LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2013)
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.2225

COMPARING AGGREGATE STABILITY TESTS FOR SOIL PHYSICAL QUALITY INDICATORS

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Received: 20 February 2013; Revised: 29 April 2013; Accepted: 30 April 2013

ABSTRACT

Although there is not a sole satisfactory methodology that applies universally up to now, aggregate stability has been proposed as an indicator of soil physical quality (SPQ). Difficulties persist when comparison of aggregate stability from different procedures are performed. The objective of this study is to evaluate appropriate aggregate stability methods that enable to distinguish the SPQ condition of both temperate and tropical medium-textured soils. Among different methods tested, results show that wet sieving using the well known fast wetting methods of Kemper & Rosenau and of Le Bissonnais rendered similar results in both environments. The mean weight diameter value of both methods for assessing aggregate stability can be considered as a dependable indicator of soil structure status for comparing soils. These aggregate stability methods are in correspondence with only one out of the eight SPQ indicators when entirely soils were used. It was concluded that the aggregate stability should be used judiciously and in concert with other indicators for an overall assessing of the SPQ condition.

KEY WORDS: temperate and tropical soils; soil structure; soil physical quality indicators

INTRODUCTION

Soil aggregate stability is the ability of the soil to retain its arrangement of solids and pore spaces after the application of a mechanical stress or destructive forces (Diaz-Zorita *et al*., 2002). When the stress applied is higher than the binding forces, weak aggregates are disrupted, and as a result, the deterioration of the soil structural quality takes place (Horn *et al*., 1994; An *et al*., 2010).

There are different methods for measuring aggregate stability that are based on the fragmentation of the soil samples after applying mechanical stresses (Amezketa, 1999). According to Lal & Shukla (2004), aggregate stability methods can be grouped into three categories: ease of dispersion by turbidimetric techniques (Emerson, 1967); evaluation of aggregate strength in terms of raindrop impact (Bruce-Okine & Lal, 1975); and aggregate size distribution and aggregate stability by wet sieving (Yoder, 1936).

From the wet sieving method, many other methodologies have been developed (Le Bissonnais, 1996), which differ in one or more of the following aspects: i) the prewetting techniques (Beare & Bruce, 1993); ii) the limit of the aggregate sizes, which determines their physical properties (Niewczas & Witkowska-Walczak, 2003); iii) the use of a single sieve or a nest of sieves (de Leenheer & de Boodt, 1959; Beare & Bruce, 1993; Le Bissonnais, 1996) and the different intensities of disruptive mechanical energy to the sample (Amezketa, 1999); and iv) the liquid used to immerse the sample (Henin *et al*., 1958; Le Bissonnais, 1996). These aspects make the comparison of aggregate stability from different procedures very difficult. Additionally, the different expressions of the stability results also complicate the comparison among them.

Other simple and sophisticate methods, such as visual soil structure information (Mueller *et al*., 2013) and aggregate stability measurements by laser granulometry with sonication (Rawlins *et al*., 2013) have been developed to monitor the soil structure or the aggregate stability as a soil physical quality (SPQ) indicator. However, in this study we focus on standard methods to measure water-stable soil aggregates (WSA), involving sieving. Although there is not a sole satisfactory methodology that applies universally up to now, aggregate stability has been proposed as one of the soil physical properties that can be used as an important physical indicator of soil quality (Arshad & Coen, 1992; Rawlins *et al*., 2013).

There are also several indirect indicators of soil structure used as SPQ indices. For instance, the relationship between the particle size distribution and the soil organic matter (Lal & Shukla, 2004), the bulk density (BD), the porosity, the air capacity (AC), the field capacity and the plant available water capacity (PAWC) (Reynolds *et al*., 2007; Reynolds *et al*., 2009). Some of these indicators are well related with S index proposed by Dexter (2004a), which is also an index of SPQ. In most soils, larger values of S index are consistent with the presence of a better-defined microstructure. The usefulness of the S index was demonstrated in a series of papers presented by Dexter (2004a, 2004b and 2004c).

