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Simulating sugarcane yield response to ETc replacements and green cane trash blanket maintenance in Brazil[1]

Simulando a resposta da produtividade da cana-de-açúcar a reposições da ETc e quantidade da palhada no Brasil

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HIGHLIGHTS:

The APSIM-Sugar agreed very well for soil moisture, biometric, and physiological variables.
ETc replacements affects stalk yield more than GCTB, above 50% ETc replacement, yield response was irrelevant.
The recommended amount of GCTB is at least 5.50 Mg ha^{-1}, considering soil health and the need for biofuel generation.

ABSTRACT: Determining the proper crop water requirement associated with the optimum amount of green cane trash blanket (GCTB) on the soil is one of the most discussed issues for sugarcane growers. In this context, this research aimed to evaluate the effects of different amounts of GCTB and ETc replacement scenarios on sugarcane yields across key producing regions in Brazil using the agricultural production systems simulator (APSIM). The sugarcane APSIM (APSIM-Sugar) was parameterized and validated for sugarcane in Brazil, compared to both 100% GCTB cover and bare soil, both fully irrigated. After validation through field data, the APSIM-Sugar model was used to simulate 25 different scenarios with varying GCTB amounts and irrigation demands in 12 regions of Brazil for a 30-year period to estimate stalk yield. Overall, modeled and field data agreed very well regarding soil moisture and biometric and physiological variables, achieving strong modeling efficiency. For most producing regions of Brazil, interaction between the factors did not increase stalk yield significantly, and up to 50% of ETc replacement resulted in the highest increases in stalk yield, with the greatest improvement between 0-25%, producing an average increase of 30 Mg ha^{-1} per year. The recommended amount of GCTB is at least 5.50 Mg ha^{-1}, taking into account soil health and the need for biofuel generation.

Key words: APSIM-Sugar, green cane trash blanket, modeling

RESUMO: Determinar as necessidades adequadas de água para as culturas agrícolas associada à quantidade ideal de palhada verde no solo é uma das questões mais discutidas pelos produtores de cana-de-açúcar. Nesse contexto, o objetivo desta pesquisa foi avaliar diferentes quantidades de resíduos da palhada da cana-de-açúcar (GCTB) e diferentes cenários de reposição da evapotranspiração sobre a produtividade da cana-de-açúcar nas principais regiões produtoras do Brasil usando o simulador de sistemas de produção agrícola (APSIM). O simulador de sistemas de produção agrícola para a cana-de-açúcar (APSIM-sugar) foi parametrizado e validado para a cana-de-açúcar no Brasil, em comparação com a manutenção de 100% da GCTB e solo descoberto, ambos totalmente irrigados. Após a validação através dos dados de campo, o modelo APSIM foi utilizado para simular 25 cenários diferentes (quantidade de GCTB e demanda de irrigação) considerando doze regiões do Brasil por 30 anos para estimar a produtividade de colmos. No geral, os dados modelados e de campo tiveram forte concordância com a umidade do solo e as variáveis biométricas e fisiológicas, alcançando uma forte eficiência de modelagem. Para a maioria das regiões produtoras do Brasil, a interação entre os tratamentos não aumenta a produtividade de colmos significativamente, e até 50% reposição da evapotranspiração resultou nas maiores taxas de aumento de colmos, com o maior incremento entre 0 e 25% com uma média de 30 Mg ha^{-1} por ano. A quantidade recomendada de palhada deixada sobre o solo é de no mínimo 5,50 Mg ha^{-1}, levando em consideração o dilema entre a conservação do solo e a necessidade de geração de biocombustíveis.

Palavras-chave: APSIM-sugar, GCTB, modelagem

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INTRODUCTION

With mechanized sugarcane harvesting, large amounts of green cane trash blanket (GCTB) are left in the field annually (10 Mg ha^{-1} [Powar et al., 2022]). Although clear criteria have not yet been established to define the amount of GCTB that can be sustainably collected without negative impacts on sugarcane production, several studies have shown that the GCTB contributes to the maintenance of moisture and organic matter in the soil after rainfall or irrigation events by reducing soil evaporation, especially during the initial periods of crop development when the leaf area index (LAI) is low (Singh et al., 2018; Marin et al., 2013).

In recent decades, sugarcane plantations have expanded to new areas with sandy soils subject to flash droughts, where irrigation is needed to assure economically feasible crop yields. Currently, irrigated sugarcane in Brazil comprises 3.6 million hectares (35% fertigation plus 9% irrigation), which represents 44% of the country's total irrigated area, and an increase of 50% in the permanent irrigated area is estimated by 2040 (ANA, 2021).

