S-Index as an indicator of physical quality in soils of the Paraná state

João H. Caviglione[1]

[1] Instituto Agronômico do Paraná/Área de Solos. Londrina, PR. E-mail: caviglione@iapar.br (Corresponding author) - ORCID: 0000-0002-2518-0031

A B S T R A C T

From the 1990s, the demand for soil quality indicators has increased with the agricultural sustainability approaches. The S-index was proposed as an indicator of soil physical quality. The objective was to evaluate the sensitivity of S-index as an indicator of soil physical quality and its correlation with bulk density, organic carbon content, macroporosity, microporosity, total porosity and clay, sand and silt contents, under field conditions in the diversity of the Paraná state. Samples were collected from 21 sites with textures from clay and heavy clay, in the layers of 0-0.1 and 0.1-0.2 m, in soil under native forest and in cultivated soil. Eight soil physical attributes were determined. A soil-water retention curve with six moisture points was fitted and the S-index was calculated for each condition. The Wilcoxon Test showed differences in S-index between soil managements with p-value = 0.0015 in the 0-0.1 m layer and less than 0.0001 in the 0.1-0.2 m layer. The observed S-index showed to be a sensitive indicator of soil physical quality and with a significant Pearson correlation with bulk density (-0.826), macroporosity (0.760), total porosity (0.836), and organic carbon content (0.583).

Índice S como indicador de qualidade física em solos do estado do Paraná

R E S U M O

A partir da década de 1990, a busca por indicadores de qualidade do solo aumentou com as abordagens de sustentabilidade agrícola. O índice S foi proposto como indicador da qualidade física de solo. Objetivou-se avaliar a sensibilidade do índice S como indicador de qualidade física do solo e verificar sua correlação com a densidade do solo, teor de carbono orgânico, macroporosidade, microporosidade, porosidade total e os teores de argila, areia e silte, em condições de campo na diversidade do Paraná. Amostras foram coletadas em 21 locais de solos argilosos e muito argilosos, nas camadas de 0 a 0,1 e 0,1 a 0,2 m, sob mata nativa e solo explorado. Determinaram-se oito atributos físicos do solo. Uma curva de retenção de água do solo, com seis pontos de umidade, foi ajustada e o índice S calculado em cada condição. O teste de Wilcoxon mostrou diferença no índice S entre os manejos com p-valor = 0,0015 na camada de 0 a 0,1 m e menor que 0,0001 na 0,1 a 0,2 m. O Índice S observado mostrou ser um indicador sensível de qualidade física do solo e apresentou correlação de Pearson significativa com a densidade do solo (-0,826), macroporosidade (0,760) porosidade total (0,836), e teor de carbono orgânico (0,583).

Introduction

Soil quality is defined by the Soil Science Society of America (SSSA) as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." (Karlen et al., 1997). From 1990, the demand for soil quality indicators has increased.

Soil attributes such as bulk density, total porosity, optimal water range, aggregate stability, soil resistance to penetration have been used as physical quality indicators because they are modified by soil use and management, besides being of easy determination and reduced cost (Stefanoski et al., 2013).

Dexter (2004) proposes the S-index, which is the tangent (slope) of the Soil-Water Retention Curve (SWRC) at its inflection point, as an indicator of soil physical quality because the S-index would reflect microstructural porosity, governed by many of the physical properties of the soil.

Dexter & Czyż (2007) identified the S value = 0.035 as the limit between soils with good and poor structural quality. They also defined other limits; S < 0.02 for soils with very poor quality and S > 0.05 for soils with optimal or very good quality.

Oliveira et al. (2014) evaluated the S-index, soil aeration capacity (ACt/Pt) and soil water storage capacity (FC/Pt) as indicators of soil physical quality, in horizons of soils of a pedosequence under semideciduous seasonal forest. These authors concluded that the three indicators were effective in differentiating the horizons with respect to their physical-hydraulic behaviors, but the results suggested the need for reevaluation of the ideal limits of the S-index, specific to tropical regions.

