Straw Removal Effects on Sugarcane Root System and Stalk Yield

Article *in* Agronomy · July 2020

DOI: 10.3390/agronomy10071048

7 authors, including:

Paul Melo
University of São Paulo
4 PUBLICATIONS 60 CITATIONS

Maurício Roberto Cherubin
University of São Paulo
137 PUBLICATIONS 1,262 CITATIONS

Izaias Pinheiro Lisboa
University of São Paulo
21 PUBLICATIONS 223 CITATIONS

Marcos Siqueira Neto
University of São Paulo
59 PUBLICATIONS 1,074 CITATIONS

agronomy

MDPI

Article

Straw Removal Effects on Sugarcane Root System and Stalk Yield

Paul L. A. Melo [1,*], Maurício R. Cherubin [2], Tamara C. A. Gomes [3], Izaias P. Lisboa [2], Lucas S. Satiro [2], Carlos E. P. Cerri [2] and Marcos Siqueira-Neto [1,4]

1 Center for Nuclear Energy in Agriculture, University of São Paulo, PO Box 96, Piracicaba SP 13416-000, Brazil; msiqueir@usp.br
2 "Luiz de Queiroz" College of Agriculture, University of São Paulo, Piracicaba SP 13418-900, Brazil; cherubin@usp.br (M.R.C.); iplisboaa@usp.br (I.P.L.); satiro@usp.br (L.S.S.); cepcerri@usp.br (C.E.P.C.)
3 Brazilian Agricultural Research Corporation, Embrapa Coastal Tablelands, PO Box 2013, Tabuleiro do Martins, Maceió AL 57061-970, Brazil; tamara.gomes@embrapa.br
4 Center of Agrarian and Environmental Sciences, Federal University of Maranhão, Chapadinha MA 65500-000, Brazil
* Correspondence: linekeramaral@usp.br; Tel.: +55-19-3429-4726

Received: 19 June 2020; Accepted: 18 July 2020; Published: 21 July 2020

Abstract: The sugarcane (Saccharum spp. L.) mechanical harvesting system leaves a large amount of straw mulch on the soil surface. The straw mulch may affect soil conditions, root regrowth, and sugarcane yield. Thus, this study assessed the response of sugarcane root system growth and stalk yield to different rates of straw removal. An experiment was conducted in a Rhodic Kandiudox with sand clay loam texture to test the impact of four rates of straw removal: no removal (18.9 Mg ha^{-1} of dry mass); moderate removal (8.7 Mg ha^{-1}); high removal (4.2 Mg ha^{-1}) and total removal on sugarcane root system and stalk yield. Higher concentrations of roots (60%) were found in the first 40 cm of soil. Moderate straw removal resulted in higher root mass (3.6 Mg ha^{-1}) and stalk production (23 Mg ha^{-1} of dry mass). However, no straw removal reduced root mass by <40% (2099 kg ha^{-1}) and reduced stalk yield by >20% (105 Mg ha^{-1}). Through regression analysis, it was estimated that retaining between 8.5 and 13 Mg ha^{-1} of straw resulted in the highest root mass and stalk yield. Managing straw removal to retain a moderate amount enables producers to sustain suitable soil conditions for sugarcane root growth and stalk production while providing straw for industrial use.

Keywords: root growth; soil penetration resistance; soil compaction; mechanized harvest; feedstock

1. Introduction

Brazil is the world's largest sugarcane producer, accounting for about 40% of global production, with 643 million tons of stalks harvested across 8.5 million hectares during the 2019/2020 harvesting season, mainly concentrated (90%) in the south-central region of the country [1]. Currently, this production results in 35 million of tons of sugar and 32 billion liters of ethanol [1]. Moreover, bagasse from sugarcane-milling processes, plus straw (i.e., dry and green leaves) have an essential role in bioelectricity co-generation and second-generation ethanol production [2,3]. Bioelectricity was responsible for about 10% of the Brazilian electricity demand in 2016 [4], whilst it is estimated that bioelectricity from straw can provide 22–37% of the demand for the state of Sao Paulo [5].

The sugarcane mechanical harvesting system leaves large amounts (10 to 20 Mg ha^{-1} of dry mass in each crop cycle) of crop residue (straw) in the field [6]. Straw mulching provides several agronomic benefits for the soil–plant system, among them being: increased soil protection against erosion processes [3,7], enhanced soil organic matter content [8,9], improved nutrient cycling [10], increased water infiltration and retention [11], reduced thermal amplitude in the soil [12] and reduced susceptibility to soil compaction due to machine traffic [13]. Thus, indiscriminate straw removal can adversely affect soil attributes and thereby sugarcane root system growth and crop yield.

Sugarcane has a fasciculated root system which develops throughout the entire crop cycle (i.e., ratoon), and is renewed after harvesting in each ratoon cycle [14]. Root mass and distribution can vary according to soil attributes (texture, profile depth, bulk density, structure, fertility, and others), water availability, temperature, plant variety and management [15,16]. Thus, straw mulch may affect sugarcane root systems, as reported by Alvarez et al. [17], who verified higher root accumulation near the soil surface, and Cury et al. [18], who found a smaller soil volume explored by the root system in areas under a mechanical harvesting system and no straw removal. In addition, straw mulch may induce potential deleterious impacts on the root system through the release of allelochemical substances from the anaerobic decomposition of these residues [19], hinder fertilizer application [20], increase proliferation of pest populations [21,22], and reduce soil warming [23]. These soil parameters may delay initial plant regrowth [24], affect root growth, and reduce crop yield [25].

In this context, scientific evidence leads us to believe that partial straw removal could bring agronomic benefits to plant growth and soil conditions [15,24,26] and surplus straw could be harvested as a potential bioenergy feedstock, increasing electricity co-generation from biomass burning and also for cellulosic ethanol production (i.e., second-generation bioethanol) [5,23,27]. Our hypothesis is that partial straw removal for bioenergy proposals does not lead to soil physical quality degradation (i.e., increases soil bulk density) and under such straw management, the sugarcane root system growth and stalk yield are not impaired. Thus, this study aims to determine how different rates of straw removal affect soil conditions (moisture and resistance to penetration) and their implications on root system growth (mass and distribution) and stalk yield of the sugarcane ratoon.

2. Material and Methods

2.1. Study Area and Experimental Design

The experiment was carried out in a commercial sugarcane field in the municipality of Capivarí, São Paulo (SP) State, Brazil (22°51′08.3″ S and 47°30′53.2″ W, 636 m above sea level). The climate is subtropical humid (Cwa, according to Köppen classification), characterized by a dry winter and rainy summer, with a mean annual temperature of 21.8 °C and annual precipitation of 1260 mm. The rainfall regime registered during the period of the experiment exceeded the historical pattern for the region, which accumulated approximately 2200 mm and a mean temperature of 24.2 °C (Figure 1A). The water balance presented accumulated precipitation of 1870 mm and a deficit of 326.2 mm during the period of the experiment (October 2014 to December 2015) (Figure 1B).

The soil is classified as a sandy clay loam Rhodic Kandiudox [28]. The soil chemical and physical characteristics are presented in Table 1. The sugarcane variety planted was CTC-14, which is highlighted as an excellent option for mechanized harvesting [29]. This variety is recognized by high yield (over 90 Mg ha^{-1}), drought tolerance and ratoon longevity [30]. Sugarcane planting was carried out in February 2013 using a double row system (i.e., 1.50 m spacing (where machinery traffic occurs) and 0.90 m spacing (without machinery traffic)). Details about the double row spacing arrangement are presented in Lisboa et al. [31]. The first harvest was carried out in October 2014.