The agricultural production systems simulator for sugarcane (APSIM-Sugar) has been used to simulate irrigation and GCTB decomposition, and their effects on nitrogen availability, evaporation, plant water use, and crop stresses (Thorburn et al., 2005). It is a powerful tool to test yields in different soil and climate types (Marin et al., 2015; Meier & Thorburn, 2016).

In this paper, experimental data were used to calibrate the APSIM-Sugar and then to evaluate different sugarcane GCTB and ETc replacement scenarios on sugarcane yields across key producing regions in Brazil.

MATERIAL AND METHODS

The APSIM-Sugar was calibrated against a field dataset collected in the experimental area of the College of Agriculture "Luiz de Queiroz" (Esalq) at the University of São Paulo (USP) in Piracicaba-SP (22° 42' 30" S, 47° 38' 01" W; 560 m above sea level). The soil in the experimental area is classified as Ultisols. The area experiences a tropical monsoonal climate, with the predominantly dry winters (average temperature 10.4°C) and wet summers (average temperature 29.5°C) associated with that climate, it is classified as Cwa based on the Koppen classification.

The plant cane was planted on October 10, 2012 using an interrow space of 1.4 m and 13 to 15 buds m^{-2} at 0.3 m depth. Cultivar RB867515 was used; it is one of the most planted in Brazil. After the harvest of the plant cane (first cycle) on October 16, 2013, this research was initiated, meaning that the data in this study are from the first ratoon. Field data collection was completed with the harvest of the first ratoon on July 15, 2014.

At this point, the experimental area of 3.5 ha was divided and assigned to one of two treatments: GCTB or bare soil (BS). In the first treatment area, a total of 11 Mg ha^{-1} of GCTB was maintained on the soil surface; in the BS area, all GCTB was removed. Both treatments received adequate fertilizers (250 Mg ha^{-1} N, 75 Mg ha^{-1} P_2O_5 and 150 Mg ha^{-1} K_2O) according to Rossetto et al. (2008), as well as regular weed and phytosanitary control.

A center-pivot irrigation system was managed based on soil water balance to ensure maximum soil water availability for both treatments (522 mm applied), and the ETo and Kc for irrigation management were estimated following Allen et al. (1998), using data from a weather station installed near the experimental field.

Throughout the study period, detailed crop growth variables, including total dry above-ground mass (TDB), stalk dry mass (SDM), LAI, and average plant height (H) were collected at 4-5-week intervals. These measurements were conducted in 10 plants per plot, with four plots selected from each treatment area. Each plot consisted of 12 lines by 25 m (Nassif et al., 2012).

Twelve frequency domain reflectometry (FDR) access tubes were installed in each treatment area at a depth of 1.5 m. Frequency data were measured every 2-3 days. For model calibration, the frequency values were obtained under field conditions at intervals of 0.10 m, up to a total of 0.90 m depth.

These FDR frequencies were converted into volumetric soil moisture values, with parameters specifically calibrated for the experimental area. These calibrations for soil moisture estimation were obtained by comparing the FDR frequencies and their respective values of soil moisture. Soil moisture was calculated using Eq. 1.

$$\theta = 10^{\frac{\left[\log\left(\frac{FR}{A}\right)\right]}{B}} \tag{1}$$

where θ corresponds to the volumetric soil moisture (cm^3 cm^{-3}) estimated from the frequency (FR) recorded by FDR data for every 0.10 m depth, and A and B correspond to the FDR calibration for the soil type of the experimental area (0.06066 and 0.75594, respectively).

Field capacity (0.34 mm mm^{-1}), permanent wilting point (WP) (0.25 mm mm^{-1}) and saturation point (0.40 mm mm^{-1}) were determined in the laboratory using samples of undisturbed soil collected from four open trenches in the experimental sugarcane field (Table 1).

Sap flow (SF) measurements (Dynamax, Inc.) were conducted using six sensors for each treatment area. Installation procedures and transpiration estimates followed Machado et al. (2006), with sensors positioned in the region of uniform internodes with a diameter greater than 0.03 m to ensure contact with the sensor. Daily plant transpiration (T)

Table 1. Wilting point (WP), field capacity (FC), soil saturation (SS) and soil water storage (SWS) capacity of soil profiles at different depths

Layer (m)	WP	FC	SS	SWS (mm)
	Pressure (KPa)			
	15000	330	0	
0-0.05	0.21	0.28	0.40	3.5
0.05-0.15	0.25	0.30	0.36	5.4
0.15-0.30	0.24	0.32	0.38	12.3
0.30-0.60	0.32	0.40	0.43	23.0
0.60-1.00	0.26	0.40	0.45	54.8
Mean	0.25	0.34	0.40	Total = 99.0

was estimated as an average SF per treatment area from the LAI of the stalks; these values were then converted to hectares (mm ha^{-1} per day).

