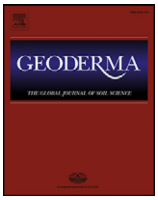
Geoderma 226–227 (2014) 397–404

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma



A comparison of methods to assess susceptibility to soil sealing

Mansonia Pulido Moncada [a,b,*], Donald Gabriels [b], Deyanira Lobo [a], Kristof De Beuf [c], Rosana Figueroa [d], Wim M. Cornelis [b]

[a] Instituto de Edafología, Facultad de Agronomía, Universidad Central de Venezuela, Av. Universidad vía El Limón, Maracay 2101, Aragua, Venezuela
[b] Department of Soil Management, UNESCO Chair on Eremology, Ghent University, Coupure links 653, B-9000 Ghent, Belgium
[c] Department of Mathematical Modeling, Statistics and Bioinformatics, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium
[d] Instituto de Ingeniería Agrícola, Facultad de Agronomía, Universidad Central de Venezuela, Av. Universidad vía El Limón, Maracay 2101, Aragua, Venezuela

ARTICLE INFO

Article history:
Received 19 April 2012
Received in revised form 8 March 2014
Accepted 17 March 2014
Available online 13 April 2014

Keywords:
Sealing
Aggregate stability
Indicators
Runoff
Soil quality

ABSTRACT

Many methods and indices have been developed for assessing seal formation. However, difficulties persist in selecting a suitable method because of the effect of the procedure on the results. The present study aims to evaluate appropriate soil sealing assessment methods that enable to distinguish the surface condition of soils with contrasting characteristics. A comparative study was conducted among the most frequently used methods, viz: wet sieving tests, raindrop impact tests under field and laboratory conditions, penetration resistance (PR), consistency index (C_{5-10}), soil stability index (StI), and crusting index (CI). Different agricultural Venezuelan 'tropical' soils were ranked according to their susceptibility to soil sealing. The ranking and the correlation between the parameters were used to assess and compare soil sealing formation measured by the different methods. According to multiple and single wet sieving tests the soils were classified into two groups as stable (kaolinitic-rich) and unstable (smectitic-rich) soils. The ranking of the soils and correlation analysis ($p < 0.05$) indicated that aggregate stability as determined by wet sieving, infiltration rate, runoff and soil loss under laboratory and field conditions was effective in predicting seal formation among smectitic-rich loam to kaolinitic-rich clayey soils. C_{5-10} and PR were not comparable tests for sealing formation ($p > 0.05$). The StI that considers soil organic matter (SOM) as the most important factor to maintain soil structure did not reflect the high stability of the kaolinitic-rich soil that lacks SOM. The CI, which indicates the risk for soil crusting formation in the function of silt fractions, is a more capable indicator for evaluating susceptibility to sealing of our soils. This study further proposes that when topsoil aggregates are characterized by high silt and smectite contents the use of wet sieving and raindrop impact tests or simple indices such as StI and CI can satisfactorily assess the susceptibility to seal formation. Differences obtained in seal formation ranking indicated that method selection impacts the measured value. It can therefore be recommended to take the effect of the method into account when interpreting the results obtained.

1. Introduction

Soil sealing and crusting formation are very common phenomena in many soils worldwide. In Venezuelan 'tropical' soils e.g., these physical degradation processes are prevalent in agricultural areas, which implies that much of the productive area of the country has a low soil surface physical quality condition (Pla, 1993). The physical degradation results in a low hydraulic conductivity and infiltrability, with problems of runoff and erosion (Gabriels et al., 1997; Pagliai, 2003; Pla, 1993).

The term 'soil seal' generally refers to a surface layer of soil with significantly reduced porosity and permeability resulting from rapid wetting of dry soil, raindrop impact, deposition of fine soil material, chemical dispersion, or a combination of these processes (Chartres and Greeves, 1998). Soil sealing is associated with a wet state while crusting refers to a dry state. Consequently, soil crusting is a result of soil sealing formation. Considering that the initial forming processes and features are the same for both 'seal' and 'crust' (Valentin and Bresson, 1997), no further distinction will be made in this article between seal and crust. Hereafter the term 'seal' will be used, unless specified as 'crust' in the name of the method or index.

The tendency of a soil to form a seal depends on the aggregate stability (LeBissonnais, 1996). The aggregate stability is affected by the complex interaction of different internal soil characteristics and external factors (Amezketa, 1999; Barthes et al., 2008; Martínez-Gamiño and Walthall, 2000; Pagliai, 2003; Six et al., 2004). Among the internal factors are soil organic matter (SOM), texture, clay mineralogy, cations, oxides and hydroxides of Fe and Al, $CaCO_3$, Mg and gypsum (Amezketa, 1999; Lado et al., 2007; Wakindiki and Ben-Hur, 2002). External factors that have received attention include the intensity and energy of rainfall, the

---

* Corresponding author at: Department of Soil Management, UNESCO Chair on Eremology, Ghent University, Coupure links 653, B-9000 Ghent, Belgium. Tel.: +32 9 264 6039; fax: +32 9 264 6247.
E-mail addresses: mansonia.pulido@ugent.be, pulidom@agr.ucv.ve (M. Pulido Moncada), donald.gabriels@ugent.be (D. Gabriels), lobod@agr.ucv.ve (D. Lobo), kristof.debeuf@ugent.be (K. De Beuf), figueroar@agr.ucv.ve (R. Figueroa), wim.cornelis@ugent.be (W.M. Cornelis).

http://dx.doi.org/10.1016/j.geoderma.2014.03.014
0016-7061/© 2014 Elsevier B.V. All rights reserved.

Table 1
Main characteristics of the ‘tropical’ soils from Venezuela.

Soil	Location	Texture class	Main clay minerals	Mean annual rainfall and temperature	USDA class (Soil survey staff, 2010)	Land use	Soil management
El Salao	Guárico (8° 40′ 06.20″ N; 65° 15′ 47″ W)	Clay	Kaolinite	970 mm 27 °C	Entic Haplusterts	Savannah pasture	No tillage
Quíbor	Lara (9° 56′ 10.09″ N; 69° 38′ 59.15″ W)	Silty clay loam	Mica	617 mm 26 °C	Typic Torrifluvents	Onion–tomato–pepper	Conventional tillage
Danac	Yaracuy (10° 21′ 52.38″ N; 68° 39′ 17.18″ W)	Loam	Mica, smectite	1212 mm 25 °C	Typic Endoaqualf	Maize	Reduced tillage
Turén	Portuguesa (09° 19′ 02″ N; 69° 05′ 05″ W)	Silt loam	Mica	1511 mm 27 °C	Fluventic Haplustepts	Maize–sorghum	Conventional tillage
El Sombrero	Guárico (9° 21′ 48.45″ N; 67° 04′ 28.36″ W)	Loam	Smectite, mica	970 mm 27 °C	Typic Haplustalfs	Onion	Conventional tillage

gradient and length of the slope, the electrolyte concentration and type of cation of the rain water, and the soil management (Assouline and Ben-Hur, 2006; Pagliai, 2003).

