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Straw Removal Effects on Soil Water Dynamics, Soil Temperature, and Sugarcane Yield in South-Central Brazil

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Abstract

The use of sugarcane straw as bioenergy feedstock has been encouraged in recent years due to its potential to mitigate greenhouse gases emissions. Nevertheless, the indiscriminate straw removal causes soil damages, impairing crop development and productivity. Experiments in three sugarcane growing locations (Quatá-SP, Chapadão do Céu-GO, and Quirinópolis-GO) were conducted over 2 years to evaluate soil water dynamics, soil temperature, and sugarcane yield under diverse edaphoclimatic conditions. Straw removal of 0%, 50%, and 100% was arranged in a randomized block design with four replications. Dielectric water potential sensors were used to record soil water potential (ψ, kPa) and soil temperature (°C) every 6 h at a 0.15-m depth. Sugarcane yields were measured annually using an instrumented truck equipped with load cells. In general, the complete and partial straw removals were detrimental to water storage and therefore to plant available water causing an increase in soil temperature during sprouting and tillering phases, which are extremely important periods for a good crop establishment and, consequently, for yield increase. For the experimental sites presenting high fertility, greater water holding capacity, high sugarcane yield potential, and considering an extended water deficit in early stages of crop development, the complete straw removal resulted in yield losses of up to 16 and 40 Mg ha^{-1}, respectively. For the experimental site presenting low sugarcane yield potential, even with low water deficit at the beginning of crop seasons, straw removal had no significant influence on sugarcane yield in the short term, since straw did not produce enough improvements to soil in order to enable benefits for water retention.

Keywords Agricultural residues · Soil management · Sugarcane trash · Edaphoclimatic interactions · Water deficit

Introduction

Removal of sugarcane straw for bioenergy production is a recent practice in Brazil, expected to expand over the next years [1], driven by projections of future global climate change and rising of fuel prices [2]. These were decisive factors for the launching of *RenovaBio*, a Brazilian government program designed to support sustainable development and use of low carbon biofuels.

Sugarcane straw represents around one-third of the total primary energy of sugarcane crop [3]. Although still incipient, the use of this crop residue for bioenergy purposes may minimize the direct and indirect land clearing pressure over natural ecosystems and food crops [4]. However, the indiscriminate removal of sugarcane straw can cause some drawbacks by reducing soil carbon, nutrient cycling, biological activity, increases soil compaction and soil erosion [5, 6], besides its effects on soil temperature, water dynamics [5, 7], and, ultimately, on sugarcane yield [8].

Soil temperature controls not only the evaporation rates [9, 10] but also the physical, chemical, and biological processes in the rhizosphere [11] and the rates of organic matter decomposition [6, 12], nutrient availability, and recycling [13]. Soil water availability is one of the most important aspects affecting plant growth and development [14], including nutrient

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absorption by roots and plant water supply in response to atmospheric demand. Hence, by avoiding or reducing straw removal, the direct evaporation from soil surface decreases [15, 16], enhancing soil organic matter [8] and improving soil physical quality [17], greatly contributing to soil moisture conservation [15, 18].

Although the effects of crop residue removal on soil temperature [9, 19–21] and soil water content [22–24] are well documented, only a few studies address sugarcane fields in Brazil [7, 25–27], mostly under a qualitative approach which considers the presence or absence of straw associated with fire practice at the harvest period.

During sugarcane mechanical harvest, the deposition of large amounts of dry mass of straw (green tops and dry leaves), ranging from 10 to 20 Mg ha^{-1}, remains in the field [3]. Carvalho et al. (2017) [5] based on available literature concluded that a residue mulch of at least 7 Mg ha^{-1}, i.e., almost 50% of the considered average (15 Mg ha^{-1}), are recommended to be left on soil surface to promote agronomic benefits [28]. Despite the general recommendation, it is important to emphasize that sugarcane cultivation areas in Brazil cover a wide variety of edaphoclimatic conditions. Moreover, the distinct harvest cycles adopted (early, middle, and late) provide interactions that should be taken into account when recommendations addressing straw removal are proposed.

We hypothesized that complete straw removal is detrimental to water storage, soil temperature fluctuation, and, consequently, to sugarcane yield. Still, the straw removal management may vary according to edaphoclimatic interactions, since it is a site-specific response. Thus, the understanding of the effects of straw removal performed on different locations under an agronomic perspective is a major contribution to improve sustainability of the use of this crop residue for bioenergy production. In this context, the objective of this study was to evaluate the effects of different straw removal rates on soil water dynamics, soil temperature, and sugarcane yield in areas under different edaphoclimatic conditions in South-Central Brazil.

Materials and Methods

Description of the Study Areas

The experimental sites were strategically chosen to represent the diverse growing conditions in São Paulo (SP) and Goiás (GO) states within South-Central Brazil. Three field experiments were carried out for scientific purposes within commercial farms in Quatá, State of São Paulo (SP) and Chapadão do Céu and Quirinópolis, both located in Goiás State (GO). Figure 1 provides information on geographic coordinates, altitude, soil type and texture, climate characteristics, harvest dates, and amount of straw produced (on dry basis) in each year.

Field experiments were set up in June 2014 after the plant cane[1] harvest cycle. Prior to setting up the field experiments, soil samples were collected for chemical and physical characterization according to [30, 31] (Table 1). Experiments were arranged in a randomized block design with four replications and three treatments, comprising three straw removal rates: (i) 0% of straw removal (0SR), (ii) 50% of straw removal (50SR) or partial removal, and (iii) 100% of straw removal (100SR) or complete removal (i.e., bare soil). Plots with 50% removal were divided into two symmetrical parts and half of the dry biomass was removed and the remainder was scattered within the plots, and those with 100% removal were left completely bare by taking away all the straw. Sugarcane residue from mechanical harvest consists of green tops (green leaves on the top and those green leaves attached in last stalk nodes) and dry leaves, i.e., senescent leaves with brown and yellowish colors, attached in the stalk and recently dried leaves deposited on the soil. Adjustment of straw mulch quantities was performed manually, using forage forks and rusks. The same procedures were performed in the trial reestablishment after harvest of the first ratoon (July 2015). Plots included ten sugarcane rows (variety RB96-6928) spaced 1.5 m and 9 m long. All plots received annual fertilization of 120 kg ha^{-1} of nitrogen (ammonium nitrate) and potassium (potassium chloride). Applications of fungicides, insecticides, and herbicides were uniform in all treatments and conducted according to the management strategies established by the sugarcane mill.

Soil Water and Temperature Measurements

Over the entire experimental field, dielectric water potential sensors (MPS-2 Decagon, Pullman, USA) connected to a data logger (Em50 Decagon, Pullman, USA) were used to record and store soil water potential (ψ, kPa) and soil temperature (°C) data every 6 h (12 am, 6 am, 12 pm, 6 pm) at a 0.15-m depth. This depth was adopted as a sample of the surface layer (0–30 cm) since it was highly affected by straw and contained most of the sugarcane roots. In Quatá-SP (sandy soil), although the first ratoon harvest occurred in June 2015, the dielectric water potential sensors were installed later in July due to operational issues. Same procedures were adopted for Chapadão do Céu-GO (clayey soil), where sensors were installed in August, after plant cane harvest (June 2014) and the first ratoon harvest (July 2015) (Fig. 1).