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Whether aggregate stability 'function' in terms of soil strength, the storage and transmission of water and air can be estimated by the parameters mentioned previously, and hence, the aggregate stability being a good indicator of SPQ can be tested through the comparison against other indicators. The objective of this study is to evaluate appropriate aggregate stability methods that enable to distinguish the SPQ condition of both temperate and tropical medium-textured soils. Additionally, the evaluation of selected methods by comparing them with other indicators of SPQ is conducted with the purpose of using aggregate stability as a dependable indicator of the soil structure status.

MATERIALS AND METHODS

Soils Description and Soil Sampling

Ten soils were selected, with six located in a tropical environment (V_1–V_6; Venezuela) and four in a temperate one (B_1–B_4; Belgium). The soils are described in Table I. Three transects were randomly laid out along the soils. Disturbed and undisturbed soil samples were taken at two spots in each transects. At each spot, the disturbed samples were taken from the upper layer to 20 cm depth and the core samples to 10 cm depth. Disturbed samples were analysed to determine the particle size distribution by the pipette method (Gee & Or, 2002), soil organic carbon (SOC) measured by wet oxidation (Walkley & Black, 1934), and the aggregate stability using different methods described hereafter.

For taking core samples, 100 cm^3 Kopecky rings were driven into the soil using a ring holder. Three core samples were taken in each spot to obtain a total of 18 for each field site. Saturated hydraulic conductivity (Ksat), soil water retention curve (SWRC), and BD were determined on the core samples.

Saturated Hydraulic Conductivity, Soil Water Retention Curve and Soil Bulk Density

The Ksat was determined using the constant head method with a closed laboratory permeameter system (Eijkelkamp Agrisearch Equipment, the Netherlands). The SWRC was constructed by measuring soil water content at eight heads using the same cores. For the pressure potential ranging from −1 to −100 cm, the sand box apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used. Pressure chambers were used to measure water content at −340 cm, −1,020 cm and −15,000 cm (Soil Moisture Equipment, Santa Barbara, C.A., USA). The procedure is described by Cornelis *et al.* (2005). Soil dry BD was determined at −100 cm matric head. Shrinkage was observed in some of the rings as well as some stones hence a correction of the volume was performed. AC ($\theta_{h=0\,cm} - \theta_{h=-100\,cm}$), PAWC ($\theta_{h=-340\,cm} - \theta_{h=-15{,}000\,cm}$) and relative water capacity (RWC, $\theta_{h=-340\,cm}/\ \theta_{h=0\,cm}$) were calculated from the SWRC data, with h denoting matric head.

Aggregate Stability

Aggregate stability was measured on air-dried soil samples by using three different methods: i) the wet sieving method with multiple sieves proposed by de Leenheer & de Boodt (1959) and adjusted by Hofman (1973); ii) the three treatments of the method by Le Bissonnais (1996); and iii) the wet sieving method using one single sieve based on Kemper & Rosenau (1986). All analyses were replicated three times for each sample.

The method of de Leenheer & de Boodt (1959) and adjusted by Hofman (1973), abbreviated here as dLdB, was conducted as described by Leroy *et al.* (2008). The results were expressed in terms of the mean weight diameter (MWD):

$$\mathrm{MWD} = \frac{\sum_{i=1}^{i=n} m_i d_i}{\mathrm{m}_i} \tag{1}$$

Where: m_i = mass of aggregate fraction i; d_i = mean diameter of fraction i.

The instability index (IS) was calculated as the difference between the initial MWD and the final MWD. The inverse of the instability index, the stability index (SI), was taken as a measure of the stability of the aggregates:

$$\mathrm{SI} = \frac{1}{\mathrm{IS}} \tag{2}$$

Classification of the aggregate stability based on SI (de Leenheer & de Boodt, 1959), for medium-textured Belgian soils include the following rating: >1 = excellent; 0·8 to 1 = very good; 0·66 to 0·8 = good; 0·5 to 0·66 = unsatisfactory; and <0·5 = bad.