This study aimed to evaluate the sensitivity of S-index as indicator of soil physical quality and verify its correlation with bulk density, organic carbon content, macroporosity, microporosity, total porosity and clay, sand and silt contents, under field conditions in the diversity of some soils of the Paraná state.

Material and Methods

Samples were collected in 21 sites in the Paraná state, in two layers (0-0.10 and 0.10-0.20 m) in soil under management and crop representative of the region and under native forest, close to one another. Forest soil was used as reference of quality, superior to the cultivated soil.

Each site had a specific management, crop and form of planting, defined by the owner (Table 1), as well as the mean contents of clay and organic carbon (OC) of the managed areas.

Samples were collected in soils with clayey and heavy clayey texture, with clay contents higher than 350 g kg^{-1}. Sandy or medium-textured soils were avoided because, although Dexter (2004) did not establish limits for the low clay contents in the soil, he describes a trend that in this situation S values are high. Figure 1 shows the 21 sites sampled in the Paraná state and the morpho-physiographic regions.

A total of 252 undisturbed soil samples were randomly collected in triplicates. Steel volumetric rings (99.37 cm³) were vertically inserted into the soil, using a manual device specifically built for this purpose. Samples were also collected to determine the contents of clay, sand, silt and organic carbon.

Soil bulk density (Ds) and gravimetric moisture content at tensions of 6, 30, 100, 300, 500 and 1,500 kPa, on tension table or Richards pressure-plate apparatus, were determined. In addition, soil organic carbon - OC contents were determined by the Walkley-Black method (Donagema et al., 2011).

Macroporosity (MacroP), microporosity (MicroP), and total porosity (PoT) were determined according to Donagema et al. (2011). Clay, sand and silt contents were determined using a pipetted with slow agitation (Donagema et al., 2011).

Table 1. Sampled sites and their main characteristics

Municipality	Soil[1]	Latitude	Altitude (m)	Crop	Planting	Clay[2] (g kg^{-1})	OC[2] (g kg^{-1})
Apucarana	LVdf	23º 37' S	785	Soybean	Direct	735 ± 2	24.8 ± 1.4
Bandeirantes	LVef	23º 06' S	412	Corn	Conventional	575 ± 2	17.7 ± 0.9
Cambará	LVef	23º 00' S	452	Corn	Direct	665 ± 2	20.0 ± 0.4
Campo Mourão	LVdf	23º 59' S	540	Soybean	Conventional	755 ± 7	19.8 ± 0.7
Cascavel	LVdf	24º 53' S	648	Corn	Direct	740 ± 9	26.1 ± 0.6
Guarapuava	LBd	25º 23' S	1.045	Soybean	Direct	670 ± 4	32.5 ± 1.9
Guaraqueçaba	PVAd	25º 14' S	19	Cassava	Conventional	545 ± 11	23.6 ± 3.1
Lapa	LVd	25º 47' S	908	Corn	Conventional	455 ± 7	29.7 ± 0.6
Laranjeiras do Sul	LVdf	25º 19' S	810	Corn	Conventional	735 ± 2	27.5 ± 1.1
Londrina	LVef	23º 21' S	584	Corn	Conventional	760 ± 0	18.7 ± 0.6
Mauá da Serra	LVdf	23º 54' S	1.017	Corn	Conventional	720 ± 4	24.7 ± 1.6
Morretes	CYbd	25º 30' S	47	Royal palm	Conventional	375 ± 2	20.9 ± 1.7
Nova Cantu	LVdf	24º 40' S	471	Corn	Conventional	720 ± 9	19.8 ± 0.8
Palmas	CHa	26º 27' S	1.092	Corn	Direct	660 ± 4	33.4 ± 1.1
Palotina	NVdf	24º 18' S	302	Soybean	Direct	640 ± 0	19.4 ± 1.0
Pato Branco	LVdf	26º 07' S	740	Corn	Direct	760 ± 9	26.7 ± 1.8
Planalto	NVef	25º 44' S	406	Corn	Conventional	360 ± 4	16.2 ± 0.9
Ponta Grossa	LVd	25º 09' S	865	Corn	Conventional	755 ± 2	29.7 ± 0.4
Quedas do Iguaçu	LVdf	25º 27' S	576	Soybean	Conventional	785 ± 6	30.8 ± 1.5
Santa Helena	NVef	24º 53' S	251	Corn	Direct	795 ± 2	16.0 ± 1.2
S. Miguel do Iguaçu	NVef	25º 11' S	306	Corn	Conventional	645 ± 15	24.7 ± 3.9