The soil-water retention characteristics were measured from undisturbed cores collected using volumetric rings from four trenches at 0–0.10-, 0.10–0.20-, and 0.20–0.30-m depths. The soil samples were saturated and then subjected to tensions ψ of 2, 6, 10, 33 (tension tables) 300, 500, 700, and 1500 kPa

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[1] First annual crop cycle

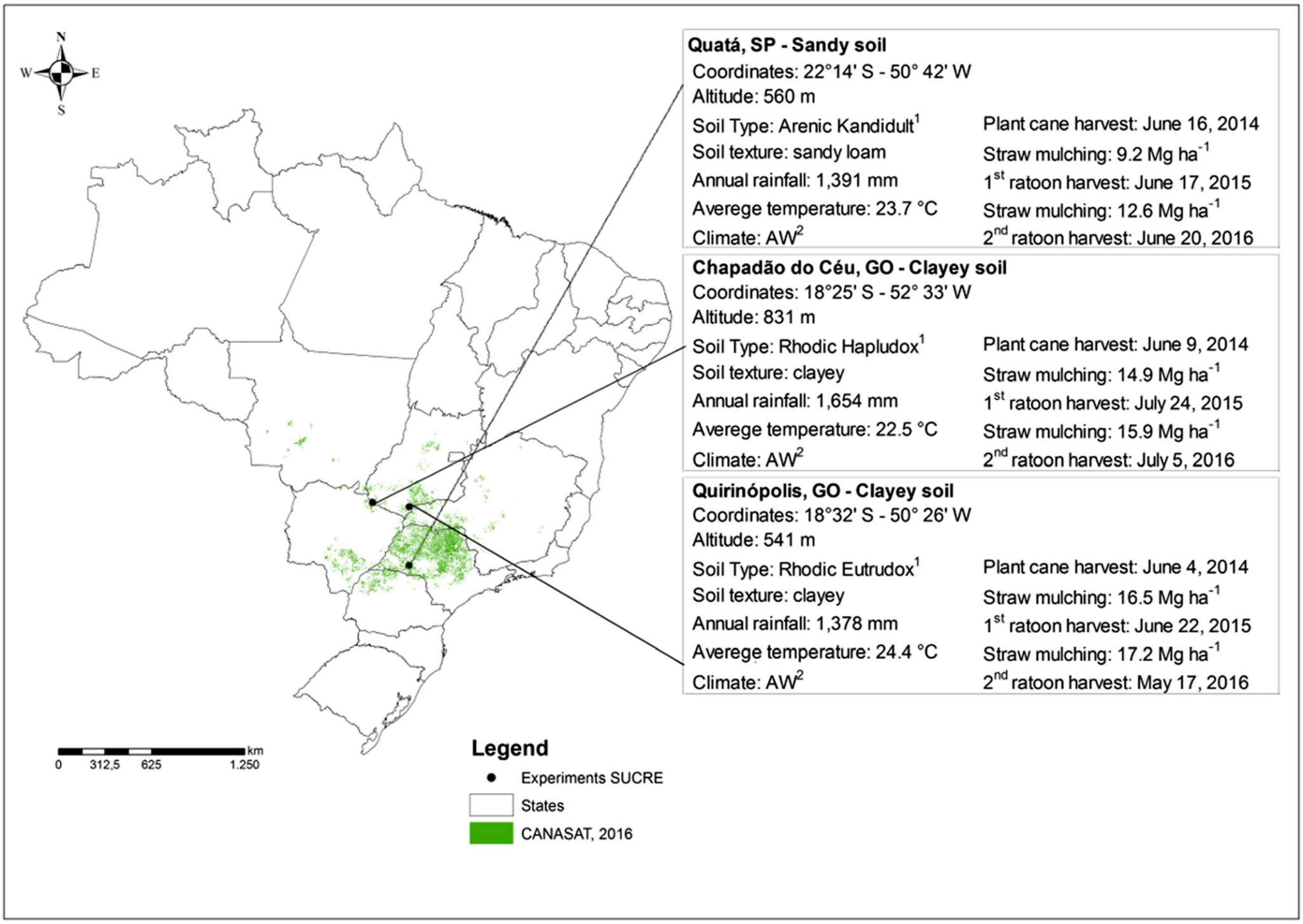

Fig. 1 Experimental site description and location: Quatá-SP, Chapadão do Céu-GO, and Quirinópolis-GO ([1][29]; [2]according to Köppen Geiger classification)

(in Richards extraction chambers). After the equilibrium of the samples at the respective tensions, they were dried in an oven at 105 °C for 48 h to constant dry mass. Soil bulk density (kg m^{-3}) and gravimetric soil water content (g g^{-1}) were calculated [31] and, subsequently, the relationship between ψ and the corresponding soil water content (θ, m^3 m^{-3}) values were

Table 1 Chemical and physical characterization of soils of each experimental site

Soil layer m	pH	SOM g dm^3	P mg dm^{-3}	K mmol dm^{-3}	Ca	Mg	H+Al	CEC	BS %	Sand g kg^{-1}	Silt	Clay	BD Mg m^{-3}	MaP m^3 m^{-3}	MiP
Quatá-SP (sandy soil)															
0–0.10	5.1	12	24	0.8	16	6	13	36	23	853	60	87	1.53	0.21	0.22
0.10–0.20	4.7	11	16	0.3	10	3	17	31	13	832	60	108	1.64	0.17	0.22
0.20–0.40	4.6	10	8	0.3	10	3	16	30	13	801	57	142	1.68	0.16	0.22
Chapadão do Céu-GO (clayey soil)															
0–0.10	5.1	33	15	2.9	33	12	27	76	49	218	161	621	1.09	0.14	0.40
0.10–0.20	5.2	24	12	2.0	28	9	28	67	39	208	150	642	1.12	0.11	0.42
0.20–0.40	4.8	24	6	1.2	16	5	37	58	22	200	145	655	1.13	0.12	0.41
Quirinópolis-GO (clayey soil)															
0–0.10	5.5	32	10	5.8	44	16	23	89	66	267	186	547	1.19	0.18	0.36
0.10–0.20	5.5	27	8	3.7	43	12	23	82	59	249	190	561	1.33	0.17	0.32
0.20–0.40	5.5	22	7	2.6	34	8	21	66	45	225	195	580	1.31	0.13	0.36

SOM soil organic matter, *CEC* cation exchange capacity, *BS* base saturation, *BD* bulk density, *MaP* macroporosity, *MiP* microporosity obtained by applying van Genuchten parameters [32] provided by the RETC program [33]. Soil water content at field capacity (θ_{FC}) was considered as corresponding to a ψ of − 10 kPa while the value at the permanent wilting point (θ_{PMP}) was − 1500 kPa, using averages obtained from the three sampled depths. These values were used to estimate the water deficit for plants through the readily available water (RAW, $m^3\ m^{-3}$), according to Eq. 1:

$$\mathrm{RAW} = p.1000\ Ze(\theta_{FC}-\theta_{PWP}) \tag{1}$$

where p is the average fraction of the total available soil water (1000Ze ($\theta_{FC}-\theta_{PWP}$)) that can be depleted from the sugarcane root zone before water stress occurs [0.5–0.65] [34, 35] corresponding, respectively, to a ψ around − 80 and − 150 kPa, adopted in this study for the three soils. Z_e is the plant rooting depth, taken as 0.30 m.