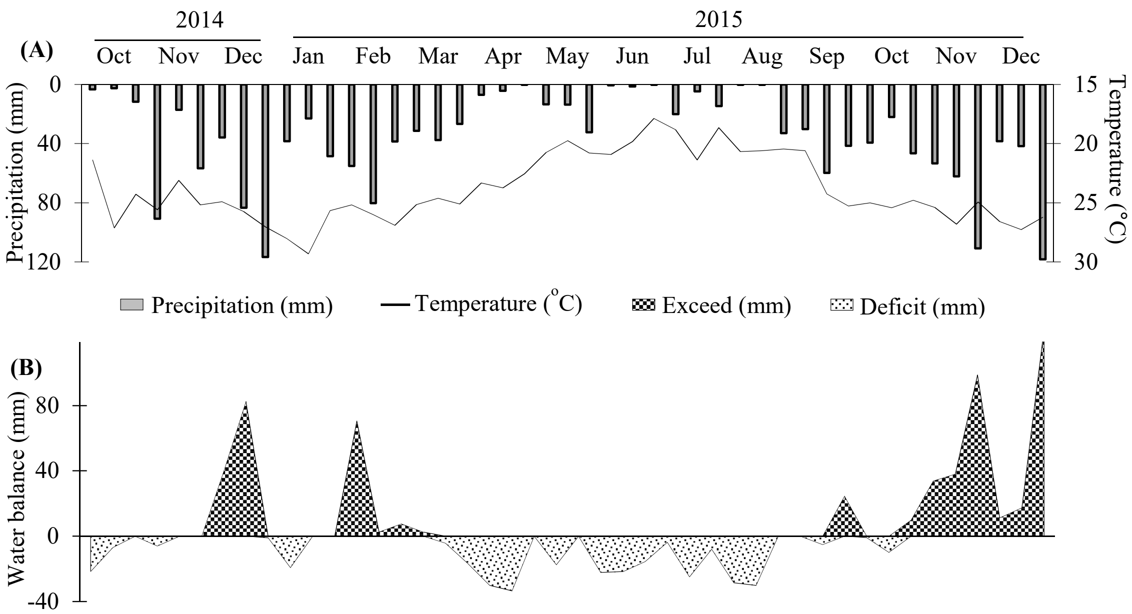

Figure 1. Precipitation and mean air temperature (**A**) and water balance (**B**) in the study site.

Table 1. Selected soil chemical and physical attributes in the study site before experiment installation (after first harvest) at the 0–30 cm soil layer.

Soil Attribute	Unit	Values
Sand	(g kg^{-1})	594 ± 21
Silt	(g kg^{-1})	68 ± 9
Clay	(g kg^{-1})	333 ± 16
Bd_{crop} [1]	(g cm^{-3})	1.42 ± 0.05
$Bd_{traffic}$ [2]	(g cm^{-3})	1.62 ± 0.1
pH $_{H2O}$		5.0 ± 0.2
C content	(g kg^{-1})	12.3 ± 1.7
N content	(g kg^{-1})	0.8 ± 0.2
Available P	(mg kg^{-1})	20.6 ± 1.4
Cation exchange capacity	(cmol$_c$ kg^{-1})	4.4 ± 0.5
Base saturation	(%)	69.0 ± 3.4
Al saturation	(%)	2.5 ± 0.3

[1] Bd_{crop} = bulk density at the center of the crop inter-row (0.90 m spacing) [2] $Bd_{traffic}$ = bulk density at the center of the traffic inter-row (1.50 m spacing).

The experiment was set up concurrently with the cane plant harvesting period in October 2014. The procedures adopted are described in Lisboa et al. [31]. The total amount of straw left on the soil surface was approximately 18.9 Mg ha^{-1} of dry mass (DM) and contained approximately 60% tops and green leaves and 40% dried leaves, with a total C content of 405 g kg^{-1} and total N concentration of 5.5 g kg^{-1}. The experimental design consisted of randomized blocks with four treatments and four replications. The treatments included different rates of straw removal, as follows: (i) no removal (NR, 18.9 Mg ha^{-1} of DM); (ii) moderate removal (MR, 8.7 Mg ha^{-1} DM); (iii) high removal (HR, 4.2 Mg ha^{-1} DM); and (iv) total removal (TR, bare soil). The different amounts of straw left on the soil surface were achieved using a sugarcane harvesting machine. For this proposal, different combinations of rotations on the primary and secondary extractor fans on the harvester were set up, according to Lisboa et al. [31].

2.2. Sampling and Quantification of Above- and Below-Ground Phytomass Yield

Sampling of the sugarcane root system was performed before the second harvest in December 2015 using a stainless-steel probe auger (diameter: 15 cm; length: 18 cm; vol: 3180 cm^3/3.2 L). In each treatment, nine points were sampled in a straight line transversely to the planting rows in the 0–20, 20–40, 40–60 and 60–80 cm layers. Each layer was sampled separately (Supplementary Material, Figure S1). A, B and C are sample points within the middle of the traffic inter-row (1.50 m spacing), 0.75, 0.45 and 0.15 m away from the planting row, respectively, while D and E are sampled points within the crop inter-row (0.90 m spacing), 0.15 and 0.45 m away from the planting row, respectively. In the laboratory, soil samples containing approximately 5.5 kg of soil plus roots were washed in a series of 5-mm and 2-mm sieves to separate roots from the soil. Thereafter, the roots were oven dried at 65 °C until constant weight was reached. The root mass (RM) was calculated according the equation:

$$RM\ (kg\ ha^{-1}) = [(RD_{A1} \times Vol_{A1}) + (RD_{B1} \times Vol_{B1}) + (\ldots) + (RD_{A2} \times Vol_{A2})] \times [(Vol_{ha}/Vol_{2.4m})]$$

where RD = root density (kg m^{-3}) in sampling point; Vol_{A1} and Vol_{A2} = soil volume (m^3) represented by each one of the points sampled, obtained by multiplying 0.15 m width × 0.2 m depth × 1 m length (Figure S1); Vol_{B1} to Vol_{B2} = soil volume (m^3) represented by each one of the points sampled, obtained by multiplying of 0.30 m width × 0.2 m depth × 1 m length, according Otto et al. [32] (Figure S1); Vol_{ha} = soil volume (m^3) of 0.20 m thickness layer in one ha; $Vol_{2.4m}$ = soil volume (m^3) of 0.20 m thickness in a complete 2.4 m transect (Figure S1).

Above-ground sugarcane phytomass quantification was carried out through harvesting plants in 2 m within one double row in December 2015. The plants were divided into stalks, dry leaves and tops plus green leaves. After this, each plant part was oven dried at 65 °C until a constant weight was achieved. Details are reported in Lisboa et al. [24].

2.3. Determination of Soil Moisture and Soil Penetration Resistance

In addition to plant sampling, soil moisture was determined in disturbed samples collected at 0–5, 5–10, 10–20, 20–30 and 30–40 cm depths located between the 1.50 m spaced rows (traffic inter-row) and 0.90 m spaced rows (crop inter-row), and gravimetric soil moisture was determined by oven-drying (105 °C) the samples until constant mass was achieved. In parallel to soil sampling, soil penetration resistance (SPR) was determined (0–40 cm) using an impact penetrometer (IAA/Planalsucar, plunger mass: 4 kg; free fall: 40 cm; cone: 30° angle and 12.8 mm diameter) [33]. These evaluations were performed between the 1.50 m spaced rows (traffic inter-row) and 0.90 m spaced rows (crop inter-row), with four replications in each point.

2.4. Data Analysis

Data of root mass, stalk production, soil moisture, and penetration resistance were processed using a one-way ANOVA approach where the straw removal rates were included as fixed effects and replications were included as random effects. Means were compared using Tukey's test ($p < 0.05$). The effect of straw retention rate on sugarcane root growth, stalk yield, and penetration resistance were evaluated through regression analysis. The models were evaluated according to the coefficient of determination. All statistical analysis was performed using R software.