[1]Soils according to Brazilian system of soil classification (SiBCS) (Santos et al., 2013): LVdf - Latossolo Vermelho Distroférrico (Hapludox); LVef - Latossolo Vermelho Eutroférrico (Hapludox); LVd - Latossolo Vermelho Distrófico (Hapludox); LBd – Latossolo Bruno Distrófico (Hapludox); NVef - Nitossolo Vermelho Eutroférrico (Rhodudults); PVad - Argissolo Vermelho-Amarelo Distrófico (Paleudult); CHa - Cambissolo Húmico Alumínico (Humudepts) and CYbd - Cambissolo Flúvico Tb Distrófico (Dystrudepts). [2]Mean contents of clay and organic carbon - OC (and standard deviation of the mean) between the layers of the cultivated soil
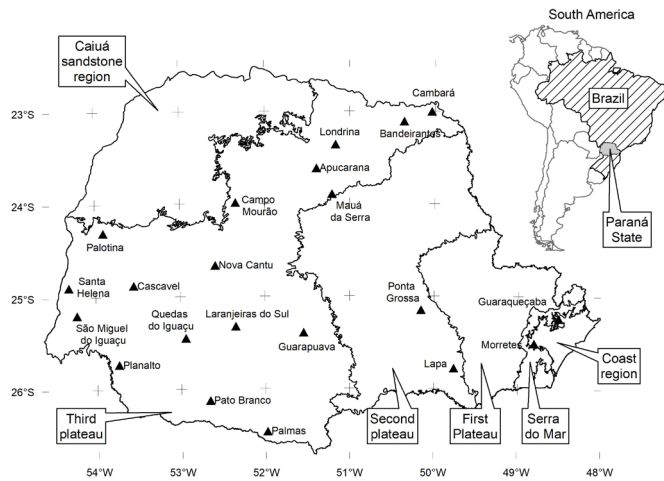
Figure 1. Distribution of the sampled sites and morpho-physiographic regions of the Paraná state

The most widely used model to describe SWRC is probably the van Genuchten-Mualem (VGM) model (Vereecken et al., 2010). The SWRC was fitted by this model, described by Eq. 1 (Genuchten, 1980), maintaining the Mualem restriction (m = 1 - 1/n).

$$\theta_h = \left(\theta_{sat} - \theta_{res}\right)\left[1 + \left(\alpha\ h\right)^n\right]^{-m} + \theta_{res} \qquad (1)$$

where:

θ_h - soil moisture content at tension h, g g^{-1};
θ_{sat} - gravimetric moisture content of the saturated soil, g g^{-1};
θ_{res} - residual gravimetric moisture of the soil, g g^{-1}; and,
m, n and α - parameters of the equation.

S-index is described as the tangent (slope) of the SWRC at its inflection point. When VGM model is adopted with the Mualem restriction, the S-index can be obtained by Eq. 2, in absolute value, with the parameters of Eq. 1 (Dexter, 2004).

$$S = -n\left(\theta_{sat} - \theta_{res}\right)\left(\frac{2n-1}{n-1}\right)^{\left(\frac{1}{n}-2\right)} \qquad (2)$$

where:

S - S-index proposed by Dexter (2004).

