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RESPONSE FUNCTION FOR THE $S_{RELATIVE}$ INDEX IN CAMBISOL TREATED WITH AND WITHOUT BOVINE LIQUID BIOFERTILIZER[1]

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ABSTRACT – The present study aimed at assessing the influence of physical properties associated with soil structure on the $S_{relative}$ index. Two soil conditions under *Ficus carica* L. cultivation were studied (with or without liquid bovine biofertilizer in the irrigation water), in the 0-0.1 m and 0-0.3 m layers. Disturbed and undisturbed soil samples were collected from the above-mentioned layers and physical analyzes, pertinent to the study objective, were performed. The response function model was applied to verify how the soil independent physical variables influence on the $S_{relative}$ index in the 0-0.1 m and 0-0.3 m layers, with 0 and 60% biofertilizer, being combined two to two. Once the response functions were known, the slopes of both functions were compared, being represented by the coefficients β11-β12 and β21-β22. This comparison enabled verifying whether there was an effect of the treatments on the response variable. In addition, the standard error of the difference between coefficients was calculated, and the Student's t-test applied. The method of multiple regression was also used to confirm the effect of the variables on the $S_{relative}$ index for the 0-0.3 m layer in both treatments. Then, the variables with greater weight were selected by a backward elimination method to estimate the $S_{relative}$. The results showed that the $S_{relative}$ index is strongly influenced by properties of the porous fraction, with total porosity and continuity of pores being of significant influence. Management with liquid bovine biofertilizer results in improvement in the soil structure, with effects measured by the $S_{relative}$ index.

Keywords: S index. Soil structure. Organic matter.

FUNÇÃO DE RESPOSTA PARA O ÍNDICE $S_{RELATIVO}$ EM CAMBISSOLO TRATADO COM E SEM BIOFERTILIZANTE LÍQUIDO BOVINO

RESUMO - Objetivou-se com esta pesquisa estudar a influência de atributos físicos associados à estrutura do solo no índice $S_{relativo}$. Foram contempladas duas situações de solo (sob cultivo de *Ficus carica* L., sem aplicação e com aplicação de biofertilizante bovino líquido na lâmina de irrigação), nas camadas de 0-0,1 m e 0 -0,3 m. Foram coletadas amostras de solo com estrutura preservada e não preservada nas camadas supracitadas e realizadas análises físicas pertinentes ao objetivo do estudo. Foi aplicado o modelo de função de resposta para verificar como as variáveis físicas do solo independentes influenciam no $S_{relativo}$, nas camadas de 0-0,1 m e 0-0,3 m tratadas com 0 e 60 % do biofertilizante combinadas duas a duas. Conhecidas as funções de resposta compararam-se as inclinações de ambas as funções, representadas pelos coeficientes $\beta_1 1$-$\beta_1 2$ e $\beta_2 1$-$\beta_2 2$, para verificar se houve efeito dos tratamentos na variável resposta. Além disso, calculou-se o erro padrão da diferença entre os coeficientes e aplicou-se o teste t de Student. Também foi aplicado o método de regressão múltipla para verificar o efeito das variáveis sobre o $S_{relativo}$ para a camada de 0-0,3 m em ambos os tratamentos. Em seguida, por meio do método backward elimination foram selecionadas as variáveis com maior peso para a estimativa do $S_{relativo}$. Concluiu-se que o índice $S_{relativo}$ é fortemente influenciado por atributos da fração porosa, sendo a porosidade total e a continuidade de poros os de influência significativa. O manejo com biofertilizante bovino líquido resulta em melhora na estrutura do solo, com efeitos mensuráveis pelo índice $S_{relativo}$.

Palavras-chave: Índice S. Estrutura do solo. Matéria orgânica.

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INTRODUCTION

Soil physical quality is designated as its ability to meet the demands of plants and ecosystems for water flows, gas and heat, as well as its capacity to resist and recover from a process by which such ability could be reduced (MCKENZIE; TISDALL; VANCE, 2014).

