


Soil Penetration Resistance and Sugarcane Rooting Under Subsuperficial Drip Irrigation Levels

Ronaldo S. Resende¹  · Fernando L. D. Cintra¹ · Edson Patto Pacheco¹ · Júlio R. A. de Amorim¹ · Renata S. B. Gomes¹ · Sandra M. da Silva²

Received: 4 January 2022 / Accepted: 15 June 2022
© The Author(s) 2022

Abstract Knowledge of the soil water regime in a dynamic equilibrium condition (steady state) of the emitter–soil–plant system is essential to evaluate the adopted irrigation management, aiming to maximize the water use efficiency in irrigation. Thus, our objective was to determine the integrated effect of four irrigation levels on the soil moisture (θ_v) distribution pattern, mechanical soil penetration resistance (PR), and sugarcane rooting. Irrigation levels were established based on the percentage of reference evapotranspiration (ET_o), as follows: 40% (W1), 70% (W2), 100% (W3), and 130% (W4) of ET_o. From the soil moisture profile and PR versus θ_v regression models, PR profiles for each irrigation level were estimated. At the end of the crop cycle, trenches were opened to assess sugarcane root system. According to the results, the water dynamic in the soil profile resulted in a soil-wetting pattern that did not match the sugarcane rooting profile. For treatments W3 and W4 the wetting pattern indicated water loss through deep percolation. For all treatments and considering the entire soil profile, the PR values ranged from < 2 to 10 MPa. Also, the roots were superficially spread and limited to the first 0.35 m in depth for all irrigation depths applied. Although the soil wetting by irrigation reduced the strength of the cohesive layer, this reduction was insufficient to allow the deepening of plant roots. The sugarcane root development was limited to the

region of the soil profile defined by a PR value approximately equal to 2.0 MPa.

Keywords Hard setting soil · Cohesive character · Wetting profile · Soil resistance to root penetration · Root growth

Introduction

Brazil is the world's largest sugarcane producer, with 757.12 million Mg harvested in 2020, accounting for 38.27% of world production and more than twice the amount produced by the second-placed country, India, which is followed by China, Pakistan, and Thailand (FAOSTAT 2020; IBGE 2020). In the 2020/2021 harvest season, the Southeast and Midwest regions of Brazil produced a total of 568.40 million Mg (CONAB 2021), amounting to 86.84% of national sugarcane production. Historically, sugarcane stands out as one of the most important agricultural crops in the Northeast region of Brazil, whose cultivated area, with 888.95 thousand hectares in 2020 (IBGE 2020), is almost entirely concentrated within geomorphological unit of the Coastal Tablelands.

The most common soil classes that occur in the Coastal Tablelands of the Brazilian Northeast are Ultisol and Oxisols, which are formed from sediments of the Barreiras Group (Jacomine 2001; Bezerra et al. 2014), a sedimentary deposit formation of estimated age between Miocene and Lower Pleistocene (Vilas Bôas et al. 2001; Bezerra et al. 2014). These soils usually have, as their main morphological feature, a natural impediment layer called “cohesive layer”, characterized by having a pedogenetic origin and exhibiting the cohesive character, which is an attribute of soil subsurface horizons that have a very hard to

✉ Ronaldo S. Resende
ronaldo.resende@embrapa.br

¹ Embrapa Tabuleiros Costeiros, Avenida Beira Mar, 3250, Aracaju, Sergipe, Brazil

² Usina Coruripe, Fazenda Triunfo, S/N - Zona Rural, Coruripe, Alagoas, Brazil

extremely hard consistency when dry and become friable or firm when wet. (Bezerra et al. 2014; Santos et al. 2018; Silva et al. 2020). Thus, the intensity of the expression of this cohesive character is related to the soil moisture level (Ribeiro 2001).

However, cohesive soils are not limited only to Brazil, since there are records of similar soils in other parts of the world, particularly Australia and some areas of the African continent, where hard setting soils with attributes very similar to those of the cohesive character occur (Bezerra et al. 2014; Silva et al. 2020; Mota et al. 2021). In a comprehensive review, Daniels (2012) pointed out that, although hard setting soils are widespread in Australia, they also have a worldwide occurrence, which has been reported in several papers from Indonesia, Argentina, Bolivia, Canada, Germany, India, Nigeria, South Africa, Sweden, Tanzania, the United Kingdom, and Zimbabwe, besides Brazil.

Although the so-called “water-saving irrigation” – local scheduling that consists of applying one or two 60 mm irrigation depths: the first right after planting or harvesting and the second 30 days after the former application – is the usual irrigation schedule used in sugarcane cropping in Northeast Brazil, full irrigation using a subsurface drip system has been increasing in recent years. In these systems, the interaction between the soil moistening profile and the pattern of root distribution is preponderant for maximizing water use efficiency. The occurrence of layers that restrict the growth of plant roots can significantly affect this interaction.

Several studies aimed to assess the formation of the wetted soil profile in a drip irrigation system (Souza and Matsura 2004; Barros et al. 2009; Fan et al. 2018). However, such assessments are often performed without considering the interaction of the soil moistening profile with the root system of the crop. Thus, knowledge of the soil water regime in the dynamic equilibrium condition (steady state) of the emitter–soil–plant system becomes essential to evaluate the adopted irrigation management, seeking to maximize the water use efficiency in irrigation.

The distribution pattern of the crop root system is related to the pattern of water and nutrient uptake (Smith et al. 2005). In sugarcane, it was observed that the rooting pattern is predominantly superficial, with roots mostly concentrated in the first 0.4–0.6 m of soil depth (Farias et al. 2008; Faroni and Trivelin 2006; Buso et al. 2009; Otto et al. 2009; Baqueiro et al. 2012). There is also a trend to increase root superficiality of the cane plant in the subsequent cropping cycles (Faroni and Trivelin 2006). This root system behavior is aggravated by the presence of any impediment or cohesive layer in the soil, due to the resistance to the penetration of the roots imposed. In modeling carried out by Inmam-Bamber et al. (2012), the

deepening of the root system was the characteristic that resulted in a greater increase in water use efficiency by the sugarcane plant, when compared to the characteristics of hydraulic conductance (root and leaf), leaf senescence, and efficiency of transpiration.

The mechanical resistance to root penetration (PR) is one of the physical properties that express the degree of compaction and, consequently, the ease or difficulty that the roots have in penetrating the soil (Ribon and Tavares Filho 2004). PR has a direct relationship with soil water content (Silva et al. 2016) and soil density, but an indirect one with soil cultivation practices (Kuhwald et al. 2016). Although it may vary according to plant species, the value of 2.0 MPa has been attributed as the one that establishes the limit or threshold beyond which the crop roots cannot penetrate the soil (Tormena 1998; Hamza and Anderson 2005). Therefore, it is important to know the relationship between soil water content and PR for each local condition (soil type, soil layer, irrigation system, irrigation management, etc.).