Soil moisture and tension data were used to fit SWRCs using the SWRC software (Dourado Neto et al., 2000).

Residual moisture was fixed at 0.01 m^3 m^{-3}. By definition, θ_{res} comprehends the moisture when in equilibrium with the air or when tension tends to infinity (Vereecken et al., 2010). These authors also describe a strong influence of this parameter within the dry range of the SWRC and that, during the optimization, θ_{res} could assume negative values. One of the recommendations to avoid negative values would be to fix the residual moisture.

The fittings of the 252 curves were evaluated based on the statistical coefficients calculated by the SWRC software. S-index was obtained by fitting the parameters of the VGM model to the observed data for each of the three curves of each condition of management, site and layer.

One curve of each triplicate of the conditions (management, site and layer) was selected based on the best coefficients. The fitting of each curve generated one coefficient of determination (R^2), Akaike Information Criterion - AIC (Burnham & Anderson, 2004) and significance level (p-value) of the analysis of variance of the fitting regression. AIC is used to differentiate models, and the smaller the difference in the AIC value, the closer the models.

Differences in the attributes between the conditions were evaluated by the Wilcoxon paired-sample test. This test was used to evaluate the S-index capacity to differentiate soil physical quality between the conditions (native forest and management). One-tailed test was adopted because the S-index of the soil under native forest should be superior.

Pearson coefficient (ρ) and p-value were used in the analysis of correlation between S-index and soil physical attributes, calculated using the program Bioestat® (Ayres et al., 2007). Initially, the conditions of soil management and layer were not differentiated (n = 84) and, subsequently, they were differentiated (n = 21).

Cargnelutti Filho et al. (2010) warned that, for large number of samples, even low Pearson correlation coefficients (ρ) can be significant. Because of that, coefficients between - 0.5 and 0.5 were considered as non-significant in the evaluations which did not distinguish layers and managements.

Results and Discussion

According to the Wilcoxon test (α = 1%), there was no significant difference in the mean contents of sand, silt and clay between cultivated soil and native forest in both layers (Table 2). This result was expected because the management would not interfere significantly with the contents of the granulometric fractions, given the mineral constitution of these fractions.

Table 2. Significant difference (Wilcoxon test) between the means of the attributes for each management, separated by layer, with standard error, maximum value, minimum value and Pearson correlation with the S-index

Attribute	0-0.10 m (n = 21)				0.10-0.20 m (n = 21)				Pearson coefficient (n = 84)	Minimum	Maximum
	Forest soil		Cultivated soil		Forest soil		Cultivated soil				
Sand (g kg^{-1})	179 ±22.5	ns	174 ±22.5		175 ±23.2	ns	170 ±21.6		-0.133 ns	70	520
Silt (g kg^{-1})	180 ±13.0	ns	177 ±11.4		163 ±12.3	ns	161 ±10.8		0.091 ns	90	340
Clay (g kg^{-1})	641 ±28.7	ns	650 ±28.4		662 ±29.1	ns	670 ±28.0		0.066 ns	350	810
PoT (m^3 m^{-3})	0.65 ±0.005	**	0.59 ±0.013		0.63 ±0.011	**	0.56 ±0.009		0.836 *	0.47	0.69
MicroP (m^3 m^{-3})	0.39 ±0.012	**	0.44 ±0.013		0.42 ±0.013	**	0.45 ±0.010		-0.367 ns	0.31	0.56
MacroP (m^3 m^{-3})	0.26 ±0.016	**	0.14 ±0.016		0.21 ±0.018	**	0.10 ±0.009		0.760 *	0.04	0.37
Ds (Mg m^{-3})	0.96 ±0.011	**	1.15 ±0.038		1.05 ±0.028	**	1.24 ±0.029		-0.826 *	0.91	1.49
OC (g dm^{-3})	32.8 ±1.14	**	23.7 ±1.32		22.8 ±1.31	**	17.7 ±1.29		0.583 *	8.0	45.9

ns - Not significant; * and **Significant at 0.05 and 0.01 probability levels

Significant difference was found in soil OC in both layers, 0-0.10 m (32.8 and 23.7 g dm⁻³) and 0.10-0.20 m (22.8 and 17.7 g dm⁻³), in cultivated soil and native forest, respectively (Table 2). Such difference was similar to results found by Costa et al. (2016), who worked with a heavy clayey Rhodic Hapludox (Latossolo Vermelho distroférrico), under direct planting, conventional planting and native forest, analyzing two depths (0.05 and 0.15 m).

