UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA DE ALIMENTOS

JOÃO ROSSI NETO

ROW SPACING AS ALTERNATIVE TO INCREASE SUGARCANE BIOMASS PRODUCTION FOR ENERGY PURPOSE

ESPAÇAMENTO ENTRELINHAS COMO ALTERNATIVA PARA AUMENTAR A PRODUÇÃO DE BIOMASSA DE CANA-DE-AÇÚCAR PARA FINS DE ENERGIA

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Thesis presented to the Faculty of Food Engineering of the University of Campinas in partial fulfillment of the requirements for the degree of Doctor in Sciences.

Tese apresentada à Faculdade de Engenharia de Alimentos da Universidade Estadual de Campinas como parte dos requisitos exigidos para a obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Henrique Coutinho Junqueira Franco
Coorientador: Prof. Dr. Oriel Tiago Kölln

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RESUMO

A coleta de dados sobre o rendimento da cana-de-açúcar, plantada em diferentes configurações de plantio, foi cuidadosamente avaliada pelo grupo de trabalho do CTBE desde 2012, coletando dados de mais de 16 safras. Durante o mestrado, avaliei 4 áreas de cultivo deste projeto sob diferentes condições edafoclimáticas e observei resultados promissores do ponto de vista do aumento da produtividade da cultura. No entanto, é necessário maximizar os resultados a longo prazo deste projeto e tentar entender o que acontece com as plantas após uma mudança no manejo das culturas. Além disso, dada a crescente demanda por etanol como fonte de energia renovável, a mudança no arranjo de plantio se apresenta como uma excelente alternativa para suprir essa demanda, além de reduzir o impacto da mecanização no solo e nas plantas. Assim, a tese se baseia na hipótese de que: a melhor distribuição das plantas no campo promove melhor distribuição das raízes; diminui a mortalidade de perfilhamento e a concorrência intraespecífica; ocorrendo ganhos substanciais de rendimento de biomassa. Portanto, o objetivo deste estudo foi avaliar a biomassa da cana-de-açúcar em diferentes configurações de plantio e condições ambientais, visando aumentar a produção de biomassa. Para isso, dois experimentos foram conduzidos em condições de campo, em solo argiloso e arenoso. Os experimentos foram conduzidos durante quatro safras de cultivo (duas em solo argiloso e duas em solo arenoso) e incorporaram um delineamento em blocos casualizados que testou seis configurações de plantio, tais como: EC, espaçamento convencional (1,50 m); EA, espaçamento alternado (0,90 × 1,50 m); ET, espaçamento triplo (0,75 x 0,75 x 1,50 m); PP 1,0 m, plantio de precisão (1,0 × 1,0 m); PP 0,75 m, plantio de precisão (0,75 x 0,75 m); e PP 0,50 m, plantio de precisão (0,5 × 0,5 m). Durante a segunda e terceira soqueiras foram avaliadas: a produção de biomassa de cana-de-açúcar (acima e abaixo do solo); parâmetros biométricos e morfofisiológicos; produtividade de colmos (Mg ha^{-1}); e produção de açúcar e fibras. Por meio da plataforma DSSAT, foi simulada a produtividade da cana-de-açúcar em diferentes espaçamentos de plantio e a previsão de produtividade. A redução do espaçamento entrelinhas de cana-de-açúcar, em condições edafoclimáticas sem restrições ao cultivo da cana-de-açúcar, aumenta a produção de biomassa seca da raiz, o rendimento de açúcar, a fibra e os colmos das culturas por hectare. O PP 0,50 m é o espaçamento com maior produtividade de colmos além de apresentar uma longevidade superior aos demais no ambiente menos restritivo. Os parâmetros morfofisiológicos da cana-de-açúcar apresentaram evidências de correlação com o aumento da produtividade em espaçamentos reduzidos, no entanto, são necessários

mais estudos nessa área para auxiliar no entendimento dos fatores envolvidos nesse aumento de produtividade. Os resultados deste estudo mostraram pela primeira vez que o uso modelo CANEGRO-cana-de-açúcar, calibrado para o espaçamento convencional (1,50 m), pode ser aplicado para simular o rendimento acima do solo e do colmo da cana-de-açúcar sob diferentes espaçamentos de entrelinhas.
Palavras chave: espaçamento entrelinhas; parâmetros morfofisiológicos; sistema radicular; *Saccharum* spp; modelagem de culturas agrícolas.

ABSTRACT

Collecting data on the sugarcane yield, planted in different planting configurations, has been thoroughly evaluated by the CTBE working group since 2012, collecting data from over 16 crop seasons. During the master's degree, I evaluated 4 crop seasons of this project under different edaphoclimatic conditions and observed promising results from the point of view of increasing crop productivity. However, it is necessary to maximize the long-term results of this project and to try to understand what happens with plants after a change in crop management. Furthermore, given the growing demand for ethanol and renewable energy source, the change in the planting arrangement presents itself as an excellent alternative for supplying that demand, besides reducing the mechanization impact on the soil and plants. Thereby, the thesis is based on the hypothesis that: the better distribution of plants in the field promotes better root distribution; decreases tillering mortality and intraspecific competition; taking place substantial yield gains of biomass. Therefore, the aim of this study was to assess the aboveground and belowground of sugarcane establishment in different configurations of planting and environment conditions aiming to increase biomass production. Two experiments were conducted under field conditions, in clayey and sandy soil. The experiments were conducted across four crop seasons (two in clayey soil and two in sandy soil) and incorporated a randomized block design that tested six planting configurations, such as: CS, conventional spacing (1.50 m); AS, alternated spacing (0.90 × 1.50 m); TS, triple spacing (0.75 × 0.75 × 1.50 m); PP 1.0 m, precision planting (1.0 × 1.0 m); PP 0.75m, precision planting (0.75 × 0.75 m); and PP 0.50 m, precision planting (0.5 × 0.5 m). During the second and third ratoons was evaluated: sugarcane biomass production (above and below ground); biometric and morphophysiological parameters; stalks productivity (Mg ha^{-1}); sugar and fiber production. Through the DSSAT platform, was simulated the sugarcane productivity in different planting spacings and yield prediction. The reduction of sugarcane row spacing, in edaphoclimatic conditions without restrictions to the sugarcane cultivation, increases root dry biomass production, the sugar yield, fiber and crop's stalks per hectare. The PP 0.50 m is the spacing with higher stalk productivity, besides presenting a longer longevity than the others in the less restrictive environment. The morphophysiological parameters of sugarcane presented evidence of correlation with increased productivity at reduced spacings, however, further studies are needed in this area to help in understanding the factors involved with this increase in productivity. The results of this study show for the first time that CANEGRO-sugarcane model calibrated

for conventional spacing (1.50 m) can be applied to simulate the sugarcane stalk and aboveground yield under different row spacings.
Keywords: Row spacing; morphophysiological parameters; root system; *saccharum spp*; crop modelling.

FIGURES LIST

TABLES LIST

SUMMARY

I – General Introduction

The sugarcane is one of the main agricultural crops of the Brazilian economy, becoming an example of the renewable source for energy production (Kohlhepp, 2010). This crops represents 16.9% of Brazilian national energetic matrix, the sugarcane has been highlighted globally as raw material for the biofuels production due to its positive energy balance (Goldemberg, 2009; Kohlhepp, 2010; Renouf et al., 2008; Smeets et al., 2009), with an average reduction of 85% in the emission of greenhouse gases compared to fossil fuels (Börjesson, 2009). Therefore, with the potential of sugarcane production and the world demand for renewable energy sources positions Brazil an important situation in the energy sector (Tolmasquim et al., 2007).

An agreement signed by Brazil at COP-21 highlights the country's importance to the sugarcane production. Due to the established objectives, there is a need to produce 942 million megagrams of sugarcane in 2030. For such, the increase in planted area and/or increase in agricultural productivity appear as alternatives and, the Sao Paulo state, since it represents the largest share of the national crop production, is of great relevance in achieving the objectives established in the agreement (Sanches et al., 2017). In this study carried out by Sanches et al. (2017), the author pointed out that, in economic terms, increased productivity constitutes a more viable alternative, since producing more in the same amount of area directly affects the production costs. In a simulation performed, the increase in crop productivity in the Sao Paulo state from 77.5 (crop season 2016/2017) to 110 Mg ha^{-1} will translated into a significant reduction in production costs, from R $ 76.29 to R $ 57.00 per megagrams of sugarcane, reduction on the order of 25%.

Brazil is the leader sugarcane production (38%), followed by India and China, with 17% and 6%, respectively (FAOSTAT, 2018). Brazil produced 633 million megagrams of sugarcane during the 2017/2018 harvest in ~ 9 million of hectares. In the same crop season, Sao Paulo state, harvested 4.6 million hectares (52% of the total), reaching a total production ~ 349 million megagrams. These numbers generated an average productivity of stalks of 73 and 76.6 Mg ha^{-1}, respectively, for Brazil and Sao Paulo state (CONAB, 2018a).

Despite the numerical achievements obtained in field, the productivity is well below the genetic potential of the cultivars currently used, with estimated values exceeding 300 Mg ha^{-1} (Waclawovsky et al., 2010), has been decreasing in the last years, particularly after the intensification of the sugarcane mechanical harvesting, independently the unfavorable climate for plant growth observed in the South-Central region (OECD-FAO, 2015; Torquato et al., 2015).

The impact of mechanization on crop management, intensified mainly due to the prohibition of burning cane fields and the require of a greater yield efficiency, has been causing damages to plants and soil (Garside et al., 2005; Naseri et al., 2007). Consequently, increasing the concern with respect to the soil physical attributes, especially, soil compaction (Braunbeck and Magalhães, 2010). Additionally, the same authors showing big concern to damages to plants, being necessary to adequate the management the planting space for the maximum crop growth. The cut width of the sugarcane harvesters is currently limited to just one row, which requires the machines implements traffic on all crop rows more than one time (Braunbeck and Magalhães, 2010).

The planting configuration change is a technique that allows to adequate the sugarcane cultivation to the mechanization of the harvest systems aiming to minimize the damage to plants and increase the crop productivity (Torquato et al., 2015). However, since the beginning of the mechanization of agricultural operations in sugarcane crop, were done by agricultural machines, mainly the sugarcane harvesters and agricultural tractors (Braunbeck and Magalhães, 2010), that define the row spacing to be adopted in the planting (Braunbeck and Magalhães, 2014). Thus, limiting alternative planting and a possible increase in the crop productivity in the narrow row spacing .

Research into the effect of row spacing on sugarcane yield has produced varied results. Nevertheless, most studies show that sugarcane exhibits a degree of physiological plasticity that results in similar yields across a range of row spacing arrangements and densities. Studies performed in Australia (Garside et al., 2009) demonstrated after three crop seasons similar yields for sugarcane crop planted using traditional wheel spacing (1.5 m single row) to those when 3 rows (0.65 m apart) were planted between wheels. However, the expenditure of seedlings in planting was higher in the last spacing mentioned (0.65 m apart), thus influencing its production cost.

Furthermore, there are conflicting data from elsewhere, with increased sugarcane yields being associated with a reduction in row spacing. Research published since 1931 (Webster, 1931) show that for most of the sugarcane producing regions of the world, 72% demonstrated an increase in productivity with a reduction in the row spacing and 28% showed no gains or a reduction in sugarcane yield. According to Lynch (1995), row spacing, plant density on rows and the root distribution are the main factors linked to crop yields.

Sugarcane roots are the main organ responsible for ensuring the supply of nutrients and water from the soil, and thus strongly influence plant yields (Smith et al., 2005). According to Vasconcelos and Casagrande (2008), the root distribution depends on two main factors: genetic, wherein the varieties show different developmental patterns within the soil profile; and environmental, where the same variety of sugarcane grown in different soil and climate conditions may vary in the root system development. In addition, root development is influenced by three sets of soil factors: pedogenetic, physical and chemical attributes, with this structure being one of the determining factors in the genotype-environment interaction (Vasconcelos and Casagrande, 2008).

Mechanized sugarcane harvesting has benefited the soil-environment system (Otto et al., 2011). However, the constant traffic is compromising the soil physical attributes, interfering directly in the development and distribution of ratoon roots and thus limiting nutrient uptake by plants (Bakker, 1999; Otto et al., 2011; Vogelmann et al., 2012). The available technology knows that the rows compacted of the ratoon covering approximately 60% of the surface of the soil (Braunbeck and Magalhães, 2014) affecting the supply of soil resources, and influencing the sugarcane development and productivity (Magalhães, 2012).

In addition, the better choice of plants arrangement in the field can modify the response of the sugarcane aboveground, thus promoting a higher crop yield. According to researchers, reduce the plants spacing, can increase the population density. As a result, occurs the increase of the leaf area index and, consequently, the interception of active photosynthetic radiation throughout the plant (Luo et al., 2004; Singels and Smit, 2009).

Aiming to increase the sugarcane productivity with reduction of environmental impacts, there was an attempt by CTBE's agricultural division in the past to develop a 9.0 m wide Controlled Traffic Structure (CTS) (Figure 1), which it will create numerous possibilities of crop planting. Then, the researchers tried to evaluate a better distribution of plants by area looking for an alternative to increase the sugarcane biomass production, which would be used in the new machine (CTS) soon. However, the project was closed.

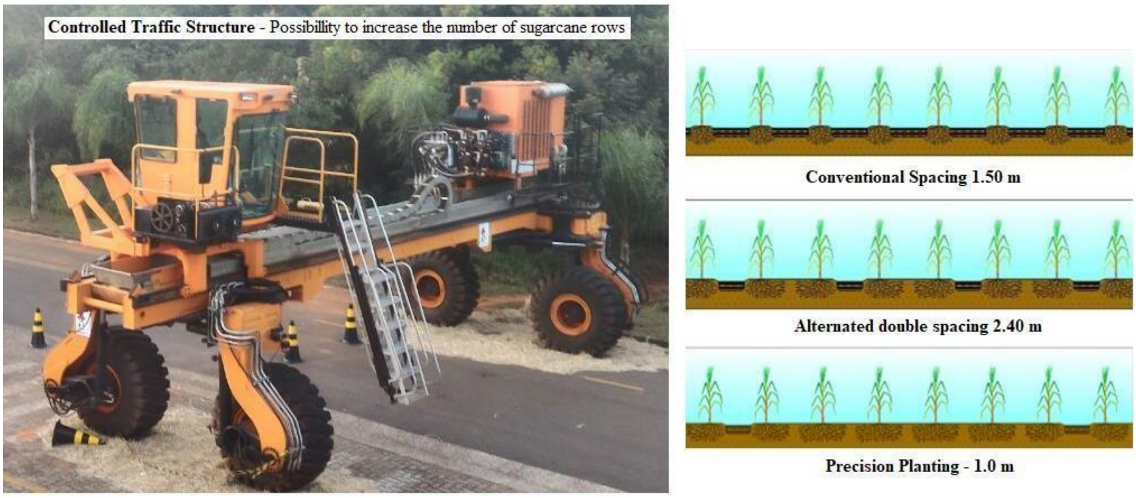

Figure 1. New machine (Controlled traffic Structure - CTS) and examples of possibility to change the row spacing and inter-row traffic.

Therefore, based on this idea we have as premises that: a) reducing the distance between rows and b) improve the plant arrangement in the area, would promote substantial increases in biomass production in comparison to current row spacing (1,5 m inter-row with 15-20 buds per meter: without precision distribution of plants). Therein, our hypothesis is: the better distribution of plants in the field promotes better root distribution (Figure 2); decreases tillering mortality and intraspecific competition; taking place substantial yield gains of biomass.

Figure 2. Example precision planting: same distance between rows and between stools.

II - Objectives

The main objective of this project was to assess the aboveground and belowground of sugarcane establishment in different configurations of planting and environment conditions aiming to increase biomass production. The specific objectives are as follows:

i. To check the behavior of the root growth through the assessments of biomass in different planting configurations;
ii. To assess the stalk performance by the assessment of biomass production, sugarcane yield (TSH), sugar (TPH), fiber (TFH) and the relations of these parameters with the root system in different planting configurations;
iii. To evaluate different plant parameters in the RB966928 and CTC 15 cultivars (Leaf area index (LAI); Dry and greens leaves; photosynthesis rates; nitrogen content - N) in the different planting configurations;
iv. Use field data to simulate and forecast the sugarcane yield (cultivar RB966928) in different row spacing, cultivated in the Guaíra-SP edaphoclimatic region, by means of modeling in software (DSSAT platform). The choice this cultivar was occurred for presenting a database more suitable for use in the CANEGRO-model.

The literature that supported the study and the experimental results of this thesis work will be presented in three chapters, namely:

Chapter 1. What is the best row spacing and plant density in sugarcane to increase biomass production? A literature review

Chapter 2. Sugarcane yield in different planting configuration and edaphoclimatic conditions in the long-term

Chapter 3. Application of the CSM-CANEGRO-Sugarcane model for predicting yield under different planting densities

Chapter 1: What is the best row spacing and plant density in sugarcane to increase biomass production? A literature review (Bioenergy Research)

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Abstract

One important factor to increase crop yield is the row spacing configuration adopted in the planting of crops. Indeed, there is a concern for sustainable agriculture around the world as plant row spacing and population density directly affect the performance of annual and perennial crops. For sugarcane crops, for instance, researches began in the 18th century and has focused on evaluating the best row spacing to increase sugar yield. In general, the most of studies (~72%) showed that the reduction of sugarcane row spacing is beneficial for crop performance. However, in some situations, reduction of row spacing had negative effects on sugar and biomass production, mainly owing to environmental conditions and soil type. In Brazil, the largest global producer of sugarcane, row spacing has been defined according to the agricultural mechanized machines, and this aspect associated with the intensification of crop mechanization and the weather conditions has contributed to negatively impact the sugarcane yield in the last 10 years. The main results presented by this review were: i- the management of plant row spacing and populations has the potential to increase sugarcane yield in Brazil and other countries; ii- sugarcane plants could be have more biomass production in reduced spacing compared to the currently row spacing adopted by growers; iii- it is necessary to consider the environmental conditions when choosing the row spacing for sugarcane cultivation; iv- the adjustment of row spacing and population reduce the cost of production.

Keywords: Planting configuration, sugarcane yield, *Saccharum* spp.

1.1. Introduction

Sugarcane (*Saccharum* spp) is one of the most sustainable raw materials to produce biofuels [13]. Due the increase in worldwide demand for renewable energy sources and for a reduction in the environmental impacts caused by petroleum-based fuels [57], the interest in biofuels is increasing. This is particularly true for sugarcane ethanol, which in its management produces low emissions of greenhouse gases (GHG) [72; 110]. Also, there is a recent interest in sugarcane for bioenergy (bioelectricity and second-generation ethanol) production has increased [68].

The other aspect that should be considered is the global demand for food, energy, and water, which has been putting pressure on the environmental and economic sustainability of all production [97], with studies suggesting that the world will need 70 to 100% more food by 2050 [46]. Thus, world agriculture is searching for alternatives to increase crop yield, due it is not viable increase the crop production through the expand of the area cultivated, as well as, there is not area enough to expansion the agriculture. Considering the expansion of cities and urban population in the last decade, as projections and analysis models show that population increases are higher than food production increases [56].

The most productive crops, such as sugarcane, which is an important crop in the Brazilian economy [115], growing in optimum conditions can convert solar energy into biomass with an efficiency of 2% resulting in high biomass yields - approximately 150 Mg ha^{-1} [55]. There is debate over exactly what the theoretical limits are for the major crops under different conditions and similarly for the maximum yield that can be obtained [56].

The effect of plant row spacing on sugarcane crops has been the focus of many studies since its establishment as a commercial crop [95]. According to Ullah et al. [116], the choice of plant spacing is one of the main factors contributing to yield outcomes for sugarcane, and previous research on spacing and planting density have shown that this strongly depends on the edaphoclimatic conditions [98]. Additionally, the optimum spacing depends on other variables such as the capacity for genotype tillering, the planting season, soil fertility, and water availability. Furthermore, Dillewijn [38] suggested that for each variety of sugarcane there is an optimum spacing level that ensures maximum production.

The adjustment of plant spacing and population density has been shown to increase yield, growth, and the efficiency of physiological attributes such as photosynthesis and solar radiation interception, in annual crops, i.e., soybean [27; 28], corn [29; 47 104; 121], rice [24; 89], and beans [23]. Therefore, new research is necessary to evaluate plant spacing and population density in semi-perennial crops, such as sugarcane, because the adjustment of these variables can increase or decreases crop yield and total biomass production [98].

In this review, we synthesized the knowledge of plant spacing in sugarcane cultivated in Brazil and other countries, including Australia, South Africa, India, and the United States, from the current literature, and showed the impact of the adjustment of plant spacing and population on sugarcane yield. Since Brazil is the highest sugarcane producer, representing 40% of the world's production [46], this review shows the current sugarcane production and yield in Brazil, the impact of mechanization on sugar crops, and discuss alternatives to change this scenario. Finally, we highlighted alternative row spacing of sugarcane cultivated in many countries and looked for the answer to the question: what is the best sugarcane spacing in Brazilian environmental conditions?

1.2. Current state of sugarcane production in Brazil

The Brazilian sugarcane area increased 250% (from 4 to 10 million of hectares) between 1980-2019 (Figure 1.1). This expansion contributed an increase in sugarcane production achieving numbers of 620 million megagrams during in crop season 2018/2019 [118]. The main producing area was the South-Central region, representing 92% of the national production; this region includes São Paulo State, which owns 54% of all sugarcane cultivated in Brazil [118].

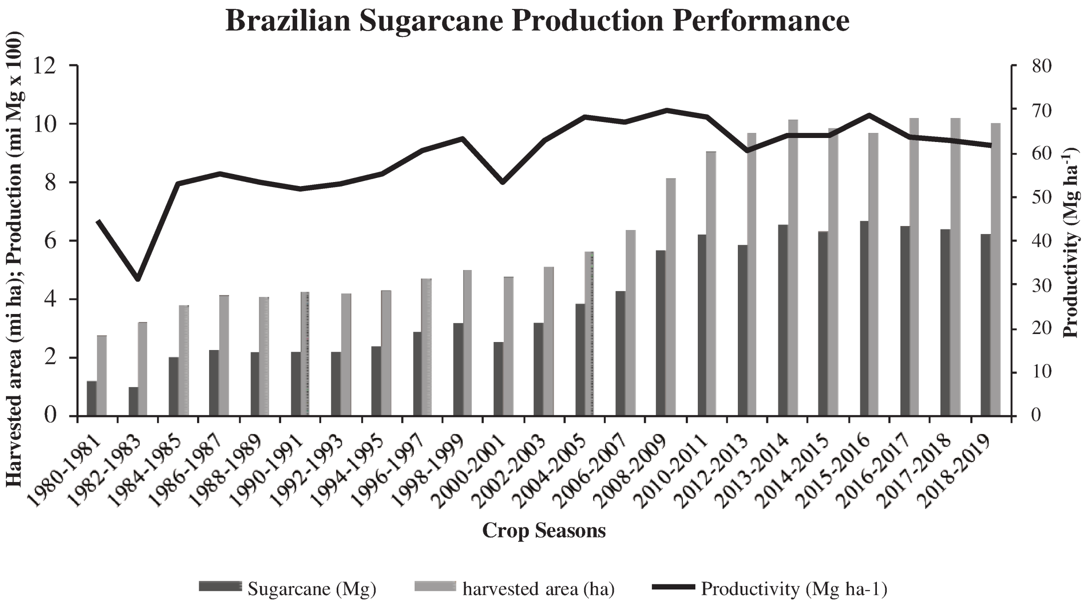

Figure 1.1. Evolution of area, production and productivity of sugarcane crop in Brazil between 1980 - 2019. Source: UNICA [118]

Projections indicate that by 2024, the sugarcane growing area in Brazil will reach 11.5 million hectares, resulting in an increase of nine million megagrams of sugar and an increase of 12.5 billion liters of ethanol [84]. However, in the same period, sugarcane yield did not experience the same increase (Figure 1.1). In 2010, there was a considerable reduction in yield and after this period yield has remained stagnant at ~70 Mg ha^{-1} [13; 50] in comparison to historical peaks which previously averaged 80 Mg ha^{-1} [118]. This drop in agricultural productivity (Figure 1.1), occurred simultaneously the intensification sugarcane crop mechanization.

Since the first reports of sugarcane in Brazil, planting and harvesting operations were all completed manually, excluding loading and transportation, and this process continued to until the mid-1990s [10]. Over 16 years (1990-2006), mechanized harvest was practiced by the traditional method of the burning of the straw, aiming to facilitate the operation [71]. In 2006, 66% of the sugarcane fields in the South-central region of Brazil utilized the original method of burning management tocrop harvest. However, the impact of burning on human health and the environment has been discovered, and legislation and limits have been set for the gradual elimination of burning [50; 87]. Deadlines, procedures, rules, and prohibitions were established to regulate burning in agricultural practices; these actions related to agronomic and energy issues [19] and required making a substantial change to the harvest procedure. Considering the intensive mechanization in Brazilian scenario, it was necessary adopting new practices that increase the productivity, to guarantee the sustainability of sugarcane yield, as well as to reduce the agricultural cost of sugarcane, which increased (12%) between 2016 -2017, leading to an early renewal (less longevity) of cane fields [50]. Therefore, the strong increase in mechanized harvesting without the original method of burning of the straw occurred, and in the South-central region of Brazil, the percentage of farmed areas using mechanized harvesting increased to 85% of all harvested areas [10] in 2015, and more recently, in 2019 the sugarcane mechanized harvesting covered approximately 97% of all sugarcane area cultivated [13,32]. The main problem associated with the mechanization of Brazilian sugarcane fields is the contradiction between the width of the machine wheels and the row spacing of the crop.

In Brazil, the most common row spacing in sugarcane fields are: ‘Conventional Spacing’ (CS) which is characterized by a separation of 1.5 m between crop rows, and ‘Alternating Spacing’ (AS; 0.9 × 1.5 m), in which there is 0.9 m gap between planting rows (double furrow) and 1.5 m between dual rows [98]. In this context, in Brazilian sugarcane plantations, crop spacing has typically been determined by the width of agricultural machinery, which limits the potential to change the row spacing [15].

The reaching of the goal to increase the yield is problematic given the reduced longevity of sugarcane plantations and the increased inter-row soil compaction caused by machine traffic [12]. The need to increase production to supply the increasing demand for sugarcane products over recent years has necessitated a growing reliance on mechanization, where, this dependency has led to the use of wider spacing than would be required for agricultural machines [92], while it was not considered that, the crop management in wider spacing reduce the plant population and consequently the biomass production. Regardless, the configuration and distribution of planting row are aspects that ensure the adequate cultivation of sugarcane and facilitate mechanized harvesting with minimum damage to plants [15].

The adjustment of plant row spacing is one option to increase sugarcane yield in Brazil, which is necessary because projections for the sector indicate that over the next 10 years the country will need to increase the amount of sugarcane production by 27% to meet the expected growth in consumption and export of sugar, ethanol, and the byproducts generated from biomass [49].

With the mechanization of sugarcane crop production [10], there is a need for further long-term research (involving plant cane and ratoons crop cycles) to evaluate the responses of sugarcane cultivated under different edaphoclimatic conditions and in response to different planting configurations. On the other hand, to define the best row spacing for Brazilian sugarcane fields, it is necessary to adjust the machines to increase operation efficiency in order to decrease losses (visible and invisible) during agricultural operations, which represent a loss of US$ 1.5 billion per year for Brazilian sugarcane [50].

Exemplifying the problem of mechanization in Brazil, Magro [74] showed that a row spacing of 1.8 m with double rows was able to increase stalk productivity by 12% compared to a spacing of 1.8 m with single rows, due to the larger number of plants in the same area. However, following the introduction of mechanized harvesting of sugarcane, there was an increase of damage to the ratoons of the crop, which required changes to the manufacturing of harvesters and haul-out. Nevertheless, the literature describing the effect of row spacing on sugarcane yield is often conflicting, being that, the decision making about the spacing will be adopt in sugarcane crop could be influencing the production [53; 96; 98; 108].

There is a requirement to better understand the effects of row spacing and population density on sugarcane in Brazil due to field studies carried out after the introduction of mechanical harvesting (1990 – 2018), which have shown that adjusting row spacing may increase sugarcane yield [8; 52; 82; 86; 98]. However, other studies show that changes to the spatial configuration and row spacing have no effect on sugarcane yield [48; 69; 98]. Therefore, only after understanding the best row spacing to sugarcane crop cultivated in Brazil, will be possible adjust the agricultural practices management to have a greater crop yield, as well as, reducing the impacts and yield decline associated to the intensive mechanization.

1.3. Mechanization impacts

In one crop, when it inserted the mechanization of the agricultural operations, when there is a miss match between the traffic zone and the crop row, occurs the crop line trampling, which could be harm the plants and reducing the plant population in the field [15]. This fact occurred in sugarcane crop in Brazil between 2010-2011 after the prohibited burning before the harvest of the cane fields (Law No. 11,241- September 19, 2002) - (Figure 1.1), and the mainly consequence was the reduction in sugarcane yield.

Therefore, there is the evidence that there is a linear relationship between sugarcane yield reduction according to the expansion of the mechanical sugarcane harvesting.

Especially to sugarcane crop cultivated in Brazil, to minimize damage to plants, wider spacing (1.5 m) is more suitable for machines and hence can reduce the costs of cultivation [93]. However, recently an alternative has emerged to reduce harvest traffic in the cane field (50%), reduce fuel consumption and still harvest with greater productivity using harvesters with two or more cane rows. According to experts in the market and the sugar-energy sector, this would be the future of mechanized sugarcane harvesting, mainly due to problems that the current available technology needs to solve (harvesting two rows in cane fields spaced 1,5 m) [26]. On the other hand, smaller spacings (potentially more productive) like of 1.0 m is more suitable for manual harvesting and its mechanization is unviable without the adaptation of the harvesters on the market today [64]. Therefore, the adoption of alternative spacings for sugarcane has been hampered because of mechanical adaptation and human resistance from machine operators and sugarcane cutters.

