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Original article

Calibration of structural stability indicators, related to the weighted average diameter of aggregates, in different soils

Calibración de la estabilidad estructural relacionado con el diámetro medio ponderado en diferentes suelos

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ABSTRACT: To assess soil fertility after it has been managed, or to monitor the evolution of its properties when subjected to the impact of some improvement measure, it is necessary to take into consideration physical analysis. Although structure is one of the properties most sensitive to changes, N. I. Savvinov method does not provide precise information related to results of its analysis and soil aggregation state. The present work aim was to evaluate and establish an indicator calibration of structural stability and their relation to the weighted average diameter of aggregates in different soils. To establish the indicator calibration, 161 samples from the cultivable horizon of different types of soils were analyzed. Soils under pasture and forest showed the best indicators of structural stability and a weighted average diameter of their aggregates more favorable for crop development; while those intended for intensive agricultural production showed values indicative of their structure degradation and the prevalence of diameters in their aggregates that affect the proper functioning of soils, so that from results a more accurate interpretation can be made regarding structural stability behavior.

Key words: soil structure, soil analysis, agricultural soils, soil degradation.

RESUMEN : Para valorar la fertilidad del suelo luego de haberse manejado, o para monitorear la evolución de sus propiedades al someterlo al impacto de alguna medida de mejoramiento, es necesario tomar en consideración los análisis físicos. A pesar de que la estructura es una de las propiedades más sensible a los cambios, en el método de N. I. Savvinov no se ofrece una información precisa relacionada con los resultados de su análisis y el estado de agregación de los suelos. El objetivo del presente trabajo fue evaluar y establecer una calibración de indicadores de la estabilidad estructural y su relación con el diámetro medio ponderado de los agregados en diferentes suelos. Para establecer la calibración de los indicadores, se analizaron 161 muestras provenientes del horizonte cultivable de diferentes tipos de suelos. Los suelos bajo pasto y bosque mostraron los mejores indicadores de estabilidad estructural y un diámetro medio ponderado de sus agregados más favorable para el desarrollo de los cultivos; mientras que aquellos destinados a la producción agrícola intensiva presentaron valores indicativos de la degradación de su estructura y la prevalencia de diámetros en sus agregados que afectan el adecuado funcionamiento de los suelos, por lo que a partir de los resultados obtenidos se permite realizar una interpretación más acertada respecto al comportamiento de la estabilidad estructural.

Palabras clave: estructura del suelo, análisis del suelo, suelos agrícolas, degradación del suelo.

INTRODUCTION

The study of fertility properties by means of laboratory analysis is necessary to determine the degradation or conservation conditions of soils after a certain type of agricultural management or to monitor any improvement technology.

The structure is an important component for soil functioning and it is considered an indicator of the degradation degree and soil recovery (1), being the analysis of aggregates, by the N. I. Savvinov method, one of the methodologies to be used to determine the resistance of the different types of structure to break down or disintegrate under the influence of external factors, mainly water, from a quantitative point of view (2).

From the method of N. I. Savvinov's method, the coefficient of dry stability (Ke_d) is determined, which reflects the structural state of the soils as found in the field and

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provides an indirect measure of the aggregate size distribution at the time of sampling, as well as the coefficient of wet stability (Ke_w), an effective tool to evaluate the distribution of the factions of stable aggregates and to understand the resistance of the soil structure (3,4), and finally, the index of structural stability (I_e), an indicator of soil degradation that can be measured by different methods (1,5,6), quantifying the resistance to disintegration and dispersion of the different aggregates, greater than 0.25 mm by the action of water (7,8).

In studies previously carried out for the characterization of different soil types, results are presented on the state of the aggregates, from their quantification in different fractions (9,10). Recently, in works where the stability of the aggregates is directly evaluated, by the aforementioned method, in soils under different agricultural management, or with intense anthropic activity (11,12). At present, there is no tool that allows an interpretation of the structural soil state, in correspondence with the values of the stability coefficients and index and the predominant average diameter. The objective of this work is to evaluate and establish a calibration of structural stability indicators and their relationship with the weighted average diameter of aggregates in different soils.

