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The use of modelling to determine the limiting conditions for resuming soil loading by tractor in an area of sugar cane under reduced tillage

Ana Laura Filho de Araújo[1], Cristiano Márcio Alves de Souza[1*], Sálvio Napoleão Soares Arcoverde[1], Paulo Alexandre Graciano Maciak[2] and Andrés Hideki Tanaka Suárez[3]

[1] College of Agricultural Science (FCA), Federal University of Grande Dourados (UFGD), Dourados, Brazil. *csouza@ufgd.edu.br
[2] Agricase, Dourados, Brazil
[3] Agrismart, Trinidad, Bolivia

Abstract
The marked growth of the sugar and alcohol sector has promoted an increase in the fleet of heavy agricultural vehicles to meet the demand for commodities; however, the intense traffic of machines in areas of insufficient soil moisture has resulted in compaction, compromising the productivity of the sugar cane. In order to determine the optimal conditions for resuming the use of tractors under a reduced tillage system, the bearing capacity was evaluated and stress distribution was modelled in a dystroferric Red Latosol cultivated with sugar cane. Soil sampling was carried out during the first ratoon crop at 120 days, using metallic cylinders installed at a depth of 0.05 m in the crop rows and 0.15 m between rows. The samples were submitted to the uniaxial compression test to determine the preconsolidation pressure of the soil. The reduced tillage gave the lowest bearing capacity at the soil surface (0.05 m), while the highest values were found at a depth of 0.15 m. The bearing capacity proved to be an efficient indicator for analysing the structural degradation of the soil by demonstrating the compressibility of the various layers and sampling positions resulting from reduced tillage and the impact of agricultural machines in the field. The prediction model for traction and soil stress distribution that was employed was able to predict the optimal performance of the tractor, and provide stress data that would allow a study of the limiting water content for the traffic of agricultural tyre tractors.

Keywords: soil compaction, preconsolidation pressure, mathematical modelling

1. Introduction
The sugar-energy sector is of great prominence in both the Brazilian and world scenarios, and plays an important economic and social role, where, in this context, Brazil is seen as the world's largest producer of sugar cane. According to data from Conab (2019), during the 2019/20 crop in the south-east of the country, sugar cane production was estimated at 79.28 t ha^{-1}, and in the central-south region, at 77.11 t ha^{-1}.
Despite having begun sugar cane production more recently (Castro, 2010), the central-south region is proving to have great productive potential. The crop season in this region runs from April to October (Horii, 2004),

however, Severiano et al. (2009) found a reduction in the off-season period, which leads to machine traffic under the conditions of high soil moisture.

The traffic of heavy machinery, without taking into account the level of soil moisture, has, over successive cropping cycles, contributed to the process of soil compaction (Severiano et al., 2010; Souza et al., 2014). It is not possible to think of any form of sugar cane production that does not use highly technified agricultural mechanisation, from planting through to harvesting (Souza et al., 2012). However, the increasingly intense use of these machines without proper management relative to the physical conditions of the soil, by compromising the structural quality of the soil, directly affects agricultural and environmental sustainability (Oliveira et al., 2003).

The main effect of transferring pressure from agricultural machinery to soils with an inadequate water content is compaction, which in turn is directly related to an increase in soil density, reduction in total porosity and macroporosity, and increased mechanical resistance to penetration (Tsegaye & Hill, 1998).

In order for there to be sustainability with a long-term guarantee of productivity, it is necessary to understand the physical indicators that alter the structure of the soil. In that way, correct soil management practices can be established that guarantee the sustainability of production (Lopes, 2007). Not all soil attributes have proved to be practical or inexpensive to determine (Bochner, 2007); however the preconsolidation pressure is one attribute that has been shown to be efficient as an indicator of correct soil management. This pressure was considered by Pereira et al. (2015) an indicator of the maximum pressure applied to the soil that results in compaction, and is related to the moisture content.

Therefore, to ensure soil sustainability, the preservation of its structure and the productivity of future crops, it is necessary to rationally manage machine traffic and the soil water content, which can be done by means of the preconsolidation pressure (Silva et al., 2010). Mathematical modelling can aid in understanding the process of transmitting the load from the tractor to the soil, and how the stresses propagate. Using modelling, simulations can be carried out to assist in decision-making concerning how to achieve the best machine performance without greatly compromising the structural quality of the soil.

The aim of this study was to evaluate bearing capacity and model stress distribution in a dystroferric Red Latosol cultivated with sugar cane, in order to determine the limiting conditions for resuming the use of tractors in an area of sugar cane under a reduced tillage system.

2. Material and Methods

2.1. Location and weather conditions

The experimental area belongs to the Jatehycaa Farm, located in the district of Dourados, in the central-west of Brazil, in the south of the state of Mato Grosso do Sul (Figure 1). The region has a tropical monsoon climate, with a dry winter, average annual rainfall of 1,500 mm, and an average temperature of 22ºC (Alvares et al., 2013).

