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Sampling plan for using a motorized penetrometer in soil compaction evaluation

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Key words:
sample size
penetration resistance
grazing pressure
soil management

ABSTRACT

This study aimed to estimate the size of blocks of observations of resistance to penetration, obtained by a motorized digital penetrometer, and the number of blocks with semi-amplitude of the confidence interval between 5 and 20% of the mean penetration resistance, for different soil depth ranges and cone diameters. Data were collected in two contrasting plots of a crop-livestock integration experiment, located in Abelardo Luz, SC, Brazil. Ten blocks were delimited and the resistance to penetration was determined in 20 points spaced by 20 cm, using a motorized digital soil penetrometer. To estimate the mean of resistance to penetration, 12 blocks of four points per experimental plot should be used for a semi-amplitude of the confidence interval equal to 10% of the mean (1 - p = 0.95). Twenty random points may be sampled to estimate mean of penetration resistance for a semiamplitude confidence interval of 10% of the man (1 - p = 0.95). The sample size for the layer of 0-10 cm is larger than in the deeper layers (0-20, 0-30 and 0-40 cm) and smaller for cones with larger diameter.

Palavras-chave:
tamanho de amostra
resistência à penetração
pressão de pastejo
manejo do solo

Plano amostral para uso do penetrômetro motorizado na avaliação da compactação do solo

RESUMO

O objetivo neste trabalho foi estimar a dimensão dos blocos de observações da resistência à penetração, obtidas por um penetrômetro digital motorizado e o número de blocos considerando-se uma semiamplitude do intervalo de confiança entre 5 e 20% da média da resistência a penetração para diferentes faixas de profundidade do solo e diâmetros do cone de penetração. Os dados foram coletados em duas parcelas contrastantes de um experimento de “integração lavoura-pecuária” localizado em Abelardo Luz, SC. Foram demarcados 10 blocos e determinada a resistência à penetração em 20 pontos distanciados em 20 cm. Foi usado um “penetrômetro de solos digital e motorizado”. Para estimar a média da resistência à penetração deve-se usar 12 blocos de quatro pontos por parcela experimental para uma semiamplitude do intervalo de confiança igual a 10% da média (1 - p = 0,95). Pode-se amostrar 20 pontos aleatórios por parcela para estimar a média da resistência à penetração para uma semiamplitude do intervalo de confiança igual a 10% da média (1- p = 0,95). O tamanho de amostra para a profundidade de 0-10 cm é maior do que nas faixas mais profundas (0-20, 0-30 e 0-40) e é menor para cones de diâmetro maior.

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Introduction

Different grazing pressures may result in different levels of soil degradation, due to animal displacement patterns (Baggio et al., 2009). The measurement of soil compaction using "penetrometers" allows the assessment of one of the important physical properties for management and evaluation of soil physical quality, since this property is related to various soil attributes (Tavares Filho & Ribon, 2008).

Soil resistance to penetration (RP) can be obtained through a non-linear function of the gravimetric water content, density and organic matter content in the soil (Tavares Filho et al., 2012). Estimates of sample size aiming higher accuracy of research results have been published for different crops (Storck, 2011; Cargnelutti Filho et al., 2011; Storck et al., 2012; Benin et al., 2013).

The number of sampled points for RP determinations ranged considerably. There are cases with less than 10 points (Silveira et al., 2010; Freitas et al., 2012; Moraes et al., 2012; Lima et al., 2013) and cases with 10 to 20 (Ralisch et al., 2008; Tavares Filho & Ribon, 2008), and others, with 16 (Coelho et al., 2012), 570 and 1333 (Mome Filho et al., 2014), 1111 (Roque et al., 2008), 7100 (Iaia et al., 2006) and 11,100 (Molin et al., 2012) points ha^{-1}. The trend is that the standard error shows values between 5 and 15% of the mean without significant decreases in its values from 15 points on (Molin et al., 2012).

This study aimed to estimate the dimension of blocks of observation obtained by a motorized digital penetrometer and the number of blocks, with semi-amplitude of the confidence interval equal to 5, 10, 15 and 20% of the mean of the soil penetration resistance, in two contrasting environments, at different depths and diameters of the penetration cone.