In each treatment, an energy balance was installed based on the Bowen ratio method system as described in Marin et al. (2019) to validate the modeled ETc from the APSIM-Sugar. ETc was calculated following the Eq. 2.

$$\mathrm{ETc} = \frac{\mathrm{Rn} - \mathrm{G}}{\lambda(1+\beta)} \qquad (2)$$

where Rn stands for net radiation (MJ m^{-2} 15 min^{-1}), G for soil heat flow (MJ m^{-2} 15 min^{-1}), β for the Bowen ratio, and λ for latent heat of evaporation.

The APSIM-Sugar was calibrated by eye-fitting and comparing simulations with observed variables, using the root of the mean square error (RMSE), bias, Willmott index (d), and modeling efficiency (EF) as measures of agreement. After calibration, the APSIM-Sugar was set up for simulating sugarcane growth and development across 12 Brazilian producing regions, examining 25 scenarios in each region (Figure 1 and Table 2). Those scenarios were represented by five amounts of GCTB (0, 2.75, 5.50, 8.25, and 11 Mg ha^{-1}) combined with five ETc replacement values (0%, 25%, 50%, 75%, and 100% of ETc).

The dominant soils for each region were selected based on regional analysis and soil profiles provided by the Radambrasil Project (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=941) and EMBRAPA (http://www.bdsolos.cnptia.embrapa.br/). The most representative soil for each region was selected following the protocols of the GYGA project (www.yieldgap.org), and pedotransfer functions for tropical soils were used for estimating water-related soil parameters. The APSIM management module was set up to represent the sugarcane cropping system of Brazil with application of 120 kg ha^{-1}, split into 30, 60, and 120 days after harvesting, parameterized according to Marin & Jones (2014). Simulations were performed to represent the first ratoon using the RB867515 cultivar.

The weather data required to perform the simulations were collected from the official database of the Brazilian Institute of Meteorology (https://portal.,inmet.gov.br/). Each climatic series consisted of 30 years of daily data (1980-2010), including rainfall and maximum and minimum air temperatures. As shown in Figure 2, on average, these regions received large

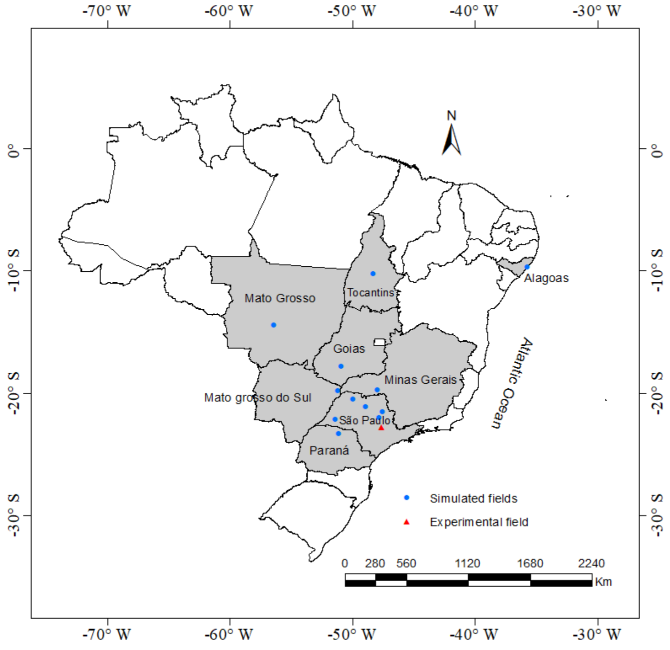


Figure 1. Selected regions where the APSIM-Sugar was applied

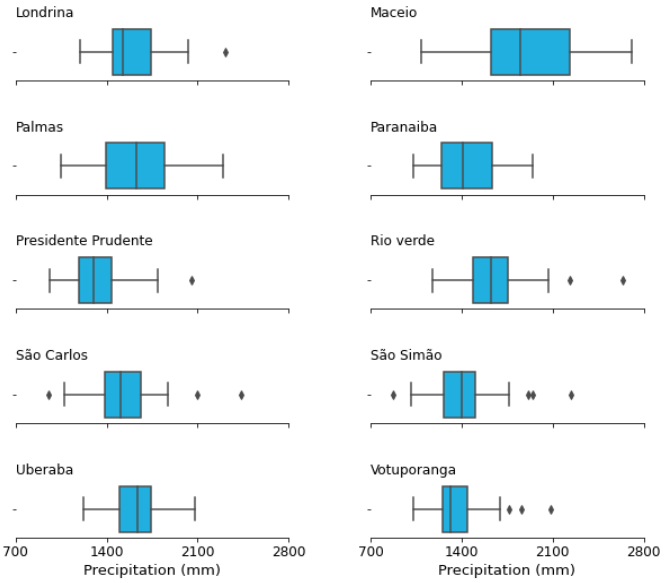


Figure 2. Mean variation of annual precipitation based on the 30 years (1980-2010) in the regions where the APSIM-Sugar simulations were conducted