Thus, the objective of this study was to assess the pattern of moisture distribution in the soil and the way it influences the soil mechanical resistance to root penetration and the distribution of the sugarcane root system for different levels of replacement of the crop water demand under subsurface drip irrigation conditions.

Materials and Methods

The study was conducted in an experimental area located at the Usina Coruripe, in the municipality of Coruripe, State of Alagoas, Northeast of Brazil, with geographic coordinates of 10°01'29" south latitude and 35°16'24" West longitude and altitude of 108 m a.s.l. The region's climate is tropical rainy type with a dry summer, according to Köppen's classification. The soil of the area used in the study is a cohesive Ultisol (Embrapa 2006), with texture ranging from sandy to sand clay loam. This soil is formed from the Barreiras group sediment and is characteristic of the Coastal Tablelands geomorphological unit (Jacomine et al. 2001). The physical-hydric characterization of the soil occurring in the experimental area is shown in Table 1.

The experimental design was completely randomized blocks, with four replications. Five levels of irrigation were evaluated, based on the percentage of the average reference evapotranspiration (ET_o) estimated in the week prior to irrigation, namely: 40% (W1), 70% (W2), 100% (W3), and 130% of ET_o (W4). The experimental plots consisted of four double rows, 11.0 m long, resulting in a total area of 79.2 m². ET_o was estimated by means of the Penman-Monteith model and data from an automatic climatological station, installed approximately 5 km from the

Table 1 Soil characterization of the experimental area¹. Coruripe Mill, Alagoas State, Brazil

Depth (m)	Granulometry (g kg ⁻¹)			Fc (m ³ m ⁻³)	Wp (m ³ m ⁻³)	Ds (Mg m ⁻³)	Textural classification
	Sand	Silt	Clay				
0.0–0.20	870	44	86	0.125	0.037	1.37	Sand
0.20–0.40	759	64	177	0.140	0.052	1.58	Sandy loam
0.40–0.60	599	99	302	0.192	0.103	1.39	Sandy clay loam

¹ Coruripe Mill, Alagoas State, Brazil

Fc: Field capacity (– 10 kPa); Wp: Wilting point (– 1.500 kPa); Ds: Soil density

experimental area (CORURIBE-A355, WMO Code: 86,619), belonging to the network of the Brazilian National Institute of Meteorology (INMET).

In the experimental area, subsurface drip irrigated sugarcane has been cultivated since 1998, with the use of fire for harvest. Sugarcane, cultivar RB 867,515, first ratoon, was planted double spaced, with 1.30 m in the wide row space and 0.50 m in the narrow row space. The initial soil tillage consisted of a subsoiling, with cutting depth between 0.50 and 0.60 m, followed by crossed plowing and harrowing, with the incorporation of 500 kg ha⁻¹ of Calmix® (70% lime + 30% gypsum), and supplemented by a furrowing at the depth of 0.30 m. Planting was performed using previously treated sets, with 15–18 sets per meter, manually inserted into furrows. Sugarcane was fertigated applying 106, 62 and 215 kg ha⁻¹ of nitrogen, phosphorus, and potassium, respectively, besides 300 kg ha⁻¹ of magnesium sulfate. The fertilizers used to supply N-P-K were urea (N–45%), calcium nitrate (N–15.5%), monoammonium phosphate (N–11% and P–55%), and potassium chloride (K–60%).

Irrigations were performed daily using a subsurface drip system with drip tube buried at 0.25 m depth, spaced 1.8 m apart, and flat, non-pressure compensating drippers with a flow rate of 1.70 L h⁻¹ and spaced 0.5 m apart.

Soil Wetting Profile

To assess the wet bulb formed, four PVC access tubes were installed in each irrigation treatment to measure the volumetric soil moisture (θ_v), by means of the frequency domain reflectometry (FDR) technique, at 0.10 m intervals, from the soil surface to 0.8 m depth. Access tubes were installed perpendicular to the drip tube (Fig. 1), at distances of 0, 0.30, 0.60, and 0.90 m, obtaining a 4 × 8 matrix of θ_v values. The soil moisture was measured by using the default calibration equation supplied by Sentek Pty Ltd, according to the following equation.

$$FR = 0.2746x \text{ VWC}^{0.3314} \quad (1)$$

where FR is the measured frequency relative (adm) and VWC is the volumetric water content (cm³ cm⁻³).

Along 65 days of the local dry season, 31 soil moisture readings were undertaken in each plot of sugarcane aged 55 to 120 days after cutting (DAC). The averaged values of soil water for the entire test period were interpolated using the ordinary Kriging method and represented by isoline maps.

Soil Mechanical Resistance to Root Penetration (PR)

To establish the relationship between the mechanical resistance of the soil to root penetration (PR) and soil water content (θ_v), four points (replications) were selected in experimental area. For each selected point, eight undisturbed soil samples were taken (corresponding to each point of retention curve), between the rows of sugarcane, at soil layers 0–0.20, 0.20–0.40, and 0.40–0.60 m, totaling 96 samples. For soil sampling, an Uhland auger with PVC rings (5.2 cm in diameter and 2.0 cm in height) was used (Pacheco and Cantalice 2011). For each sampled soil layer, the first 5 cm of soil was removed, so that the Uhland auger could be driven, resulting in undisturbed soil sampled depths of 5 to 7, 25 to 27, and 45 to 47 cm, that represent the top of each sampled layer. To preserve the physical characteristics and moisture of the soil, the cylinders containing the undisturbed samples were wrapped in aluminum foil, paraffined, and labeled (Pacheco 2010; Pacheco and Cantalice 2011).

At the lab, each sample was allowed to stabilize in eight soil water matric potentials (– 1, – 4, – 6, – 10, – 33, – 100, – 500, and – 1,500 kPa) and were subjected to soil penetration resistance test (PR) using a benchtop electronic penetrometer, with a cone shank 4 mm in diameter and 45° in angle (Pacheco and Cantalice, 2011). The shank penetration speed was calibrated to 10 mm min⁻¹, with each test lasting 80 s. For the calculation of the average penetration resistance, the penetration

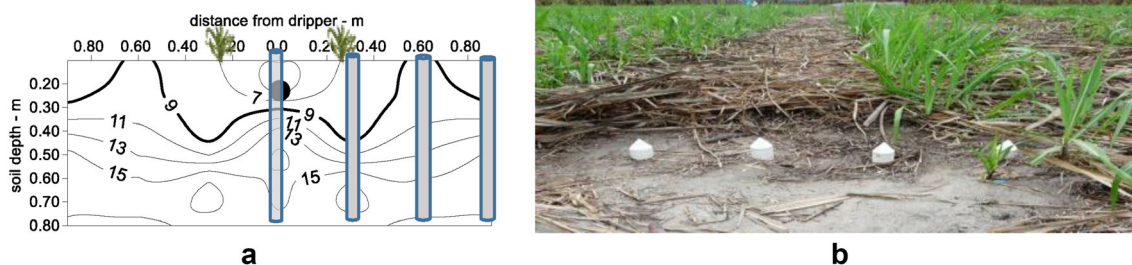


Fig. 1 Schematic **a** and field **b** arrangement of access tubes for measuring soil moisture, perpendicular to the planting line

force data between the times 40 and 80 s were considered, and the penetration force data (kgf) were recorded every second. The penetration resistance was calculated according to Eq. 2 (Pacheco 2010; Pacheco and Cantalice 2011).

$$PR = (F_p/0.1275) \times 0.09806 \quad (2)$$

where PR is the soil penetration resistance in laboratory (MPa), F_p is the averaged penetration force (kgf); 0.1257 is the cone area (cm²) and 0.09806 is the conversion factor (kgf cm⁻² to Mpa).