MATERIALS AND METHOS

Samples of various soil types (161) subjected to different uses and management, taken at random, at 0-20 cm depth (Table 1), distributed in different provinces of the country, were analyzed (Figure 1).

For the stability analysis of the aggregates (2), a shovel and a plastic tray were used, trying not to damage the conformation of the soil, and thus maintain a better conservation of its structure during its transfer, taking 500 g of each sample. To determine the coefficient of dry stability (Ke_d), the soil was passed through a column of sieves of mesh size between 10 mm and 0.25 mm (dry sieving T_s); once the masses of the aggregate fractions retained in each sieve and the percentages of each in relation to the total mass of the sample were recorded, the Ke_d was calculated with the following formula:

$$\text{Kes} = \frac{\Sigma\ \%\ 0{,}25\text{mm a } 10\text{mm}}{\% > 10\text{mm} + < 0{,}25\text{mm}}$$

The wet stability coefficient (Ke_w) was determined using 10 % of the mass of each of the fractions recorded in the T_s, except for the fraction smaller than 0.25 mm; each sample was added to a 500 mL test tube with water and five 180º turns were made at one-minute intervals. Subsequently, the contents of the test tube were passed into a column of

Table 1. Number of samples analyzed by soil type

Soil types	Sample number	Soil use
Ferrallitic Red Leached (FRRL)	5	Forest
	5	Fruit trees
	5	Crops
	36	Pastures
Ferruginous Nodular Gley (GNF)	91	Pastures
Agrogenic Vertic brown medium washed (Pagv)	3	Crops
Agrogenic brown medium washed (Pag)	3	Pastures
Medium-washed mellow brown (Pm)	3	Forest
Carbonated mellow brown (Pmk)	10	Crops
Total	161	

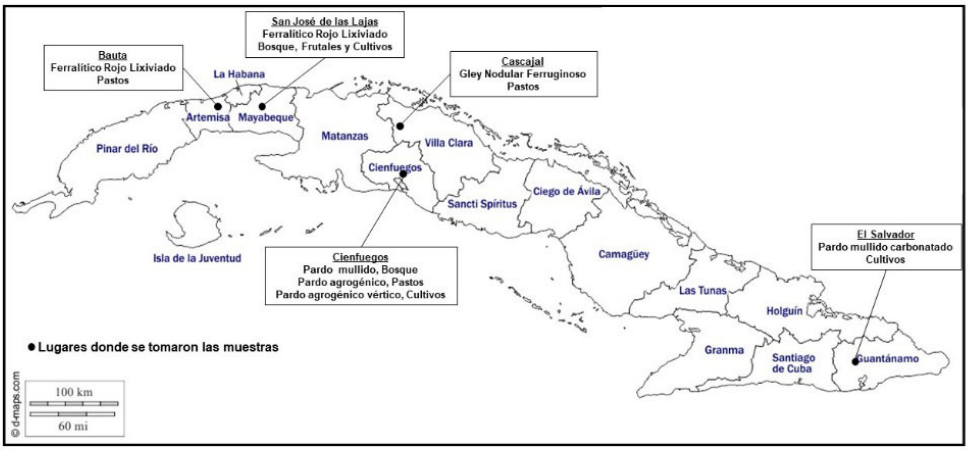


Figure 1. Location by provinces of 161 samples of soils subjected to different uses and handling, taken for the determination of stability coefficients, structural stability index and weighted average aggregate size

sieves with a mesh size between 5 mm and 0.25 mm (wet sieving, T_w), which was placed inside a tank with water to perform oscillatory movements. The soil retained in each of the sieves was collected in metallic sieves and dried on a heating plate. Once the aggregates were dried, their mass and percentage were measured; the mass of the fractions <0.25 mm was determined by difference. To calculate the Ke_w value, the formula was used:

$$\mathrm{Keh}=\frac{\% < 0{,}25\mathrm{mm}}{\Sigma\,\% > 0{,}25\mathrm{mm}}$$

The value of the structural stability index (I_e) was calculated from the formula:

$$\mathrm{Ie}=\frac{\Sigma\,\% > 0{,}25\mathrm{mm}\ (\mathrm{Th})}{\Sigma\,\% > 0{,}25\mathrm{mm}\ (\mathrm{Ts})}$$