There are certain obstacles to overcome when trying to assess soil sealing (Chartres and Greeves, 1998). A wide variety of assessment methods that account for the mechanisms and processes involved in aggregate stability are available. According to Valentin and Bresson (1997) soil sealing can be assessed directly through a morphological change in aggregate diameter, or indirectly through a decrease in infiltration rate, hydraulic conductivity and percolation rate or through an increase in surface strength and runoff. However, these methods are tedious and costly, and hence many indices have been developed to indirectly derive the soil's susceptibility to sealing from simple and more available data as texture and SOM content, from dispersion tests, from instability indices (size distribution of aggregates and fragments released by aggregate breakdown), from consistency indices (Atterberg limits) and from mechanical strength test (modulus of rupture and rupture stress) (Valentin and Bresson, 1997).

When evaluating risk to surface sealing, seal formation is expected when a combination of two main factors is present: i) the type of disruptive forces (a mechanism affected by method of evaluation) and ii) the susceptibility to break down the aggregates (as result of the rupture of the binding bonds) under the disruptive forces (Pagliai, 2003). Many methods and indices have been developed for assessing seal formation. However, difficulties persist in selecting a suitable method because of the effect of the procedure on the results.

The different processes which involve the breakdown of aggregates by the methods and indices to assess soil sealing can result in different rankings of the studied soils (Amezketa, 1999; Levy and Mamedov, 2002). Among the procedures developed for assessing soil sealing, methods and indices that involve different mechanisms (i.e., aggregate wetting, raindrop impact) and parameters (i.e., clay, silt, SOM) responsible for breaking down aggregates in the topsoil were selected for comparison. The objective of this study was to evaluate appropriate soil sealing assessment methods that enable the distinguishing of the surface condition of soils with contrasting characteristics. We hypothesize that the ranking of the studied soils, in terms of their susceptibility to sealing, and the correlation between the parameters evaluated will indicate that the method of evaluation has an effect on the seal formation measurement in the different ‘tropical’ soils from the northern agricultural region of Venezuela.

2. Materials and methods

2.1. Soils and sampling

Soil samples were taken from five fields in different agricultural regions of Venezuela. Soils differ in texture, clay mineralogy, soil use and management, and in historical land use (Table 1). All the soils, except *El Salao* soil, have problems of soil sealing, being one of the most important soil physical degradation factors in these agricultural regions.

El Salao soil, considered as reference soil in this study, differs in its long-term history of land use with respect to the other soils (*Quíbor*, *Danac*, *Turén* and *El Sombrero*). It is located on a long-term savannah pasture. The savannah pasture field is not seeded, but annually subjected to involuntary burning (typical in that area) and grazing. *El Salao* is a clay soil (40% clay) with abundant kaolinite content, an acid pH and a high SOM content (Table 2).

Quíbor, *Danac*, *Turén*, and *El Sombrero* soils have been under monoculture and conventional tillage for about 30 years (Table 1). In these soils mineral particles with diameters between 2 and 100 μm are dominant and the clay mineralogy is dominated by smectite (Table 2). The cropped soils are weakly acid to neutral. The SOM content, according to Gilabert et al. (1990), is low in *Quíbor* and *Danac*, but medium in *Turén* and *El Sombrero* (Table 2). *Quíbor* and *Turén* have calcareous parental material. However, the $CaCO_3$ behaves physically as pseudo silt particles. The Na^+ and K^+ contents are very low in all the soils. Table 2 displays other soil characteristics as well.

Nine disturbed 0–5 cm depth soil samples were taken at random from a 0.5 ha plot in each site. The soil samples were air dried and sieved to obtain different aggregate size fractions.

2.2. Assessment of soil sealing

2.2.1. Wet sieving methods

Two methods were applied: multiple and single wet sieving. The distribution of the water stable aggregate (WSA) fractions was determined

Table 2
Physical and chemical soil characteristics.

Soil	Particle size distribution (%)							SOM[a]	pH	EC	Exchangeable cations			
	<2 μm	2–50 μm	50–100 μm	100–250 μm	250–500 μm	500–1000 μm	1000–2000 μm		(1:1 H_2O)		Ca^{2+}	Mg^{2+}	Na^+	K^+
								(%)		($dS\ m^{-1}$)	($cmol_c\ kg^{-1}$)			
El Salao	40	31	21	4	2	1	1	3.4	4.3	0.1	0.6	4.8	0.4	0.7
Quíbor	26	59	11	2	1	1	0	1.7	7.7	1.4	91.0	1.3	0.3	0.8
Danac	18	37	36	3	2	2	2	1.9	5.9	0.1	4.1	0.9	0.04	0.4
Turén	16	67	16	1	0	0	0	3.3	7.9	0.2	45.8	0.4	0.1	0.8
El Sombrero	22	41	32	4	1	0	0	3.3	6.6	0.1	14.9	1.7	0.03	0.9

[a] SOM = organic carbon content multiply by 1.724; EC = electrical conductivity.

with the multiple wet sieving method of Yoder (1936). Previous to wet sieving the aggregates between 4 and 2 mm in diameter were placed on a set of sieves (2.00, 1.00, 0.50 and 0.25 mm) and allowed to wet by capillarity for 30 min. The set of sieves was then gently shaken up and down under water for 10 min at a constant, automatically controlled speed. The mean weight diameter (MWD) of aggregates was calculated from all the aggregate fractions obtained from wet sieving (Kemper and Rosenau, 1986).

In the second method, a single sieve was used to determine the fraction smaller than 0.25 mm (P250) after wet sieving (El Swaifi and Dangler, 1982) from 100 g of air dried aggregates between 4 and 2 mm in diameter. The same wet sieving procedure as described above was conducted, including prewetting of the samples by capillarity. The P250 value includes individual particles and microaggregates as well.

2.2.2. Absolute sealing index

Soil sealing, as a result of fragmentation and dispersion caused by raindrop impact, was evaluated by the absolute sealing index (ASI), corresponding to the final percolation rate of a sealed soil under raindrop impact (Nacci and Pla, 1991). A 70 g subsample of air-dry aggregates, between 4 and 2 mm, was placed on a 71 cm^2 ceramic funnel to form a 10 mm thick bed. The funnel was placed underneath a drop forming system with drops of 4.5 mm diameter on average, installed at 2.5 m height. The percolation rate through the seal (mm h^{-1}) was measured at different time intervals during 1 h rainfall test with an intensity of 100 mm h^{-1}.

2.2.3. Rainfall simulation

The soils were subjected to simulated rainfall in the laboratory and in the field. In the laboratory, the soil pans (30 cm long, 20 cm wide and 15 cm deep) were packed with a 3 cm layer of aggregates between 8 and 4 mm, placed over a 12 cm layer of air dried soil <8 mm. The pan was inclined at 3% slope and placed underneath a 2.5 m high drop type rainfall simulator (drops of 5.5 mm diameter on average). A 100 mm h^{-1} intensity rainfall was applied on air-dry soil for 1 h and runoff and soil loss were measured.