Regression analyses were performed, using the SAEG 9.1 statistical program, to obtain the adjustment parameters “a” and “b” of the mathematical models of soil resistance to penetration in the laboratory (PR) as a function of the volumetric soil moisture (θ_v), according to Eq. 3.

$$PR = a x e^{-(b x \theta_v)} \quad (3)$$

where PR is the soil penetration resistance (MPa); e is the Napierian logarithm; a and b are fitting parameters of the mathematical model and θ_v is the volumetric soil water content.

The PR versus θ_v regression equation determined for each soil layer (Eq. 3) was applied to the 4×8 matrix of θ_v values, obtaining the matrix of PR values. The set of PR values was interpolated using the ordinary kriging method and represented by isoline maps for each irrigation management level.

Sugarcane Rooting Pattern

For each irrigation treatment, four trenches were opened immediately after sugarcane harvest, with the soil wall to be analyzed positioned perpendicular to the planting line. The trenches were $1.0 \times 0.8 \times 0.8$ m in length, width, and depth, respectively. The length of the sugarcane roots was measured in the range of 0 to 0.60 m in depth, subdivided into 12 equal extracts of 5 cm. The root length measurement was performed by processing and analyzing digital images, in a 20×20 cm grid on the soil wall of the trenches. The trench wall was scarified with a nail roller,

cleaned, and the exposed roots were painted with white paint (Cintra and Neves 1996). In sequence, each root was touched up with white synthetic enamel. The SIARCS software (Cruvinel et al. 1996) was used for image treatment, providing as output the root density (cm cm⁻²).

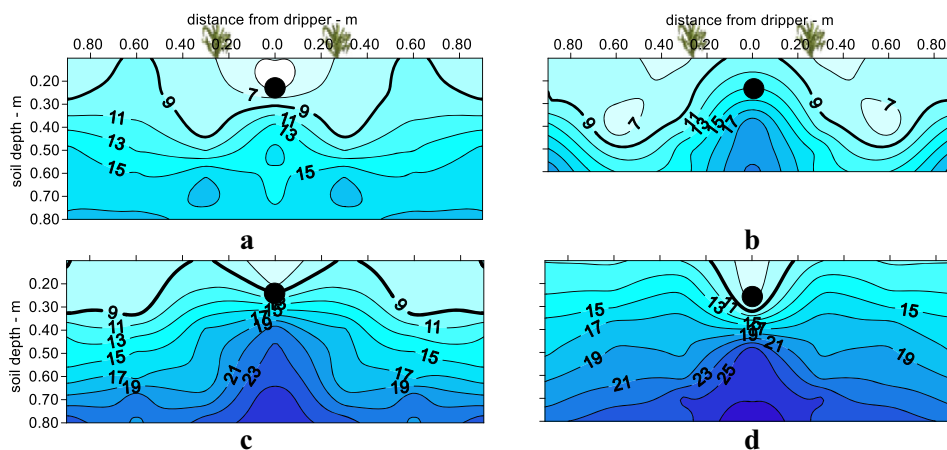
Results and Discussion

Soil Wetting Profile

In the time of soil wetting measurements (55 to 120 days after cutting), total precipitation was 52 mm and 85% of this was concentrated in two days at the beginning of the data collection period. During this same period, the reference evapotranspiration (ET_o) summed 312 mm, resulting in a daily average of 4.7 and 260 mm total water deficit. Thus, the major sugarcane water supply was provided by irrigation. The soil water profiles for each irrigation level are presented in Fig. 2. For better reader visualization, a mirroring of all the isoline maps hereafter was produced, assuming an isotropic behavior of the variable, in relation to the dripper tube location.

In the first 0.40 m soil layer, the moisture content at field capacity and permanent wilt point conditions is 13.25 and 4.45 cm³ cm⁻³, respectively (Table 1). In this layer, the W1, W2, W3, and W4 treatments gave averaged soil water content 8.5, 10.5, 11.5, and 12.5 cm³ cm⁻³, respectively. These values corresponded to soil water storage capacity depletion of 55, 33, 22, and 11%, respectively. For sugarcane, Pires et al. (2008) recommend that the soil moisture depletion should not exceed the range of 50 to 65% of the water storage capacity. Considering the 0–0.20 and 0.20–0.40 m averaged soil water retention curve, the continuous highlighted line in Fig. 2 defines the isoline corresponding to the limit of 50% water storage: above that isoline is the area where soil water is below so-called “readily available water” for sugarcane. This area decreases as the irrigation level increases and represents 25, 31, 18, and 4% of the total area of the observed profile, for treatments W1, W2, W3, and W4, respectively.

Fig. 2 Soil water profile (%v/v) for irrigation levels 40% ETo–W1 (a), 70% ETo–W2 (b), 100% ETo–W3 (c), and 130% ETo–W4 (d) – (the central black circle represents the buried dripper tube at 0.25 m depth; the continuous highlighted line defines the isoline corresponding to the limit of 50% water storage



In both W1 and W2 treatments, a significant part of the profile presented a wetting pattern below the limit of 50% of soil water storage capacity. This happened just in the root zone of the crop (Figs. 2a and 2b). Conversely, for most of the profile under W4 treatment, the soil water content remained above the soil field capacity, which is $19.2 \text{ cm}^3 \text{ cm}^{-3}$ for the 0.40 to 0.60 m soil layer (Table 1 and Fig. 2d). In treatments W3 and W4, a water capillary rising occurs, in relation to the water emission point, which results in a condition that is more favorable for moistening the superficial part of the soil profile.

The cohesive soil layer is associated with low permeability and hydraulic conductivity (Cintra 1998; Santos et al. 2019), which affects the soil water dynamics, promoting lateral water movement and superficial rainwater accumulation. From this point of view, in a superficial drip irrigated system would be expected an accumulation zone of irrigation water just above the cohesive soil layer. However, in the present study, we assumed that the sub-surface irrigation system, combined with a long-term low-frequency water application, allowed to overcome the lower hydraulic conductivity, and resulted in a lateral distribution and accumulation of moisture in a deepest part of the soil profile, indicating a water accumulation zone (Figs. 2c and d).