Some alternatives, in the last decade, were tested to minimize the mechanization impacts in sugarcane field, as well as, to assess the effects of planting spacing on sugarcane production (CTBE). These tests were aimed at with the goal to mitigate many of the limitations faced by the sugarcane sector. Among these limitations, to mitigate soil compaction between crop rows, increasing fuel efficiency, and maximizing the sustainability of the ethanol energy balance. In addition, this new concept of crop management aims to eliminate current restrictions imposed by mechanization and to establish improvements in terms of row spacing, plant distribution on field, and better use of soil, water, air and light by plants. However, the Brazilian project trialing the new sugarcane harvesting machine was stopped owing to a lack of financial support to solve the problems that the prototype presented in field conditions (personal communication).

The same concept was adopted in the cultivation of cereals and cotton with gantry-type harvesting structures and resulted in satisfactory reductions in soil compaction [3]. Therefore, one of the options is to adopt equidistant spacing between plants and crop rows. This involves the use of buds or seedlings that are distributed along planting rows at fixed distances. This type of plant arrangement is suitable for in-line crop production systems because the traffic sites are maintained, and this system has already been applied in sugarcane fields in Australia [76]. For example, in a trials in which the sugarcane was planted in row spacings of 1.5 m with a distance between plants of 0.5 m, in this situation, there is a low competition between the plants by the nutrients, as also, the sugarcane plants could be express the potential to growth, and the last, there is an economic production sustainable, due to the reduction with a cost by seedling during the planting operation.

The advancement of mechanized harvesting in Brazil occurred more quickly than the systematization of cropland, which led to a great reduction in Brazilian sugarcane yields and, hence, in total sugar production. The problems related to mechanical harvesting occur mainly due to stalk losses [59] and due to mineral and vegetal impurities in raw material [21; 103] which promotes high stalk losses [10; 20] and reduced ratoon sprouting in the next crop cycle [73]. One of the major factors is the randomization of the traffic of equipment that sometimes overlaps the planted row and increases the risk of soil compaction in that area, mainly because of a mismatch between the width of the machines (generally 1.85 m) and the spacing of the planted rows in Brazil (generally 1.5 m) [50].

Owing to the introduction and progression of mechanization in agricultural operations for sugarcane planting, harvesting, and agricultural practices, it was necessary developed a new strategy to be adopted in areas of replanting. The crop rows should be planned prior to planting, considering the total dimensions of the area to achieve greater efficiency of agricultural operations [102], and consequently reduce problems of overlap of passages and excessive traffic in the field. In general, systematization starts at the field plot, which is the basic unit for sugarcane. In each area and shape are variable according to the soil type and topography as well as to the intrinsic conditions of each location (roads, currencies, etc.). Usually, the blocks have a maximum area of 20 hectares and may vary from region to region [102].

Sugarcane yield depends on a balance between soil conditions suitable for plant growth (friable soil) and conditions required for mechanized operations (compacted soil). These characteristics have been obtained using traffic control of agricultural operations. In order to lessen overlapping and increase productivity and longevity of sugarcane fields, the use of autopilot during harvesting is mandatory. This technology enables the control of inter-row traffic resulting in reductions of up to 78% in terms of overlapping on ratoons [17].

As reported by Echeverry [39], cultivated areas using traffic control presented higher yields during five consecutive harvests compared to those without traffic control; an average reduction in sugarcane yield of 17% (19 Mg ha^{-1}) was observed in areas without traffic control. There was no difference between the areas in the first harvest as the areas were not subjected to machinery traffic. In the following harvests, the area without traffic control had lower yields than those with traffic control (Figure 1.2), especially because of trampling on ratoons. In this sense, there may be an increase in sugarcane yield when the mechanization impacts are reduced in sugarcane fields (Figure 1.2). This is possible using traffic control [17, 39; 50], which consists of standardizing the width of machines at multiple or coincident spacings that direct traffic to the center of the lines beyond increasing population density and crop productivity.

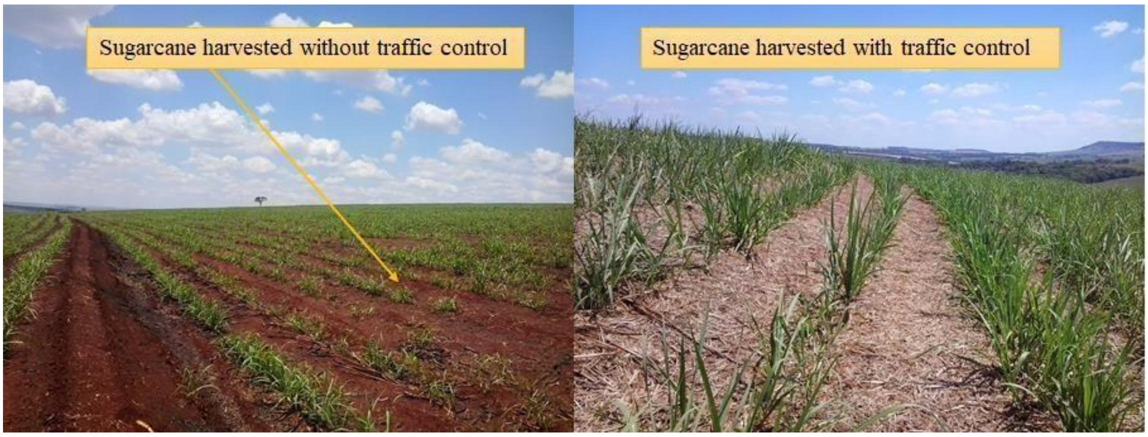

Figure 1.2. Effect of traffic control in sugarcane sprouting (ratoon cane) at 60 DAH – Days After Harvest after four crop cycles. Source: Rossi Neto, J. 2012

Other aspects can also be identified and modified such as enhancing the harvest machine parameters (speed, base cutter height and others) and minimizing the losses and damage in ratoon in the fields [21]. On the other hand, exploring how reduced spacing between lines, and increasing the distance between plants without limiting machine traffic, may have a positive impact on the economic sustainability of the sugarcane field, as it reduces spending on seedlings for the establishment of the crop and increases productivity gains due to reduced row spacing [98].

1.4. Current spacing in Brazilian sugarcane fields

The common types of spacing adopt in Brazilian conditions are: single row (conventional: 1.5m of rows pacing 1.5 m) and dual row spacing (1.5 m or 1.6 m × 0.9 m). There is another kinds of dual row, where the row spacing is 1.5x0.3m, usually adopted under drip irrigation. According to a UDOP survey, single row spacing is used by 88% in Brazilian sugarcane fields, while only 12% of the total sugarcane area is cultivated is in dual row spacing. Furthermore, approximately 90% of the companies told that, the decision of which spacing to use was directly dictated by the harvesting machines [117].

With the prohibited burning before the harvest of the cane fields (Law No. 11,241- September 19, 2002) in 2008, dual row spacing gained popularity in Brazil, mainly due the low mechanical harvest cost when compared to the cost obtained in single row spacing [117]. Nevertheless, the initial decision to change the row spacing was strongly influenced by the incompatibility of existing equipment on the market. Recently, there was the emergence of equipment made specifically for dual row spacing, including equipment from the main manufacturers of harvesters.

According to Moraes Neto [79], the reasons for adopting the dual row spacing are: i-the facility to adaptation the gauges of the harvester and the haul out, with the plant row in the field which minimize the trampling and the ratoon damage; ii- extend the longevity of the cane fields; iii- and improve the performance of the mechanical harvester. In UDOP's research [117], several experts from the sugar-energy sector mentioned the advantages of adopting dual row spacing, including: adequacy of sugarcane straw in agronomic management, weed control, better utilization of the population density in the planted areas, reduction in the level of stomping and compacting of soil, and improvements to traffic control and harvest operating income.

The adoption of alternative spacing usually requires improvements in management aiming to increase the efficiency in crop production. According to Paggiaro, in an interview in CANAONLINE [18], the dual row spacing can increase sugarcane yield (~12%) compared to conventional spacing of the same sugarcane variety. In addition to the gains in productivity, the author described a reduction (18%) in the cost of mechanized harvesting. However, the same study claims that there is still not much data in the literature pertaining to varietal adaptation for the new row spacing, and that dual row spacing presents larger losses than conventional row spacing. Furthermore, the adoption of double spacing presents some problems, such as: adaptation of the current harvesters to harvest the two rows, requiring the development of machinery and equipment; higher spent on seedlings at planting, increasing the production cost; and pest control [18; 26]. In a study examining the ideal row spacing for the mechanized harvesting of sugarcane, Bedine and Conde [9] concluded that the complexity of mechanized harvest systems will require attention and that constant improvements to field operations.

Currently, the most common spacing used (1.5 m between the rows) when compared to other spacings (less commonly) could be shown negative aspects, such as:

Barbieri et al. [7], found an increase in stalk density in the smallest spacing (1.1 m and 1.2 m) compared with the spacing of 1.5 m. In a similar study of dual row spacing, Roach [96] observed higher productivity compared to the conventional spacing of 1.5 m. Collins [31] showed that the production of stalks and sugar was lower using a spacing of 1.5 m compared to the smaller spacings. According to Devi et al. [35], higher productivity can be achieved when used the combined spacing 0.3 × 1.2 m, in comparison to the spacing of 0.9 m. Ismael et al. [65] observed consistently greater sugarcane productivity in the dual row spacing when compared to the conventional spacing in twelve experimental areas.

Recent studies have examined triple spacing (1,5m x0,75mx 0,75m) which has proven to be quite promising. Belardo et al. [10] evaluated the performance of a sugarcane harvester in crops with three different spacings and found more satisfactory results in terms of harvest and productivity from triple spacing compared to the conventional spacing. However, Rossi Neto et al. [98] found that there were no differences during two crop seasons when analyzing the productivity of single row (1. 5 m), dual row (0.9 × 1.5 m), and triple row spacing (0.75 × 0.75 × 1.5 m) in two edaphoclimatic environments.

It is important highlight that in almost all of researches mentioned above the sugarcane yield was calculated without mechanical harvest, which it was adopted the manually harvest in these experiments. Considering the problems with losses and impurities in a reduction spacings, i.e, combined or triple, there is not obtained reduction in biomass and sugar yield compared to the conventional row spacing [50]. Therefore, the conventional row spacing (1.5 m) adopted in most sugarcane areas in Brazil is better than dual or triple row spacing due to the low losses when compared to other spacings. Regardless, it is necessary understand the best row spacing to increase plant performance to produce more biomass and sugar, which it is possible through the reduction of sugarcane row spacing, since there is not losses of sugarcane and sugar yield, as well as, it is possible adopting the mechanical agriculture operations. Upon knowing the best row spacing the next step is to adjust the mechanical agricultural operations to use it.

1.5. Reduction of sugarcane row spacing

The adjustment of population of plant density in sugarcane through the choice of the best row spacing is one alternative to maximize the sugarcane yield [99]. Since the beginning of the 18th century, row spacing adopted for commercial varieties of sugarcane were smaller than those currently used, ranging from 0.6 to 0.91 m in the Louisiana producing areas of the United States [62]. A similar row spacing was also described for other regions of the world including South America, Africa, and Asia, where there is a strong reliance on the use of animals and human labor. Shunmugasundaram and Venugopal [105] performed a revision about sugarcane rows pacing in India and concluded that the optimal row spacing ranged from 0.6 to 1.05 m and varied based on different locations. The same results were obtained in Brazilian conditions where the reduction in row spacing increased the sugarcane yield, mainly when the traditional spacing (near 1.5 m) was changed to 0.9 m (Table 1.1).

Table 1.1. Works that evaluated the sugarcane yield such as response to different row spacing planting.

Mainland	Country	Scientific Work	Year	Length of Crop Cycle*	Texture*	Spacing Reduction	Yield
South America	Brazil	Menezes Veiga, F. [78]	1950	n.a	n.a	1.8 to 0.9	(+)
		Aguirre Jr and Arruda [1]	1954	PC	Clayey	1.8 to 1.0	(+)
		Arruda, H.C. [4]	1961	PC/R_1	Clayey	1.8 to 1.0	(+)
		Paranhos [88]	1972	PC/R_1	Clayey	1.9 to 1.0	(+)
		Pereira Junior [90]	1984	PC	n.a	1.8 to 1.0	(+)
		Espironelo et al. [44]	1987	PC/R_1	Clayey	1.5 to 1.2	(+)
		Barbieri et al. [7]	1987	PC/R_1/R_2/R_3	n.a	1.7 to 1.1	(+)
			1987	PC/R_1/R_2	n.a	1.3 to 1.1	(-)
			1987	PC/R_1/R_2	n.a	1.5 to 0.9	(+)
			1987	PC/R_1/R_2	n.a	1.5 to 0.9	(-)
			1987	PC/R_1	n.a	1.5 to 0.9	(+)
		Berto et al. [11]	1987	PC	Sandy	1.6 to 1.0	(+)
		Basile Filho et al. [8]	1993	PC	Clayey	1.45 to 1.0	(+)
		Ernandes [43]	2005	PC	n.a	1.4 to 1.1	(+)
		Muraro et al. [82]	2011	PC/R_1	n.a	1.3 to 0.9	(+)
		Fabris et al. [45]	2014	PC	Sandy	1.5 to 1.0	(+)
		Ferreira Junior et al. [48]	2014	PC	Medium/Clayey	1.4/0.6 to 1.0	=
		Rossi Neto et al. [98]	2018	PC/R_1	Clayey	1.5 to 0.5	(+)
			2018	PC/R_1	Sandy	1.5 to 0.5	=
North America	United States	Webster [120]	1931	n.a	n.a	1.52 to 0.91	(+)
		Hebert et al. [60]	1965	n.a	n.a	1.83 to 1.12	(+)
		Freeman [51]	1968	PC	Sandy loam	1.68 to 1.07	(+)
		Matherne [75]	1971	PC/R_1/R	Mhoon silt loam	1.83 to 0.91	(+)
			1971	PC	Mhoon silt loam	1.83 to 0.91	(+)
		Irvine and Benda [62]	1980	PC	n.a	1.52 to 0.19	(+)
		Ingram [61]	1986	PC	Loamy fine sand	1.5 to 0.75	(+)
		Richard, Jr. et al. [95]	1991	PC/R_1/R_2	Silt loam	1.8 to 0.9	(+)
Asia	India	Bains [6]	1959	n.a	n.a	0.9 to 0.6	(+)
		Kanwar and Sharma [67]	1974	PC/R_1	Sandy loam	1.8 to 0.6	(+)
		Nagendran et al. [83]	1999	n.a	n.a	1.5 to 0.75	(-)
		Singh [109]	2000	PC/R_1	Sandy loam	120/30 to 0.75	(+)
		Raskar and Bhoi [94]	2003	PC/R_1	Clayey	0.9 to 0.3	=
		Asokan et al. [5]	2005	PC	Sandy loam	0.9 to 0.75	=
		Devi et al. [35]	2005	PC/R_1	Sandy loam	1.5 to 0.9	(+)
		Chattha et al. [22]	2007	PC/R_1	Sandy	1.2 to 0.45	(-)
	Pakistan	Ehsanullah et al. [40]	2011	PC	Sandy clayey loam	1.2 to 0.6	(+)
		Sajjad et al. [100]	2014	PC	n.a	1.35 to 0.75/0.6	(+)
		Ullah et al. [116]	2016	n.a	n.a	1.8 to 0.6	(-)
	Vietnam	Mui et al. [81]	1996	PC/R_1/R_2	n.a	1.5 to 0.75	(+)
		Mui et al. [80]	1997	PC/R_1	n.a	1.5 to 0.9	(+)
Africa	Egypt	El-Shafai et al. [42]	2010	PC	Sandy loam	1.2 to 0.8	(+)
		El-Lattief [41]	2016	PC/R_1	Clay loam	1.4 to 1.0	(+)
	Kenya	Amolo and Abayo [2]	2006	PC/R_1	n.a	1.5 to 0.5	=
			2006	PC	n.a	1.5 to 0.5	(+)
		Omoto et al. [84]	2013	PC	n.a	1.2 to 0.4	(+)
	Mauritius	Ismael et al. [65]	2007	PC/R_1/R_2/R_3	n.a	1.8/0.5 to 1.6	=
			2007	PC/R_1/R_2	n.a	1.8/0.5 to 1.6	(+)
	South Africa	Thompson and Toit [114]	1965	n.a	n.a	<0.91	(+)
		Boyce [14]	1968	PC	Sandy loam	2.3 to 0.9	(+)
		Smit and Singels [111]	2006	PC/R_1	Clayey	2.66 to 0.73	(+)
		Singels and Smit [107]	2009	R_1	Clayey	2.79 to 0.64	(+)
Oceania	Australia	Bull [16]	1975	PC/R_1	Sandy loam	1.4 to 0.5	(+)
			1975	PC/R_1	Sandy loam	1.4 to 0.5	(+)
			1975	PC/R_1	Sandy loam	1.4 to 0.5	(+)
		Garside et al. [53]	2009	PC/R_1/R_2	n.a	2.3(c) to 1.5	=
			2009	PC/R_1/R_2	n.a	2.1(d) to 1.5(a)	=
			2009	PC	n.a	1.8(b) to 1.5	=
			2009	PC/R_1	n.a	1.8(b) to 1.5	=
		Garside and Bell [54]	2009	PC	n.a	1.5 to 0.5	=
			2009	PC	n.a	1.5 to 0.5	=

*not assessed this information in some studies (n.a). PC = Plant cane; R = Ratoon cane. = no gain in yield. (+) yield increase. (-) yield decrease

The results (Table 1.1) show that across most production environments tested, a reduction in spacing tends to increase the crop productivity. However, this may be limited either by the necessity of using machinery for cultivation and harvesting or by weather conditions.

Many studies were conducted around the world – 51 studies (Table 1.1), which evaluated 60 fields encompassing plant cane or ratoon cane. It is possible identify that the reduction of sugarcane row spacing increases the yield, as studies conducted since 1931 suggest that for most of the sugarcane producing regions of the world, 72% demonstrate an increase in productivity with a reduction in the row spacing of the crop; 28% showed no gains or a reduction in sugarcane yield (Table 1.1). Nevertheless, there is a difference in the response of sugarcane to the reduction of row spacing depending on the crop cycle (Table 1.1). Plant cane generally has a greater yield than ratoon, and in fields, row spacing reduction does affect sugarcane yield, because is related to other intrinsic factors, i.e., environmental conditions, soil texture, variety.

In general, the studies (Table 1.1) evaluating the effect of changing sugarcane row spacing on sugarcane productivity, showed that reducing row spacing increased the yield. However, for some of the spacings tested, it is not possible use mechanized harvesting, considering that harvest machines create traffic on the field and contribute to trampling, soil compaction, and a high loss index. In this sense, it is important to highlight that in almost all studies, the harvesting was performed manually. Considering all studies in Table 1.1, the best row spacing for sugarcane varied according to the field's geographic location and environmental conditions, but overall higher gains were found between 0.5–1.0 m interrow spacing.

Another aspect to emphasize in our review is that among the studies, 46% evaluated only the plant cane cycle (Table 1.1). This fact could be associated to the ability of sugarcane plants to adapt to different row spacings and populations which means that after the first cycle, the yield increase disappears and the row spacing does not have an effect [44; 53]. In the other view, the studies that evaluated the ratoon cycle [7; 52; 67; 95; 98] showed that the soil texture could influence the response of the sugarcane, and that the best spacing to increase the sugarcane yield is different from clayey to sandy soils.

Researchers found that the use of wider spacings allows greater use of soil resources by the crop [64] and produces plants with larger diameters and lengths in comparison to smaller spacings [64; 67; 98]. More recent studies corroborate these earlier findings. For example, El-Shafai et al. [42] evaluated row spacings of 0.8, 1.0, and 1.2 m and found larger stalk diameters for plants grown under conditions of wider spacing. In relation to the number of stalks per hectare, Irvine [63] observed a decrease because of an increase in the spacing of sugarcane, despite a slight increase in the weight per tiller. However, Amolo and Abayo [2] found that after a period of two or three years, this difference declined considerably, especially for crops spaced at 0.9 m or less. Evaluating the yield of sugarcane (Mg ha^{-1}) grown with wider and smaller spacings, Rajula Shanthy and Muthusamy [92] found a greater average yield of 20-30 Mg ha^{-1} in the wider spacings. Even though wider row spacing or between plant spacing can result in individual plants with high productivity [62], when compared based on per unit area, the highest productivity will typically be obtained from smaller spacings [62; 66; 96; 98]. According to James [66], in unlimited conditions, reducing the spacing between rows promotes larger stalks and increased sugar yield.

In the literature, there were several studies that evaluated crop productivity across different climate, soil conditions, and technological levels [14, 42, 52, 62, 75, 82, 119]. While evaluating 10 spacings of sugarcane, Irvine and Benda [62] observed an increase in population density, biomass, and sugar per hectare with reduction of row spacing. Muraro et al. [82] noted that a row spacing of 0.9 m have the higher sugarcane production. El-Shafai et al. [42] studied the effect of 0.8 m, 1.0 m, and 1.2 m row spacings for sugarcane production for two agricultural crops and reported greater biomass production for the spacings of 0.8 and 1.0 m. Matherne [75] found higher crop stalk productivity in spacings of 0.91 and 1.06 m compared to a spacing of 1.8 m. In the work presented by Veiga and Amaral [119], inter-rows with a spacing of 0.9 m lead to higher sugarcane production than spacings of 1.5 m and 1.8 m. However, there were no differences in production between the spacings of 0.9 and 1.2 m. Studying the effects of different plant spacings on sugarcane farming productivity, Galvani et al. [52] found that a 9% increase was associated with a reduction in row spacing from 1.8 m to 0.9 m. According to Boyce [14], for every 0.30 m increase in sugarcane spacing there was a yield decrease near 6 Mg ha^{-1} $year^{-1}$ in regions where soil moisture was not a limiting factor.

Coleti [30] found that across 23 field experiments cultivated with three agricultural crops in sugarcane producing areas in other countries, a reduction in row spacing increased crop productivity in 22 out of the 23 trials, with average gains of 32% on productivity. In Brazilian areas, we reviewed data from 27 works and found increased productivity for closer spacings in 25 of these works, with gains of 19%. We concluded that for every 0.03 m reduction in spacing there was a 1% gain in productivity.

The productivity gains by the crop with the reduction of row spacing can be explained in some ways. According to Irvine et al. [64], the two primary components of sugarcane productivity are stalk population and weight observed in field experiments in the United States. For Brazilian conditions, evaluating the sugarcane production according to different planting configurations and edaphoclimatic conditions, Rossi Neto et al. [99] showed that population density per hectare was mainly variable that had the strongest correlation with sugarcane yield.

Higher crop productivity from reduced spacing also occurs because productivity gains are associated with a higher leaf area index, driven by: an increase in the net rate of photosynthesis through increased absorption of solar radiation [52]; reduced competition with weeds [7], which minimizes the cost of herbicides and fertilizers and reduces soil erosion susceptibility [58]; larger leaf surfaces resulting in faster saturation times for solar interception due to a more densely closed canopy [54]; and most importantly, the increase in the population density per hectare [7; 8; 16; 64; 67; 75; 96; 99; 111].

Considering our review (Table 1), the correct choice of sugarcane row spacing can bring different rates of yield gains, which can be less than 15% (low response), 15-30% (moderate response), or greater than 30% (high response), Figure 1.3.

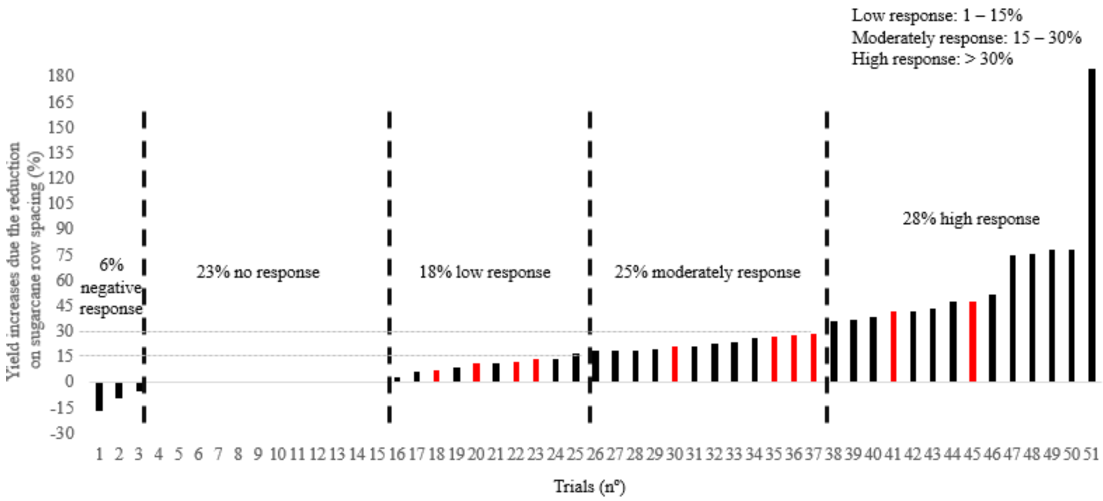

Figure 1.3. Gains or losses in sugarcane yield according to the reduction on row spacing, in trials selected in the Table 1.1. PS: The gain or losses in yield (%) was calculated with the difference between the yield in traditional space adopted and the best spacing to increase the yield. Red color in the bars refer to Brazilian trials.

Therefore, the adjustment of row spacing in sugarcane is important and necessary to increase sugarcane production around the world. Currently, Brazil produces nearly 650 million megagrams of sugarcane annually [118] (Figure 1.1), according to this review the Brazilian scenario (red bars in Figure 1.3) shows that the yield gain in Brazilian fields is in the low or moderate response. In this context, the adoption of the best row spacing could increase sugarcane productivity between 97 and 150 million megagrams, and this value represents 50% of India´s sugarcane production [46]. Considering that the total area cultivated with sugarcane in Brazil (10 M ha) and considering that 100 Mg of stalks produces 12 Mg of straw [77] and 14 Mg of dried bagasse [91], there is the potential to increase the amount of bagasse generated after juice extraction from 15 to 29 million Mg ha^{-1} yr^{-1} and the amount of straw from 4 to 10 million Mg ha^{-1} yr^{-1}. This would create a considerable amount of feedstock that would be also be available for the cogeneration of electric energy from the burning of this material in boilers [112] and the from the production of second generation ethanol [36; 91]. Additionally, the higher amount of straw produced can also improves sugarcane production when maintained on soil surface [19; 25].

In 15 (29%) of 51 trials, reducing sugarcane row spacing did not increase the yield and, in some cases, (trials 1, 2, and 3) reducing spacing decreased the yield (Figure 1.3). A reduction in row spacing promotes an increase in population mainly in clayey soils sites [30; 98], where the yield gain tends to be smaller between the spaces tested than in sandy soils. Also, the reduced spacing can represent an obstacle for mechanization in major producing areas. Therefore, to adjust only in plant row spacing may not be enough and it may be necessary to adjust the row spacing with the plant density considering the environmental conditions, because increases or decreases in the sugarcane and sugar yield could be directly related to the sugarcane genotype [37; 70; 101].

1.6. Planting density

Similarly, to the abovementioned, spatial arrangement and population density are factors related crop yield [33; 52; 99]. Smaller row spacing promotes an increase in the population density per area and consequently increases biomass [40; 107; 109]. On the other hand, high population density can result in thinner stalks due to competition between plants, suggesting an inverse relationship between tiller density and tiller weight [40]. However, especially in this situation, a population density with smaller tiller densities can produce good results for sugarcane yield, as is reported in some studies [5;

35; 40]. This is particularly the case in conditions where soil moisture is not limiting, as demonstrated by the fact that an increase of 0.3 m in the row spacing can be enough to cause a reduction in the population stand of the crop [52]. The high values for the standard deviation obtained in the descriptive statistics for each row spacing treatment are associated with the genotypes and the edaphoclimatic conditions at each of the sites, thus demonstrating that the population density is strongly influenced by these factors [37; 101].

In pioneer review of the historical data presented by Stolf and Barbosa [113], some interesting points are provided about the use of different seedling densities in the Brazilian sugarcane plantations. The authors reported that during the 1950's it was typical to use 6 buds m^{-1} for the planting of the crop. Over the following decades (1960's and 1970's), this amount increased to 12 buds m^{-1}, 15 buds m^{-1} by the 1980's, reaching 20 buds or more nowadays [50]. Not surprisingly, different planting configurations will produce distinct plant densities and thereby modify the quantity of seedlings (seed-thatched) that are required per hectare [54]. Collins [31] used three row spacings (1.5 m, 1.0 m, and 0.5 m) and three bud densities per meter (2.5, 5, and 10 m^{-1} buds) and found that the production of stalks and sugar was greatest when using a spacing of 0.5 m with 10 m^{-1} buds.

The high number of rows in denser spacing increases the number of seedlings required, which subsequently increases the production cost. When evaluating three planting densities designed to improve sugarcane productivity and quality, Ehsanullah et al. [40], observed that a density of 75,000 buds per hectare produced the greatest height, diameter, weight per tiller, number of internodes per sugarcane, productivity, and total sugar. This conclusion is controversial because in some situations, works showed that reducing the number of buds per meter to reduce the number of seedlings required for planting is often not the best option. In an experiment developed in Brazil that used a spacing of 1.4 m and tested four densities of buds per meter in the planting of sugarcane (12, 18, 24 and 30 m^{-1} buds), Daros et al. [34] verified that a reduction in the number of buds decreased the productivity during two crop seasons (plant cane and first ratoon). In contrast, Silva et al. [106] reported no effect of the number of seedlings (5, 7.5 and 10 Mg ha^{-1}) required per hectare on crop productivity combined with four types of row spacings. These results show that it is possible to substantially reduce the number of seedlings without diminishing the crop productivity. This is possible because of the plasticity and ability of the crop to adapt to different densities of plants by indeterminate growth allow this [53].