Material and Methods

The data were collected in two plots (paddocks) of contrasting treatments, of a long-term experiment involving the study of the crop-livestock integration, on a farm in the municipality of Abelardo Luz-SC, Brazil. The soil in the experimental area is typical dystrophic Brown Latosol, with very clayey texture (69.5% of clay, 26.8% of silt and 3.7% of sand) and a prominent A horizon (EMBRAPA, 1999). The factorial experiment consisted of two levels of grazing intensity (grazing pressure), through the grazing method of continuous stocking and variable stocking rate (Mott & Lucas, 1952), in order to maintain two canopy heights, 10 and 20 cm, and two levels of nitrogen fertilization applied as top-dressing, 0 and 200 kg ha^{-1} of N, in the form of urea. The experiment was set in a randomized block design with three replicates.

This study used the paddock A, with area of 1,011 ha (26° 31' 34.22" S; 52° 15' 36.50" W; altitude of 851 m), to represent the application of nitrogen and high grazing pressure (canopy height of 10 cm), which possibly shows higher soil compaction. The paddock B, with area of 1,173 ha (26° 31' 34.48" S; 52° 15' 34.27" W; altitude of 851 m) had no N application and low grazing pressure, which indicates its lower soil compaction.

In each paddock, 10 observation blocks were randomly demarked diagonally to the direction of sowing of forages (black oat + Italian ryegrass), with grazing avoiding the areas close to the drinkers. In each one of the ten blocks per paddock, the resistance to penetration (RP) was determined in 20 points, spaced by 20 cm (in a straight line, inside the block). This operation used a motorized digital soil penetrometer (DLG, Model PNT-2000-M), which recorded RP values every 10 mm of depth (between the surface and 400 mm) using the cone 3 (71.25 mm^2). The unit of measurement of soil compaction was the resistance to penetration of the cone, expressed in MPa. In total, 400 points were evaluated on September 22, 2014.

Using the results of the mean of RP in the range of 0-40 cm of depth, for each observation block and paddock, the mean (m) and the variance (s^2) were estimated between the 20 points. It was also estimated the first-order spatial autocorrelation coefficient (ρ) using the sequence of readings of the points in the block. Considering X_i as equal to the value (RP) observed in the point i, it follows that:

$$D_i = X_i - \bar{X} \quad (1)$$

and

$$\hat{\rho} = \frac{\sum_{i=2}^{n} D_i D_{i-1}}{\sum_{i=1}^{n} D_i^2} \quad (2)$$

The optimum evaluation size (Xo, number of adjacent points in the block) was estimated through the method of maximum curvature of the coefficient of variation model using the expression (Paranaíba et al., 2009):

$$Xo = \left(\frac{10}{m}\right)\left[2\left(1-\hat{\rho}^2\right)s^2 m\right]^{1/3} \quad (3)$$

Using just half of the points (even points or odd points) per block (n = 10; distance between points = 40 cm), new estimates of Xo were obtained. The means of RP and Xo of each block were compared between two paddocks by the bootstrap t-test (5000 re-samples, p = 0.05) using the application BioEstat 5.3 (Ayres et al., 2012).

Using the results of RP means for each range of depth (0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm), the statistics m, s^2, ρ and Xo were again estimated and the means were compared by the bootstrap t-test (5000 re-samples, p = 0.05)

Considering the RP (range of 0-40 cm of depth), the sequence of 20 points in each block was divided into lots of 20/Xo and determined the mean of RP per lot (composite sample) as the new observed variable. With the values of RP mean of each lot, in the 10 blocks of each paddock, the following statistics were calculated: mean, variance, coefficient of variation and sample size (n_o, number of sequences of Xo points) per paddock. For this, the following expression, was used:

$$n_o = \frac{t_{\alpha/2}^2 CV^2}{D^2} \quad (4)$$

where:

CV - coefficient of variation, in percentage;

D - semi-amplitude of the confidence interval, in percentage (D = 5%, D = 10%, D = 15% and D = 20% were used for the mean); and

t - critical value of the t distribution, at 0.05 probability level (Bussab & Morettin, 2004).

Considering n = 200 points per paddock as independent, the sample size (number of points) was estimated using Eq. (4) for the means of RP obtained in different depth ranges: 0 to 10 cm; 0 to 20 cm; 0 to 30 cm and 0 to 40 cm.

Considering that the penetrometer has three penetration rods with cones of 323 mm^2 (Cone 1), 129 mm^2 (Cone 2) and 71.25 mm^2 (Cone 3), data were obtained in 20 points, in a different site, in a straight line and spaced by 50 cm. For each marked point, the RP value was obtained using the cone 2 and, 5 cm distant on each side, the cone 1 (left side) and cone 3 (right side) were used. The following statistics were estimated: mean, coefficient of variation, the first-order spatial autocorrelation coefficient (ρ) and the sample size for different values of estimation errors.