The period with the least rainfall occurs from the first ten days of June to the second 10 days of September, with the second ten days of August having the least rainfall. The highest rainfall values occur during October and November, and from December to March, with December being the wettest month (Fietz et al., 2017).

Figure 1. Location of the district of Dourados, Mato Grosso do Sul (MS) state, Brazil.

2.2. The soil and characteristics of the terrain

The soil in the experimental area is a dystroferric Red Latosol (Santos et al., 2013). This has a low base saturation (V<50%), with an Fe_2O_3 content ranging from 180 to 360 g kg^{-1} for most of the first 100 cm of the B horizon (including BA). A physical analysis of the soil showed that to a depth of 30 cm, the proportion of clay, silt and sand is 603, 147 and 250 g kg^{-1}, respectively (Arcoverde et al., 2020).

The soil in question is deep and has a clayey texture (65% to 70% clay), however, due to the presence of aggregates, the water retention capacity is lower than in typically clayey soils, and as such, water infiltration is high with a low cation exchange capacity. The clay fraction is type 1:1, with a predominance of kaolinite and iron oxide (Rezende, 2016).

The area is at an altitude of 430 m; despite this high altitude, the region is located in a flat, central area. The farm has a flat terrain, and underwent chemical and physical correction when the soil was prepared for growing sugar cane.

2.3. Experimental area

The sugar cane RB855156 cultivar was planted manually on 21 July 2016, and the area was managed under reduced tillage. Each sample experimental unit had an area of 37.5 m^2, with the planting rows spaced 1.5 metres apart.

For sugar cane cultivation, reduced tillage was carried out at a depth of 0.15 m, using an offset harrow with

16 discs, 0.76 m in diameter (30") in each section. A 4x2 FWA model NH 8030 tractor was used to prepare the soil and direct furrowing. This had an engine power of 89.79 kW (122 hp), rotation of 2200 rpm, reduced 3rd gear, 14.9-28" front tyres and 23.1-30" rear tyres, and a ballast weight of 4.51 Mg.

For covering the furrows and for the cropping treatments (180 days after planting), a 4x2 FWA model MF292 tractor was used, with an engine power of 68.74 kW (92 hp), rotation of 2,200 rpm, reduced 3rd gear, 7.50-18" front tyres and 18.4-34" rear tyres, and a weight of 3.40 Mg. The KO Cross-s 2000 sprayer with 9.5-24" tyres was employed, with a 14 m bar and weight of 1.40 Mg.

In October 2017, mechanised two-pass harvesting was carried out between the crop rows employing a model JD 3520 sugar cane track harvester, with the sugar cane collected using a model BH 180 tractor equipped with low-pressure, high-flotation tyres, pulling two grain bins with a capacity of 10 Mg of chopped sugar cane.

From planting the crop to harvesting, the soil density at a depth of 0.05 m varied from 1.30 Mg m^{-3} to 1.47 Mg m^{-3}, and at a depth of 0.15 m, from 1.40 Mg m^{-3} to 1.46 Mg m^{-3}. This variation in density was due to the effect of six passes of the agricultural machinery over the ground.

2.4. Soil sampling

Sampling took place at 120 days during the first ratoon cycle of the sugar cane. Trenches were opened perpendicular to the planting rows. Undisturbed soil samples were then removed with the aid of metal cylinders (64.5 mm in diameter and 25.4 mm in height) with a volume of 8.3×10^{-5} m^3, which were centred on and between the rows of sugar cane at a depth of 0.05 and 0.15 m, respectively, as described in Pereira et al. (2015).

Seven samples were collected from five different points at each depth, giving a total of 70 samples (7 samples x 5 points x 2 depths). After collection, the samples were properly sealed with cling film and placed in a refrigerator to preserve their physical characteristics.

2.5. Preconsolidation pressure

After due preparation of the samples, they underwent a process of saturation, until the water depth reached a height of two thirds that of the ring in order to later stabilise the water content. The seven samples from each depth were subjected to the following pressures: 0.006, 0.01, 0.033, 0.066, 0.1, 0.3 and 1.5 MPa, using a tension table for the pressure of 0.006 MPa and a Richards chamber for the other pressures, as per Klute (1986).

Once the samples had reached equilibrium at the above pressures, a model CNTA-IHM/BR-001/07 automatic consolidometer was used to carry out the uniaxial compression test, following the Bowles method (1986) as modified by Dias Junior (1994). The pressures used in the process were: 25, 50, 100, 200, 400, 800 and 1,600 kPa, and as per the methodology, each pressure was applied up to 90% deformation of the samples. After compression, the samples were placed in an oven for 48 hours at a temperature of between 105 and 110ºC, in order to determine the soil moisture and density, as per Teixeira et al. (2017).