In degraded soils, the addition of organic material such as liquid bovine biofertilizer (organic waste from biodigestion) has been an anthropic action to improve the functional performance of agricultural systems. Such use has improved the soil quality in addition to providing nutrients, acting as a cementing agent between soil particles and improving some soil properties related to the its structure, especially density and resistance to penetration (ALENCAR et al., 2015; KITAMURA et al., 2008; RAUBER et al., 2012).

Knowing the changes in the soil quality through the interaction of properties is important for proper management practices to be implemented when the soil is used in cultivated areas (ALENCAR et al., 2015). In this context, we have attempted to identify, select, and assign quantitative values for the best quality indicators of the performance of certain soil functions. Among several indicators, Assis Júnior et al. (2016) presented an assessment index for soil structure ($S_{relative}$), which derived from the S index proposed by Dexter (2004).

The relativized S index ($S_{relative}$) allows inferring quantitatively about the effects of different uses and management on the soil structure. Among the advantages of the aforementioned indicator, it is worth noting the lack of ranges of indicative values of soil quality as in the S index (ASSIS JÚNIOR et al., 2016). According to Silva et al. (2010) and Jong van Lier (2014), the limits used in the S index are provisional and are not valid for several conditions described in the literature. The assessment index of the soil structure - the $S_{relative}$ - has proved to be a sensitive indicator of physical changes occurring in the soil (ALENCAR, 2014; ASSIS JÚNIOR et al., 2016).

Understanding the interactions between soil properties and the $S_{relative}$ index is crucial to enable the use of this indicator as a tool to infer about the soil quality. Accordingly, the response function is a tool able help to understand the interactions mentioned above.

Regarding the researches related to soil science, the response function has been used to verify the influence of water depths and fertilization levels with nitrogen and phosphorus on productive and economic yields (CARVALHO et al., 2013; PAIVA et al., 2012; SILVA et al., 2008; SILVA et al., 2012b). The response function is used to characterize how a response is influenced by a number of factors, to identify, know and analyze the maximum or minimum responses of the relationship between the response variables and the quantitative factors affecting them (CUSTÓDIO; MORAIS; MUNIZ, 2000).

In this scenario, the study started from the following hypotheses: 1) Since the $S_{relative}$ index is dependent on soil structure, it is strongly influenced by the porous fraction properties, particularly by the area available for the flow and the pore continuity; 2) and the application of biofertilizer influences on soil structure, thereby causing effects on the $S_{relative}$ index. Therefore, this research aimed at knowing the influence of physical properties associated with the soil structure, with and without biofertilizer application, on the $S_{relative}$ index.

MATERIAL AND METHODS

The study site is located in Chapada do Apodi, in the Teaching, Research, and Extension Unit, one of the units of the Federal Institute of Education, Science and Technology (IFCE - Campus Limoeiro do Norte), located in the municipality of Limoeiro do Norte, Ceará state. The experimental area, cultivated with fig (*Ficus carica* L.), has the geographical coordinates 5 ° 10 '57.64 "S and 38 ° 0' 45.97" W in its center and altitude of 145 m. The secondary forest taken as a reference is located 400 m away from the cultivated area. The soil of the experimental area is classified as typical eutrophic Cambisol - CXve (Typic Haplocambids) (SANTOS et al., 2013). Some physical soil properties are shown in Table 1.

The experiment was carried out in open field, cultivated with fig and under biofertilizer application. The biofertilizer applied to the soil was produced by means of an anaerobic process in plastic containers (200-liter volume). A hose was adapted to the lid and its other end was immersed in a container with water at a height of 0.20 m for gas output. The proportion used to produce the biofertilizer was 50% (volume/volume = v / v) of the fermentation of fresh bovine manure and water for a period of 30 days.

The biofertilizer dosages were formulated with the following proportions: B0% - 0% biofertilizer and 100% water, B60% - 60% biofertilizer and 40% water. The biofertilizer was applied to the soil from October 2010 to August 2012, totaling 23 months, 4 crop cycles, 46 applications, and a total of 138 L of the solution applied to the soil per plant.