In the field, a simulated rainfall of 100 mm h^{-1} during 1 h was produced with a portable drop type rainfall simulator (drops of 5.5 mm diameter on average), and applied to 20 cm × 30 cm micro-plots bordered with a half-buried frame with an opening at the lower side to collect runoff and soil loss. The duration of the rain in both experiments was sufficient to obtain steady-state runoff conditions, defined when four consecutive runoff samples yielded the same volume. Steady state runoff rates are typically used for comparing different soils because the variation is minimized (Reichert et al., 2009).

2.2.4. Crust penetration resistance

After each rainfall simulation the resistance to crust penetration (PR) was measured every 48 h in the pans and at the sampling time in the field with a pocket penetrometer (flat tip with an area of 0.28 cm^2). The maximum PR value in the erosion pans and the PR value in the field correspond to the equivalent unconfined compressive strength. Water content was determined for each penetration resistance measurement.

2.2.5. Consistency index

Consistency index, derived from the Atterberg tests (Kretschmer, 1996), is considered to be a useful and simple tool for the prediction of phenomena related to soil erosion as soil sealing. Air dried soil samples <2.0 mm were wetted with distilled water by alternately and repeatedly stirring, kneading, and chopping with a spatula and placed in a Casagrande cup (De Ploey, 1981). The consistency index (C_{5-10}) is calculated as the difference in water content (% dry weight) required to close a 2 mm wide grove previously driven in the soil over a distance of 1.00 cm after 5 (W_5) and 10 blows (W_{10}) by the Casagrande apparatus. De Ploey (1981) pointed out that a soil with a $C_{5-10} < 2.5$ is considered as unstable soil while $C_{5-10} > 2.5$ refers to stable soil.

$$C_{5-10} = W_5 - W_{10}. \tag{1}$$

2.2.6. Soil stability index

Particle size distribution and soil organic carbon (SOC) content were used to calculate the structural stability index (StI) suggested by Pieri (1992), which expressed the risk for soil structural degradation associated with SOC depletion:

$$\text{StI} = \frac{1.72 \times \text{SOC}}{\text{Clay} + \text{Silt}} \times 100 \tag{2}$$

where SOC is the soil organic carbon content (%) and Clay + Silt is the combined clay and silt content of the soil (%). StI < 5% indicates a structurally degraded soil; 5% < StI < 7% indicates a high risk of soil structural degradation; 7% < StI < 9% indicates a low risk of soil structural degradation; and StI > 9% indicates sufficient SOC to maintain the structural stability.

2.2.7. Crusting index

The crusting index (CI) proposed by FAO (1980), is derived from soil characteristics:

$$\text{CI} = \frac{(1.5 \times \text{FineSilt}) + (0.75 \times \text{CoarseSilt})}{\text{Clay} + (\text{SOM} \times 10)}. \tag{3}$$

Soils low in clay (%) and in SOM (%) content and high in silt (%) content are highly prone to sealing and crusting. CI < 0.2 indicates no crust formation and a value >2 is considered a critical limit for high crust formation risk.

2.3. Statistical analysis

Non-parametric Kruskal–Wallis rank sum tests were conducted to detect statistical differences among soils for each measured variable. Further, Spearman correlation tests were conducted between each pair of variables. These analyses were performed using the statistical package SAS (SAS Institute, 1989). All tests were conducted at the 5% significance level. Differences between methods were revealed and displayed by means of a hierarchical cluster analysis on the standardized data using the average dissimilarities method (Kaufman and Rousseuw, 1990). In order to evaluate the associations between the physical–chemical soil characteristics and the soil sealing measurement methods, a canonical correlation analysis was conducted (e.g. Johnson and Wichern, 2002). The statistical software suite R version 2.14.0 (R Development Core Team, 2011) was used for the cluster and canonical correlation analysis.

3. Results and discussion

3.1. Effectiveness of the selected methods to assess seal formation

3.1.1. Multiple and single wet sieving

The indices obtained from the different wet sieving methods are presented in Table 3. Regarding the multiple wet sieving test, the WSA distribution showed significant differences ($p < 0.05$) among soils for each aggregate fraction obtained after wet sieving. *El Salao* (kaolinite-rich) soil displayed a great resistance to aggregate breakdown, with a high proportion of 4–2 mm aggregates (78%) left as compared to the other soils. In the latter, the proportion of the aggregate fraction <0.25 mm was significantly higher (47–98%), as compared to the other fractions. Soils were ranked in a decreasing order of susceptibility to sealing using the significant differences of the percentage of 4–2 mm

Table 3
Mean values of parameters from wet sieving, drop impact, consistency index, soil stability index and crusting index.

Soils	WSA distribution (wt.%)					MWD (mm)	P250 (%)	C_{5-10}	ASI (mm h^{-1})	StI (%)	CI
	4–2	2–1	1–0.5	0.5–0.25	<0.25						
	(mm)										
El Salao	78 a (17.5)	4 b (4.4)	5 bc (4.6)	4 c (2.8)	9 d (6.2)	2.26 a (0.5)	20 d (5.7)	2.3 bc (1.5)	22.5 a (11.5)	4.89 a (1.15)	0.7 d (0.2)
Quíbor	0 b (0.0)	0 c (0.0)	1 d (0.5)	1 d (0.0)	98 a (0.5)	0.14 c (0.0)	88 b (2.5)	3.8 a (0.8)	0 b (0.0)	1.89 c (0.08)	2.5 a (0.2)
Danac	2 b (1.0)	5 b (1.6)	7 b (1.7)	8 b (1.3)	78 b (5.0)	0.29 c (0.0)	76 c (5.0)	1.9 c (0.5)	2.9 b (1.9)	3.76 b (0.58)	1.8 b (0.1)
Turén	1 b (1.0)	1 c (0.7)	3 cd (1.0)	3 cd (0.9)	92 a (1.5)	0.19 c (0.0)	93 a (1.9)	3.1 ab (0.6)	1.1 b (0.5)	3.96 b (0.60)	2.4 a (0.4)
El Sombrero	5 b (2.4)	15 a (2.1)	17 a (2.0)	16 a (1.6)	47 c (5.4)	0.63 b (0.1)	75 c (3.3)	1.9 c (0.5)	3.6 b (0.6)	4.02 b (0.65)	1.4 c (0.2)

Different letters in the same column refer to significant differences ($p < 0.05$).
Standard deviation for each measure is given in parentheses.
WSA is the water stable aggregates, MWD is the mean weighted diameter, P250 is the particles smaller than 250 μm, C_{5-10} is the consistency index, ASI is the absolute sealing index, StI is the soil stability index and CI is the crusting index.

aggregates: *Quíbor* (0%) = *Turén* (1%) = *Danac* (2%) = *El Sombrero* (5%) > *El Salao* (78%). When the results were expressed in MWD, the same tendency in terms of susceptibility to seal formation was obtained (Table 3).