Normality, randomness and trends (Mann-Kendall) of the data were verified by the application WinSTAT® for Microsoft® Excel. For the other procedures, the R software (R Development Core Team, 2014) and the application Microsoft Office Excel were used.

Results and Discussion

The mean values of resistance to penetration (RP) in the range of 0-40 cm, in each sampling block, in both paddocks (Table 1) fit to the normal distribution (Kolmogorov-Smirnov test; p > 0.05), do not follow trends (Mann-Kendall test, p > 0.05) and are random (Runs test, p > 0.05). This fact allows performing analysis of variance and comparing means of blocks (using 20 points as replicates) by the t-test. In both paddocks, the means of blocks differ significantly and the variances of blocks are heterogeneous by the Bartlett test.

The overall mean of RP (mean in the range of 0-40 cm) of the paddock A (higher grazing pressure) is significantly superior to the overall mean of paddock B (lower grazing pressure), but the optimum block size (Xo, number of adjacent points) is the same in both paddocks with contrasting grazing pressures. In experiments, this fact is very important, because it is possible to determine only one value of Xo, approximately equal to four points per block, for any paddock (experimental unit) of the experiment.

Using only 10 even points or only 10 odd points (n = 10 points per block), the distance between points is equal to 40 cm; in this case, RP means of paddock A are also superior to the respective means of paddock B and there is no significant difference with respect to optimum block size (Xo) (Table 1). This fact results from the randomness of the values or the lack of spatial dependence. Spatial dependence, estimated by the first-order spatial autocorrelation coefficient (ρ) is, on average, almost null, in the cases of 20 cm between points and 40 cm between points (even or odd points). With distances between points higher (1.0 x 1.4 m) than those used in the present study, Iaia et al. (2006) observed spatial dependence in only 10% of the evaluated semivariogram models. With a grid of points much more spaced (50 x 50 m), the spatial dependence was strong (Coelho et al., 2012). Since the experimental plots are in general small, one may think that RP values are independent.

Performing the same analyses with the RP values for the means of different depth ranges (Table 2), similar results are found: values of Xo are the same and the RP mean of paddock A is significantly higher than that of paddock B, except for the depth range of 30-40 cm, in which the consequences of grazing pressure (number of animals per paddock) did not influence RP values. This result is very significant for the definition of the sampling plan for the estimate of RP in specific depth ranges.

Table 1. Mean of resistance to penetration (RP, MPa), variance (s^2), first-order spatial autocorrelation coefficient (ρ) and optimum block size (Xo, number of adjacent points), in two cattle grazing conditions and three scenarios of measurement of resistance to penetration in the depth range of 0-40 cm

