

# Straw management effects on sugarcane growth, nutrient cycling and water use in the Brazilian semiarid region

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**ABSTRACT:** It was evaluated how straw management modifies the development, growth, nutrient cycling and crop water productivity of sugarcane in the semiarid region of Brazil. The experiment was carried out using two plots with 5 ha each, being one without straw on the soil surface and one with 27.2 Mg·ha<sup>-1</sup> covering the soil. Sugarcane growth and development and straw decomposition coefficient were evaluated, whereas the industrial yield, juice quality, dry matter partitioning, and crop water productivity were determined at harvesting. The straw decomposition coefficient was 0.0049 Mg·ha<sup>-1</sup>·day<sup>-1</sup>, and the remaining dry mass was equal to 24%. The straw affected the sugarcane growth and development until the first 100 days. The individual internode volume can be adopted as an indicator of the effect of straw on sugarcane growth because the internode volumes up to the sixth position in the with-straw treatment crop were lower than in the no-straw treatment, which was not observed in other variables of the stalks. Keeping straw on the soil surface reduced the crop lodging. Yield and juice quality were not affected, but crop water productivity was increased by keeping sugarcane straw in the field.

**Key words:** trash blanket, decomposition, evapotranspiration.

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## INTRODUCTION

Brazil is one of the world's largest producers of sugarcane and its by-products, and the sugarcane yield depends on the volume of water received, type of soil, crop cycle, cultivar, climate, and the irrigation system adopted (Marin et al. 2020; Marin and Jones 2014; Silva et al. 2014 a, b). Because of technological advances in irrigation, areas are cultivated with sugarcane in the Brazilian semiarid region all year round. Recently, furrow irrigation systems with low application efficiency have been replaced by subsurface drip systems, improving the water use efficiency and increasing the crop yield.

The stalk juice is used for production of sugar or ethanol, whereas the straw and bagasse can be converted into cellulosic ethanol, burned for energy production, or kept in the field as mulch (Fortes et al. 2012). There is a tendency to keep straw in the field as a management practice to improve agricultural yield, reduce greenhouse gas emissions and save water (Aquino et al. 2018; Bu et al. 2013; Kader et al. 2017; Olivier and Singels 2015).

The presence of straw, commonly referred to as green cane trash blanketing, on sugarcane fields reduces the need for irrigation, erosion risk, weed emergence, and carbon emission (Hu et al. 2018; Sousa Junior et al. 2018); it improves microbiota and soil physical properties (Souza et al. 2005), releases nutrients (as nitrogen) into the soil (Sousa Junior et al. 2018; Vitti et al. 2008; Costa et al. 2014), and modifies the microclimate (Sandhu et al. 2013; Silva et al. 2019), besides increasing the crop water productivity (Olivier and Singels 2012; 2015; Vianna et al. 2020). On the other hand, excess straw



changes crop growth and development (Olivier and Singels 2012; 2015; Marin et al. 2014) by increasing the risk of fire and infestation of pests and diseases and impairing sprouting (Awe et al. 2015).

Crop responses to the presence of straw on soil surface depends on the interaction of genotype, soil, climate, and management practices (Ramburan and Nxumalo 2017; Marin et al. 2014). The management of straw depends on its decomposition rate and persistence in the field, which are linked to C:N ratio of plant material (Awe et al. 2015; Fortes et al. 2012).

The Brazilian semiarid region is characterized by high temperatures and low rainfall (Moura et al. 2007), which favor the straw decomposition rate in irrigated fields (Thongjoo et al. 2005; Zhou et al. 2016). It represents 18% of the Brazil area and has c.a. 18,000 irrigated hectares (IBGE 2019). The water use and water productivity in this region has become even more important in the last decade since there is a dispute over irrigation water with other crops (Teixeira 2010; Teixeira et al. 2013).

Despite the importance of this region, no study investigating the sugarcane growth and development, water use and straw management effects in the tropical semiarid region of Brazil is known. In such environmental conditions, straw is supposed to decompose at higher rates, and the adverse effects of excessive mulching on the crop can be lower than those observed in the subtropical climate (Aquino et al. 2018; Lisboa et al. 2018). To fill in the knowledge gap about the sugarcane crops in the Brazilian semiarid and the effect of straw on the crop, an experiment was conducted to evaluate the effects of straw management on the growth, development, and crop water productivity of sugarcane in the Brazilian semiarid region.

## MATERIAL AND METHODS

### Site description, treatments, and crop management

The experiment was carried out in a sugarcane field (9°29'51"S; 40°21'43"W; 400 m a.s.l.) in the Brazilian semiarid region. The soil of the experimental area is a Vertisol type (Embrapa 2013). The climate in the region is semiarid, with rainfall of 513 mm·year<sup>-1</sup>, distributed between summer and autumn, and atmospheric demand of 1,887 mm·year<sup>-1</sup>, according to the historical series from 1965 to 2015.

The sugarcane cultivar used in the experiment was VAT 90-212, planted in February 2013, using whole stalks with 12 buds on average per linear meter, in furrows 0.2 m deep arranged in double rows spaced at 0.7 × 1.3 m. The first harvest was performed after 18 months from planting and the second (ratoon), after 12 months, on August 21, 2015. Then this study was started and conducted until July 28, 2016 (342 days).