Table 2. Characteristics of the regions where the APSIM-Sugar simulations were performed

Location	State	Soil type	Climate type	Latitude (°)	Longitude (°)	Altitude (m)	Tmean (°C)	Pmean (mm)
Catanduva	São Paulo	Ultisols	Aw	-21.11	-48.93	570	23.8	1330
Diamantino	Mato Grosso	Oxisols	Aw	-14.40	-56.45	286	26.5	1833
Londrina	Paraná	Oxisols	Cfa	-23.32	-51.13	566	22.1	1608
Maceió	Alagoas	Oxisols	As	-9.67	-35.70	64	25.3	1903
Palmas	Tocantins	Oxisols	Aw	-10.19	-48.30	280	26.9	1628
Paranaíba	Mato Grosso do Sul	Oxisols	Aw	-19.75	-51.18	331	26.9	1628
Presidente Prudente	São Paulo	Ultisols	Aw	-22.11	-51.40	432	24.1	1446
Rio Verde	Goias	Oxisols	Aw	-17.80	-50.92	774	23.7	1660
São Carlos	São Paulo	Oxisols	Cfa	-21.97	-47.87	856	21.4	1544
São Simão	São Paulo	Oxisols	Cfa	-21.48	-47.55	617	23.0	1433
Uberaba	Minas Gerais	Oxisols	Aw	-19.74	-47.95	737	23.1	1650
Votuporanga	São Paulo	Ultisols	Aw	-20.47	-49.98	502	24.5	1376

Tmean - mean annual temperature; and Pmean - average precipitation; for each year of the 30-year study period amounts of precipitation over the 30 years, with the largest amount in Maceio-AL (from 1090 to 2700 mm), followed by Palmas-TO (from 1050 to 2290 mm). The lowest precipitation amounts (outliers) were identified in Diamantino-MT (991 mm), São Carlos-SP (952 mm), and São Simão-SP (1013 mm).

In the experimental year (2013-2014), due to high atmospheric demand, a total of 522.6 mm of water was delivered through the center-pivot irrigation system to maintain proper soil moisture (Figure 3). Irrigation was essential to keep the plants free from water stress due to the high temporal variability of precipitation events during the first ratoon. The soil water availability remained above 65% based on the field capacity (FC), with the exception of the first few days of the first ratoon; stalk removal prevented the irrigation system from functioning fully during that brief period. At 244 days after plant cane harvesting (DAH), irrigation was cut off to increase sugar concentration in the stalks.

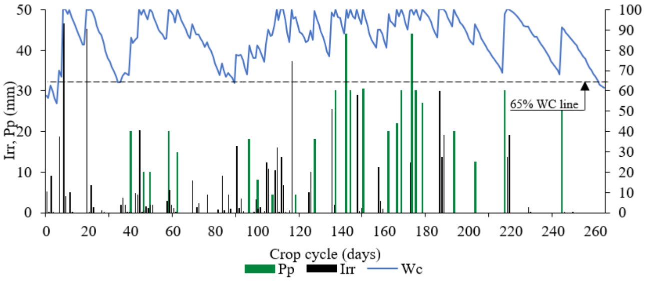
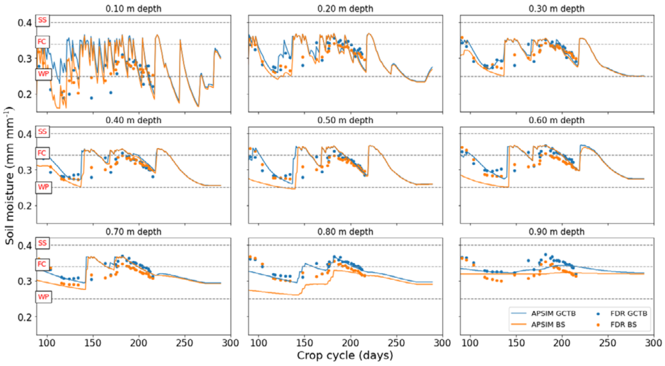


Figure 3. Daily water content in the soil (WC), precipitation (Pp), and irrigation (Irr) throughout the first ratoon

RESULTS AND DISCUSSION

In the first ratoon, the average temperature was 23.5 °C, with an average relative humidity of 86% and an average ETo of 3 mm per day. Overall, ETo of 797 mm was accumulated during the crop cycle, with a total rainfall of 643 mm (dry year) throughout the growing season. Higher temperatures and ETo were observed over the first 120 DAH, corresponding to the period from October 2013 to February 2014. Sugarcane responds positively to high air temperatures, radiation, and soil moisture, especially in the budding and vegetative growth stages (Marin et al., 2014a). In the maturation phase, milder temperatures and low soil moisture are desirable to inhibit vegetative development and increase the concentration of sucrose in stalks (Scarpari & Beauclair, 2009; Marin et al., 2013). Thus, the weather conditions were adequate in the study year-region, with an average temperature higher than 25 °C during the initial and development stage and lower than 20°C in the maturation stage. Furthermore, despite the low rainfall volume in the period, irrigation ensured adequate soil moisture.