3. Results

3.1. Straw Removal Effects on Root System Mass and Distribution

The majority of the root mass was concentrated in the surface layers (0–20 and 20–40 cm), regardless of the straw removal rate (Figure 2). This pattern of root distribution was similar for sample points at the same distance from the plant growth row. For all straw removal rates, there was a reduction in root mass in the traffic inter-row (1.50 m) compared to the crop inter-row (0.90 m) (Figure 2). The lowest root mass was found in the center of the traffic inter-row (point A1 and A2). As the sampling points neared the plant growth row, a larger root mass was measured, with the highest values occurring at points in the crop inter-row (points D and E).

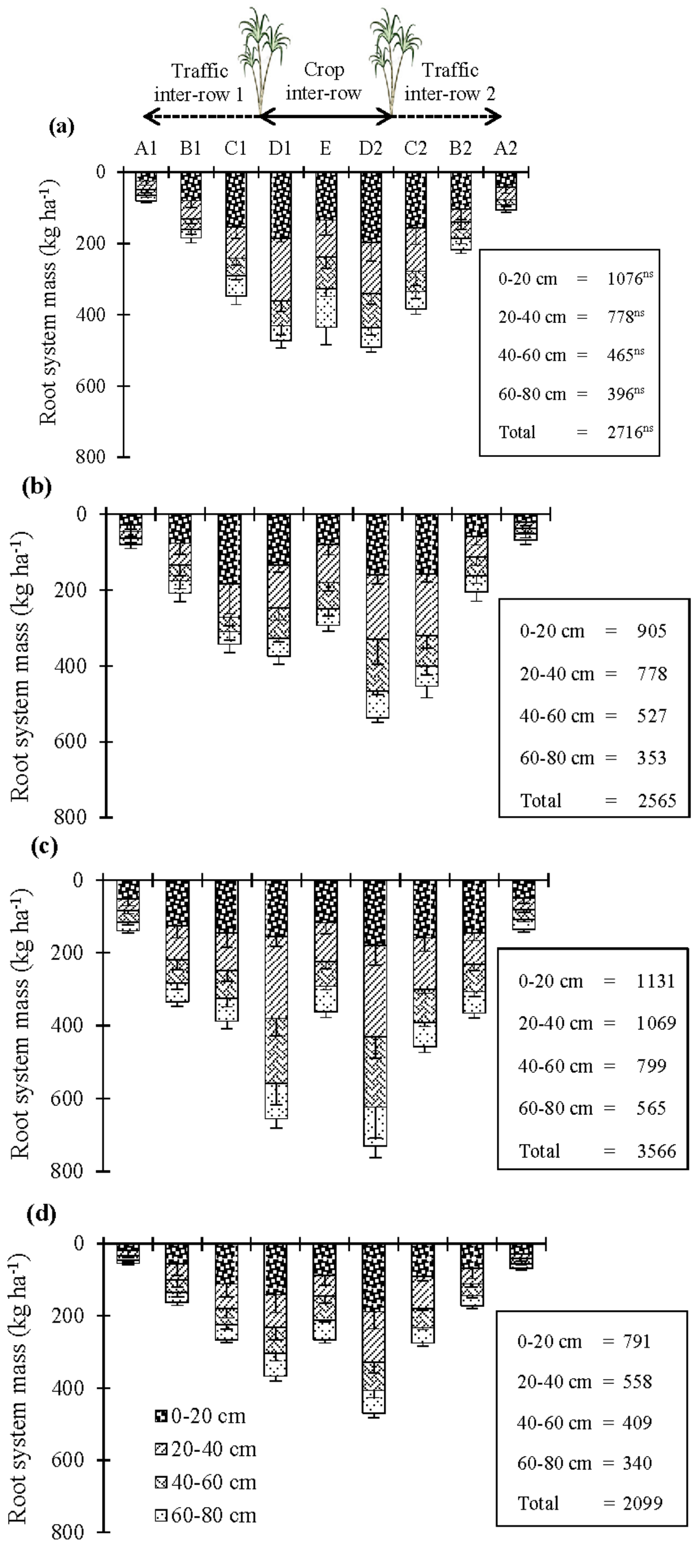

Figure 2. Sugarcane root system dry mass (kg ha^{-1}) at the sampled points in the traffic inter-rows (A, B and C) and in the crop inter-row (D and E) to the sugarcane (CTC-14 variety) straw managements (**a**) total removal (TR) = 0 Mg ha^{-1}, (**b**) high removal (HR) = 4.2 Mg ha^{-1}, (**c**) moderate removal (MR) = 8.7 Mg ha^{-1} and (**d**) no removal (NR) = 18.9 Mg ha^{-1}. Results from an Oxisol field cultivated with sugarcane in Capivarí, São Paulo (SP), Brazil. Comparison of the means by depth between straw managements do not differ by Tukey's test at the $p < 0.05$ level (boxes). ns = not significant ($n = 4 \pm$ standard error (SE)).

The overall average sugarcane root mass for the 0–80 cm soil layer was 2737 kg ha^{-1}. The root system distribution in the soil profile occurred as following: 976 kg ha^{-1} (36%) was found in the upper soil layer (0–20 cm), decreasing in the sub-surface layers to 796 kg ha^{-1} (30%) in the 20–40 cm soil layer, 550 kg ha^{-1} (20%) in the 40–60 cm soil layer, and 414 kg ha^{-1} (14%) in the 60–80 cm layer (Figure S2).

Straw removal rates had little influence on sugarcane root system growth within each sample point over the short term (Table S1). Despite this fact, better root distribution across the depths was observed under MR (Figure 2c). Under these straw rates, the total root mass quantified (0–80 cm) was 3566 kg ha^{-1}, which is around 24% and 41% higher than the amount of root measured under TR (2716 kg ha^{-1}) and NR (2099 kg ha^{-1}), respectively (Figure 2). Root mass as affected by retained residue resulted in varying optimum amounts among soil depths (Figure 3). Taking into account the regression model adjusted for the upper surface layer ($y_{0\text{–}20\ cm} = 1018.6 + 12.40x - 1.253x^2$), it was estimated that 5 Mg ha^{-1} of straw would be enough to obtain the maximum root mass (1049 kg ha^{-1}). Using the regression model adjusted for the other depths (Figure 3), the optimum straw amounts increased to 8.3 Mg ha^{-1} in the 20–40 cm soil layer, resulting in 976 kg ha^{-1}; and the same straw rate (i.e., 9.4 Mg ha^{-1}) for the 40–60 and 60–80 cm soil layers, which would result in 728 and 497 kg ha^{-1} dry mass of roots, respectively.

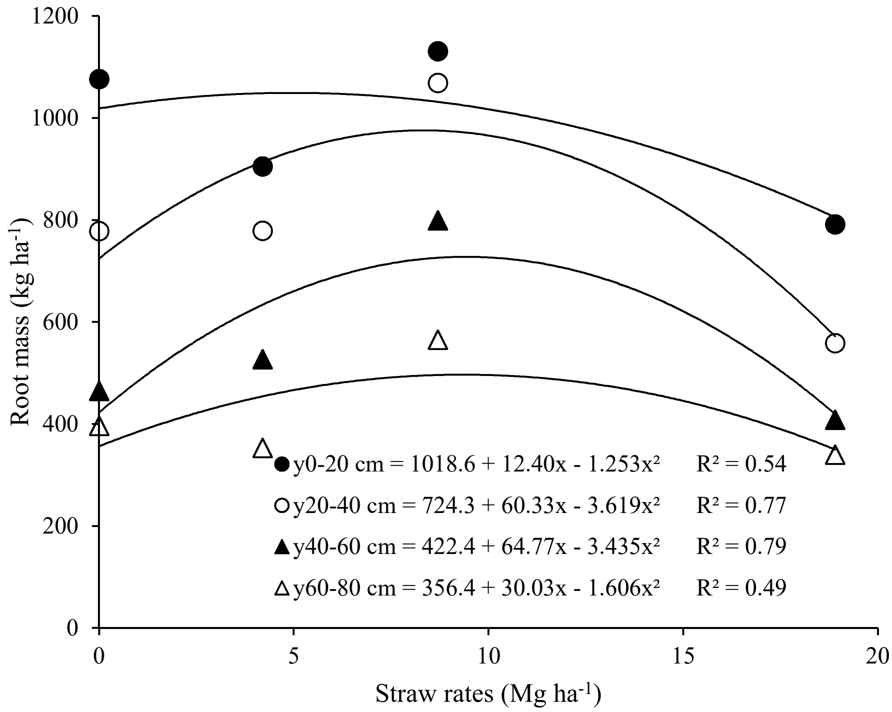

Figure 3. Relationship between sugarcane root system dry mass (kg ha^{-1}) and straw amounts (Mg ha^{-1}) for each soil depth (n = 4), in an Oxisol field cultivated with sugarcane in Capivarí, SP, Brazil.