Sugarcane with-straw treatment was imposed at two levels of soil cover – one with and the other without straw (no-straw treatment) on soil surface. There were two adjacent experimental plots (about 5 ha) harvested manually on August 21, 2015 – the first one burning soon after and the second one without burning where straw was kept. Straw level was set between August 31 and September 10, 2015, yielding 27.2 Mg dry mass·ha<sup>-1</sup> covering 100% soil surface. On average, straw composition was 48 g C·kg<sup>-1</sup> and 0.41 g N·kg<sup>-1</sup>. The initial amount of straw deposited in the field (27.2 Mg·ha<sup>-1</sup>) was within the range (10 to 30 Mg·ha<sup>-1</sup>) reported for sugarcane (Trivelin et al. 1996).

This study used a subsurface drip irrigation system with self-compensating labyrinth-type emitters (1.6 L·h<sup>-1</sup>), spaced at 0.5 m and embedded in the hoses, which were buried at 0.2 m depth. The amount of irrigation water applied was based on the reference evapotranspiration (ET<sub>0</sub>) and crop coefficient, according to Silva et al. (2012 a). To estimate ET<sub>0</sub>, Penman Monteith's method (Allen et al. 1998) and weather data were used. The weather data were collected from an automated weather station (ET107, Campbell Scientific, Logan UT, USA) at 800 m from the experimental plots, with sensors (global solar radiation, CS305 sensor; temperature and air relative humidity, HMP60 sensor; rain, TR525 sensor; wind speed, 034B sensor; wind direction, WindSonic-2D sensor) connected to a CR1000 datalogger, taking readings every 60 s and recording the average every 30 min. Total irrigation volume was 1,557 mm, and rainfall was 345 mm, resulting in an applied water depth of 1,937 mm at 342 days after cutting (DAC). During the crop cycle, fertigation was performed with

420 kg N·ha<sup>-1</sup>, 6.1 kg P<sub>2</sub>O<sub>5</sub>·ha<sup>-1</sup>, 3.7 kg K<sub>2</sub>O·ha<sup>-1</sup>, and 2.5 kg·ha<sup>-1</sup> of commercial micronutrient product with 1.8% B; 0.8% Cu; 3.0% Fe; 2.0% Mn; 0.10% Mo, and 9.0% Zn. Phytosanitary treatment for the control of sugarcane pests and diseases was always performed.

### Straw decomposition, carbon and nitrogen release, extraction and exports

Measurements of straw amount were taken at 20, 105, 195, 258, 307, and 342 DAC, from September 11, 2015 to July 28, 2016. For this, four samples of 1.0 m<sup>2</sup> of the crop residue were weighed individually. The samples were fractionated and dried in a forced-air ventilation oven (60 °C) for 48 h until they obtained constant weight. The remaining straw dry mass (RSDM) was used to fit the exponential model  $Y = a e^{-k \text{DAC}}$ , where  $a$  is the initial RSDM (Mg·ha<sup>-1</sup>) and  $k$  is the straw decomposition coefficient (day<sup>-1</sup>). The model was used to estimate the straw decomposition rate, average half-life ( $t_{1/2} = \ln(2)/k$ , in days), the time required to decompose 50% of the initial RSDM, time at which 5% of the dry mass remained ( $t_{5/100} = 3/k$ , in days), and the time for new straw deposition ( $t_{\text{nsd}}$ , in days).

Subsamples of the above ground biomass and straw were milled in a Wiley-type mill to quantify carbon and nitrogen content according to Silva and Queiroz (2002). The amounts of C and N released by straw were calculated from the difference of C and N contents at the beginning and at end of the cycle, considering the amount of decomposed straw. The stock of C and N were obtained by the product of the C and N content and the accumulation of dry biomass by the plant. In the no-straw treatment, it was assumed that the release of C and export of N occurs from the harvesting of the plant aerial part. In the with-straw treatment, the release of C and N was based on harvested stalks as the other structures remained in the field as straw.

### Biomass, intercepted radiation and auxiliary estimates

There were four subplots (2-m length) per experimental plot used to count the stalks number (SN). The stalks height (SH, cm) was recorded in three replicates per subplot (12 replicates per experimental plot), with measurements taken from the soil surface to the visible dewlap of the first fully expanded leaf. In addition, five plants per experimental plot were sampled, weighed, fractionated into fully expanded leaves, sheaths, dead leaves and sheaths, emerging leaves, and stalks, and then the fresh biomass was obtained. The internode number (IN, units), length (IL, cm), and width (IW, mm) were recorded from soil surface to top canopy position (bottom-up). Then, all samples were dried in a forced-air circulation oven (60 °C) until constant mass was reached. Fully expanded leaves, sheaths, dead leaves and sheaths, emerging leaves, and pseudostalks were considered as straw (crop residue subject to post-harvest deposition) and subdivided into leaf structures (leaf dry biomass-LDB, sheath dry biomass-SDB, and dead leaf and sheath dry biomass-DLSDB) and pointers (emerging leaf dry biomass-ELDB and pseudostalk dry biomass-PSDB). The sum of the dry mass of previous cited structures resulted in the total dry biomass (TDBAP). All biometric and biomass procedures followed Silva et al. (2012 b; 2014 b). The relationships between SN and SH and accumulated degree days (ADD, °C day) were fitted. The ADD was based on the temperature data registered by the weather station and calculated according to the equation:  $\text{ADD} = [(t_{\text{max}} + t_{\text{min}})/2 - t_b]$ , where  $t_{\text{max}}$  and  $t_{\text{min}}$  are the maximum and minimum air temperatures, respectively (°C), and  $t_b$  is the basal temperature (10 °C) (Sinclair et al. 2004). Biomass partitioning, stalk height growth (SHS, cm), and internode volume (VI, cm<sup>3</sup>) were estimated (Sinclair et al. 2004; 2005; Singels et al. 2005). Before harvesting, crop lodging was measured from the count of lodging plants in three replicates per subplot (12 replicates per experimental plot) (Carlin et al. 2008).