The values for pressure and deformation were properly analysed and plotted on a graph using the CA-Linker v1.4 software, thereby obtaining the soil compression curve, from which the preconsolidation pressure was estimated. In order to obtain a mathematical model of the preconsolidation pressure at both depths, it was necessary to determine the linear models based on the exponential model.

The exponential model was defined as per Equation 1, applying the logarithm of the values for preconsolidation pressure obtained with the CA-Linker v1.4 system, which generated the linear model as shown in Equation 2.

$$\sigma_p = 10^{(a+b\theta)} \quad (1)$$

$$\log(\sigma_p) = a + b\theta \quad (2)$$

where,

'a' and 'b' - empirical coefficients of the fit of the model;

θ - soil moisture, $m^3\ m^{-3}$;

σ_p - preconsolidation pressure, kPa.

2.6. Stress distribution in the soil under vehicle loading

Predicting stress distribution in an elastic medium subject to any type of load can be based on an analysis of the stress distribution under the resultant load. To model the pressure bulb in the soil, the dynamic load on the wheel sets and the soil parameters were considered, as described in Equation 3.

$$\sigma_r = \frac{\nu W_d}{2\pi z^2} \cos^{\nu}(\alpha) \quad (3)$$

where,

σ_r - soil stress, kPa;

ν - concentration factor for the state of the soil, dimensionless;

z - soil depth, m;

W_d - dynamic load on the wheel set, kN;

α - angle between the vertical and the radius of the pressure bulb, rad.

The Sigma method of determination was used to analyse the stresses throughout each depth. This considered angles of 0, 20, 40, 60, 80 and 90 degrees, and seven pressures from the maximum and minimum determined between the load and the contact area of both the front and rear tyres with the soil. In modelling the graph using the Sigma factor, the ratio of the radius to the depth reached by the stress was calculated.

Tractor displacement over the soil causes mechanical stress directly below the tyre. The characteristics of the stress distribution are dependent on the parameters of the tyre, such as wheel load and inflation pressure, as well as on the conditions of the soil (Keller, 2005). The contact pressure of the tyre with the soil was determined as described in O'Sullivan et al. (1999).

Using the data of the 4x2 FWA model NH 8030 tractor, the dynamic load on the front and rear axles was determined, from which it was possible to describe the pressure bulb for three soil conditions: firm soil; friable soil of normal density; and dry soil with a moisture content below the friable.

Knowing the pressures on the soil and the depth at which they occur, it was possible to determine by using the selected preconsolidation models, which level of moisture would limit the tractor traffic that would cause compaction. This solution is feasible because the empirical models of this work represent variations in soil physical attributes, such as density from 1.20 to 1.76 Mg m^{-3}, moisture from 0.274 to 0.451 m^3 m^{-3}, cone index from 0.94 to 5.66 MPa, and porosity from 0.33 to 0.55 m^3 m^{-3}, determined as described in Suárez (2018).

2.7. Modelling the tractive capacity of the tractor

In order to analyse the traction and weight transfer of the tractor, either at the optimal moment or for a specific operation, it is necessary to know the width of the front and rear tyres, the diameter of the front and rear wheel rims, and the deflection index of the tyres. For the tractor, use was made of the total weight, the portion of the weight on the front and rear axles, the distance between the axles, and the height of the drawbar. For the soil, the cone index was determined, as per Standard S313-3 (Asabe, 2006a).

Using the Excel® software, a computational model was implemented to determine the net traction force as a function of wheel slippage and tyre loading, as described in Standard D497.5 (Asabe, 2006b). The dynamic loads on the tyres were determined using Equations 4 and 5. The mobility coefficient of the front and rear tyres was then determined using Equation 6.

$$W_{dr} = W_{sr} + \frac{T_f y}{d} \tag{4}$$

$$W_{df} = W_{sf} - \frac{T_f y}{d} \tag{5}$$

$$B_n = \frac{I_c b d}{W_d}\left(\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}\right) \tag{6}$$

where,

W_{dr} - dynamic load on the rear axle, kN;

W_{sr} - static load on the rear axle, kN;

T_f - tractive force, kN;

y - height of the drawbar, m;

W_{df} - dynamic load on the front axle, kN;

W_{sf} - static load on the front axle, kN;

d - wheelbase, m;

B_n - mobility coefficient calculated for the front and rear tyres, adm.;

Ic - soil cone index, kPa;

b - tread width of the front and rear tyres, m;

h - tread depth of the front and rear tyres, m;

δ - front and rear tyre deflection, m.

After determining the mobility coefficient, the rolling resistance of the ground on the front and rear tyres was determined. For this, it is necessary to consider an additional force, which must be included in calculating the power required for traction (Souza et al., 2002). This force can be determined using the rolling resistance coefficient, obtained with Equation 7.

$$M_R = W_d\left(\frac{1}{B_n} + 0.04 + \frac{0.5s}{\sqrt{B_n}}\right) \quad (7)$$

where,

M_R - rolling resistance of the wheel set, kN;

s - wheel slippage, decimal.