3.2. Straw Removal Effects on Soil Conditions and Sugarcane Root System

Soil penetration resistance increased as straw retention decreased (Figure 4A,B), and were directly related to soil moisture reduction (Figure 4C). This pattern was also observed in both inter-rows (i.e., 1.50 m and 0.90 m). In the crop inter-row, the straw effect was observed up to 10 cm in depth, with a significant difference between TR compared to the other straw removal treatments ($p < 0.05$; Figure 4A). Under the traffic inter-row, the effect of the straw removal was more notable to 20 cm, where a higher SPR value was observed under HR following MR and NR ($p < 0.05$; Figure 4B). Within the 0–10 cm depth, SPR under TR was almost 180% (11.4 MPa) higher in the traffic inter-row compared to the crop inter-row (4.10 MPa; Figure 4A,B). Below 30 cm, in the traffic inter-row, SPR decreased as the depth increased, while for the crop inter-row, no changes in SPR were observed below 20 cm ($p > 0.05$; Figure 4A,B).

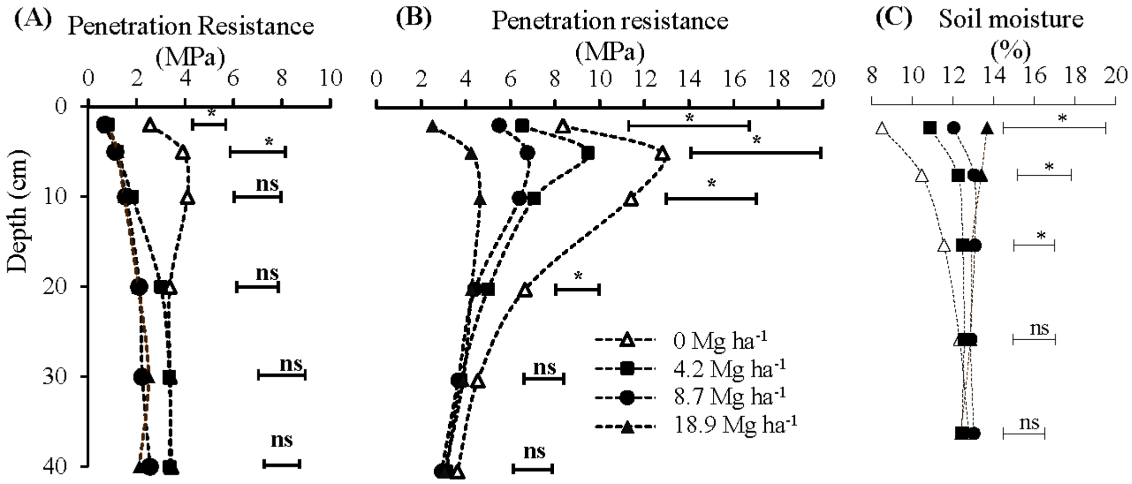

Figure 4. Soil penetration resistance (MPa) in the crop inter-row (**A**) and in the traffic inter-row positions (**B**), and soil moisture (**C**) in the sugarcane (CTC-14 variety) field under straw removal managements (Δ TR = 0 Mg ha^{-1}; ■ HR = 4.2 Mg ha^{-1}; • MR = 8.7 Mg ha^{-1} and ▲ NR = 18.9 Mg ha^{-1}) in an Oxisol field in Capivarí, SP, Brazil. Horizontal bars represent the Least Significant Difference (LSD) in the Tukey's test ($p < 0.05$), * = significant and ns = not significant ($n = 4 \pm$ SE).

The relationships between the straw rates and root density (RD), as well as SPR, were best fit to quadratic models with significant responses to straw retention ($R^2 = 0.69 \sim 0.99$; Figure 5). Under lower straw removal rates, higher root density and lower soil penetration resistance was observed. The most striking effect of straw on the root mass, as well as on attenuation of the soil penetration resistance due to machine traffic (Figure 5A,C), was found in the traffic inter-row zone (0–20 cm). These effects were less noticeable in the crop inter-row positions (Figure 5B,D).

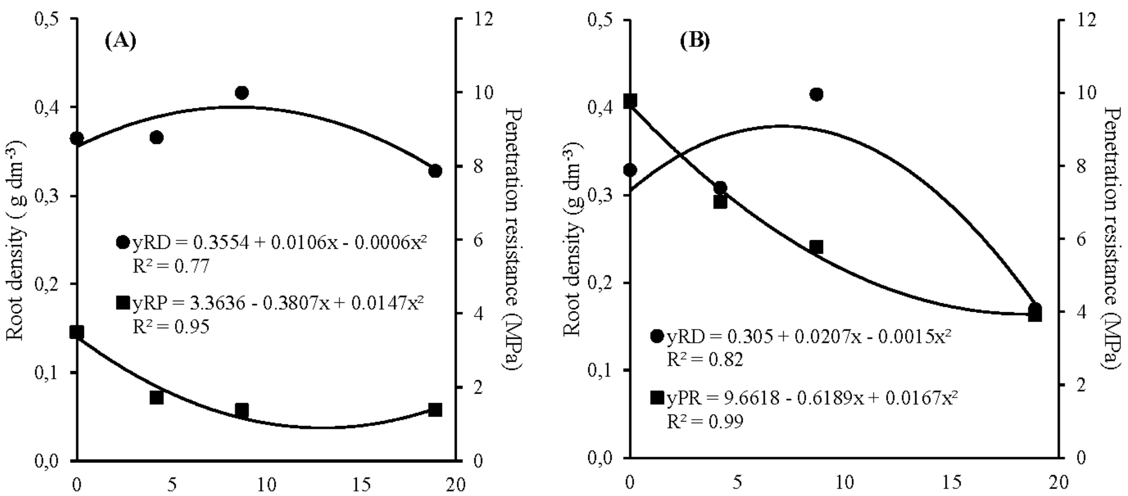

Figure 5. *Cont.*

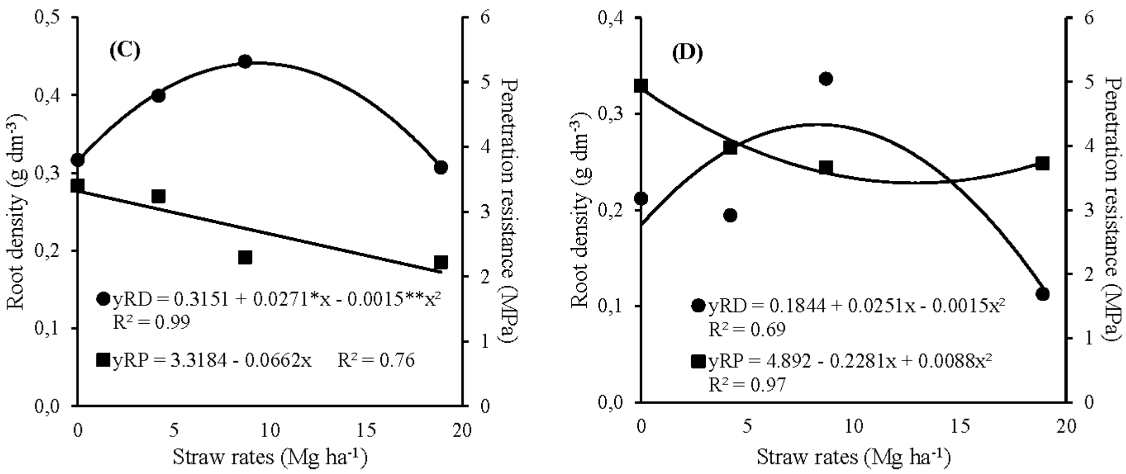

Figure 5. Relationship between sugarcane (•) root density (kg m^{-3}) and (■) soil penetration resistance (MPa) under straw removal managements (TR = 0 Mg ha^{-1}; HR = 4.2 Mg ha^{-1}; MR = 8.7 Mg ha^{-1} and NR = 18.9 Mg ha^{-1}) in the 0–20 cm soil layer to the crop inter-row (**A**) and traffic inter-row (**B**); and in the 20–40 cm soil layer to the crop inter-row (**C**) and traffic inter-row (**D**) (n = 4). Results from an Oxisol field cultivated with sugarcane in Capivarí, SP, Brazil, * and ** = significant at 0.05 and 0.01 levels.