In the 0-0.10 m layer, significant differences were found in Ds (0.96 and 1.15 Mg m⁻³) and MacroP (0.26 and 0.14 m³ m⁻³) between forest soil and cultivated soil, respectively (Table 2).

Similar results between cultivated soil and forest soil with respect to both Ds and MacroP were also found by Tavares Filho et al. (2014), who studied a Rhodic Hapludox (Latossolo Vermelho distroférrico) managed for 20 years up to the 0.5 m depth.

The mean coefficient of determination was higher than 0.99 and AIC was between -13.8 and -18.6, expressing a good fit of the curves (Table 3).

Management differentiation by the S-index was more pronounced in the 0.10-0.20 m layer than in the 0-0.10 m layer. The difference in the p-values of the Wilcoxon paired-sample test of each layer indicates this condition, equal to 0.0015 and lower than 0.0001 in surface and subsurface, respectively, in addition to the lower number of sites in which S-index did not distinguish the good quality of the forest soil.

There were seven situations in which the S-index was not able to differentiate managements (Table 3), and the value for the cultivated soil was higher than or equal to that of the native forest. Out of these seven situations, five were in the 0-0.10 m layer (Apucarana, Campo Mourão, Mauá da Serra, Palmas and Ponta Grossa) and two were in the 0.10-0.20 m layer (Guaraqueçaba and São Miguel do Iguaçu).

There was no Pearson correlation of the S-index in all conditions with sand, silt and clay contents and MicroP. However, the correlation was positive (Table 2) with PoT (0.836), OC (0.583) and MacroP (0.760) and negative with Ds (- 0.826). A best-fit line of the S-index with the attributes was illustrated in Figures 2 and 3, not being a regression analysis.

This result is consistent with the theory about the S-index (Dexter & Czyż, 2007), because there would be very little or no dependence on textural porosity (between particles), evidencing that the S-index depends on soil PoT, especially on MacroP, since it represents soil structural porosity (microcracks, microaggregates and biopores).

The attributes with significant Pearson correlation (PoT, soil organic carbon, MacroP and Ds) were selected for a correlation analysis in which the conditions of layer and management were distinguished. Correlations of MacroP and OC with the S-index were not statistically significant in at least one condition.

The conditions in which MacroP was significantly correlated with the S-index were: native forest soil in the 0.10-0.20 m layer, 0.663 (**); cultivated soil in the 0-0.10 m layer, 0.821 (**) and cultivated soil in the 0.10-0.20 m layer, 0.474 (*). With the OC, significant correlations occurred in the following conditions: native forest soil in the 0.10-0.20 m layer, 0.481 (*) and cultivated soil in the 0.10-0.20 m, 0.467 (*). These data were not presented in graphs or tables.

Pearson correlation was significant in all conditions for Ds, oscillating between - 0.687 and - 0.900 (Figure 2), and for PoT, between 0.916 and 0.462 (Figure 3). Ds and PoT were also the two attributes with highest Pearson correlation coefficients in general (Table 2).