The average diameter of each class (X_i) was determined from the average between the diameters of the openings between each sieve and the proportion of aggregates in each class (W_i), the latter by dividing the soil weight of each fraction by the total sample weight. Finally, the weighted average diameter of dry (WAD_d) and wet (WAD_w) aggregates was calculated using the equations of the Manual of Methods of Soil Analysis (13), shown below:

$$\mathrm{DMPs}=\sum(\mathrm{Xis}*\mathrm{Wis})$$
$$\mathrm{DMPh}=\sum(\mathrm{Xih}*\mathrm{Wih})$$

where:

WAD_d :dry weighted mean diameter, in mm.

WAD_w :wet weighted mean diameter, in mm.

W_{id} :proportion of aggregates in each class/sieve (i), by T_d, in %.

X_{id} :average diameter of each class, by T_d, in mm.

W_{iw} :proportion of aggregates in each class/sieve (i), by T_w, in %.

X_{iw} :average diameter of each class, by T_w, in mm.

The Aggregate Stability Index (ASI) from the weighted average diameter and expressed in %, was calculated according to the formula:

$$\mathrm{IEA}=\frac{\mathrm{DMPh}}{\mathrm{DMPs}}\mathrm{x}100$$

where:

ASI:aggregate stability index, expressed in %.

WAD_w :wet weighted mean diameter, in mm.

WAD_d :dry weighted mean diameter, in mm.

Statistical processing

To establish the calibration levels of the coefficients and stability index of the aggregates, first, a discriminating variable (Management code) was created considering the type of soil (Table 2), except for the Ferrallitic Red Leached dedicated to pastures, then, a discriminant analysis was performed on the created variable; then a frequency histogram with 5 types was made.

Finally, individuals were coded according to soil type and agricultural destination, as shown in Table 3, to assess the joint effect on the evaluated coefficients.

Table 2. Coding of the groups created, according to their agricultural use, for discriminant analysis

Soil type	Handling code
FRRL-Forest	1
FRRL-Fruit trees	2
FRRL-Crops	3
GNF-Pastures	4
FRRL-Pastures	5

Table 3. Coding of the groups, according to soil type and agricultural use, for the analysis of variance

Soil type and agricultural use	Code
FRRL (Forest)	1
FRRL (Frui trees)	2
FRRL (Crops)	3
GNF (Pastures)	4
FRRL (Pastures)	5
Pagv (Crops)	6
Pag (Pastures)	7
Pm (Forest)	8
Pmk (Crops)	9

The groups obtained were subjected to an analysis of variance, and when significant differences were found between the means of the different indicators studied, they were compared according to Duncan's Multiple Range test ($p < 0.05$).

All analyses were performed with the statistical package Statgraphics Plus for Windows v. 5.1.

RESULTS AND DISCUSSION

The discriminant analysis yielded 94.4 % of correctly classified cases, which allowed us to consider the five groups formed as correct. The mean values and standard error of each group are shown in Table 4.

Dry stability coefficient

Ke_d value depends, fundamentally, on the amount of aggregates recorded in the 10 mm to 0.25 mm diameter range; the greater the amount of aggregates in this diameter range, the higher the Ke_d value and the better the aggregate condition of the soil.

The histogram of frequencies with five Ke_d categories is presented in Table 5.

In the samples analyzed, the mean value of Ke_d was 1.61, ranging from 0.14 to 3.69.

