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Modelling the trash blanket effect on sugarcane growth and water use

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ABSTRACT

The traditional practice of burning at the pre-harvesting of sugarcane has being phased-out in Brazil, resulting in the maintenance of a crop s residue layer on soil surface, namely the Green Cane Trash Blanket (GCTB). New technologies for electricity and second-generation ethanol (2G) production from crop residues have raised the question on what would be the optimum amount of crop residue left on the field to keep the agronomic and environmental benefits of GCTB. To support informed decision making on sugarcane trash management, we updated, evaluated and applied a new version of the SAMUCA model to simulate the sugarcane growth and water use under the GCTB effect. The updated model was calibrated and parameterized for bare soil and GCTB conditions and evaluated across different Brazilian regions. Thirty-year simulations were then conducted with the updated model to quantify the effects of GCTB on sugarcane growth and water use where sugarcane is traditionally grown in Brazil. The updated version of SAMUCA model showed equal or superior performance when compared with widely-used process-based models for sugarcane. Based on our 30-year simulations, the GCTB exhibited a high probability to promote a beneficial effect on sugarcane yields in dry climates (> 90%), with the potential for increasing, on average, 14 ton ha^{-1} of fresh cane yield in Petrolina, Brazil. Although the beneficial effect on yields were not significant in humid regions, the maintenance of 12 ton ha^{-1} of GCTB was associated with a high probability (> 87%) in reducing the water use of sugarcane cropping system by 89 mm, on average, potentially reducing irrigation demand in the early stages of crop development while protecting crop production under dry spell events. The new version of SAMUCA model offers as a tool for decision making on mulch management in sugarcane plantations.

1. Introduction

Sugarcane crop is the main feedstock for sugar production in the world and has emerged as the second major source of biofuel (Goldemberg et al., 2014). It's a crop of significant social, economic and environmental importance in many developing countries where nearly 75% of global production is concentrated in Brazil, India, China, Thailand and Pakistan (FAO, 2019). Brazil is the largest producer (38%), with approximately 10 million ha of sugarcane plantations, producing 635 million metric tons (MMT) of harvested stalk fresh mass, 38 MMT of sucrose, and 32 billion litres of bioethanol per year (CONAB, 2019).

In the last decade, the traditional practice of burning at pre-harvesting of sugarcane has been phased-out in Brazilian plantations due to increased concerns on environmental and public health (Le Blond et al., 2017). As a result, a rapid pace of mechanisation and non-burning (green cane) sugarcane harvest took place in practically all sugarcane plantations in Brazil (Scarpare et al., 2016; Vianna and Sentelhas, 2016). This transition has required agronomic and operational adaptations specifically for managing the 10-to-20 ton ha^{-1} of crop residues (Leal et al., 2013), namely the Green Cane Trash Blanket (GCTB) sometimes also called "mulch cover", "straw blanket" or "trash blanket". Two of the most pronounced short-term effects associated to GCTB are the maintenance of soil moisture and reduced soil temperature (Olivier and Singels, 2012), considered as important aspects mainly for warmer areas in the Central region (Cerrado) of Brazil where sugarcane has rapidly expanded over the last years (Scarpare et al., 2016). New technologies for electricity and second-generation ethanol (2G) production from crop residues (Dias et al., 2011) have also increased the interest from mills to take the crop residues for energy co-

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generation. Such opportunity for increasing revenues raise the question on what would be the optimum amount left on the field to keep the agronomic and environmental benefits of GCTB.

Process-based models (PBM) integrate soil-plant-atmosphere and management interactions in cropping systems and have been used to support science and informed decision making on where and how agricultural crops can be managed in a sustainable way (Tsuji et al., 2013). Several PBMs for sugarcane have been developed and are well described in the literature (Marin et al., 2015). However, only two of these are available for end users, namely the DSSAT-CANEGRO (DC) (Jones and Singels, 2018) and the APSIM-Sugar (AS) (Keating et al., 1999). The DC model does not make a distinction between air and soil temperatures for simulating the underling crop processes, though the reduced soil evaporation rates in the presence of mulch is accounted for and well documented by Porter et al. (2010). The AS model is able to simulate GCTB decomposition and its effects on nitrogen availability and evaporation reduction as well (Thorburn et al., 2005). A third sugarcane model (SAMUCA – *Agronomic Modular Simulator for Sugarcane*) was developed by Marin and Jones (2014) focusing on the specific features of sugarcane farming systems in Brazil and due to relatively small number of available sugarcane PBMs for simulation ensembles (Asseng et al., 2013). Marin et al. (2017) have, however, reported evidences that the soil-water balance of standalone version of SAMUCA required improvements and further validation for reducing uncertainties of simulations under diversity of soil and climates where sugarcane has been grown in Brazil.

The objective of this study was to update the SAMUCA's algorithms to improve soil moisture simulations also accounting for the new scientific evidences regarding the sugarcane growth and development under GCTB conditions. The updated model was parameterized and calibrated with a sugarcane field experiment carried out under bare soil and GCTB condition in Piracicaba, Brazil. After calibration, we evaluated the model's performance against an independent dataset of field experiments under different edaphoclimatic conditions across Brazil. Finally, the updated SAMUCA model was applied to four Brazilian locations where sugarcane is traditionally cultivated to aid GCTB management dimensioning, as trash blanketing is now widely employed in most of the Brazilian sugar industry.

2. Material and methods

2.1. Overview of the SAMUCA model updates and new features

A new version of the SAMUCA model was developed and embedded into a simulation platform (Fig. 1). The updated soil-water balance subroutine operates the one-dimensional "*tipping bucket*" method, considering the daily water inputs (rainfall + irrigation), evapotranspiration rates, runoff and drainage. A numerical algorithm for solving soil heat flux was also employed to simulate the soil temperature dynamics (Kroes et al., 2009). When GCTB is simulated, a layer with thermal and hydrological characteristics of sugarcane mulch is added to soil surface, affecting soil evaporation, runoff and heat transfer (Porter et al., 2010; Van Donk and Tollner, 2000).

Algorithms of the SAMUCA model were also updated to account for the scientific findings regarding the sugarcane physiology that were not accounted by DC and AS. These include (a) the biomass partitioning simulation at the phytomer level (Singels and Inman-Bamber, 2011; Lingle and Thomson, 2012); (b) the computation of structural and sugars components with a source-sink method (O'Leary, 2000); (c) canopy carbon assimilation using measured leaf assimilation rates and carboxylation efficiency (Goudriaan, 2016); d) the distinction between air and soil temperature to simulate soil related processes such as tillering, root growth and shoot emergence (Laclau and Laclau, 2009; Bezuidenhout et al., 2003). The last one is specifically important to account for the GCTB effect on sugarcane growth and development. Full details of model updates and new features can be found in *Appendix A* of supplementary material.

2.2. Field experiments description for model calibration and evaluation

The new version of SAMUCA was calibrated and parameterized using field measurements of a sugarcane experiment at the College of Agriculture "Luiz de Queiroz" (ESALQ/USP) in Piracicaba, Brazil (Lat: 22°41'55"S Lon: 47°38'34"W Alt: 540 m). Chopped stalks of the widely planted variety RB867515 were used for planting 13–15 buds m^{-1} at 1.4 m row spacing down to a depth of 0.2 m at Oct-16–2012. Four sequential seasons of approximately 1-year long were then carried out (1 plant cane + 3 ratoons) through the years 2012-to-2016. At the first season (plant-cane), sugarcane was grown under bare soil conditions. From the 1st ratooning, two treatments took place to evaluate the sugarcane growth and water use under with mulch cover (WM) and bare soil (NM) conditions (Fig. 2). Aiming to represent the commercial sugarcane fields' conditions, approximately 12 t ha^{-1} of green cane straw (Lisboa et al., 2018) was homogeneously applied on the soil surface of WM treatment for each ratooning season. Agricultural practices were adopted to represent high yield farming systems and to ensure the crop was free from pests, diseases and nutritional stress. The site's climate is characterised by a hot and humid summer with dry winter (Cwa - Köppen classification), and the soil classified as Typic Hapludox.