The soil water storage (h, mm) was obtained by multiplying the daily θ by the layer thickness of the evaluated soil profile (0.30 m) and then daily changes in soil water storage (Δh, mm) were calculated according to Eq. 2:

$$\Delta h = 1000Ze(\theta_i-\theta_{i-1}) \tag{2}$$

where θ_i is the soil water content ($m^3\ m^{-3}$) on day i and θ_{i-1} of the previous day (i−1).

The water input and output from the soil system were estimated through cumulative daily changes in soil water storage ($\sum\Delta h$), i.e., the sum of positive and negative daily values of Δh obtained during the entire sugarcane development cycles and divided into four stages of 3 months each, starting after cane harvest. This split in crop cycles was made aiming to better understand the effects of straw removal on specific phenological phases.

Regarding soil temperature (°C) during the early stage of sugarcane development (120 days after harvesting), the amplitude values related to 50% and 100% straw removal rates were compared to no removal treatment values at different times (0, 6, 12, and 18 h and average).

Sugarcane Yield Measurements

Plots were mechanically harvested to determine sugarcane yield in megagrams of fresh mass of millable stalk per hectare. The sugarcane yield of four central rows of each plot was automatically transferred upon cutting to an instrumented truck containing a load cell specifically designed for weighing biomass.

Statistical Analysis

Soil water storage and soil temperature were analyzed by the mean absolute deviation (MAd), root mean square deviation (RMSd), determination coefficient (R^2), and the *bias*, comparing the treatments 0SR, 50SR, and 100SR.

Sugarcane yields were subjected to variance analysis (ANOVA) for the assessment of differences among treatments (0SR, 50SR, and 100SR). If the ANOVA results were significant ($p < 0.05$), average values of sugarcane yields were compared using Tukey's test ($p < 0.05$). Both analyses were performed using Statistica software (Dell Inc.) [36].

Results

Soil Water Content (θ) and Soil Water Storage (h)

The temporal variability of θ ($m^3\ m^{-3}$) differed among treatments throughout the experiment period, especially in early stages of crop development. At lower rainfall levels and mild air temperatures from June to October, i.e., until canopy closure, values of θ were particularly different, with lower values observed under 100SR. At higher rainfall and temperature levels, from November onward, the values of θ were similar regardless of the amount of straw maintained on surface (Fig. 2a, d, g).

In Quatá-SP, values of θ for all straw removal rates dropped below the threshold value (RAW), limiting water availability for almost 4 months after plant cane harvest (Fig. 2a). Under 100SR rate, the water input (+$\sum\Delta h$) and output (−$\sum\Delta h$) from sandy soil were remarkably higher (+ 137 and − 134 mm) than results reported for 0SR (+ 73 and − 65 mm) and 50SR (+ 64 and − 61 mm) throughout the first ratoon cycle (Table 2). The subsequent cropping season (i.e., second ratoon) presented a less marked variation in θ and Δh due to rain surplus throughout the full crop cycle (Fig. 2a and Table 2).

On other locations (Chapadão do Céu-GO and Quirinópolis-GO), θ reached the critical point limiting water availability soon after harvesting, especially under 100SR and 50R (Fig. 2d, g). The +$\sum\Delta h$ and −$\sum\Delta h$ from clayey soils were less intense among treatments than in sandy soil, especially because of higher water holding capacities and major differences in h observed at the onset of crop cycle (Table 2). Furthermore, for all locations, the statistical *bias* test revealed that soil water storage was lower under both 50SR and 100SR when compared to 0SR (Fig. 2b, c, f, h, i).

Soil Temperature

The highest values of soil temperature at a 0.15-m depth were found in 100SR treatment. For partial removal (50SR), an intermediate value was obtained, and for 0SR milder soil, temperatures were observed during the first 3–4 months after straw deposition. After that period,