Table I. Description and characteristics of the tropical (V1–V6; Venezuela) and temperate (B1–B4; Belgium) soils

Soil	Textural class	Geographic coordinates	Location	Clay	Silt	Sand	SOC
				(g kg^{-1})			
V1	Sandy clay loam	10° 22′N 67° 12′W	La Colonia Tovar, Aragua	285·2	198·6	516·2	42·6
V2	Clay loam	10° 15′N 67° 37′W	Maracay, Aragua	291·0	282·3	426·7	24·4
V3	Loam	10° 21′N 68° 39′W	Danac, Yaracuy	172·8	350·7	476·5	7·5
V4	Loam	8° 46′N 67° 45′W	La Fundación, Guárico	229·5	485·8	284·7	20·3
V5	Silt loam	9° 0′N 67° 41′W	El Cujicito, Guárico	261·0	583·0	156·0	29·1
V6	Silty clay	9° 02′N 67° 41′W	Las Nubes, Guárico	423·1	501·3	75·6	16·1
B1	Sandy loam	50° 59′N 3° 31′E	Kruishoutem, Flanders	136·5	119·6	743·9	11·6
B2	Silt loam	50° 46′N 3° 35′E	Nukerke, Flanders	164·5	627·9	207·6	13·4
B3	Silt loam	50° 47′N 3° 25′E	Heestert, Flanders	125·4	657·7	216·9	9·4
B4	Loam	50° 47′N 2° 49′E	Kemmel, Flanders	97·7	531·8	370·5	9·6

The procedure of Le Bissonnais (1996), shortened here as LB, involves three treatments, which represent different wetting procedures: fast wetting (LB1), slow wetting (LB2) and mechanical breakdown by shaking after prewetting (LB3). The aggregate stability resulted from the three treatments was expressed by calculating MWD and SI from Equations (1) and (2). Le Bissonnais (1996) suggested the following classes of stability according to MWD values measured with the three treatments: >2 = very stable; 1·3 to 2 = stable; 0·8 to 1·3 = medium; 0·4 to 0·8 = unstable; and <0·4 = very unstable.

Finally, the Yoder method modified by Kemper & Rosenau (1986), denoted here as KR, calls for air-drying and rehumidifying the soil samples prior to wet sieving in distilled water to determine the recovery of aggregated particles on a single sieve (0·25 mm). Fast wetting (FW) and slow wetting (SW) were applied to determine the aggregate stability by using the wet sieving apparatus by Eijkelkamp Agrisearch Equipment (the Netherlands). The SW of aggregates was performed on a tension table at a matric potential of −3 cm for 30 min. For both prewetted conditions, 2 to 1 mm air-dried aggregates were wet sieved for 3 min at a constant, automatically controlled speed. From the WSA, the MWD was calculated:

$$\mathrm{MWD} = \frac{\mathrm{W_s\,d}}{\mathrm{W_t}} \tag{3}$$

Where: $\mathrm{W_s}$ is the stable soil aggregate fraction; d is the mean diameter of the fraction; $\mathrm{W_t}$ is the total weight of the sample.

In this study, for dLdB and LB methods, a very stable soil was considered as having >70% of WSA remained on the sieve of 0.5 mm and those above it. An unstable soil has <50% WSA. For KR method, a stable soil was considered having >70% of the aggregates remaining on the sieve of 0.25 mm after wet sieving, and an unstable soil has <50%.

Soil Structure and Soil Quality Indices

Structural stability index

Particle size distribution and 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:

$$\mathrm{StI} = \frac{1\cdot 72 \times \mathrm{SOC}}{\mathrm{Clay} + \mathrm{Silt}} \times 100 \tag{4}$$

Where: SOC is the SOC content (%) and Clay + Silt is the soil's combined clay and silt content (%). 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.

Index of soil physical quality, S index

The SWRCs were used for deriving the parameters of the van Genuchten equation (van Genuchten, 1980) by curve fitting with the m = 1 to 1/n constraint:

$$\theta(h) = \theta_{res} + \frac{\theta_{\mathrm{sat}} - \theta_{res}}{\left[1 + |\alpha \mathrm{h}|^{n}\right]^{m}} \tag{5}$$

Where: θ_{sat} is the soil water content at saturation; θ_{res} is the residual soil water content; h is the suction in centimetres; α as well as n and m are parameters, respectively, related to h and the curve's slope at its inflection point. The estimation of these parameters was performed with the Retention Curve programme (RETC).