Photosynthetically active radiation above ( $\text{PAR}_A$ ) and below ( $\text{PAR}_B$ ) the canopy was measured from a previously calibrated ceptometer (AccuPAR-L80, Decagon Devices Inc., Pullman WA, USA). Measurements with the ceptometer were taken between 11:00 and 13:00 h, with four measurements above and four below the sugarcane canopy in an alternating manner so that the instrument covered half the crop row. The readings were made in ten subplots, always in the same positions, under clear sky conditions (Silva et al. 2012 b; 2014 b). By means of the difference between  $\text{PAR}_A$  and  $\text{PAR}_B$ , the intercepted PAR fraction (fPAR, dimensionless) was calculated (Singels et al. 2005).

## Industrial yield and juice quality indicators

Sugarcane yield was measured in tons of stalks per hectare (TSH, Mg·ha<sup>-1</sup>), from extrapolation of the average weight of 20 subplots of 35.2 m<sup>2</sup> per experimental plot, sampled before the final crop harvest. Subsamples of stalks were used for evaluation of juice quality, such as raw sugar percentage (SRP, %), total reducing sugars (TRS, %), total soluble solids (°Brix), purity (%), fiber content (%) and sucrose percentage of the juice (Pol, %), and estimates of crude sugar yield (CSY, Mg·ha<sup>-1</sup>) and crude alcohol yield (CALY, m<sup>3</sup>·ha<sup>-1</sup>) (Silva et al. 2014 b).

## Crop water productivity

Crop water productivity (CWP) was calculated on the basis of dry biomass, TSH, CSY, carbon, and nitrogen and obtained from the ratio between TDBAP, LDB, SDB, DLSDB, TSH, CALY or CSY, and cumulative evapotranspiration during the cycle ( $\Sigma ET$ ) (Silva et al. 2011 a). The CWP for carbon and nitrogen (kg·ha<sup>-1</sup>·mm<sup>-1</sup>) was based on the product of CWP and the carbon and nitrogen content (w, g·kg<sup>-1</sup>) (Silva et al. 2014 b). The  $\Sigma ET$  was computed from application of the energy balance method (Bowen's ratio), with micrometeorological data collected in towers installed inside the experimental area. The latent heat flux ( $\lambda E$ ) was calculated according to Silva et al. (2011 b) and analyzed by applying the criteria defined by Perez et al. (1999). According to the recommendations of these authors, the physical consistency of hourly meteorological data was evaluated, based on data from the water vapor pressure profile, sensor resolution, and signals from the temperature and water vapor pressure gradients. The towers (7 m) were used for monitoring the temperature and relative humidity (HMP155A, Vaisala Inc., Helsinki, Finland) at two levels above the crop (0.50 and 2.0 m), radiation balance (RN-Lite, Kipp and Zonen, Delft, the Netherlands) at 6.8 m from the soil surface, and soil heat flow (HFP01SC Soil Heat Flux Plate, Hukseflux, Delft, the Netherlands) at 0.05 m depth adjacent to the crop row. All sensors in each tower were connected to a datalogger (CR1000, Campbell Scientific, Logan UT, USA), taking readings every 60 s and recording the average every 10 min.

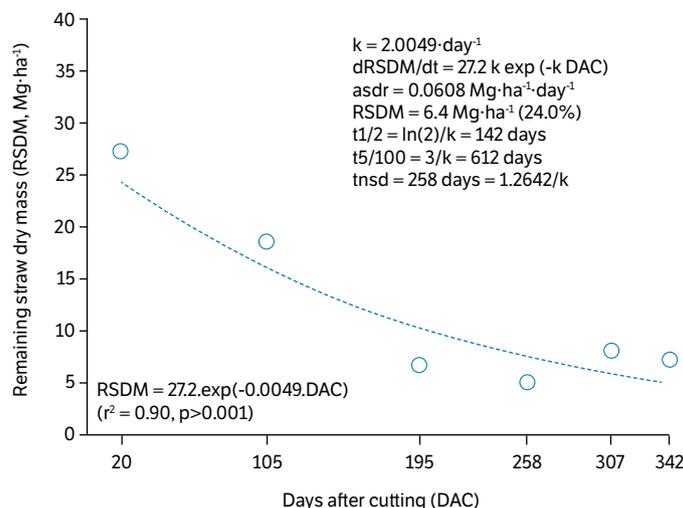
## Data analysis and statistical procedures

Fischer's parametric test ( $p < 0.05$ ) was used to evaluate the effects of keeping straw on sugarcane growth (12 replicates) and development (10 subplots), total mass on a dry basis per sugarcane structural part (5 replicates), yield (20 subplots), and juice quality (20 subplots). All statistical procedures were performed using XLSTAT v. 2017 software (Addinsoft, Boston MA, USA, www.xlstat.com). Adjustments of mathematical models, such as sigmoid, Gaussian, exponential, and linear, were performed, with the significance of the models and of their parameters evaluated using F and Student's t-tests ( $p < 0.05$ ).