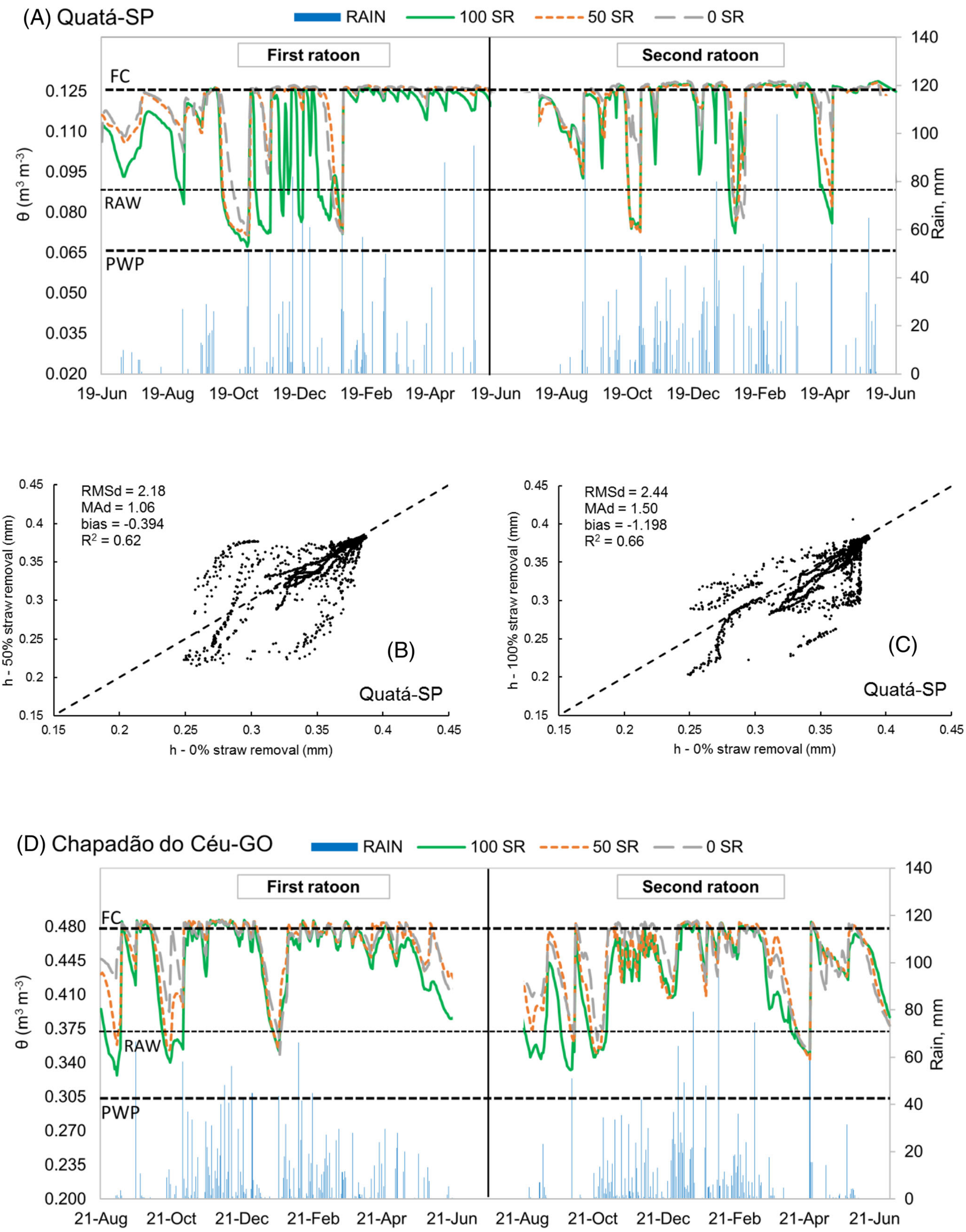

Fig. 2 **a**, **d**, **g** Soil water content (θ, m^3 m^{-3}) under different straw removal rates during the first and second ratoons and the corresponding rainfall (mm) distribution (FC field capacity, PWP permanent wilting point, and RAW readily available water). **b**, **e**, **h** Soil water storage in 0SR versus 50SR. **c**, **f**, **i** Soil water storage in 0SR versus 100SR (at 0.15-m depth) for Quatá-SP, Chapadão do Céu-GO, and Quirinópolis-GO (100SR, 50SR, and 0SR denote 100%, 50%, and 0% of removal rates)

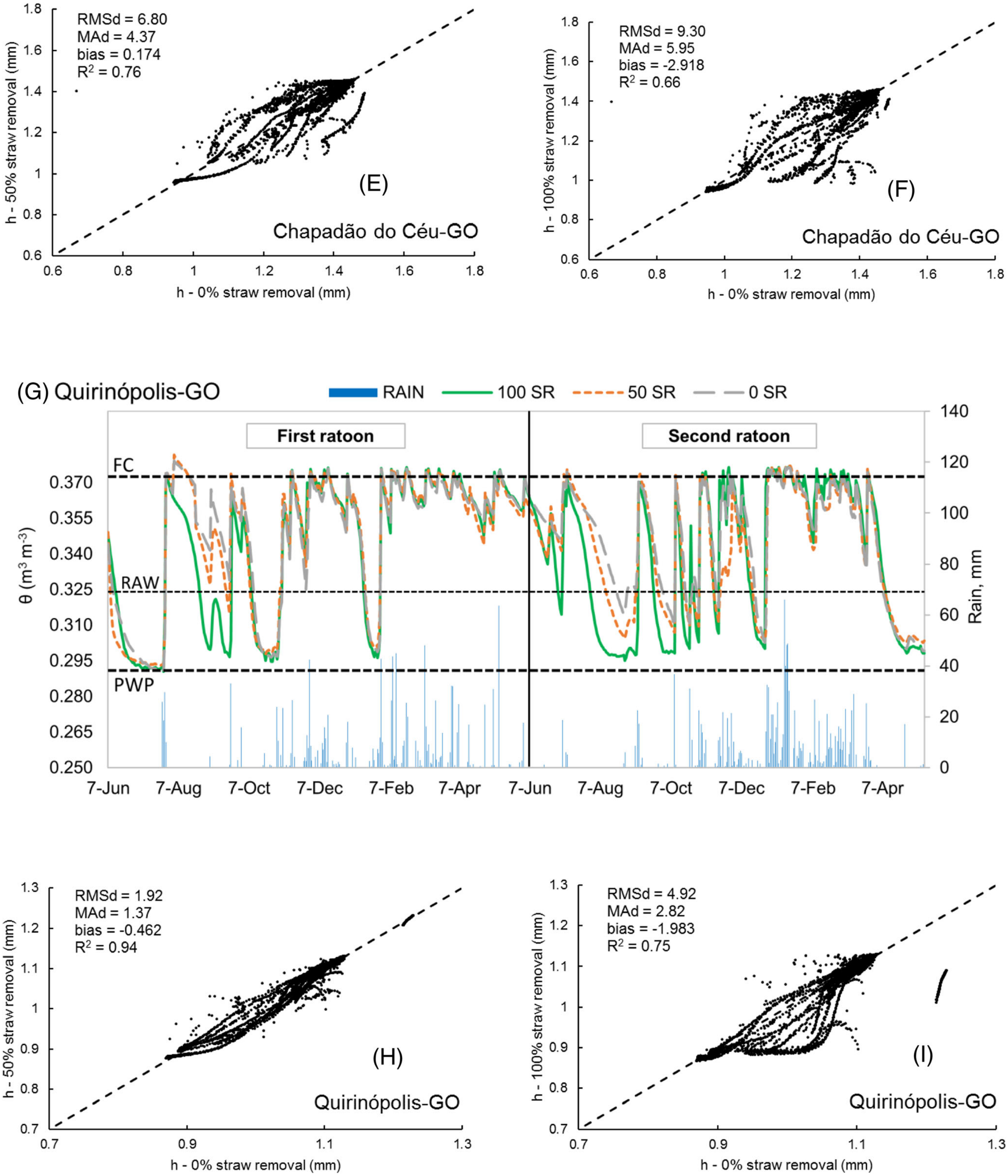

Fig. 2 (continued)

temperature values were similar for all treatments (Fig. 3a, d, g). Moreover, results revealed a trend of high soil temperatures in 100SR than 0SR treatment (Fig. 3c, f, i). The highest temperature amplitudes were recorded under 100SR at 18 pm. Additionally, higher temperature amplitudes were observed on clayey soils (5.8 °C and 6.5 °C, respectively, Chapadão do Céu-GO and Quirinópolis-GO) than on sandy soil, 4.5 °C (Table 3).