The soil moisture values simulated by the APSIM-Sugar and measured via FDR corresponded well across the crop cycle (Figure 4). The comparability of the simulated and measured volumetric soil moisture across all depths showed that the model accurately simulated the variations of soil water. Both showed low RMSE in the deeper soil layers due to the low soil moisture variation throughout the crop growing season (Table 2). The GCTB treatment area had greater similarity to the APSIM-Sugar measurements than the BS, with a lower RMSE, bias closer to zero, and higher EF and d in the whole soil profile as well as relatively high EF, except at the 0.10 m depth.



WP - wilting point; FC - field capacity; SS - soil saturation

Figure 4. Soil moisture dynamics across the different depths measured using FDR and simulated by the APSIM-Sugar for green cane trash blanket (GCTB) and bare soil (BS)

The greatest variations in the simulated data were at the first 0.10 m depth, varying between 0.18-0.36 mm mm^{-1}. Being closest to the soil surface, this layer experiences greater water loss by evaporation into the atmosphere. According to the modeled data, the GCTB treatment contributed to greater soil moisture at all depths in January, February, and March, since the GCTB reduces soil surface exposure while the stalks are still in full vegetative development and the LAI is low. This echoes the findings of De Andrade et al. (2022).

In March (around 136 DAH), soil water content was similar in the whole soil profile. This is when the sugarcane had reached its maximum LAI, fully covering the soil surface and minimizing water loss via evaporation; thus most water was lost through transpiration at this point. Campos et al. (2017) explained that soil evaporation is greater in the beginning of crop development due to lower LAI, which allows more sunlight to reach the soil surface as it is not intercepted by leaves.

The model overpredicted the soil moisture around 150 days after harvesting at 0.2-0.7 m depth when there were very high amounts of precipitation after the drier period, as shown in Figure 3.

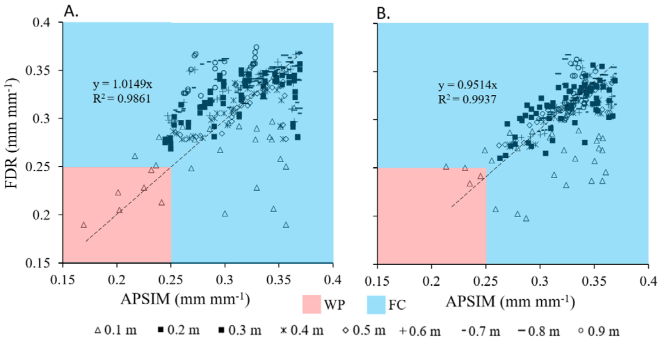
Considering the line forced to pass through the origin, overall, both BS and GCTB treatments had $R^2 > 0.95$ and an angular coefficient close to 1 ($b = 1.01$ and $b = 0.95$ for BS and GCTB, respectively) in both the APSIM-Sugar simulations and the observed FDR data (Table 3). The portion in pink (Figure 5) shows the soil water values within the WP (lower than 0.25 mm mm^{-1}) at the 0.10 m depth due to the intense soil evaporation, which made it difficult to maintain soil moisture at FC in this layer (0-0.10 m). The majority of the values within WP come from the BS treatment area earlier in the season, though, because of the absence of GCTB soil cover.

In terms of RMSE, Arbat et al. (2008) found model performances similar to those in our study, which confirms the quality of the adjustment since the results simulated by the models are close to the experimental data measured by these authors.

Root water absorption may have interfered with the simulated results, since the APSIM-Sugar assumes a decrease

Table 3. Root of the mean square error (RMSE), and modelling efficiency (EF), Willmott index (d) and bias for soil moisture values simulated by APSIM-Sugar and measured in the field via FDR for the green cane trash blanket (GCTB) and bare soil (BS) treatment areas