At the end of the experiment, the amount of organic matter added to the soil through the 60% biofertilizer was approximately 1.24 kg per available area to the plant. Samples of the biofertilizer were analyzed in the Laboratory of Soil, Water, and Vegetable Tissues (LABSAT) of the IFCE for chemical characterization (Table 2).

Table 1. Soil physical characteristics.

Use and management system	Layer	Granulometry (Particle-size distribution analysis)				Textural class
		Sand	Silt	Clay	Natural clay	
	-- m --	----------g kg^{-1}----------				
Control Biofertilizer (0 %)	0.0 – 0.1	539	269	192	131	Sandy loam
	0.1 – 0.2	518	252	230	145	Sandy clay loam
	0.2 – 0.3	466	254	280	184	Sandy clay loam
Biofertilizer (60 %)	0.0 – 0.1	542	261	197	158	Sandy loam
	0.1 – 0.2	488	244	268	152	Sandy clay loam
	0.2 – 0.3	460	257	283	193	Sandy clay loam

Table 2. Chemical properties of the pure bovine biofertilizer and the estimated doses, after diluted in water, in the different concentrations.

Biofertilizer	Macronutrients						Micronutrients					
	---------- cmol$_c$ dm^{-3} ----------						---------- mmol$_c$ dm^{-3} ----------					
	N	P	K	Ca	Mg	S	Fe	Zn	Cu	Mn	B	Na
Pure (100 %)	27.9	11.8	3.0	2.9	2.3	3.3	3.0	0.2	0.06	0.3	0.4	7.6
60 %	16.8	7.1	1.7	1.7	1.4	2.7	2.0	0.1	0.04	0.2	0.3	4.6
	C.E. (dS m^{-1})			C (%)			C/N			pH		
Pure (100 %)	7.05			1.08			13.8			7.78		
60 %	4.23			0.648			13.8			8.14		

Source: adapted from Silva (2012).

To assess soil quality under fig cultivation, two situations (with and without the application at 60% liquid bovine biofertilizer in the irrigation water depth) were evaluated in the 0-0.1 m layer (surface layer) and in the 0-0.3 m layer (effective root depth). For that, disturbed and undisturbed soil samples were collected in the above-mentioned layers. The undisturbed samples were collected using Uhland soil sampler, in 0.05-m-high steel rings with a diameter of 0.05 m. These samples were analyzed in the laboratory for grain size analysis, soil bulk and particle densities, intrinsic soil air permeability (K_{air}), pore continuity index (K_1), aeration porosity (ε_{air}), soil penetration resistance, soil water retention curve, total porosity, macroporosity, microporosity, S index and $S_{relative}$ index.

In the particle size analysis, 1 mol L^{-1} sodium hydroxide was used for the chemical dispersion of the particles. Clay content was determined by the pipette method and sand content through sieving. Silt content was determined through difference considering the initial sample of soil minus the sum of sand and clay (DONAGEMA, 2011).

Particle density (ρ_p) was determined through the volumetric flask method and soil bulk density (ρ_s) was determined using undisturbed soil samples, collected in cylinders of known volume, and dried at 105 °C until constant mass. Intrinsic soil air permeability was determined through the decreasing pressure method. An amount of air, corresponding to the pressure of 1 kPa in the reservoir, passed through the volumetric ring containing an undisturbed soil sample, balanced at tensions of 2, 6, 10, 33, and 100 kPa. During the procedure, the pressure decay over time was measured electronically until reaching a balance with the atmospheric pressure using the software PermeAr, v.1.0 (SILVEIRA et al., 2011). The coefficient of soil air permeability (K_{air}) was determined using equation 1,

$$K_{air} = \frac{2.3.L.\eta.V}{A.P_{atm}} \times |b| \quad , \qquad (1)$$

Where: K_{air} is the soil air permeability coefficient (m^2), V is the air volume passing through the cylinder (m^3), η is the dynamic air viscosity (Pa.s), L is the height of the volumetric ring (m), A is the cross-section of the soil sample (m^2), P_{atm} is the atmospheric air pressure (Pa) and b is the angular coefficient of the linear regression of the pressure (ln of pressure) over time.