## RESULTS

### Straw decomposition and releases of carbon and nitrogen

The average straw decomposition rate was 0.0608 Mg·ha<sup>-1</sup>·day<sup>-1</sup>. At the end of the cycle (342 days), the remaining dry mass was 6.4 Mg·ha<sup>-1</sup> (Fig. 1). However, an increase from 5.0 to 8.2 Mg·ha<sup>-1</sup> in dry mass above the soil occurred from 258 to 307 days, and this was due to the deposition of new leaves. Therefore, the total decomposition was 76%, considering the initial amount of straw (27.2 Mg·ha<sup>-1</sup>), the deposition of new leaves (3.2 Mg·ha<sup>-1</sup>), and the remaining dry mass (6.4 Mg·ha<sup>-1</sup>). The time related to the increase in straw dry biomass (tnsd) can be estimated as  $tnsd = 1.2642/k$ , where  $k$  is the decomposition constant, in days<sup>-1</sup>. The straw carbon concentration at the beginning of the cycle was 470 g C·kg<sup>-1</sup>, reaching 440 g C·kg<sup>-1</sup> at the end. On the other hand, the straw nitrogen concentration was higher at the end of the cycle (7.4 g N·kg<sup>-1</sup>) when compared to the beginning (4.1 g N·kg<sup>-1</sup>). The decomposed straw (20.8 Mg·ha<sup>-1</sup>) promoted the release of 10.2 Mg C·ha<sup>-1</sup> and



**Figure 1.** Dry mass of the remaining straw over time, decomposition rate ( $k$ ), remaining dry mass, half-life ( $1/2$ ), 95% decomposition time ( $t5/100$ ) and time of new straw deposition ( $tnsd$ ). Vertical lines indicate standard error of estimate ( $n = 4$ ).

63.1 kg N·ha<sup>-1</sup> during 342 days of crop cycle, representing 78 and 57% of the initial amounts, respectively (13.0 Mg C·ha<sup>-1</sup> and 110.6 kg N·ha<sup>-1</sup>).

## Sugarcane growth and development

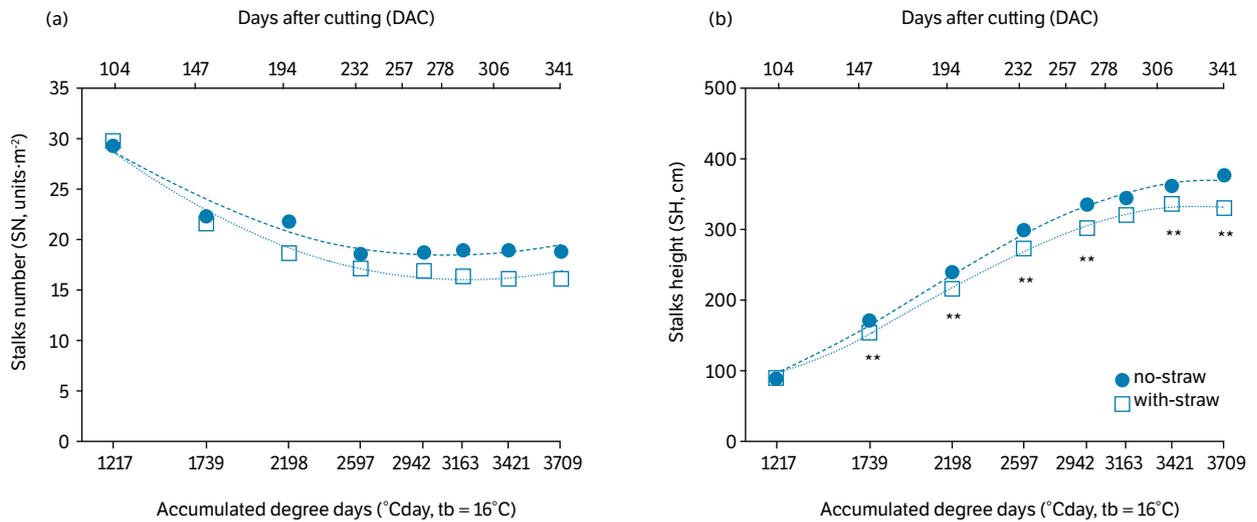
The number of stalks per area was not affected when covering soil surface with straw ( $p = 0.076$ , Fig. 2a), but it was 2.6 stalks per m<sup>2</sup> on average higher in no-straw cultivation. The stalk height was decreased ( $p = 0.014$ ) by straw, with an average difference of 0.38 m between stalks of the two cropping systems (Fig. 2b). Plant height affects crop lodging, and this phenomenon was noticed earlier when soil was not covered by straw (Fig. 3a). In Fig. 3b, the data shows that there was no effect on the IN, but in Fig. 3c, it is possible to see that the largest individual volumes occurred between the 3<sup>rd</sup> and 14<sup>th</sup> positions on the stalk. It was also observed that the volumes up to the sixth position in the straw crop were lower than in the no-straw treatment, although there was no significant difference in the first three positions. At the end of the cycle, straw did not affect the total stalk volume ( $p = 0.522$ , Fig. 3c). Sugarcane development was also delayed in the with-straw treatment even with the air temperature being higher than in the no-straw treatment (0.7 °C). Sugarcane plants took 248 °C day more to reach 80% soil cover (Fig. 4a).