Depth (m)	Soil cover	RMSE	EF	D	Bias
0.10	BS	0.06	-0.60	0.47	12.3
	GCTB	0.07	-4.32	0.44	15.6
0.20	BS	0.03	0.21	0.81	-2.8
	GCTB	0.03	0.73	0.88	3.7
0.30	BS	0.03	0.11	0.83	-1.9
	GCTB	0.02	0.92	0.96	1.9
0.40	BS	0.02	0.35	0.90	0.1
	GCTB	0.02	0.87	0.95	4.7
0.50	BS	0.02	0.50	0.92	1.6
	GCTB	0.02	0.84	0.93	3.5
0.60	BS	0.04	0.29	0.77	-5.7
	GCTB	0.02	0.86	0.93	4.4
0.70	BS	0.04	0.47	0.82	-4.4
	GCTB	0.02	0.88	0.94	4.0
0.80	BS	0.03	0.74	0.90	-3.4
	GCTB	0.02	0.94	0.97	1.4
0.90	BS	0.05	0.25	0.24	-12.8
	GCTB	0.02	0.93	0.96	2.4



WP - wilting point; FC - field capacity; p-value: 0.00001 by t test

Figure 5. Relationship between modeled (APSIM-Sugar) and observed (FDR) soil water content for bare soil (A) and green cane trash blanket (B) treatments considering the whole soil profile

in the root system mass by 17% after harvesting. Under field conditions, however, this can vary considerably, and, consequently, impact simulation efficiency. In addition, root growth in the APSIM-Sugar is determined by the proportion of above-ground biomass and the water stress of the period (Marin et al., 2015). Furthermore, the effect of GCTB on water infiltration and drainage must be taken into account when identifying the soil profile because the organic matter influences the infiltration rate and water evaporation in the initial periods of crop development due to the low LAI.

For all crop variables, it was noticed that overall, the simulated data had a pattern similar to that of the observed data for the RB867515 cultivar (Figure 6). Overall, the simulated data were higher for the areas with the GCTB treatment than for those with BS; this might occur due to the higher soil moisture in the soil profile for areas with GCTB cover (Figure 4).

For instance, after heavy rainfall events, GCTB minimizes water percolation and nutrient leaching, and consequently positively influences crop growth. The GCTB treatment showed almost 10% higher LAI for modeled values, 28% higher for ETc, 21% higher for T, 29% for H, 27% for SDM, and 24% for TDB than BS treatment.

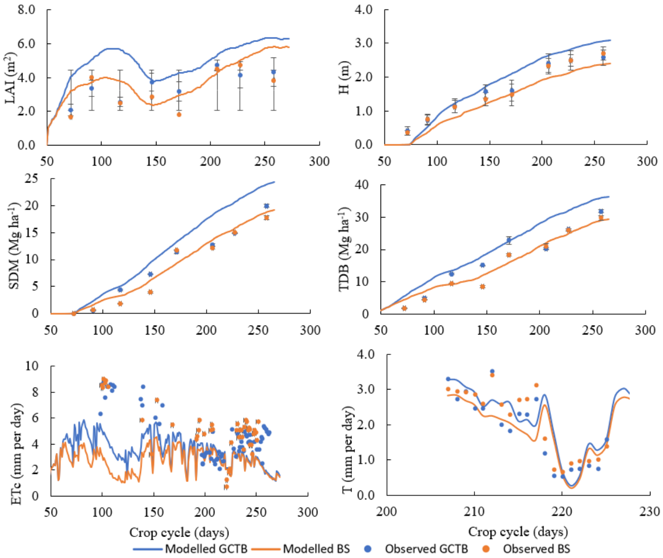


Figure 6. Simulated and measured results of leaf area index (LAI), heigh, dry stalk, total dry matter (TDB), evapotranspiration (ETc) and transpiration (T) for throughout the first ratoon using the APSIM-Sugar. GCTB: green cane trash blanket; BS: bare soil

However, such values also indicate that the APSIM-Sugar model overestimated these variables for GCTB treatment; such overestimations were comparable with those found in other models predicting the sucrose concentration for sugarcane in Brazil using DSSAT/CANEGRO (e.g., Marin et al., 2011; Nassif et al., 2012).

Nevertheless, the statistical results showed good agreement between simulated and observed data, with emphasis on the simulation of SDM, TDB, and H, for which EF reached 0.89 and 0.92 for TDB with GCTB and BS treatment, respectively (Table 4).