Aeration porosity (ε_{air}) was calculated as the difference between total porosity and the volumetric water content at each matric potential established. Pore continuity index (K_1) was suggested to determine whether differences in K_{air} can only be attributed to differences in ε_{air} or if they can partially be attributed to other geometric aspects of the air-filled porous space, such as pore-size distribution, tortuosity, and continuity, and was obtained through equation (2),

$$K_1 = \frac{K_{air}}{\varepsilon_{air}} \quad . \qquad (2)$$

Soil penetration resistance was determined in undisturbed structure samples, with water content corresponding to the tension of 10 kPa. For that, we used a static electronic penetrometer, equipped with a load cell of 20 kgf, a cone with a 4 mm diameter rod, a base area of 12.566 mm², and a 60° angle with a velocity of penetration of 1 cm min^{-1}, record of one reading per second, coupled to a microcomputer to acquire the data via its own software. The procedure included three replicates per sample, with 180 readings per repetition, totaling 540 readings in each sample, disregarding the first and last centimeter of the soil sample.

In the determination of the soil water retention curve, the saturation water content was considered equal to soil total porosity (TP); Haines' funnel was used for low matric potentials (2, 4, 6, 8 and 10 kPa) and Richards' porous plate apparatus was used for the others (33, 100, 300, 700, 1000 and 1500 kPa). The curve fitting was performed according to the mathematical model proposed by van Genuchten (1980), equation 3:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|\phi|)^n\right]^m}, \quad (3)$$

θ_r and θ_s are, respectively, residual and saturation water contents (m^3 m^{-3}), *f* is the soil water matric potential (kPa), *a is a* scaling factor for *f*, and *m* and *n* are parameters related to the curve shape. The software SWRC, version 2.0, was used, fixing θ_r and θ_s at the soil water contents measured in the laboratory at saturation and at the tension of 1,500 kPa, respectively. The parameters*a, m,* and *n* were fitted using the Newton-Raphson iterative method, with no dependence between *m* and *n*.

Soil porosity was obtained through *TP= [1- (*r_s*/*r_p*)]*, where *TP* is the total porosity (m^3 m^{-3}), and ρ_p and ρ_s are soil particle and bulk densities (Mg m^{-3}) respectively. Microporosity was determined using Haines' funnel, through the application of a 6-kPa tension on the samples, until the water occupying the pores with diameter ≤50 μm was drained. Macroporosity was calculated as the difference between total porosity and microporosity.

The slope at the inflection point (S index) was determined based on the parameters of the equation by Van Genuchten, according to the equation (DEXTER, 2004).

$$S = -n\left(u_{sat} - u_{res}\right)\left[1 + \frac{1}{m}\right]^{-(1+m)}. \quad (4)$$

The $S_{relative}$ index was calculated as the ratio between the value of S obtained through the soil-water characteristic curve for the management considered and the value of the reference curve S. The S used as reference was obtained through the soil-water characteristic curve for the secondary native forest, constructed with a disturbed sample, taking a sample of air-dried fine earth (ADFE), which went through a process of dispersion in water, following the method described for particle-size distribution analysis. As stated, the purpose of the dispersion was to make the arrangement of the soil particles solely dependent on the textural porosity. After carrying out the dispersion process, the samples containing sand, silt, and clay in solution were sent to the oven at 45 ° C until they achieved constant mass.

Subsequent to the dispersion, the material was used to construct the soil-water characteristic curve and the value of S index was obtained from it. As described by Alencar (2014), the $S_{relative}$ index was obtained using equation (5)

$$S_{relative} = \frac{S_{undisturbed}}{S_{disturbed}}, \quad (5)$$

It must be highlighted that the values of S in both forms of soil structure derive mathematically from equation 3, but substituting a volume-based moisture for gravimetric moisture.