The soils with high susceptibility to sealing were characterized by high silt (>40%) and smectite content, which are considered the main factors for low aggregate stability and high susceptibility to dispersion (Poesen, 1986; Wakindiki and Ben-Hur, 2002).

Not surprisingly, comparison of the indicators obtained from multiple wet sieving (WSA and MWD) and single wet sieving (P250) showed that the soils studied could be divided into two groups: stable (*El Salao*) and unstable (*Turén*, *Quíbor*, *Danac*, and *El Sombrero*). The two methods of wet sieving applied to obtain these indicators, simulate identical aggressive forces, which promote the same mechanics of the breakdown of the unstable aggregates. Both methods start with removing the air from the aggregates (prewetting with water) before the energy is applied (mechanical shaking). They also involve the same wet sieving duration, the immersion of aggregates into the same liquid (distillate water) and the same aggregate size. Hence, the fractions of aggregates 4–2 mm and <0.25 mm, MWD and P250 could be used as comparative indicators of susceptibility to sealing. This is also supported by the fact that they are significantly correlated ($r > 0.90$, $p < 0.01$) and are ranking the different soils in a similar way.

Furthermore, multiple sieving and single sieving methods have been widely used under different conditions. Many authors have found that these methods allow evaluating soil aggregate stability (Barthes and Roose, 2002; Beare and Bruce, 1993). They consider the MWD as a good parameter for assessing seal formation, runoff and erosion as well (Diaz-Zorita et al., 2002; Lado et al., 2004a,b). For evaluating soil sealing the single sieving method is preferred over the multiple sieving method, because it is less time-consuming.

3.1.2. Absolute sealing index

The ASI test required only 2 to 5 min of raindrop impact to form a seal on the smectite-rich cultivated soils but more than 30 min on the non-cultivated soil (kaolinite-rich). The ASI showed that *El Salao* soil had the highest final percolation rate (22.5 mm h^{-1}) after the seal formation. The other soils had percolation rates lower than 5 mm h^{-1} (Table 3). The ranking in decreasing order of susceptibility to sealing is: *Quíbor* = *Turén* = *Danac* = *El Sombrero* > *El Salao*. A significant correlation was found between ASI and 4–2 mm aggregates, <0.25 mm aggregates, MWD and P250 (Table 4), confirming ASI as being a comparative indicator of susceptibility to sealing for different soils. Even though they involve different mechanisms of breakdown, they produce the same degradation effect on the aggregates and lead to soil sealing. In the wet sieving test with slow wetting slaking was prevented. This refers to lower compression forces acting on the aggregates. However, the low aggregate stability of smectite-rich soils (*Quíbor*, *Turén*, *Danac*, and *El Sombrero*) was confirmed by ASI.

Table 4
Correlation matrix with Spearman coefficients for the soil properties and soil sealing assessment methods.

	Clay	Silt	Silt + very fine sand	SOM	MWD	P250	ASI	Runoff lab	Soil loss lab	PR lab	Runoff field	Soil loss field	PR field
4–2 mm	0.63^{***}	-0.70^{***}	-0.63^{***}	0.46^{**}	0.98^{***}	-0.96^{***}	0.85^{***}	-0.85^{***}	-0.61^{***}	Ns	-0.42^{**}	-0.52^{***}	0.65^{***}
<0.25 mm	-0.53^{***}	0.64^{***}	0.57^{***}	-0.55^{***}	-0.92^{***}	0.92^{***}	-0.78^{***}	0.63^{***}	0.65^{**}	Ns	0.58^{***}	0.74^{***}	-0.40^{*}
MWD	0.62^{***}	-0.67^{***}	-0.63^{***}	0.51^{***}	1.00	-0.96^{***}	0.85^{***}	-0.80^{***}	-0.62^{***}	Ns	-0.48^{***}	-0.60^{***}	0.58^{***}
P250	-0.55^{**}	0.77^{***}	0.58^{***}	-0.38^{**}	-0.96^{***}	1.00	-0.86^{***}	0.78^{**}	0.72^{***}	Ns	0.47^{***}	0.63^{***}	-0.61^{***}
C_{5-10}	Ns	0.32^{*}	Ns	Ns	-0.33^{*}	0.32^{*}	Ns	Ns	Ns	Ns	0.37^{*}	0.37^{*}	Ns
ASI	0.49^{**}	-0.63^{***}	-0.46^{**}	0.45^{**}	0.85^{***}	-0.86^{***}	1.00	-0.73^{***}	-0.58^{**}	Ns	-0.41^{**}	-0.51^{***}	0.51^{**}
StI	Ns	-0.39^{**}	Ns	0.81^{***}	0.67^{***}	-0.44^{**}	0.68^{***}	-0.39^{**}	-0.43^{**}	-0.49^{***}	-0.44^{**}	-0.57^{***}	Ns
CI	-0.41^{**}	0.67^{***}	0.44^{**}	-0.49^{**}	-0.81^{***}	0.86^{**}	-0.70	0.55^{**}	0.66^{***}	Ns	0.57^{***}	0.77^{***}	-0.38^{*}
Runoff lab	-0.35^{*}	0.67^{***}	0.35^{*}	-0.34^{*}	-0.81^{***}	0.78^{**}	-0.73^{***}	1.00	0.65^{***}	Ns	0.34^{*}	0.42^{**}	-0.48^{**}
Soil loss lab	Ns	0.78^{***}	Ns	Ns	-0.62^{***}	0.72^{***}	-0.58^{***}	0.65^{***}	1.00	Ns	0.42^{**}	0.67^{***}	-0.3^{*}
PR lab	Ns	Ns	Ns	-0.40^{**}	Ns	Ns	Ns	Ns	Ns	1.00	Ns	Ns	Ns
Runoff field	Ns	0.37^{*}	Ns	-0.41^{**}	-0.48^{**}	0.47^{**}	-0.41^{**}	0.34^{*}	0.42^{**}	Ns	1.00	0.66^{***}	Ns
Soil loss field	Ns	0.57^{**}	Ns	-0.42^{**}	-0.60^{***}	0.63^{***}	-0.51^{***}	0.42^{**}	0.67^{***}	Ns	0.66^{***}	1.00	Ns
PR field	0.61^{***}	-0.44^{**}	-0.63^{***}	Ns	0.58^{**}	-0.61^{**}	0.51^{***}	-0.48^{**}	-0.30^{*}	Ns	Ns	Ns	1.00

4–2 mm is the per cent of aggregates between 4–2 mm in diameter; <0.25 mm is the per cent of aggregates <0.25 mm in diameter; SOM is the soil organic matter; MWD is the mean weighted diameter; P250 is the per cent of particles < 250 μm; C_{5-10} is the consistency index; ASI is the absolute sealing index; StI is the soil stability index; CI is the crusting index; PR is the penetration resistant; and Ns is not significant, n = 45.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Table 5
Runoff, soil loss and penetration resistance of the 'tropical' soils from Venezuela.