The pyramidal shape of the wetted bulb differs from the elliptical shape usually found in laboratory tests (Fan et al. 2018). This wetting pattern indicates that, beyond the capillary rise suggested above, water loss through deep percolation, resulting in a possible anaerobic condition for crop roots. Despite that, even for the highest depth of applied water, aerial growth of stem roots was not found in the field. Aerial root growth was observed by Tetsushi and Karim (2007) in an environment of soil water saturation.

Soil Mechanical Resistance to Root Penetration (PR)

Considering the sandy characteristic of the upper layer (Table 1), the soil moisture influence on PR is small. For the 0.20 to 0.40 m layer, the existence of the cohesive layer from a pedogenetic source resulted in an increase in the soil density and PR values, causing the moisture to play a major role in the expression of the cohesive soil layer. For each soil layer evaluated in the present study, Table 2 shows the exponential regression equations for estimating PR from soil moisture.

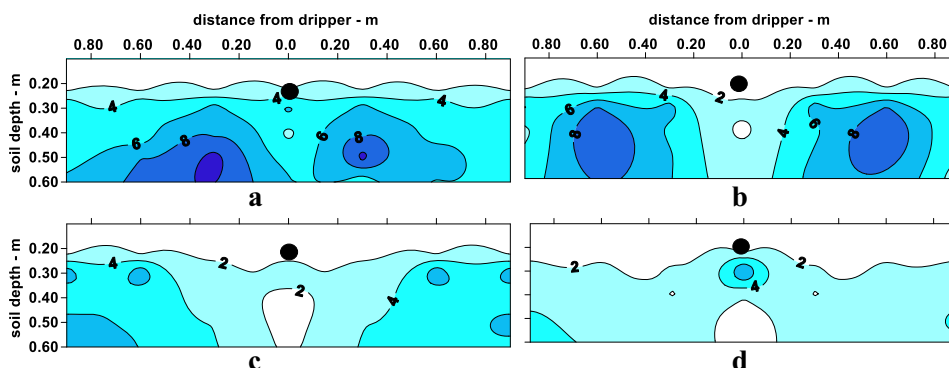
The application of the $PR \times \theta$ mathematical models from Table 2 to the soil moisture values from each evaluated irrigation management condition (Fig. 2) allowed to build the PR profiles associated with these managements (Fig. 3). For all irrigation managements, the soil layer which remained with PR values below 2.0 MPa was delimited by soil depth ranging from 0.20 to 0.30 m.

As the irrigation depth increased, the estimated PR values decreased in the deeper soil layers. For treatment W1, the soil wetting pattern resulted in PR above 4.0 MPa at a depth below 0.25 m. For treatments W2 and W3, the wetting bulb resulted in a central and well-defined zone of the soil in which the PR value was reduced, even in the region where the cohesive layer is found (Figs. 3b and c). In this central region (just below the dripper tube), the PR values ranged from < 2.0 to 4.0 MPa for all irrigations levels, while in the lateral and deeper part of the profile they reached up to 10.0 MPa (Fig. 3a). In addition to increasing the area of the soil profile with PR up to 2.0 MPa, in treatment W4 the greater lateral distribution of the wetting bulb resulted in PR values between 2.0 and 4.0 MPa for most of the soil below 0.30 m.

Even though increasing soil moisture decreased the intensity of the subsoil cohesive character, it was not enough to reduce the PR below 2.0 MPa. Considering the PR versus θ_v regression equation determined for each layer

Table 2 Exponential regression equations for estimating PR (MPa) from volumetric soil moisture (θ_v)

Soil layer	Model	R ²
0–0.20 m	PR = 1.26. e ^{-13.07. θ_v}	0.62
0.20–0.40 m	PR = 13.01. e ^{-11.19. θ_v}	0.54
0.40–0.60 m	PR = 37.69. e ^{-12.58. θ_v}	0.65

Fig. 3 Soil resistance profile to root penetration (MPa) as a function of irrigation levels 40% ET_o-W1 (a), 70% ET_o-W2 (b), 100% ET_o-W3 (c), and 130% ET_o-W4 (d) – full-colored black circle represents drip tube

(Table 2), for the two deeper layers, the soil moisture necessary for PR not to be restrictive (< 2.0 MPa) is bigger than soil moisture at the field capacity condition—Table 1 ($0.14 \text{ cm}^3 \text{ cm}^{-3}$ in the 0.20–0.40 m layer and $0.19 \text{ cm}^3 \text{ cm}^{-3}$ in the 0.40–0.60 m layer). Therefore, the limiting factor for root development is not the water available (deficit or surplus), but the mechanical resistance to root penetration, which provides an optimal hydric interval (OHI) condition close to zero. For all irrigation levels, PR ranged from 0.3 to 9.6 MPa. The PR values estimated here were higher than those measured in Oxisols by Pereira et al. (2002), Souza and Alves (2003), and Baquero et al. (2012), which reached up to 3.5 MPa in the first 0.40 m of soil depth but were lower than those found by Silveira et al. (2010) in Ultisols cropped with citrus, with 8.67 and 9.78 MPa in layers 0–0.20 and 0.20–0.40 m, respectively.

Sugarcane Rooting Pattern

The roots were superficially spread and limited to the first 0.35 m in depth for all irrigation depths applied (Fig. 4). Regarding lateral growth pattern, roots were concentrated at 0.6 m from the dripper tube, except for treatment W4, in which roots were spread beyond 0.80 m. (Fig. 4d).

Considering the entire soil profile, the extreme values of root density—darker blue areas in Fig. 4—were observed in treatments W2 (4.57 cm cm^{-2}) and W4 (3.27 cm cm^{-2}). This similarity of root density for all irrigation levels is also in line with the results reported by Landell et al. (2005) for the varieties IAC93-3046 and IAC87-3396.

The values of root density for different soil depths and lateral distance from the dripper tube are presented in Tables 3 and 4. Based on the ANOVA, the F test revealed no significant effect ($p > 0.05$) from the irrigation levels factor on sugarcane root density. There was also no significant interaction ($p > 0.05$) for irrigation level *versus* soil depth interaction, meaning that the irrigation level effect on sugarcane root density was similar for all soil depths evaluated. As expected, there was significant variance ($p < 0.05$) in the root density with respect to soil depth (Table 3).