Following the procedures described by Nunes (1998), the response function model was applied to verify how the independent soil physical variables influence on the $S_{relative}$ in the 0-0.1 m layers treated with 0 and 60% biofertilizer. The first order linear model (Equation 6) was used to adjust the response variable according to the soil physical variables, combined two to two,

$$z = \beta_0 + \beta_1 x + \beta_2 y, \quad (6)$$

Where: z is the response variable, β_0, β_1, and β_2 are coefficients of the equation and x and y are independent variables. Once the response functions were known, the Student t test at 15% was applied to the parameters of each equation.

Subsequently, the slopes of both functions, represented by the coefficients $\beta_1 1$ and $\beta_1 2$, were compared for the application of 0 and 60% biofertilizer, respectively, assuming a common variance of the samples estimated by $S^2_{z.x}$, to verify if there were effects of the treatments on the response variable *z*. The standard error for the estimation of the coefficients was calculated by equation 7,

$$s_{z.x} = \sqrt{\frac{\sum (z - \hat{z})}{n - 2}}, \quad (7)$$

Where: *z* is equal to *z1* and *z2,* which are, respectively, the response variables for application of 0 and 60% biofertilizer, and *z* is equal to $\hat{z}1$ and $\hat{z}2$ which are, respectively, the estimates of the response functions for application of 0 and 60% biofertilizer. Then, the estimation of S^2_{ZX} was calculated using equation 8,

$$s_{z^2x} = \frac{(n_1 - 2)s_{z1.x} + (n_2 - 2)s_{z2.x}}{n_1 - 2 + n_2 - 2}, \quad (8)$$

Where: *n* is the number of samples.

In addition, the standard error of the difference between $\beta_1 1$-$\beta_1 2$ and $\beta_2 1$-$\beta_2 2$, equation 9, was calculated and Student's t-test was applied at 10%, rejecting H_0 when | t | was greater than the tabulated critical value for $t_{\alpha/2\ n1+n2-4}$,

$$t = \frac{\beta_1 1 - \beta_1 2}{\sqrt{s_{z^2x}\left(\frac{1}{\sum x_1^2} + \frac{1}{\sum x_2^2}\right)}} \quad (9)$$

The error of $\beta_2 1$ is calculated by replacing $\beta_1 1$-$\beta_1 2$ by $\beta_2 1$-$\beta_2 2$ in equation 9.

The method of multiple regression was also applied to verify the effect of the variables on the $S_{relative}$ for the 0-0.3 m layer in both treatments. Then, by means of the *backward elimination* method, the variables with greater weight for the estimation of the $S_{relative}$ were selected at 10% significance level. All data were submitted to the Shapiro-Wilk normality test at 5% significance level.

RESULTS AND DISCUSSION

We observed in Table 3 a low variability for soil density and total porosity, and an intermediate variability for the other properties (WARRICK; NIELSEN, 1980). Once the Shapiro-Wilk test was applied, at 5% significance level, we verified that, except for the intrinsic parameter of soil air permeability, the data of the other properties followed normal distribution and, therefore, deviations are considered not random and the arithmetic mean can be adopted as a representative of the central tendency of population values.

Table 3. Descriptive statistics for the attributes soil bulk density (ρ_s), total porosity (TP), macroporosity, microporosity, intrinsic soil air permeability (K_{air}), pore continuity index (K_1), soil penetration resistance (PR) e $S_{relative}$.

Statistical parameters	Soil attributes							
	ρ_s	TP	Macro	Micro	K_{air}	K1	PR	$S_{relative}$
Average	1.480	0.428	0.104	0.323	1.394	2.393	0.898	1.563
Standard deviations	0.101	0.038	0.054	0.042	0.469	0.350	0.256	0.298
Coefficient of variation (%)	7	9	51	13	34	15	29	19
Shapiro-Wilk (p-value)	**0.863**	**0.672**	**0.117**	**0.279**	0.008	**0.163**	**0.472**	**0.672**

Values in bold show normal distribution by the Shapiro-Wilk test at 5% significance.