Table 2 Cumulative daily changes (positive and negative) in soil water storage ($\sum \Delta h$, mm) among straw removal rates separated by a 3-month period during the first and second ratoons in Quatá-SP, Chapadão do Céu-GO, and Quirinópolis-GO. 100SR, 50SR, and 0SR denote 100%, 50%, and 0% removal rates

Stage	$\sum \Delta h$ (+)			$\sum \Delta h$ (−)		
	100 SR	50 SR	0 SR	100 SR	50 SR	0 SR
Quatá-SP	First Ratoon—2014/2015					
19 June–17 Sept	19.1	8.6	18.5	−17.6	−9.3	−11.5
18 Sept–17 Dec	62.1	30.5	31.8	−63.5	−26.5	−29.6
18 Dec–17 March	46.2	21.2	19.4	−42.2	−21.2	−19.5
18 March–17 June	9.9	3.5	3.7	−11.1	−4.1	−4.4
Annual average	137.3	63.8	73.4	−134.3	−61.0	−65.0
	Second Ratoon—2015/2016					
28 July*–15 Sept	14.8	11.9	7.1	−11.3	−9.8	−6.8
16 Sept–15Dec	39.6	28.1	19.0	−38.5	−27.5	−18.3
16 Dec–15 March	40.0	19.1	24.5	−40.1	−19.2	−24.6
16 March–8 June	19.0	15.5	10.3	−18.5	−15.1	−10.7
Annual average	113.4	74.6	61.0	−108.5	−71.7	−60.3
Chapadão do Céu-GO	First Ratoon—2014/2015					
21 Aug*–5 Sept	3.0	3.3	10.0	−18.1	−21.4	−6.2
6 Sept–5 Dec	142.3	108.0	87.1	−99.0	−73.8	−79.6
6 Dec–6 March	73.7	59.1	61.7	−74.4	−59.6	−62.3
7 March–20 June	39.1	52.1	40.0	−67.8	−67.6	−58.9
Annual average	258.1	222.4	198.8	−259.4	−222.4	−207.1
	Second Ratoon—2015/2016					
20 Aug*–19 Sept	46.7	40.4	24.9	−36.3	−34.3	−14.9
20 Sept–19 Dec	101.4	75.4	82.1	−88.8	−65.3	−76.4
20 Dec–19 March	79.1	63.6	64.0	−73.5	−61.0	−61.8
20 March–4 July	33.1	46.7	40.9	−73.6	−80.3	−63.5
Annual average	260.3	226.2	212.1	−272.0	−240.9	−216.6
Quirinópolis-GO	First Ratoon—2014/2015					
7 June–5 Sept	30.7	35.5	36.3	−40.0	−33.9	−30.1
6 Sept–5 Dec	67.0	64.3	61.6	−51.0	−58.4	−60.8
6 Dec–6 March	45.4	40.6	44.7	−47.6	−42.3	−46.5
7 March–22 June	29.3	30.8	28.2	−37.1	−38.3	−30.1
Annual average	172.5	171.3	170.8	−175.7	−172.9	−167.5
	Second Ratoon—2015/2016					
25 June–23 Sept	42.4	32.1	27.6	−53.9	−39.4	−31.2
24 Sept–23 Dec	95.3	63.1	66.0	−99.1	−71.5	−75.5
24 Dec–25 March	60.3	58.3	58.6	−39.0	−37.5	−39.5
26 March–13 May	0.9	1.2	1.4	−23.7	−22.7	−23.5
Annual average	199.0	154.7	153.6	[1]−215.7	−171.2	−169.8

*Missing data

Sugarcane Yield

In Quatá-SP, straw removal did not show significant impact on sugarcane yields during the first and second ratoon cycles. Conversely, sugarcane yields in Chapadão do Céu-GO and Quirinópolis-GO were considerably reduced by straw removal in two harvest evaluated years (Fig. 4a, b, c). In Chapadão do Céu-GO, the treatment 100SR resulted in yield losses of 16 and 12 Mg ha^{-1} compared to 0SR during the first and second ratoons, respectively, while 50SR yields were reduced by 14 Mg ha^{-1} compared to 0SR treatment in the first ratoon cycle (Fig. 4b). A

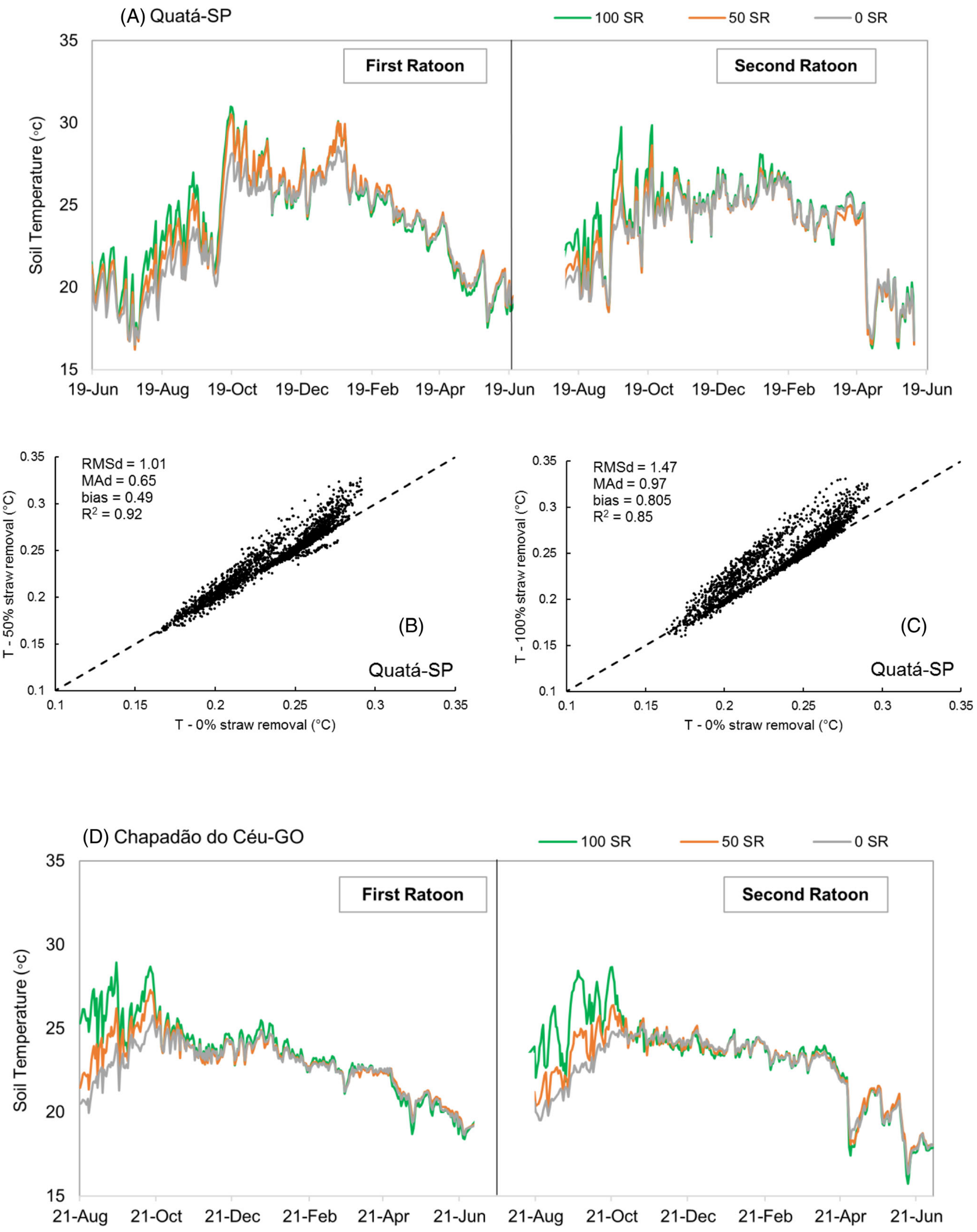

Fig. 3 **a**, **d**, **g** Soil temperature (°C) under different straw removal rates during the first and second ratoons. **b**, **e**, **h** Soil temperature in 0SR versus 50SR and **c**, **f**, **i** soil temperature in 0SR versus 100SR (at 0.15-m depth) for Quatá-SP, Chapadão do Céu-GO, and Quirinópolis-GO (100SR, 50SR, and 0SR denote 100%, 50%, and 0% of removal rates)