The adoption of precision spacing increases the payback of planting costs, due to the reduction in the number of setts. By increasing the planting density using precision spacing of 0.75 or 0.5 m between rows and plants, yield gains improved between 8 – 14% per year in Brazilian conditions, as well as, this amplitude is associated with the edaphoclimatic conditions [98]. In the search for competitive gains from the sugarcane agricultural sector, using such a high density of buds during planting can completely undermine the adoption of reduced spacing, as it substantially increases the number of seedlings in the planting, due to the increase in the planting rows in these spacings (> m per ha). Thus, it is important that when reducing row spacings the density of seedlings for the establishment of the crop must be reviewed and, above all, the habit of undetermined growth of the plant (tillering) for the closing of the crop canopy should be taken into consideration [54].

1.7. Concluding remarks and perspectives

The management of sugarcane row spacing can improve the sustainability of biomass production around the world. Knowing the best row spacing and plant density it is possible to increase the sugarcane stalk yield by around 30%, being that this gain is associated with other aspects, such as, radiation, soil moisture, temperature during crop development, according to the row spacing adopted.

Overall, the best planting row spacing was traditionally from 0.5 to 1.0 m, and the exact spacing was dependent on edaphoclimatic conditions. i.e., soil texture, geographic localization, sugarcane variety and agronomic practices adopted (fertilization rates, irrigation or not irrigation, mechanical harvest traffic). In Brazilian conditions, the best row spacing is between 0.75 to 1.0 m, which is lower than the conventional row spacing (1.5 m). Therefore, to increase the Brazilian production there is a need to change the plant row spacing. Regardless, in the last decade the sugarcane productivity decreased by 12% in Brazil because of the impact of mechanization on the fields. In the other words, the advance of mechanization and the absence of traffic control occurred more quickly than the systematization of the areas. Thereby, sugarcane was "imprisoned" in a scenario in which plant row spacing did not maximize production potential, and in which plants were trampled during agricultural operations.

The Brazilian scenario occurs in other countries too, according to the literature (51 studies) that evaluated sugarcane row spacing, where the reduced spacing shown high yield when compared to the conventional spacings. However, in the Brazilian scenario and in other countries, it is not possible to adopt these spacings, because it is necessary to use mechanical harvest. In this context, gains related to the adoption of the correct plant row spacing for sugarcane crop will occur when researchers develop the equipment to carry out agricultural operations with traffic control to reduce damage to the soil and plants in sugarcane areas planted under reduced row spacing.

Nevertheless, there is a long way to go to obtain increases related to plant row spacing management, though this review shows the importance of row spacing, highlights the research needed to evaluate the spacing effect during ratoon cycles, and correlates these with other factors associated (soil texture, variety, environmental conditions).

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1.8. References

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Chapter 2: Sugarcane yield in different planting configuration and edaphoclimatic conditions in the long-term (Sugar Tech)

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Abstract

The canopy is an important structure to increase the biomass accumulation by plants just like the root system is responsible by the water supply and soil resources. The change in the sugarcane planting configuration can modify, quantitatively or qualitatively, these structures and, consequently, the final biomass yield. Accordingly, the objective of this work was to assess, during four crop seasons, sugarcane yield as well as aboveground and roots parameters of plants cultivated in different planting configuration, in areas with total absence of machine traffic and mechanical agricultural operation. For this, two experiments were conducted under field conditions, in clayey and sandy soil. The experiments were performed during four crop seasons under a randomized block design with six treatments (planting configurations), such as: CS, conventional spacing (1.50 m); AS, alternated spacing (0.90 × 1.50 m); TS, triple spacing (0.75 × 0.75 × 1.50 m); PP 1.0 m, precision planting (1.0 × 1.0 m); PP 0.75m, precision planting (0.75 × 0.75 m); and PP 0.50 m, precision planting (0.5 × 0.5 m). During the cycle of second and third ratoon was evaluated the plant population, root and aboveground biomass production, sugarcane stalks yield and the sugar and fiber production. The planting of the equidistant spacing PP 0.50 m, in edaphoclimatic conditions without restrictions to the sugarcane cultivation, increases the sugar yield, fiber and stalk yield per hectare. The reduction of sugarcane row spacing, independently of edaphoclimatic conditions, increases the production of dry biomass of root up to the depth of 1 m in ratoons crop cycles. The planting configuration,

associated with the maturation type of the sugarcane cultivar and the production environment, influence in the cane fields longevity.

Keywords: Row spacing, root system, *Saccharum* spp., precision planting,

2.1 Introduction

The sugarcane is the fourth crop most cultivated in Brazil (IBGE 2018), contributing for wealth generation and presenting great economic, social and environmental importance for the producing regions (CNI 2017). Furthermore, the crop represents a large part of renewable energy production in the country, thus obtaining a prominence in the global scenario. In view of the increase in global demand for renewable energy sources (CNI 2017; Sanches et al. 2017), becoming necessary to develop agricultural production technologies to reach the raw material demand, especially to sugarcane crop.

The Brazilian sugarcane production has shown a significant increase in the last decades, due to the increasing in sugarcane area cultivated – plant cane and ratoon cane (CONAB 2018a). However, in the center-south region of Brazil, crop productivity declined in the last decade (CONAB 2018a; OECD-FAO 2015; Torquato et al. 2015), due to the intensification of the mechanical process in sugarcane fields, including the mechanical harvest (green cane), which in the last crop season represented 97% of the total harvest area in this region (CONAB 2018b). Furthermore, low crop yields are related to soil degradation and compaction induced by intensive machinery traffic, crop damage associated with mechanical harvesting, pest proliferation, lifespan of sugarcane fields, climate constraints, and low sector's capacity of investments (Bordonal et al. 2018; Dias and Sentelhas 2018; Lisboa et al. 2018).

The increase in biomass yield per area (productivity) is economically the main mechanism to increase crop production (Sanches et al. 2017). In this context, among the many management practices adopted throughout the crop seasons, the change in planting spacing has been gaining prominence in the sugarcane industry (Rossi Neto et al. 2018; Torquato et al. 2015). Nevertheless, the decision to change the row spacing is strongly affected by exchange and incompatibility of existing equipment on the agricultural market (Moraes Neto 2002) resulting, in a limited production in the field.

Studies have shown that the reduction of row spacing may be an alternative to promote greater productivity in cane fields by the world (Barbieri et al. 1987; James 2004; Rossi Neto et al. 2018). The standardization of a same distance between row spacing and clumps (equidistant spacing) can, in addition to promoting a better plants distribution in the field, to present an economy to the country's sugarcane industry, increasing the productivity and decreasing spending of seedlings in the planting time (Rossi Neto et al. 2018).

The gains on sugarcane yield according to the adjustment of the best row spacing to plant growth promotes several factors above and belowground, such as: a better distribution of the root system along the soil profile, aiding in water absorption and nutrients (Rossi Neto et al. 2018; Vasconcelos and Casagrande 2008); the fastest closing of the canopy (Garside and Bell 2009), reducing competition with weeds and obtaining a better use of solar radiation (Smit and Singels 2006; Luo et al. 2004); optimization of population density, highlighted by the greater the correlation with yield (Rossi Neto et al. 2017). Therefore, it is necessary to understand how the management of planting spacing will affect the ratoons longevity, due in the scientific literature few studies were conducted during the plant cane and ratoon cane cycle, as well as, the yield response according to the row spacing adopted maybe occurs after some crop seasons (Barros and Milan 2010; Teodoro et al. 2013). In this context, a greater economic return in the long term, postpone of cost with renovation time of a sugarcane area (Borba and Bazzo 2009).

A new farming environment was created by intense mechanization in the last decade, and so experts in the sector highlight the importance of management practices aimed at cane fields preserving. Among the management addressed, the better plants distribution on the field and the establishment of a noncompetitive population density represents an important function to achieve this objective. In this way, defining a planting spacing that supports a better plants development, thus ensuring the ratoons longevity is an important step for the Brazilian sugarcane industry in view of the growing global demand by biofuels. Therefore, the objective of this work was to assess, during four crop seasons, sugarcane yield as well as aboveground and roots parameters of plants cultivated in different planting configuration, in areas with total absence of machine traffic and mechanical agricultural operation.

2.2. Materials and Methods

2.2.1. Description of the experimental fields

Two experiments were installed in commercial sugarcane areas located in State of Sao Paulo - Brazil. The first experiment (clayey soil – Site 1) was conducted in a commercial area of Guaíra mill (20º24’17’’S; 48º12’10’’W), located in Guaíra-SP. The weather of this area is classified as subtropical Aw (Köppen and Geiger 1928), with maximum temperatures exceeding 23°C, minimum temperatures of less than 17°C and 550 m. The mean of annual rainfall in this region is 1.402 mm. The soil of the experimental area was classified as Typic Eutrustox (USDA 2010). The production environment of the experimental area was characterized as "A2" (Prado 2005).

The second experiment (sandy soil - Site 2) was conducted in a commercial area of Zilor mill (22º52’85’’S; 48º82’14’’W), located in Lençóis Paulista-SP. The weather of this area is classified as subtropical Aw (Köppen and Geiger 1928) and 560 m. The average annual rainfall across the region is 1.314 mm. The soil of the experimental area was classified as Rhodic Hapludox (USDA 2010). The production environment of the experimental area was characterized as "C2" (Prado 2005).

2.2.2. The installation of the experiments

Prior to planting, lime and phosphate fertilizer (1 Mg ha^{-1} of magnesium thermophosphate) was applied according to the specific requirements indicated from the soil analysis, and the soil was prepared with a disc harrow. After this, the planting was carried out in July 2012 in site 1 and in October 2012 in site 2.

The chemical characterization of the soil was carried out before planting and after liming and phosphate fertilizer application in both sites. The soil samples were randomly collected from each experimental area, subdivided into the layers; 0.00-0.20 m, 0.20-0.40 m, 0.40-0.60 m, and 0.60-0.80 m (Table 2.1) and analyzed according to the methodology described in Raij et al. (2001).

Table 2.1. Chemical soil analysis from the experimental areas collected before the opening of the furrow for the sugarcane planting.

Depth	O.M.	pH	P	K	Ca	Mg	H+Al	CEC	Bs	B	Cu	Fe	Mn	Zn
m	*g dm^{-3}*	*$CaCl_2$*	*mg dm^{-3}*	*mmol$_c$ dm^{-3}*					*%*	*mg dm^{-3}*				
Typic Eutrustox, clayey soil														
0.0-0.2	28	5.7	44	14.5	46	11	19.7	91	79	0.1	4.4	9	8.4	0.5
0.2-0.4	24	5.9	32	11.6	35	9	23.8	79	72	0.4	4.7	9	9.9	0.4
0.4-0.6	17	5.6	14	8.1	21	6	25.0	60	60	0.3	4.0	6	5.8	0.1
0.6-0.8	13	5.6	7	6.7	15	4	20.8	46	57	0.3	2.8	4	3.3	0.1
Rhodic Hapludox, Sandy soil														
0.0-0.2	15	4.7	11	4	13	5	-	46	48	un.	un.	un.	un.	un.
0.2-0.4	14	4.8	26	5	13	4	-	43	43	un.	un.	un.	un.	un.
0.4-0.6	10	4.8	7	4	9	4	-	40	48	un.	un.	un.	un.	un.

O.M. - Organic Matter; **pH** - pH Value; **P** - Phosphorus; **K** - Potassium; **Ca** - Calcium; **Mg** - Magnesium; **H+Al** - Potential acidity; **CEC** - Cation Exchange Capacity; **Bs** - Base saturation; **B** - Boron; **Cu** - Copper; **Fe** - Iron; **Mn** - Manganese; **Zn** - Zinc. **un.**: unvalued

The physical characterization of sites using granulometry analysis (pipette method), aggregates (wet sieving), soil density and porosity (tension table), and soil resistance to penetration by the impact penetrometer (Stolf 1991) are shown in Table 2.2.

Table 2.2. Physical soil analysis from the experimental areas collected before the opening of furrows for sugarcane planting.

Depth	Granulometry			Aggregates	Density	Porosity			SPR
	Sand	Silt	Clayey	WAD		Macro	Micro	TP	
m	$g\ kg^{-1}$			*Mm*	$Mg\ m^{-3}$	$m\ m^{-3}$			*MPa*
				Typic Eutrustox, clayey soil					
0.0-0.1	125	359	516	1.03	1.28	0.03	0.52	0.55	6.33
0.1-0.2	104	350	546	0.90	1.28	0.07	0.48	0.55	5.90
0.2-0.4	91	304	605	0.75	1.34	0.04	0.49	0.52	3.94
0.4-0.6	77	280	643	0.87	1.19	0.07	0.47	0.54	3.83
0.6-1.0	77	289	634	0.70	1.22	0.06	0.48	0.54	un.
				Rhodic Hapludox, Sandy soil					
0.0-0.1	682	14	145	un.	1.64	0.10	0.21	0.30	2.29
0.1-0.2	683	16	142	un.	1.64	0.05	0.19	0.23	3.31
0.2-0.4	619	18	172	un.	1.71	0.02	0.29	0.31	3.65
0.4-0.6	623	20	178	un.	1.72	0.03	0.21	0.24	3.20
0.6-1.0	593	23	180	un.	1.71	0.09	0.20	0.29	3.04

SPR - Soil Penetration Resistance; **TP** - Total Porosity; **WAD** - Weighted Average Diameter. **un.**: unvalued

2.2.3. Experimental design

At planting, different numbers of seedlings were used according to the planting density target for each treatment. For the conventional treatments CS, AS, and TS, the seedlings were planted using a density from 18 to 20 buds per meter of furrow. For the precision planting treatments (PP 1.0 m, PP 0.75 m, and PP 0.5 m), two bullets with two buds each placed on plant furrow aiming to obtain a good initial plant stand (Figure 2.1). The points are equidistant from each other, that is, they have the same distance between row spacing and plants.

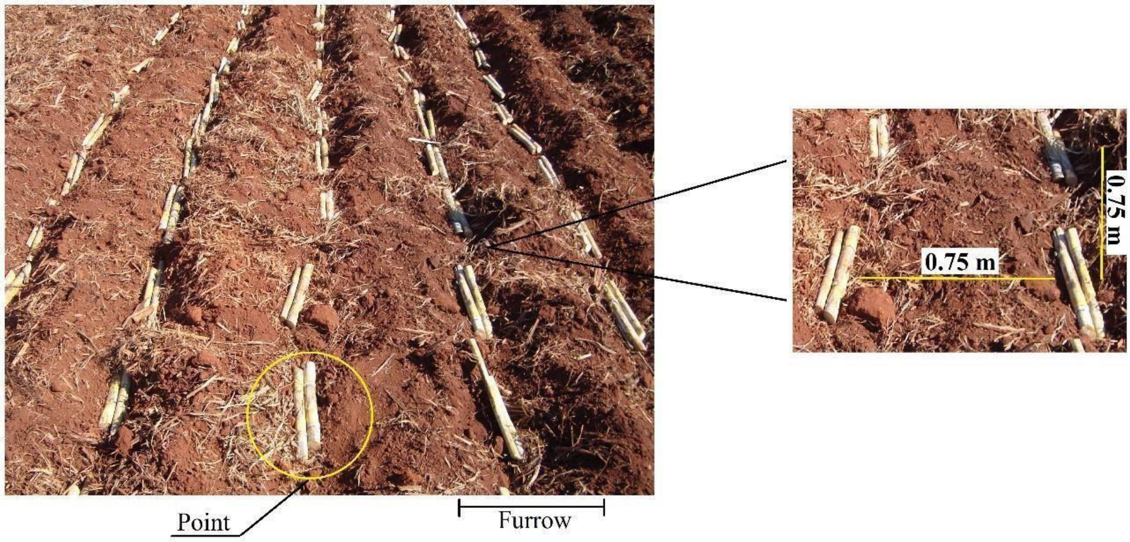


Figure 2.1. Illustration of the precision planting of the sugarcane.

The studies were carried out in a randomized block design, with six treatments with four replicates. The established treatments were the following: CS, single 1.5 m row spacing or conventional spacing, which provides 6667 linear meters of furrow per hectare with within furrow planting density of 18-20 buds per meter of row (similar density to that used in commercial sugarcane crop); AS, alternated spacing that provides a spacing of 0.90 × 1.50 m double row spacing which provides 8333 m of furrow per hectare with the same planting density of 18-20 buds per meter of row; TS, triple spacing that offers a spacing of 0.75 × 0.75 × 1.50 m row spacing, which provides 10,000 m of furrow per hectare with a similar within row planting density as above (18–20 buds per meter of furrow); PP 1.0 m, precision planting that offers a spacing of 1.0 × 1.0 m between plants and row spacing, totaling 10,000 plants per hectare; PP 0.75 m, precision planting that offers spacing of 0.75 × 0.75 m between plants and row spacing, totaling 17,777 plants per hectare; PP 0.5 m, precision planting that offers a space of 0.5 × 0.5 m between plants and row spacing, totaling 40,000 plants per hectare (Figure 2.2).

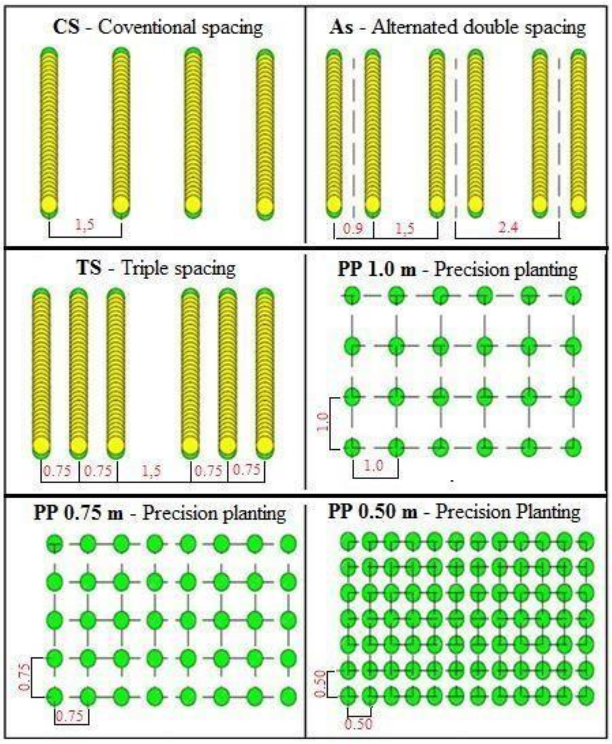


Figure 2.2. Illustration of the row spacing and plants tested in the experimental areas.

In site 1, each plot consisted of a 24-m wide and 15-m long, with the number of planting furrows per plot varying according to the row spacing (Figure 2.3). The sugarcane cultivar RB966928 was used, which is widely planted in the south-central region of Brazil. This crop cultivar is recognized as a high tillering in plant cane, as well as good sprouting and excellent closing of row spacing in the subsequent ratoon crop (RIDESA 2010).

In site 2, each plot consisted of a 24-m wide and 50-m long and only the sugarcane cultivar CTC 15 was planted (Figure 2.3), which has as characteristic high resistance to hydric stress, rapid plant growth, wide adaptability and good productivity in all crop season (COPLACANA 2015). The number of rows per plot it is in accordance with the row spacing of each treatment. In the experiment of site 2 the treatments PP 1.0 m and 0.50 m were not installed.

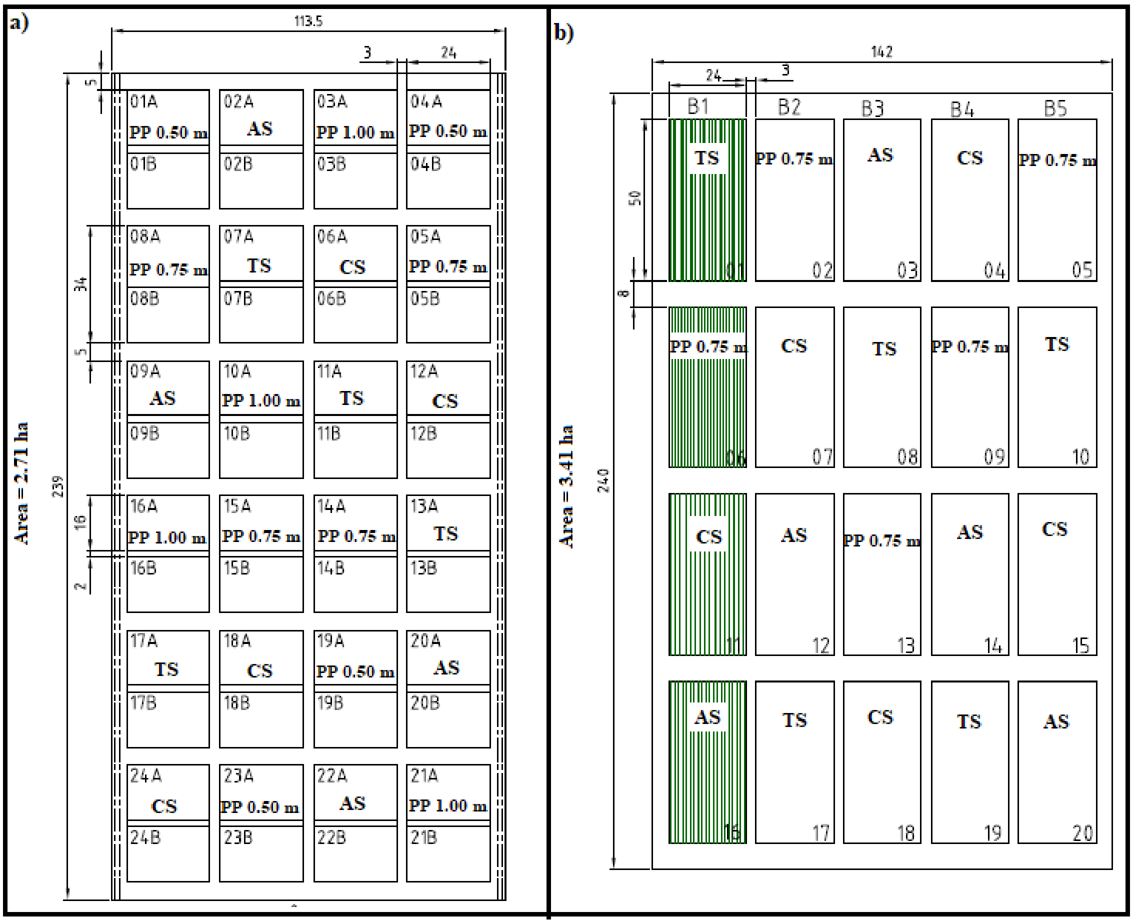


Figure 2.3. Experimental sites details located in the Guaíra **(a)** and **(b)** Zilor sugarcane mill. **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

2.2.4 Field evaluation

The biometrics evaluations, biomass accumulated, and morphophysiological aspects were measured throughout of crop plant growth during the crop seasons 2015/2016 and 2016/2017. In site 1, the evaluations during the crop season 2015/2016 occurred at 144, 235, 314 and 452 days after harvest (DAH) while in the crop season 2016/2017 carry out at 78, 158, 225 and 371 DAH. Regarding site 2, there weren't evaluations during the crop season 2015/2016, occurring only in the harvest time at 388 DAH. Already for crop season 2016/2017, the evaluations were performed at 45, 136, 211 and 386 DAH.

Sugarcane yield assessments, technological attributes (sugar and fiber) and root system were measured at the harvest time of the crop seasons 2015/2016 and 2016/2017, specifically carried out in August in the site 1 and October in the site 2.

2.2.5. Biometric Parameters

The number of tillers were performed in central area of the plot (four rows with 10 meters of length). For height and diameter measurements within the area of tillers account, 10 tillers were selected for it. The diameter (mm) was measured in the middle third of the stalk using a digital caliper; the height (cm) were measured from the ground to the height of the leaf +1 (total visible dewlap - TVD).

2.2.6. Sugarcane Biomass

2.2.6.1. Sugarcane biomass aboveground

Sampling of the above ground part of the sugarcane were performed in 2.0 meters of cane row, in central area of the plot in the same periods of biometric and root evaluation. The weight of the entire plant material (dried leaves, tops and stalks) of each treatment was obtained directly in the field. After weighing, each plant sample were ground in chopper forage, for collecting a subsample. These subsamples packed in plastic bags closed and after weighed in analytical balance (accuracy of 0.01 g) after the samples were drying in a forced-air-circulation oven at 65 ºC (72 hours) and weighed again for determination of moisture of the material. With the moisture of the samples were calculated the accumulation of dry biomass (Mg ha^{-1}).

To estimate the dry biomass accumulation from the sugarcane aboveground in the treatments (CS, AS, TS, PP 1.0m, PP 0.75m and PP 0.50m), during the experimental period, the logistic function was used (Equation 2.1):

$$\boldsymbol{Y} = a/((1 + \exp((-k * (x - xc)))) \qquad (2.1)$$

Where: Y - Aboveground dry biomass in kg ha^{-1}; xc - days after sugarcane harvesting (DAH); a - maximum aboveground dry biomass produced in the period between harvestings. The constant k was estimated using the Origin program.

This function is characteristic for plant growth representation and widely used in works of this subject (Franco et al. 2011; Lucchesi 1984; Machado et al. 1982; Oliveira et al. 2010).

In each experiment, six equations were obtained according to plant spacing, the which described the aboveground biomass dry weight variation in the time. The physiological index used to evaluate possible differences between treatments was the dry matter production rate (DMPR), obtained by manipulating the adjustment functions, according to the model described by Lucchesi (1984).

2.2.6.2. Sugarcane root biomass and development

The experiments were managed aiming to minimize the possibility of restrictions on root development, such as compaction, that could be caused by machine traffic. Thus, it was presumed that the possible differences in root development would be associated with planting arrangement. The analysis methodology of the root system was the same used by Otto et al. (2009) with modifications according rows spacing treatments (Figure 2.4).

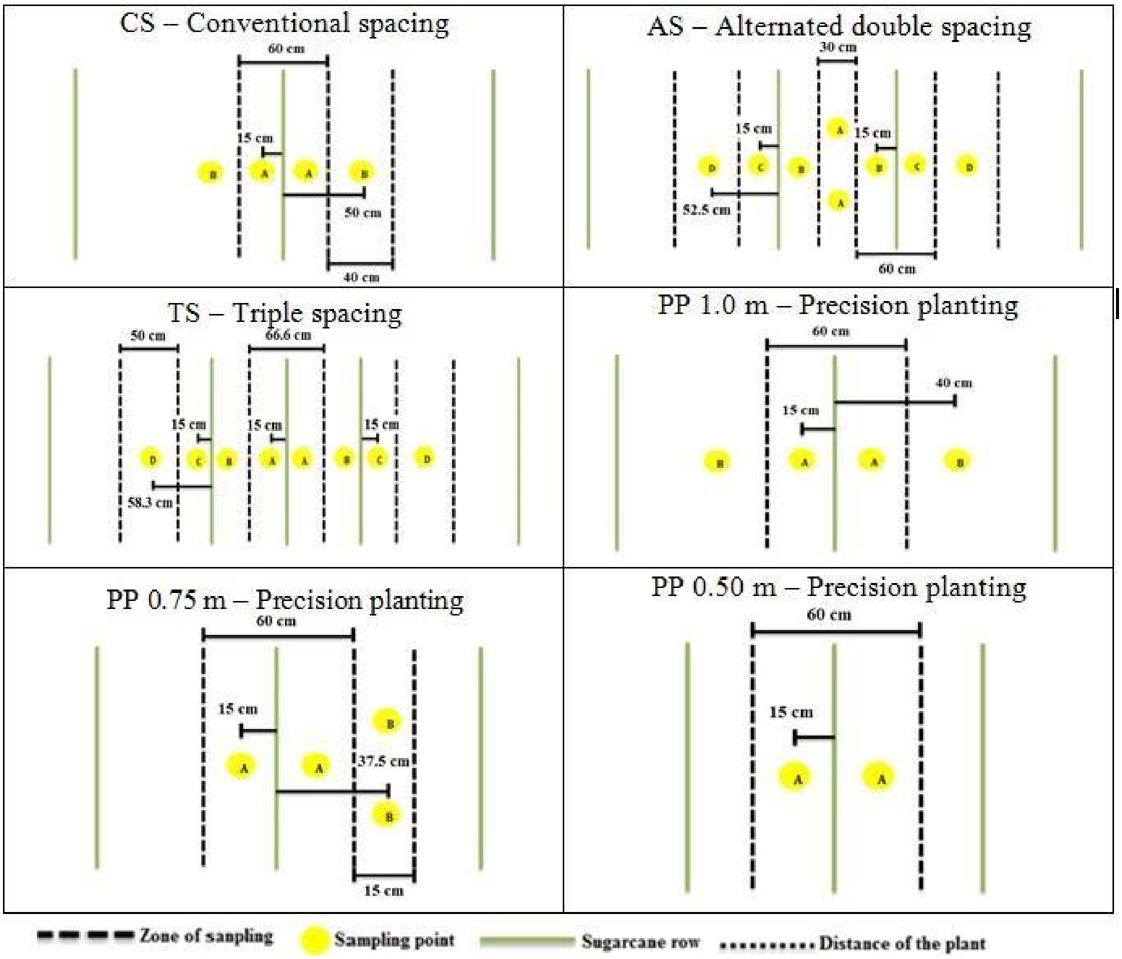


Figure 2.4. Sampling of the root system sugarcane with different row spacing and plants distribution.

Stainless steel probes 1.2 m long with an internal diameter of 0.055 m were used to collect soil samples and roots from the depth's ranges; 0.00-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60 and 0.60-1.00 m. After sample collection, soil was separated from the roots by dry sieving (mesh sieve - 1.0 mm). Separated roots were rinsed in running water and dried in a ventilated oven at 65°C to determine their dry matter biomass.

After weighing, the amount of dry root biomass was calculated for each layer from the six different planting configurations using the equation (2.2):

$$\boldsymbol{DBR} = ((Sv * Rm)/Pv)/1.000.000 \tag{2.2}$$

Where: **DBR** – dry biomass of root (Mg ha^{-1}); **Sv** – Soil volume in each range and layer assessed (m^3 ha^{-1}); **Rm** – Root mass collected from the layer (g); **Pv** – root sampling Probe volume of assessed layer (m^3); **1.000.000** – conversion from grams to Megagrams.