Soil	Laboratory condition				Field condition			
	Runoff (%)	Soil loss ($g\ m^{-2}\ mm^{-1}$)	PR (kPa)	Water content[a] (%)	Runoff (%)	Soil loss ($g\ m^{-2}\ mm^{-1}$)	PR (kPa)	Water content (%)
El Salao	28.9 d (23.2)	1.6 b (1.4)	216 b (54.5)	8.8 a (2.9)	32.4 b (11.4)	1.2 d (0.5)	438 a (27.2)	2.7 c (1.8)
Quíbor	70.4 ab (5.1)	43.4 a (10.6)	284 a (48.7)	4.0 b (2.9)	59.8 a (15.3)	16.3 a (7.4)	371 b (55.3)	4.3 b (2.8)
Danac	59.2 c (11.7)	9.7 b (4.2)	233 ab (22.3)	2.4 b (0.5)	45.2 ab (14.6)	6.4 bc (3.0)	258 c (73.3)	8.4 a (1.3)
Turén	65.6 bc (5.5)	46.1 a (19.2)	135 c (16.3)	2.3 b (0.46)	53.3 a (10.2)	12.3 ab (4.1)	247 c (32.5)	4.0 c (1.6)
El Sombrero	73.4 a (6.1)	31.1 a (7.8)	277 a (38.4)	3 b (0.3)	35.5 b (15.9)	3.7 cd (2.1)	243 c (30.0)	3.2 c (0.3)

Different letters in the same column refer to significant differences ($p < 0.05$); standard deviation for each measure is given in parentheses; and PR is penetration resistance.

[a] Gravimetric water content.

3.1.3. Runoff and soil loss

The results from the raindrop impact methods are presented in Table 5. The highest runoff (59–73%) and soil loss (10–46 $g\ m^{-2}\ mm^{-1}$) occurred on smectite-rich cultivated soils, whereas the non-cultivated soil (kaolinite-rich) was resistant to aggregate breakdown. The runoff and soil loss determined in the field were positively correlated with runoff and soil loss measured in the laboratory (Table 4) indicating that susceptibility to seal formation of these soils can be determined as well as under laboratory as under field conditions. Spearman coefficients in Table 4 show that a significant correlation exists between runoff and soil loss under laboratory ($0.55 < r < 0.85$) and field ($0.37 < r < 0.77$) conditions and the other indicators (Table 4). These results confirm that susceptibility to soil sealing is correlated with aggregate stability from wet sieving and mechanical breakdown by raindrop impact, as mentioned by Barthes and Roose (2002) and LeBissonnais (1996).

As could be expected, the higher runoff and soil loss under field conditions were due to the packing of the laboratory soil pans with larger sized aggregates than under natural field conditions. Runoff is indeed affected by the initial aggregate sizes (Lado et al., 2004b). In general, the larger the aggregate size the lower the rate of runoff and soil loss. The response of the soil to seal formation and the final infiltration rate of the seal also depended on antecedent soil water content prior to rainfall (Lado et al., 2004a; Vermang et al., 2009). Under field conditions the soils can be wetted at different rates resulting in different water contents before they are exposed to high intensity rainstorms, whereas under our laboratory condition air-dried soils were exposed only to fast wetting. In laboratory experiments on a silt loam soil with simulated rain, Vermang et al. (2009) found lowest runoff and soil loss rates, highest aggregate stability and lowest seal formation with the highest antecedent water contents (which was at a typical 'field capacity' value in their study), which supports our findings.

Correlation analysis indicated that aggregate stability as determined by ASI, runoff and soil loss under laboratory and field conditions was effective in predicting soil susceptibility to seal formation. Even if these laboratory and field conditions include different sizes of aggregates, they produce the same degradation mechanics on the aggregates. The similarity found among raindrop impact and wet sieving tests suggests that for the Venezuelan 'tropical' soils under study, the wet mechanical cohesion of aggregates was similar, irrespective of the wetting method.

3.1.4. Crust penetration resistance

The values of PR under laboratory (135–284 kPa) and field (243–438 kPa) conditions in all the soils refer to limitation in seedling emergence (Table 5). Lozano et al. (2000) found that for soils with dominance of particles between 2 and 250 μm in diameter, the maize and sorghum seedling emergence was reduced from 80 to 100% when the PR of the crust was in a range of 300–430 kPa, and from 30 to 50% when PR was between 200 and 250 kPa.

The PR can only be compared among soils if soil water contents are also taken into account, since the latter have an effect on soil strength (Amezketa et al., 2003). The soil water content was very low under laboratory and field conditions (Table 5). Under laboratory condition the water content was significant higher in the kaolinite-rich soil and not significantly different in the other soils, suggesting that for the smectite-rich soils differences in PR are only related to other soil characteristics. Under field conditions the water content was significantly different among the soils, making it difficult to analyze the results.

The seals formed in the pans were the result of one simulated rainfall event. The successive crusts were very thin and the soil material under the crust consisted of undisrupted aggregates. In contrast, the crusts evaluated in the field were thick and with horizontal arrangement of the sediment, there were evidences of cumulative processes of sedimentation and deposition due to successive rainfall events (Boiffin and Monnier, 1986). According to Tanaka et al. (1999) the soil crusting degree is directly related to the number of rainfall events. No correlation was found between the PR under laboratory and field conditions (Table 4). Hence, under the evaluated conditions and the soils studied the PR does not provide a comparable indicator of susceptibility to soil sealing.

3.1.5. Consistency index

The $C_{5–10}$ values show that *Quíbor* and *Turén* are stable soils (>2.5) and the others are unstable (<2.5). This is not as one would expect according to the clay and the SOM content of the soils. The $C_{5–10}$ has been reported by De Ploey (1981) as positively related to the percentages of clay and the SOM content for loam and sandy loam soils. Using the mean values of $C_{5–10}$ the ranking with respect to susceptibility to sealing in a decreasing order is: *El Sombrero* (1.9) = *Danac* (1.9) > *El Salao* (2.3) > *Turén* (3.1) = *Quíbor* (3.8). According to De Ploey and Mücher (1981) stable and well-structured soils are more hydrophobic than unstable material. Therefore, more water must be added to a remolded stable material in order to lower its consistency. Smectitic soils are expected to be very plastic, whereas kaolinitic soils are expected to be slightly plastic to plastic. Our results show that the $C_{5–10}$ is not a capable indicator for ranking the evaluated soils according to their susceptibility to seal formation. This is supported by the fact that a low or a not significant correlation was found between $C_{5–10}$ and the other methods evaluated in this study (Table 4).