Table 3. S-index of each site, mean and standard error, mean Akaike Information Criterion and standard error, mean coefficient of determination, and the p-value of the Wilcoxon paired-sample test

Site	Sampling condition			
	0-0.10 m		0.10-0.20 m	
	Native forest	Cultivated soil	Native forest	Cultivated soil
Apucarana	0.033	* 0.036	* 0.039	0.022
Bandeirantes	* 0.035	0.016	0.013	0.012
Cambará	* 0.038	0.020	* 0.044	0.018
Campo Mourão	0.034	* 0.050	* 0.046	0.017
Cascavel	* 0.042	0.034	0.026	0.018
Guarapuava	* 0.045	* 0.037	0.027	0.025
Guaraqueçaba	0.027	0.022	0.017	0.019
Lapa	* 0.043	0.018	0.024	0.015
Laranjeiras do Sul	* 0.045	* 0.035	0.031	0.024
Londrina	0.033	0.025	* 0.037	0.023
Mauá da Serra	0.018	0.021	* 0.042	0.010
Morretes	* 0.045	0.027	0.025	0.019
Nova Cantu	* 0.044	* 0.036	* 0.047	0.029
Palmas	0.032	0.032	* 0.035	0.025
Palotina	0.027	0.015	0.020	0.012
Pato Branco	0.028	0.027	* 0.035	0.017
Planalto	* 0.043	0.025	* 0.041	0.017
Ponta Grossa	0.031	0.032	0.026	0.015
Quedas do Iguaçu	* 0.038	0.022	0.034	0.024
Santa Helena	0.033	0.028	0.031	0.015
São M. do Iguaçu	0.030	0.013	0.014	0.017
Mean ± SD	0.036±0.0016	0.027±0.002	0.031±0.0022	0.016±0.0011
Mean AIC ±SD	-13.8 ±0.77	-17.3±0.86	-15.1 ±0.85	-18.6 ±0.65
R² (mean)	0.9929	0.9943	0.9930	0.9933
p-value (Wilcoxon)	0.0015 **		<0.0001 **	