The root density on the topsoil layer (0.0–0.15 cm) differed significantly ($p < 0.05$) from that measured in the layer immediately below (0.15–0.30 cm) in relation to W1, W2, and W3 irrigation treatments. In these two layers, the root density was significantly greater ($p < 0.05$) than that observed in 0.30–0.45 m and 0.45–0.60 m layers for W1, W3, and W4 irrigation levels. Sugarcane showed a superficial rooting pattern for all irrigation treatments, with the two upper layers, corresponding to the soil depth of 0.0–0.30 cm, concentrating 95% of the total roots.

Based on the ANOVA, for the lateral pattern of root distribution (Table 4) the F test revealed no significant effect ($p > 0.05$) of the irrigation levels factor when considering the entire soil profile. Also, there was no statistical significance ($p > 0.05$) for interaction between irrigation levels and lateral distance of the roots from drip tube interaction, indicating that the sugarcane root density in the lateral distances from drip tube evaluated does not depend on the irrigation level applied. There were significant ($p < 0.05$) differences in root density with respect to the

Fig. 4 Sugarcane root density (cm cm⁻²) as a function of irrigation levels 40% ETo–W1 (a), 70% ETo–W2 (b), 100% ETo–W3 (c), and 130% ETo–W4 (d) – full-colored black circle represents drip tube

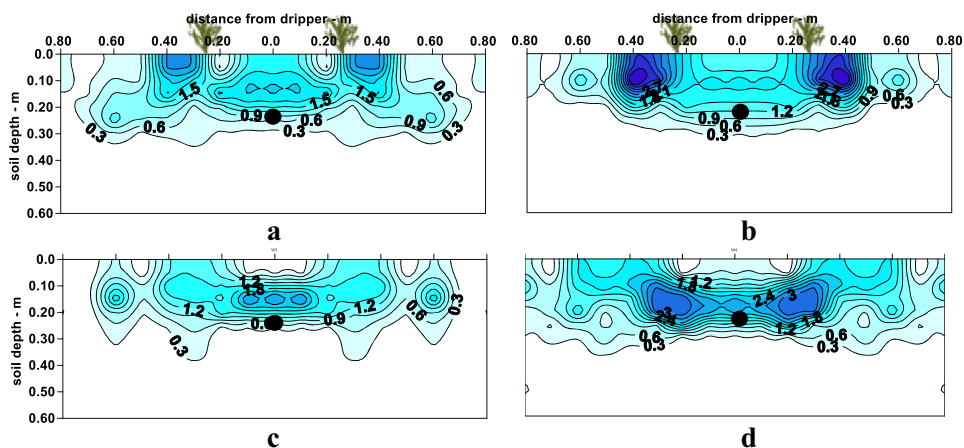


Table 3 Sugarcane root density for different soil depths and irrigation levels

Depth (m)	W1	W2	W3	W4	Mean	W1	W2	W3	W4	Mean
	Root density (cm cm ⁻²) ^a					%				
0.0–0.15	0.534a	0.640a	0.555a	0.542a	0.568	62	71	64	56	63
0.15–0.30	0.283b	0.222b	0.276b	0.369a	0.287	33	25	32	38	32
0.30–0.45	0.040c	0.030b	0.030c	0.042b	0.035	5	3	3	4	4
0.45–0.60	0.009c	0.008b	0.009c	0.013b	0.010	1	1	1	1	1
Mean	0.286 ^{ns}	0.297 ^{ns}	0.287 ^{ns}	0.318 ^{ns}						

^aAveraged root density comprising 0.8 m lateral distance from dripper

- Means followed by the same letter, in the column, do not differ from each other by the Tukey test ($p < 0.05$)

- W1–40% ETo, W2–70% ETo, W3–100% ETo and W4–130% ETo

Table 4 Sugarcane root density for different lateral distances (m) from dripper tube and irrigation levels

Lateral dist. (m)	0–0.20	0.20–0.40	0.40–0.60	0.60–0.80	0–0.20	0.20–0.40	0.40–0.6	0.60–0.80
	Root density (cm cm ⁻²) ^a				%			
W1	0.326a	0.307a	0.158ab	0.075b	38	35	18	9
W2	0.323a	0.409a	0.118b	0.051b	36	45	13	6
W3	0.308a	0.331a	0.186ab	0.045b	35	38	22	5
W4	0.312a	0.354a	0.196ab	0.105b	34	39	18	9
Mean	0.317a	0.350a	0.165b	0.069c	36	40	18	7

^aAveraged root density from topsoil to 0.6 m depth

- Means followed by the same letter, in the line, do not differ from each other by the Tukey test ($p < 0.05$)

- W1–40% ETo, W2–70% ETo, W3–100% ETo and W4–130% ETo

lateral distance from drip tube (Table 4). For all treatments, 94% of roots were concentrated within an area 0.60 m away from the drip tube. In this range, there was no difference between 0.0 and 0.20 cm, 0.20–0.40 cm, and 0.40–0.60 cm distance segments for W1, W3 and W4.

Although some studies (Vasconcelos and Casagrande 2008; Smith et al. 2005; Carr and Knox 2011) indicate that the sugarcane root system has the potential to reach up to

4 m, predominantly observed pattern of root distribution was shallower and approximately 80% of the roots are found in the first 0.40 m of depth. In addition to soil, other factors can contribute to (1) More superficial pattern of rooting in sugarcane, for instance: a. irrigation applied at high frequency; (2) Evidence showing that the root system is not completely replaced when ratooning occurs, and (3) It is possible that improvements in yield through breeding

have come at expense of roots (Smith et al. 2005). Besides that, varietal differences (Vasconcelos and Casagrande, 2008) and timing of root sampling along the crop cycle (Laclau and Laclau 2009) constitute factors which determine sugarcane rooting pattern. Otto et al. (2009), by using the monolith method for root sampling, observed 87% of the sugarcane roots are found in the first 0.40 m of depth. Ohashi et al. (2015), when evaluating three sugarcane cultivars in oxisols, reported a similar rooting depth. Other authors (Medina et al. 2002; Baquero et al. 2012) also observed the small depth of rooting in sugarcane. Otherwise, Battie-Laclau and Laclau (2009) in a Xanthic Ferralsols (FAO classification) without any physical or chemical barrier, observed the maximum depth reached by sugarcane roots at the harvest was 4.7 and 4.25 m in the rainfed and irrigated crop, respectively and 50% of root intersects were observed bellow 1.0 m, in the two water supply regimes.

In the present study, the subsurface drip irrigation system with the installation depth of the dripper of 0.25 m—close to the maximum crop roots depth—imposes a great challenge for both rational irrigation management and crop fertigation to avoid water percolation and nutrients leaching. Subsoiling has been the main management tool worldwide used to overcome problems related to cohesive layers (Shukla et al., 2017). Biological practices could also be effective in improving root environment—soil water movement and soil gas exchange—by increasing biopore number or total soil porosity. Cintra et al. (2006) when growing *Crotalaria spectabilis* (Fabaceae) previously the sugarcane planting; found higher root density at deeper layers, compared to use of organic composts applied in the bottom of the plowing furrow of the sugarcane cropping.