Block	High-grazing pressure paddock				Low-grazing pressure paddock			
	Mean	s^2	ρ	Xo	Mean	s^2	ρ	Xo
Using 20 points per block (20 cm between points)								
1	3.452 b*	0.146	-0.094	2.89	2.872 ab	0.171	0.311	3.34
2	3.909 a	0.725	0.115	4.54	2.858 ab	0.139	0.201	3.19
3	3.185 bc	0.450	-0.011	4.46	2.644 b	0.063	0.111	2.61
4	3.036 cd	0.088	0.320	2.58	2.702 b	0.074	-0.014	2.72
5	2.787 d	0.236	-0.255	3.84	2.851 b	0.403	-0.083	4.61
6	3.480 b	0.787	0.074	5.06	2.607 b	0.179	-0.112	3.73
7	3.150 bc	0.153	-0.022	3.14	2.779 b	0.114	0.205	3.05
8	3.263 bc	0.236	-0.205	3.49	2.798 b	0.135	0.161	3.22
9	3.250 bc	0.439	0.042	4.36	3.050 a	0.806	-0.094	5.55
10	2.920 cd	0.118	-0.011	3.02	2.825 ab	0.221	-0.133	3.79
Mean	3.243 A[1]	0.338	-0.005	3.74 A	2.799 B	0.231	0.055	3.58 A
CV (%)[2]	9.8			22.4	4.5			25.2
Using 10 points per block (40 cm between even points)								
1	3.477	0.143	0.141	2.85	2.862	0.202	-0.069	3.66
2	3.800	0.406	-0.259	3.74	2.935	0.176	-0.119	3.43
3	3.065	0.257	0.037	3.79	2.665	0.043	0.437	2.13
4	3.073	0.121	0.064	2.94	2.675	0.040	0.114	2.21
5	2.961	0.405	-0.395	4.27	2.701	0.072	-0.039	2.70
6	3.733	2.310	0.195	6.83	2.491	0.051	-0.786	1.84
7	2.995	0.088	-0.218	2.65	2.803	0.148	0.074	3.34
8	3.148	0.165	-0.073	3.20	2.808	0.191	0.130	3.62
9	3.184	0.637	-0.212	4.93	3.036	0.255	0.042	3.81
10	2.858	0.163	-0.314	3.30	2.601	0.059	0.198	2.56
Mean	3.229 A	0.469	-0.103	3.85 A	2.758 B	0.124	-0.002	2.93 A
CV (%)	10.1			32.6	5.9			24.6
Using 10 points per block (40 cm between odd points)								
1	3.427	0.164	-0.110	3.02	2.882	0.159	0.340	3.23
2	4.018	1.098	0.004	5.14	2.781	0.104	-0.312	2.89
3	3.306	0.661	-0.172	4.89	2.623	0.090	-0.336	2.84
4	3.000	0.063	0.003	2.40	2.730	0.115	-0.172	3.10
5	2.614	0.026	-0.266	1.92	3.001	0.727	-0.174	5.39
6	3.327	0.118	-0.513	2.50	2.723	0.298	-0.410	4.05
7	3.305	0.182	0.170	3.18	2.755	0.092	0.152	2.87
8	3.379	0.304	0.278	3.66	2.789	0.094	-0.150	2.86
9	3.316	0.279	-0.167	3.66	3.064	1.445	-0.190	6.67
10	2.982	0.077	-0.355	2.47	3.049	0.297	-0.106	3.98
Mean	3.267 A	0.297	-0.113	3.29 A	2.840 B	0.342	-0.136	3.79 A
CV (%)	11.1			32.5	5.4			34.2

*Blocks with means not followed by the same letter (lowercase) differ by t-test ($p < 0.05$); [1] Paddocks with means not followed by the same letter (uppercase) differ by the bootstrap t-test ($p < 0.05$); [2] CV – Coefficient of variation

Considering Xo = 4 points per block, the results of mean, variance, coefficient of variation and sample size for different semi-amplitudes of the confidence interval (D%) are shown in Table 3, for five lots (20/Xo = 5) of Xo points per block. For example, for lot 5 (mean of the points 17 to 20 of each block), the sample size (number of blocks of Xo = 4 adjacent points) considering D = 10% of the mean is equal to five (n_o = 4.6). The other results of n_o vary with the lots and the mean of five lots can be an estimator for the number of blocks of Xo points per paddock. Multiplying the mean of n_o by Xo results in the total number of points per paddock, 48 points for paddock A and 24 points for paddock B (lower grazing pressure).

Alternatively and considering the randomness of the lack of spatial dependence of RP values, 200 points of each paddock (10 blocks of 20 points) can be used to estimate sample size (Table 4). For instance, for a semi-amplitude of the confidence interval (D) equal to 10% (D = 10% of the RP mean in the depth range of 0-40 cm), 20 points (paddock A) and 15 points (paddock B) should be randomly sampled on the entire experimental paddock (plot). This value is almost half the value obtained by the concentration of Xo points (blocks) in n_o replicates (Table 3). Similarly, Molin et al. (2012) concluded that, from 15 points (replicates) on, the standard error tends to be between 5 and 15% of the mean, without expressive decreases in its values with the increase in the number of points. In addition, Tavares Filho & Ribon (2008) concluded that the number of representative samples for RP determination varies with the management system and sampling depth. Thus, the best representativeness of the mean of RP results occurs for n > 15 (no tillage and perennial crop) or n > 20 (0-10 cm) and 15 (20-60 cm) in the case of conventional tillage. Such values are close to those obtained in the present study, with D = 10% of the estimation error and for both paddocks. For both paddocks, the sample sizes for the ranges of 0-20, 0-30 and 0-40 cm were similar, but lower than those obtained in the range of 0-10 cm. In the surface (0-10 cm), there is higher heterogeneity with respect to RP and the sample size must be larger, because the area affected by cattle trampling is the most superficial (Andreolla & Gabriel Filho, 2006) and the animals do not move uniformly inside the paddock; their displacement is influenced by the location of the salt holder, drinker, direction of the rest of the herd, presence of better patches of forages, areas of thermal comfort, among others, which leads to the higher variability of RP in the surface layer (Baggio et al., 2009).