The gross traction force for the front and rear tyres was determined using Equation 8. The drawbar force was calculated using Equation 9, and the tractive efficiency using Equation 10. The values for drawbar force were determined using an iterative process, as reported in Souza et al. (2002).

$$F_t = W_d[0.88(1 - e^{-0.1B_n})(1 - e^{-7.5s}) + 0.04] \quad (8)$$

$$T_f = F_{tr} + F_{tf} - M_{Rr} - M_{Rf} \quad (9)$$

$$TE = (1 - s)\frac{T_f}{F_t} \quad (10)$$

where,

F_t - gross traction force of the front (f) and rear (r) wheel sets, kN;

M_R - rolling resistance of the front (f) and rear (r) wheel sets, kN;

TE - tractive efficiency, dec.

2.8. Data analysis

The preconsolidation pressures together with the values for volumetric moisture were adjusted to a linear regression (Equation 2) to determine the model for the bearing capacity of the soil.

The models were compared using the homogeneity test for linear models described in Snedecor & Cochran (1989). To obtain the linear models from the exponential model (Equation 1), the logarithm of the values for preconsolidation pressure was applied. The homogeneity test for linear models considers two models, which are compared via an analysis of intercept ‘a’, the angular coefficient ‘b’, and the homogeneity of the data (F-test), as described in Pereira et al. (2015).

In order to analyse the effect of the condition and state of the soil on the performance of the tractor and its pressure due to tyre loading, the following were studied: a friable soil of normal density; a soil that was firm following preparation; and a hard soil, 120 days after the sugar cane harvest, represented by cone indices of 900, 1500 and 2000 kPa, respectively.

3. Results and discussion

3.1. Soil preconsolidation model

The models and the selected curves were compared following the methodology of Snedecor and Cochran (1989) using regression line comparison. The results were grouped in Table 1, which shows the two curves selected to characterise the bearing capacity of the soil under reduced tillage for sugar cane cultivation. The estimated values for parameters ‘a’ and ‘b’ in the models were 3.372 and -2.786 in the 0-10 cm layer, and

4.735 and -5.580 in the 10-20 cm layer. The fitted curves of the models showed coefficients of determination of 0.81 and 0.86. These results agree with those of Pereira et al. (2015) who, evaluating the bearing capacity of a red dystroferric Latosol cultivated with sugar cane under different tractor-bin sets, found an R^2 for the models that ranged from 0.78 to 0.87.

Table 1. Estimates of coefficients 'a' and 'b' of the models, confidence interval, and coefficient of determination (R^2) for the bearing capacity of the soil (Equation 1), sampled in two layers of a dystroferric Red Latosol under reduced tillage, in first-cut ratoon sugar cane

Soil layer	Coefficient b			Coefficient a			R^2
	Estimated value	Confidence interval		Estimated value	Confidence interval		
		L_l	L_u		L_l	L_u	
0-10 cm	-2.7862*	-2.6394	-2.8022	3.3721	3.1618	3.7375	0.81
10-20 cm	-5.5800*	-5.4174	-5.6240	4.7347	4.4880	4.7694	0.86

L_l and L_u: lower and upper limits of the 95% confidence interval by t-test, respectively. *: significant by t-test at 5% probability.

Figure 2 shows the bearing capacity curves for the 0-0.10 and 0.10-0.20 m layers. A smaller soil bearing capacity can be seen for the depth of 0-0.10 m over the entire range of water content. This smaller bearing capacity is associated with the lower values for density in this layer, a result of the increase in macroporosity due to less mechanical movement from the reduced tillage (Arcoverde et al., 2019).

The values for soil bearing capacity decreased with the increase in moisture, which, according to Vischi Filho et al. (2015), can be attributed to the management, which gives rise to disaggregation with less contact between the primary soil particles, and contributes to a reduced bearing capacity at high moisture levels.

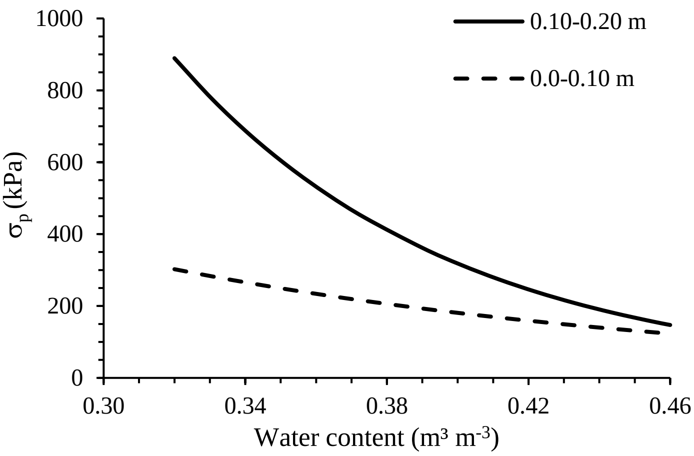


Figure 2. Models of bearing capacity as a function of water content, in the 0.0-0.10 m and 0.10-0.20 m layers.