From the present results, a relationship between the level of soil wetting and the density of roots has not been clearly established. The average root density in the entire soil profile ranged from 0.286 cm cm⁻² in treatment W1 to 0.318 cm cm⁻² in treatment W4 (Table 3). The highest root densities were observed in the soil layer 0.0–0.15 m, which averaged 0.568 cm cm⁻² (63% of total roots), lower than that found by Ohashi et al. (2015), who found root density of 0.75 cm cm⁻² cropping sugarcane cultivar SP79-1011 in Oxisol, which had a 0.20–0.40 soil layer presenting a RP ranging from 2.5 to 3 MPa.

Overlapping the PR profiles (Fig. 3) and the rooting profiles (Fig. 4), we can see that the limit of root depth matches the 2.0 MPa isoline; this value is often found in the literature as being critical for most agricultural crops root development (Tormena 1998; Hamza and Anderson 2005; Cherubin et al. 2016).

The assertion that moisture reduces the effect of the cohesive layer (Jacomine 2001; Bezerra et al. 2014; Santos et al. 2018; Silva et al. 2020) proved to be true in the light of the field results obtained. However, the reduction occurred to an insufficient magnitude to promote the development of sugarcane root in depth. Although the higher irrigation depths (W3 and W4) resulted in a significant PR decrease, in the area underlying the dripper, the values observed remained above 2.0 MPa. In sugarcane cultivar SP81 3250, the growth of the roots was not affected when the PR was lower than 0.75 MPa but decreased significantly between 0.75 and 2.0 MPa; the growth was severely restricted when the PR was higher than 2.0 MPa (Otto et al. 2011). For the RB96-6928 cultivar cropped in Oxisol, Barbosa et al. (2018) observed PR values greater than 1.5 MPa severely restricting the root system, while in a clay soil such restriction occurred at values above 2.5 MPa.

Even considering the physical limitation imposed by the cohesive layer on root system deepening and that irrigation was not able to mitigate this limitation, the increasing levels of irrigation resulted in an exponential productive response of sugarcane. The yields were 114.4, 120.9, 123.9, and 122.1 Mg ha⁻¹ for treatments W1, W2, W3, and W4, respectively. These yields are bigger than the obtained by Dantas Neto et al. (2006) in a sandiest irrigated soil and under similar climate characteristics, but lower than 180–200 Mg ha⁻¹ obtained by Andrade Junior et al. (2017), when cropping sugarcane drip irrigated in oxisol without occurrence of cohesive soil layer. Thus, we assumed that irrigation applied at high frequency, combined with the management of fertigation acted as compensatory factors to the limitations of the root development of sugarcane. Therefore, considering that there was no significant relationship between sugarcane yield and total rooting, the question that remains is what would be expected sugarcane yield in the absence of soil cohesive layer? For comparative purpose, when cropping RB 96,579 variety in production fields of Coruripe Mill, the historical yield data for drip-irrigated sugarcane averaged 98 Mg ha⁻¹, but with a wide range of 50 to 270 Mg ha⁻¹ (database of the Coruripe Mill—data unpublished).

Although the drip irrigation method is associated with higher water use efficiency, the data presented here show that for soils with a subsurface impediment or cohesive layer, the subsurface drip system needs to be better evaluated, since the wetting bulb formed may not coincide with the so-called “effective rooting depth”. In this case, a low efficiency both of water application and, consequently, of macro and micronutrient absorption by the crop (if its application is via irrigation water) are expected.

Conclusion

Under subsurface drip irrigation, the water dynamic in the soil profile with cohesive layer resulted in a soil-wetting pattern that did not match the sugarcane rooting profile. Although capillary rise of water favored the moistening of the upper part of the soil profile, in the lower part there was water loss by deep percolation, implying in decrease in both the water and fertigation efficiency.

Regarding the soil mechanical resistance to root deepening, although the soil wetting provided by irrigation reduces the effect of the soil cohesive layer, such reduction was insufficient to allow adequate deepening of the sugarcane root system. Thus, the root development of sugarcane cultivar RB 867,515 was restricted by the limit of 2.0 MPa of the soil mechanical resistance to root penetration.