In this aspect, when creating a sampling plan, the researcher must consider the time of displacement between the points inside the paddock to obtain the RP values with the motorized penetrometer, because the device is activated by a cable connected to a car battery (17 kg) and must be transported somehow from point to point. When the points were concentrated (20 points per block in 10 blocks per paddock), the mean time was equal to 40 s per point (90 points h^{-1}). In the option 1, with 12 blocks of Xo = 4 points (48 points), the required time is 48 x 40 = 1920 s. In the option 2, with 20 points (equidistant or random), the time is 20 x 40 = 800 s. The time difference is 1120 s, which is divided by eight additional displacements (20 from the option 2 minus 12 from the option 1), resulting in 140 s or 2 min and 20 s per displacement. If the displacement time is greater than 140 s, the option of using points grouped in blocks is advantageous. In fact, it is worthwhile spending some time in the office to create a sampling plan in order to spend less time at the field, perform a task in a more appropriate time or even increase the precision of RP estimates. The largest sample size estimated

Table 2. Mean of resistance to penetration (RP, MPa) and optimum block size (Xo, number of adjacent points), in different ranges of evaluation depth in two cattle grazing conditions

Ranges (cm)	High grazing pressure		Low grazing pressure	
	RP	Xo	RP	Xo
0 to 10	3.055 a*	4.79 a	2.304 b	5.03 a
10 to 20	3.388 a	4.29 a	2.998 b	4.03 a
20 to 30	3.229 a	4.36 a	2.705 b	4.08 a
30 to 40	3.302 a	4.16 a	3.187 a	4.28 a

*Means not followed by the same letter, in the row, differ by the bootstrap t-test (p < 0.05)

Table 3. Mean of resistance to penetration (RP, MPa), variance (s^2), coefficient of variation (CV) and sample size (n) for semi-amplitude of the confidence interval - D (1 - p = 0.95) equal to 5, 10, 15 and 20% of the mean, in five lots of four points per block in two cattle grazing conditions

Paddock	Lot 1	Lot 2	Lot 3	Lot 4	Lot 5	Mean	Xo*n
			High-grazing pressure paddock				
Mean	3.362	3.269	3.228	3.111	3.246	3.243	
s^2	0.475	0.115	0.086	0.136	0.068		
CV (%)	20.5	10.4	9.1	11.8	8.0		
$n_{(D=5\%)}$	121.1	31.0	23.7	40.5	18.5	47	188
$n_{(D=10\%)}$	30.3	7.7	5.9	10.1	4.6	12	48
$n_{(D=15\%)}$	13.5	3.4	2.6	4.5	2.1	5	20
$n_{(D=20\%)}$	7.6	1.9	1.5	2.5	1.2	3	12
			Low-grazing pressure paddock				
Mean	2.852	2.725	2.778	2.854	2.783	2.799	
s^2	0.121	0.026	0.058	0.063	0.044		
CV (%)	12.2	6.0	8.7	8.8	7.5		
$n_{(D=5\%)}$	43.0	10.2	21.7	22.2	16.3	23	92
$n_{(D=10\%)}$	10.8	2.6	5.4	5.5	4.1	6	24
$n_{(D=15\%)}$	4.8	1.1	2.4	2.5	1.8	3	12
$n_{(D=20\%)}$	2.7	0.6	1.4	1.4	1.0	2	8

Table 4. Mean of resistance to penetration (RP, MPa), variance, coefficient of variation (CV), for n = 20 points, per cattle grazing condition and range of mean depth of RP and sample size (n) for semi-amplitude of the confidence interval - D (1 - p = 0.95) equal to 5, 10, 15 and 20% of the mean of RP

Statistic	Depth ranges - cm			
	0-10	0-20	0-30	0-40
		High grazing pressure		
Mean	3.055	3.221	3.224	3.243
Variance	0.626	0.470	0.441	0.414
CV (%)	25.9	21.3	20.6	19.8
$n_{(D=5\%)}$	136.8	92.5	86.7	80.3
$n_{(D=10\%)}$	34.2	23.1	21.7	20.1
$n_{(D=15\%)}$	15.2	10.3	9.6	8.9
$n_{(D=20\%)}$	8.6	5.8	5.4	5.0
		Low grazing pressure		
Mean	2.304	2.651	2.669	2.799
Variance	0.401	0.260	0.211	0.235
CV (%)	27.5	19.2	17.2	17.3
$n_{(D=5\%)}$	154.3	75.6	60.3	61.2
$n_{(D=10\%)}$	38.6	18.9	15.1	15.3
$n_{(D=15\%)}$	17.1	8.4	6.7	6.8
$n_{(D=20\%)}$	9.6	4.7	3.8	3.8

for the condition of higher grazing pressure should not be attributed exclusively to the higher RP mean, but also to the greater variability of RP, caused by animal trampling. The number of sampled points in the different published studies is probably related to the type of the equipment, determination of data of other variables in the same points and the availability of human resources.