Soil moisture and evapotranspiration were monitored throughout crop growth to determine water use in WM and NM conditions. Daily evapotranspiration rates were determined by integration of 15-min latent heat flux measurements taken by the Bowen Ratio Method (BRM) installed at each treatment (Fig. 2). A total of 24 Frequency Domain Reflectometry (FDR) access tubes were placed across the field experiment at the middle of first ratoon season (2013/2014), where frequencies were monitored at every 3 days or at one day after a rainfall/irrigation event. Undisturbed soil samples were taken in five depths (5, 15, 30, 60 and 100 cm) and at four random locations within the experimental area, to obtain the soil hydrological characteristics (Table 1) and to calibrate the FDR probe's scaled-frequencies for volumetric content outputs (cm^3 cm^{-3}). Soil temperature measurements were taken in both treatments by thermocouples placed down to a depth of 1, 5, 20 and 40 cm only for the 2nd Ratoon (2014/2015). Meteorological data, including maximum and minimum air temperatures, solar radiation, rainfall and irrigation applications are shown in Fig. B2 of *Appendix B*. Crop growth and development was monitored by regular biometric sampling. Non-destructive samples were taken for monitoring tiller population, stalk diameter and stalk height, number of appeared green leaves, leaf area index (LAI), leaf angle of insertion, blade area and shape (length and width). Stalk and leaf mass (fresh and dry) and sucrose content on fresh cane basis (POL) was obtained by regular destructive sampling. Leaf nitrogen content and carbon assimilation rates were also taken to support our study. Full description of equipment sets, measurements and calibration details are given in *Appendix B*.

We parameterized the biophysical characteristics of mulch based on previous literature, assuming the water holding capacity (Sm) of GCTB as 3.8 kg kg^{-1}, the specific area covered by mulch (A_m) as 32 cm^2 g^{-1}, and the GCTB light extinction coefficient (k) and albedo (α) as 0.8 and 0.4, respectively (Porter et al., 2010). The apparent thermal conductivity of sugarcane trash at dry (λ_{dry}) and wetting ($d\lambda_{wet}$) conditions were set as 0.1, 0.03, according to Van Donk and Tollner (2000). To calibrate crop parameters that were not obtained directly from field experiment measurements or literature we employed the constrained BFGS (Broyden–Fletcher–Goldfarb–Shanno) optimisation method using the R software (Fig. A14).

After calibration, an independent dataset was used to evaluate the new model's performance in simulating the main components of sugarcane growth and development across different soil and weather conditions in Brazil (Table 2). In all sites the RB867515 variety was planted, where measurements of stalk dry and fresh mass, sucrose

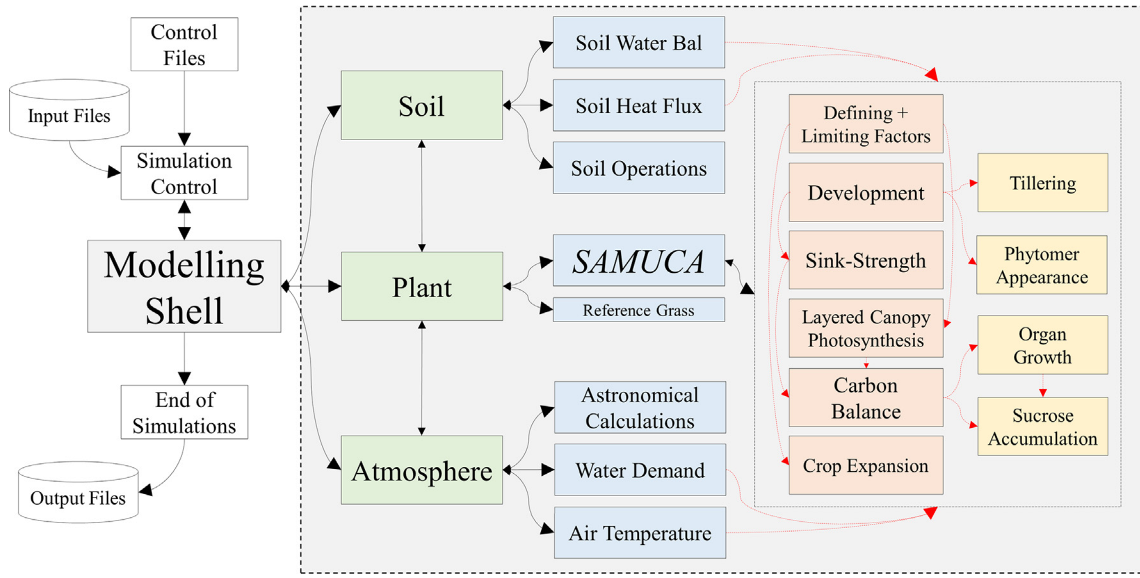

Fig. 1. Simulation shell framework with model subroutines and information flow through the simulation process. Red arrows represent direct relationship in the processes of sugarcane crop growth and development. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

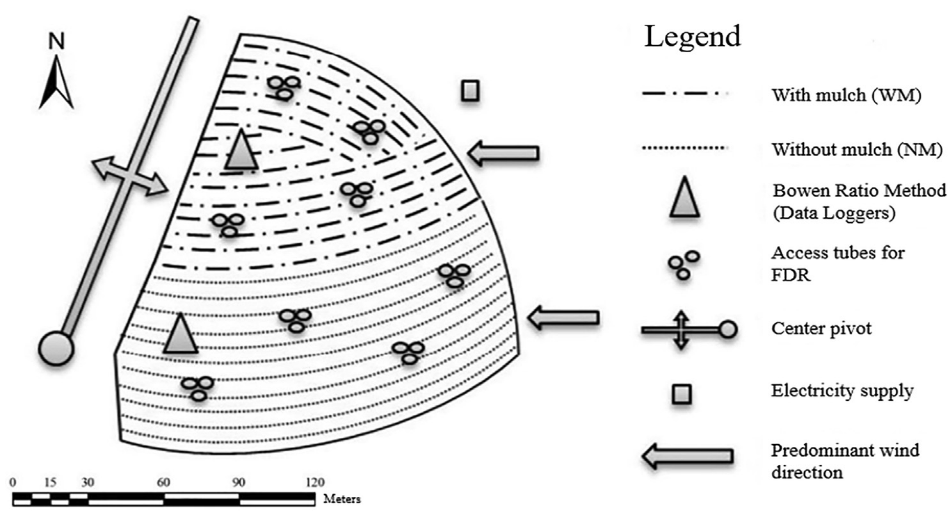

Fig. 2. Experimental area sketch presenting the predominant wind direction, location of evapotranspiration measurements and access tubes for FDR soil moisture probe in the with mulch (WM) and no mulch (NM) treatments of the trial in Piracicaba, Brazil.

content (POL), tillering, stalk height and Leaf Area Index (LAI) were regularly taken throughout crop growth. Soil characteristics and management practices such as planting and harvesting dates, row spacing and irrigation applications (mm day^{-1}) on each site were prescribed to the model as input information. This same database was previously used for assessing the performance DC and AS and is fully described by Marin et al. (2015). The performance of the new version of SAMUCA model was quantified in terms of the statistical indexes of precision (r^2), accuracy (d), Nash–Sutcliffe efficiency (eff), root mean square error (RMSE) and bias (Wallach et al., 2018).