2.2.7. Physiological parameters

2.2.7.1. Leaf chlorophyll content

Leaf chlorophyll content (SPAD index) was estimated nondestructively, using a SPAD-502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA). This index was used preferentially because of the strong relationship between readings of portable chlorophyll meter and leaf chlorophyll content has been demonstrated by several authors (Yadava 1986; Marquard and Tipton 1987; Markwell et al. 1995).

In this study, collected the middle of leaf removing the center rib, ensuring the total seal of the measuring chamber. In each treatment held four repetitions with 10 measurements, totaling 400 measurements per treatment. The repetitions were performed in four rows in the center, in a random manner.

2.2.7.2. Sugarcane photosynthetic parameters

Photosynthetic parameter data was collected between 9:30 am – 15:30 pm during the evaluations of crop season, using equipment IRGA LI 6400 XT under natural light conditions. The data included net photosynthetic rate (PN, μmolm^{-2} s^{-1}), transpiration rate (E, mmolm^{-2} s^{-1}), stomatal conductivity (GS, mmolm^{-2} s^{-1}), and Internal carbon dioxide concentrations (Ci). The PN equals the rate of photosynthetic CO_2 fixation minus the rate of CO_2 loss during respiration. The E is the amount of evaporation per unit time from a leaf surface. The g_s is the Stomatal conductivity (Lü et al. 2000; Luo et al. 2004). Measurements were performed, at both sites, three times in each plot throughout the crop season being 7 plants per plot were evaluated. The first youngest fully expanded (+1) leaves at the top canopy were measured reciprocally at the middle to upper section excluding the midrib. The direction of leaf chamber was adjusted towards sun light to ensure that measurements were done under a uniform light intensity.

2.2.8. Morphological parameters

2.2.8.1. Leaf area index (LAI)

The leaf area index (LAI) was analyzed using the Ceptometer, PAR/LAI (Model LP-80, Decagon, Pullman, WA, USA). The readings were performed putting the photosensitive ruler of appliance horizontally in the middle of sugarcane line keeping the other sensor where there is total solar radiation. The readings were occurred always at 13 hours, period of high solar radiation. However, the LAI was measured just in the first and second-time evaluation due to the size and the plants lodged by your weight.

2.2.8.1. Sugarcane dry and greens leaves

In the same time of the LAI evaluation was evaluated the number of dry and green leaves in 10 plants per plot for each treatment.

2.2.9. Crop Yield

2.2.9.1. Productivity of stalks and technological parameters of sugarcane

The sugarcane yield (Mg ha^{-1}) from all plots was assessed by manually harvesting the stalks present within a 100 m^2 central area. The stalks were separated from the tops and dry leaves and subsequently weighed using a dynamometer coupled to a grab loader. The stalk yield assessment area was unaffected by machine traffic during all years of the experiment.

For the assessment of the technological parameters (fiber and Pol – sucrose content) 10 stalks were collected per plot, following the methodology of collection and analysis of CONSECANA (2003). Prior to harvest, the population of plants per hectare was assessed by counting all viable stalks for industrialization present within a 15 m^2 area in the center of the stalk yield assessment area.

2.2.9.2. Longevity of cane field under different planting spacings

The longevity of the cane field was studied by analyzing the sugarcane yield, planted in different row spacings and between plants, over four crop seasons for two different edaphoclimatic regions. In both areas, were included the plant cane, and ratoon cycles (first, second and third ratoon).

For the Site 1, it was used the sugarcane yield data from Rossi Neto et al. (2018) for the plant cane cycles and the first ratoon added to the data found in this study. Regarding site 2, the information concerning the first two crop cycles was be obtained from the thesis of the Guilherme Adalberto Ferreira Castioni (Castioni 2017).

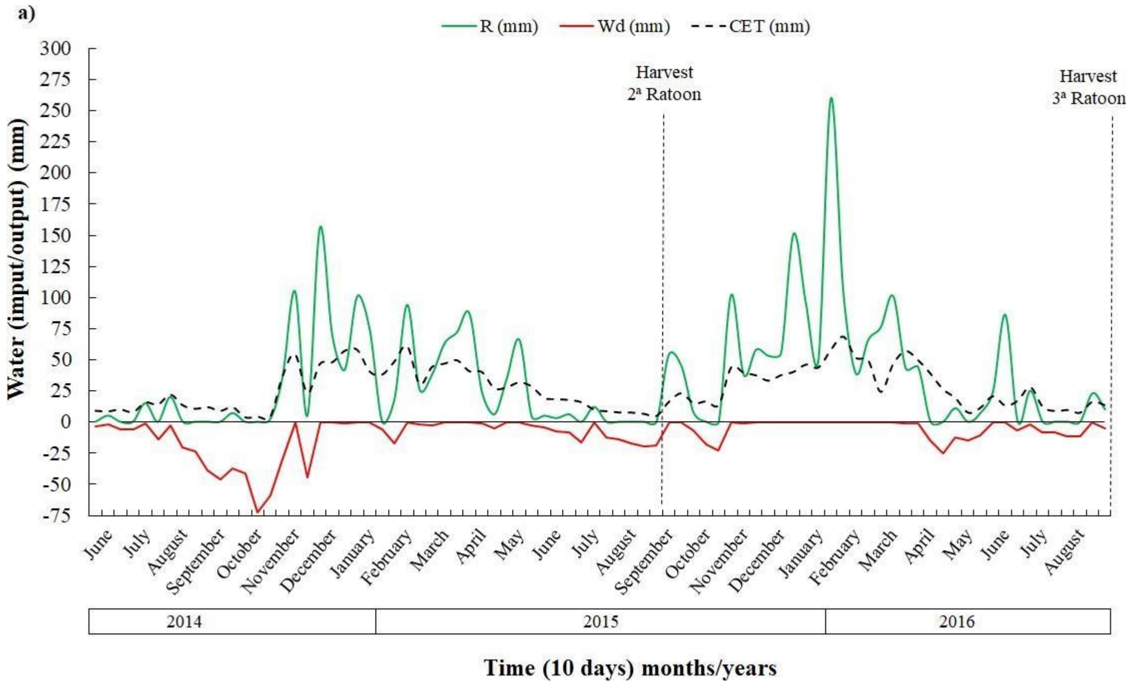
To observe the maintenance of sugarcane yield throughout the crop seasons, an analysis was performed by means of the productivity difference between the harvests during the period evaluated. The calculation was performed using equation (2.3) adapted of Alvarez et al. (1987), as follows:

$$\boldsymbol{QMgCH} = (PPH - PCH)/PPH) * 100 \qquad (2.3)$$

Where: **QMgCH** – Productivity difference between crop seasons (%); **PPH** – Productivity of the previous harvest (Mg ha^{-1}); **PCH** – Productivity of the current harvest (Mg ha^{-1}); **100** – conversion from Megagrams per hectare to percentage .

2.2.10. Weather data

Weather data were obtained from automatic weather stations installed near the experimental areas. Through the adapted methodology of Thornthwaite and Mather, the weather data were used for the preparation of climatological water balance (Figure 2.5, Site 1 – Figure 2.6, Site 2).



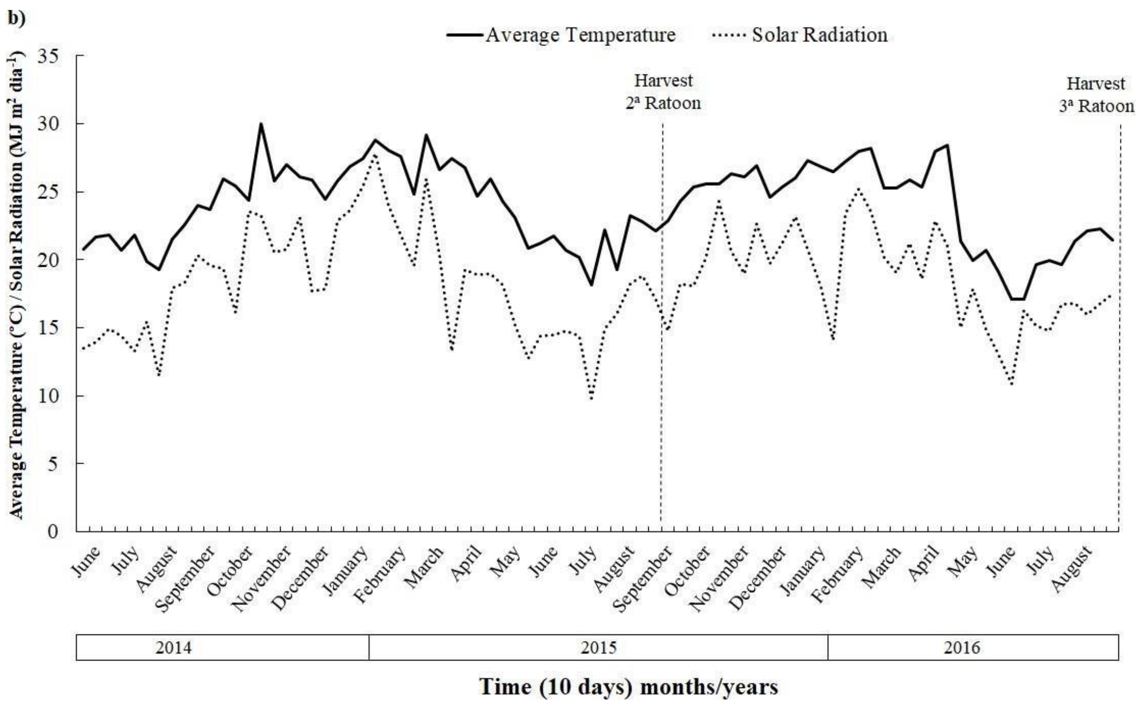


Figure 2.5. The weather balance of the site 1, during the period from May/2014 to Aug/2016, was shown by **(a)** water extract balance (R = rainfall; Wd = Water deficit; CET = Crop Evapotranspiration) and **(b)** with the average temperature the air and solar radiation.

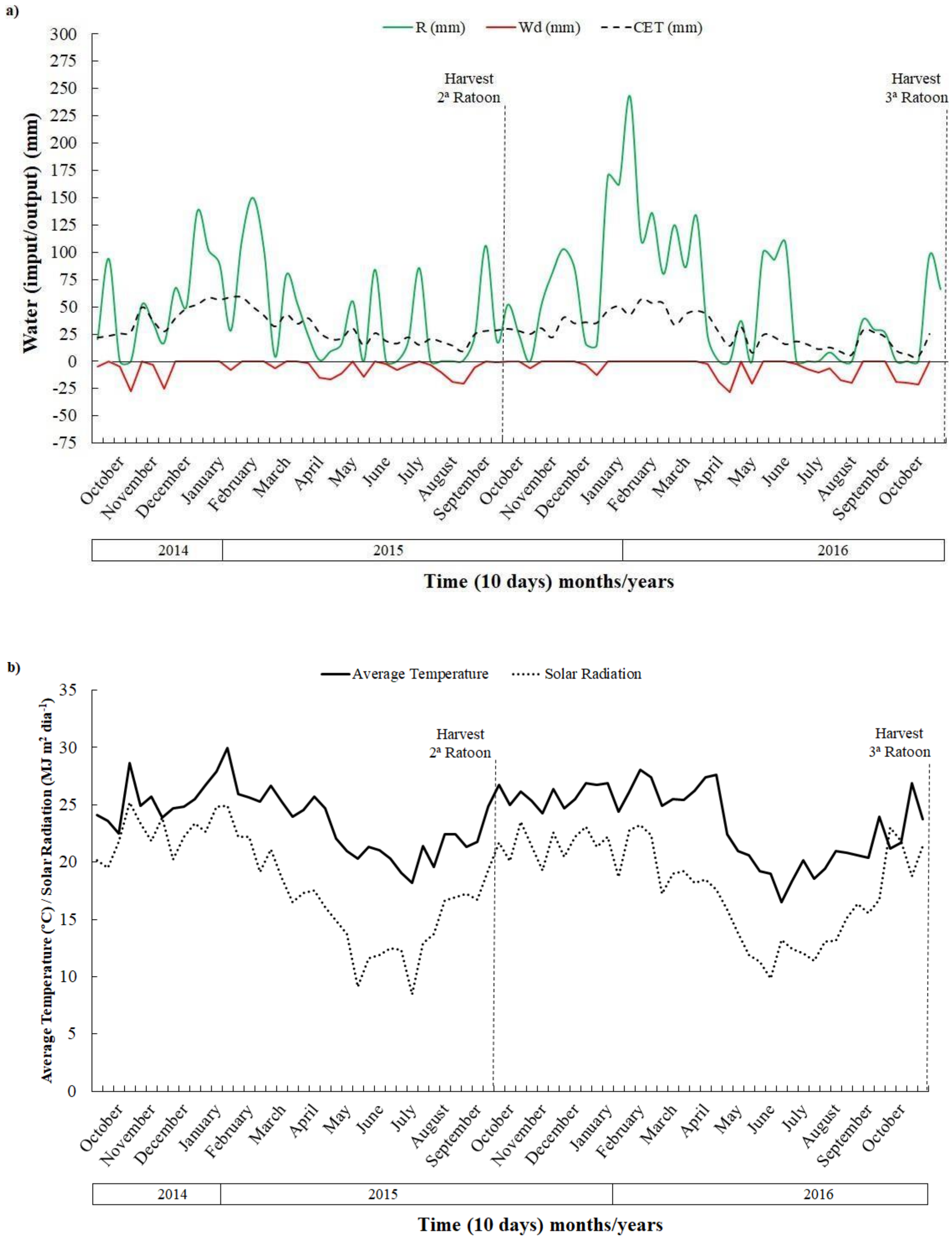


Figure 2.6. The weather balance of the site 2, during the period from Sept/2014 to Oct/2016, was shown by **(a)** water extract balance (R = rainfall; Wd = Water deficit; CET = Crop Evapotranspiration) and **(b)** with the average temperature the air and solar radiation.

In site 1, the second ratoon cycle lasting 454 days, the precipitation was 1.197 mm. The seasonal evapotranspiration in dryland management was 1.765 mm (Figure 2.5). In the third ratoon cycle, lasting 369 days, precipitation was 1.627 mm. The crop evapotranspiration in dryland management was 1.078 mm.

In site 2, the second ratoon cycle lasting 388 days, precipitation was 1.706 mm. The crop evapotranspiration in dryland management was 1.229 mm (Figure 2.6). In the third ratoon cycle, lasting 386 days, precipitation was 2.223 mm. The crop evapotranspiration in dryland management was 1.024 mm.

2.2.11. *Data and Statistical analysis*

The results were submitted to analysis of variance using the F test at a 5% probability level for significance. The data was later analyzed to compare the averages using t test (LSD) at 5% probability through the Sisvar program (Ferreira 2014).

2.3. Results and Discussion

2.3.1. Morphological parameters of sugarcane

2.3.1.1. Leaf Area Index (LAI)

A gradual increase in the LAI of the crop was observed at all spacings throughout the cycle, regardless of the edaphoclimatic conditions and cultivar (Tables 2.3 and 2.4). During the second ratoon (Site 1), the LAI not presented significant difference ($p<0.05$) until 235 DAH among treatments (Table 2.3). Nevertheless, all treatments reached the LAI values above 4 being that, this value is enough for the sugarcane crop to intercept 95% of incident solar radiation (Machado et al. 1985).

Table 2.3. Leaf area index of sugarcane planted in different spacings during second and third ratoon in site 1.

LAI	2ª Ratoon		3ª Ratoon	
	October	January	November	January
	144	235	78	158
Treatments	DAH		DAH	
CS	0.4	4.2	2.0	4.8 b
AS	0.4	4.6	2.5	6.1 a
TS	0.4	5.2	2.6	5.1 ab
PP 1.00 m	0.4	4.0	2.0	3.2 c
PP 0.75 m	0.4	4.7	2.3	3.3 c
PP 0.50 m	0.4	4.1	1.9	4.3 bc
LSD 5%	**0.21**	**2.06**	**1.16**	**1.14**
F test α	**p<0.98**	**p<0.81**	**p<0.70**	**p<0.00**
CV%	**33**	**31**	**35**	**17**

The row spacing effect in sugarcane leaf area index (**LAI**) identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD**, least significant difference; **CV**, coefficient of variation; **CS**: conventional spacing; **AS**: alternated spacing; **TS**: triple spacing; **PP 1.0m**: precision planting of 1.0m; **PP 0.75 m**: precision planting of 0.75 m; **PP 0.50m**: precision planting of 0.50m.

During the third ratoon, there was a significant difference in LAI among the row spacings. This difference was verified at 158 DAH, when the plants in AS row spacing showed higher values than the plants cultivated in others planting configuration, except the plants in TS which has the same performance (Table 2.3). Regarding the LAI value attained in this cycle, different from the previous cycle, not all the spacings reached the ideal value until the second evaluation in 158 DAH.

In site 2, there was no evaluation of LAI during the second ratoon. For the third ratoon, there was no difference in the LAI among row spacing and the LAI value do not reach the ideal value until the second evaluation in 136 DAH (Table 2.4).

Table 2.4. Leaf area index of sugarcane planted in different spacings during third ratoon in site 2.

LAI	November	**3ª Ratoon**	February
	45		136
Treatments		DAH	
CS	0.9		3.4
AS	1.2		3.4
TS	1.2		3.1
PP 0.75 m	1.1		2.6
LSD 5%	**0.65**		**1.06**
F test α	**p<0.59**		**p<0.38**
CV%	**36**		**21**

The row spacing effect in sugarcane leaf area index (LAI) identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD**, least significant difference; **CV**, coefficient of variation; **CS**: conventional spacing; **AS**: alternated spacing; **TS**: triple spacing; **PP 0.75 m**: precision planting of 0.75 m.

Despite few studies on the subject, it was expected that increasing the population density by reducing plant spacing would increase the leaf area index of the crop as observed by Singels and Smit (2009). However, it was clear that the method used was not effective, requiring an adaptation to observe the foliar differences in the final phenological stages of crop development.

2.3.1.2. Sugarcane dry and green leaves

The green leaves of the cultivar RB966928, in the mean of treatments (%), decreased over the cycles reaching stabilizing until crop harvest in site 1 (Figure 2.7a, b). For dry leaves, the inverse process has occurred, increasing and subsequently stabilizing (Figure 2.7a, b). It can also be observed that only in the second ratoon crop the dry leaves per plant exceeded that of green leaves.

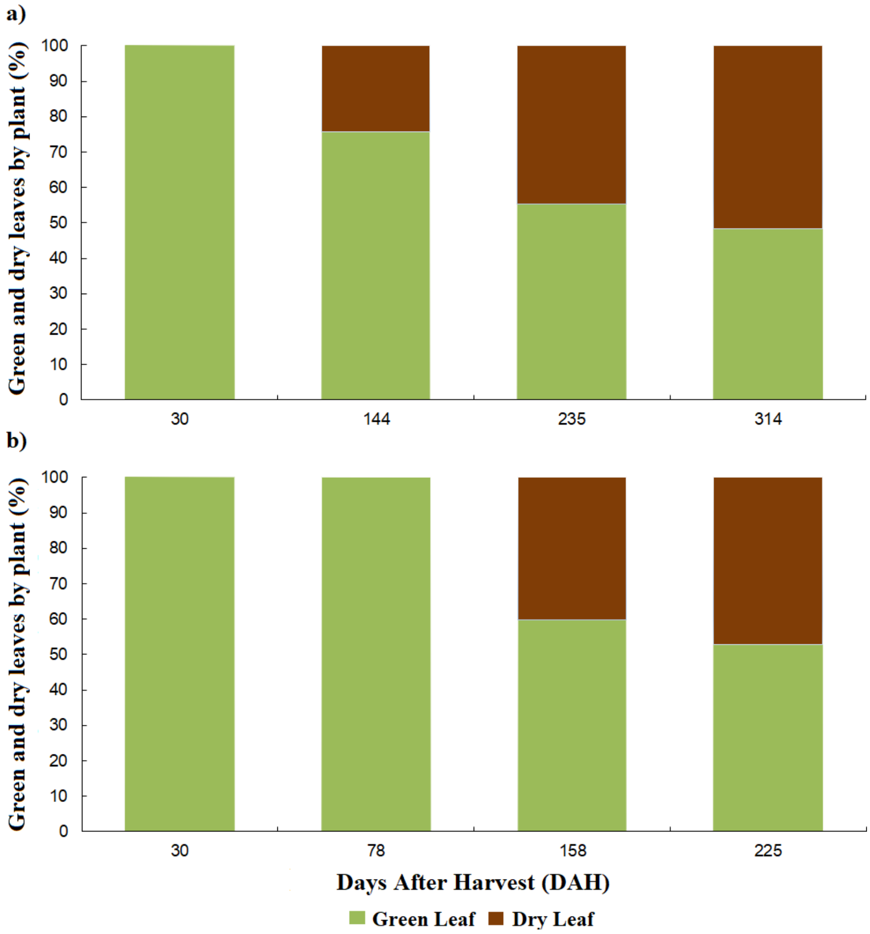


Figure 2.7. Percentage of green and dry leaves per sugarcane plant during the second **(a)** and third ratoon crop **(b)** in site 1.

Same behavior occurred with CTC 15 cultivar in site 2 conditions (Figure 2.8). During the crop season, as took place in the fourth sugarcane crop in site 1, the dry leaves (%) exceeded the green leaves during the cycle. This process of older of the leaves was more intense than in the cultivar RB966928 due to the presence of orange rust on the plants of all treatments. According to Cruz et al. (2014), this disease has become a problem in Brazilian sugarcane fields in the last decade reducing crop yields (in order of 20 to 40% in tons of stalk per hectare and 15 to 20% in sucrose content), mainly due to the reduction of photosynthetic area of the leaves.

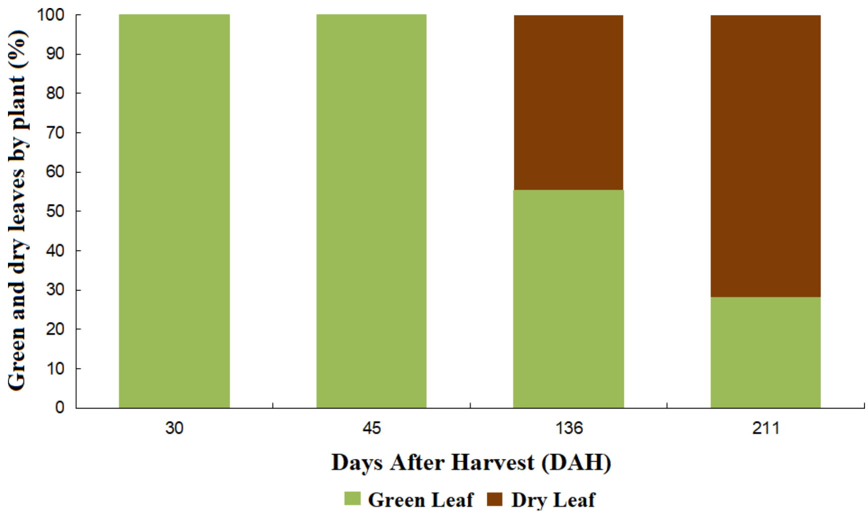


Figure 2.8. Percentage of green and dried leaves per sugarcane plant during the third ratoon in site 2.

The leaf development of cultivar CTC15 was also affected by other factors, being: the soil conditions, as chemical and physical limitations (Table 2.1 and 2.2); and the harvest season, making it costly for the cultivar to go through a long period of restricted weather conditions affecting its development (Figure 2.6 a).

Thus, associated with the foliar area and consequently, the crop photosynthesis, the leaf development presented the same behavior in both locations and rows spacing. This result shows a contrast with the results observed by Bonaparte and Brawn (1976) in maize and Singels and Smith (2009) in sugarcane. These authors have verified a lesser leaf number by reducing the spacing and/or increasing the population density.

2.3.2. Physiological parameters of sugarcane

2.3.2.1. Leaf chlorophyll content

SPAD index measured of cultivars planted, in both experimental fields, declined progressively throughout the crop seasons evaluated for all planting spacings (Tables 2.5 and 2.6). Furthermore, there was no interference of the planting management in the leaf chlorophyll content, occurring thus due to the crop physiological aging process (Rhein and Silva 2017).

Table 2.5. SPAD index of sugarcane planted em different spacings during second and third ratoon in site 1.

SPAD	2ª Ratoon			3ª Ratoon		
	October	January	April	November	January	April
	144	235	314	78	158	225
Treatments	DAH			DAH		
CS	43.6 ab	42.3	36.8	45.8	39.4	38.9
AS	40.3 c	41.3	36.4	44.1	39.1	38.9
TS	41.7 abc	41.0	36.0	45.0	38.1	37.5
PP 1.00 m	44.4 a	41.3	35.5	44.6	38.4	36.6
PP 0.75 m	44.3 a	42.0	36.7	44.3	38.7	39.8
PP 0.50 m	41.1 bc	42.9	37.6	45.3	37.6	37.5
LSD 5%	**2.82**	**1.95**	**1.87**	**2.36**	**1.41**	**4.20**
F test α	**$p<0.02$**	**$p<0.35$**	**$p<0.30$**	**$p<0.67$**	**$p<0.14$**	**$p<0.61$**
CV%	**4**	**3**	**3**	**4**	**2**	**7**

The row spacing effect in sugarcane SPAD index identified with different letters are significantly different ($\alpha = 0.05$; Student's t test) within the same DAH (day after harvest). **LSD**, least significant difference; **CV**, coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

During the second ratoon in site 1, differences among treatments were only observed at 144 DAH in the second ratoon, where the PP 1.00 m and PP 0.75 m were superior to the treatments AS and PP 0.50 m, being like the others (Table 2.5). Furthermore, all the spacings had average chlorophyll content indices above 40 (SPAD index) until 235 DAH. On the other hand, in the next crop season, the index values declined below the 40 already at 158 DAH (Table 2.5). According to Torres Netto et al. (2005), SPAD index below 40 indicates the beginning of a chlorophyll deficiency, affecting the photosynthetic process of the plants.

There was no evaluation of the SPAD index during the second ratoon in site 2. When analyzing the leaf chlorophyll content of the crop in the third ratoon, similar behavior to the cultivar RB966928 in site 1 was observed, with occurred no difference among spacings (Table 2.6).

Table 2.6. SPAD index of sugarcane planted em different spacings during the third ratoon in site 2.

SPAD	**3ª Ratoon**		
	November	February	May
	45	136	211
Treatments		DAH	
CS	44.3	37.3	36.2
AS	44.8	36.6	35.9
TS	44.7	35.9	36.9
PP 0.75 m	44.2	37.0	37.7
LSD 5%	**2.62**	**2.23**	**3.56**
F test α	**p<0.93**	**p<0.55**	**p<0.68**
CV%	**4**	**4**	**6**

The row spacing effect in sugarcane SPAD index identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD**, least significant difference; **CV**, coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 0.75 m:** precision planting of 0.75 m.

Currently, there are no studies using this indicator with planting spacing in the sugarcane crop. The SPAD index, correlated with the content of chlorophyll and carotenoids in sugarcane (Almeida Silva et al. 2014), has been studied as a good indicator of disturbances in plants affected by environmental factors (Torres Netto et al. 2005; Zhao et al. 2010; Almeida Silva et al. 2014) and by management as the effect the doses of the herbicide (Almeida Silva et al. 2009; Ferreira et al. 2010) and nitrogen fertilization recommendation (Amaral and Molin 2011).

Thus, with the results presented above, the scarcity of studies with the SPAD index in different sugarcane planting spacings and the knowledge importance to identify conditions for the choice of good management, further studies are necessary.

2.3.2.2. Sugarcane photosynthetic parameters

Only the photosynthetic parameter net photosynthetic rate (PN) measured at 225 DAH presented difference among treatments took place in site 1. At this time, the plants under precision spacings showed higher values than the those cultivated in the others row spacing (Table 2.7).

Table 2.7. Photosynthetic parameters of sugarcane planted at different spacings during the third ratoon in site 1.

3ª Ratoon	78 DAH - November			
Treatments	PN *μmol m⁻² s⁻¹*	g_s *mol m⁻² s⁻¹*	Ci *μmol mol⁻¹*	E *mmol m⁻² s⁻¹*
CS	28	0.20	139	5.36
AS	27	0.19	129	6.15
TS	25	0.17	113	4.51
PP 1.0 m	25	0.19	152	5.68
PP 0.75 m	27	0.20	141	5.41
PP 0.50 m	31	0.22	133	5.73
LSD 5%	**4.56**	**0.03**	**39.81**	**1.49**
F test	**p<0.14**	**p<0.21**	**p<0.45**	**p<0.34**
CV%	**11**	**13**	**20**	**18**
Treatments	**158 DAH - January**			
CS	17	0.14	179	3.48
AS	16	0.13	174	3.15
TS	14	0.12	164	3.16
PP 1.0 m	16	0.12	161	2.96
PP 0.75 m	16	0.12	160	2.75
PP 0.50 m	16	0.13	175	2.82
LSD 5%	**4.65**	**0.03**	**35.93**	**0.95**
F test	**p<0.92**	**p<0.32**	**p<0.79**	**p<0.62**
CV%	**19**	**16**	**14**	**21**
Treatments	**225 DAH - April**			
CS	11 c	0.07	110	1.98
AS	14 bc	0.09	123	2.36
TS	14 bc	0.08	100	2.32
PP 1.0 m	16 abc	0.09	95	2.46
PP 0.75 m	17 ab	0.10	109	2.58
PP 0.50 m	20 a	0.12	113	3.12
LSD 5%	**4.94**	**0.03**	**38.09**	**0.79**
F test	**p<0.02**	**p<0.21**	**p<0.69**	**p<0.13**
CV%	**22**	**28**	**23**	**21**

The row spacing effect in sugarcane photosynthetic parameters identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m. **PN:** Net photosynthetic rate; **g_s**: Stomatal conductivity; **Ci:** Internal carbon dioxide concentrations; **E:** Transpiration rate.