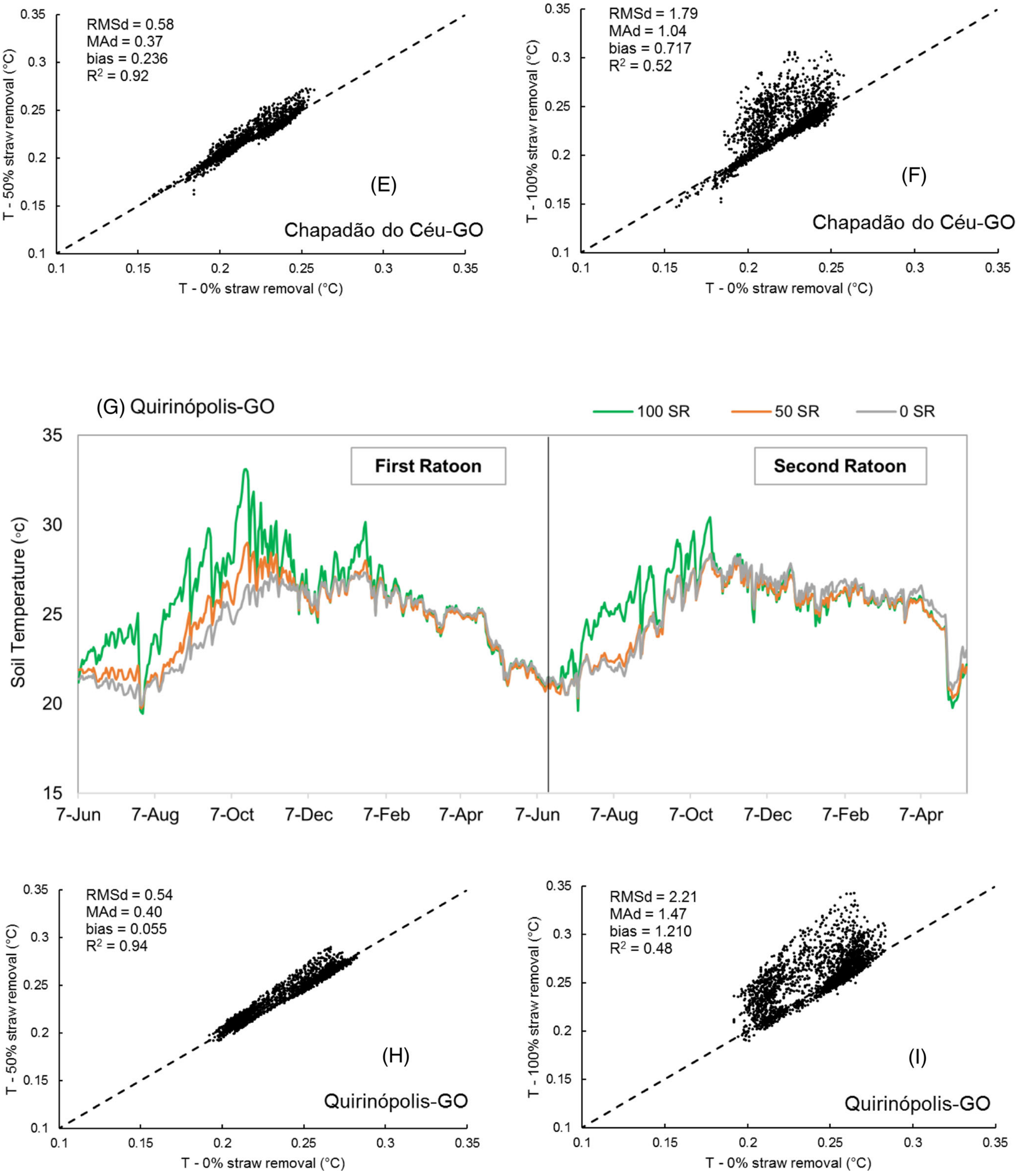

Fig. 3 (continued)

remarkable decrease in sugarcane yield was observed in Quirinópolis-GO as a result of 100SR, with losses of 40 and 22 Mg ha^{-1} in comparison to 0SR in the first and second ratoons, respectively (Fig. 4c).

Discussion

The removal of sugarcane straw for bioenergy production reduced soil water storage, increased soil temperature, and

Table 3 Amplitude of soil temperature (°C) related to treatments 50SR and 100SR in comparison to 0SR at different times (0, 6, 12, 18 h and average) at a 0.15-m depth during early stage of sugarcane development in the first and second ratoons

Time (h)	0		6		12		18		Average	
	50SR	100SR	50SR	100SR	50SR	100SR	50SR	100SR	50SR	100SR
Quatá-SP										
First ratoon	2.8	3.6	2.4	3.7	1.9	3.1	3.6	3.7	2.6	3.5
Second ratoon	2.3	3.5	−2	3.6	1.9	3.5	1.3	4.5	1.9	3.7
Chapadão do Céu-GO										
First ratoon	1.8	5.1	1	4.1	0.5	2.8	1.3	5.8	1.2	4.4
Second ratoon	0.4	2.2	0.6	2	0.5	2.5	0.8	3.7	0.6	2.6
Quirinópolis-GO										
First ratoon	1.5	5.3	1.3	4.5	0.9	5.9	1.6	6.5	1.4	5.6
Second ratoon	0	2.1	0.3	2	0.4	1.7	0.2	2.8	0.2	2.2