## Yield, juice quality indicators and C and N release/export by the sugarcane harvest

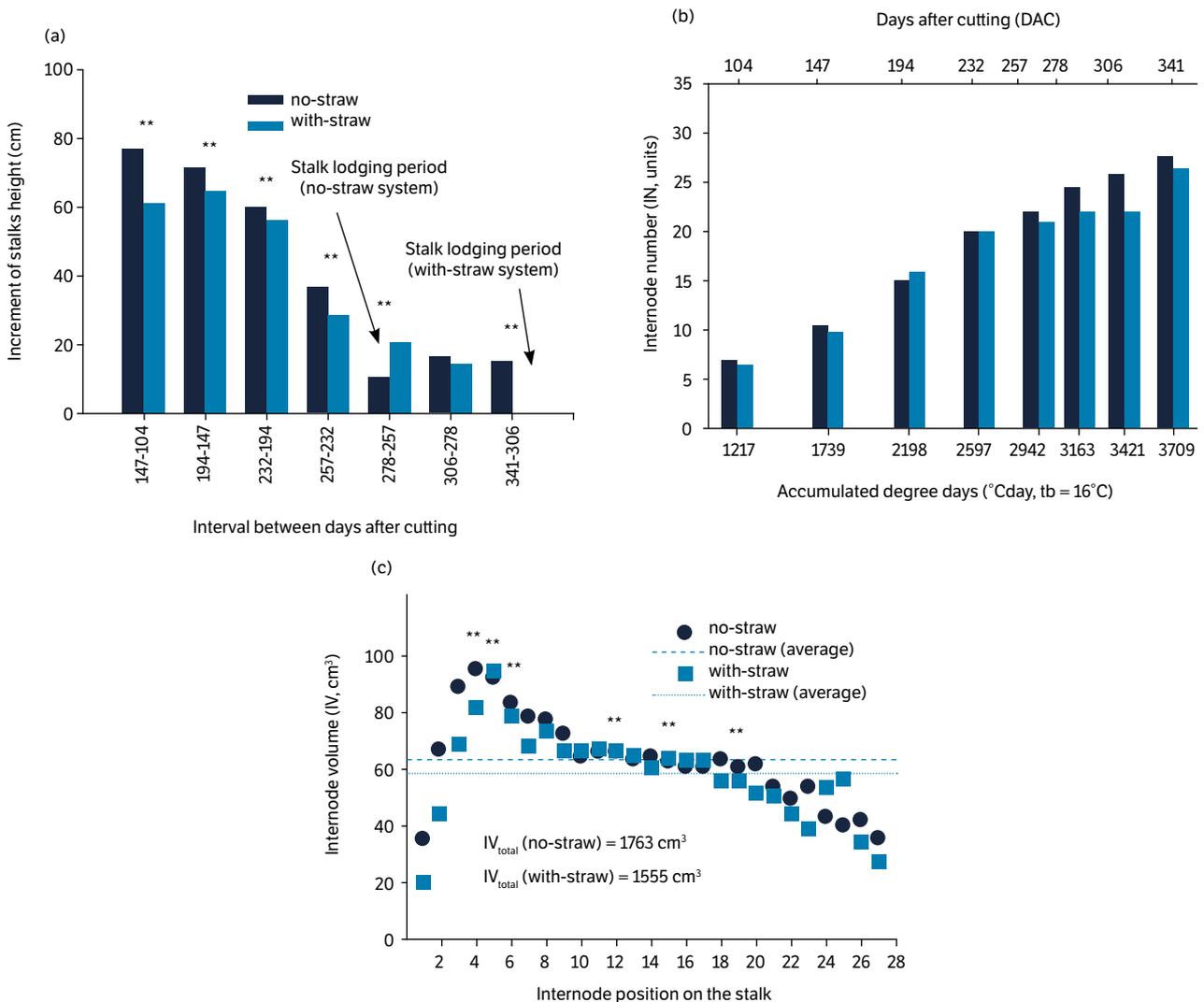
The final biomass partitioning for the stalks was similar between treatments (80% in the no-straw treatment vs. 78% in the straw treatment). Neither the total dry biomass nor the stalk yield was affected by straw deposition ( $p = 0.229$ , Fig. 4b; Table 1). Only purity and fiber content were increased when straw was used to cover soil surface (Table 1). While the amount of carbon accumulated by plants was not affected by straw maintenance, the amount of N extracted was ( $p = 0.014$ , Table 1). Carbon and N release/export was significantly higher in the with-straw treatment ( $p = 0.008$ , Table 1).