The following equation was used to calculate the slope at the inflection point, S index, in terms of the parameters of the function:

$$\mathrm{S} = -n\left(\theta_{\mathrm{sat}} - \theta_{res}\right)\left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n}-2\right)} \tag{6}$$

Because the index depends on θ_{res}, it was necessary to set the residual water content in Equation 5 equal to zero to prevent negative fitted values being obtained (Cornelis *et al*., 2005). This was also performed by Dexter (2004b) and should allow better comparison between the various soils. The following categories of this SPQ index have been suggested by Dexter (2004c): S > 0·035 = good; 0·02 < S 0·035 = poor; and S < 0·02 = very poor.

Statistical data analysis

Differences between coefficients of variation of the aggregate stability methods were determined with an analysis of variances, with methods as factor, on the ration of the absolute deviations associated with each observation from its respective group mean divided by the group mean. A post hoc Duncan test was used to detect statistical differences among methods. Further, a Spearman correlation test was conducted between each pair of variables. Similarities between methods were revealed and displayed by multidimensional scaling (ALSCAL procedure of SPSS) on the standardised data by ranking. This procedure assigns observations to specific locations in a chosen conceptual two-dimensional space such that the distances between points in the space match the given similarities as closely as possible. These analyses were performed using the statistical package SPSS (version 17·0, SPSS Inc., USA).

RESULTS

Comparison of Methods for Measuring Aggregate Stability

Similitudes by ranking soils and expressing results

To present the aggregation data by using a common index, results from the three aggregate stability methods were expressed in terms of MWD. Others as WSA and SI were selected according to the methodology used. Method abbreviations are shown in Table II.

Table II. Mean of the aggregate stability indices values for soils from tropical (V1–V6; Venezuela) and temperate (B1–B4; Belgium) environments

	V1	V2	V3	V4	V5	V6	B1	B2	B3	B4
MWD_{dLdB}	3·63 (0·06)	3·58 (0·15)	2·29 (0·31)	1·93 (0·70)	3·97 (0·08)	2·62 (0·50)	2·11 (0·22)	1·71 (0·33)	2·92 (0·33)	0·82 (0·17)
SI_{dLdB}	1·22 (0·10)	1·15 (0·21)	0·46 (0·07)	0·40 (0·15)	2·07 (0·31)	0·55 (0·16)	0·43 (0·04)	0·37 (0·04)	0·66 (0·14)	0·28 (0·01)
MWD_{LB1}	1·78 (0·19)	1·86 (0·22)	0·51 (0·06)	0·79 (0·33)	2·99 (0·09)	0·93 (0·17)	0·73 (0·10)	0·67 (0·09)	0·53 (0·07)	0·33 (0·06)
MWD_{LB2}	3·46 (0·01)	3·37 (0·05)	1·64 (0·16)	1·99 (0·44)	3·46 (0·02)	1·89 (0·33)	3·25 (0·05)	2·85 (0·37)	1·60 (0·17)	2·04 (0·27)
MWD_{LB3}	3·15 (0·12)	3·18 (0·06)	1·50 (0·10)	1·82 (0·43)	3·38 (0·02)	1·99 (0·34)	0·65 (0·08)	1·98 (0·18)	0·71 (0·03)	0·80 (0·08)
MWD_{KRFW}	0·73 (0·05)	0·61 (0·07)	0·18 (0·02)	0·42 (0·11)	1·00 (0·02)	0·58 (0·07)	0·46 (0·10)	0·41 (0·10)	0·40 (0·08)	0·38 (0·12)
MWD_{KRSW}	1·02 (0·03)	0·82 (0·03)	0·77 (0·05)	0·68 (0·02)	1·01 (0·02)	0·84 (0·03)	0·84 (0·02)	0·90 (0·17)	0·83 (0·01)	0·76 (0·04)
WSA_{KRFW}	70·8 (4·67)	82·2 (5·39)	37·1 (4·37)	43·1 (10·43)	93· 4 (1·47)	57·3 (5·97)	44·9 (8·34)	37·9 (9·95)	34·5 (7·17)	39·6 (11·46)
WSA_{KRSW}	92·7 (1·70)	99·3 (0·42)	91·1 (0·88)	68·9 (0·87)	97·7 (0·24)	83·6 (0·24)	82·3 (1·00)	83·7 (0·75)	77·2 (0·62)	74·4 (3·21)

