  1.29  1.17  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB835054 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.49</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.61</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>472.5</tt_emerg_to_begcane>
   <green_leaf_no>11.7</green_leaf_no>
   <tillerf_leaf_size>     1    1.78  1.66  1.55  1.52  1.20  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB835486 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.48</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.61</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>515.4</tt_emerg_to_begcane>
   <green_leaf_no>11.7</green_leaf_no>
   <tillerf_leaf_size>     1    3.01  2.92  2.34  1.75  1.43  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB845210 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.50</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.65</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>449.0</tt_emerg_to_begcane>
   <green_leaf_no>12.2</green_leaf_no>
   <tillerf_leaf_size>     1    1.50  2.93  1.71  1.48  1.25  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB855156 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.47</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.63</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>494.8</tt_emerg_to_begcane>
   <green_leaf_no>11.7</green_leaf_no>
   <tillerf_leaf_size>     1    2.38  1.58  1.54  1.50  1.17  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```

```
<!-- Variety RB855453 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.45</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.58</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>602.4</tt_emerg_to_begcane>
    <green_leaf_no>10.5</green_leaf_no>
    <tillerf_leaf_size>     1    2.14  1.38  1.35  1.35  1.31  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB855536 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.48</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.61</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>644.4</tt_emerg_to_begcane>
    <green_leaf_no>10.5</green_leaf_no>
    <tillerf_leaf_size>     1    2.70  1.78  1.62  1.62  1.46  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB863129 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.47</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.60</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>541.1</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    2.52  2.75  2.17  1.59  1.26  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB931011 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.45</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.58</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>490.0</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    2.12  2.65  2.16  1.67  1.35  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB947532 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.50</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.63</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>428.5</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    1.50  2.19  1.75  1.30  1.20  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB951541 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.53</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.66</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>377.5</tt_emerg_to_begcane>
    <green_leaf_no>11.7</green_leaf_no>
    <tillerf_leaf_size>     1    2.47  2.55  2.19  1.84  1.32  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```

```
<!-- Variety RB957508 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.50</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.64</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>438.8</tt_emerg_to_begcane>
   <green_leaf_no>14.8</green_leaf_no>
   <tillerf_leaf_size>     1    2.90  2.89  2.49  2.08  1.35  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB99395 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.59</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.77</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>337.6</tt_emerg_to_begcane>
   <green_leaf_no>8</green_leaf_no>
   <tillerf_leaf_size>     1    1.50  2.86  1.82  1.37  1.23  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB012046 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.55</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.72</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>353.5</tt_emerg_to_begcane>
   <green_leaf_no>11.9</green_leaf_no>
   <tillerf_leaf_size>     1    1.50  2.88  1.81  1.58  1.35  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety RB012090 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.45</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.55</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>573.8</tt_emerg_to_begcane>
   <green_leaf_no>12.5</green_leaf_no>
   <tillerf_leaf_size>     1    3.18  3.03  2.47  1.91  1.33  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety CTC2 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.52</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.70</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>379.7</tt_emerg_to_begcane>
   <green_leaf_no>11.7</green_leaf_no>
   <tillerf_leaf_size>     1    1.50  3.08  1.88  1.25  1.23  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety SP80-1816 -->
  <x_leaf_no>         1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
   <extinction_coef>0.55</extinction_coef>    <!-- single row 1.5 m -->
   <extinction_coef>0.64</extinction_coef>    <!-- alternate 1.5×0.9 m-->
   <cane_fraction>0.72</cane_fraction>
   <tt_emerg_to_begcane>505.6</tt_emerg_to_begcane>
   <green_leaf_no>13.2</green_leaf_no>
   <tillerf_leaf_size>     1    2.71  2.98  2.57  2.16  1.32  1  </tillerf_leaf_size>
   <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```

```
<!-- Variety IACSP87-3396 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.53</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.67</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>485.9</tt_emerg_to_begcane>
    <green_leaf_no>11.6</green_leaf_no>
    <tillerf_leaf_size>      1    2.26  1.93  1.64  1.54  1.25  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
<!-- Variety IACSP95-5000 -->
  <x_leaf_no>          1   15   20   25   30   35   40   45   50   60   </x_leaf_no>
  <y_rue_leaf_no_fact>  1 1 0.96 0.86 0.77 0.65 0.56 0.52 0.49 0.48   </y_rue_leaf_no_fact>
    <extinction_coef>0.50</extinction_coef>    <!-- single row 1.5 m -->
    <extinction_coef>0.61</extinction_coef>    <!-- alternate 1.5×0.9 m-->
    <cane_fraction>0.72</cane_fraction>
    <tt_emerg_to_begcane>552.5</tt_emerg_to_begcane>
    <green_leaf_no>11.6</green_leaf_no>
    <tillerf_leaf_size>      1    2.35  1.65  1.48  1.31  1.19  1  </tillerf_leaf_size>
    <tillerf_leaf_size_no>1    9     11    13    17    25    40</tillerf_leaf_size_no>
```