According to Suzuki et al. (2008), the increase in density promotes a reduction in the void space of the soil, and consequently leads to an increase in compaction, which helps to reduce deformation and the compression index. As a result, the susceptibility of the soil to compaction is reduced, increasing the bearing capacity and favouring machine traffic. However, high densities can also limit plant root growth (Lima et al., 2006; Suzuki et al., 2008).

As a result, the deeper layer (Figure 2), where the mean values for density were greater than the mean values in the more superficial layer, showed greater resistance to compaction and a higher bearing capacity. Concerning the water content of the soil, deeper layers tend to conserve more water, since the evaporation rate of the water from the soil is lower than in the more superficial layers.

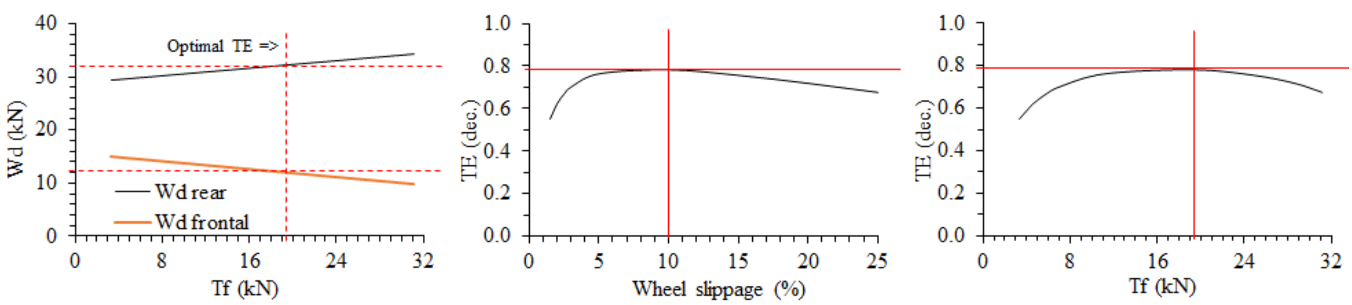
It should be noted that it is in the surface layers where the cumulative effect of mechanisation is greater, a result of continuing machine traffic throughout the sugar cane cycles (Vischi Filho et al., 2015). According to the authors, due to the residual effect of subsoiling, there are no significant structural changes below 30 cm, to the point of restricting the development of the sugar cane ratoons.

Regarding the soil water content, Imhoff et al. (2004) and Saffih-Hdadi et al. (2009) observed a reduction in the compression index with the increase in water content. This is due to the water acting as a lubricant in the soil, reducing the internal friction between particles and the resistance of the aggregates to breakage (Pacheco and Cantalice, 2011), allowing the soil particles to be better accommodated during the compression process (Lima et al., 2006; Silva et al., 2009).

Since the central theme of the work in question is the correct management of agricultural traffic on a dystroferric Red Latosol with a varying soil water content, it is important to emphasise that one of the main factors responsible for compaction in sugar cane plantations is the traffic of the tractor-bin set during harvesting, and of self-propelled machines when applying inputs, as these have a small soil-tyre contact area, exerting pressure on the soil surface that can exceed 450 kPa (Silva et al., 2006).

3.2. Analysing the traction of 4x2 FWA tractors

To analyse the traction of the 8030 tractor, graphs were prepared using the computational model that show the moment of maximum tractive efficiency of the tractor in relation to the dynamic load distribution applied to the axles, wheel slippage and drawbar force (Figure 3).



(A) (B) (C)

Figure 3. Front and rear dynamic loads (A) occurring at the drawbar force (T_f) that maximises tractive efficiency (TE), wheel slippage that maximises TE (B), and drawbar force that maximises tractive efficiency (C), for a cone index of soil friable or of normal density.

From the analysed graphs, it was possible to determine the dynamic loads that would guarantee the maximum tractive efficiency of the tractor, this being 11.9 kN at the front and 32.2 kN at the rear (Figure 3A). The wheel slippage to guarantee maximum tractive efficiency is 10% (Figure 3B), with a drawbar force of 19 kN to guarantee better fuel consumption (Figure 3C).

After analysing the graphs and determining the maximum point of tractive efficiency for the three types of soil under study, it was possible to prepare Table 2. From a cone index of 1500 kPa onwards, there was no gain in tractive efficiency for the tractor travelling on soil under reduced tillage, with the drawbar force stationary at 20.0 kN.