Table 1
Soil depth (DP), wilting point (WPP), field capacity (FCP), saturation point (STP), saturated hydraulic conductivity (K_{sat}), soil texture (sand, silt, clay) and organic carbon (Porg), and Mualen-van Genuchten Coefficients (θres, θsat α, n) adjusted to soil moisture at variable matric potentials ($-10 > \psi s > -15{,}000$ hPa).

DP (cm)	WPp (cm^3 cm^{-3})	FCp (cm^3 cm^{-3})	STp (cm^3 cm^{-3})	K_{sat} (cm h^{-1})	θres (cm^3 cm^{-3})	θsat (cm^3 cm^{-3})	α (cm^{-1})	n (–)	P_{sand} (g g^{-1})	P_{silt} (g g^{-1})	P_{clay} (g g^{-1})	P_{org} (g g^{-1})
5	0.216	0.285	0.380	1.70	0.122	0.421	0.198	1.145	0.185	0.15	0.65	0.015
15	0.240	0.303	0.352	1.01	0.021	0.359	0.043	1.067	0.185	0.15	0.65	0.015
30	0.278	0.347	0.390	0.49	0.000	0.394	0.023	1.060	0.199	0.17	0.62	0.011
60	0.307	0.394	0.428	0.21	0.000	0.430	0.008	1.071	0.199	0.17	0.62	0.011
100	0.253	0.393	0.456	0.21	0.008	0.459	0.008	1.127	0.211	0.16	0.62	0.009

Table 2
Summary of sugarcane field experiments datasets across Brazil used for model evaluation.

Site	ID	Planting and harvesting dates	Weather	Water treatment	Soil type
União/PI 4°51′S,42°52‘W, 68 m	UNII	9/29/2007 and 06/16/2008	27 °C, 1500 mm, Aw	Irrigated (total = 235 mm)	Oxisol
União/PI 4°51′S,42°52‘W, 68 m	UNIR	9/29/2007 and 06/16/2008	27 °C, 1500 mm, Aw	Rainfed	Oxisol
Coruripe/AL 10°07′S,36°10‘W, 16 m	CLER	8/16/2005 and 09/15/2006	21.6 °C 1401 mm, Aś	Rainfed	Fragiudult
Aparecida do Tab./MS 20°05S,51°18′W,335 m	ATAB	7/1/2006 and 09/08/2007	23.5 °C, 1560 mm, Aw	Rainfed	Typic Hapludox
Colina/SP 20°25′S,48°19′W, 590 m	COLI	2/10/2004 and 12/01/2005	22.8 °C, 1363 mm, Cwa	Rainfed	Typic Hapludox
Olímpia/SP 20°26′S,48°32′W, 500 m	OLIM	2/10/2004 and 12/01/2005	23.3 °C, 1349 mm, Cwa	Rainfed	Typic Hapludox

2.3. Quantifying the effect of GCTB on sugarcane growth and water use across different Brazilian conditions

Four locations were selected accordingly to the economic, social and environmental relevance of sugarcane crop and the contrasting edaphoclimatic conditions to quantify the effect of GCTB on fresh cane yields and water use with the new version of SAMUCA model (Fig. 3). Daily meteorological data from 1980-to-2010 and the hydraulic and texture characteristics of predominant soil was obtained for each location from the study of Vianna and Sentelhas (2016). Thirty-year simulations were run considering 1-year growth cycle of ratooning sugarcane with planting/harvesting in the dry season (July: Piracicaba, Jataí and Petrolina; and January: Recife), commonly employed in Brazil. The amounts of GCTB simulated were 0 (bare soil), 6, 12, and 18 ton ha^{-1} aiming to represent the range of mulch amounts generally found on commercial farms (Lisboa et al., 2018). Simulation results of fresh cane yields and total evapotranspiration were subjected to descriptive statistics and Tukey significance test ($p < 0.05$) to identify the effects of GCTB amounts across different locations. In addition, the probability of a beneficial effect ($p\text{-}benef = n[Y_{mulch} > Y_{bare}]/30$) of GCTB on fresh cane yields and in reduction of evapotranspiration ($p\text{-}reduc = n[ET_{mulch} < ET_{bare}]/30$) was computed from the 30 years simulations results for each site.

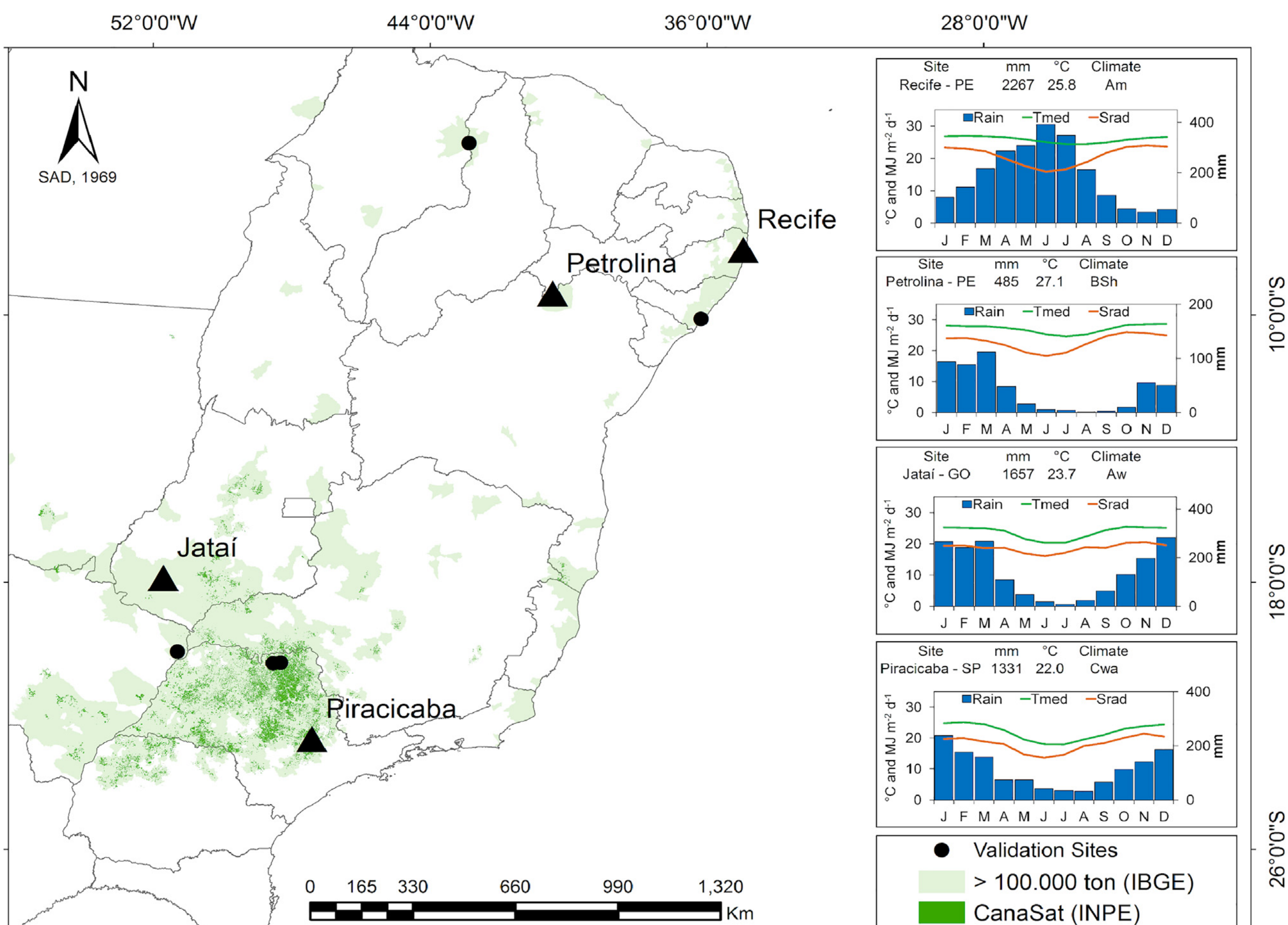

Fig. 3. Location of the four selected sites for the 30-year simulations (triangles), the sites where the validation was performed (circles), the Brazilian counties with over than 100,000 ton year^{-1} fresh cane production and sugarcane land use identified by the CanaSat/INPE Project (Aguiar et al., 2011).