Treatments 100SR, 50SR, and 0SR denote 100%, 50%, and 0% removal rates

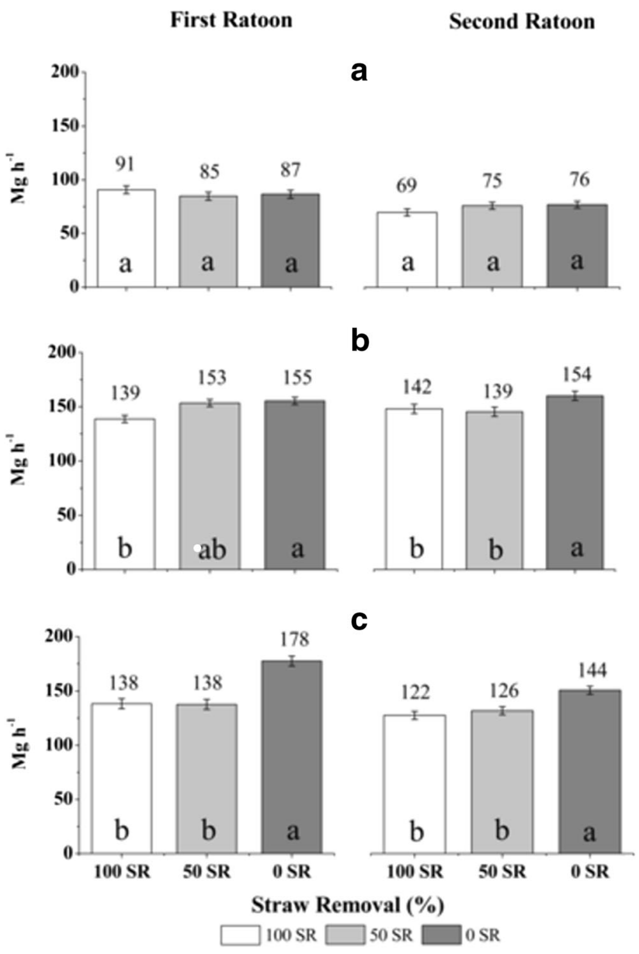

Fig. 4 Sugarcane yield (Mg ha^{-1}) for the first and second ratoons in response to straw removal rates in Quatá-SP (a), Chapadão do Céu-GO (b), and Quirinópolis-GO (c). Mean values followed by the same letter for each crop cycle do not show significant differences according to Tukey test ($p < 0.05$). (100SR, 50SR, and 0SR denote 100%, 50%, and 0% removal rates)

reduced sugarcane yields, especially in Chapadão do Céu and Quirinópolis, in the State of Goiás. On these locations, severely dry and warm seasons are often observed (Fig. 5b, c in the Appendix), coinciding with the setting up of the experiment (straw deposition in June–July) and initial crop growth phases (sprouting and beginning of tillering). Although occurring during a relatively short period of time, this regrowth plays an important role on the establishment of a good crop since the water deficit that usually takes place at this time period limits the maximum expression of potential yield [37]. In dry and warm seasons, the straw layer reduces soil water losses from evaporation and protects the soil against direct incidence of solar radiation. Thus, our findings show that both the complete and partial straw removal resulted in limited water availability for plant growth and development in the period soon after harvesting (Fig. 2a, d, g). It was also observed that the magnitude of water deficiency in Quatá-SP is generally less intense than those observed in the sites located in Goiás (Fig. 5a), indicating a less remarkable effect of straw mulching on this location.

Although climate conditions ultimately control plant-water relations, soils regulate water dynamics by holding water against gravitational forces enhancing water availability. In sandy soil (Quatá-SP), treatment 100SR caused abrupt oscillation in $\sum\Delta h$, indicating high rates of water losses resulted from soil evaporation and fast infiltration that quickly promoted depletion of water availability for plant supply [38]. Soil water evaporation in response to environmental conditions varies among locations [39] and it is also temporally affected by the growth stage/shading caused by the leaf area [40] and atmospheric evaporative demand [16, 40]. Moreover, it is influenced by factors related to water dynamics into soil profile, function of porosity and pore size distribution, which are primarily governed by soil structure and texture, soil organic matter content [41, 42], and soil coverage [17].

In sandy soil (Quatá-SP), despite its low total porosity, the movement of air and percolating water occur rapidly, mainly because of prevalence of macropores (Table 1). In these low aggregated and poorly structured soils, the water holding capacity is lower than fine texture soils (clay soils) [43], whose pore size distribution consists mainly of micropores. Both locations Chapadão do Céu-GO and Quirinópolis-GO present similar soil type, granulometry (clayey), and microporosity (Table 1), which may cause a slower flow of water in depth, since water in soil micropores is tightly held to clay particles. However, clay content promotes the increase of water availability for plant growth through stable soil aggregate formation. Well-aggregated soils, such as observed in Quirinópolis-GO, present larger amount of macropores (Table 1), and consequently higher water holding capacity compared to less aggregated soils with similar texture [44], as demonstrated by the smallest oscillation in $\sum \Delta h$ (Table 2).

Our findings are consistent with studies conducted in southeastern Brazil [25, 26], where a reduction in soil water content was observed with higher rates of straw removal. Despite the beneficial effects of straw as a physical barrier [45] for the enhancement of soil water storage capacity [9, 46, 47], it also protects soil against disruptive effects of raindrop impact [48] by intercepting rainfall and reducing runoff and wind speed, protecting the soil from erosion [49].

The main effects of 50% and 100% straw removal on soil temperature occurred during the regrowth period, i.e., in the three first months when sugarcane canopy is not closed, since the bare soil absorbs more solar radiation causing it to warm up faster than soils covered with crop residues (Fig. 3a, d, g). Additionally, mulched soils present higher albedo and lower thermal straw conductivity in relation to bare soils [50, 51]. The greatest soil temperature amplitude was observed in Quirinópolis-GO comparing bare soil and no straw removal, reaching up to 6.5 °C (Table 3) in early October, when air temperatures were above 40 °C (Fig. 5c in the Appendix). Considering that the proper average soil temperature for sugarcane development ranges from 20 to 30 °C [52], it is quite possible that the complete straw removal played a detrimental role on crop development [17]. Our results are in line with findings reported for Southern Brazil [7] which verified that the total straw removal contributed to increase the maximum and the average soil temperatures by 10.6 and 4.1 °C, respectively. Similarly, a study performed by Oliveira et al. [27] reported significant differences in soil temperatures of up to 7 °C between mulched and bare soil treatments during the early period of crop establishment.

Interactions between soil water content and soil temperature produce significant effects on soil chemical, hydrological, and biological attributes affecting the evaporation rate, soil water storage, nutrient cycling, plant germination, and sugarcane yield [12, 53, 54]. Our findings reinforce the hypothesis that the interactions of different soil and climate conditions bring consequences to sugarcane yields promoted by straw removal (Fig. 4). In Quatá-SP, characterized by a low fertility soil with low productivity potential, presented rainfall rates above ETc[2] in both crop seasons (Fig. 5a in the Appendix) and water deficit for plant growth after crop establishment, which indicates that neither the complete nor the partial straw removals had significant influences on sugarcane yield (Fig. 4a). Although this study focuses on observations during only two growing seasons, avoiding or reducing straw removal in the long term can lead to improvements in physical [17] and chemical soil attributes [55], promoted by constant sugarcane residue inputs, such as increases in soil organic carbon stock [56] and in soil nutrients, particularly nitrogen and potassium [57, 58].

Chapadão do Céu-GO and Quirinópolis-GO locations are characterized by high fertility soils with moderately high-water availability and high productivity potential. In particular, the well-aggregated soil with larger amount of macropores in Quirinópolis-GO improved the water storage, since the straw was maintained on soil surface during a period of severe water deficit, as reported for both ratoons (ETc above rainfall). This management practice increased water availability and reduced soil temperature fluctuations along the day, consequently increasing sugarcane yield. In the state of Goiás, located in the expansion frontier [59], the magnitude of water deficit can severely limit sugarcane yield [60, 61], indicating that management practices for improvement of θ, such as straw mulching, are strongly recommended [62].