3.1.6. Indices for estimation the susceptibility to soil sealing based on soil physical characteristics

The results from the StI did not reflect the greater aggregate stability of the kaolinitic soil (*El Salao*) compared with the smectitic soils (the other soils) (Table 3). The StI indicates that higher levels of SOM are needed to maintain the soil structure in these soils where there is a dominance of clay and silt particles. On the other hand, Guerra (1994) found that soils with low OC (<2.3%) but with high clay content (>22%) have a resistance against runoff and soil loss. This suggests that clay may compensate the deficiency in SOM, probably because the organic compounds need to form bonds with clay particles for producing strong aggregates. It has been found that kaolinitic soils have the capacity to form more stable aggregates through electrostatic binding between the minerals (Barthes et al., 2008; Denef and Six, 2005). This makes aggregates less dispersible and more flocculative, preventing seal formation (Lado et al., 2004b; Wakindiki and Ben-Hur, 2002).

StI does not take into consideration neither the interaction of factors like SOM–clay, nor the components of SOM and the clay mineralogy. This is a disadvantage for the StI to be an indicator of susceptibility to sealing for stable kaolinitic-clayey soils.

On the other hand, the CI value for the kaolinitic soil was close to 0.2, a value reported by FAO (1980) for soils with no crust formation. The other soils had values higher than or near 2, which is considered a critical limit for high risk seal formation. The CI proposed by FAO (1980) was significantly correlated with the other methods (Table 4), and enabled the distinguishing of the soil susceptibility to sealing, and ranking the soils in the same order as wet sieving tests and raindrop impact tests: *Quíbor* = *Turén* > *Danac* > *El Sombrero* > *El Salao*. The CI also involves clay, and SOM content as contributing factors to soil structure, in comparison with the StI. However, the CI expressed the risk for soil crusting formation in the function of the silt fractions, which is apparently a more capable indicator for evaluating susceptibility to sealing and crusting for our soils. Although the condition of soil sealing formation is different in the field as compared to the laboratory, also different factors are responsible for promoting sealing in different soils. CI can be considered as a good qualitative indicator of the susceptibility for sealing.

3.2. Association of soil sealing formation with soil characteristics

Low risk to seal formation was associated with high clay content, while a high seal formation was associated with high silt and very fine sand contents. The particle size fractions (silt, clay, silt + very fine sand) and the 4–2 mm aggregates, <0.25 mm aggregates, P250, MWD, ASI, CI and runoff (laboratory) were significantly correlated (Table 4). This confirmed that the particle size (silt, clay, silt + very fine sand) plays a determinant role in aggregate stability and in soil susceptibility to seal formation (Table 4). A positive correlation between clay content and aggregate stability has been reported by many authors (Bronick and Lal, 2005; Lado et al., 2004a; Levy and Mamedov, 2002). On the other hand, Canton et al. (2009) and Idowu (2003) reported that particle size did affect neither the wet aggregate stability nor the aggregate size distribution of soils.

Although *Turén* and *El Sombrero* had medium SOM content (Gilabert et al., 1990), they were very unstable with a high susceptibility to sealing. A link with SOM content is apparently absent in these soils, suggesting the interaction of other factors or the action of different SOM components into the soils. However, we found significant positive correlation among the soils between the SOM content and 4–2 mm aggregates, MWD and ASI, and a significant negative correlation between the SOM content and P250, CI, runoff and soil loss (Table 4).

With regard to the effect of clay mineralogy, it can be said that in the clayey kaolinite-rich soil studied here, the fraction of 4–2 mm aggregates was high and the soil susceptibility to seal formation was low. Reichert et al. (2009) evaluated the aggregate stability with two different techniques on soils with a different clay mineralogy. They found the largest aggregates in clayey soils rich in kaolinite, and Fe and Al oxyhydroxides, but not in 2:1 clay type silicates. High smectitic clay content increases the susceptibility to dispersion, slaking and swelling, and promotes seal formation, runoff and erosion (Lado et al., 2007; Levy and Mamedov, 2002).

Also the effect of the long-term history of land use might have affected the susceptibility to sealing. The most stable soil was found under a long-term savannah pasture and unstable soils under conventional arable cropping, confirming the results found by Amezketa (1999) and Pagliai et al. (2004).

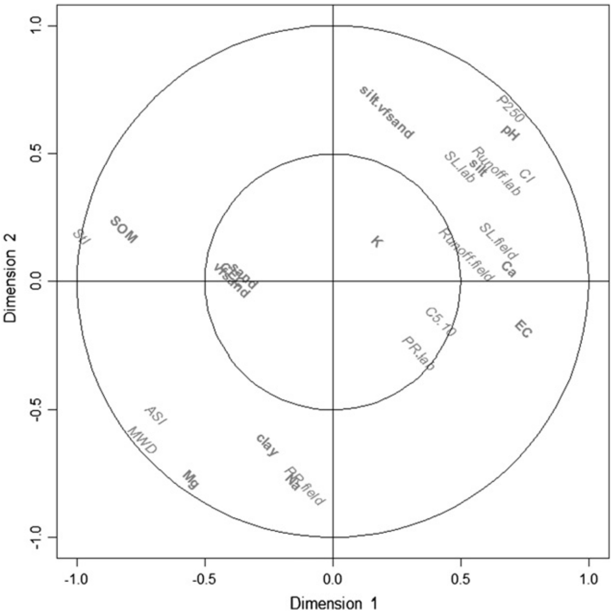


Fig. 1. Associations between physicochemical soil characteristics and the different soil sealing measurement methods. Plot illustrates the first two canonical variables. MWD is the mean weighted diameter; ASI is the absolute sealing index; StI is the soil stability index; PRfield is the penetration resistant under field condition; P250 is the per cent of particles < 250 μm; CI is the crusting index; SL.field is the soil loss under field condition, SL.lab is the soil loss under laboratory condition; Runoff.lab is the runoff under laboratory condition; Runoff.field is the soil loss under field condition; C_{5-10} is the consistency index; PR.lab is the penetration resistant under laboratory condition; SOM is the soil organic matter; CEC is the cation exchange capacity; and EC is the electrical conductivity.

A canonical correlation analysis (CCA) was conducted to identify and quantify the associations between physicochemical soil characteristics (clay, silt, sand, silt + very fine sand, pH, EC, K, Ca, Mg, Na, CEC and SOM) and the different soil sealing measurement methods. Fig. 1 displays the contribution of the original variables to the first two canonical variables. This denotes linear combinations of the original variables that maximize the correlation between the physico-chemical variables and the soil sealing assessment methods. This respective contribution is given by their coefficients on the X- and Y-axes. Close distances between dots indicate associations of parameters but not necessarily causality. For instance, for the first canonical variable (X-axis), a large value for P250 (large positive value on X-axis) is more likely to be associated with soils containing large pH, silt, Ca and EC values (large positive value on X-axis) and small Mg and SOM values (large negative value on X-axis). Whereas large values of ASI or MWD (large negative vale on X-axis), are more likely to occur in soils with large Mg and SOM values. Similar interpretations can be given for the second canonical variable (Y-axis), which still corresponds to an overall correlation of the two sets of variables of more than 0.99. The CCA confirms that there exists an association between different soil sealing measured methods and the soil characteristics.