3.3. Straw Removal Effects on Root System and Stalk Production

Moderate straw removal (MR) led to higher stalk yield (133.6 Mg ha^{-1}). NR and HR showed a slight reduction (approximately 1.5%) compared to MR. However, TR induced a reduction of approximately 20% in above-ground mass (29 Mg ha^{-1}) and stalk yield (105 Mg ha^{-1}) compared to the treatments with no straw removal (Figure 6).

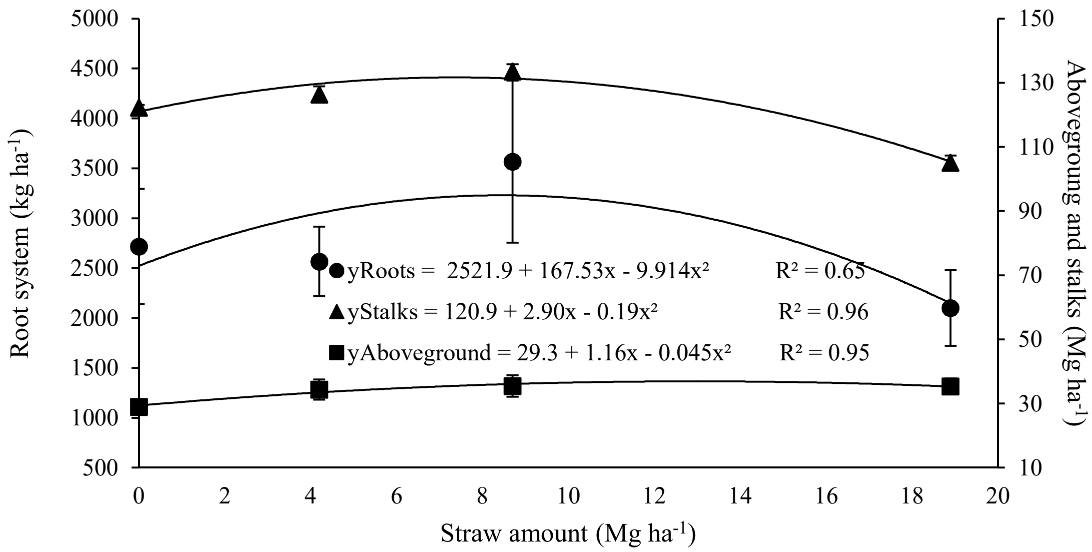

Figure 6. Relationship between sugarcane (■) above-ground mass (Mg ha^{-1}), (▲) stalk production (Mg ha^{-1}), and (•) root system dry mass (kg ha^{-1}) vs. straw removal rates (Mg ha^{-1}) (n = 4). Results from an Oxisol field cultivated with sugarcane in Capivarí, SP, Brazil.

Different rates of straw removal did not affect ($p > 0.05$) the sugarcane root:shoot ratio, with values ranging from 0.06 (NR) to 0.10 (TR) (Table S2). The root mass, above-ground mass and stalk production as affected by the increasing rate of straw removal were adjusted to a quadratic model (Figure 6). Based on the regression models, it was estimated that quantities of straw between 8.5 and 13 Mg ha^{-1} provided maximum root mass and highest above-ground mass and stalk yield, which are 3.2, 37 and 131 Mg ha^{-1}, respectively.

4. Discussion

4.1. Effects of Straw Removal on Sugarcane Root System

The highest concentration of sugarcane roots (60%) was found in the first 40 cm of soil. This observation is consistent with several studies that reported values of 60–80% for the same layer with different sugarcane varieties and soil textures [17,34–36]. The predominance of roots within the upper soil layers is due to several factors, such as (i) the fasciculate root system of the crop [37], (ii) higher nutrient cycling from crop residue and root system decomposition [10,38], (iii) higher soil organic matter content [8,9], and (iv) higher moisture content (Figure 4) favored by the straw kept on the soil surface. Higher soil moisture under straw mulching reduces soil mechanical resistance and increases soil water content for root growth [38,39]. However, root systems developed within the upper soil layers may impair sugarcane yields, especially in periods of drought, when plants are more susceptible to water stress (mainly in sandy soils) [17,40].

In our study, straw maintenance did not lead to higher root concentrations within the upper soil layers (Figure 2). This unexpected finding may have occurred due to suitable soil water availability during the crop cycle (Figure 1), which is similar to that observed by Alvarez et al. [17]. In general, the sugarcane water demand is around 1500 to 2000 mm for the crop cycle [41]. Precipitation means above this amount were recorded during the period of this study which may have resulted in enough soil water availability for plant growth (Figure 1). Under such conditions, soil water content as affected by straw retention may have not influenced root growth.

Overall, higher sugarcane root system distribution within the soil profile is associated with both greater volume of soil explored and better crop yield [42]. In this study, better root distribution occurred under moderate straw removal (8.7 Mg ha^{-1}). Under similar straw rates (i.e., 10 Mg ha^{-1}), Aquino et al. [15] reported increases in sugarcane root mass, and emphasized that larger amounts of straw maintenance only favors the root system during periods of soil water deficit. However, in this study, extreme straw management (lowest or highest straw removal rates) adversely affected root system growth (Figure 3).

Total root mass quantified in the 0 to 80 cm soil layer (2737 kg ha^{-1}) was lower than that reported by Silva-Olaya et al. [43], who observed quantities above 7000 kg ha^{-1} at the first sugarcane ratoon (variety RB86-7515). However, it is worth mentioning that Silva-Olaya et al. [43] sampled up to 100 cm of depth in sandy soil, and only the roots near to the plant row was sampled. Usually this area has a higher root concentration, as shown in Figure 2. In addition, sandy soil may induce root system elongation in order to search for water. In this sense, Barbosa et al. [35] and Otto et al. [44] reported higher root mass in soils of medium texture compared to soils with higher clay content.

4.2. Effects of Straw Removal on Soil Compaction and Sugarcane Root System

Higher straw removal rates impair soil conditions to root growth due to a reduction in soil moisture [7] and increased soil resistance to penetration within the upper soil layer [45]. Depletion of soil physical quality [46] negatively impacts root development [47,48] and, consequently, reduces sugarcane yields [48,49].

Our findings show that sugarcane root distribution responded to more favorable soil physical conditions, such as lower compaction, which favored better root growth laterally and vertically. Overall, lateral sugarcane root system growth and higher root mass was concentrated near to the plant rows [17,18,32,34,37].

One of the benefits of straw retention is the reduction of soil water losses by evaporation. Soil moisture is one of the main parameters that influences soil resistance to penetration. In addition, the machinery traffic for crop management (i.e., agrochemical and fertilizer applications) and harvesting may be considered the main factor responsible for the increase of soil resistance to penetration at the traffic inter-row. In this sense, Marasca et al. [50], using an automatized soil penetrometer in an Oxisol field with a medium sandy texture, found soil resistance to penetration between 4.0 and 5.0 MPa within the upper 45 cm layer in the crop inter-rows under bare soil conditions, whereas Tavares-Filho et al. [51], with an impact penetrometer also in an Oxisol field with a sandy clay loam, reported values ranging from 1.80 to 7.66 MPa for the traffic inter-row within the 0–20 cm layer. In addition, Castioni et al. [13] recently showed deleterious impacts of intensive straw removal on soil resistance to penetration and other indicators of soil physical quality.