Acknowledgments The authors are grateful to Usina Açúcar and Álcool Coruripe S.A. for their continued support in all steps of this study.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Baquero, J.E., R. Ralisch, C.D. de Medina, J. Tavares Filho, and M.D. de Guimarães. 2012. Soil physical properties and sugarcane root growth in a red oxisol. *Revista Brasileira De Ciência Do Solo* 36 (1): 6–70. <https://doi.org/10.1590/S0100-06832012000100007>.
- Barbosa, L.C., Z.M. de Souza, H.C.J. Franco, R. Otto, J. Rossi Neto, A.L. Garside, and J.L.N. Carvalho. 2018. Soil texture affects root penetration in Oxisols under sugarcane in Brazil. *Geoderma Regional* 13: 15–25. <https://doi.org/10.1016/j.geodrs.2018.03.002>.
- Barros, A.C., M.V. Folegatti, C.F. Souza, and B.L. Santoro. 2009. Soil water distribution for subsurface and surface drip irrigation. *Revista Brasileira De Engenharia Agrícola e Ambiental* 13 (6): 700–707. <https://doi.org/10.1590/S1415-43662009000600006> (in Portuguese).
- Battie-Laclau, P., and J.-P. Laclau. 2009. Growth of the whole root system for a plant crop of sugarcane under rainfed and irrigated environments in Brazil. *Field Crops Research* 114: 351–360. <https://doi.org/10.1016/j.fcr.2009.09.004>.
- Bezerra, C.E.E., T.O. Ferreira, R.E. Romero, J.C.A. Mota, I.M. Vieira, L.R.S. Duarte, and M. Cooper. 2014. Genesis of cohesive soil horizons from north-east Brazil: Role of argilluviation and sorting of sand. *Soil Research* 53 (1): 43–55. <https://doi.org/10.1071/SR13188>.
- Carr, M.K.V., and J.W. Knox. 2011. The water relations and irrigation requirements of sugarcane (*Saccharum officinarum*): A review. *Experimental Agriculture* 47 (1): 1–25. <https://doi.org/10.1017/S0014479710000645>.
- Cherubin, M.R., D.L. Karlen, A.L.C. Franco, C.A. Tormena, C.E.P. Cerri, C.A. Davies, and C.C. Cerri. 2016. Soil physical quality response to sugarcane expansion in Brazil. *Geoderma* 267: 156–168. <https://doi.org/10.1016/j.geoderma.2016.01.004>.
- Cintra, F.L.D., W.M.P. de Mello Ivo, L.V. da Silva, and M. de L. da S. Leal. 2006. *Sugarcane root distribution in crop systems under organic fertilizer and Crotalaria spectabilis*. Aracaju: Embrapa Tabuleiros Costeiros. <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/370902>. Accessed 21 February 2022. (in Portuguese).
- Cintra, F.L.D., and P.L. Libardi. 1998. Physical characterization of a soil class of the “tabuleiro costeiro” ecosystem. *Scientia Agrícola* 55 (3): 367–378. <https://doi.org/10.1590/S0103-90161998000300004> (in Portuguese).
- Cintra, F.L.D., and C.S.V. Neves. 1996. Aspectos metodológicos do estudo do sistema radicular de plantas perenes através de imagens. *Boletim Da Sociedade Brasileira De Ciência Do Solo* 21 (3): 91–94 (in Portuguese).
- CONAB – Companhia Nacional de Abastecimento. 2021. *Acompanhamento da safra brasileira de cana-de-açúcar – Safra 2020/21: Terceiro levantamento*. 8(3): 1–63. <https://www.conab.gov.br/info-agro/safras/cana>. Accessed 19 Feb 2021. (in Portuguese).
- Cruvinel, P.E., S. Crestana, and L.A.C. de Jorge. 1996. Métodos e aplicações do processamento de imagens digitais. In: *Instrumentação Agropecuária: Contribuições no limiar do novo século*, ed. S. Crestana, P.E. Cruvinel, S. Mascarenhas, C.I. Biscegli, L. Martin Neto, and L.A. Colnagoca, 91–151. Brasília, DF: Embrapa- SPI. (in Portuguese).
- da Silva, C.P., B.G. de Almeida, R.E. Romero, T.L. de Alencar, M.G. Lobato, O.L. de Sousa, S.L. da Silva, M.C. Costa, and J.C. Mota. 2020. Cohesive character in Alfisols, Ultisol and Oxisols in northeast of Brazil: Relationship with tensile strength and particle size. *Geoderma Regional* 23: e00341. <https://doi.org/10.1016/j.geodrs.2020.e00341>.
- Daniel, I.G. 2012. Hardsetting soils: A review. *Soil Research* 50 (5): 349–359. <https://doi.org/10.1071/SR11102>.
- de Souza, Z.M., and M.C. Alves. 2003. Water movement and resistance to penetration in a dystrophic Red Latosol of cerrado under different uses and management. *Revista Brasileira De Engenharia Agrícola e Ambiental* 7 (1): 18–23. <https://doi.org/10.1590/S1415-43662003000100004> (in Portuguese).
- de Andrade Junior, A.S., E.A. Bastos, V.Q. Ribeiro, C.A. Sobrinho, and H.S. da Silva. 2017. Stalk yield of sugarcane cultivars under different water regimes by subsurface drip irrigation. *Revista Brasileira De Engenharia Agrícola e Ambiental* 21 (3): 169–174. <https://doi.org/10.1590/1807-1929/agriambi.v21n3.p169-174>.
- de Buso, P.D., H.S. Koehler, E. Daros, J.L. Zambon, O.T. Ido, J.C. Bepalhok Filho, H. Weber, R.A. Oliveira, and H. Zeni Neto. 2009. Sugarcane root system of RB85536 variety planted in one bud and three buds setts. *Scientia Agraria* 10 (5): 343–349. <https://doi.org/10.5380/rsa.v10i5.15185> (in Portuguese).
- de Silveira, D.D., J.F. de Melo Filho, J.A.A.S. do Sacramento, and E.C. Silveira. 2010. Relação umidade versus resistência à penetração para um argissolo amarelo distrocoeso no recôncavo da Bahia. *Revista Brasileira De Ciência Do Solo* 34: 659–667.
- De Conti, M.C., C.S. Neves, I.C. de Batista Fonseca, and A.F. Torreti. 2002. Root system distribution and sugar-cane production under