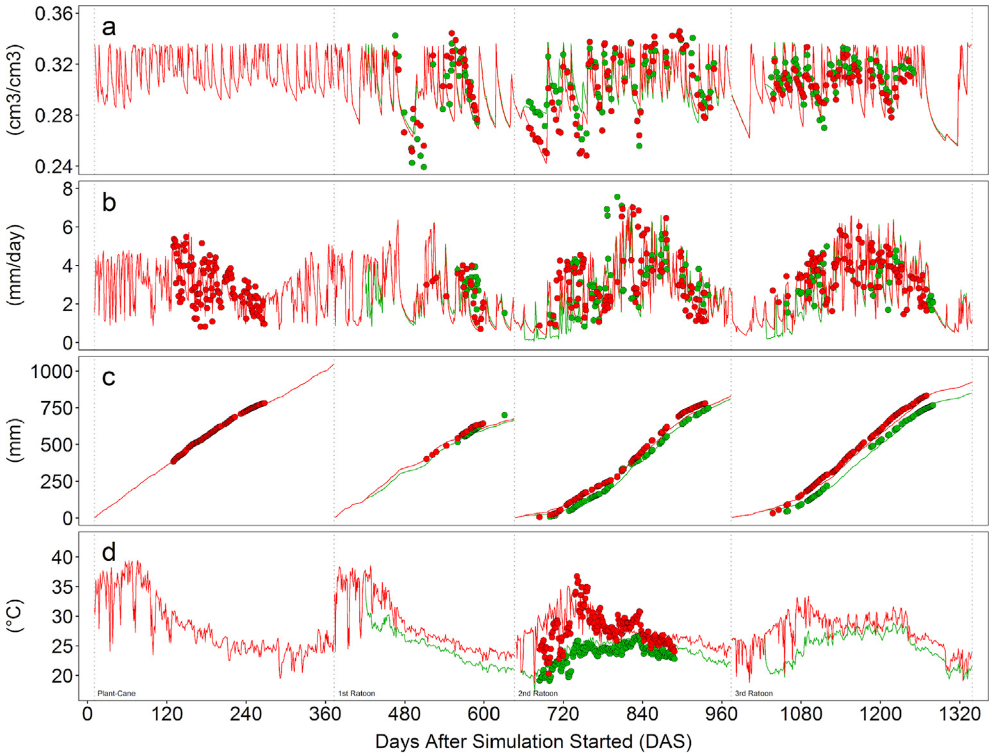

Fig. 4. Comparison between simulated (solid lines) and observed (circles) soil water content at 10 cm ($cm^3\ cm^{-3}$) (a), daily (b) and accumulated (c) evapotranspiration rates; and soil temperature (°C) (d) for the WM (green) and NM (red) treatments of the trial in Piracicaba, Brazil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Performance of the updated model on simulating sugarcane growth and water use under GCTB

After calibration and parameterization, the new version of SAMUCA model captured the differences in ET, soil moisture and temperature between the WM and NM treatments conducted in the Piracicaba experiment (Fig. 4). Simulation results of ET, soil moisture and temperature exhibited the highest differences between treatments in early seasons, approximately when the days after planting (DAP) were below 100. Soil moisture simulations of WM treatment were, on average, +5.8% (0.016 $cm^3\ cm^{-3}$) higher than bare soil (0.273 $cm^3\ cm^{-3}$) during the early growth stages (DAP $<$ 100, Fig. 4a). Simulations of soil temperature were, on average, 6.3 °C colder in WM than NM at this time as well, with maximum difference of 10.4 °C (Fig. 4d). Similarly, ET simulations were 0.3 mm day^{-1} lower on average in the WM treatment before canopy closure (Fig. 4b). Differences between simulation results of soil moisture, temperature and ET for WM and NM treatments were progressively reduced with canopy development. Simulations of accumulated ET in the course of crop growth agreed well with observations, where the total ET for WM was consistently lower than NM, with a maximum difference of 69.9 mm in the 3rd ratoon (Fig. 4c).

The statistical indexes for precision (r^2) and accuracy (d) for simulations of water moisture in the topsoil (10 cm) were 0.38 and 0.78, respectively, with a modelling efficiency (EF) of 0.27, and RMSE of 0.018 $cm^3\ cm^{-3}$. When comparing all soil compartments together (10–60 cm, Fig. A17), soil moisture simulations presented quite better performance (r^2 = 0.69, d = 0.91, EF = 0.62 and RMSE = 0.025 $cm^3\ cm^{-3}$, Table 3). Simulations of soil temperature showed similar performance as obtained for soil moisture simulations (r^2 = 0.56, d = 0.84, EF = 0.53). Despite of an RMSE of 2.1 °C, the difference between simulated and observed mean soil temperatures were only 0.9 and 0.1 °C for WM and NM treatments, respectively (Table 3). Simulations of daily ET showed poor precision and modelling efficiency (r^2 = 0.31, EF = 0.12) though reasonable accuracy (d = 0.66). Nevertheless, the agreement with accumulated ET rates was satisfactory, with high values of precision and accuracy ($>$ 0.98) and an RMSE of 14.7 mm.

The updated version of SAMUCA model was able to simulate the crop components throughout the sequential sugarcane seasons of Piracicaba experiment, including the differences on peak of tillering observed at the second ratooning (DAS = 770, Fig. 5). Simulations of stalk fresh and dry biomass presented satisfactory precision and accuracy (r^2 $>$ 0.88 and d $>$ 0.96), with modelling efficiencies above 0.87 and RMSE of 16.9 and 3.7 ton ha^{-1}, respectively (Table 4). Leaf area index and tiller population exhibited lower statistical indexes of performance than stalk biomass (r^2 $>$ 0.69 and d $>$ 0.90), though with similar average simulated and observed values for both treatments (Table 4). Simulations of sucrose content on stalk fresh basis (POL) and stalk height had the best agreement among crop components (r^2 $>$ 0.88, d $>$ 0.96 and EF $>$ 0.86), with RMSEs of 0.67% and 31 cm, respectively, for both treatments.

3.2. Model evaluation at different edaphoclimatic conditions in Brazil

Simulations of stalk fresh and dry biomass yields exhibited good precision and accuracy (r^2 $>$ 0.89 and d $>$ 0.94) with a modelling efficiency of 0.84 and RMSE of 19.6 and 4.1 ton ha^{-1}, respectively (Table 5). Stalk dry biomass measured at harvest ranged from 18.1 to 39.4 ton ha^{-1}, where the longer crop cycles (490 days) at Colina and Olímpia obtained the highest yields (Fig. 6). The same pattern was also observed for stalk fresh biomass, where fresh cane yields ranged from 73 to 179 ton ha^{-1}. Although rainfed and irrigated treatments were conducted at União, a small effect of water stress was observed on stalk biomass (Fig. 6), which is likely explained by the high annual rainfall at this site (1500 mm, Table 2) and due to the slightly higher soil moisture promoted by the GCTB. The comparison between observed and simulated sucrose content on stalk fresh basis (POL) resulted in an RMSE of 1.09% with lower precision when compared to biomass performance (r^2 = 0.66) though with good accuracy (d = 0.89) (Table 5). The values of POL presented similar pattern across regions, increasing from 9.7 to 15.5% between 294 and 490 days after planting (Fig. 6).