## Crop water productivity

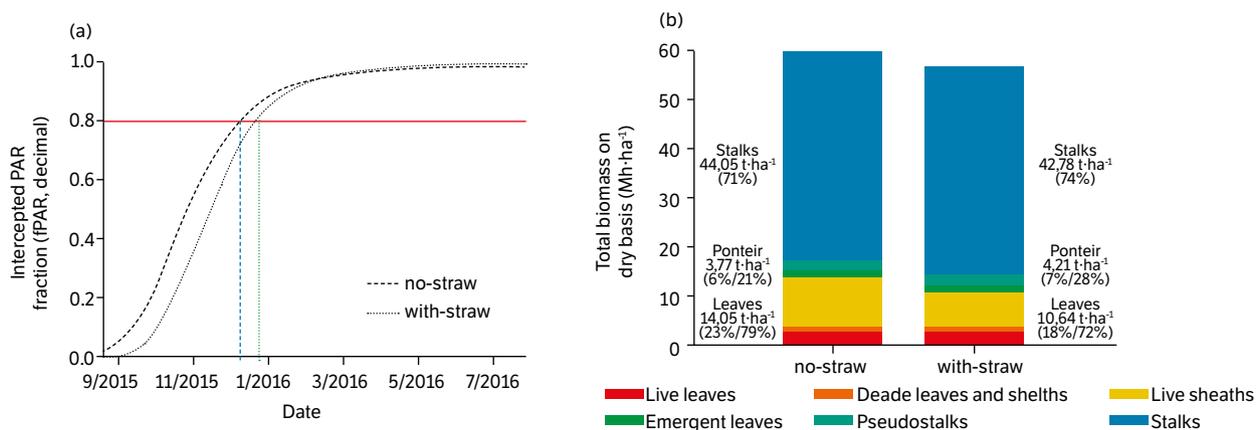
Soil cover decreased overall evapotranspiration by 25% (whole cycle), resulting in a 26% increase in CWP on TDBAP basis (Table 2). When considering TSH, sugar, and alcohol yields, CWP was even higher (28, 38, and 37%, respectively).



**Figure 2.** Number (a) and height (b) of millable stalks of sugarcane under straw management in the Brazilian semiarid region. \*\* indicates significant difference by Fischer's parametric test ( $p < 0.05$ ).



**Figure 3.** (a) Increment in height, (b) internode number per stalk over time and (c) internode volume in relation to its position, from bottom-up, on the stalk of sugarcane under straw management in the Brazilian semiarid region. \*\* indicates significant difference by Fischer's parametric test ( $p < 0.05$ ).



**Figure 4.** (a) Plant cover index (b) and total mass on a dry basis per sugarcane structural part under straw management in the Brazilian semiarid region.

**Table 1.** Industrial yield, juice quality indicators and carbon and nitrogen extraction/exports at harvest to the 341 days after cutting of sugarcane under straw management in the Brazilian semiarid.

Crop	TSH	Brix	Purity	Fiber	SRP	TRS	Pol	CSY	CALY	Extraction		Export	
										C	N	C	N
	Mg·ha <sup>-1</sup>	°	%	%	%	Mg·ha <sup>-1</sup>	%	Mg·ha <sup>-1</sup>	m <sup>3</sup> ·ha <sup>-1</sup>	Mg·ha <sup>-1</sup>	kg·ha <sup>-1</sup>	Mg·ha <sup>-1</sup>	kg·ha <sup>-1</sup>
No-straw	166.76a	18.62a	85.67b	15.73b	12.65a	126.88a	15.97a	21.08a	15.12a	2.89a	8.92b	2.89a*	8.92a*
With-straw	160.16a	20.03a	85.90a	15.84a	13.62a	136.08a	17.21a	21.77a	15.56a	2.98a	10.50a	2.03b**	6.70b**

Means in the vertical followed by the same letter are not different from each other at the 5% ( $\alpha < 0.05$ ) significance level by the Fisher's F parametric test (comparison between two samples), that is, there is no effect of the maintenance on the straw over the respective yield index. TSH: tons of stalk per hectare; SRP: sugar raw percentage; TRS: total reducing sugars; Pol: sucrose percentage in the juice; CSY: crude sugar yield; and, CALY: crude alcohol yield. \* Exports from the harvesting of all the structures of the plant aerial part; \*\* Exports only from harvesting the stalks.

**Table 2.** Crop water productivity (CWP) in basis on dry biomass, stalks per hectare, sugar crude yield, carbon and nitrogen, under straw management in the Brazilian semiarid.

Crop	CWP <sub>TDBAP</sub>	CWP <sub>Leaves</sub>	CWP <sub>Pointer</sub>	CWP <sub>Straw</sub>	CWP <sub>Stalks</sub>	CWP <sub>TSH</sub>	CWP <sub>CSY</sub>	CWP <sub>CALY</sub>	CWP <sub>C</sub>	CWP <sub>N</sub>
	kg·ha <sup>-1</sup> ·mm <sup>-1</sup>							L·ha <sup>-1</sup> ·mm <sup>-1</sup>	kgN·ha <sup>-1</sup> ·mm <sup>-1</sup>	gN·ha <sup>-1</sup> ·mm <sup>-1</sup>
No-straw	38.24b	8.83a	2.37b	11.20b	27.04b	104.75b	13.24b	9.50b	1.82b	5.60b
With-straw	48.26a	8.91a	3.53a	12.44a	35.82a	134.13a	18.24a	13.03a	2.50a	8.79a

Means in the vertical followed by the same letter do not differ from each other at the significance level of 5% ( $\alpha < 0.05$ ) by the F parametric test of Fisher (comparison between two samples). TDBAP: total dry biomass of the aerial part; Leaves: dry biomass of leaf and sheaths, both live and dead; Pointer: dry biomass of pseudostalk and emergent leaves; Straw: Leaves and pointer; TSH: tones of stalks per hectare; CSY: sugar crude yield; CALY: alcohol crude yield; C: carbon and N: nitrogen.