Otherwise, in site 2 conditions, the stomatal conductivity (g_s) and transpiration rate (E) showed difference ($p<0.05$) among treatments at 45 DAH (Table 2.8), when the plants in CS had higher values of gs and E than the plants in others row spacings excluding those cultivated in TS.

Table 2.8. Photosynthetic parameters of sugarcane planted at different spacings during the third ratoon in site 2.

3ª Ratoon	45 DAH - November			
	PN	**g_s**	**Ci**	**E**
Treatments	*μmol m⁻² s⁻¹*	*mol m⁻² s⁻¹*	*μmol mol⁻¹*	*mmol m⁻² s⁻¹*
CS	41	0.36 a	175	6.94 a
AS	36	0.28 c	160	5.80 b
TS	39	0.33 ab	170	6.53 ab
PP 0.75 m	37	0.29 bc	160	6.06 b
LSD 5%	**4.3**	**0.04**	**14.1**	**0.83**
F test	**p<0.14**	**p<0.00**	**p<0.10**	**p<0.05**
CV%	**7**	**8**	**5**	**8**
Treatments	**136 DAH – February**			
CS	22	0.15	136	3.53
AS	23	0.16	153	3.67
TS	21	0.15	148	3.62
PP 0.75 m	21	0.16	163	3.24
LSD 5%	**6.8**	**0.03**	**34.1**	**1.40**
F test	**p<0.93**	**p<0.82**	**p<0.39**	**p<0.89**
CV%	**19**	**14**	**14**	**25**
Treatments	**211 DAH - May**			
CS	13	0.08	121	2.43
AS	13	0.09	136	2.65
TS	12	0.08	131	2.42
PP 0.75 m	13	0.08	116	2.40
LSD 5%	**5.0**	**0.3**	**47.9**	**0.7**
F test	**p<0.94**	**p<0.63**	**p<0.78**	**p<0.86**
CV%	**24**	**18**	**24**	**19**

The row spacing effect in sugarcane photosynthetic parameters identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 0.75 m:** precision planting of 0.75 m. **PN:** Net photosynthetic rate; **g_s**: Stomatal conductivity; **Ci:** Internal carbon dioxide concentrations; **E:** Transpiration rate.

When analyzing the physiological results, a difference in net photosynthesis rate was observed only from the 225 DAH for third crop cycle in site 1. At this time, as smaller the planting spacing and best the plants distribution in the field as greater was the photosynthesis value observed in the plants. This result suggests that, despite the limitations related to the number of evaluated leaves (leaf +1), from this phase of the crop development the effect of spacing starts to influence the photosynthesis of the plants and crop yield.

The increase in photosynthesis with the reduction of the plant spacing too can be found on maize crop, who is very important grass to Brazil (Sangoi et al. 2004; Acciares and Zuluaga 2006; Nummer Filho and Hentschke 2006). According to Nummer Filho and

Hentschke (2006), in reduced spacing, there is a greater interception of sunlight at the beginning of the crop development due to the best spatial arrangement of the plants. With that, it makes it possible for a greater accumulate of photoassimilates at plants in relation to the wider spacing and, contributed also, with the development of the plants in periods of your high demand. Moreover, the fast shading of the soil surface reduces the amount of soil water lost by evaporation, which, in association with the best soil exploitation by the root system arising from the most equidistant distribution of the plants, increases the uptake efficiency and use of water (Sangoi et al. 2004).

Despite the sugarcane photosynthetic parameters presented evidence of correlation with increased productivity at reduced spacings, further studies are needed in this area to help in understanding the factors involved with this increase in productivity. From the results this work, future studies with photosynthetic parameters should focus more after the 200 days of the crop cycle. It is believed that in this period a micro-climate is created between the cultivation rows, favoring the process of plants photosynthesis in the equidistant spacing.

2.3.3. Biometrics index

2.3.3.1. Tillers

The population density per meter (m) and area (ha), in the second sugarcane ratoon crop cycle in site 1, increased rapidly until 100 DAH for the TS treatments, PP 1.00 m and PP 0.75 m (Figure 2.9). For the other row spacings, this period was longer, extending until 225 DAH. After that, all the spacings showed a fall and subsequent maintenance until the crop harvest. The TS treatment presented the highest population density (m, ha) at the crop harvest.

During the third sugarcane ratoon crop cycle, the population density presented the same behavior as the previous cycle. However, the maximum value occurred previously, at 75 DAH. After reaching this maximum presented a sharp drop and subsequent maintenance until the crop harvest. As a highlight, the CS presented a greater population density per meter (m) at the crop harvest, while the PP 0.50 m showed per area (ha) - (Figure 2.9).

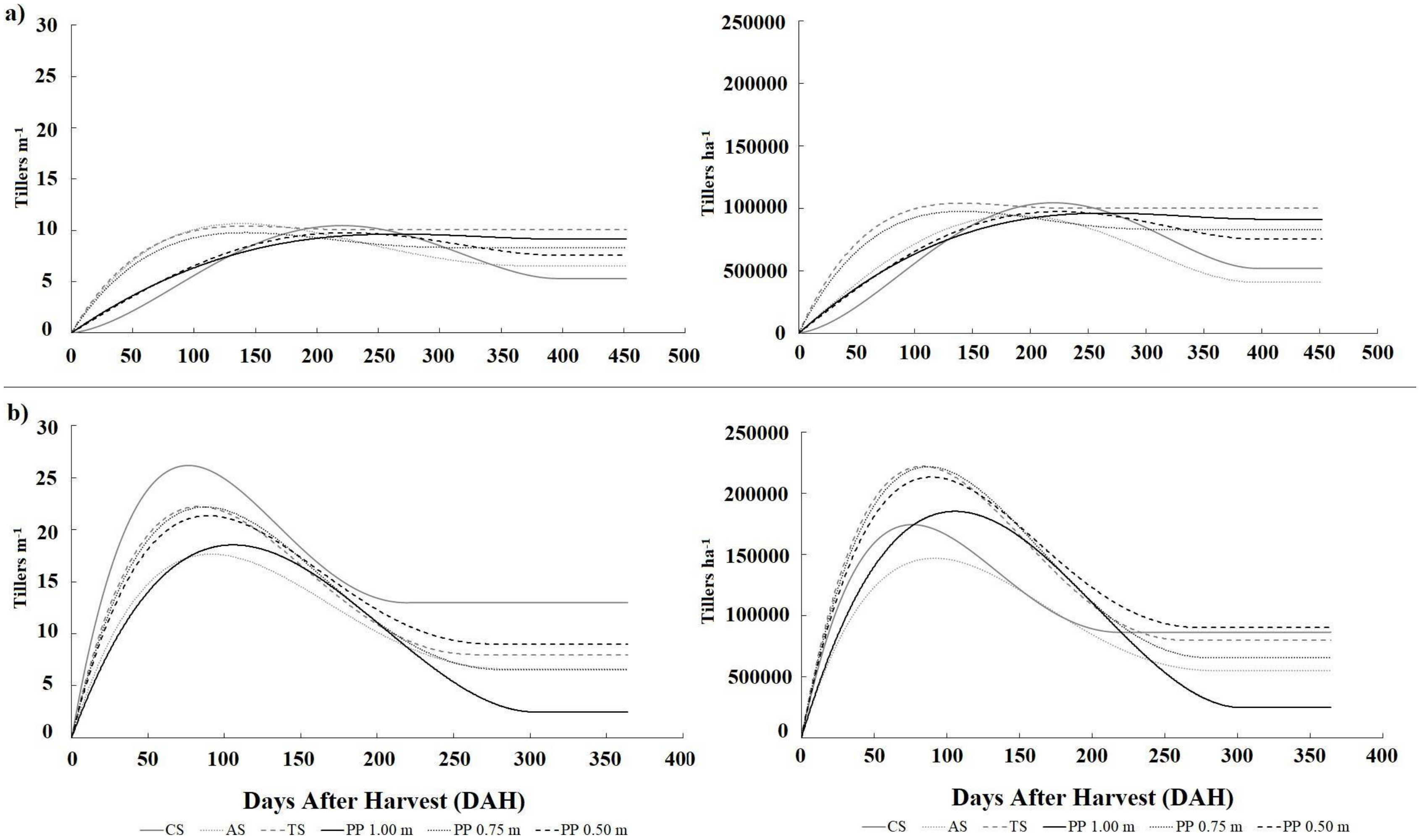


Figure 2.9. The tiller population density per meter (m) and area (ha) during the second **(a)** and third sugarcane ratoon crop cycle **(b)** in site 1. **Note:** The third harvest in site 1 had a longer cycle (more of 12 months) due to Sugar Mill operational logistics. **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

The population density per meter (m) and area (ha), in the third sugarcane ratoon crop cycle in site 2, presented the same behavior that seen during the same crop cycle in site 1 (Figure 2.10). The maximal value was reached at 75 DAH, going through a reduction period, then stabilized until the crop harvest. As seen in site 1, the wider spacing (CS) presented a greater population density per meter (m) at the crop harvest, while the denser spacing (PP 0.75 m) showed per area (ha) - (Figure 2.10).

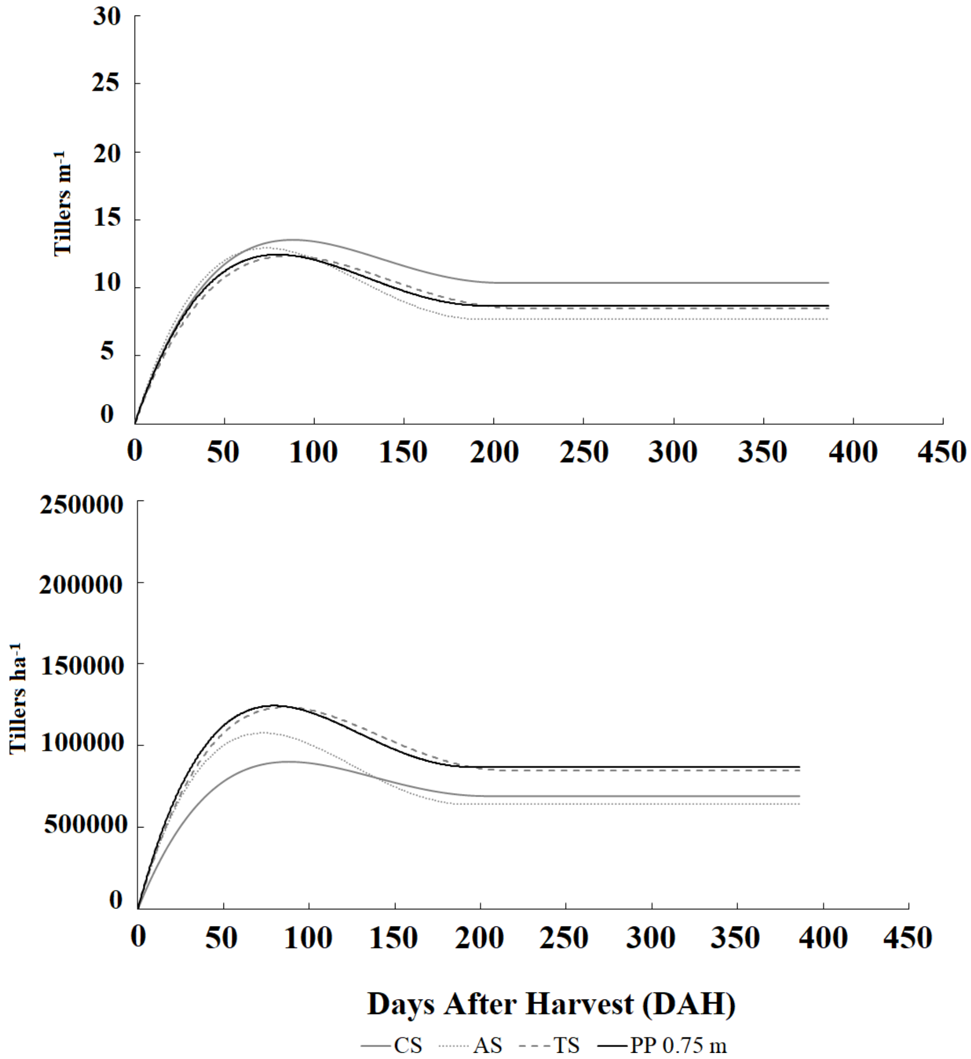


Figure 2.10. The tiller population density per meter (m) and area (ha) during the third sugarcane ratoon crop cycle in site 2.

Note: CS: conventional spacing**; AS:** alternated spacing; **TS:** triple spacing**; PP 0.75 m:** precision planting of 0.75 m.

The results showed that row spacing and population density have a key role in maximizing sugarcane yield and improving its quality (Figures 2.9 and 2.10).

Furthermore, its behavior during the crop seasons confirms the results observed by Rossi Neto et al. (2018).

According to Sangoi (2001), there is an optimum population density for maize cultivation and that a population of plants above this could limit the conversion of the interception of light into grain production. In this study, it was speculated that the optimal population density of sugarcane was not overcome with the studied spacing, making it necessary because, according to Rossi Neto et al. (2017), the population density is the crop parameter that presents the highest correlation with final productivity.

The high correlation between productivity and sugarcane population density was observed in our research. Sugarcane yield was directly affected by the row spacing adopted and that smaller the spacing the greater the crop productivity. It is therefore evident the importance of understanding the behavior of the population density for sugarcane crop.

2.3.3.2. Height, diameter and Internodes

During the second sugarcane ratoon crop cycle, there was a significant difference in the plant's height index among the row spacings at 452 DAH in site 1. In this period the treatments PP 0.75 m, PP 1.00 m were higher than PP 0.50 m. However, in the third ratoon, the spacings not presented significant difference ($p<0.05$) - (Table 2.9). In relation to stalks diameter and the number of internodes by the plant, there was not a significant difference ($p<0.05$) among the row spacings in both sites in the second and third sugarcane ratoon crop cycle.

Table 2.9. Plant height (m), plant diameter (mm), number of internodes (units) during the second and third sugarcane ratoon crop cycle in the spacings in site 1.

Site 1	2ª Ratoon				3ª Ratoon			
	144	235	314	452	78	158	225	371
Treatments	DAH				DAH			
	Height (m)							
CS	0.19	1.58	2.26	3.14 ab	0.41	1.77	2.67	3.08
AS	0.16	1.60	2.29	3.14 ab	0.38	1.76	2.53	2.92
TS	0.16	1.57	2.14	3.28 a	0.38	1.67	2.51	3.20
PP 1.0 m	0.17	1.70	2.33	3.30 a	0.33	1.73	2.47	2.97
PP 0.75 m	0.16	1.44	2.26	3.32 a	0.37	1.72	2.49	3.03
PP 0.50 m	0.16	1.52	2.11	3.00 b	0.32	1.69	2.51	2.82
LSD 5%	**0.03**	**0.19**	**0.38**	**0.22**	**0.06**	**0.09**	**0.25**	**0.44**
F test	**P<0.23**	**p<0.17**	**p<0.77**	**p<0.05**	**P<0.07**	**p<0.23**	**p<0.63**	**p<0.56**
CV%	**12**	**8**	**11**	**5**	**13**	**4**	**7**	**10**
	Diameter (mm)							
CS	12.4	24.7	24.9	24.6	11.7	25.5	25.5	24.6
AS	11.2	25.1	24.0	23.3	10.9	26.3	24.7	24.3
TS	11.0	24.8	24.0	23.9	9.9	25.4	23.7	23.8
PP 1.00 m	10.3	26.6	24.6	23.7	9.3	27.9	25.0	23.9
PP 0.75 m	10.6	25.3	25.5	24.2	10.9	27.1	25.0	23.2
PP 0.50 m	9.2	26.2	23.8	23.3	9.6	25.5	25.2	24.4
LSD 5%	**2.32**	**2.27**	**1.24**	**1.03**	**2.22**	**1.97**	**1.32**	**1.57**
F test	**P<0.16**	**p<0.40**	**p<0.07**	**p<0.23**	**P<0.20**	**p<0.08**	**p<0.12**	**p<0.53**
CV%	**14**	**6**	**3**	**4**	**14**	**5**	**4**	**4**
	Internodes							
CS	un.	7	13	24	un.	7	17	27
AS	un.	7	14	24	un.	7	16	25
TS	un.	6	12	25	un.	7	16	27
PP 1.00 m	un.	8	13	25	un.	7	16	25
PP 0.75 m	un.	6	13	24	un.	7	16	27
PP 0.50 m	un.	6	12	22	un.	7	16	24
LSD 5%	**un.**	**1.13**	**1.44**	**2.97**	**un.**	**0.81**	**0.80**	**5.21**
F test	**un.**	**p<0.07**	**p<0.21**	**p<0.42**	**un.**	**p<0.40**	**p<0.31**	**p<0.45**
CV%	**un.**	**11**	**8**	**8**	**un.**	**8**	**3**	**13**

The row spacing effect in sugarcane biometrics attributes identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**;** **AS:** alternated spacing**;** **TS:** triple spacing**;** **PP 1.0m:** precision planting of 1.0m**;** **PP 0.75 m:** precision planting of 0.75 m**;** **PP 0.50m:** precision planting of 0.50m. **un.:** unvalued.

During the second and third sugarcane ratoon crop cycle, in site 2, there was not a difference significant ($p<0.05$) among treatments for all parameter's biometrics (Table 2.10).

Table 2.10. Plant height (m), plant diameter (mm), number of internodes (units) during the second and third sugarcane ratoon crop cycle in the spacings in site 2.

Site 2	2ª Ratoon	3ª Ratoon			
	388	45	136	211	386
Treatments	DAH	DAH			
		Height (m)			
CS	3.03	0.20	1.06	1.67	2.02
AS	3.07	0.21	1.07	1.69	2.14
TS	2.88	0.24	1.11	1.81	2.05
PP 0.75 m	3.07	0.21	1.03	1.70	1.91
LSD 5%	**0.4**	**0.03**	**0.19**	**0.18**	**0.30**
F test	**P<0.75**	**P<0.12**	**P<0.84**	**P<0.39**	**P<0.42**
CV%	**9**	**11**	**11**	**7**	**9**
		Diameter (mm)			
CS	25.4	13.8	25.3	24.3	23.5
AS	26.2	13.7	23.3	23.4	23.5
TS	24.7	14.2	23.6	23.1	21.6
PP 0.75 m	26.2	12.8	24.1	23.3	21.3
LSD 5%	**1.7**	**3.19**	**1.89**	**1.25**	**2.25**
F test	**P<0.19**	**P<0.79**	**P<0.17**	**P<0.20**	**P<0.10**
CV%	**4**	**15**	**5**	**3**	**6**
		Internodes			
CS	21	un.	4	11	19
AS	20	un.	4	11	20
TS	19	un.	4	11	18
PP 0.75 m	20	un.	5	10	18
LSD 5%	**1.8**	**un.**	**0.95**	**1.45**	**1.40**
F test α	**P<0.24**	**un.**	**P<0.75**	**P<0.64**	**P<0.18**
CV%	**5**	**un.**	**13**	**8**	**5**

The row spacing effect in sugarcane biometrics attributes identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 0.75 m:** precision planting of 0.75 m. **un.:** unvalued.

Therefore, the plants evaluated in different sugarcane planting spacing adoptedin this study did not show differences of the values of biometric indexes (height, diameter and number of internodes), regardless of the edaphoclimatic conditions and cultivar used.

2.3.4. Sugarcane biomass

2.3.4.1. Sugarcane biomass aboveground

The dry biomass accumulation from the sugarcane aboveground, in both sites and row spacings, show the form sigmoid characteristic of the plant's growth and, according to Machado et al. (1982), defining three phases of the crop development (Figure 2.11).

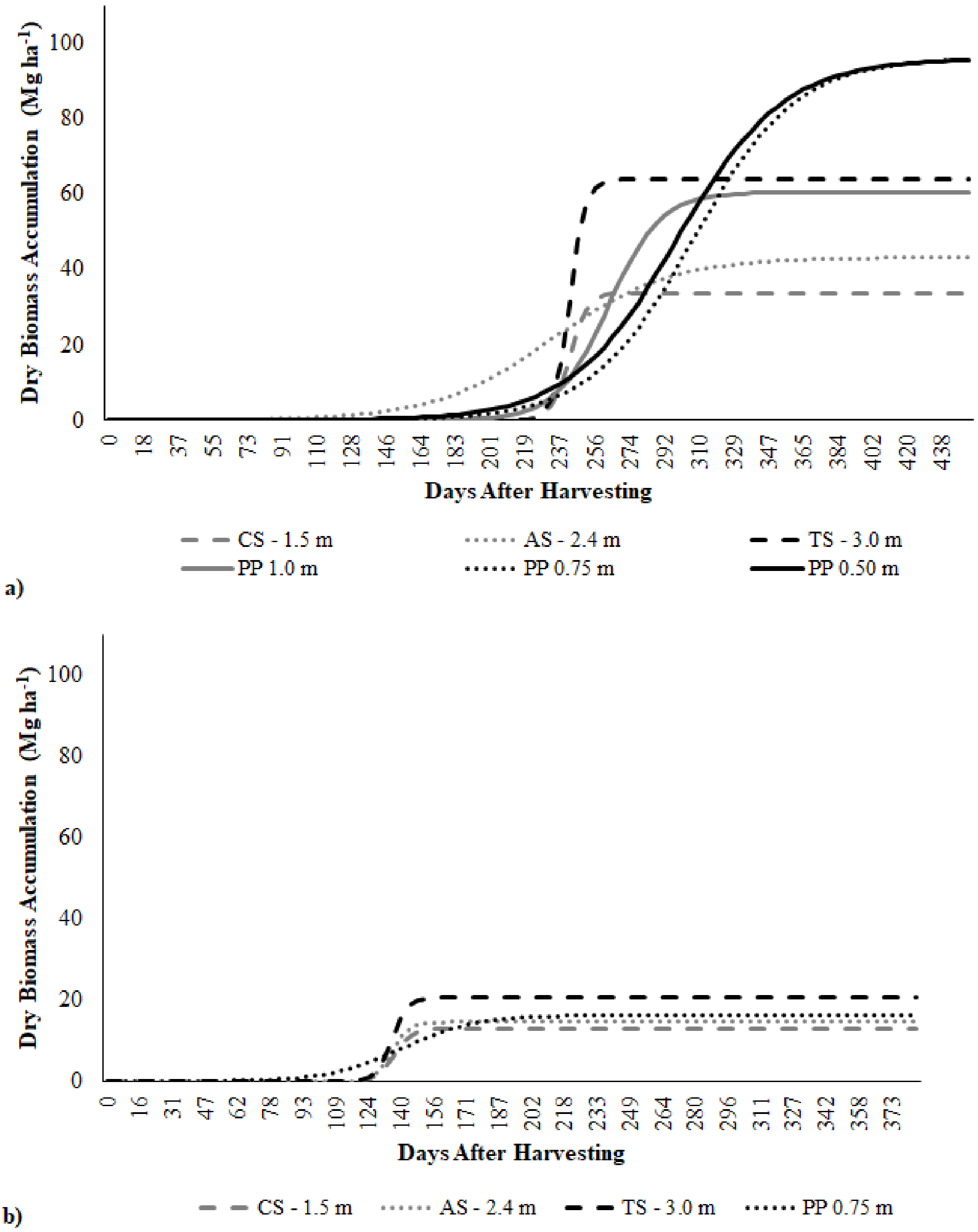


Figure 2.11. Dry biomass accumulation (Mg ha^{-1}) of the sugarcane aboveground during **a** second ratoon (site 1) and **b** third ratoon (site 2) related to the planting configuration.

The initial phase lasted on average 228 days in site 1, being accumulated 6.71 Mg ha^{-1}, representing 10% of the total dry biomass accumulated. At this stage, the TS had the longer initial development phase, 0 to 274 days after harvest (DAH) ending at the time of greater water availability for crop (Figure 2.11). Differently from the AS treatment that presented shorter period from 0 to 180 DAH.

Otherwise in site 2, the initial phase lasted 130 days, being accumulated 5.0 Mg ha^{-1}, representing 31% of the total dry biomass accumulated. At this stage, the CS had the longer initial development phase, 0 to 130 days after harvest (DAH) ending also at the time of greater water availability for crop (Figure 2.11). Differently from the PP 0.75 m treatment that presented shorter period from 0 to 100 DAH.

After the initial phase, the plants are in the phase of the largest accumulation of dry biomass (second phase) in which, in both edaphoclimatic conditions, occurred at the time of higher availability hydric for the crop. In site 1, this phase lasted 64 (CS, TS), 100 (AS, pp 1.00 m) and 137 (pp 0.75 m, pp 0.50 m) days. Otherwise in site 2, this phase occurred for a period of 40 (CS, as and TS), while for the treatment PP 0.75 m lasted 110 days.

During this phase, the spacings that presented a higher dry biomass accumulation in site 1 were PP 0.75 m and PP 0.50 m with, 81.2 and 80.6 Mg ha^{-1}, respectively. In site 2, the TS spacing was the one that presented the largest biomass accumulation with 14.7 Mg ha^{-1}.

The third growth phase denominated the plant maturation phase (Oliveira et al. 2010), it was different between spacings in site 1 (Figure 2.11). As highlighted, the lower spacings presented the highest final yield in dry biomass, being 95.7 Mg ha^{-1} to spacing PP 0.75 m and 95.6 Mg ha^{-1} to PP 0.50 m. For the site 2 conditions, the last phase of dry biomass accumulation lasted the same period between conventional planting spacings (CS, AS and TS) with 214 days against, 144 days of the PP 0.75 m treatment. The spacing with higher dry biomass production it was TS with 20.7 Mg ha^{-1}.

The dry matter production rate (DMPR) that was obtained by means of the derivative of the equation (2.1), representing a bell-shaped curve which was found in the treatments in both the soil textures (Figure 2.12). At the beginning, the DMPR value is low, increasing until it reaches the maximum value to then decrease sharply (Machado et al. 1982).

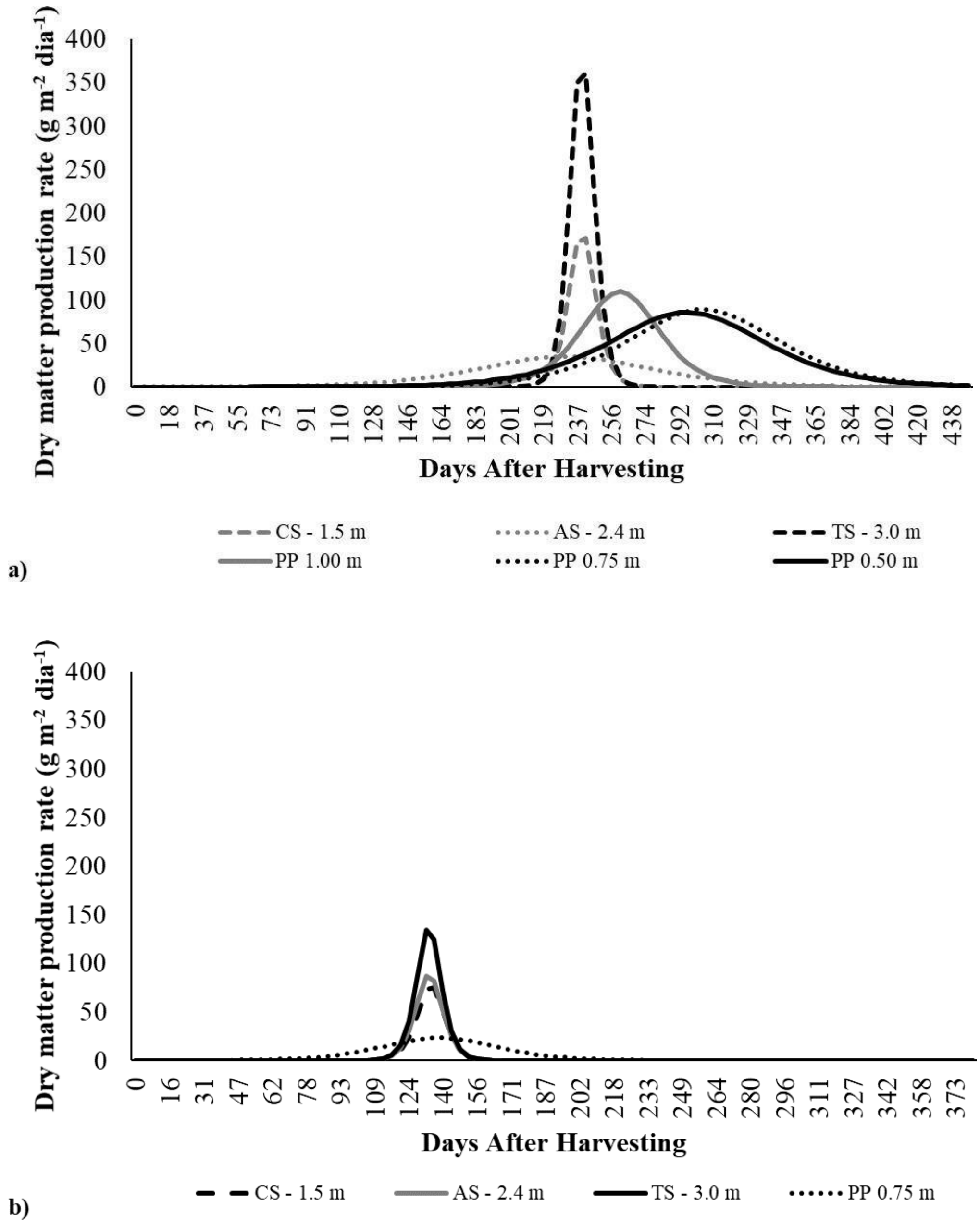


Figure 2.12. Dry matter production rate (g m^{-2} dia^{-1}) from the sugarcane aboveground during **a** second ratoon (site 1) and **b** third ratoon (site 2) related to the planting setting.

The maximum DMPR values, in site 1, were reached at different times of the second sugarcane ratoon crop cycle by spacings, being the largest value found for the TS spacing (361 g m^2 day^{-1}) - (Figure 2.12). Otherwise in site 2, the cultivar CTC 15 presented a lower maximum TPMS, in all treatments in relation to the site 1 conditions, however, the TS spacing also presented the highest value (134 g m^2 day^{-1}).