The Student's t test was applied, at 15% significance level, to the coefficients of the mathematical model $z = \beta_0 + \beta_1 x + \beta_2 y$ (Table 4), considering only the situations where there was significance for at least one of the coefficients β_1 and β_2 in one of the treatments. In doing so, only the variables soil density, total porosity (TP), and pore continuity index (log *K1*) were significant under no biofertilizer application. When the 60% biofertilizer was applied, there was a significant effect for the variables soil penetration resistance and macroporosity. In this case, the equations in which the coefficients were not significant were excluded, since they had no influence on the estimation of the $S_{relative}$ index.

When analyzing the relations of the bivariate linear model of first order, in which these variables were significant, we observed that the soil density is inversely related to the $S_{relative}$ index while the variables, pore continuity, total porosity, soil penetration resistance, and macroporosity are directly related.

Thus, an increase in the soil bulk density values leads to an increase in the values of $S_{relative}$ and, consequently, a reduction in the soil structural quality. According to the results obtained by Andrade and Stone (2009), Dexter (2004), Li et al. (2011), Silva et al. (2012a), and Yang et al. (2015), soil bulk density increasing values lead to a slope reduction of the tangent line through the inflection point of the soil-water characteristic curve and; consequently, the S index values and the $S_{relative}$ index values are reduced. Thereby, the inverse relationship found in this study between the soil density and the $S_{relative}$ index is evident, since it is dependent on the S index.

When analyzing the soil bulk density property, the addition of biofertilizer had no significant effect, at least during the assessed period. Nogueira (2009) found similar results studying the application of biofertilizer on physical properties of a Cambisol area also located in Chapada do Apodi.

Table 4. Response functions for the $S_{relative}$ (S_r) starting from the variables soil bulk density, pore continuity index, soil penetration resistance, macro and microporosity and total porosity in the Cambisol treated with and without bovine liquid biofertilizer.

Variables	Without biofertilizer (0 %)	R^2	With biofertilizer (60 %)	R^2
S_r *vs* ρ_s *vs* log*K1*	$S_r = -1.73-0.15\rho_s+1.25\log K1$ β_0: P > |t| = 0.84 β_1: P > |t| = 0.94 β_2: P > |t| = 0.71	0.20	$S_r = 6.15-2.39\rho_s-0.49\log K1$ β_0: P > |t| = 0.70 β_1: P > |t| = 0.10 β_2: P > |t| = 0.20	0.98
S_r *vs* ρ_s *vs* PR	$S_r = -0.23+2.08\rho_s-1.69PR$ β_0: P > |t| = 0.78 β_1: P > |t| = 0.17 β_2: P > |t| = 0.13	0.96	$S_r = 5.17-2.49\rho_s+0.01PR$ β_0: P > |t| = 0.35 β_1: P > |t| = 0.52 β_2: P > |t| = 0.99	0.78
S_r *vs* Macro *vs* PR	$S_r = 4.39-8.26Macro-2.33PR$ β_0: P > |t| = 0.21 β_1: P > |t| = 0.35 β_2: P > |t| = 0.28	0.83	$S_r = 2.15+0.78Macro-0.74PR$ β_0: P > |t| = 0.44 β_1: P > |t| = 0.93 β_2: P > |t| = 0.65	0.60
S_r *vs* Micro *vs* log*K1*	$S_r = 3.97-12.46Micro+0.47\log K1$ β_0: P > |t| = 0.72 β_1: P > |t| = 0.55 β_2: P > |t| = 0.86	0.52	$S_r = 16.28-31.39Micro-1.97\log K1$ β_0: P > |t| = 0.37 β_1: P > |t| = 0.42 β_2: P > |t| = 0.36	0.71
S_r *vs* Micro *vs* TP	$S_r = 7.39-25.54Micro+4.23TP$ β_0: P > |t| = 0.72 β_1: P > |t| = 0.55 β_2: P > |t| = 0.86	0.97	$S_r = -6.18+12.79Micro+8.20TP$ β_0: P > |t| = 0.04 β_1: P > |t| = 0.05 β_2: P > |t| = 0.02	0.99

For the variables total porosity and log *K1*, an increase in their values contributes to the increase of the $S_{relative}$ index. The total porosity is a physical property sensitive to changes in soil structure, i.e. a reduction in its values indicates a process of soil degradation (DEXTER, 2004; SILVA et al., 2012a). Therefore, since the $S_{relative}$ is a sensitive indicator of structural quality, it is directly related to the total porosity. Results found by Andrade and Stone (2009) and Silva et al. (2012a), analyzing the correlation between total porosity and the S index indicate a positive correlation, corroborating the results found in this study.