Crop water productivity on TSH basis reached 134.13 kg·ha<sup>-1</sup>·mm<sup>-1</sup> when straw was covering the soil. The straw also increased CWP on carbon (+26%) and nitrogen (+111%) bases ( $p=0.043$ , Table 2).

## DISCUSSION

The decomposition constant ( $k$ ) of 0.0049 day<sup>-1</sup> – equivalent to an average decomposition rate of 0.0608 Mg·ha<sup>-1</sup>·day<sup>-1</sup> – can be considered high (Fig. 1) when compared to Pimentel et al. (2019), who found values of  $k$  from 0.0021 to 0.0041 day<sup>-1</sup> using 3.5 and 14.0 Mg·ha<sup>-1</sup> of straw in the field, as well as Sousa Junior et al. (2018), who observed values of  $k$  of 0.0012 and 0.0026 day<sup>-1</sup> using 3.5 and 21.0 Mg·ha<sup>-1</sup>, respectively. The value of  $k$  depends on straw quantity, composition, and management,

microbial activity, and environmental conditions (Fortes et al. 2012; Pimentel et al. 2019; Sousa Junior et al. 2018), and the hot Brazilian semiarid region favors the decomposition rate in irrigated fields (Thongjoo et al. 2005; Zhou et al. 2016). The decomposition of 76% of the straw during the experiment can also be considered high when compared to studies conducted in other regions (Fortes et al. 2012; Pimentel et al. 2019; Vitti et al. 2008). Still, it seems to be related to a high C:N ratio (118) at the beginning of crop cycle, which hinders mineralization of the nutrients within the biomass. The remaining 24% dry mass (RSMD =  $6.4 \text{ Mg}\cdot\text{ha}^{-1}$ , Fig. 1) is near the range from 25 to 36% found by Vitti et al. (2008) and within the range from 8 to 49% found by Pimentel et al. (2019), who used  $9.0 \text{ Mg}\cdot\text{ha}^{-1}$  and  $3.5$  to  $14.0 \text{ Mg}\cdot\text{ha}^{-1}$ , respectively, on the soil surface under subtropical conditions in Southern Brazil.

The higher decomposition rates are expected to affect the following crop cycles since the half-life of the remaining dry mass ( $t_{1/2}$ ) was 142 days and the time for decomposition of 95% of the initial straw ( $t_{5/100}$ ) would be 612 days, above the 342-day cycle duration of this study. Even with the high values of  $k$  ( $0.0049 \text{ day}^{-1}$ ) and total decomposition (76%), the great values of  $t_{1/2}$  and  $t_{5/100}$  are indicative that keeping  $27.2 \text{ Mg}\cdot\text{ha}^{-1}$  of sugarcane straw on the soil surface at each harvest can be considered excessive even for the irrigated and hot environment where the experiment was conducted. So, a maximum of  $20.8 \text{ Mg}\cdot\text{ha}^{-1}$  ( $27.2$  minus  $6.4 \text{ Mg}\cdot\text{ha}^{-1}$ ) can be kept on the soil surface to minimize accumulation for the subsequent cycle. Keeping sugarcane straw in excessive quantities might impair the following cycle. In Southern Brazil, where the climate is classified as tropical-humid, Sousa Junior et al. (2018) stated that  $t_{1/2}$  depends directly on the straw amount and the  $k$ -value (560, 402, 259, and 262 days for 3.5, 7.0, 14.0, and  $21.0 \text{ Mg}\cdot\text{ha}^{-1}$  and  $k$ -value equal to 0.0012, 0.0017, 0.0027, and 0.0026, respectively).

The benefits of keeping sugarcane straw varies according to climate conditions and sugarcane-harvesting season (Aquino et al. 2018; Lisboa et al. 2018). In the relatively colder Southern Brazil (subtropical climate, states of São Paulo and Paraná), Lisboa et al. (2018) and Aquino et al. (2018) suggested that  $4$ – $10 \text{ Mg}\cdot\text{ha}^{-1}$  of straw (dry basis) on the soil surface would be required to sustain crop yield long-term without any negative effect on the sugarcane development.

Carbon release rates were greater than N mineralization rates, as the C:N ratio was reduced by 59% during the experiment. This trend was verified by Vitti et al. (2008), Pimentel et al. (2019) and Sousa Junior et al. (2018). According to these authors, the presence of sugarcane straw can increase C and N stocks within the surface soil layer. On the other hand, complete sugarcane straw removal depletes soil C stocks and reduces N cycling in sugarcane fields.