AIC - Akaike Information Criterion; ±SD - Standard deviation of the mean; R² - Coefficient of determination; *Values of S-index ≥ 0.035, considered as soils of good structural quality according to the criterion of Dexter & Czyż (2007)
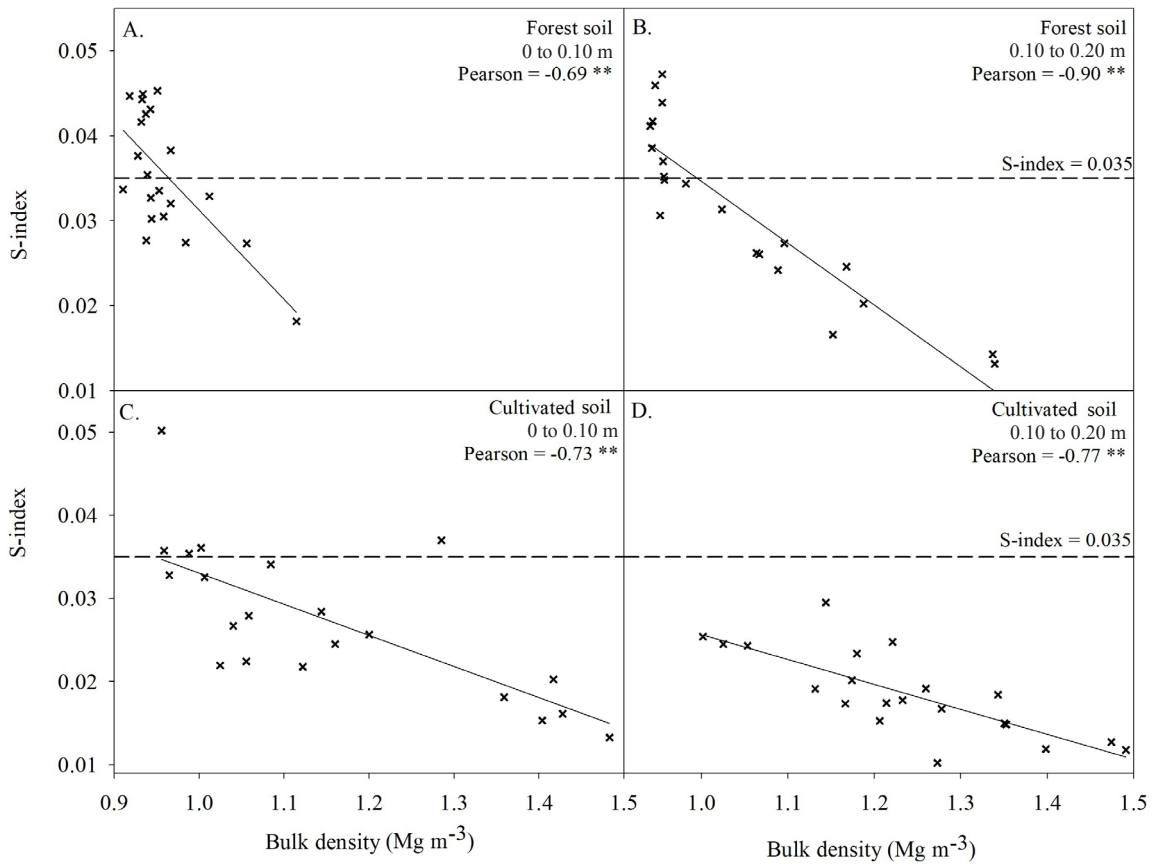
Figure 2. Correlation between S-index and bulk density in the sampled sites (n = 21) for: forest soil in the 0-0.10 m layer (A); forest soil in the 0.10-0.20 m layer (B); cultivated soil in the 0-0.10 m layer (C); cultivated soil in the 0.10-0.20 m layer (D)
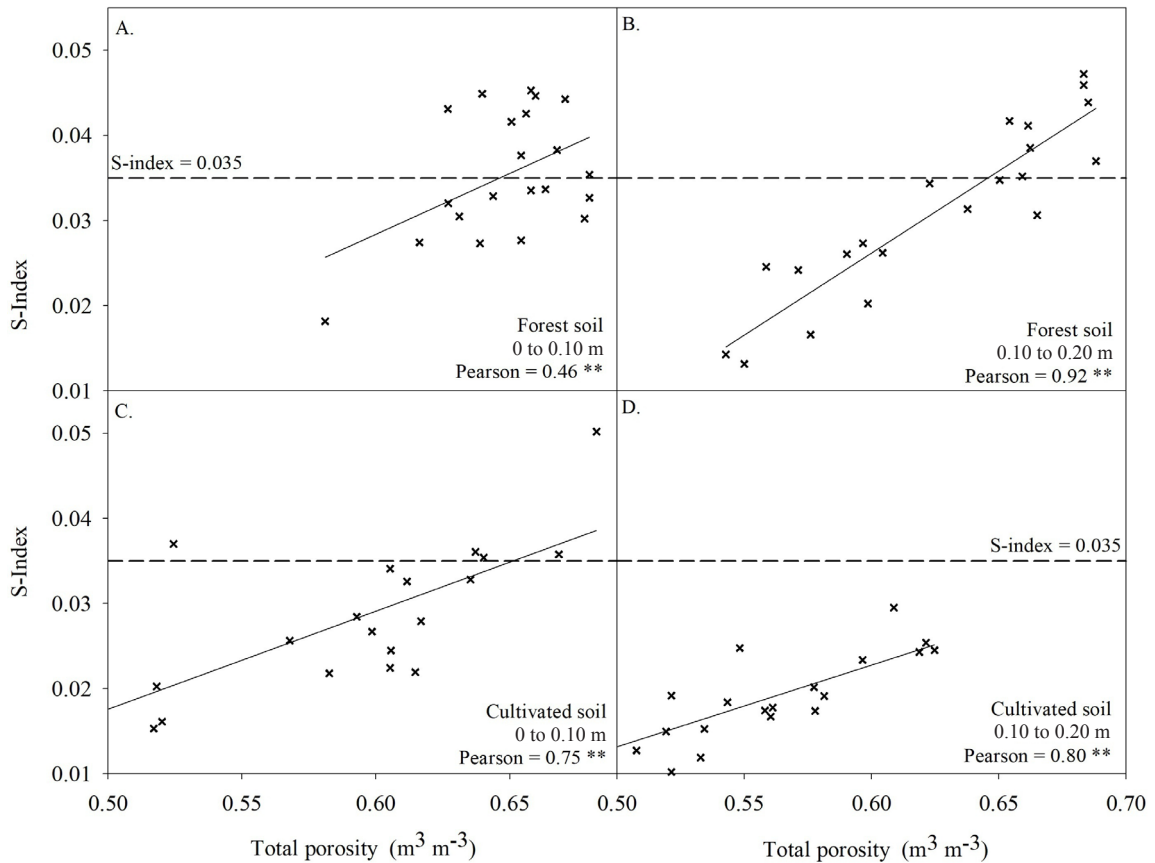