It can be seen that as there was no change in the weight of the tractor through the addition or removal of ballast, the tractive efficiency increased due to an improvement in the tractive condition of the soil, resulting in a change in traction force and in the dynamic load on the axle.

Table 2. Cone index (C_i), slippage (s), drawbar force (T_f), front (W_{df}) and rear (W_{dr}) dynamic loads, tractive efficiency (TE), concentration factor (ν), and ratio between the mean tyre contact pressure with the soil and the maximum pressure of a dystroferric Red Latosol under reduced tillage, in first-cut ratoon cane

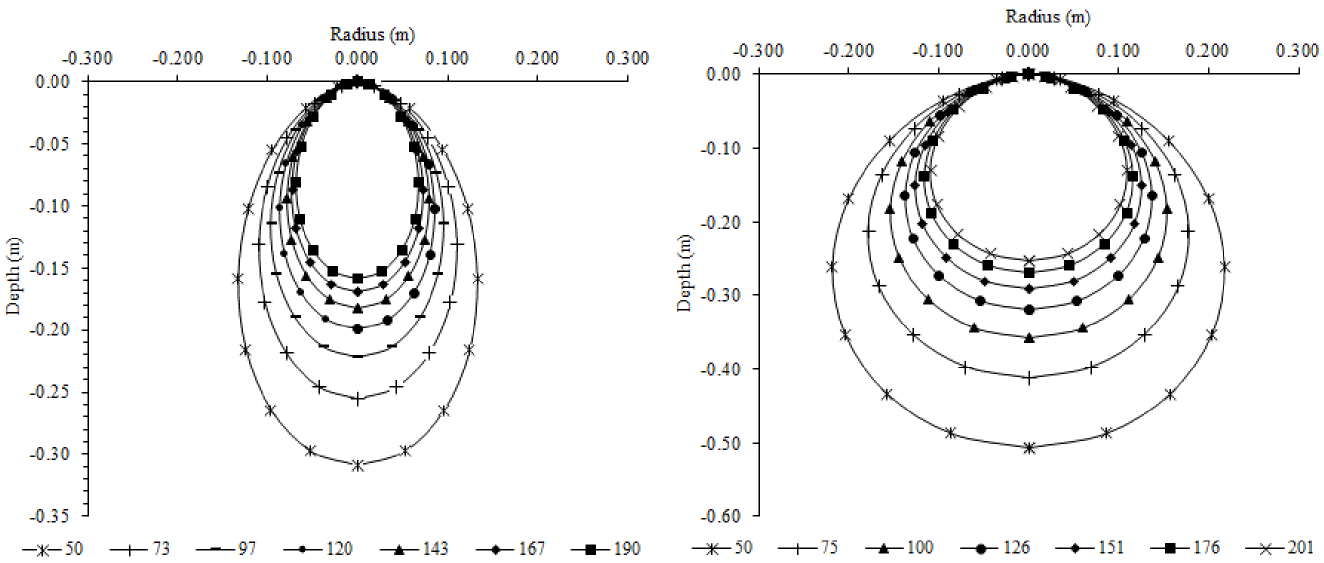
Condition of the soil	C_i (kPa)	s (%)	T_f (kN)	W_{df} (kN)	W_{dr} (kN)	TE (%)	ν^*	$\frac{P_{max}}{P_{mean}}$ *
Friable, of normal density[1]	900	10	19.4	12.0	32.2	77.8	5.0	2.000
Firm[2]	1500	8	20.0	13.4	30.8	80.4	4.5	1.500
Hard[3]	2000	7	20.0	13.3	30.9	81.1	4.0	1.125

*Source: SÖHNE (1958). [1]soil immediately after preparation with reduced tillage. [2]soil when harvesting the sugar cane. [3]soil after 120 days of first ratoon sugar cane.

3.3. Analysing soil stress

So with these data concerning analysis of the ground pressure bulb, the soil stress distribution was obtained for both the rear and front axles. In each case, the greatest effect of load concentration occurred in the 0-0.10 m layer, showing that the tractor caused greater reaction in the surface layers of the soil, possibly generating additional compaction in these layers. However, at this depth it is possible that the furrowers are able to break up the layer if it is compacted.