Table 3
Statistical indexes of performance of the calibrated SAMUCA model in simulating soil moisture, temperatures and evapotranspiration rates for a sugarcane field cultivated under GCTB (WM treatment) and bare soil (NM treatment) at the trial in Piracicaba, Brazil.

Variables	Treatment	Bias	RMSE	EF	r^2	D	$\bar{X}$	$\bar{Y}$
Topsoil Moisture 10 cm ($cm^3\ cm^{-3}$)	WM	−0.0039	0.018	0.197	0.331	0.753	0.307	0.303
	NM	−0.0023	0.019	0.330	0.415	0.799	0.303	0.301
	WM + NM	−0.0031	0.018	0.276	0.379	0.781	0.305	0.302
Soil Moisture* ($cm^3\ cm^{-3}$)	WM	0.0008	0.024	0.620	0.677	0.905	0.349	0.349
	NM	−0.0031	0.025	0.617	0.707	0.910	0.347	0.344
	WM + NM	−0.0012	0.025	0.619	0.691	0.908	0.348	0.346
Daily ET ($mm\ d^{-1}$)	WM	−0.0280	1.259	−0.212	0.205	0.681	2.98	2.96
	NM	−0.0733	1.164	0.103	0.314	0.751	3.12	3.04
	WM + NM	−0.0451	1.100	0.120	0.315	0.752	3.01	2.97
Total ET (mm)	WM	−0.9985	11.61	0.997	0.997	0.999	534.9	533.9
	NM	−10.045	21.47	0.989	0.991	0.997	530.2	520.2
	WM + NM	−3.2351	14.68	0.993	0.994	0.998	555.7	552.5
Soil Temperature (°C)	WM	0.9068	1.381	0.373	0.647	0.824	23.6	24.5
	NM	0.1171	2.655	0.071	0.157	0.623	27.7	27.8
	WM + NM	0.5230	2.099	0.534	0.563	0.840	25.6	26.1

RMSE: Root mean squared error; EF: Modeling efficiency; r^2: Determination index; d: accuracy index of Wilmot; $\bar{X}$: Mean observations; $\bar{Y}$: Mean simulations; Bias = $\bar{Y} - \bar{X}$; ET: evapotranspiration.
* At soil depths of 10, 30 and 60 cm (Fig. A17).

Tiller population and LAI showed an RMSE of 3.15 tiller m^{-2} and 0.76 $m^2\ m^{-2}$, respectively, with relatively lower precision than stalk biomass ($r^2 > 0.45$) though with good accuracy ($d > 0.82$) (Table 5). Peak of tiller population ranged from 18.2 to 22.6 tillers m^{-2} and stabilized at 8.9 tillers m^{-2} after 230 days after planting (Fig. 6). The simulated LAI values reached a maximum value of 4.4 $m^2\ m^{-2}$ at Olímpia after 160 DAP, whereas the LAI obtained for the Coruripe site was of 1.8 $m^2\ m^{-2}$ at the same period under rainfed conditions. After 220 DAP the LAI values oscillated between 2.1 and 3.8 $m^2\ m^{-2}$ at all locations (Fig. 6). Only one site presented measured stalk height (CLER), which exhibited an RMSE of 0.33 m, and precision (r^2) and accuracy (d) indexes higher than 0.94. For POL, the model exhibited an RMSE of 1.09%, with precision (r^2) and accuracy (d) indexes of 0.66 and 0.89, respectively (Table 5).

3.3. Quantifying the effect of GCTB on fresh cane yield and water use in Brazil

The 30-year simulations of stalk fresh biomass showed no expressive difference among treatments, except at Petrolina (Fig. 7). Jataí, Piracicaba and Recife exhibited similar cane fresh yield results, ranging between 98 and 166 ton ha^{-1}, while Petrolina had the lowest average yields (43 ton ha^{-1}). In Jataí, Piracicaba and Recife, the simulations of fresh cane biomass were slightly higher (+7%) under bare soil condition than the GCTBs treatments only until the mid-season (Fig. 7); thereafter, no significant difference was noticed among treatments for these regions. On the other hand, we found significant effects of GCTB on fresh cane yield simulations at Petrolina, where 6 and 12 ton ha^{-1} of GCTB was associated with 9.1–14 ton ha^{-1} increase on the average fresh cane yields, respectively (Table 6). Further, the probability of a beneficial effect of GCTB in fresh cane simulations at Petrolina was over than 90%, with fresh cane yields increases ranging from 1.1 to 48.3 ton ha^{-1} when cultivated under 12 ton ha^{-1} of GCTB (Fig. 8).

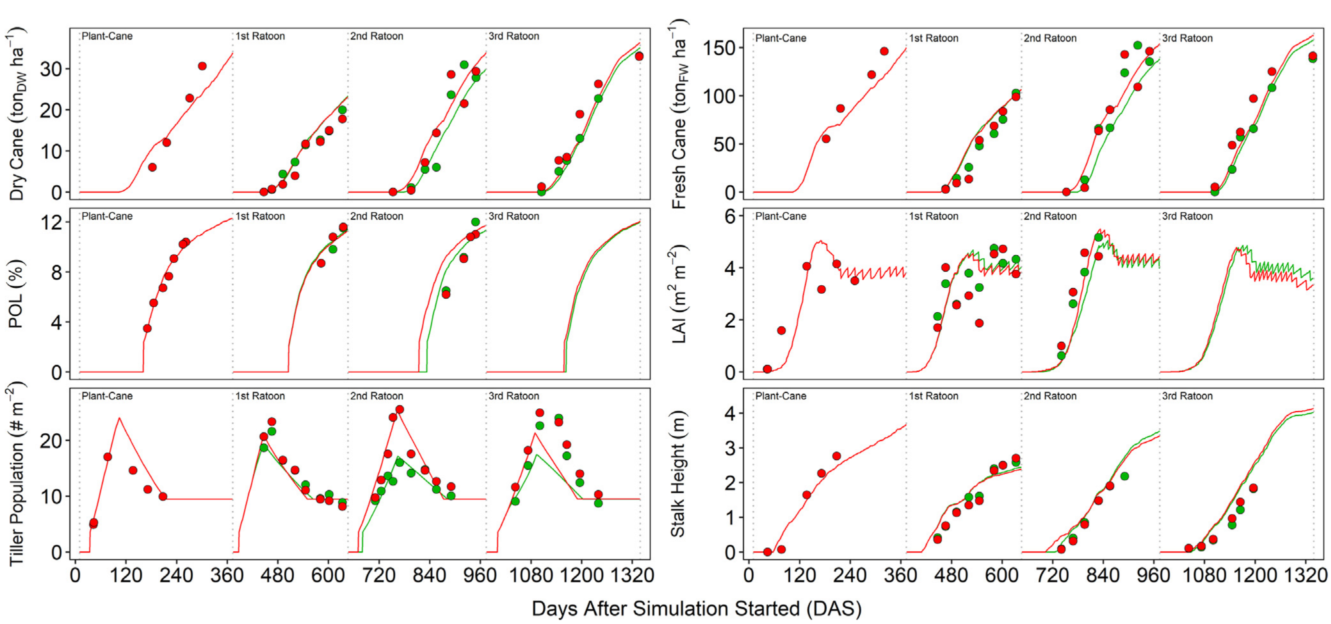

Fig. 5. Comparison between simulated (lines) and observed (circles) dry and fresh cane biomass (ton ha^{-1}), sucrose content (POL, %), leaf area index (LAI, $m^2\ m^{-2}$), tiller population (# m^{-2}) and stalk heights (m) for the WM (green) and NM (red) treatments of the trial in Piracicaba, Brazil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Statistical indexes of performance of the calibrated SAMUCA model in simulating sugarcane crop components cultivated under GCTB (WM treatment) and bare soil (NM treatment) at the trial in Piracicaba, Brazil.