Figure 2 shows the behavior of Ke_d and WAD_d of the samples analyzed, showing that in the Ferruginous Nodular Gley and Red Ferrallitic Leached soils dedicated to pastures, Ke_d is classified as High (Table 5), with the highest values of the coefficient and the WAD_d of their aggregates ranged between 4 and 7 mm. The other soils

Table 4. Means and standard error obtained from the discriminant analysis of each indicator of the groups created, according to their agricultural use

Indicators	Soil				
	FRRL-Forest	FRRL-Fruit trees	FRRL-Crops	GNF-Pastures	FRRL-Pastures
			Mean/± Se χ		
Ke_d	0.81/±0.12	0.73/±0.09	0.64/±0.33	1.78/±0.36	1.94/±0.69
Ke_w	0.44/±0.21	0.62/±0.15	0.94/±0.74	0.39/±0.11	0.12/±0.04
I_e	0.69/±0.11	0.63/±0.06	0.57/±0.15	0.92/±0.07	0.92/±0.03
WAD_d	10.36/±0.66	11.08/±0.44	11.01/±1.45	4.43/±1.35	7.58/±1.27
WAD_w	2.32/±1.49	1.55/±0.36	0.7/±0.29	2.52/±0.46	3.17/±0.45
IEA (%)	21.98/±13.67	14/±3.04	6.51/±3.07	60/±11.47	42.59/±7.05

analyzed were classified as Regular, with Ke_d values below 1.10 and aggregate WAD_d above 10 mm.

Soils with high Ke_d have a predominance of aggregates with diameters between 1 and 10 mm. As the formation of aggregates in these diameter fractions increases, the soil gains in agronomic value, since it presents less massive structures (14), allowing the establishment of an adequate balance of macro and micropores, which favors the air-water relationship in the soil (15).

These results coincide with those of other authors, who have shown that soils with a WAD_d of around 7 mm have a good structure for adequate crop development (16).

On the contrary, in soils with Regular Ke_d values, the presence of aggregates with diameters less than 0.25 mm or greater than 10 mm is marked, due to the presence of medium and large aggregates on the surface, indicating that the structural condition of the soil is not adequate, which is directly manifested in the development of crops (17).

Wet stability coefficient

The Ke_w value depends on the amount of aggregates larger than 0.25 mm recorded after the wet sieving process, since the greater the amount of aggregates recorded in that diameter range, the lower the value of the coefficient and the better the resistance of the aggregates to dehydration due to the effects of water.

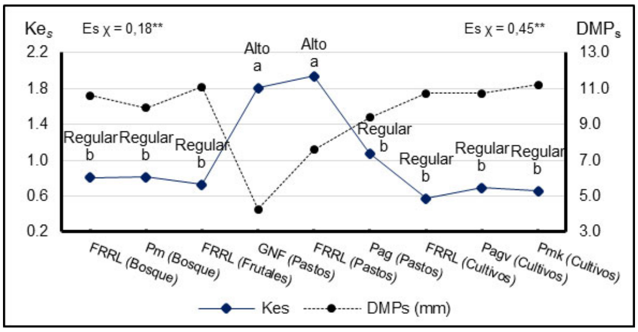
The histogram of frequencies with 5 classes made it possible to establish five Ke_w categories, as shown in Table 6.

In the samples analyzed, the mean Ke_w value was 0.40; values ranged from 0.04 to 2.88.

Regarding the behavior of Ke_w and WAD_w (Figure 3), according to the results obtained, the Ferrallitic Red Leached, Brown Agrogenic Brown soils cultivated with pasture and Ferrallitic Red Leached under forest presented a Ke_w classified as Very high and the Ferruginous Nodular Gley soil with pasture as high (Table 6). The WAD_w of the aforementioned soils remained between 3 and 3.5 mm. In the other soils analyzed, the Ke_w values were considered Regular to Very low, reflecting in them a WAD_w of their aggregates, after wet sieving, lower than 1 mm.