Our findings showed that straw maintenance increased soil water content and decreased soil resistance to penetration within the crop inter-row (0–20 cm soil layer) (Figure 4A). Straw maintenance on the soil surface reduces the contact area between machine tires and soil surface, resulting in decreased punctual pressure from machinery traffic on the soil [52–54].

4.3. Effects of Straw Removal on Sugarcane Yield

The highest stalk yield was obtained under moderate straw removal (MR). Through quadratic models, we estimated that approximately 10 Mg ha^{-1} (8–13 Mg ha^{-1}) of straw retention provided the greatest root development and, consequently, the highest sugarcane yield. Corroborating with these results, several authors reported better agronomic performance of several sugarcane varieties in different soil types due to straw maintenance [24,25,55]. However, straw maintenance higher than 10 Mg ha^{-1} is also associated with a reduction in plant sprouts, stalk yield [24,25] and sucrose concentration in stalks [56], particularly in the region where the study was conducted, which is cooler than other sugarcane-producing regions in Brazil [25]. Overall, decreasing of initial sugarcane phytomass yield (tillering) occurs even under lower quantities of straw; this is especially remarkable under cooler regions [24], but in most cases, the crop is able to recover from the negative impacts caused by straw retention in earlier growth stages [15,24,57].

Although few undesirable effects are associated with straw retention, several recent studies have addressed the benefits of straw retention. The benefits of straw maintenance for the soil–plant system are associated with an increase in water availability [11,12], decrease in soil temperature [12], reduction in soil compaction [13,45], and increase in soil carbon content [8]. However, the soil response to straw removal is site-specific [8,45] and the decision about the amount of straw to be removed should be made based on holistic and integrated knowledge [25]. Despite this fact, through an extensive literature review, Carvalho et al. [23] verified that most agronomic benefits for the soil–plant system are provided when around 7 Mg ha^{-1} is left on the field. Also, higher stalk yields have been reported under moderate straw removal (approximately 9 Mg ha^{-1}) [24] and 10 Mg ha^{-1} [55]. In this sense, our findings may explain higher yields under moderate straw removal, since the better root distribution and mass were also observed under moderate straw removal (Figure 6). Better root distribution increases the volume of soil explored, which may increase water and nutrient uptake by the plant. These conditions potentially improve plant growth and, consequently, phytomass yield. Although we strongly recognize that it is mandatory to consider specific edaphoclimatic conditions to perform sustainable straw removal, our findings provide relevant understanding about why moderate straw removal has been suggested in several studies in which straw removal management was framed [15,24,55,57].

The different rates of straw removal did not affect the root:shoot ratio ($p < 0.05$) and the values of this parameter ranged from 0.059 to 0.101 (Table S2). The absence of responses in this parameter to straw removal rates may be related to the short-term in which the study was conducted. Despite this, the root:shoot values found are in accordance with Korndörfer et al. [16], who evaluated the root mass in five sugarcane varieties and reported 0.10 as a mean value for the root:shoot ratio. Nevertheless, it seems that the root:shoot ratio increases along the crop cycle, as reported by Silva-Olaya et al. [43], who found values of 0.15, 0.18 and 0.29, respectively for the cane plant, first and second ratoon cycles. High root:shoot ratio values indicate that the plants allocated more resources to the roots instead of the shoot (i.e., stalk and straw) [58].

5. Conclusions

Straw removal (high to total) reduces soil moisture and increases soil penetration resistance; however, root growth was little affected by straw removal, at least in the short term. The slight effects of straw on the root system and yield of the sugarcane suggest that moderate straw removal (keeping around 10 Mg ha^{-1} on soil surface) is enough to sustain soil physical conditions for root growth and improve sugarcane yield, while part of the straw can be removed for industrial uses.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/7/1048/s1. Figure S1: Sampling strategy for evaluation of the sugarcane root system (biomass and distribution) at nine sampling points from the middle of the traffic interlines (A, B and C points) to crop interline (D and E points), Figure S2: Relative distribution of sugarcane roots (CTC14 variety) in the soil profile, Table S1: Sugarcane root dry mass (kg ha^{-1}) as affected by increasing rates of straw retention on the soil surface, Table S2: Root dry mass, aboveground mass and root:shoot ratio of sugarcane plants under different amounts of straw removal.

Author Contributions: P.L.A.M.: field sampling, writing, review; M.R.C.: writing and review; T.C.A.G.: data analyses, writing, review; I.P.L.: data analyses, writing, review; L.S.S.: field sampling, writing; C.E.P.C.: financial support, writing and review; M.S.-N.: data analyses, writing, review. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank The Brazilian Development Bank (BNDES) for funding our research (Project #14.2.0773.1). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasil (CAPES); Finance Code 001". Paul L. Amaral and Lucas S. Satiro thank the National Council for Scientific and Technological Development (CNPq) for providing his Master's degree scholarship. Maurício R. Cherubin thanks the São Paulo Research Foundation (FAPESP) for the research grant (Process # 2018/09845-7). Izaias P. Lisboa thanks CNPq (Process #155753/2018-5) for providing his post-doctoral fellowship. Marcos Siqueira-Neto thanks the Foundation for Research and Scientific and Technological Development of Maranhão and CNPq (Process #03572/2016) for providing his fellowship in Scientific and Technological Regional Development.

Acknowledgments: We are grateful to Admilson Margato, Ralf Araújo, Lilian Duarte, Sandra Nicolete and Dagmar Vasca for the strong assistance in the experiment conduction and samples analyses in the laboratory.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. CONAB (2020) Companhia Nacional de Abastecimento. Acompanhamento da Safra Brasileira de Cana-de-Açúcar: Primeiro Levantamento. Available online: http://www.conab.gov.br (accessed on 14 April 2020).
2. Dias, M.O.S.; Cunha, M.P.; Jesus, C.D.F.; Rocha, G.J.M.; Pradella, J.G.C.; Rossel, C.E.V.; Maciel Filho, R.; Bonomi, A. Second generation ethanol in Brazil: Can it compete with electricity production? *Bioresour. Technol.* **2011**, *102*, 8964–8971. [CrossRef] [PubMed]
3. Silva, A.G.B.; Lisboa, I.P.; Cherubin, M.R.; Cerri, C.E.P. How Much Sugarcane Straw is Needed for Covering the Soil? *Bioenergy Res.* **2019**, *12*, 858–864. [CrossRef]
4. EPE Empresa de Pesquisa Energética. Energia Renovável: Hidráulica, Biomassa, Eólica, Solar, Oceânica. 2016. Available online: http://epe.gov.br (accessed on 22 September 2018).
5. Cervi, W.R.; Lamparelli, R.A.C.; Seabra, J.E.A.; Junginger, M.; Hilst, F.V.D. Bioelectricity potential from ecologically available sugarcane straw in Brazil: A spatially explicit assessment. *Biomass Bioenergy* **2019**, *122*, 391–399. [CrossRef]
6. Leal, M.R.L.; Galdos, M.V.; Scarpare, F.V.; Seabra, J.E.A.; Walter, A.; Oliveira, C.O.F. Sugarcane straw availability, quality, recovery and energy use: A literature review. *Biomass Bioenergy* **2013**, *53*, 11–19. [CrossRef]
7. Castioni, G.A.; Cherubin, M.R.; Menandro, L.M.S.; Sanches, G.M.; Bordonal, R.O.; Barbosa, L.C.; Franco, H.C.J.; Carvalho, J.L.N. Soil physical quality response to sugarcane straw removal in Brazil: A multi-approach assessment. *Soil Tillage Res.* **2018**, *184*, 301–309. [CrossRef]
8. Bordonal, R.O.; Carvalho, J.L.N.; Lal, R.; Figueiredo, E.B.; Oliveira, B.G.; Scala, N.L., Jr. Sustainability of sugarcane production in Brazil. A review. *Agron. Sustain. Dev.* **2018**, *38*, 13. [CrossRef]
9. Sousa Junior, J.G.A.; Cherubin, M.R.; Oliveira, B.G.; Cerri, C.E.P.; Cerri, C.C.; Feigl, B.J. Three-year soil carbon and nitrogen responses to sugarcane straw management. *Bioenergy Res.* **2018**, *11*, 249–261. [CrossRef]