Variables	Treatment	Bias	RMSE	EF	r^2	d	$\bar{X}$	$\bar{Y}$
Dry cane (ton ha^{-1})	WM	−0.3994	3.305	0.902	0.908	0.972	13.46	13.06
	NM	0.1729	3.673	0.877	0.877	0.966	13.89	14.07
	WM + NM	−0.2455	3.680	0.876	0.884	0.963	14.58	14.33
Fresh cane (ton ha^{-1})	WM	−4.5726	16.752	0.877	0.891	0.964	74.91	70.34
	NM	−2.4582	16.857	0.877	0.882	0.964	77.83	75.37
	WM + NM	−5.2759	16.898	0.868	0.890	0.961	82.16	76.89
POL ($\%_{[Fresh]}$)	WM	0.1956	0.68	0.919	0.926	0.978	8.19	8.38
	NM	0.301	0.88	0.866	0.883	0.965	8.29	8.60
	WM + NM	0.1846	0.67	0.921	0.927	0.980	7.97	8.16
LAI (m^2 m^{-2})	WM	−0.0890	0.861	0.686	0.780	0.931	2.85	2.76
	NM	0.0036	1.023	0.549	0.688	0.901	2.79	2.79
	WM + NM	−0.0187	0.937	0.649	0.766	0.924	2.67	2.65
Tiller population (# m^{-2})	WM	−0.4317	2.764	0.650	0.659	0.886	12.77	12.34
	NM	−0.3146	2.905	0.740	0.743	0.922	14.07	13.75
	WM + NM	0.0862	2.716	0.729	0.731	0.920	12.69	12.78
Stalk height (m)	WM	0.1442	0.326	0.879	0.904	0.966	1.26	1.40
	NM	0.1414	0.330	0.876	0.906	0.964	1.22	1.36
	WM + NM	0.0940	0.309	0.902	0.919	0.972	1.27	1.36

RMSE: Root mean squared error; EF: Modeling efficiency; r^2: Determination index; d: accuracy index of Wilmot; $\bar{X}$: Mean observations; $\bar{Y}$: Mean simulations; Bias = $\bar{Y} - \bar{X}$; ET: evapotranspiration.

Table 5
Statistical indexes of performance of the new version of SAMUCA model in simulating sugarcane crop components across different Brazilian regions.

Variables	Bias	RMSE	EF	r^2	d	$\bar{X}$	$\bar{Y}$
Dry cane (ton ha^{-1})	0.6239	4.129	0.875	0.924	0.956	19.44	20.07
Fresh cane (ton ha^{-1})	0.5868	19.578	0.861	0.891	0.943	84.91	85.49
POL ($\%_{[Fresh]}$)	−0.2852	1.090	0.586	0.660	0.896	13.23	12.95
LAI (m^2 m^{-2})	−0.0985	0.765	0.338	0.455	0.822	2.59	2.50
Tiller population (# m^{-2})	0.9859	3.151	0.627	0.674	0.895	14.03	15.02
Stalk height (m)	0.0450	0.334	0.851	0.961	0.945	0.96	1.01

RMSE: Root mean squared error; EF: Modeling efficiency; r^2: Determination index; d: accuracy index of Wilmot; $\bar{X}$: Mean observations; $\bar{Y}$: Mean simulations; Bias = $\bar{Y} - \bar{X}$; ET: evapotranspiration.

Despite of the non-significance, the average fresh cane yields were 2.6 ton ha^{-1} higher for all locations under 6 ton ha^{-1} of GCTB compared to bare soil (Table 6). In Jataí and Piracicaba, the probability of a beneficial effect of GCTB ranged from 41.9 to 54.8%, with fresh cane yields differences ranging from −12.1 to +31.4 ton ha^{-1} when comparing GCTB treatments with bare soil (Fig. 8). The amount of 12 ton ha^{-1} of GCTB promoted the highest's increase in fresh cane yields of Jataí (+24.2 ton ha^{-1}) and Piracicaba (+25.9 ton ha^{-1}), noticed in the years 1989 and 1984 (Fig. A25), respectively. In contrast, an amount of 18 ton ha^{-1} of GCTB reduced the fresh cane yields in Recife from 123.1 to 120 ton ha^{-1}, on average. The largest negative impact of GCTB on fresh cane yields simulated in Recife was of −15.3 ton ha^{-1}, also associated with 18 ton ha^{-1} of GCTB (Fig. 8). The 18 ton ha^{-1} of GCTB also presented the lowest probability of a beneficial effect on fresh cane yield in Recife (25.8%), though the 6 ton ha^{-1} of GCTB was associated with 77.4% probability of a beneficial effect in Recife (Table 6).

The total ET was significantly reduced under GCTB conditions in all locations (Table 6). The average reduction of ET ranged from 45.2 mm, for 6 ton ha^{-1} of GCTB at Petrolina, to 98.4 mm, under 12 ton ha^{-1} of GCTB at Piracicaba. Coefficients of variation (CV%) of total ET dropped to 5.8% at Jataí and to 9% at Piracicaba GCTB conditions. At Petrolina, the CV% for total ET increased from 16%, at bare soil, to 27% under 18 ton ha^{-1} of GCTB. The GCTB of 6 and 12 ton ha^{-1} promoted total ET reductions of over than 196 mm at Jataí and Piracicaba in the years of 2008 and 1981, respectively, while keeping same level of yields among GCTB amounts (Fig. A25). However, the same amounts of GCTB were associated with an increase of 258 and 142 mm in total ET for the same locations but for the years of 1989 and 1984, respectively. At Recife, all amounts of GCTB were associated with total ET reductions, except for the year of 1998 (single outlier at each GCTB of Fig. 7). The probabilities of reductions in total ET (*p-reduc*) due to GCTB were over than 64.5% for all locations (Table 6). At Jataí and Piracicaba, the *p-reduc* ranged from 80.6% to 93%, whereas at Recife, the *p-reduc* was of 96.8% for all GCTB amounts. In all locations, the 12 ton ha^{-1} of GCTB was associated with the highest's probabilities (*p-reduc* ≥ 87.1%) of reduction on water use from the sugarcane cropping system.

4. Discussion

The new version of SAMUCA model was able to capture the differences of soil moisture and temperature under bare soil and GCTB conditions. The mechanism employed in the updated model attenuates the heat transfer to soil surface when GCTB is present, also considering the solar radiation transmitted through the canopy as the energy budget for soil heat transfer and evaporation. The methods proposed by Porter et al. (2010), coupled with SAMUCA model, resulted in satisfactory performance when simulating the reducing effect of GCTB on soil evaporation (Figs. 4 and A22). As a result, our early season soil moisture simulations became higher under the GCTB compared to bare soil conditions. Although the processes governing energy balance and water movement below the soil surface may be more complex, this approach was effective in mimicking the patterns of soil temperature and moisture under GCTB found in our field experiment at Piracicaba and in recent literature (Ruiz Corrêa et al., 2019; Olivier and Singels, 2012). Moreover, the RMSE and accuracy indexes (d) obtained in our soil moisture simulations were comparable with the results found on a wide range of environments and crops (Liu et al., 2013, 2011; Eitzinger et al., 2004; Singh et al., 2006; Inman-Bamber and McGlinchey, 2003).