3.3. Similarity of soil sealing assessment methods

Not all of the soil sealing assessment methods were significantly correlated among each other (Table 4). The C_{5-10} and PR were not able to rank the soils in the same way as the other methods according to their soil sealing susceptibility. This was reflected in the non-significant correlation of C_{5-10} and PR with the other methods. There was a predominance of lower significant correlation coefficients with runoff and SL in the field, though statistically significant. The parameters evaluated in the field are not related to soil fractions but rather to the entire soil sample.

Fig. 2 gives a visual impression of the similarity of all methods in evaluating the susceptibility to sealing for the different soils. Methods in the dendrogram placed close to each other provide similar results as compared to methods that are more separated one from the other. At a height of 7, a total of 5 distinct clusters could be distinguished. The first cluster consists of MWD, ASI and StI, while the second cluster was essentially PR in the field. The third cluster is characterized by P250, CI and SL and runoff under both field and laboratory conditions. The fourth cluster is formed by C_{5-10} and the fifth cluster is formed by PR under laboratory condition.

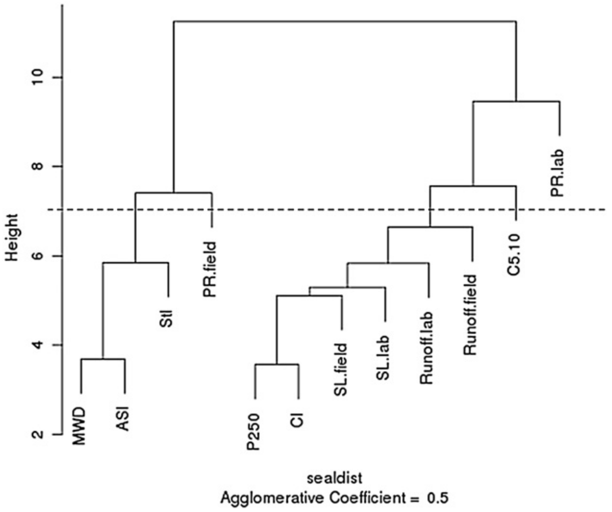


Fig. 2. Visual impression of the similarity of all methods in evaluating the susceptibility to sealing for the different Venezuelan 'tropical' soils. Dendrogram Agnes average linkage of all methods at all sites. See also legend of Fig. 1 for abbreviations.

High values measured by the methods shown in the first cluster correspond with a low risk of soil sealing. In contrast, cluster 3 joined methods for which a high value was associated with a high risk of soil sealing. Methods with a larger distance from these clusters are considered the most dissimilar ones, being C_{5-10} and PR under laboratory and field conditions. This confirms the deficiency of association with the other methods already mentioned. The MWD and ASI in the left branch and P250 and CI in the right branch of Fig. 2 are combined in a small distance between sequential vertical lines. These methods are similar to one another within clusters 1 and 3, respectively.

The similarities obtained from the wet sieving tests, under the conditions prevailing in this study, ASI, CI, and runoff and soil loss under simulated rain, illustrate that there is no effect of different mechanisms involved. They could be suitable to derive comparable indicators for assessing seal formation in the Venezuelan 'tropical' soils. We suggest that the method used to assess seal formation in different soils has to be sufficiently sensitive to evaluate aggregates with low aggregate stability. Wet sieving and drop impact tests are among the most suitable methods for evaluating those soils.

4. Conclusions

Although MWD, P250, ASI, CI, and runoff and soil loss under simulated rainfall, involve a different mechanism to evaluate surface structural stability, they enabled the assessment and comparison of susceptibility to sealing among smectite-rich loam to kaolinite-rich clayey soils. Measuring C_{5-10} and PR are not comparable tests for soil susceptibility to sealing formation of the Venezuelan 'tropical' soils. Although PR is generally proposed as being a suitable indicator for soils within the same range of water content, our studied soils could however not confirm this. StI did not reflect the high stability of the kaolinitic-clayey soil in this study, because it considers SOM as the most important factor to maintain the soil structure, a condition not predominant in this soil. The close similarities between MWD, ASI, P250 and CI suggest that these tests can be used as a comparable indicator of sealing for the evaluated Venezuelan 'tropical' soils. This study further proposes that when topsoil aggregates are characterized by high silt and smectite contents the use of wet sieving (slow wetting) and raindrop impact tests or simple indices such as StI and CI can satisfactorily assess the susceptibility to seal formation. Differences obtained in seal formation ranking indicated that method selection impacts the measured value. It can therefore be recommended to take the effect of the method into account when interpreting the results obtained.

Acknowledgments

This research was supported by the Consejo de Desarrollo Científico y Humanístico (CDCH) of the Universidad Central de Venezuela (UCV). The authors are also grateful to the anonymous referees for their helpful comments and suggestions.

References

Amezketa, E., 1999. Soil aggregate stability: a review. J. Sustain. Agric. 14, 83–151.

Amezketa, E., Aragues, R., Perez, P., Bercero, A., 2003. Techniques for controlling soil crusting and its effect on corn emergence and production. Span. J. Agric. Res. 1, 101–110.

Assouline, S., Ben-Hur, A., 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena 66, 211–220.

Barthes, B., Roose, E., 2002. Aggregate stability as an indicator of soil susceptibility to runoff and erosion; validation at several levels. Catena 47, 133–149.

Barthes, B.G., Kouakoua, E., Larre-Larrouy, M.C., Razafimbelo, T.M., de Luca, E.F., Azontonde, A., Neves, C., de Freitas, P.L., Feller, C.L., 2008. Texture and sesquioxide effects on water-stable aggregates and organic matter in some tropical soils. Geoderma 143, 14–25.

Beare, M.H., Bruce, R.R., 1993. A comparison of methods for measuring water stable aggregates implications for determining environmental effects on soil structure. Geoderma 56, 87–104.

Boiffin, J., Monnier, G., 1986. Infiltration rate as affected by soil surface crusting caused by rainfall. In: Callebaut, F., Gabriels, G., De Boodt, M. (Eds.), Assessment of Soil Surface Sealing and Crusting. Proceedings of Symposium, Ghent, Belgium, 1985, pp. 210–217.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22.

Canton, Y., Sole-Benet, A., Asensio, C., Chamizo, S., Puigdefabregas, J., 2009. Aggregate stability in range sandy loam soils: relationships with runoff and erosion. Catena 77, 192–199.

Chartres, C.J., Greeves, G.W., 1998. The impact of soil seals and crusts on soil water balance and runoff and their relationship with land management. Towards Sustainable Land Use, vols. I & Ii 31 pp. 539–548.

De Ploey, J., 1981. Some laboratory techniques for investigating land erosion. Erosion and sediment transport measurement. Proceedings of the Florence Symposium. IAHS Publ, no. 133, pp. 423–442 (Online: http://iahs.info/redbooks/a133/iahs_133_0423.pdf).