Table 5. Calibration of the values of the coefficient of dry stability (Ke_d) from the histogram of frequencies made with the results of 161 samples of different Soils

Values Ke_d	Category
>2.00	Very high
(1.10 - 2.00	High
(0.55 - 1.10	Regular
0.30 - 0.55	Low
<0.30	Very Low



FRRL: Ferrallitic Leached Red, Pm: Brown mellow GNF: Nodular Ferruginous Gley, Pag: Agrogenic brown, Pagv: Vertic agrogenic brown, Pmk: Carbonated mellow brown. Means with equal letters do not differ according to Duncan's test (p<0.05)

Figure 2. Calibration of the values of the coefficient of dry stability (Ke_d and its relationship with the WAD_d in the different types of soils, according to their use

Table 6. Calibration of the values of the coefficient of wet stability (Ke_w) from the histogram of frequencies made with the results of 161 samples of different soils

Values Ke_w	Categoría
<0.30	Very hight
0.30 - 0.45	Hight
(0.45 - 0.70	Regular
(0.70 - 1.10	Low
>1.10	Very low

This behavior in soils that show a very high and high Ke_w, that is, the lowest values of this indicator, could be due to the action of a dense network of pasture roots, to which the particles adhere due to the presence of radical exudates (18,19), improving the formation of micro-aggregates, which later fuse in macro-aggregates, to form a relatively stable structure in the soil (20).

In relation to the values of WAD_w obtained in soils with better fertility conditions, in previous works, high values of this indicator were reported in soils with forest and cultivated with pasture, in comparison with other agricultural systems (21).

These results with respect to WAD_w are in agreement with what has been stated by other authors, where wet aggregates between 1 and 5 mm in diameter represent those of greater agronomic value for adequate plant development (22).

In soils with a certain degree of degradation by continuous cultivation, most of their aggregates do not maintain stability, which causes low values in the WAD_w, an effect that could be related to the decrease in the content of organic matter, which brings with it a more aggressive transformation of its aggregates.

Structural stability index

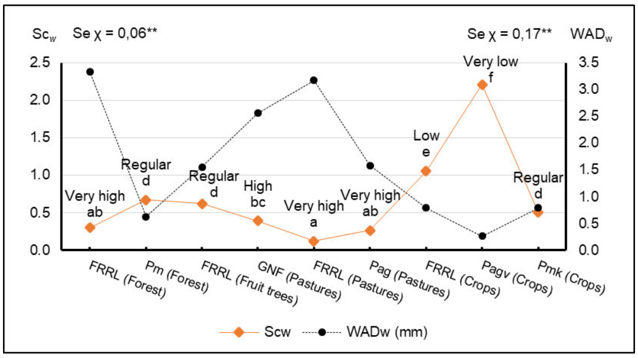
The value of the structural stability index by this method is based on the ratio between the fractions greater than 0.25 mm in the wet and dry sieving. The greater the amount of these aggregates quantified in the wet sieving, the higher the value of the index, since this indicator, as it approaches one, indicates the existence of a smaller proportion of aggregates smaller than 0.25 mm, showing that the soil has a better state of aggregation of its particles (22).

The histogram of frequencies with 5 classes made it possible to establish five categories of I_e, as shown in Table 7.

In the samples analyzed, the mean value of I_e was 0.86; the values ranged from 0.26 to 1.04.

Figure 4 shows the behavior of the I_e and the percentage of the ASI of the soils analyzed. According to the results of the Ie, the Ferruginous Nodular Gley and Ferrallitic Red Leached soils dedicated to pasture were classified as Very high, presenting, in turn, the highest percentages of the ISA and the Ferrallitic Red Leached soils under forest and Agrogenic Brown with pasture were considered as High (Table 7). The other soils were classified with an I_e from Regular to Very low, as they presented lower values of the indicator and an aggregation percentage lower than 20 %.