The APSIM-Sugar was used to simulate the stalk fresh yield (SFY) for different Brazilian edaphoclimatic conditions under different amounts of GCTB and water demand based on ETc. In this context, different SFYs were obtained for each studied site over the 1-year growth cycle of rooting sugarcane, mainly

Table 4. Bias, root of the mean square error (RMSE), modelling efficiency (EF) and the Willmott agreement index (d) for the biometric and physiological variables simulated by the APSIM-Sugar

GCTB treatment	Bias	RMSE	EF	d
TDM	2.19	3.19	0.89	0.97
DSM	3.38	3.96	0.64	0.93
LAI	1.67	1.85	-3.05	0.52
H	18.48	35.29	0.80	0.96
T	0.54	0.72	0.42	0.87
ETc-APSIM × ETc-Bowen	-1.10	2.08	-0.21	0.50
Bare soil treatment				
TDM	-0.78	2.65	0.92	0.98
DSM	0.30	1.08	0.97	0.99
LAI	0.51	0.99	-0.17	0.72
H	-28.47	30.64	0.85	0.96
T	0.36	0.60	0.59	0.90
ETc-APSIM × ETc-Bowen	-1.10	2.08	-0.21	0.50

H - plant height; LAI - leaf area index; T - transpiration; ETc-Bowen - evapotranspiration using the Bowen ratio method; TDM - total dry mass; DSM - dry stem mass ; GCBT - green cane trash blanket due to the different soil types and climate (30-year average, 1980-2010) (Figure 7).

All simulated sites presented an average yield greater than the actual overall average yield for Brazil of 74.5 Mg ha^{-1} (CONAB, 2021), even for rain-fed simulations. This is likely because the APSIM-Sugar, like other farming system models, does not represent actual management (e.g., weed presence, fertilization, pests, diseases) as it occurs on farms.

The observed responses to irrigation might be related to the large amounts of rainfall unevenly distributed over seasons and years in all selected regions (as shown in Figure 2), which would explain the simulations showing irrigation influencing the sugarcane yields more than the GCTB amounts.

Overall, a 25% water replacement increased the yield in all regions' simulations more than those using rain-fed scenarios; however, with 50% water replacement, we noticed that only half of the regions in the simulation - Diamantino-MT, Palmas-TO, Paranaiba-MS, Uberaba-MG, Rio Verde-GO, and São Simão-SP - showed increases in SFY. Water replacement above 50% did not increase SFY in any region (Figure 7), suggesting that full irrigation might not be a useful strategy. Still, there are several studies in the literature showing that the practice of irrigation promotes an increase in the sugarcane yields (e.g., Gonçalves et al., 2019), especially when levels of water requirement are based on ETc (Dias et al., 2019).

Besides a large amount of rainfall during summer, these results might also be related to the fact that the cultivar used in this study (RB867515) is relatively drought-resistant, reaching reasonable yields even under low soil water availability. Simulations for Rio Verde-GO reached over 250 Mg ha^{-1} for some simulated combinations, which would relate not only to the large rainfall amounts, solar radiation, and air temperature levels, but also to highly suitable soil conditions for sugarcane growth.

The contribution of GCTB to SFY was relatively small in all regions, and the interaction between applied irrigation and amount of GCTB also had a generally small influence on SFY. However, indiscriminate GCTB removal may intensify