10. Cherubin, M.R.; Lisboa, I.P.; Silva, A.G.B.; Varanda, L.L.; Bordonal, R.O.; Carvalho, J.L.N.; Otto, R.; Pavinato, P.S.; Soltangheisi, A.; Cerri, C.E.P. Sugarcane Straw Removal: Implications to Soil Fertility and Fertilizer Demand in Brazil. *Bioenergy Res.* **2019**, *12*, 888–900. [CrossRef]
11. Gmach, M.R.; Scarpare, F.V.; Cherubin, M.R.; Lisboa, I.P.; Santos, A.K.B.; Cerri, C.E.P.; Cerri, C.C. Sugarcane straw removal effects on soil water storage and drainage in southeastern Brazil. *J. Soil Water Conserv.* **2019**, *74*, 466–476. [CrossRef]
12. Ruiz Corrêa, S.T.; Barbosa, L.C.; Menandro, L.M.S.; Scarpare, F.V.; Reichardt, K.; Moraes, L.O.; Hernandes, T.A.D.; Franco, H.C.J.; Carvalho, J.L.N. Straw Removal Effects on Soil Water Dynamics, Soil Temperature, and Sugarcane Yield in South-Central Brazil. *Bioenergy Res.* **2019**, *12*, 749–763. [CrossRef]
13. Castioni, G.A.F.; Cherubin, M.R.; Bordonal, R.O.; Barbosa, L.; Menandro, L.M.S.; Carvalho, J.L.N. Straw Removal Affects Soil Physical Quality and Sugarcane Yield in Brazil. *Bioenergy Res.* **2019**, *12*, 789–800. [CrossRef]
14. Vasconcelos, C.M.; Casagrande, A.A.; Perecin, D.; Jorge, L.A.C.; Landell, M.G.A. Avaliação do sistema radicular da cana-de-açúcar por diferentes métodos. *Rev. Bras. Ciência Solo* **2003**, *27*, 849–858. [CrossRef]
15. Aquino, G.S.; Medina, C.C.; Porteira, A.L., Jr.; Santos, L.O.; Cunha, A.C.B.; Kussaba, D.A.O.; Santos, J.H., Jr.; Almeida, L.F.; Santiago, A.D. Sistema radicular e produtividade de soqueiras de cana-de-açúcar sob diferentes quantidades de palhada. *Pesqui. Agropecuária Bras.* **2015**, *50*, 1150–1159. [CrossRef]
16. Korndôrfer, G.H.; Primavesi, O.; Oeuber, R. *Crescimento e Distribuição do Sistema Radicular da Cana-de-Açúcar em Solo LVA*; Coopersucar: Piracicaba, Brazil, 1989; p. 82.
17. Alvarez, I.A.; Castro, P.D.C.; Nogueira, M.C.S. Crescimento de raízes de cana crua e queimada em dois ciclos. *Sci. Agric.* **2000**, *57*, 653–659. [CrossRef]
18. Cury, T.N.; De Maria, I.C.; Bolonhezi, D. Biomassa radicular da cultura de cana-de-açúcar em sistema convencional e plantio direto com e sem calcário. *Rev. Bras. Ciência Solo* **2014**, *38*, 1929–1938. [CrossRef]
19. Viator, R.P.; Johnson, R.M.; Grimm, C.C.; Richard Junior, E.P. Allelopathic, autotoxic, and hormetic effets of postharvest sugarcane residue. *Agron. J.* **2006**, *98*, 1526–1531. [CrossRef]
20. Pinheiro, P.L.; Recous, S.; Dietrich, G.; Weiler, D.A.; Giovelli, R.L.; Mezzalira, A.P.; Giacomini, S.J. Straw removal reduces the mulch physical barrier and ammonia volatilization after urea application in sugarcane. *Atmos. Environ.* **2018**, *194*, 179–187. [CrossRef]
21. Dinardo-Miranda, L.L.; Fracasso, J.V. Sugarcane straw and the populations of pests and nematodes: A review. *Sci. Agric.* **2013**, *70*, 305–310. [CrossRef]
22. Castro, S.G.Q.; Dinardo-Miranda, L.L.; Fracasso, J.V.; Bordonal, R.O.; Menandro, L.M.S.; Franco, H.C.J.; Carvalho, J.L.N. Changes in Soil Pest Populations Caused by Sugarcane Straw Removal in Brazil. *Bioenergy Res.* **2019**, *12*, 878–887. [CrossRef]
23. Carvalho, J.L.N.; Nogueirol, R.C.; Menandro, L.M.S.; Bordonal, R.O.; Borges, C.D.; Cantarella, H.; Franco, H.C.J. Agronomic and environmental implications of sugarcane straw removal: A major review. *GCB Bioenergy* **2017**, *9*, 1181–1195. [CrossRef]
24. Lisboa, I.P.; Cherubin, M.R.; Lima, R.P.; Cerri, C.C.; Satiro, L.S.; Wienhold, B.J.; Schmer, M.R.; Jin, V.L.; Cerri, C.E.P. Sugarcane straw removal effects on plant growth and stalk yield. *Ind. Crop. Prod.* **2018**, *111*, 794–806. [CrossRef]
25. Carvalho, J.L.N.; Menandro, L.M.S.; Castro, S.G.Q.; Cherubin, M.R.; Bordonal, R.O.; Barbosa, L.C.; Gonzaga, L.C.; Tenelli, S.; Franco, H.C.J.; Kolln, O.T.; et al. Multilocation Straw Removal Effects on Sugarcane Yield in South-Central Brazil. *Bioenergy Res.* **2019**, *12*, 813–829. [CrossRef]
26. Pimentel, L.G.; Cherubin, M.R.; Oliveira, D.M.S.; Cerri, C.E.P.; Cerri, C.C. Decomposition of sugarcane straw: Basis for management decisions for bioenergy production. *Biomass Bioenergy* **2019**, *122*, 133–144. [CrossRef]
27. Cherubin, M.R.; Oliveira, D.M.S.; Feigl, B.J.; Pimentel, L.G.; Lisboa, I.P.; Gmach, M.R.; Varanda, L.L.; Morais, M.C.; Satiro, L.S.; Popin, G.V.; et al. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. *Sci. Agric.* **2018**, *75*, 255–272. [CrossRef]
28. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; USDA-Natural Resources Conservation Service: Washington, DC, USA, 2014.
29. CTC Centro de Tecnologia Canavieira. Bula Técnica Variedades, CTC 14. Edição Julho/2018. Available online: http://variedadesctc.com.br/produtos/ctc-14/ (accessed on 13 September 2018).
30. Goes, T.; Marra, R.; Araújo, M.; Alves, E.; Souza, M.O. Sugarcane in Brazil Current technologic stage and perspectives. *Rev. Política Agrícola* **2011**, *20*, 52–65.