Thus, the results showed that the plants under precision spacings in site 1 presented the biggest and longest period of dry biomass accumulation than the those cultivated in the others row spacing. The dry biomass accumulation, in both edaphoclimatic conditions, it was of 324 days to site 1 and 175 in site 2 (Figures 2.11 and 2.12). However, despite to the results, it was observed that due to the reduced number of evaluations throughout the cycle, the model did not perform as observed by Rossi Neto (2015).

2.3.4.2. Sugarcane root biomass and development

There were significant differences between the planting spacing treatments for the root biomass production in both sites when assessed at the end of the ratoons (Table 2.11).

Table 2.11. Root dry biomass production (Mg ha^{-1}) of sugarcane grown in different spacing planting in two sites experimental.

Treatments	2ºRatoon	3ºRatoon	Average	2ºRatoon	3ºRatoon	Average
	Mg ha^{-1}					
	Typic Eutrustox, clayey soil			*Rhodic Hapludox, Sandy soil*		
CS	1.20 cd	1.14 bc	1.17 c	1.61 bc	1.30 c	1.46 c
AS	0.92 d	2.19 a	1.55 b	1.37 c	2.50 b	1.92 b
TS	1.68 a	1.53 b	1.60 b	2.68 a	2.87 ab	2.78 a
PP 1.00 m	1.31 bc	0.96 c	1.13 c	un.	un.	un.
PP 0.75 m	1.71 a	1.48 b	1.59 b	2.01 b	3.05 a	2.53 a
PP 0.50 m	1.55 ab	2.65 a	2.10 a	un.	un.	un.
LSD 5%	**0.30**	**0.52**	**0.36**	**0.44**	**0.41**	**0.33**
F test (α)	**p<0.00**	**p<0.00**	**p<0.00**	**p<0.00**	**p<0.00**	**p<0.00**
CV%	**14**	**21**	**16**	**14.35**	**10.81**	**9.56**

The row spacing effect in sugarcane root dry biomass production up to 1.0 m depth identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m. **un.**: unvalued.

In site 1, the PP 0.75 m and TS spacings, were the treatments which presented the greatest root dry biomass production, which was greater than AS, CS, TS, and like the PP 0.50 m at second ratoon (Table 2.11). A similar trend was not observed in site 2, being the TS spacing higher to others spacings (p<0.05) (Table 2.11). With respect to the third ratoon, the PP 0.50 m and AS spacings, were the treatments which presented the greatest root dry biomass production, which was significantly greater than others spacings in site 1 (Table 2.11). In the other experiment field, the precision planting (PP 0.75 m) was greater than CS and AS, and like TS.

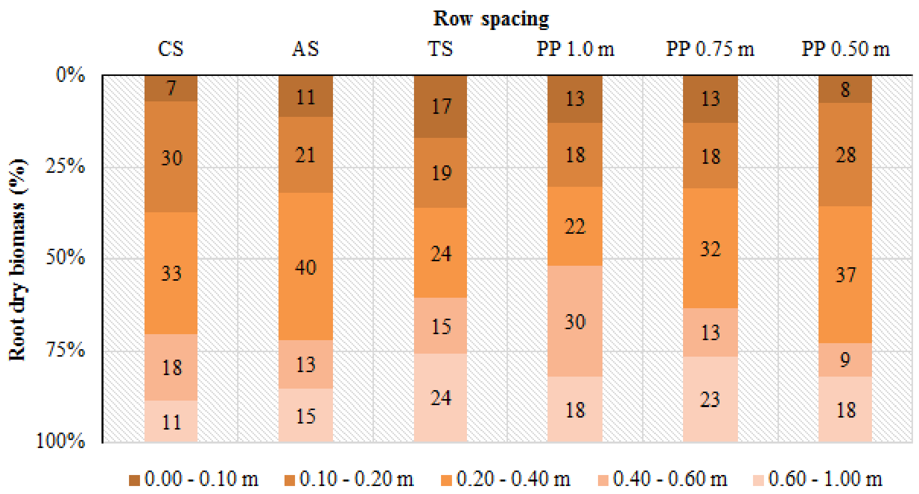
According to the root dry biomass production average measured during two crop cycles, plants grown under conditions of reduced spacing (PP 0.50 m) yielded greater biomass than all other treatments in site 1 (Table 2.11). A similar trend was not observed in site 2, where the TS spacing presented significantly the same production that PP 0.75 m. The results from the sugarcane root system no corroborating with the data previously presented by Rossi Neto (2018), in which total production of dry root biomass no explain the sugarcane yield across different planting configurations. This study proves that have a trend the denser spacings produced more root dry biomass with the aging of the cane fields, corroborating yet with the data of the sugarcane yield.

This information emphasizes the need of sugarcane industry in to modify the management of planting adopted, once the current, limited root growth of crop through compaction of the interrow (Otto et al. 2009a,b; Otto et al. 2011). Therefore, this change is important because the root system is present as a source of supply of the soil resources (Korndörfer et al. 1989; Smith et al. 2005), besides being essential for the crop regeneration after the harvest (Glover 1968).

Root distribution at depth in soil profile

There were differences in the concentration dried biomass of root (%) in the layers in soil profile among the rows spacing in both sites and ratoons (Figures 2.13 and 2.14). In site 1, except for treatment PP 1.00 m, the highest concentration of dried biomass of root (%) was at the layer of 0.20 to 0.40 m for the crop second ratoon (Figure 2.13). However, in the crop third ratoon, the layer with the highest concentration of dried biomass of root (%) varied among treatments.

2ª ratoon



3ª ratoon

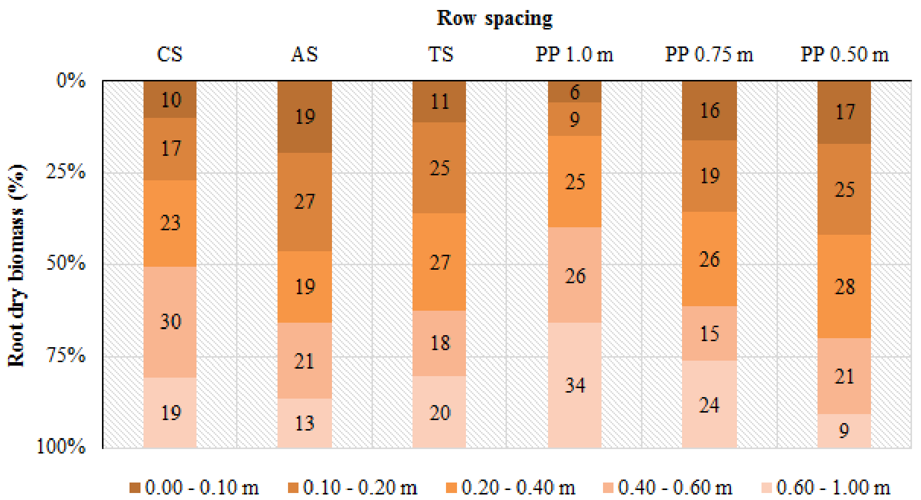
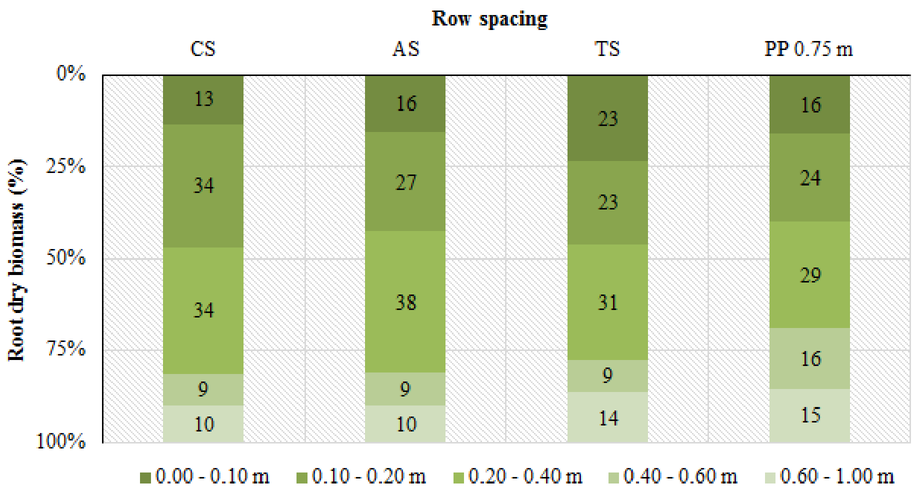


Figure 2.13. Root distribution at depth in soil profile (%) in each row spacings in site 1, in the second and third ratoon crops.

In site 2, the highest concentration of dried biomass of root (%) in the soil profile was at the layer 0.20 to 0.40 m for the crop second ratoon (Figure 2.14). However, this behavior was observed only by the PP 0.75 m treatment in the crop third ratoon, while the others spacing presented greater concentration at the layer 0.10 to 0.20 m. The high superficiality of the sugarcane root system found in all the spacings in site 2 may be related to the low content of nutrients in the soil (Table 2.1) and weather conditions (Figure 2.6).

2ª ratoon



3ª ratoon

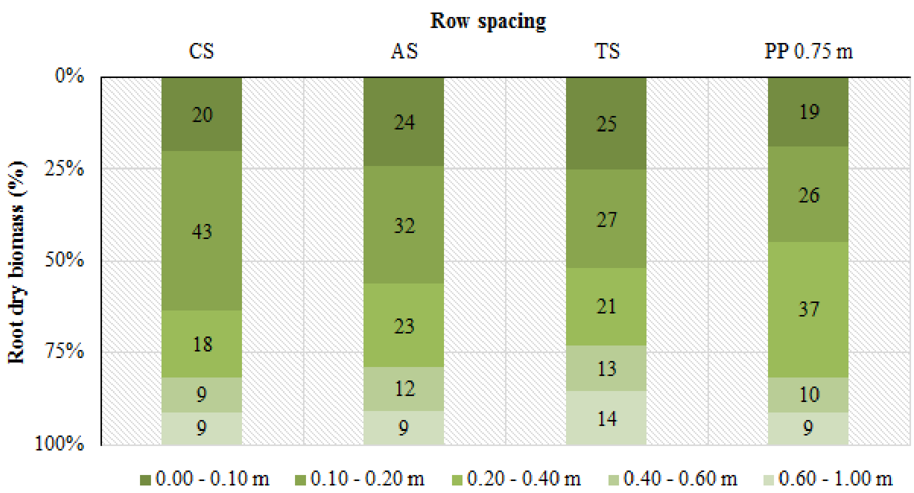


Figure 2.14. Root distribution at depth in soil profile (%) in each row spacings in site 2, in the second and third ratoon crops.

The percentage dry biomass of root in the average of the treatments up to the depth of 0.40 m for RB966928 cultivar in site 1, was 65 and 58% respectively for the second and third ratoon crop (Figure 2.13). This drop is probably associated with the better hydric condition of the soil found during this cycle; it is not being necessary exploration by root system in depth for the resources catchment. However, this behavior was not observed from one cycle to another for CTC 15 cultivar in site 2 (Figure 2.14), increasing the percentage dry biomass of root of 77 to 79%, up to the depth of 0.40 m.

As observed above mentioned, several studies carried out in the last century, verified a percentage of roots in the first layers of the soil profile (Lee 1926; Lee and Weller 1927; Inforzato 1957; Blackburn 1984; Korndörfer et al. 1989; Ball-Coelho et al.

1992; Smith et al. 2005; Oliveira et al. 2014; Cury et al. 2014; Castioni 2017; Barbosa et al. 2018; Rossi Neto et al. 2018), showing thus a superficiality of the sugarcane root system. Furthermore, the superficiality of the roots system varied due to the crop cycle (ratoons), the edaphoclimatic conditions and the management adopted for the crop (spacing planting).

Evaluating the production of sugarcane biomass in the San Francisco Valley, Oliveira et al. (2014) found that 92% of the root system was present within the top 0.40m. Similarly, Ball-Coelho et al. (1992) who studied the root dynamics of both plant and ratoon cycles estimated that 62-69% of the total mass of roots occurred within the top 0.50m. Analyzing root biomass to a depth of 1.00 m, under different soil preparation systems with and without limestone, Cury et al. (2014) found that 60 to 70% of the total root mass occurred at depths less than 0.40m. Rossi Neto et al. (2018) evaluating the behavior of sugarcane roots different plant spacing treatments and edaphoclimatic conditions, observed a greater concentration of roots to a depth of 0.40m independent of the adopted spacing and cycle of crop. In site 1 these concentrations ranged from 70 to 90%, while in site 2 conditions these values varied from 64 to 92%.

Nevertheless, the relative depth of the sugarcane root system is of utmost importance because, as has been shown for larger plants, the greater the root system the more able the plant is to explore the volume of the soil and thus take advantage of available nutrients and water (Korndörfer et al. 1989; Chopart et al. 2010). In this context, the treatment with a greater number of roots (%) in depth was that of PP 1.0 m for site 1. This treatment presented 48% of the total dry biomass, in the depth of 0.40 to 1.00 m , at the time of the second harvest and 60% at the third ratoon. In site 2, CTC15 showed variation in the deeper layers measured, and it was not possible to obtain accurate information.

In general, the results demonstrated a response variability in root system development up to 1.00 m deep. According to Vasconcelos and Casagrande (2008), the architecture and distribution of plant roots may vary because the cultivars present different patterns within the soil profile. Furthermore, the same sugarcane cultivar cultivated under different edaphoclimatic conditions may present substantial variation in the root system (Faroni 2004).

It was also highlighted the superficiality of the crop root system independent of the cultivar and edaphoclimatic conditions. This fact goes against the hypothesis is that in the absence of traffic restrictions between the lines the plants would explore a greater volume of soil, especially those planted in geometrically equidistant spacing (except the PP 1.00 m treatment). Despite of the PP 1.00 m treatment be an exception with a greater depth of the root system in site 1, there was no correlation between root depth (%) and stalk yield.

2.3.5. Sugarcane Yield

There were differences (p<0.05) in sugarcane yield among the row spacings only in site 1 for the third ratoon crop and in accumulated total (Table 2.12).

Table 2.12. Sugarcane yield, measured in the crop harvest, in different planting spacings in site 1 and 2.

Treatments	**2ºRatoon**	**3ºRatoon**	**Accumulated**	**2ºRatoon**	**3ºRatoon**	**Accumulated**
	Mg ha^{-1}					
	Typic Eutrustox, clayey soil			*Rhodic Hapludox, Sandy soil*		
CS	123	127 b	250 b	94	40	134
AS	129	140 b	268 b	83	52	135
TS	132	126 b	258 b	74	53	127
PP 1.00 m	135	129 b	263 b	un.	un.	un.
PP 0.75 m	138	143 b	281 b	101	58	159
PP 0.50 m	160	179 a	338 a	un.	un.	un.
LSD 5%	**23**	**30**	**49**	**21.98**	**15.27**	**28.36**
F test (α)	**p<0.06**	**p<0.01**	**p<0.01**	**p<0.08**	**p<0.11**	**p<0.11**
CV%	**11**	**14**	**12**	**15.59**	**18.89**	**12.78**

The row spacing effect in sugarcane yield identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m. **un.**: unvalued.

The crop yield planted in the PP 0.50 m spacing was higher (p<0.05) than the other spacings in the third ratoon and in the accumulated total (Table 2.12). In addition, this treatment produced 52 Mg ha^{-1} (third ratoon) and 88 Mg ha^{-1} (accumulated total) more than the most adopted spacing in Brazil (CS). Despite there were no differences among spacings in the second ratoon, probably because of weather conditions during the crop season (Figure 2.5a), the smaller spacing (PP 0.50 m) produced 37 Mg ha^{-1} more than CS.

The results showed that the reduction of planting spacing in site 1, especially below 1.00 m, increases the sugarcane yield. In addition, the reduction associated with the equidistant spacing decreases the expense of planting seedlings, increasing the producer's profit. The data corroborating with the previous study (Rossi Neto et al. 2018) and the literature review (chapter 1), where almost all studies cited in site 1 had a sugarcane yield increase with the spacing reduction.

Nevertheless, although the smaller spacings produce more in site 1, in environments more restrictive to the plant growth (site 2), the change did not interfere with crop yield statistically (Table 2.12). This result also corroborates with the data from a similar environment in the previous study (Rossi Neto et al. 2018). In addition, after a study of the spacing of sugarcane planted in similar soil in Brazil (chapter 1), it was observed that there was no yield gain by reducing plant spacing below 1.00 m, which could be a limiting spacing for the sugarcane crop in this soil texture.

Moreover, it is necessary to highlight that the sugarcane cultivar CTC15 yield was influenced by the cycle duration (exposure of the cultivar to a long period of edaphoclimatic restrictions) and consequently the harvest season, in addition to the edaphoclimatic conditions of the site 2 (Figure 2.6). Thus, in environments with such restrictions, regardless of the type of cultivar maturation, it is necessary to anticipate the harvest season. In this scenario, it is necessary for a longer study time on the planting management in order to obtain the most profitable spacing and determine the limiting spacing in the different production environments of Brazil. After that, it becomes necessary to the search of mechanisms by the sugarcane industry to implement a new row spacing for crop and, consequently, to meet the growing global demand.

2.3.6. Sugar and Fiber production

There were no differences in the Pol of the raw material for the two sites in both cycles evaluated (Table 2.13). However, in the final sugar production (Mg ha^{-1}) in site 1, the PP 0.50 m spacing differed from the others during the third ratoon producing 9.1 Mg ha^{-1} more than in CS. When comparing the sugar yield (g $tiller^{-1}$), the treatments with larger spacings were higher in the second ratoon. The same behavior not observed in the crop the third ratoon, the AS spacing differed from the others, with no significant difference from the PP 0.50 m.

The production of sugarcane fiber (%) in site 1 differ among the spacing treatments during the second sugarcane ratoon crop cycle, where the CS spacing was different to the others, with no significant difference from spacings PP 1.00 m and PP 0.50 m. However, in the final fiber production (Mg ha^{-1}) in site 1, the spacing more reducing (PP 0.50 m) differed from others in the second and third ratoon crops, with no significant difference from the PP 1.00m in the second ratoon. In the fiber yield (g $tiller^{-}$

^{1}), the CS treatment differed from the others in the second ratoon. However, the ASbeen greater in the third ratoon crop, with no significant difference from the PP0.50m.

Table 2.13. Sugar and Fiber production measured in the harvest of the sugarcane field planted in different configurations of planting in site 1.

Treatments	POL	Sugar		Fiber	Fiber	
	%	Mg ha^{-1}	g tiller^{-1}	%	Mg ha^{-1}	g tiller^{-1}
			2ª Ratoon			
CS	15.7	19.3	308 a	11.5 a	14.2 b	226 a
AS	16.2	20.9	201 bc	10.8 bc	14.0 b	134 bc
TS	15.9	20.9	245 ab	10.9 bc	14.3 b	169 b
PP 1.0 m	15.6	21.0	211 bc	11.4 ab	15.5 ab	154 b
PP 0.75 m	15.5	21.3	153 cd	10.4 c	14.4 b	103 cd
PP 0.50 m	15.4	24.7	114 d	11.0 abc	17.6 a	82 d
LSD	**0.98**	**3.67**	**66.3**	**0.65**	**2.48**	**48.4**
F test (α)	**p<0.60**	**p<0.11**	**p<0.00**	**p<0.02**	**p<0.05**	**p<0.00**
CV%	**4**	**11**	**21**	**4**	**11**	**22**
			3ª Ratoon			
CS	16.4	20.8 b	241 b	11.3	14.3 b	165 bc
AS	16.8	23.5 b	332 a	11.7	16.4 b	232 a
TS	16.9	21.3 b	237 b	11.3	14.2 b	157 c
PP 1.0 m	16.7	21.5 b	266 b	11.6	15.0 b	186 bc
PP 0.75 m	16.5	23.5 b	264 b	11.5	16.4 b	185 bc
PP 0.50 m	16.7	29.9 a	285 ab	11.7	20.9 a	199 ab
LSD	**1.0**	**4.5**	**53.9**	**0.6**	**3.1**	**37.0**
F test (α)	**p<0.89**	**p<0.00**	**p<0.01**	**p<0.36**	**p<0.00**	**p<0.00**
CV%	**4**	**13**	**13**	**3**	**13**	**13**

The row spacing effect in sugar and fiber production identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **Pol**, apparent sucrose; **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

There were no differences in the Pol and Fiber (%) of the raw material among the spacings for the second ratoon in site 2 (Table 2.14). At third ratoon crop, there was a company misconception responsible for the technological analysis regarding the sample's identification, where in this case, a general average of the Pol and fiber (%) was used for the treatments (Table 2.14).

The final sugar production (Mg ha^{-1}), in site 2, there were no significant differences among the spacings in both cycles evaluated. In relation de sugar production (g tiller^{-1}), at second ratoon the CS differed from others while in the third ratoon, no observed differences among the spacings ($p<0.05$).

The final fiber production (Mg ha^{-1}), site 2, the spacings PP 0.75 m and CS differed from TS, with no significant difference from the AS ($p<0.05$). Differently, in the fiber production (g tiller^{-1}), the treatment CS differed from the others, with no significant difference from the PP 0.75m (Table 2.14).

Table 2.14. Sugar and Fiber production measured in the harvest of the sugarcane field planted in different configurations of planting in site 2.

Treatments	Pol	Sugar		Fiber	Fiber	
	%	Mg ha^{-1}	g tiller^{-1}	%	Mg ha^{-1}	g tiller^{-1}
			2ª Ratoon			
CS	15.7	14.7	416 a	13.8	13.0 a	367 a
AS	15.5	12.9	188 bc	14.3	11.8 ab	173 bc
TS	15.9	11.7	146 c	13.5	10.0 b	124 c
PP 0.75 m	14.8	15.0	287 b	13.7	13.9 a	269 ab
LSD 5%	**0.9**	**3.3**	**118**	**0.7**	**2.7**	**108**
F test (α)	**p<0.14**	**p<0.15**	**p<0.00**	**p<0.20**	**p<0.04**	**p<0.00**
CV%	**4**	**15**	**29**	**3**	**14**	**29**
			3ª Ratoon			
CS	17	6.7	104	15	5.8	92
AS	17	8.6	138	15	7.6	122
TS	17	8.8	105	15	7.8	94
PP 0.75 m	17	9.6	101	15	8.5	89
LSD 5%	**un.**	**2.54**	**30.1**	**un.**	**2.25**	**26.7**
F test (α)	**un.**	**p<0.11**	**p<0.06**	**un.**	**p<0.11**	**p<0.06**
CV%	**un.**	**19**	**17**	**un.**	**19**	**17**

The row spacing effect in sugar and fiber production identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **Pol**, apparent sucrose; **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 0.75 m:** precision planting of 0.75 m. **un.**: unvalued.

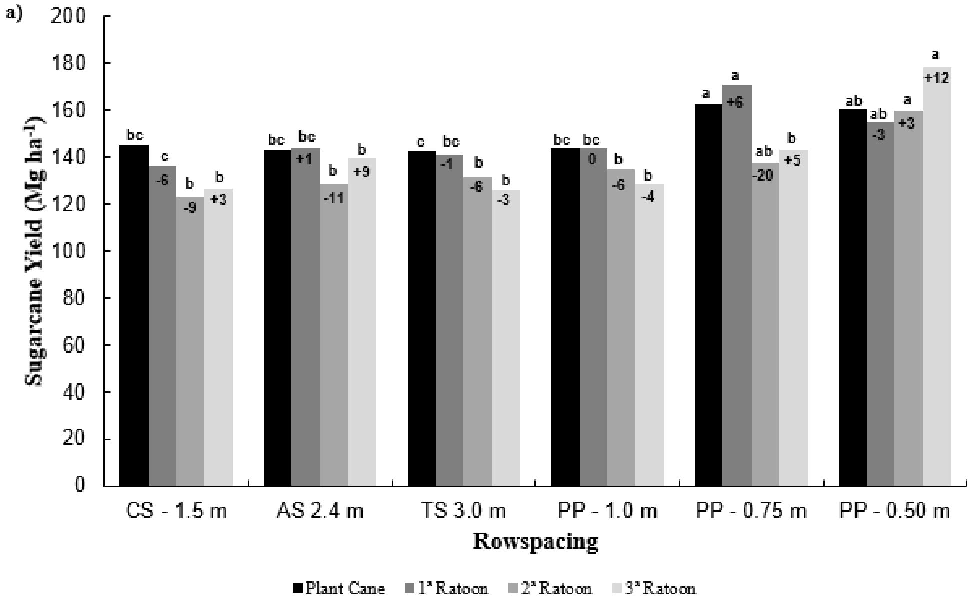
Although the raw material produced by the various spacing treatments no differed in relation to Pol technological attribute, for both sites and during the second and third ratoons, they all exceeded 14%, which according to (Ripoli and Ripoli 2004) is considered ideal to ensure high efficiency during the sugar production process. Other works evaluating the spacing effect in sugarcane crop also found Pol values above 14% (Garside et al. 2009; Ehsanullah et al. 2011; Sajjad et al. 2015; Ullah et al. 2016; Rossi Neto et al. 2018). All these studies, including our own, show that the changes in planting spacing do not affect the Pol of the sugarcane at the harvest time.

Despite there was no effect of crop growth condition (spacing) on the fiber and Pol content, but there were notable improvements to the total sugar and fiber production (Mg ha^{-1}) for the denser spacing treatments during the two crop seasons in site 1. However, when analyzing production per tiller, the wider spacing was higher for both sites when considering the second ratoon, which may be related to the difference in populations between the precision spacing and other spacing.

The fiber content (%) differed only for site 1 during the second ratoon. Despite this, they remained between 11 and 13% and even exceeded the highest value, also being according to (Ripoli and Ripoli 2004).

2.3.7. Sugarcane longevity under different planting spacings

The sugarcane yield throughout the crop seasons was different for the planting spacings studied. Furthermore, a same row spacing presented different behavior when planted under different edaphoclimatic conditions (Figure 2.15a, b).



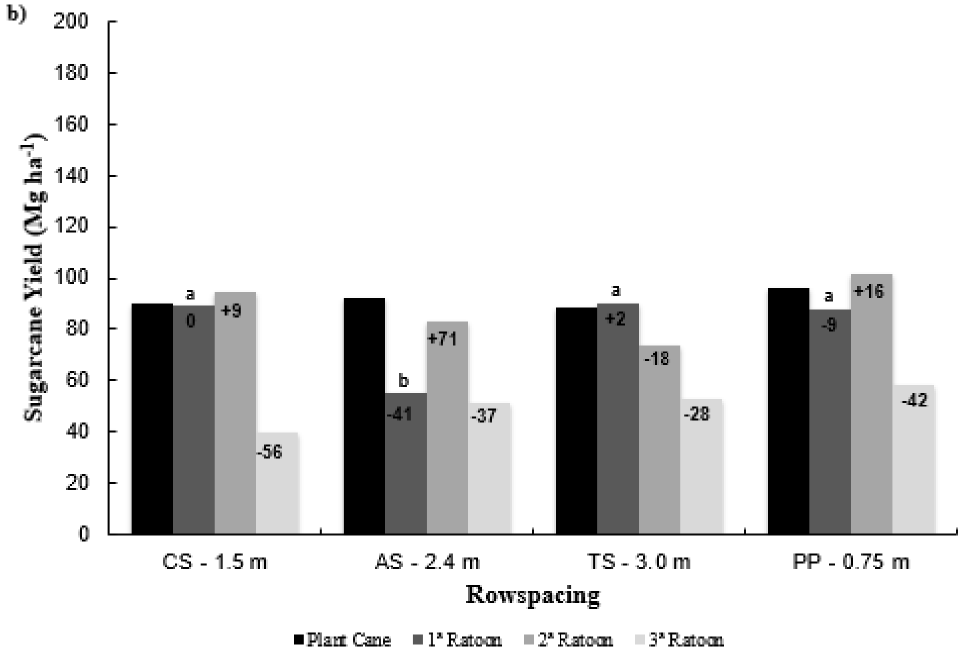


Figure 2.15. Effect on sugarcane yield (inside the bar - %) throughout the crop seasons for different planting spacings in site 1 (a) and 2 (b).

Note: Equal letters (among the treatments in each crop season) do not differ from each other by the t-test at 5% probability. In the crop season where there are no letters, there was no statistical difference. The values within each bar represent the variation (%) of the productivity in relation to the previous crop season for each treatment.

In site 1, the best performance was observed at the denser and equidistant spacing (PP 0.50 m). Despite the small crop productivity decrease of 3% from the first to the second harvest, in the following crop seasons, the treatment obtained gains of 3 and 12%, respectively (Figure 2.15a). Furthermore, the average and total sugarcane yield (along the four crop seasons) planted in the PP 0.50 m spacing was higher ($p<0.05$) than the other spacings, with no significant difference from the PP 0.75 m (Table 2.15). Otherwise, the worst performances were observed by TS and PP 1.00 m treatments, showing a continues decrease in productivity during the crop seasons. Regarding the PP 0.75 m, although it presented the highest productivity in the second harvest, it was the spacing that most suffered during the period of water stress (Figure 2.5a) during the third cycle, with a 20% drop in productivity harvest.

Table 2.15. Average and total sugarcane yield in different planting configurations over four harvests in edaphoclimatic conditions (Site 1 and 2)

Treatments	Average	Total	Average	Total
	Mg ha^{-1}			
	Typic Eutrustox, clayey soil		*Rhodic Hapludox , Sandy soil*	
CS	133 c	531 c	78 ab	313 ab
AS	139 bc	556 bc	70 b	282 b
TS	136 c	542 c	76 b	305 b
PP 1.00 m	138 bc	551 bc	un.	un.
PP 0.75 m	154 ab	615 ab	86 a	343 a
PP 0.50 m	163 a	654 a	un.	un.
LSD 5%	17	68	8.5	34
F test (α)	p<0.00	p<0.00	p<0.01	p<0.01
CV%	7.8	7.8	6.8	6.8

The row spacing effect in sugarcane yield identified with different letters are significantly different (α = 0.05; Student's t test) within the same DAH (day after harvest). **LSD:** least significant difference; **CV**: coefficient of variation; **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m. **un.**: unvalued.