Figure 3. Correlation between S-index and soil total porosity in the sampled sites (n = 21) for: forest soil in the 0-0.10 m layer (A); forest soil in the 0.10-0.20 m layer (B); cultivated soil in the 0-0.10 m layer (C); cultivated soil in the 0.10-0.20 m layer (D)

S-index correlations were negative with Ds (Figure 2) and positive with PoT (Figure 3) and both correlations were strong (Callegari-Jacques, 2003). Only the correlation with PoT in forest soil in the 0-0.10 m layer was moderate ($\rho = 0.462$), but still significant with $\alpha = 5\%$.

Andrade & Stone (2009) studied 2364 samples of the soil analysis data set, with results of texture, bulk density, particle density and soil water retention, all located in the Cerrado region, with textures from sandy to heavy clayey, but without information on management. These authors concluded that S-index was highly correlated with bulk density, PoT and MacroP, with the respective determination coefficients (R^2) between 0.66** and 0.51** for bulk density, between 0.64** and 0.50** for PoT and between 0.60** and 0.40** for MacroP.

The S-index theory (Dexter, 2004) confirms the correlation between S-index and PoT, MacroP and Ds, because it would be assessing the structural porosity and pore functionality with the connectivity of soil microstructure.

Andrade & Stone (2009) established a different limit from the one presented by Dexter & Czyż (2007). These authors identified S = 0.045, instead of 0.035, as a limit between soils with good and poor structural quality, and also defined the limit for soils with very poor quality as below 0.025, instead of 0.020.

Although the S-index was correlated with Ds and soil porosity (PoT and MacroP), adopting absolute limits of both 0.035 and 0.045, for the results, is questionable, to say the least. Assuming that the quality of the soil under forest and in the surface would be the best, only 10 sites of the 21 reached the limit of 0.035 (good physical condition). It should also be considered that, in 7 situations, the S-index was lower for the forest soil than for the cultivated soil.

These considerations were also made by Rossetti et al. (2013) and Lier (2014), who do not consider S-index as an absolute indicator of soil quality. In addition, its limit could not be absolute, either 0.035 or 0.045.

Under local conditions, the S-index was correlated with organic carbon and not correlated with the granulometric fractions or texture. Although without statistical analysis, there was no correlation with type of soil, altitude, latitude or planting system. However, a trend related to the soybean crop was detected; approximately 50% of the samples had S-index higher than the limit of 0.035 (Dexter & Czyż, 2007). Nonetheless, conclusions on this require further research.

Conclusions

1. S-index was sensitive to soil physical quality because it significantly differentiated managements in the Paraná state.

2. S-index was significantly correlated with total porosity, bulk density, macroporosity and organic carbon content, under the conditions evaluated.

3. Using S-index in the Paraná state as absolute indicator of soil physical quality is questionable because, in 10 sites of soil under forest, the limit of good physical condition was not reached; therefore, instead of a limit with absolute value, the S-index needs to be interpreted.

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