31. Lisboa, I.P.; Cherubin, M.R.; Cerri, C.C.; Cerri, D.G.P.; Cerri, C.E.P. Guidelines for the recovery of sugarcane straw from the field during harvesting. *Biomass Bioenergy* **2017**, *96*, 69–74. [CrossRef]
32. Otto, R.; Trivelin, P.C.O.; Franco, H.C.J.; Faroni, C.E.; Vitti, A.C. Root system distribution of sugar cane as related to nitrogen fertilization, evaluated by two methods: Monolith and probes. *Rev. Bras. Ciência Solo* **2009**, *33*, 601–611. [CrossRef]
33. Stolf, R. Teoria e teste experimental de fórmulas de transformação dos dados de penetrômetro de impacto de resistência do solo. *Rev. Bras. Ciência Solo* **1991**, *15*, 229–235.
34. Ball-Coelho, B.; Sampaio, E.V.S.B.; Tiessen, H.; Stewart, J.W.B. Root dynamics in plant and ratoon crops of sugarcane. *Plant Soil* **1992**, *142*, 297–305. [CrossRef]
35. Barbosa, L.C.; Souza, Z.M.; Franco, H.C.J.; Otto, R.; Rossi Neto, J.; Garside, A.L.; Carvalho, L.N. Soil texture affects root penetration in Oxisols under sugarcane in Brazil. *Geoderma Reg.* **2018**, *13*, 15–25. [CrossRef]
36. Rossi Neto, J.; de Souza, Z.M.; Kölln, O.T.; Carvalho, J.L.N.; Ferreira, D.A.; Castioni, G.A.F.; Barbosa, L.C.; de Castro, S.G.Q.; Braunbeck, O.A.; Garside, A.L.; et al. The arrangement and spacing of sugarcane planting influence root distribution and crop yield. *Bioenergy Res.* **2018**, *11*, 291–304. [CrossRef]
37. Smith, D.M.; Inman-Bamber, N.G.; Thorburn, P.J. Growth and function of the sugarcane root system. *Field Crop. Res.* **2005**, *92*, 169–183. [CrossRef]
38. Bengough, A.G.; McKenziel, B.M.; Hallett, P.D.; Valentine, T.A. Root elongation, water stress, and mechanical impedance: A review of limiting stresses and beneficial root tip traits. *J. Exp. Bot.* **2011**, *62*, 59–68. [CrossRef] [PubMed]
39. Moraes, M.T.; Bengough, A.G.; Debiasi, H.; Franchini, J.C.; Levien, R.; Schnepf, A.; Leitner, D. Mechanistic framework to link root growth models with weather and soil physical properties, including example applications to soybean growth in Brazil. *Plant Soil* **2018**, *428*, 67–92. [CrossRef]
40. Faroni, C.E.; Trivelin, P.C.O. Quantificação de raízes metabolicamente ativas de cana-de-açúcar. *Pesqui. Agropecuária Bras.* **2006**, *41*, 1007–1013. [CrossRef]
41. Doorenbos, J.; Kassam, A.H. *Efeito da Água no Rendimento Das Culturas*; Editora da UFPB: Paraíba, Brazil, 1994; Volume 33, p. 307.
42. Cantarella, H. Calagem e adubação do milho. In *Cultura do Milho: Fatores que Afetam a Produtividade*, 1st ed.; Bull, L.T., Cantarella, H., Eds.; Potafos: Piracicaba, Brazil, 1993; Volume 1, pp. 147–196.
43. Silva-Olaya, A.M.; Davies, C.A.; Cerri, C.E.P.; Allen, D.J.; Mello, F.F.C.; Cerri, C.C. Quantifying above and belowground biomass carbon inputs for sugar-cane production in Brazil. *Soil Res.* **2017**, *55*, 640–648. [CrossRef]
44. Otto, R.; Franco, H.C.J.; Faroni, C.E.; Vitti, A.C.; Oliveira, E.C.A.; Sermarini, R.A.; Trivelin, P.C.O. The role of nitrogen fertilizers in sugarcane root biomass under field conditions. *Agric. Sci.* **2014**, *5*, 1527–1538. [CrossRef]
45. Satiro, L.S.; Cherubin, M.R.; Safanelli, J.L.; Lisboa, I.P.; Rocha Junior, P.R.; Cerri, C.E.P.; Cerri, C.C. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. *Geoderma* **2017**, *11*, 86–95. [CrossRef]
46. Souza, G.S.D.; Souza, Z.M.D.; Cooper, M.; Tormena, C.A. Controlled traffic and soil physical quality of an Oxisol under sugarcane cultivation. *Sci. Agric.* **2015**, *72*, 270–277. [CrossRef]
47. Cherubin, M.R.; Karlen, D.L.; Franco, A.L.; Cerri, C.E.P.; Tormena, C.A.; Cerri, C.C. A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality. *Soil Sci. Soc. Am. J.* **2016**, *80*, 215–226. [CrossRef]
48. Esteban, D.A.A.; Souza, Z.M.; Tormena, C.A.; Lovera, L.H.; Lima, E.S.; Oliveira, I.N.; Ribeiro, N.P. Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. *Soil Tillage Res.* **2019**, *187*, 60–71. [CrossRef]
49. Souza, G.S.D.; Souza, Z.M.D.; Silva, R.B.D.; Barbosa, R.S.; Araújo, F.S. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. *Rev. Bras. Ciência Solo* **2014**, *38*, 135–146. [CrossRef]
50. Marasca, I.; Lemos, S.V.; Silva, R.B.; Guerra, S.P.S.; Lanças, K.P. Soil compaction curve of an Oxisol under sugarcane planted after in-row deep tillage. *Rev. Bras. Ciência Solo* **2015**, *39*, 1490–1497. [CrossRef]
51. Oliveira-Filho, F.; Miranda, N.O.; Medeiros, J.F.; Silva, P.C.M.; Mesquita, F.O.; Costa, T.K.G. Zona de manejo para preparo do solo na cultura da cana-de-açúcar. *Rev. Bras. Eng. Agrícola Ambient.* **2015**, *19*, 186–193. [CrossRef]

52. Braida, J.A.; Reichert, J.M.; Veiga, M.; Reinert, D.J. Resíduos vegetais na superfície e carbono orgânico do solo e suas relações com a densidade máxima obtida no ensaio de Proctor. *Rev. Bras. Ciência Solo* **2006**, *30*, 605–614. [CrossRef]
53. Gupta, S.C.; Schneider, E.C.; Larson, W.E.; Hadas, A. Influence of corn residue on compression and compaction behavior of soils. *Soil Sci. Soc. Am. J.* **1987**, *51*, 207–212. [CrossRef]
54. Reichert, J.M.; Brandt, A.A.; Rodrigues, M.F.; Reinert, D.J.; Braida, J.A. Load dissipation by corn residue on tilled soil in laboratory and field-wheeling conditions. *J. Sci. Food Agric.* **2016**, *96*, 2705–2714. [CrossRef]
55. Aquino, G.S.; Medina, C.C.; Costa, D.C.; Shahab, M.; Santiago, A.D. Sugarcane straw management and its impact on production and development of ratoons. *Ind. Crop. Prod.* **2017**, *102*, 58–64. [CrossRef]
56. Campos, L.H.F.; Carvalho, S.J.P.; Christoffoleti, P.J.; Fortes, C.; Silva, J.S. Sistemas de manejo da palhada influenciam acúmulo de biomassa e produtividade da cana-de-açúcar (var. RB855453). *Acta Sci. Agron.* **2010**, *32*, 345–350. [CrossRef]
57. Lisboa, I.P.; Cherubin, M.R.; Lima, R.P.; Gmach, M.R.; Wienhold, B.J.; Schmer, M.R.; Jin, V.L.; Junior, E.F.F.; Guerra, H.P.; Cerri, C.C.; et al. Sugarcane Straw Blanket Management Effects on Plant Growth, Development, and Yield in Southeastern Brazil. *Crop Sci.* **2019**, *59*, 1732–1744. [CrossRef]
58. Ashraf, M.; Shahzad, S.M.; Arif, M.S.; Riaz, M.; Ali, S.; Abid, M. Effects of potassium sulfate on adaptability of sugarcane cultivars to salt stress under hydroponic conditions. *J. Plant Nutr.* **2015**, *38*, 2126–2138. [CrossRef]