Based on fixed percentages of the total straw produced from harvest, which were the criteria adopted in this study, the straw mulching showed high variability on each location and cropping season. Thus, we advocate that the use of a fixed amount of straw could improve comparative assessments of the effects of sugarcane straw removal on each location. Although sugarcane growth curves present similar overall shapes (sigmoid), straw removal and harvest season (early, middle and late) affect specific phases of the curves differently in each ratoon cycle [28]. Thus, under rainfed conditions, a different yield response is expected for sugarcane areas harvested in contrasting seasons in terms of water deficit, i.e., at the beginning of the dry season, when the water deficit is low and in the wet season, within the water surplus period occurring in its early stages.

Plant growth and crop productivity are site-specific response to edaphoclimatic conditions [63], so straw removal responses are also specific for different climate and soil conditions. Therefore, on these same locations, different harvest periods associated with fixed amounts of straw can lead to somewhat different conclusions regarding straw removal for bioenergy production.

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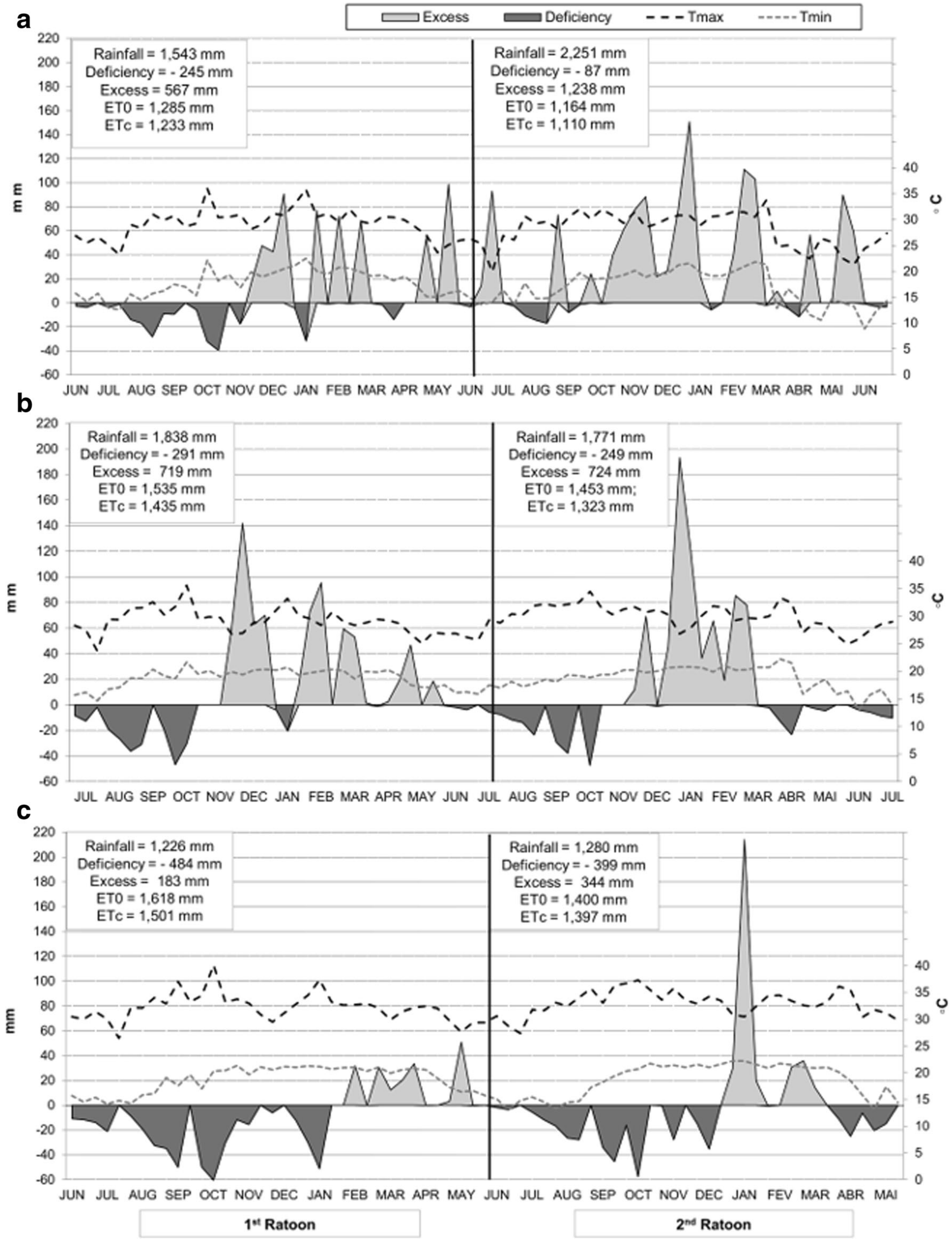
[2] The crop evapotranspiration calculated by multiplying the reference crop evapotranspiration (ET0) by a crop coefficient (Kc) for sugarcane in each phenological phase



Conclusions

The complete and partial straw removal were detrimental to water storage and therefore to plant available water, causing an increase in soil temperature in early crop development, i.e., during sprouting and tillering phases, which are extremely important periods for a good crop establishment and, consequently, for yield increases.

Our study showed that straw removal recommendations are site-specific, since it is a response of edaphoclimatic interactions. Thus, despite the differences in the amount of straw used at each location, since percentage removal rates were

◀ **Fig. 5** Crop-water balance (excess and deficiency, mm) and maximum and minimum air temperatures (°C) patterns for Quatá-SP (**a**), Chapadão do Céu-GO (**b**), and Quirinópolis-GO (**c**) during the first (2014/2015) and second ratoon (2015/2016) cycles (ET_0 and ETc are the reference and crop evapotranspirations, both in mm)

applied instead of fixed amounts, high rates of straw removal should be avoided on locations that present greater water holding capacity, high sugarcane yield potential, extended water deficit, and extremely warm season in early stages of crop development. The straw removal from locations with low sugarcane yield potential, even showing low water deficit in the beginning of the crop season, did not have a significant influence on sugarcane yield in the short term, since straw did not produce enough improvements to soil so as to enable benefits for water retention. Therefore, the avoidance or reduction of straw removal on a long-term perspective may lead to important improvements on soil quality, resulting in different responses of straw management.

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Appendix

In order to characterize climate variability and to enhance the analysis of results, Figure S1 presents the crop-water balance based on the Thornthwaite and Mather method [64], as well as the maximum and minimum temperature patterns for the first and second ratoons, at the three locations. Meteorological data was obtained from weather stations located in each location. The reference evapotranspiration (ET_0, mm) was estimated based on the FAO-56 Penman-Monteith method [35] and the crop evapotranspiration under standard conditions (ETc, mm) was estimated using the appropriate crop coefficient (kc) for each phenological phase, according to [65].

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