As verified for the soil bulk density, the application of biofertilizer had no significant effect on the total porosity of the soil. As both variables have an inverse relationship, in which the increase of one causes a decrease in the other, and vice versa, the lack of soil porosity alterations is justified since soil density remained unchanged either.

Log *K1*, an indicator of pore continuity obtained from the ratio between K_{air} and ε_{air}, is important as an index that allows inferences about gas exchanges between the soil and the atmosphere. Thus, high values of pore continuity are signs of improvement in soil structure, which explains the direct relationship between the log *K1* and the $S_{relative.}$ Through this analysis, we could verify the absence of a significant effect of applying 60% biofertilizer on pore connection, being measured by log *K1*. Using the same function, Nascimento et al. (2015) reported less pore connectivity after 60% biofertilizer application compared with the control, which might be attributed to pore obstruction by organic residues.

Regarding the increase in the values of soil penetration resistance up to a certain value, which resulted in a higher value of the $S_{relative}$, indicating improvement in the soil structural quality, it can be explained by an increasing microporosity and, therefore, an increase in root penetration resistance. According to Nascimento et al. (2015), the ratio between macrospores and microspores was 1: 2.4 in the soil without biofertilizer application, and 1: 3.0 in soil with the application (60%), proving microporosity increase after biofertilizer application. For Kiehl (1979), an ideal soil should present the ratio of 1 macropore to 2 micropores in order to allow a good flow of gases and heat and good condition of water storage.

It is worth noting that although increases in the values of soil penetration resistance in this research have been beneficial, they should not reach values that would restrict root growth and plant development. Penetration resistance values between 2 and 2.5 MPa have been pointed as the critical limits for root growth of most vegetables (SILVEIRA et al., 2010).

The pore distribution by size significantly influences the behavior of the soil-water characteristic curve, affecting the $S_{relative}$ index. Laurani et al. (2004) and Alencar et al. (2015) found results that corroborate the statements about the influence of the pore distribution on the curve of soil water retention. The increase in the macroporosity values results in a higher slope of the tangent line through the inflection point of the soil-water characteristic curve, which increases the value of the S index, and the value of the $S_{relative.}$ Andrade and Stone (2009) and Silva et al. (2012a) found positive and significant correlations between the

macroporosity and the S index. Alencar et al. (2014) found similar results when studying the correlation between the macroporosity and the $S_{relative}$.

Regarding the comparison between the coefficients β_1 and β_2 for the $S_{relative}$ in treatments with biofertilizers 0 and 60%, when the Student's t-test was applied at a 10% significance level (Table 5), there was a difference between the coefficients, evidencing the influence of the biofertilizer application on the $S_{relative}$ response. In this case, it can be deduced that a mathematical function of the two comparisons cannot solely represent the relation between the pairs of independent variables and the dependent variable $S_{relative}$ for the treatments applied to the soil.

Table 5. Significance test for the difference between the response functions coefficients for $S_{relative}$ (Sr) in Cambisol treated with and without bovine biofertilizer.

Variables	Contrast of treatments	β_1		β_2	
		t observed	t tabulated	t observed	t tabulated
S_r *vs* ρ_s *vs* log K1	B0% x B60%	13.89	2.132	7.989	2.132
S_r *vs* ρ_s *vs* PR	B0% x B60%	3.732	2.132	9.124	2.132
S_r *vs* Macro *vs* PR	B0% x B60%	4.106	2.132	6.047	2.132
S_r *vs* Micro *vs* log K1	B0% x B60%	24.03	2.132	14.96	2.132
S_r *vs* Micro *vs* TP	B0% x B60%	91.07	2.132	39.10	2.132

To evaluate the effect of the application of the biofertilizer 60% on the response functions, we used the mean value of the observations of each variable in each mathematical function that showed a difference between the coefficients. As a result, it follows that the application of biofertilizer 60% positively acted on the $S_{relative}$ since the respective values were higher than in the treatment without biofertilizer application. As a result, it can be inferred that the application of the biofertilizer 60% resulted in an improvement in the soil structural quality, emphasizing that this form of management is technically correct and may be used as a way to mitigate the harmful effects on soil physical properties when it is cultivated.