To our knowledge, this study is the first evaluating, altogether, the algorithms of ET, soil moisture and soil temperature for sugarcane and such approach would be valuable for crop modellers interested in dimensioning irrigation requirements and understanding the soil moisture dynamics. We also recognize that soil temperature and moisture not only affects sugarcane tillering and evaporation rates but may also change the physical, chemical, and biological processes in the rhizosphere, where the GCTB exerts a significant role (Thorburn et al., 2005; Leal et al., 2013). Therefore, we consider the inclusion of the

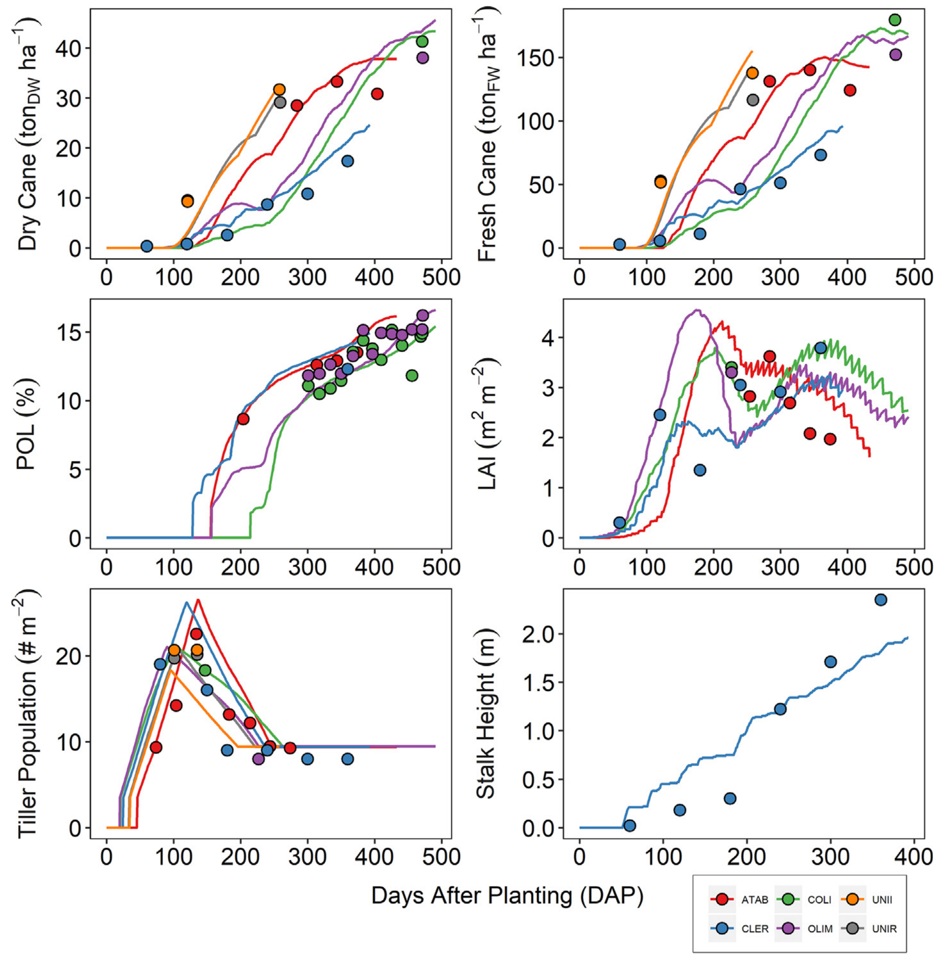

Fig. 6. Comparison of simulated (lines) and observed (circles) dry and fresh cane biomass (ton ha^{-1}), sucrose content (POL, %), leaf area index (LAI, m^2 m^{-2}), tiller population (# m^{-2}) and stalk heights (m) across different Brazilian regions. Code IDs for each site are provided in Table 2.

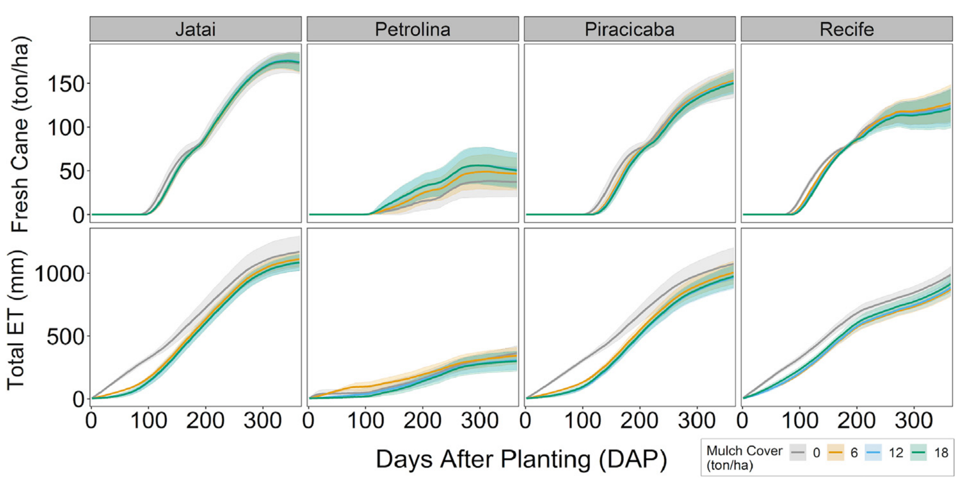

Fig. 7. Fresh cane biomass (ton ha^{-1}) and total evapotranspiration (mm) throughout sugarcane growth under variable GCTB (bare to 18 ton ha^{-1}) and bare soil simulated for 30 years at Jataí, Petrolina, Piracicaba and Recife. Solid lines represent the mean and coloured ribbons corresponds to the standard deviation of simulations for all the 30-years simulations (1980-to-2010).

effects of nutrients-limited environments in sugarcane growth as an emergent opportunity for future model improvements of SAMUCA model.

Compared with the prior standalone version (Fig. A20), simulations of LAI and tillering resulted in slightly higher values of RMSE, but the new version obtained higher modelling efficiency in simulating stalk biomass, POL and tillering than the calibration presented by Marin and Jones (2014). Yet, the new version of SAMUCA showed equal or superior performance when compared with the DC and AS models (Fig. A21). Such results can be attributed to the new biophysical mechanisms included in the model as well as to the more detailed simulations achieved by the discretization on phytomer level (Figs. A15 and A16). For example, after the inclusion of the linear relationship between the sucrose with total sugars contents at phytomer level (Fig. A8), the performance of POL simulations was considerably improved in comparison to the prior version (Fig. A20b).

The inclusion of the approach proposed by Bezuidenhout et al. (2003) coupled to soil temperature resulted in more realistic tillering

Table 6
Simulated fresh cane yields (ton ha^{-1}) and total evapotranspiration (mm) mean, coefficient of variation (CV, %), statistical differences ($p < 0.05$, $n = 30$) and probabilities of a beneficial effect of GCTB on fresh cane (*p-benef*) and in reduction of evapotranspiration (*p-reduc*) among variable GCTB amounts (bare soil, 6, 12 and 18 ton ha^{-1}) at Jataí, Petrolina, Recife and Piracicaba for 30 years (1980-to-2010).