The lower initial growth of the sugarcane promoted by keeping straw is due to the physical barrier imposed, but it may also be associated with lower soil temperature, which reduces plant growth (Awe et al. 2015; Ramburan and Nxumalo 2017; Sandhu et al. 2013; Vianna et al. 2020). In agreement with results found in this paper, Ramburan and Nxumalo (2017) found reductions in the number and height of stalks due to keeping straw, regardless the region in South Africa, the cultivar, and the season of the beginning of the cycle (summer or winter). Higher VI occurred between the 3<sup>rd</sup> and 14<sup>th</sup> positions (Fig. 3c), quite similar to those observed by Silva et al. (2012 b), who found higher magnitudes between the 2<sup>nd</sup> and 17<sup>th</sup> positions for the cultivar RB 92-579.

It was observed that volumes up to the 6<sup>th</sup> position in the straw crop were lower than in the no-straw treatment. This result indicates that sugarcane presented initial growth limitation because of keeping the straw, which was not observed in other variables of the stalks since their measurements were initiated only on day 104 (Figs. 3a, 3b, and 4b). Thus, the individual VI up to the 6<sup>th</sup> position can be considered a good indicator of the effect of straw on sugarcane growth even if their measurements are obtained only at harvest. However, measurement of biometric variables over time allows us to indicate when the crop overcomes the physical obstacle promoted by straw. It was observed that sugarcane development was slower in the with-straw treatment (248 °C day more to reach 80% ground cover, Fig. 4a). This result is similar to that mentioned by Olivier and Singels (2015) and Carvalho et al. (2019), who verified a reduction in sugarcane development rate because of keeping straw in the climatic conditions of South Africa and Brazil, respectively.

Crop lodging is a phenomenon common in sugarcane cultivation without straw. Carlin et al. (2008) observed that lodging increases IL and IN and the yield of sugarcane cultivars (IAC86-2210 and SP80-184) but promotes bud sprouting (thicker stalks and larger and shorter leaves), which reduces the quality of the raw matter due to the decreased content of sucrose and the high content of reducing sugars (Berding and Hurney 2005). Thus, maintaining the straw in the field may also help to reduce crop lodging.

Straw did not affect the stalk yield ( $p > 0.05$ , Table 1), as observed by Olivier and Singels (2015), Souza et al. (2005), and Olivier and Singels (2012). The last observed reductions were of 4 and 15% in the cycle of plant cane and ratoon, respectively. The presence of straw on the soil increased the juice purity, and the remaining other industrial indexes were not negatively affected by the straw (Table 1), as found by Ramburan and Nxumalo (2017), Nxumalo et al. (2017), and Aquino et al. (2018).

The N content was 18% greater in the with-straw treatment than in the no-straw treatment because of the benefit of N and C release from the decomposed straw and improvement of the thermal and water regime of the soil that favors crop development and soil microbial activity (Awe et al. 2015; Fortes et al. 2012). In the no-straw treatment, C and N fixed by the plant throughout the cycle are released at harvest, while in the straw treatment, 26% of the C and 53% of the N is kept within the area of cultivation (Table 1). Fixation of these elements over time compensates for the partial negative effects on initial crop growth promoted by straw. However, not all N applied in fertilization ( $420 \text{ kg} \cdot \text{ha}^{-1}$ ) or released by straw decomposition ( $63.1 \text{ kg N} \cdot \text{ha}^{-1}$ ) was available to the plant, because the microorganisms present in the soil immobilized N for its own use, as a consequence of high C:N (118) (Pimentel et al. 2019).

The CWP depends on the cultivar, the water management practice adopted, and the crop cycle (plant cane or ratoon) (Olivier and Singels 2015; Silva et al. 2012 a), but it is strongly affected by the maintenance of straw in the field. It was observed that CWP increased due to the reduction of evaporation promoted by straw (25%) and the small biomass change ( $-5.3\%$  in comparison to the no-straw treatment, Table 2), as observed by Bu et al. (2013), Olivier and Singels (2015), and Yan et al. (2017). In terms of TSH, the CWP for straw cultivation obtained was  $134.13 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$ , a value higher than that reported by Olivier and Singels (2012), Silva et al. (2011 a) and Nassif et al. (2019). The straw also increased the  $\text{CWP}_C$  and  $\text{CWP}_N$  by the crop, as a result of the reduction in evapotranspiration and the increase in carbon stock and nitrogen extraction by the crop, which in turn might be associated with the improvement of soil microbial activity (Kader et al. 2017).

## CONCLUSION

It was investigated the effect of straw management on the growth, yield, and CWP of sugarcane cultivated in an irrigated tropical semiarid environment. Although the straw presented a high decomposition rate in the semiarid environment, it was suggested keeping no more than  $20.8 \text{ Mg} \cdot \text{ha}^{-1}$  of straw on soil surface. Growth and development of the crop were affected through the first 100 days of the cycle, with a reduction in stalk height and lower crop development rate.

Keeping sugarcane straw on the soil surface may also help to reduce crop lodging. Most of the industrial indexes regarding juice quality are not negatively affected by the presence of straw. The carbon and nitrogen fixation released by decomposed straw over time compensates the slower rates of initial crop growth by keeping straw. The straw increases the N extraction and N and C cycling in the field. Crop water productivity increased in terms of dry biomass, stalks yield, crude sugar, ethanol, carbon, and nitrogen.

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