The RP values obtained for the three cone diameters fit to the normal distribution (Kolmogorov-Smirnov test; $p > 0.05$), do not follow trends (Mann-Kendall test, $p > 0.05$) and are random (Runs test, $p > 0.05$). The randomness is also evidenced by the low first-order spatial autocorrelation coefficient (ρ), which is almost null for the three cone diameters (Table 5). RP means differ significantly ($p < 0.05$) with respect to cone diameter; in relation to cone 2 (medium diameter), cone 1 (larger diameter) underestimates and cone 3 (smaller diameter) overestimates it. Considering that RP values have normal and random distribution, the difference in RP magnitude due to cone diameters does not invalidate the evaluation of RP in experimental plots, if the same cone diameter is used in all the plots.

Only the linear correlation between the values obtained with cone 1 (larger diameter) and cone 2 (medium) is significant ($r = 0.72$; $p < 0.05$). The values obtained with cone 3 (smaller diameter) are much more random, even at short distances (5 cm) from the points where the other cones were used.

The cones with medium and small diameter have the highest coefficients of variation and, therefore, the sample size is higher for different semi-amplitudes of the confidence interval (Table 5). Since in the study of the diameters a different area was used, another paddock, it is only possible to infer that the sample size for cones with larger diameters can be smaller for a same semi-amplitude of the confidence interval, compared with that obtained with cone 3 in the study of two paddocks. However, considering the RP of the area to be evaluated, it is not always possible to use cone 1 (larger diameter), because of the difficulty of penetration, despite being a motorized device. Thus, cone 1 (larger diameter) should be used whenever it is possible, because in larger areas there is greater homogeneity between the observations and higher precision of the estimate of RP mean. In studies on the optimum size of experimental plots, the relationship between plot size and precision also occurs (Cargnelutti Filho et al., 2011; Storck, 2011), i.e., the use of larger plots results in higher experimental precision.

Table 5. Mean of resistance to penetration (RP, Mpa), coefficient of variation (CV) in percentage, first-order spatial autocorrelation coefficient (ρ) and sample size (n) for semi-amplitude of the confidence interval - D (1 - p = 0.95) equal 5, 10, 15 and 20% of the RP mean, for three cone diameters

Statistic	Cone 1 (323 mm^2)	Cone 2 (129 mm^2)	Cone 3 (71.25 mm^2)
Mean	1.721 c[(1)]	1.933 b	2.217 a
CV (%)	9.9	16.1	13.9
ρ	0.027	0.118	0.013
$n_{(D=5\%)}$	23.2	61.3	45.7
$n_{(D=10\%)}$	5.8	15.3	11.4
$n_{(D=15\%)}$	2.6	6.8	5.1
$n_{(D=20\%)}$	1.5	3.8	2.9

[(1)]Cones with RP mean not followed by the same letter differ by t-test ($p < 0.05$)

Considering that RP can be indirectly obtained by a function of soil moisture (Tavares Filho et al., 2012) and that the determination of soil moisture in each point is a much more laborious process, the simple knowledge on RP is sufficient to describe the agricultural use conditions of each experimental plot and the sample size for the determination of this character.

Conclusions

1. In order to estimate the mean of resistance to penetration of the smaller-diameter cone in the soil, 12 blocks of four points (spaced by 20 or 40 cm) must be used per experimental paddock, in any range of depth for a semi-amplitude of the confidence interval equal to 10% of the estimated mean, with degree of confidence of 95%.

2. Alternatively and considering the independence between the evaluated points, 20 points can be sampled per paddock (high compaction) to estimate the mean of resistance to penetration of the smaller-diameter cone in the soil, for a semi-amplitude of the confidence interval equal to 10% of the estimated mean, with degree of confidence of 95%.

3. The sample size for the superficial depth range (0-10 cm) is larger than in deeper layers (0-20, 0-30 and 0-40 m).

4. The values of resistance to penetration, obtained with the larger-diameter cone, are less heterogeneous and the sample size can be smaller.

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