In the situation where the soil layer was considered from 0-0.3 m, a multiple linear regression analysis was performed with the purpose of assisting the interpretation of the complex relations between the independent variables and the $S_{relative}$ index, in order to explain such relations in simpler terms and with fewer variables. Equation 10 represents the relationship between all independent variables and the $S_{relative}$ index for treatment without biofertilizer application.

$$S_r = -35.26 + 13.74\rho s - 0.57Kair + 1362.30Macro + 1363.93Micro - 1326.81TP + 0.81K1 - 0.53PR, \quad (10)$$

$R^2 = 0.86$; $p>0.85$

The prediction of the $S_{relative}$ values based on equation 10 requires a greater demand of time and work to obtain the information related to the variables that appear in the mathematical function. Considering the *backward elimination* method in which the removal of variables with a lower weight occurs after using the F test (Table 6), the equation 10 was reduced to Equation 11, a simpler function since it has fewer variables, facilitating the understanding of the $S_{relative}$ behavior. It is important to highlight the reduction of the work and the time to obtain variables, since only the variables soil density, macroporosity, microporosity and pore continuity index are required.

Table 6. Summary of the elimination of the variables by the method of backward elimination for Cambisol without application of biofertilizer.

Steps	Variables removed	Value F	Pr > F
1	log *Kair*	0.12	0.7420
2	Total porosity	2.54	0.1720
3	Soil penetration resistance	3.76	0.1005

$$S_r = -31.55 + 12.13\rho s + 32.18Macro + 33.52Micro + 0.34K1, \quad (11)$$

$R^2 = 0.65$; $p>0.9$

In treatments where the biofertilizer 60% was applied, equation 12 represents the most complex relationship between all variables and the $S_{relative}$ index.

It is observed a larger number of independent variables to be excluded from the initial multiple linear equation when compared to the treatment without biofertilizer application, evidencing the influence of the biofertilizer mentioned previously (Table 7).

$$S_r = 12.49 - 4.79\rho s + 0.28Kair + 695.60Macro + 701.76Micro - 707.14TP - 0.36K1 - 0.49PR,$$

$$R^2 = 0.86;\ p>0.85 \quad (12)$$

Table 7. Summary of the elimination of the variables by the method of backward elimination for Cambisol with application of biofertilizer.

Steps	Variables removed	Value F	Pr > F
1	log *Kair*	0.07	0.7983
2	log *K1*	0.00	0.9495
3	Macroporosity	0.39	0.5531
4	Soil penetration resistance	2.48	0.1596
5	Total porosity	1.95	0.1998

In treatments where the biofertilizer 60% was applied the final process suggests that equation 13 is the resultant and the representative of the relations between the analyzed variables and the $S_{relative.}$ Thus, the results make the time saving and the cost reduction to obtain the variables evident since based on this equation only the soil density and the microporosity are indispensable.

$$S_r = 2.60 - 1.61\rho s + 4.24Micro, \quad (13)$$

$$R^2=0.74;\ p>0.99$$

In view of the above, the importance of a retroactive elimination in the multiple linear regression analysis is evident for the adequate choice of independent variables that are necessary to understand in a simple way the behavior of the dependent variable, which in this case is the $S_{relative}$. In addition, it became clear that the $S_{relative}$ index correlates inversely with soil density and directly with properties of the porous part, which makes it a strong indicator to be used to monitor changes in soil structure.

CONCLUSIONS

The $S_{relative}$ index is strongly influenced by properties of the porous fraction, being the total porosity and pore continuity those of significant influence.

The management with liquid bovine biofertilizer results in improvement in soil structure, with effects measured by the $S_{relative}$ index.

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