De Ploey, J., Mücher, H.J., 1981. A consistency index and rain-wash mechanisms on Belgian loamy soils. Earth Surf. Process. Landforms 6 (3–4), 319–330.

Denef, K., Six, J., 2005. Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. Eur. J. Soil Sci. 56, 469–479.

Diaz-Zorita, M., Perfect, E., Grove, J.H., 2002. Disruptive methods for assessing soil structure. Soil Tillage Res. 64, 3–22.

El Swaifi, S.A., Dangler, E.W., 1982. Rainfall erosion in the tropics. Soil Erosion and Conservation in the Tropics. Special Publication, vol. 43. American Society of Agronomy.

F.A.O., 1980. Metodología provisional para la evaluación de la degradación de los suelos (Roma-Italia. 86 pp.).

Gabriels, D., Horn, R., Villagra, M.M., Hartman, R., 1997. Assessment, prevention and rehabilitation of soil structure caused by soil surface sealing, crusting and compaction. In: Lal, R., Blum, W.H., Valentine, C., Stewart, B.A. (Eds.), Methods for Assessment of Soil Degradation. Advances in Soil Science. CRC Press, Boca Raton, Florida USA, pp. 129–165.

Gilabert, J., López de Rojas, I., Pérez de Roberti, R., 1990. Manual de métodos y procedimientos de referencia. Análisis de suelos para diagnóstico de fertilidad. CENIAP, Maracay (Versión preliminar, 164 pp.).

Guerra, A., 1994. The effect of organic matter content on soil erosion in simulated rainfall experiments in W. Sussex, UK. Soil Use Manag. 10, 60–64.

Idowu, O.J., 2003. Relationships between aggregate stability and selected soil properties in humid tropical environment. Commun. Soil Sci. Plant Anal. 34, 695–708.

Johnson, R.A., Wichern, D.W., 2002. Applied Multivariate Statistical Analysis, 5th ed. Prentice-Hall, Upple Saddle River, NJ.

Kaufman, L., Rousseuw, P.J., 1990. Finding Groups in Data: An Introduction to Cluster Analysis. Wiley, New York.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution, In: Klute, A. (Ed.), Methods of Soil Analysis Part 1, Physical and Mineralogical Methods, 2nd edition. Agronomy Monograph, No 9. American Society of Agronomy, Inc., Madison, WI, pp. 425–442.

Kretschmer, H., 1996. Koernung und Konsistenz, In: Blume, H.-P., Felix-Henningsen, P., Fischer, W.R., Frede, H.G., Horn, R., Stahr, K. (Eds.), Handbuch der Bodenkunde, 1st ed. Ecomed, vol. I (Chapter 2.6.1.1).

Lado, M., Ben-Hur, M., Shainberg, I., 2004a. Soil wetting and texture effects on aggregate stability, seal formation, and erosion. Soil Sci. Soc. Am. J. 68, 1992–1999.

Lado, M., Paz, A., Ben-Hur, M., 2004b. Organic matter and aggregate size interactions in infiltration, seal formation, and soil loss. Soil Sci. Soc. Am. J. 68, 935–942.

Lado, M., Ben-Hur, M., Shainberg, I., 2007. Clay mineralogy, ionic composition, and pH effects on hydraulic properties of depositional seals. Soil Sci. Soc. Am. J. 71, 314–321.

LeBissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility. 1. Theory and methodology. Eur. J. Soil Sci. 47, 425–437.

Levy, G.J., Mamedov, A.I., 2002. High-energy-moisture characteristic aggregate stability as a predictor for seal formation. Soil Sci. Soc. Am. J. 66, 1603–1609.

Lozano, Z., Lobo, D., Pla, I., 2000. Limitaciones a la emergencia de plántulas de maíz (*Zea mays* L.) y sorgo (*Sorghum bicolor* L.) en algunos suelos de Venezuela. Rev. Fac. Agron. (Maracay) 26, 15–25.

Martínez-Gamiño, M.A., Walthall, P.M., 2000. Physical, chemical, and mineralogical properties affecting soil crust formation in soils of Mexico and Louisiana, USA. Terra 18 (3), 179–185.

Nacci, S., Pla, I., 1991. Técnicas y equipos desarrollados en el país para evaluar propiedades físicas de los suelos. Serie B, No 17. FONAIAP, Maracay (Venezuela) (40 pp.).

Pagliai, M., 2003. Soil surface sealing and crusting–soil compaction. College on Soil Physics. ICTP, Trieste Italy (24 pp.)

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil Tillage Res. 79, 131–143.

Pieri, C.J.M.G., 1992. Fertility of Soils: A Future for Farming in the West African Savannah. Springer-Verlag, Berlin, Germany.

Pla, I., 1993. Degradación de suelos y sustentabilidad de los sistemas agrícolas. Memorias de la Segunda Reunión Bienal de la Red Latinoamericana de Labranza Conservacionista. FONAIAP, Guanare — Portuguesa pp. 16–18.

Poesen, J., 1986. Surface sealing on loose sediments: the role of texture, slope and position of stones in the top layer. In: Callebaut, F., Gabriels, D., De Boodt, M. (Eds.), Assessment of Soil Surface Sealing and Crusting. Proceedings of the symposium, Ghent, Belgium, pp. 354–362.

R Development Core Team, 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria 3-900051-07-0 (URL http://www.R-project.org/).

Reichert, J.M., Norton, L.D., Favaretto, N., Huang, C.H., Blume, E., 2009. Settling velocity, aggregate stability, and interrill erodibility of soils varying in clay mineralogy. Soil Sci. Soc. Am. J. 73, 1369–1377.

SAS Institute Inc., 1989. Fourth edition. SAS/ATAT® User's Guide, Version 6, vol. 2. SAS Institute Inc., Cary, NC (846 pp.).

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79, 7–31.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Tanaka, U., Yokoi, Y., Kosaki, T., Kyuma, K., 1999. Mechanisms and processes of crust formation on artificial aggregates — III. Relations between natural rainfall characteristics and degree of crusting. Soil Sci. Plant Nutr. 45, 537–549.

Valentin, C., Bresson, L.M., 1997. Soil crusting. In: Lal, R., Blum, W.H., Valentine, C., Stewart, B.A. (Eds.), Methods for Assessment of Soil Degradation. Advances in Soil Science. CRC. Press, Boca Raton, Florida USA, pp. 89–107.

Vermang, J., Cornelis, W.M., Demeyer, V., Gabriels, D., 2009. Aggregate stability and erosion response to antecedent water content of a loess soil. Soil Sci. Soc. Am. J. 73, 718–726.

Wakindiki, I.I.C., Ben-Hur, M., 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration, and erosion. Soil Sci. Soc. Am. J. 66, 897–905.

Yoder, R.E., 1936. A direct method of aggregate analysis of soil and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28, 337–351.