The high stability presented in soils cultivated with pasture is given, besides the effect of the mechanical action of roots, to the fact that the protection of the organic matter of the microbial degradation in the aggregates is enhanced, due to a lower alteration of the soil and its aggregates remain physically stable (23). Previously, studies were carried out on the influence of different management systems on Ferrallitic Red soil properties, reflecting that

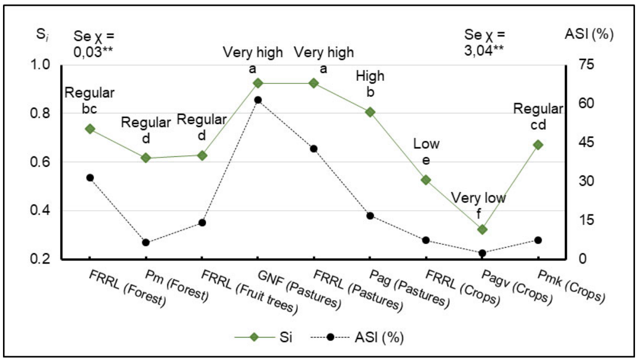


FRRL: Ferrallitic Leached Red, Pm: Brown mellow GNF: Nodular Ferruginous Gley, Pag: Agrogenic brown, Pagv: Vertic agrogenic brown, Pmk: Carbonated mellow brown. Means with equal letters do not differ according to Duncan's test (p<0.05)

Figure 3. Calibration of the values of wet stability (Ke_w) coefficient and its relationship with WAD_w in the different types of soils, according to their use

Table 7. Calibration of the values of the Structural Stability Index (I_e) from the histogram of frequencies made with the results of 161 samples of different soils

Value I_e	Category
>0.90	Very high
>0.70 - 0.90	High
>0.55 - 0.70	Regular
0.40 - 0.55	Low
<0.40	Very low



FRRL: Ferrallitic Leached Red Ferrallitic, Pm: Brown mellow GNF: Nodular Ferruginous Gley, Pag: Agrogenic brown, Pagv: Vertic agrogenic brown, Pmk: Carbonated mellow brown. Means with equal letters do not differ according to Duncan's test (p<0.05)

Figure 4. Calibration of the values of the Structural Stability Index (I_e) and its relation with the percentage of the Aggregate Stability Index (ASI) determined from the weighted average diameter of the aggregates in the different types of soils

pastures conserved the stability of the structure, unlike other production systems (24).

Another factor that offers high stability to soil aggregates is organic matter, which together with other components, intervenes in the formation of the structure, exerting a direct effect on the resistance reflected by the aggregates after wetting. It has been demonstrated that this constitutes a strong bonding agent between soil particles, increasing their internal cohesion and ensuring their stability, which reduces the effects of collapse and bursting of aggregates to smaller fractions (23,25), besides having a hydrophobic effect on soil aggregates.

In soils where tillage is carried out, the organic matter oxidizes, decreasing the possibility of maintaining the soil structure (18). In this condition of low stability of its structure, the percentage of particles with diameters smaller than 0.5 mm increases when wet sieving is carried out. Since, during the process of direct immersion of dry soil in water at atmospheric air pressures, aggregate breakage occurs more easily, because the compression of air occluded in the aggregate causes it to burst when it is displaced by the water, smaller aggregates and primary particles are generated (16).

At the same time, under field conditions, the effect of rain causes mechanical disaggregation of the aggregates (25). Exposing the finer particles to the erosion process and increasing the surface sealing phenomenon, the pores are blocked, causing limitations in water infiltration, soil compaction problems and, as a consequence, affecting plant rooting (26,27).

CONCLUSIONS

- A calibration of the coefficients and stability index is established by the method of N. I. Savvinov, classified as Very high, High, Regular, Low and Very low.
- Soils with dry and wet stability coefficients values considered as Very High and High are dominated by aggregates resistant to the effects of humidity and with a medium diameter that favors edaphic functioning.
- Soils with a structural stability index classified as Very high show high percentages in the aggregate stability index.
- The handling to which the soil is subjected influences its structural stability, with those destined for pasture being more stable, regardless of the soil type.

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