Regarding in site 2, it was not possible to identify a cultivar yield behavior planted in different planting spacing (Figure 2.15b). Nevertheless, when observing the average and total sugarcane yield (along the four crop seasons) the PP 0.75 m spacing was higher ($p<0.05$) than the other spacings, with no significant difference from the CS (Table 2.15).

In this site (2), it was observed the maintenance and an increase in the crop productivity for the CS in the first three harvests. However, because a severe attack of the sugarcane rust, presented a strong drop (56%) in the fourth harvest (Figure 2.15b). This yield stability is wasn´t found for the other treatments. Despite a 2% increase in the productivity showed by the TS treatment in the second harvest, the same showed a trend to drop from the third harvest. Already for the other treatments occurred a decrease of the productivity in the second harvest, an increased yield in the next cycle and drop again in the last season because of the disease (Figure 2.15b).

The results of this analysis indicate that the planting configuration adopted, associated with the sugarcane harvest season and the production environment, influence the cane fields longevity. In site 1 condition, the cultivar harvested on early of crop season (RB966928), presented greater longevity of ratoon yield when it is management in a denser spacing. On the other hand, the cultivar harvested in late of crop season (CTC 15) the spacing reduction did not characterize the maintenance of the ratoon yield, reducing the sugarcane longevity, especially in sandy soil texture. As mentioned in the item Sugarcane yield (2.3.5), it is necessary to highlight that the sugarcane cultivar CTC 15 yield was influenced by the cycle duration (exposure of the cultivar to a long period of edaphoclimatic restrictions) and consequently the harvest season, in addition to the edaphoclimatic conditions characteristic of the site 2 (Figure 2.6).

Until nowadays, some one-off studies have been carried out aiming to increase the cane fields longevity. Benedini (2016), in a report to RPAnews magazine, commented that the number of sugarcane harvests depends on some techniques used by the producers during the crop cultivation. Among the techniques cited in the reporting, the planting spacing is presented as one of the main ones, and its change is essential for improving the cane fields longevity.

However, for Benedini e Conde (2008), the row spacing of 1.50 m is the ideal because it allows a harvest without damages to the ratoons and, consequently, greater longevity to the sugarcane field. According to this authors, to modify the row spacing, like its reduction, increase the harvester traffic and the accompanying vehicles, compaction the soil and cause damage to the ratoons. This problem is a result of the dependence of the sector on existing machines, limiting the change in plant spacing. In this context, it is evident that the spacing change will cause damage to the ratoons being, the current spacing, the most recommended.

On the other hand, this work showed that the best distribution of the sugarcane plants can be used as a mechanism to increase the productivity and longevity of the cane fields (Figure 2.15a, b; Table 2.15). This result was evidenced because the equidistant spacing PP 0.50 m produced 123 Mg more than the CS in the sum of the four crop seasons. In addition, it also showed a yield of 30 Mg ha^{-1} more than CS.

Thus, exploring the possibility of the adoption of reduce spacings with the increasing the distance between plants without limitations of the machine traffic, would have a positive impact on the economic sustainability of the cane field, because, besides reducing the spending on seedlings in the crop establishment will increased productivity gains due to reduced row spacing (Rossi Neto et al. 2018). Trials with this goal have never been carried out in the most important region of sugarcane production in the world, the South-central region of Brazil.

2.4. Conclusion

- The planting of the equidistant spacing PP 0.50 m, in edaphoclimatic conditions without restrictions to the sugarcane cultivation, increases the sugar yield, fiber and sugarcane yield per hectare.
- The reduction of sugarcane row spacing, independently of edaphoclimatic conditions, increases the production of dry biomass of root up to the depth of 1 m in ratoons cycles.
- The planting configuration, associated with the sugarcane harvest season and the production environment, influence in the cane fields longevity.

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Chapter 3: Application of the CSM-CANEGRO-Sugarcane model for predicting yield under different planting densities (Scientia Agricola)

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Abstract

Plant spacing management is one way to increase sugarcane biomass production the use of tools, such as crop models, can reduce the amount of the time required to obtain information through traditional field experiments and assist in decision-making by stakeholders. The objectives of this study were (1) to evaluate the performance of the CSM-CANEGRO-Sugarcane model for simulating yield under different plant spacing; and (2) to evaluate the performance of the model as a yield forecast tools for the edaphoclimatic region of Guaíra, State of Sao Paulo, Brazil. The sugarcane and soil data for were obtained from a field experiment conducted during the 2012-2013 (used for model parameterization) and 2014-2015 (used for model evaluation) cropping season in a commercial area at Guaíra Sugar Mill. Weather data were obtained from the Instituto Nacional de Meteorologia (INMET), the Agência Nacional de Águas (ANA), and the Departamento de Águas e Energia Elétrica de Sao Paulo (DAEE). The model performance was quantified by different statistical tests (RMSE, index of agreement and R^2). The results show for the first time that the CANEGRO-sugarcane model calibrated for conventional spacing (1.50 m) can be applied to simulate the sugarcane stalk and aboveground yield under different row spacings. This work confirms that the CANEGRO-sugarcane model is an important tool to help the sugarcane industry better understand the behavior of sugarcane in different spacings between rows and plants and to determine the best management option to maximize the crop production. Nevertheless, further studies are needed to better calibrate the model and obtain a better and earlier

forecast of crop productivity. **Keywords:** DSSAT, Row spacing, Simulation, Forecasting, Sugarcane yield.

3.1. Introduction

The Brazilian sugarcane industry currently represents around 2% of the national GDP, producing different forms of sustainable and renewable agrienergy (sugar, ethanol, electricity and other products). Therefore, sugarcane is one of the main agricultural crops of the Brazilian economy (CNI, 2017; Tolmasquim et al., 2007). In addition, the global demand for renewable energy sources puts Brazil in a prominent position as sugarcane products represent 43.5% of all renewable energy and 17.5% of all energy that originates in the country (UNICA, 2018). The current sugarcane industry is largely the result of increased crop production during the past decades, mainly due to the increase of the area harvested (FAOSTAT, 2018; UNICA, 2018) as well as increased investment. However, there are concerns about the projections of supply and demand of the biofuels (renewable agrienergy), and the socio-environmental aspects related to crop production (EPE, 2017a, b). Therefore, there is a need to incorporate new technologies to help increase Brazilian sugarcane production while at the same time reducing environmental impacts.

One way to increase crop yield is to increase production efficiency. Insugarcane, one technique that has been studied for increasing productivity is management of plant spacing management (Rossi Neto et al., 2018; Torquato et al., 2015). Although field research has produced promising results, the sugarcane industry has always faced problems in adopting alternative plant spacing, mainly due to the absence of adequate machinery (Braunbeck and Magalhães, 2010) and the lack of information about optimal management in the production environments. To solve this problem, further studies on crop response for different plant spacings are needed. However, these studies are expensive and time-consuming.

An alternative to complement field studies is crop simulation models (Soler et al., 2007), which represents the dynamic functioning of the soil-plant-atmosphere system and its interaction with the crop management practices (Andrade, 2009). These models are widely accepted as useful tools for research and management purposes in agriculture, including sugarcane industries worldwide (Singels and Bezuidenhout, 2002). Additionally, the models can help improve the monitoring of crop and income forecasting (Marin et. al., 2011), assess the use of natural resources, and estimate the risk associated with different management practices (Jones et al., 2003). According to Cheroo-Nayamuth et al. (2000), models can be powerful tools that can increase research efficiency, enabling the analysis of the performance of crops under edaphoclimatic conditions.

The outputs provided by the simulation models can be used as a tool to make appropriate crop management decisions and to provide farmers and stakeholders with alternative options for farming systems (Singh et al., 2010; Tsuji et al., 1998). Early forecasts of productivity are crucial to planning market operations, while predictions during the harvesting months can provide reliable yield estimates prior to the availability of official yield data (Pagani et al., 2017; Soler et al., 2007). Currently, there are many different crop simulation models (CSM) that are being used across the globe; the CSM-CANEGRO-Sugarcane model (Jones and Singels, 2008; Singels et al., 2008) is the most used model for sugarcane (Hoffman et al., 2018; Jones and Singels, 2018; Marin et al. 2011). The CSM-CANEGRO-Sugarcane model was based on the CERES-Maize model (Jones and Kiniry, 1986) and developed in South Africa to determine optimal harvest timing due to the risk of stalk borer *Eldana sacchararina* (Inman-Bamber, 1991). The model was added to the Decision Support System for Agrotechnology Transfer model set (DSSAT version 3.1) and the most recent DSSAT Version 4.7.5 (DSSAT, 2019). The model been applied in several regions of the world for analysis and advancement of sugarcane production systems (Hoffman et al., 2018; Jones and Singels, 2018; Marin et al., 2011).

With the growing need to modify sugarcane management by seeking more efficient plant spacing and the recognition of modeling as an auxiliary tool in field research, the objectives of this study were (1) to evaluate the performance of the CSM-CANEGRO-Sugarcane model for simulating yield under different plant spacing; and (2) to evaluate the performance of the model as a yield forecast tools for the edaphoclimatic region of Guaíra, State of Sao Paulo, Brazil.

3.2. Material and methods

3.2.1. Field Experiment

An experiment using the sugarcane cultivar RB966928 was conducted in a commercial sugarcane area belonging to Guaíra mill (20°24′17″S; 48°12′10″W, 550 m), located in the city of Guaíra, Sao Paulo, Brazil. The climate of the region, according to the Köppen classification (Köppen and Geiger, 1928), is Aw: drier season in winter (June to September) and an average temperature of 18 °C or higher in all months of the year.

The region has maximum temperatures exceeding 23 °C, minimum temperatures of less than 17 °C and the annual rainfall across the region is 1402mm.

Prior to planting, the soil was prepared with a disc harrow, limed and fertilized with phosphate fertilizer (1 Mg ha^{-1} of magnesium thermophosphate) according to the specific requirements indicated from the soil analysis (Table 3.1). Due to the high clayey soil fertility, fertilization was not carried out during the plant cane cycle. However, nitrogen fertilization was carried out during the subsequent ratoon crop using an N rate of 120 kg ha^{-1} N, source ammonium nitrate (32% N). No other nutrients were applied because the soil had adequate supplies.

Table 3.1. Chemical soil analysis from the experimental area collected before the opening of the furrow for the sugarcane planting.

Depth	**O.M.**	**pH**	**P**	**K**	**Ca**	**Mg**	**H+Al**	**CEC**	**Bs**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
m	*g* dm^{-3}	$CaCl_2$	*mg* dm^{-3}	*mmol*$_c$ dm^{-3}					*%*	*mg* dm^{-3}				
Typic Eutrustox, clayey soil														
0.0-0.2	28	5.7	44	14.5	46	11	19.7	91.2	79	0.1	4.4	9	8.4	0.5
0.2-0.4	24	5.9	32	11.6	35	9	23.8	79.4	72	0.4	4.7	9	9.9	0.4
0.4-0.6	17	5.6	14	8.1	21	6	25.0	60.1	60	0.3	4.0	6	5.8	0.1
0.6-0.8	13	5.6	7	6.7	15	4	20.8	46.5	57	0.3	2.8	4	3.3	0.1

O.M. - Organic Matter; **pH** - pH Value; **P** - Phosphorus; **K** - Potassium; **Ca** - Calcium; **Mg** - Magnesium; **H+Al** - Potential acidity; **CEC** - Cation Exchange Capacity; **Bs** - Base saturation; **B** - Boron; **Cu** - Copper; **Fe** - Iron; **Mn** - Manganese; **Zn** - Zinc. **un.**: unvalued

Sugarcane was planted on July 28, 2012 and a different number of seedlings was based on the desired plant density for each treatment. For the conventional treatments CS, AS, and TS, the seedlings were planted using a density from 18 to 20 buds per meter of furrow. For the precision planting treatments (PP 1.0 m, PP 0.75 m, and PP 0.5 m), two billets with two buds each placed on plant furrow aiming to obtain a good initial plant stand. The buds amount used in each treatment was quantified by sampling 10 m of furrow, weighing all the propagation material present.

The sugarcane cultivar RB966928, which is widely planted in the South-Central Region of Brazil, was used. This cultivar is recognized for having a high tillering in plant cane, as well as good sprouting and excellent closing of row spacing in the subsequent ratoon crop (RIDESA, 2010).

Also, care was taken to not compact the soil with machinery to avoid poor root development and, consequence, less absorption of nutrients in the soil. Furthermore, to avoid the trampling of plants with the machines in the planting line of the cane field.

Thus, it is expected that the differences that have occurred are strictly related to the arrangements for plant spacing.

3.2.2. Experimental Design

The study was carried out in a randomized block design, with six treatments with four replicates. The established treatments were the following: single 1.5 m row spacing or conventional spacing (CS), with a planting density of 12 plants per meter^2 (similar density to that used in commercial sugarcane crop); alternated spacing that provides a spacing of 0.90 × 1.50 m double row spacing (AS), with a planting density of 15 plants m^2; TS, triple spacing that offers a spacing of 0.75 × 0.75 × 1.50 m row spacing, which provides 10,000 m of furrow per hectare with a planting density of 18 plants m^2; PP 1.0 m, precision planting that offers a spacing of 1.0 × 1.0 m between plants and row spacing, with a planting density of 4 plants m^2; PP 0.75 m, precision planting that offers spacing of 0.75 × 0.75 m between plants and row spacing, with a planting density of 7 plants m^2; PP 0.5 m, precision planting that offers a space of 0.5 × 0.5 m between plants and row spacing, with a planting density of 16 plants m^2.

3.2.3. Plant measurements

To carry out the modeling study through the DSSAT program some evaluations were made in the sugarcane crop. The crop biometric parameters and the biomass accumulation aboveground were performed during crop seasons 2012/2013 and 2014/2015 (model evaluation), every three months from of the planting. Sugarcane yield assessments, technological attributes, and distribution and biomass accumulation of root system were measured during the harvest period of the crop seasons 2012/2013 (plant cane) and 2014/2015 (second ratoon), is specifically carried out in June 2013 and August 2015, with approximately 12 months of crop development.

The sampling of the number of tillers was always performed in the same 10 m of cane row inside each plot. For measuring height, 10 tillers were selected from the same 10 m of row; the height was measured from the soil surface to the second highest leaf of the tiller (top leaf +1; also defined as total visible dewlap - TVD). The sampling of the biomass aboveground, due be a destructive method, was performed in a 2.0 m row in locations that were previously marked outside of the evaluation area for final stalk yield (TSH). The fresh weight of all individual plant material, including dead leaves, tops, and stalks, was determined in the field for each individual plot. After weighing, each plant sample was ground in a forage chopper to collect a subsample. These subsamples were stored in plastic bags, sealed and weighed on an analytical balance (accuracy of 0.01 g). The samples were then dried in a forced-air-circulation oven at 65 ºC for 72 hours and weighed again. Soil moisture of the subsamples was determined to calculate the dry biomass of leaves, tops, and stalks (Mg ha^{-1}).

The methodology for the root system measurements and analysis were the same as those used by Rossi Neto (2018). Stainless steel probes 1.2 m long with an internal diameter of 0.055 m were used to collect soil samples and roots at depths of 0.00-0.10, 0.10-0.20, 0.20-0.40, 0.40-0.60 and 0.60-1.00 m. After sample collection, the roots were separated from the soil by means of dry sieving (mesh sieve - 1.0 mm). The separated roots were rinsed in running water and dried in a ventilated oven at forced-air-circulation oven at 65 ºC for 72 hours 65°C to determine root biomass. The amount of dry root biomass was calculated for each layer and for each plot using the formula (Equation 3.1):

$$\mathrm{DBR} = [((\mathrm{Sv} * \mathrm{Rm})/\mathrm{Pv})/1.000.000] \quad (3.1.)$$

Where **DBR** is the dry biomass root (Mg ha^{-1}), **Sv** is soil volume in each range and layer assessed (m^3 ha^{-1}), **Rm** is root mass collected from the layer (g), **Pv** is root sampling probe volume of assessed layer (m^3), and **1.000.000**, conversion from grams to Mg.

The sugarcane stalk yield (Mg ha^{-1}) from all plots was assessed by manually harvesting the stalks within a 100 m^2 central area. The stalks were separated from the tops and dry leaves and subsequently weighed using a dynamometer connected to a grab loader. In order to assess the technological attributes (sugarcane Pol - Percentage by weight of apparent sucrose), ten stalks were collected per plot, following the methodology of collection and analysis of CONSECANA (2003).

3.2.4. Soil and Weather data

The soil of the experimental area was classified as Typic Eutrustox (USDA, 2010). In the soil characterization (Table 3.2), that was conducted prior the planting, were determined include soil texture (pipette method), bulk density (tension table), and soil chemistry (methodology described by Raij et al. 2001). The soil samples were randomly collected in the experimental area, subdivided into the layers 0.0-0.1, 0.1-0.2m, 0.2-0.4m, 0.4-0.6m and 0.6-1.0m.

Table 3.2. Soil properties for the experiment conducted in Guaíra, SP, Brazil.

Depth (m)	Clay	Silt (%)	OC	pH (H_2O)	BD (g cm^{-3})	Field capacity	Wilting point (cm^3 cm^{-3})	SWC
0.0-0.1	52	36	1.6	6.2	1.28	0.427	0.274	0.571
0.1-0.2	55	35	1.6	6.2	1.28	0.428	0.271	0.578
0.2-0.4	61	30	1.4	6.4	1.34	0.430	0.272	0.538
0.4-0.6	64	28	1.0	6.1	1.19	0.461	0.272	0.580
0.6-1.0	63	29	0.8	6.1	1.22	0.382	0.218	0.526

OC = Organic carbon; **BD** = Bulk density; **SWC** = Saturated water content

The daily weather data, from 1980 to 2015, was obtained from dataset provided by Xavier et al. (2016). This dataset was also previously validated against weather stations by Battist et al. (2019). The data included daily maximum and minimum temperature, wind speed recorded at a height of 2 m; precipitation; solar radiation; and relative humidity. The monthly climate data for the sugarcane growing season are shown in Figure 3.1.

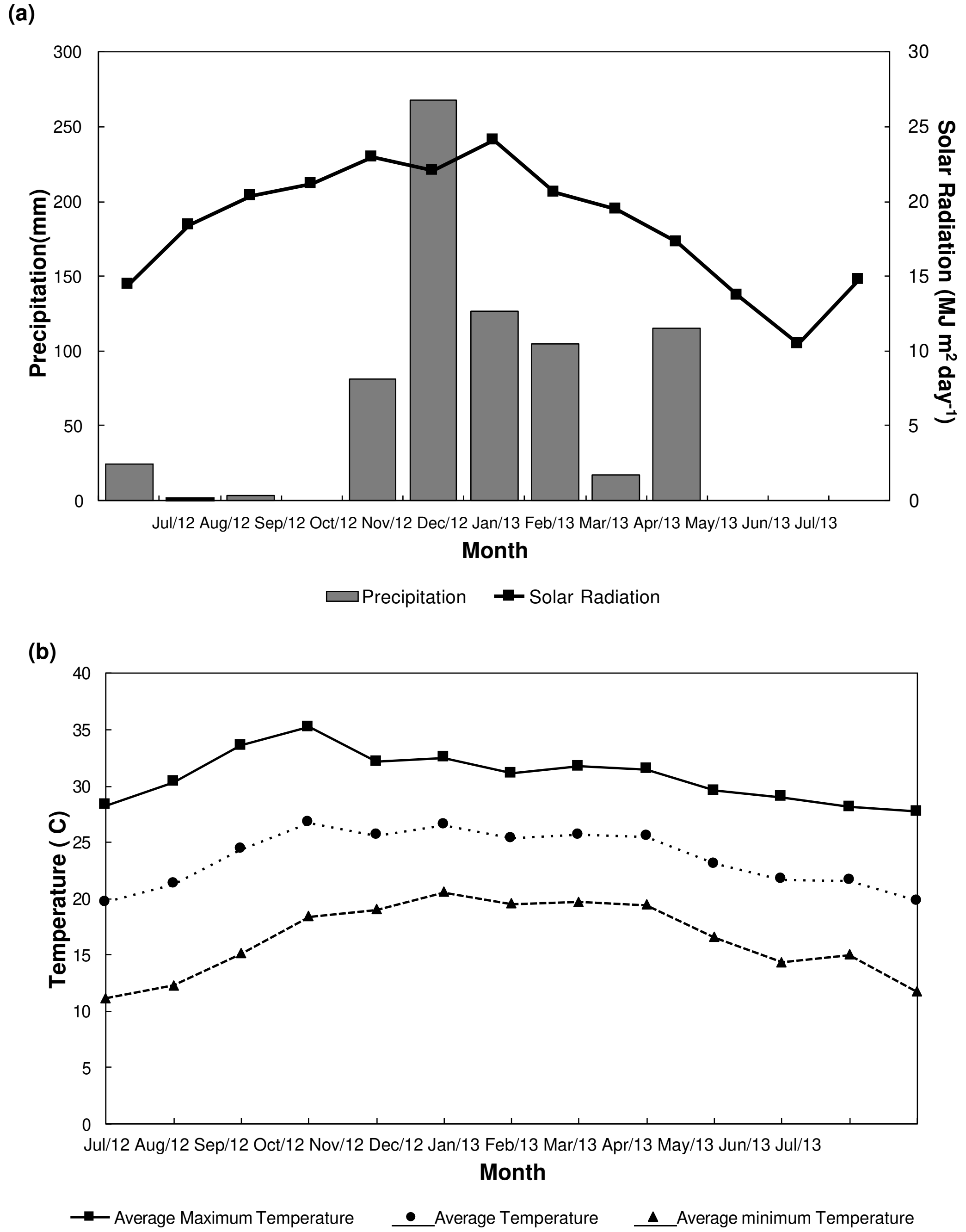

Figure 3.1. Monthly climate conditions for Guaíra, Sao Paulo State, Brazil from July 2012 through July 2013; average monthly solar radiation and monthly total precipitation (a); average maximum and minimum air temperature (b).

3.2.5. CSM-CANEGRO-Sugarcane model

The CANEGRO-Sugarcane (Jones and Singels, 2008; Singles et al., 2008), which is part of DSSAT v.4.7.2 (DSSAT, 2019) was used in this study. The model simulates growth and development of sugarcane crop, including values of above and belowground biomass, leaf area, height, and sugar (Jones and Singels, 2008; Singels et al., 2008).

Model inputs include detailed crop management, daily weather data (rainfall, solar radiation, temperature, humidity and wind speed), soil physical and chemistry properties, and genetic trait coefficients to represent cultivar differences (Singels et al., 2014). The model simulates sugarcane growth and development, as well as a soil and plant water balance, on daily basis, starting at planting until final harvest (Ritchie, 1998). The genetic trait coefficients of the CANEGRO-Sugarcane model capture the genetic control of how the sugarcane crop responds to environmental conditions and crop management factors. These are normally grouped into three categories, namely species (identical values for all cultivars), ecotype (identical values for groups of similar cultivars) and cultivar coefficients (specific to cultivars).

The current CANEGRO-Sugarcane model in DSSAT requires a set of 22 cultivar-specific parameters that must be identified for each cultivar (Table 3.3).

Table 3.3. CANEGRO-Sugarcane Cultivar Coefficients for running of DSSAT.

Category	Parameter	Description	Units
Biomass accumulation	MaxPARCE	Maximum (no stress) radiation conversion efficiency expressed as assimilate produced before respiration, per unit of PAR	g MJ^{-1}
Biomass partitioning	APFMX	Maximum fraction of dry mass increments that can be allocated to aerial dry mass	Mg Mg^{-1}
	STKPFMAX	Fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop	Mg Mg^{-1}
Sucrose accumulation	SUCA	Maximum sucrose contents in the base of stalk	Mg Mg^{-1}
	TBFT	Temperature at which partitioning of unstressed stalk mass increments to sucrose is 50% of the maximum value	°C
Canopy-leaves	LFMAX	Maximum number of green leaves a healthy, adequately-watered plant will have after it is old enough to lose some leaves	leaves
	MXLFAREA	Maximum leaf area assigned to all leaves above leaf number MXLFARNO	cm^2
	MXLFARNO	Leaf number above which leaf area is limited to MXLFAREA	leaf
	LER0	Maximum leaf elongation rate	°C day
Leaf phenology	PI1	Phyllocron interval 1 for leaf numbers below Pswitch	°C day
	PI2	Phyllocron interval 2 for leaf numbers above Pswitch	°C day
	PSWITCH	Leaf number at which the phyllocron changes.	leaf
Tiller phenology	POPTT16	Stalk population at/after 1600°Cd^{-1}	Stalks m^{-2}
	TAR0	Maximum tiller appearance rate (shoots per primary shoot)	°C day
	TDELAY	Delay between appearance of primary shoot and first secondary shoot	°C day
	SER0	Maximum stalk elongation rate	°C day
Phenology	TTPLNTEM	Thermal time to emergence for a plant crop	°C day
	TTRATNEM	Thermal time to emergence for a ratoon crop	°C day
	CHUPIBASE	Thermal time from emergence to start of stalk growth	°C day
	TT_POPGROWTH	Thermal time to peak tiller population	°C day
Lodging	LG_AMBASE	Aerial mass (fresh mass of stalks, leaves, and moisture) at which lodging starts	Mg ha^{-1}

The cultivar used in this study was RB966928, which was previously evaluated for the CANEGRO-Sugarcane model by Souza (2016) - (personal communication). The experimental data collected during the 2012-2013 growing season were used for re-calibrating model using the trial and error method, including both statistical and visual analysis. This is the same procedure that was used by Costa (2014) for the APSIM model and by Barros et al. (2016) forthe CANEGRO-Sugarcane. Final model performance was evaluated by comparing the simulated versus observed values from the second ratoon cycle for the 2014-2015 growing season. The data that were used for model evaluation included biometric parameters and observed sugarcane yields.

3.2.6. Yield forecasting

The CSM-CANEGRO-Sugarcane model was used for yield forecasting of the RB966928 cultivar for the Guaíra region, Sao Paulo State, Brazil, in plant cane cycle. The daily historical weather data (Xavier et al., 2016) for Guaíra for 32 years were combined with the daily weather data recorded for the 2012-2013 growing season. A monthly yield forecast was conducted, starting on September 5, 2012, until June 5, 2013. For these forecasts, the antecedent daily weather data for 2012 were used until the forecast date, complemented with 32 years of historical weather data for the remainder of the growing season. For each forecast date, the mean and standard deviations for the forecasted yield were determined.

3.2.7. Statistical analysis

The model performance for simulations of the growth variables of cultivar RB966928 (weight of aboveground dry biomass and stalk) was quantified by different statistical tests, including: Root Mean Square Error (RMSE), in which the error in RMSE refers to the difference between the simulated and observed value; index of agreement (d), evaluating the model accuracy, indicating the degree of distance from the estimated values in relation to the observed values; and coefficient of determination (R^2), used to analyze how differences in one variable can be explained by a difference in a second variable (Wallach et al., 2006). Additionally, the model's performance was evaluated by comparing the results from the simulations performed with CANEGRO-Sugarcane model with actual data observed in the field (Yang et al., 2014).

3.3. Results and Discussion

3.3.1. Cultivar coefficients

The initial values in the calibration were based on the final values of the Souza (2016) study. For this study, the re-calibration was necessary because of the results with the use of initial values showed high deviations. After calibration the error (RMSE) decreased by 18% for the aboveground biomass and 26.5% for the stalk biomass. However, not all cultivar coefficients had to be modified as well as there was no need to calibrate the ecotype coefficients. The results of the re-calibration of the genetic coefficients for cultivar RB966928 using the experimental data described earlier are shown in Table 3.4.

Table 3.4. Values of the cultivar's parameters used in the parameterization of the CSM-CANEGRO-Sugarcane model for the cultivar RB966928 and the default cultivar NCo376.

Parameters	**NCo376**	**RB966928**		**Units**
	Default cultivar	Calibrated	Re-Calibrated	
MaxPARCE	9.90	10.50	10.50	g MJ^{-1}
APFMX	0.88	0.92	0.60	Mg Mg^{-1}
STKPFMAX	0.65	0.90	0.90	Mg Mg^{-1}
SUCA	0.58	0.58	0.58	Mg Mg^{-1}
TBFT	25.00	25.00	25.00	°C
LFMAX	12.00	10.00	10.00	Leaves
MXLFAREA	360.00	407.00	384.00	cm^2
MXLFARNO	15.00	15.00	15.00	Leaf
LER0	-	-	0.25	°C day
PI1	69.00	150.00	180.00	°C day
PI2	169.00	170.00	180.00	°C day
PSWITCH	18.00	18.00	18.00	Leaf
POPTT16	13.30	13.00	13.00	Stalks m^{-2}
TAR0	-	-	0.04	°C day
TDELAY	-	-	50.00	°C day
SER0	-	-	0.14	°C day
TTPLNTEM	428.00	400.00	390.00	°C day
TTRATNEM	203.00	40.00	850.00	°C day
CHUPIBASE	1050.00	880.00	1400.00	°C day
TT_POPGROWTH	600.00	260.00	500.00	°C day
LG_AMBASE	220.00	220.00	220.00	Mg ha^{-1}

Default Cultivar: Parameters found in DSSAT program for the cultivar NCo376; **Calibrated**: The coefficients calibrated previous for sugarcane cultivar in the State of Rio Grande do Sul, Brazil (Souza, 2016); **Re-Calibrated**: The coefficients calibrated for sugarcane cultivar in the State of Sao Paulo, Brazil. **(-)** Not available value.
The parameters definitions can be found in table 3.3.

The cultivar coefficients MaxPARCE, STKPFMAX, SUCA, TBFT, LFMAX, MXLFARNO, PSWITCH, POPTT16, LG_AMBASE did not have to modify for the new calibration and, therefore, the values of the parameterization carried out previously were used (Table 3.4). Already the other cultivar coefficients (APFMX, MXLFAREA, PI1, PI2, TTPLNTEM, TTRATNEM, CHUPIBASE, and TT_POPGROWTH) were calibrated for the highest values of r Square and agreement index as well as the lowest RMSE value.