Variable	Site		Bare Soil	6 ton ha^{-1}	12 ton ha^{-1}	18 ton ha^{-1}
Fresh Cane (ton ha^{-1})	Jataí	Mean	172.6a	174.4a	174.9a	174a
		CV%	7%	6%	6%	6%
		p-benef	–	54.8%	54.8%	45.2%
	Petrolina	Mean	37.4b	46.5ab	51.4a	50.5a
		CV%	46%	39%	38%	40%
		p-benef	–	90.3%	100.0%	90.3%
	Recife	Mean	123.1a	126.4a	122.3a	120a
		CV%	15%	16%	17%	18%
		p-benef	–	77.4%	41.9%	25.8%
	Piracicaba	Mean	149.4a	152.3a	150.5a	149.1a
		CV%	11%	8%	8%	8%
		p-benef	–	54.8%	45.2%	41.9%
Total ET (mm)	Jataí	Mean	1166.6a	1108.1b	1079.6b	1082.6b
		CV%	11%	5%	6%	6%
		p-reduc	–	80.6%	87.1%	87.1%
	Petrolina	Mean	360.2a	341.3ab	305.2b	298.5b
		CV%	16%	19%	24%	27%
		p-reduc	–	64.5%	90.3%	87.1%
	Recife	Mean	976.6a	859.5c	872.6bc	902.4b
		CV%	6%	7%	7%	7%
		p-reduc	–	96.8%	96.8%	96.8%
	Piracicaba	Mean	1069.9a	1000b	960.9b	969.2b
		CV%	12%	9%	9%	9%
		p-reduc	–	80.6%	93.5%	90.3%

simulations. Our results as well as previous studies (Olivier and Singels, 2012; Lisboa et al., 2018; Ruiz Corrêa et al., 2019) showed that GCTB reduces soil temperatures and delays the tillering process during the winter months. Bezuidenhout et al. (2003) found a linear decline on tiller population when the canopy light interception exceeded 60%, reinforcing the reliability of our model parameterization (*ltthreshold = 0.40*). Although non-optimum conditions of soil nitrogen (N) can also be associated with reduced tillering rates in sugarcane (Thorburn et al., 2005), the N contents in our experiment of Piracicaba were significantly higher at the GCTB treatment (Tables B2 and B3), suggesting that soil temperature was the major driver for tillering. Nonetheless, as the treatments of Piracicaba trial had no replications, this effect cannot be statistically attributed solely to GCTB, though independent studies also found similar results (Lisboa et al., 2018; Olivier and Singels, 2012).

The 30-year simulations results were in agreement with experimental data reported across Brazil and South Africa (Lisboa et al., 2018; Olivier and Singels, 2012; Ramburan and Nxumalo, 2017; Ruiz Corrêa et al., 2019), where SAMUCA showed a consistent increasing trend of fresh cane due to the presence of GCTB as a mediated effect of increased soil moisture during crop initial development stages (sprouting and tillering). In addition, the outstanding beneficial effects of mulch in fresh cane obtained in Jataí and Piracicaba simulations coincided with one of the driest years of both climate series (Fig. A25), reinforcing the positive effect of GCTB on fresh cane under dry spell events. Further, a consistent beneficial effect of GCTB on fresh cane was observed in our simulations for a semi-arid climate, represented by the Petrolina site (Fig. 8). Similar results were found by Ramburan and Nxumalo (2017) in trials conducted in South Africa, where annual rainfall ranged from 707 to 857 mm. Some of the negative effects of GCTB on fresh cane yield found in Recife can be attributed to the lower soil temperature, because the well distributed rainfall events at this location on early crop season assure the water supply to crop and raises the importance of soil temperature as the main driving factor for crop development (Figs. A23 and A24).

The simulations of total ET were 5–17% lower under GCTB conditions compared to the bare soil cultivation (Fig. 8). These results are consistent to the evapotranspiration rates obtained by Olivier and Singels (2012), where GCTB promoted an average reduction of 16–23% of water demand in comparison to the bare soil treatment. Despite of

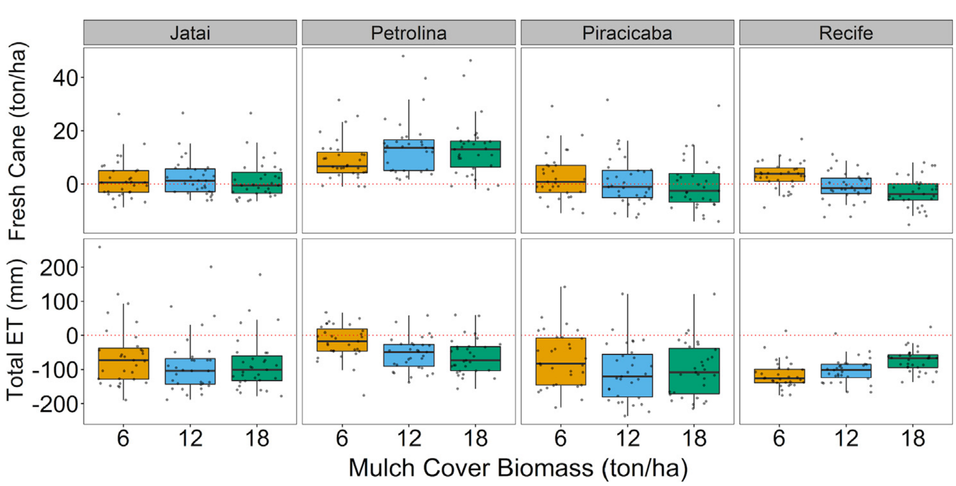

Fig. 8. Boxplots of differences between the bare soil simulations and the variable GCTB (6, 12 and 18 ton ha^{-1}) amounts for final fresh cane yield (above) and total evapotranspiration (below) through 30-years at Jataí, Petrolina, Piracicaba and Recife. Red-dashed line represent zero difference between GCTB and bare soil whereas black dots represents the differences for all the 30-year (1980-to-2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

high probabilities of total ET reductions (*p-reduc* > 64.5%), GCTB simulations also showed ET increases in some circumstances compared to the bare soil cultivation (Fig. 8). Such higher ET values were associated with higher yield outputs for GCTB than bare soil (e.g. year 1989 in Jataí, Fig. A25). The maintenance of soil moisture at the early stage led by the GCTB can reduce the demand for the common practice of "saving irrigations" at initial developmental stages of sugarcane (Vianna and Sentelhas, 2016), leading to a more sustainable production. Further, the reduction of the coefficient of variation (Table 6) of fresh cane at Petrolina and Piracicaba suggest a better yield stability promoted by GCTB, maintaining the soil moisture under water shortage periods.

5. Conclusions

The new version of SAMUCA captured well the differences between soil temperature and moisture of a sugarcane field cultivated under bare soil and GCTB conditions. Those differences were directly considered in the mechanisms of crop development and water use (e.g. tillering and soil evaporation). The new version of SAMUCA showed equal or superior performance when compared with the prior version and with widely used process-based models. The long-term simulations agreed with independent field experiment results reported in the literature where mulch cover promoted a consistent beneficial effect under dry climates with high probability (> 87%) of reduction in water use of sugarcane cropping system under 12 ton ha^{-1} of GCTB. Although the model limitations must be put into consideration for the final decision, when properly calibrated, this new model emerges as low-cost and fast tool for supporting decision making on mulch management in sugarcane plantations.

CRediT authorship contribution statement

Murilo dos Santos Vianna: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Daniel Silveira Pinto Nassif:** Data curation, Writing - review & editing, Investigation, Conceptualization. **Kássio dos Santos Carvalho:** Visualization, Investigation, Validation, Formal analysis. **Fábio Ricardo Marin:** Supervision, Conceptualization, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105361.

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