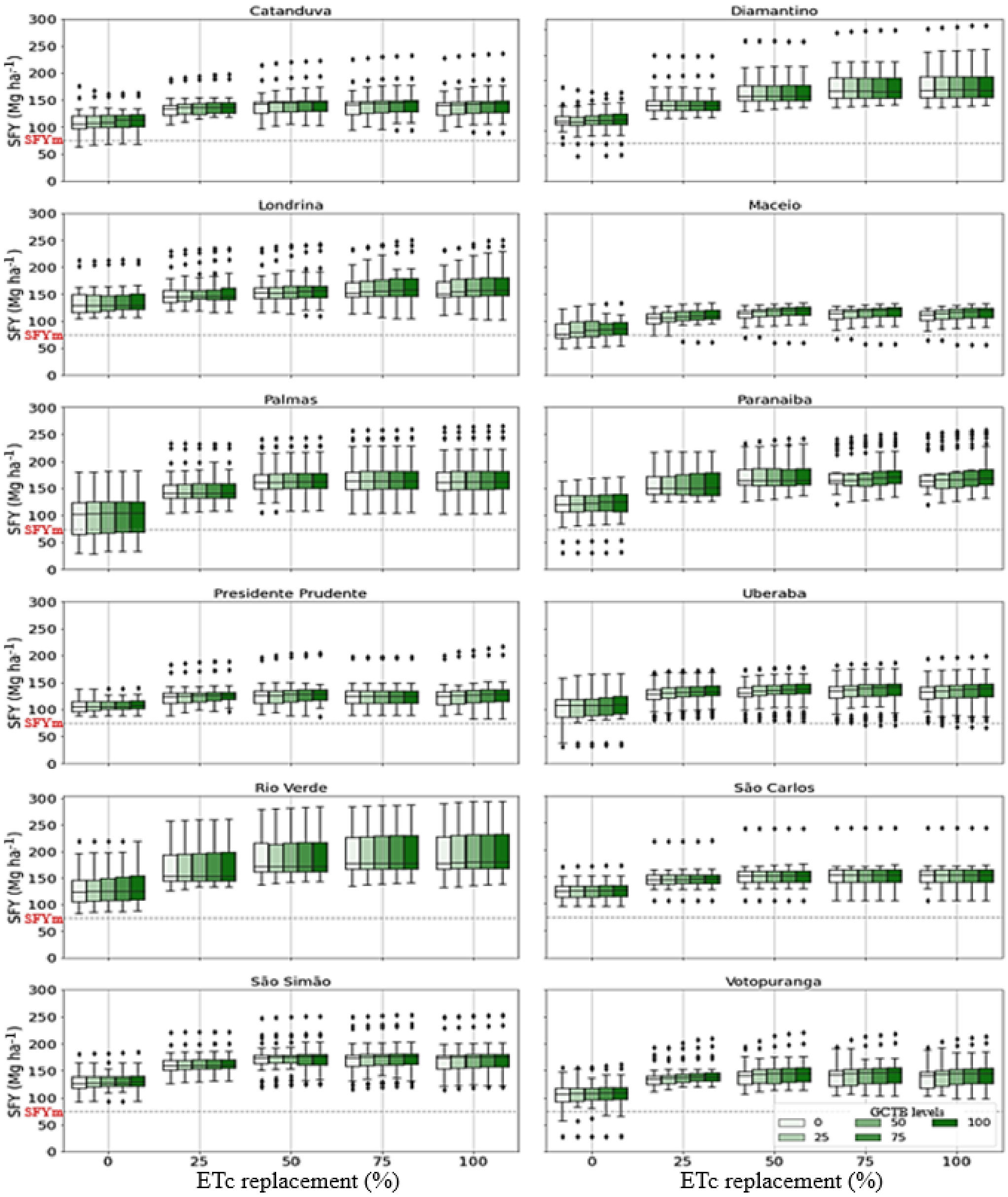


Figure 7. Stalk fresh yield (SFY) (Mg ha^{-1}) for different ETc replacement and green cane trash blanket amounts (GCTB) for different sugarcane-producing regions in Brazil. SFYm is the actual overall SFY for Brazil (74.5 Mg ha^{-1})

soil degradation in sugarcane fields, as reported in several experiments across the world (Silva et al., 2019).

For instance, Silva et al. (2019) found that soil cover increases exponentially and reached 90% of covering at 3 Mg ha^{-1}, with complete coverage with around 7 Mg ha^{-1}; the latter was identified as the minimum that should be kept on the soil surface to ensure good soil quality and a sustainable sugarcane yield over time. Any GCTB over that required amount could be converted into bioenergy production.

The weak effect of GCTB on SFY may be due to the decrease in the entry of thermal energy and solar radiation into the soil it can cause, thus impairing crop germination and tillering even as it improves soil moisture. Similar results were observed by Souza et al. (2020) comparison of areas with and without GCTB on sugarcane SFY. Still, given the stabilization of the nitrogen cycle seen during the simulations in areas that maintain large amounts of GCTB, it may require a longer time to reduce the carbon/nitrogen ratio of the GCTB, providing a period of competition for mineral nitrogen between the soil and the crop (Awe et al., 2015).

It is important to mention that the simulations considered a 30-year time series for crop regrowth and for carbon cycling in the soil, which might be an overly short period of time in terms of possible yield gains (Marin et al., 2014b). Even so, previous studies conducted via short-term evaluations in sugarcane crop systems confirmed that even when GCTB removal did not influence the crop yield, it could still be sufficient to reduce soil organic matter and nutrient cycling and increase compaction (Satiro et al., 2019). Still, Sousa et al. (2018) reported that only after three years of keeping sugarcane GCTB on the soil surface, carbon and nitrogen stocks within the surface soil layer were significantly increased. Furthermore, according to Sousa et al. (2017), after only one year of decomposition, GCTB N releases reached 23% of the total N available.

According to our simulations, the best amount of GCTB to maintain would be around 5.50 Mg ha^{-1}, which is less than what has been suggested in the literature based on the experimental evidence then available (Silva et al., 2019). This amount would be sufficient to assure more than 95% of soil coverage and protection against the negative effects of water erosion. Guided by our findings, going forward farmers can implement more sustainable irrigation practices alongside careful GCTB management in Brazil, and also support the sugarcane industry in better decision-making.

Conclusions

1. The APSIM-Sugar model properly simulated crop development and growth, as well as soil moisture, in agreement with the experimental data gathered from the RB867515 cultivar.

2. Based on the simulations from the APSIM-Sugar, ETc replacement affected stalks' fresh yield more than the GCTB did. Simulated sugarcane growth for different Brazilian regions demonstrated responses between 20-50 Mg ha^{-1} per year (average of 30 Mg ha^{-1} per year) for ETc replacement of 25%; replacement of ETc above 50% produced an insignificant yield response.

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