- vinasse treatments. *Semina Ciências Agrárias* 23 (2): 179–184. <https://doi.org/10.5433/1679-0359.2002v23n2p179>.
- dos Santos, M.M., F.D. Pereira, L.D. Souza, E.B. Santos, and F.G. da Silveira. 2019. Hidrodinamics in typical coastal trail soil in recôncavo bahiano. *Irriga* 24 (4): 770–780. <https://doi.org/10.15809/irriga.2019v24n4p770-780>.
- Fan, Y.-W., N. Huang, J. Zhang, and T. Zhao. 2018. Simulation of soil wetting pattern of vertical moistube-irrigation. *Water* 10 (5): 601. <https://doi.org/10.3390/w10050601>.
- FAOSTAT – FAO (Food and Agriculture Organization of the United Nations) Statistics. 2020. *Crops and livestock products*. <https://www.fao.org/faostat/en/#data/QCL>. Accessed 19 Feb 2022.
- Farias, C.H., P.D. Fernandes, H.M. Azevedo, and N.J. Dantas. 2008. Growth indices of irrigated and non-irrigated sugar cane in Paraíba, Brazil. *Revista Brasileira De Engenharia Agrícola e Ambiental* 12 (4): 356–362. <https://doi.org/10.1590/S1415-43662008000400004> (in Portuguese).
- Faroni, C.E., and P.C.O. Trivelin. 2006. Quantification of sugarcane active metabolism roots. *Pesquisa Agropecuária Brasileira* 41 (6): 1007–1013. <https://doi.org/10.1590/S0100-204X2006000600017> (in Portuguese).
- Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82 (2): 121–145. <https://doi.org/10.1016/j.still.2004.08.009>.
- IBGE – Instituto Brasileiro de Geografia e Estatística. 2020. SIDRA – Sistema IBGE de Recuperação Automática. *Produção Agrícola Municipal – 2020a*. <https://sidra.ibge.gov.br/pesquisa/pam/tabelas>. Accessed 19 Feb 2022. (in Portuguese).
- Inman-Bamber, N.G., P. Lakshmana, and S. Park. 2012. Sugarcane for water-limited environments: A theoretical assessment of suitable traits. *Field Crops Research* 134: 95–104. <https://doi.org/10.1016/j.fcr.2012.05.004>.
- Jacomine, P.K.T. 2001. Evolução do conhecimento sobre solos coesos no Brasil. In: *Workshop: coesão em solos dos Tabuleiros Costeiros*, ed. F.L.D. Cintra, J.L. dos Anjos, and W.M.P. de M. Ivo, 19–46. Aracaju: Embrapa Tabuleiros Costeiros. (in Portuguese).
- Kuhwald, M., M. Blaschek, R. Minkler, Y. Nazemtseva, M. Schwanebeck, J. Winter, and R. Duttmann. 2016. Spatial analysis of long-term effects of different tillage practices based on penetration resistance. *Soil Use and Management* 32 (2): 240–249. <https://doi.org/10.1111/sum.12254>.
- Landell, M.G. de A., M.P. Campana, P. Figueiredo, A.C.M. Vasconcelos, M.A. Xavier, M.A.P. Bidóia, H. do Prado, M.A. Silva, L.L. Dinardo-Miranda, A. da S. dos Santos, D. Perecin, R. Rossetto, D.N. Silva, A.L.M. Martins, P.B. Gallo, R.A.D. Kanthack, J.C. Cavichioli, A. de A. Veiga Filho, I.A. dos Anjos, C.A.M. Azania, L.R. Pinto, and S.A.C. D. de Souza. 2005. *Variedades de cana-de-açúcar para o Centro-Sul do Brasil: 15ª liberação do Programa Cana IAC (1959–2005)*. Campinas: Instituto Agrônomo de Campinas. (in Portuguese).
- Mota, J.C.A., C.P. da Silva, B.G. de Almeida, R.E. Romero, T.L. de Alencar, M.G. Lobato, O.L. de Sousa, S.L. da Silva, and M.C. Costa. 2021. Cohesive character in Alfisols, Ultisol and Oxisols in Northeast of Brazil: Relationship of tensile strength with silicon, aluminum and iron from poorly crystalline compounds. *Geoderma Regional* 24: e00361. <https://doi.org/10.1016/j.geodrs.2021.e00361>.
- Ohashi, A.Y., R.C. de Pires, R.V. Ribeiro, and A.L. de Silva. 2015. Root growth and distribution in sugarcane cultivars fertigated by a subsurface drip system. *Bragantia* 74 (2): 131–138. <https://doi.org/10.1590/1678-4499.0295>.
- Otto, R., P.C.O. Trivelin, H.C.J. Franco, C.E. Faroni, and A.C. Vitti. 2009. Root system distribution of sugar cane as related to nitrogen fertilization, evaluated by two methods: Monolith and probes. *Revista Brasileira De Ciência De Solo* 33 (3): 601–611. <https://doi.org/10.1590/S0100-06832009000300013>.
- Otto, R., A.P. Silva, H.C.J. Franco, E.C.A. Oliveira, and P.C.O. Trivelin. 2011. High soil penetration resistance reduces sugarcane root system development. *Soil and Tillage Research* 117: 201–210. <https://doi.org/10.1016/j.still.2011.10.005>.
- Pacheco, E.P., and J.R.B. Cantalice. 2011. Compressibility, penetration resistance and least limiting water range of a Yellow Ultisol under sugarcane in the Coastal Tablelands of Alagoas State. *Revista Brasileira De Ciência Do Solo* 35 (2): 403–415. <https://doi.org/10.1590/S0100-06832011000200010> (in Portuguese).
- Pacheco, E.P. 2010. *Estudo da compressibilidade e qualidade de um Argissolo Amarelo cultivado com cana-de-açúcar nos Tabuleiros Costeiros de Alagoas*. (Tese de Doutorado). Recife: Universidade Federal Rural de Pernambuco. (in Portuguese).
- Pereira, J.O., J.A.C. Siqueira, M.A. Uribe-Opazo, and S.D. de Silva. 2002. Soil penetration resistance as a function of tillage system and soil water content. *Revista Brasileira De Engenharia Agrícola e Ambiental Campina Grande*. 6 (1): 171–174. <https://doi.org/10.1590/S1415-43662002000100030> (in Portuguese).
- Pires, R.C.M., F.B. Arruda, and E. Sakai. 2008. Irrigação e drenagem. In *Cana-de-açúcar*, 631–670, ed., L.L. Dinardo-Miranda, A.C.M. de Vasconcelos, and M.G. de A. Landell. Campinas: Instituto Agrônomo de Campinas. (in Portuguese).
- Ribeiro, M.R. 2001. Características morfológicas dos horizontes coesos dos solos dos Tabuleiros Costeiros. In: *Workshop: coesão em solos dos Tabuleiros Costeiros*, ed. F.L.D. Cintra, J.L. dos Anjos, and W.M.P. de M. Ivo, 161–168. Aracaju: Embrapa Tabuleiros Costeiros. (in Portuguese).
- Ribon, A.A., and J. Tavares Filho. 2004. Models for the estimation of the physical quality of a yellow red latosol (oxisol), under pasture. *Brazilian Archives of Biology and Technology* 47 (1): 25–31. <https://doi.org/10.1590/S1516-89132004000100004>.
- Santos, H.G., P.K.T. Jacomine, L.H.C. Anjos, V.A. Oliveira, J.F. Lumberras, M.R. Coelho, J.A. Almeida, J.C. Araújo Filho, J.B. Oliveira, and T.J. F. Cunha. 2018. *Sistema brasileiro de classificação de solos*. Brasília, DF: Embrapa. <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1094003>. Accessed 7 Mar 2022. (in Portuguese).
- Shukla, S.K., R.L. Yadav, S.K. Awasthi, and A. Gaur. 2017. Soil microbial biomass nitrogen, in situ respiration and crop yield influenced by deep tillage, moisture regimes and N nutrition in sugarcane-based system in subtropical India. *SugarTech* 9 (2): 125–135. <https://doi.org/10.1007/s12355-016-0442-1>.
- Smith, D.M., N.G. Inman-Bamber, and P.J. Thorburn. 2005. Growth and function of the sugarcane root system. *Field Crops Research* 92: 169–183. <https://doi.org/10.1016/j.fcr.2005.01.017>.
- Souza, C.F., and E.E. Matura. 2004. Water distribution in soil and drip irrigation design. *Revista Brasileira De Engenharia Agrícola e Ambiental* 8 (1): 7–15. <https://doi.org/10.1590/S1415-43662004000100002> (in Portuguese).
- Tetsushi, H., and A. Karim. 2007. Flood tolerance of sugarcane in relation to growth, physiology and root structure. *South Pacific Studies* 28 (1): 10–22.
- Tormena, C.A., A.P. Silva, and P.L. Libardi. 1998. Caracterização do intervalo hídrico ótimo de um Latossolo Roxo sob plantio direto. *Revista Brasileira De Ciência Do Solo* 22 (4): 573–581. <https://doi.org/10.1590/S0100-06831998000400002>.

- Vasconcelos, A.C.M. de, and A.A. Casagrande. Fisiologia do sistema radicular. 2008. In: *Cana-de-açúcar*, 79–98, ed., L.L. Dinardo-Miranda, A.C.M. de Vasconcelos, M.G. de A. Landell. Campinas: Instituto Agronômico de Campinas. (in Portuguese).
- Vilas Bôas, G.S., F.J. Sampaio, and A.M.S. Pereira. 2001. The Barreiras Group in the Northeastern coast of the State of Bahia, Brazil: Depositional mechanisms and processes. *Anais Da*

Academia Brasileira De Ciências 73 (3): 417–427.
<https://doi.org/10.1590/S0001-37652001000300010>.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.