During the re-calibration, the parameters APFMX, POPTT16 and TTPLNTEM showed less values than the previously calibrated by Souza (2016). In contrast, the other parameters (MXLFAREA, PI1, PI2, TTRATNEM, CHUPIBASE and TT_POPGROWTH) showed higher values. These differences presented by the calibrated previously and the re-calibrated data, for the same cultivar, highlight the importance of the adjustment of the CANEGRO model.

After the last update of the CANEGRO model (Version 4.7.2), four new cultivar coefficients were introduced (LER0, TAR0, TDELAY, and SER0). These new coefficients were calibrated from the cultivar NCo376; however, only the TAR0 parameter required calibration for the conditions of the studied region (Table 3.4).

By analyzing the change in the parameters individually, the statistical indexes using for the aboveground biomass and stalk (RMSE, d-index and r Square), showed that the individual calibration of each parameter presented varied results (Figure 3.2).

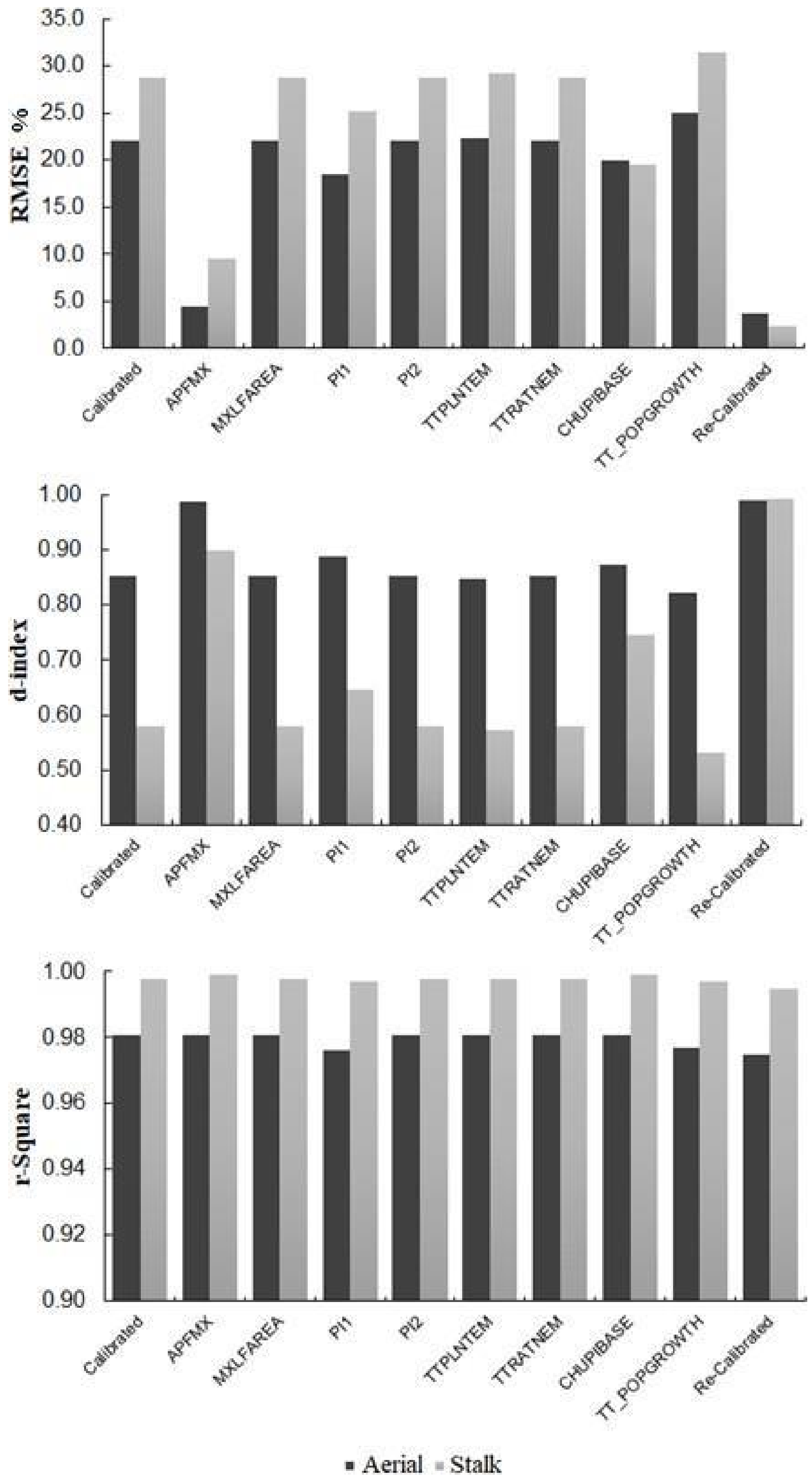

Figure 3.2. Analysis of the statistical indexes for the aerial (aboveground biomass) and stalk (RMSE, d-index and r-Square) in the individual calibration of cultivar coefficients from the calibration performed by Souza (2016) "Calibrated" for sugarcane cultivar RB966928 in Guaíra, Sao Paulo State, Brazil.

The results showed that the model was more sensible to the APFMAX parameter (Figure 3.2), i.e. the re-calibration with the changes of just this parameter was almost the same as the re-calibration considering all parameters (best calibration). These results, in the cultivar coefficients analyze, may be related to the different response for both the above and belowground processes of the same cultivar under different edaphoclimatic conditions (Barbosa et al., 2018; Maule et al., 2001; Rossi Neto et al., 2018).

3.3.2. CSM-CANEGRO-Sugarcane model

The CANEGRO-sugarcane model showed satisfactory performance, except for PP 0.50 m treatment, in the simulation of the aboveground dry biomass and stalk of sugarcane RB966928 cultivar in the plant cane crop season for the region of Guaíra, Sao Paulo, Brazil (Figure 3.3). For the PP 0.50m, the crop model underestimated the sugarcane dry biomass production along the agricultural crop (Figure 3.3).

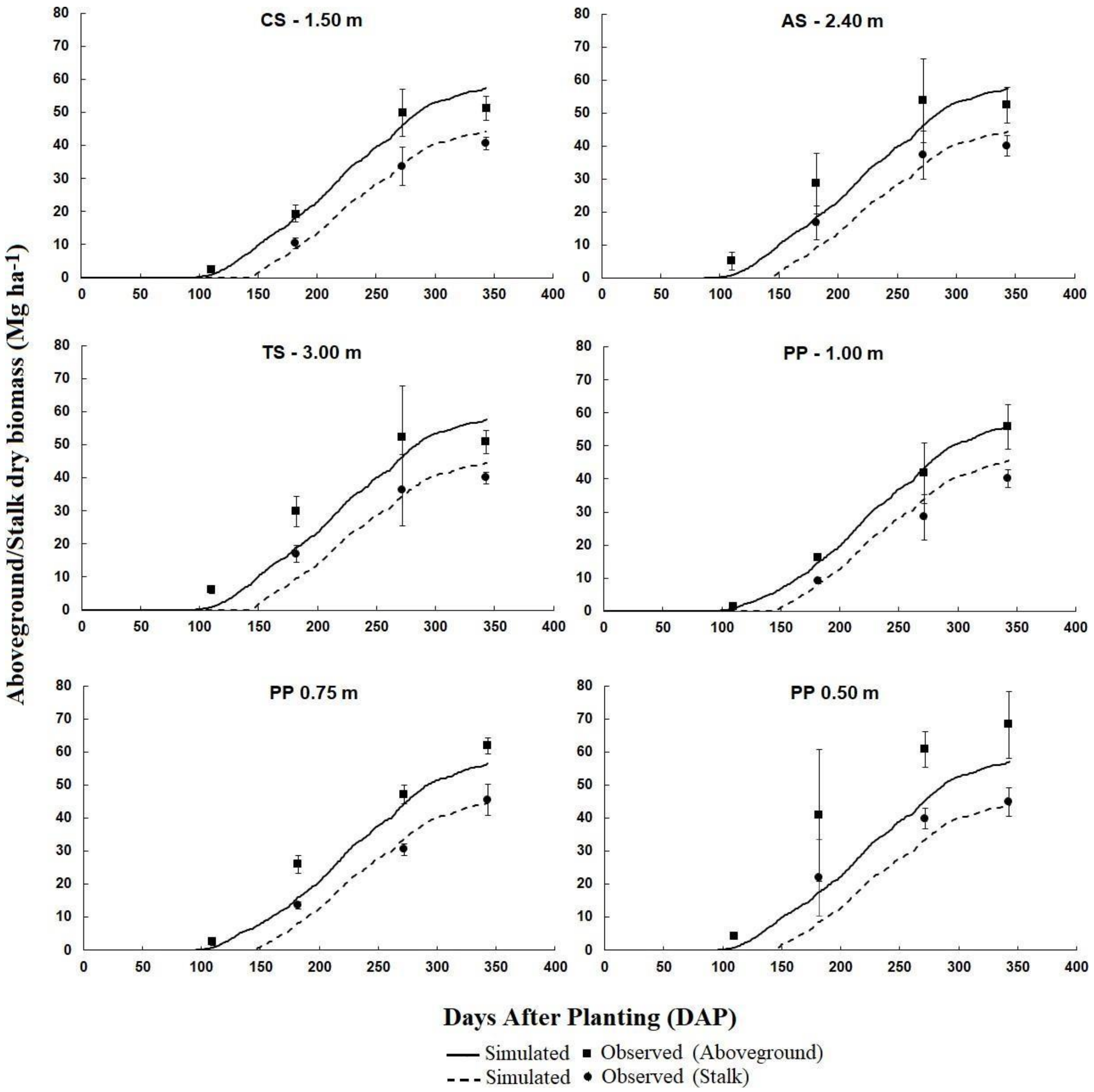

Figure 3.3. The observed and simulated weight of the aboveground dry biomass and stalk for six planting spacing for the RB966928 cultivar of sugarcane at Guaíra, Sao Paulo State, Brazil.

Note: CS: conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

Despite satisfactory performance during the crop season, the simulated final stalk weight and for aboveground biomass overestimated or underestimated the observed data (Table 3.5). For the CS treatment, the simulated final stalk weight and for aboveground biomass was overestimated in 9 and 12%, respectively (Figure 3.3 and Table 3.5). Using the same plant spacing, this response was also observed by Souza (2016), where the simulation for cultivar RB966928 was conducted for a very different climate in southern

Brazil. According to Bezuidenhout and Singels (2007a, b) the model simplifies commercial field conditions and often overestimates yield, especially when there are biotic stresses due to weeds, pests, or diseases.

Table 3.5. Observed and simulated average yield (final weight at harvest) for six plant spacing using the RB966928 cultivar of sugarcane for the plant cane cycle (Re-Calibration) at Guaíra, Sao Paulo State, Brazil.

	Treatments					
Final Weight	CS	AS	TS	PP 1.00 m	PP 0.75 m	PP 0.50 m
	Stalks Dry biomass (Mg ha^{-1})					
Observed	40.6	40.1	40.0	40.2	45.6	45.0
Simulated	44.4	44.5	44.6	45.6	44.8	44.1
Variation (%)	9	11	11	13	-2	-2
	Aboveground Dry biomass (Mg ha^{-1})					
Observed	51.4	52.5	51.0	55.8	61.9	68.4
Simulated	57.4	57.5	57.7	56.2	56.6	57.1
Variation (%)	12	10	13	1	-9	-17

Variation: Difference found between the simulated and observed weight in cane field. **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

The difference found in the cycle end, between simulated and observed results, might be associated with the decrease in the observed final weight to the previous weight (Measurement performed three months before harvest). Sometimes lodging occurs in the experiment prior to harvest, affecting final yield and yield components. This was found by Oliveira et al. (2010) who studied growth and dry biomass production in sugarcane for cultivar RB872552 under full irrigation. In research conducted at some of the main sugarcane centers, observed a decrease in crop productivity due lodging of the plants prior to final harvest (Singh et al., 2002).

As with CS, occurred an overestimated of the final simulated values for the AS, TS and PP 1.00 m treatments (Table 3.5). This result can be explained also by lodging of the sugarcane occurs prior to harvest (above mentioned). In contrast, for the spacings PP 0.75 and PP 0.50 m (denser), the final values were underestimated for the final weight of stalk and aboveground biomass by the model (Table 3.5).

3.3.3. Evaluation Model

For model evaluation, the second ratoon crop cycle used. The CANEGRO-Sugarcane model showed satisfactory performance for in the simulation of the weight of aboveground dry biomass and the stalk, except for the denser spacing as in the model re-calibration (Figure 3.4).

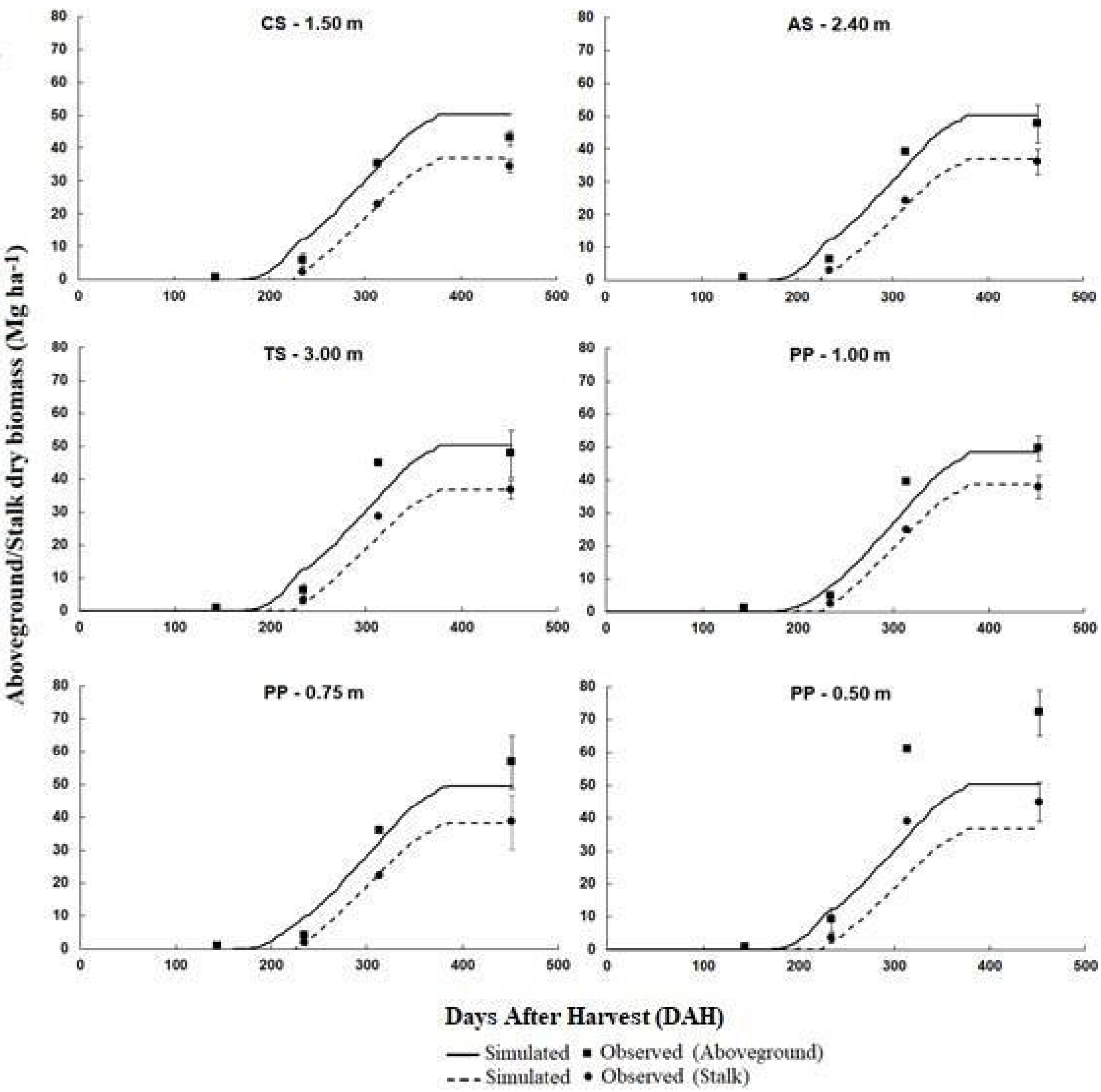

Figure 3.4. The observed and simulated weight of the aboveground dry biomass and stalk for model evaluation in six planting spacing for the RB966928 cultivar of sugarcane at Guaíra, Sao Paulo State, Brazil.

Note: CS: conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

As in the plant cane cycle, the simulated final values of biomass aboveground (except PP 1.00 m) and stalk dry mass for the second ratoon were higher than those observed in the field for the CS, AS, TS and PP 1.00 m spacings. However, the simulated values were closer to the values observed, with featured on TS treatment that presented practically identical values (Table 3.6). Regarding the denser spacings, the behavior was the same observed at the plant cane cycle (Table 3.6). In this cycle, there was no observed the problem with the lodging of the plants.

Table 3.6. Observed and simulated average yield (final weight at harvest) for six plant spacing using the RB966928 cultivar of sugarcane for second ratoon (evaluation model) at Guaíra, Sao Paulo State, Brazil.

	Treatments					
Final Weight	CS	AS	TS	PP 1.00 m	PP 0.75 m	PP 0.50 m
	Stalks Dry biomass (Mg ha^{-1})					
Observed	34.5	36.0	36.8	37.7	38.5	44.7
Simulated	37.0	36.9	36.9	38.8	38.1	36.9
Variation (%)	7	2	0	3	-1	-13
	Aboveground Dry biomass (Mg ha^{-1})					
Observed	43.0	47.6	47.7	49.6	56.8	72.0
Simulated	50.4	50.4	50.4	48.6	49.5	50.4
Variation (%)	17	6	6	-2	-13	-30

Variation: Difference found between the simulated and observed weight in cane field. **CS:** conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

Thus, due to the demand by information from the sugarcane industry and the need for a tool that helps to understand the development of the planted crop in the different planting management, the results this study showed great potential for the CANEGRO-model to simulate the biomass accumulation of the RB966928 cultivar for Guaíra region.

3.3.4. Yield forecasting

The yield forecasts (circles) conducted throughout the crop season resulted in values different from the observed yield (triangle) in the field at harvest time for the six plant spacings (Figure 3.5).

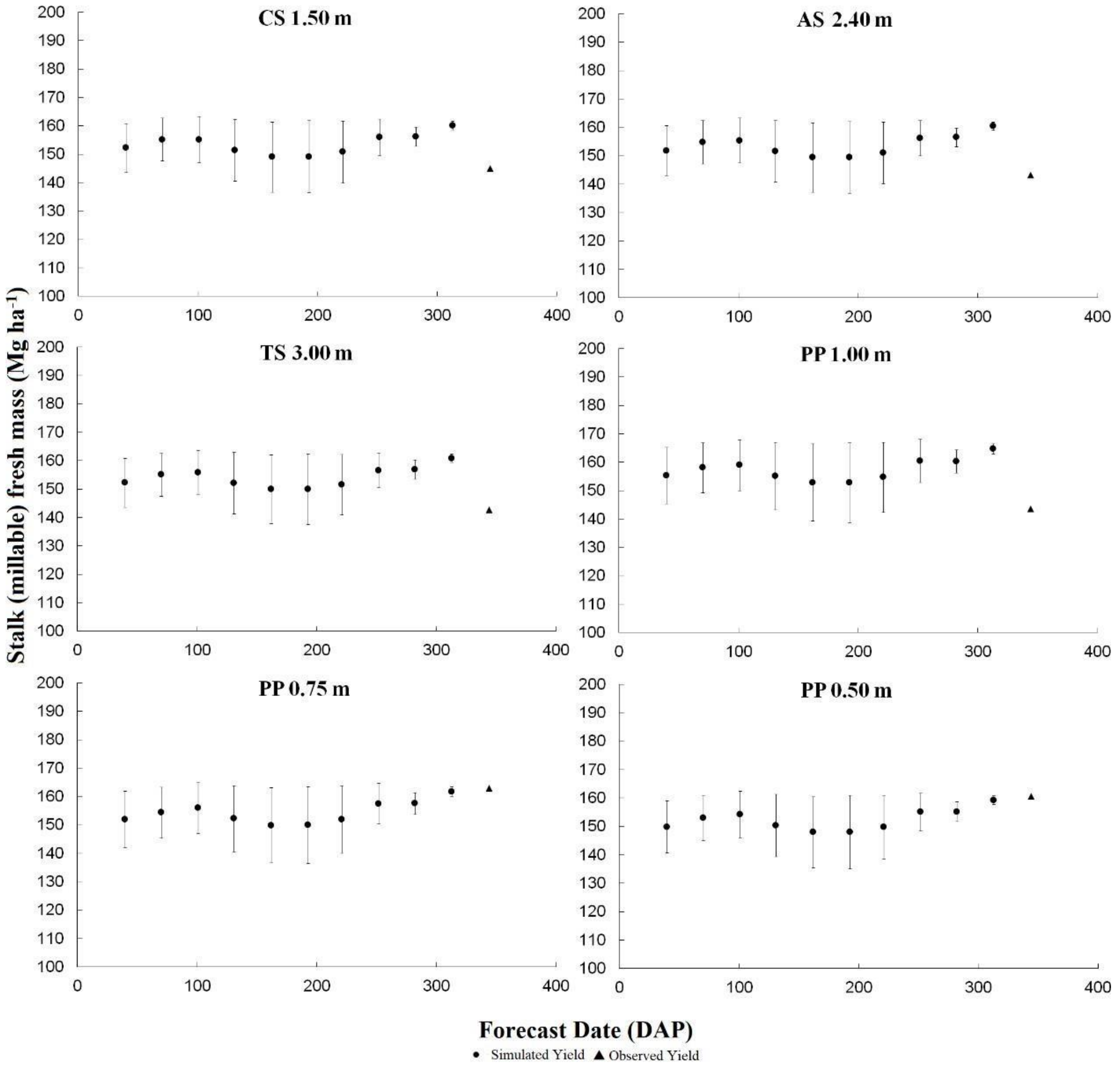

Figure 3.5. Average forecasted yield and standard deviation for the crop season 2012/13 as a function of the forecast date and observed yield (Mg ha^{-1}) for six spacings of sugarcane.

Note: CS: conventional spacing**; AS:** alternated spacing**; TS:** triple spacing**; PP 1.0m:** precision planting of 1.0m**; PP 0.75 m:** precision planting of 0.75 m**; PP 0.50m:** precision planting of 0.50m.

There was high variability for the early yield forecasts conducted from November until April, the time with the highest temperature and precipitation in the region studied, as seen by the large standard deviation associated with each forecast (Figure 3.5). This yield variability may be related to different sets of weather data generated by the model when combined specific years with the original year (2012/2013), resulting in different responses in the sugarcane plants' development.

When the simulations were conducted for an extensive period with actual weather records for 2012/2013, the standard deviation of simulated yield decreased for all row spacings reaching low values approximately 90 days prior to harvest (Figure 3.5). For all spacings, the estimated yield had a standard deviation that was close to 0 on 5 June (Figure 3.5).

The sugarcane yield forecasting results close to the harvest date at the different spacings were expected due to the simulations carried out by the CANEGRO-model (Figure 3.3). The model forecasted a productivity of 160 Mg ha^{-1} for CS treatment close to crop harvesting, overestimating the observed value by 15 Mg. The treatments AS and TS had the same productivity in the field (143 Mg ha^{-1}); however, the predicted value for AS was overestimated in 17 Mg (better) against 18 Mg of the TS. The PP treatment 1.00 m presented the lowest performance, and the model overestimated the productivity observed in the field (144 Mg ha^{-1}) by 21 Mg. On the other hand, the denser spacings had the best productivity forecast being 1 and 2 Mg less, PP 0.75 m and PP 0.50 m respectively, than that observed in the field.

The sugarcane yield forecasts mentioned above (close to harvest) were influenced to the CSM-Canegro model results (Figure 3.3 and Table 3.4). The model was adjusted based on all temporal measurements; however, the final simulated stalk biomass was similar with the observed data for treatments PP 0.75 and 0.50 (Table 3.4). Thus, these treatments showed the best performances for the forecast yield.

The results of this study showed that simulation models can satisfactorily forecast productivity of sugarcane planted at different plant spacings. However, further studies are needed to better calibrate the model and obtain a better and earlier forecast of crop productivity.

3.4. Conclusion

The results of this study show for the first time that CANEGRO-sugarcane model calibrated for conventional spacing (1.50 m) can be applied to simulate the sugarcane stalk and aboveground yield under different row spacings.

This work confirms that the CANEGRO-sugarcane model is an important tool to help the sugarcane industry better understand the behavior of sugarcane in different spacings between rows and plants and to determine the best management option to maximize the crop production.

The CANEGRO-model parameterization is essential for each sugarcane production environment and, the coefficient APFMX, shows up with an important tool to help with model calibration in planting spacing studies in Brazilian conditions.

3.5. References

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III - General Discussion

In view of the increase in global demand for renewable energy sources, technologies are needed to maximize sugarcane production on the field. In this scenario the management of sugarcane planting spacing can improve the sustainability of biomass production around the world. Furthermore, knowing the best row spacing and plant density it is possible increase the sugarcane stalk yield.

Several studies have been conducted over the years (Table 1) showing that, in more than 70% of them, changing in the planting spacing increases the sugarcane yield. Overall, the best plant row spacing in productivity was traditionally from 0.5 to 1.0 m (Table 1), and the exact spacing was dependent on edaphoclimatic conditions. i.e., soil texture, geographic localization, sugarcane cultivar and cultural practices adopted (fertilization rates, irrigation or not irrigation, mechanical harvest traffic). In Brazilian conditions, the best row spacing is between 0.75 and 1.0 m, which is lower than the conventional row spacing is 1.5 m (Table 1).

The results founded in Brazilian experimental fields (Chapter 2) corroborated with the previously presented results (Rossi Neto et al., 2018), and in literature review (Table 1) in addition to answering questions raised about planting spacing in sugarcane (Rossi Neto, 2015). In the edaphoclimatic conditions of site 1 it was possible to observe an increase in sugarcane production and longevity with adoption of the equidistant spacing of 0.50 m (Figure 2.15 and Table 2.12). In addition, was observed a lower seedling expense using equidistant planting indicating a higher profitability for the sugar mill owner. This results demonstrate the need of the sugarcane industry in the region to invest more in planting management.

Already in constrained environment conditions to sugarcane cultivation (site 2), crop yields were similar among the planting spacings (Table 2.12). Previous results (Rossi Neto et al., 2018) showed that in these environments the crop show problems in expressing it productive potential. Also, planting spacing management showed yield differed when occurred these environmental conditions. However, this fact was not observed in this study, once the plants suffered to disease attack in forth crop season, and there was no showed difference among the spacings (Table 2.12). By analyzing the cane fields longevity in this conditions, did not a productivity increase trend was observed along the crop seasons for all spacings.

The results confirmed that, based on these two experimental areas, the environment condition (soil and climate) + sugarcane harvest season directly affected the sugarcane productivity. In environment with less agricultural restriction (site 1) were reduced the spacing with better clumps distribution (equidistant planting), increasing the crop yield in the two-year accumulated (Table 2.12). On the other hand, in sandy soil (site 2) no differences were observed between treatments. This is an interesting fact, and it contradicts, in part, one of the historical claims of the Brazilian sugar industry that in restrictive environments the increase in planting density should be increased.

Although field research has produced promising results, the sugarcane industry has always faced problems in adopting alternative plant spacing, mainly due to the absence of adequate machinery (Magalhães and Braunbeck, 2010) and the lack of information about optimal management in the production environments. In addition, in the last decade the sugarcane productivity decreased by 12% in Brazil because of the impact of mechanization on the fields. In the other words, the advance of mechanization and the absence of traffic control occurred more quickly than the systematization of the areas. Thereby, sugarcane was "imprisoned" in a scenario in which plant spacing did not maximize production potential, and in which plants were trampled during agricultural operations. To solve this uncertainties in the cane fields, further studies are needed under different edaphoclimatic conditions. However, these studies are expensive and time-consuming.

As alternative for traditional fields experiments the use of tools, such as crop models, can optimize the use of resources required (time, financial and human) to obtain information and assist in decision-making by stakeholders. In sugarcane, this tool has been used to study and simulate several studies, however, related to the management of planting is recent interest in the scientific community. In this work, the DSSAT program showed satisfactory performance to simulate the sugarcane development in different planting spacings in Guaíra region. Furthermore, the program has proved to be a promising tool for predicting sugarcane yield (Chapter 3).

Thus, according thesis results the adoption of a different planting spacing than that usually adopted in the cane fields (equidistant planting) represents an alternative to increase production and, consequently, supply the projected demand for the next crop seasons according the last COP-21 meeting (Sanches et al. 2017). Moreover, it proves that crop modeling is an important tool to understand how these new planting spacing behaves in different sugarcane production environments. However, further studies are needed to enable the adoption of these spacings in Brazilian cane fields and other producing countries.

IV – General Conclusion

The present work shows that the best distribution of plants on the field (equidistant spacing) is a management alternative to increase the sugarcane yield. The use of equidistant spacing increases the production of sugar, fiber, stalks per area and positively influences the cane fields longevity under edaphoclimatic conditions, without restrictions on cultivation. Nevertheless, with edaphoclimatic restrictions the best distribution of plants in the field it was not enough to increases the crop yield. Despite, it becomes evident the need of the agricultural machinery industry to develop harvesters and other machines that allow the adoption of equidistant spacings. The root dry biomass production, up to the depth of 1 m increases in the ratoon's cycles with the use equidistant spacings. Moreover, this work proves that the CANEGRO-sugarcane model is an important tool to help the sugarcane industry better understand the behavior of sugarcane in different planting spacings and thus, to determine the best management option to maximize the crop production. The DSSAT program simulate the sugarcane development and can predict yield at different configuration planting of satisfactorily way for the Guaíra region.

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