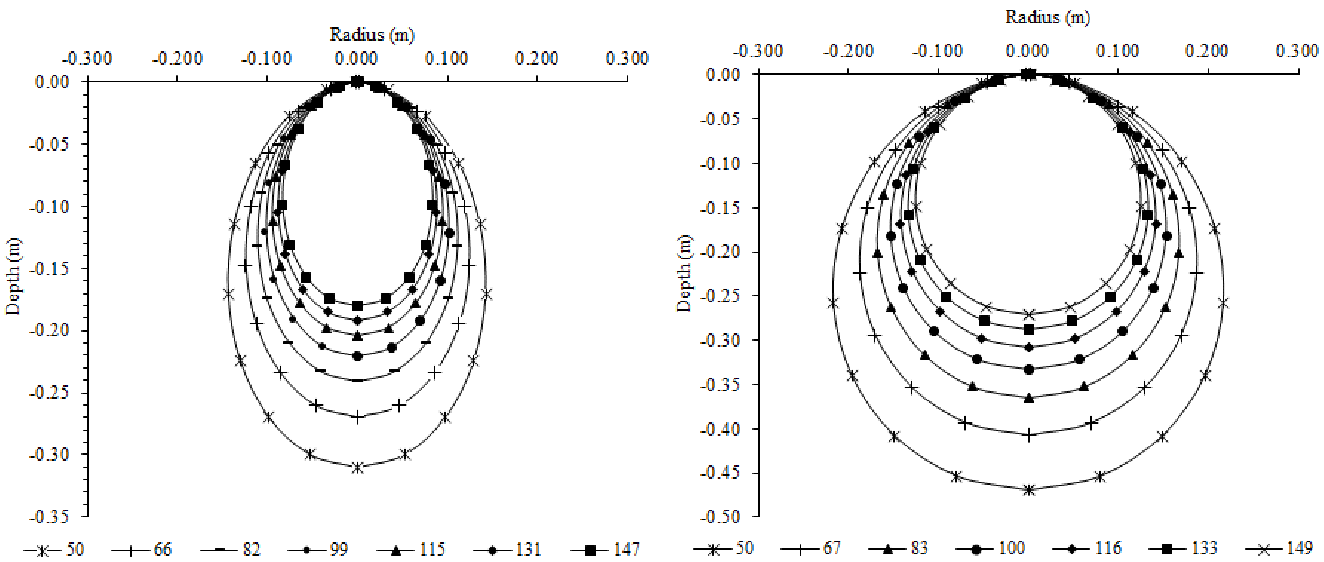
In order to deepen the analysis of soil stress and apply the model to a practical study, the use of a cone index of 900 kPa, characteristic of soft soils and/or soils with a good moisture content (Table 2), resulted in the stress distribution shown in Figure 4.



(A) (B)

Figure 4. Pressure distribution bulb for soil with a cone index of 900 kPa, concentration factor of 5, front tyre loading of 11.90 kN (A), rear tyre loading of 32.2 kN (B), and insufflation pressure of 83 kPa.

The model was able to predict soil stress in relation to its vertical and horizontal distribution for the front (Figure 4A) and rear (Figure 4B) tyre loadings. The highest simulated stress for the front tyre was 190.0 kPa, while for the rear tyre it was 201.0 kPa, occurring at a depth of 15 and 26 cm, respectively. Figure 5 shows the soil stress distribution at a concentration factor of 4.5 and cone index of 1500 kPa for the stress under the front and rear tyres, respectively. It can be seen that in this case the maximum stress on the soil under each tyre was similar, occurring at a depth of 18 cm for the front tyre and at 27 cm for the rear tyre.
On the other hand, working on hard soil with a relatively high cone index resulted in a maximum stress of 110 and 112 kPa for the soil under the front and rear tyres, respectively. These stresses were predicted to occur at a depth of 19.6 and 29.6 cm for the front and rear tyres (Figure 6).



(A) (B)

Figure 5. Pressure distribution bulb for soil with a cone index of 1500 kPa, concentration factor of 4.5, front

tyre loading of 13.4 kN (A), rear tyre loading of 30.8 kN (B), and insufflation pressure of 83 kPa.

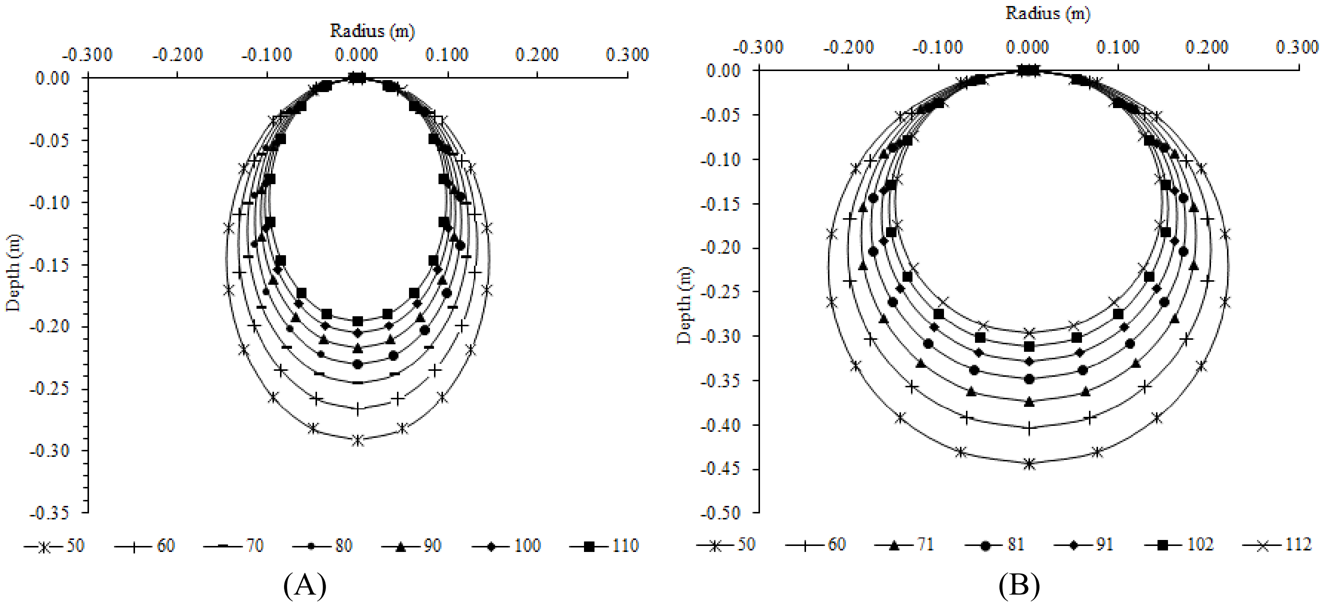


Figure 6. Pressure distribution bulb for soil with a cone index of 2000 kPa, concentration factor of 4, front tyre loading of 13.3 kN (A), rear tyre loading of 30.9 kN (B), and insufflation pressure of 83 kPa.

In all the cases under analysis, the greatest predicted soil stress occurred below the depth of 15 cm, which is in line with Couto (2012), who states that as the depth and distance from the centre of the tyre increase, normal stresses are reduced in magnitude, possibly resulting in less soil deformation at greater depths, but extending over larger areas.

3.4. Critical condition analysis for traffic

Table 3 shows the limiting water content under the front and rear tyres for tractor traffic. It can be seen from the simulated data that soils of lower density have a lower water content, leading to compaction and proving to be more susceptible to external loading. As the soil becomes firmer, it can bear a greater load for a slight increase in the limiting water content. The limiting water content for tractor traffic was lower at the depth of 0.05 m than at 0.15 m, reflecting the greater bearing capacity in this layer, as described in Figure 2.

Table 3. Values for the depth of maximum stress, the stress under the tyres, and limiting water content for machine traffic in a dystroferric Red Latosol at risk of consolidation under reduced tillage, in first-cut ratoon sugar cane

Depth of maximum stress at the front	Depth of maximum stress at the rear	Stress under the front tyre	Stress under the rear tyre	0-10 cm layer		10-20 cm layer	
				θ_f	θ_r	θ_f	θ_r
---------- cm ----------		----- kPa -----		--------------- $m^3 m^{-3}$ --------------			
15.0	26.0	190	201	0.39	0.38	0.44	0.44
18.0	27.0	147	149	0.43	0.43	0.46	0.46

19.6	29.6	110	122	0.48	0.46	0.48	0.47

θ_f and θ_r – limiting water content under the front and rear tyres, respectively.

In general, for a humidity ranging from 0.38 to 0.48 m^3 m^{-3}, soil stress varied between 110 and 201 kPa. Working with a Red Latosol, Kondo and Dias Júnior (1999) found a variation in the preconsolidation pressure of from 77 to 183 kPa, for a humidity of 0.42 and 0.27 kg kg^{-1}, respectively. This shows that additional compaction can occur when soil stress exceeds the respective pre-consolidation pressure. It is therefore essential to allow machine traffic in clayey soils when the soil water content is low, in order to preserve its structural quality.

Suárez (2018), working with physical-hydric properties of the same soil submitted to reduced tillage, observed that its field capacity increases with the density. Therefore, given this and considering the data in Table 3, it is estimated that the traffic of the analysed tractor should not be performed when the soil has more than 84% of the moisture that characterises the field capacity.

Thus, as presented in Queiroz et al. (2020), it is possible with the methodology adopted in this work to elaborate a database of soil limiting moisture and its location on the farm using precision agriculture and with the study of the loads transmitted by each machine to propose the best management aiming at reducing soil compaction. In addition, soil moisture sensors can be installed strategically distributed by agricultural areas of interest for real-time monitoring.

4. Conclusion

The bearing capacity proved to be an efficient indicator for analysing the structural degradation of the soil, by demonstrating the compressibility at different depths as a function of the impact of the agricultural machines in the field.

The model implemented for traction and predicting soil stress distribution was able to predict the performance of the tractor and provide stress data that would allow the limiting water content for the traffic of wheeled agricultural tractors to be studied.

The management of a dystroferric Red Latosol using reduced tillage was an excellent choice to provide a soil structure capable of supporting the traffic of the tractor analysed at maximum tractive efficiency, being able to resume mechanised operations under non-limiting conditions below 84% of the moisture of the field capacity.

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