MWD_{dLdB}, mean weight diameter after drop impact and wet sieving; SI_{dLdB}, stability index after drop impact and wet sieving; MWD_{LB1}, mean weight diameter after LB1; MWD_{LB2}, mean weight diameter after LB2; MWD_{LB3}, mean weight diameter after LB3; MWD_{KRFW}, mean weight diameter after fast wetting; MWD_{KRSW}, mean weight diameter after slow wetting; WSA_{KRFW}, percentage of water-stable aggregates after fast wetting; WSA_{KRSW}, percentage of water-stable aggregates after slow wetting.
Standard deviation for each index is given in parenthesis (±)

The difference between initial MWD and final MWD represents a comparison of the aggregate status after dry and wet sieving. In case of the method of dLdB, the initial MWD was 4·45 mm. Soils V1, V2 and V5 showed less than 20% reduction in MWD. Soils V6 and B3 showed 30 to 40% and the other soils more than 50% MWD reduction. Higher instability is manifested by a higher reduction of MWD, hence lower SI. Soils V1, V2 and V5 have a high SI_{dLdB} (>1, excellent), B3 has a good aggregate stability ($SI_{dLdB} = 0{\cdot}68$) and the other soils showed a low SI_{dLdB} (≤0·66).

As illustrated in Figure 1a and 1b, >70% of WSA comprises the size fractions between 2 and 8 mm in diameter of the soils V1, V2 and V5, and between 50 and 70% of the soils V3, V6, B1, B2 and B3. Other soils have a higher proportion (> 50%) of the mass of aggregates in fractions <0·5 mm in diameter. Overall, the method of dLdB indicated that the soils with a higher aggregate stability and 'good' structural condition are V1, V2, V5 and B3.

Figure 2 displays the aggregate size distributions of the 0 to 20 cm soil layer, obtained after treatments according to the LB method. The aggregate size fractions were clearly affected by the treatment used. In the soils from the tropical environments, V1, V2 and V5 showed the highest proportion of aggregates in the fraction 5 to 2 mm with the three treatments. The other soils, after treatment LB1 > 50% of aggregates (in terms of mass) was retained between the sieves of 0·5 and 0·05 mm, and between 40 and 50% of aggregates, was retained in between 2 and 0·2 mm after treatments LB2 and LB3.

In the 'temperate' soils (B1 to B4), the trend in aggregate distribution among the three treatments of LB was different compared with the 'tropical' soils. When LB1 was applied, >50% of aggregate (in terms of mass) was collected in the fractions between 0·5 and 0·1 mm. After treatment LB2, B1 and B2 soils showed a very low breakdown of aggregates with 91 and 82%, respectively, remaining in the fraction 5 to 2 mm, which was not the case of B3 and B4. When LB3 was applied, fractions between 2 and 0·5 mm add up to >50% of aggregates for B1, B3 and B4. But with soil B2, >50% of the aggregates was collected in the fraction 5 to 2 mm.

These differences between LB treatments are also evidenced in the values of MWD. The MWD obtained after the different treatment of LB resulted in the order MWD_{LB2} $MWD_{LB3} > MWD_{LB1}$ for the soils except V6 and B1. The soils are according to the MWD_{LB1} values classified as very stable for V5, stable for V1 and V2, medium for V6 and unstable for the other soils. In terms of MWD_{LB2}, all soils are considered as very stable or stable. Finally, considering the MWD_{LB3}, soils are stable or very stable except for B1, B3 and B4, which are classified as unstable soils.

For both tropical and temperate soils, the higher MWD values obtained after treatment LB2, compared with the other treatments of LB method, suggest that this procedure prevents the disruption of the aggregates much more than the others. The differences in trends found by the used treatment of the LB method evidenced that a better discrimination

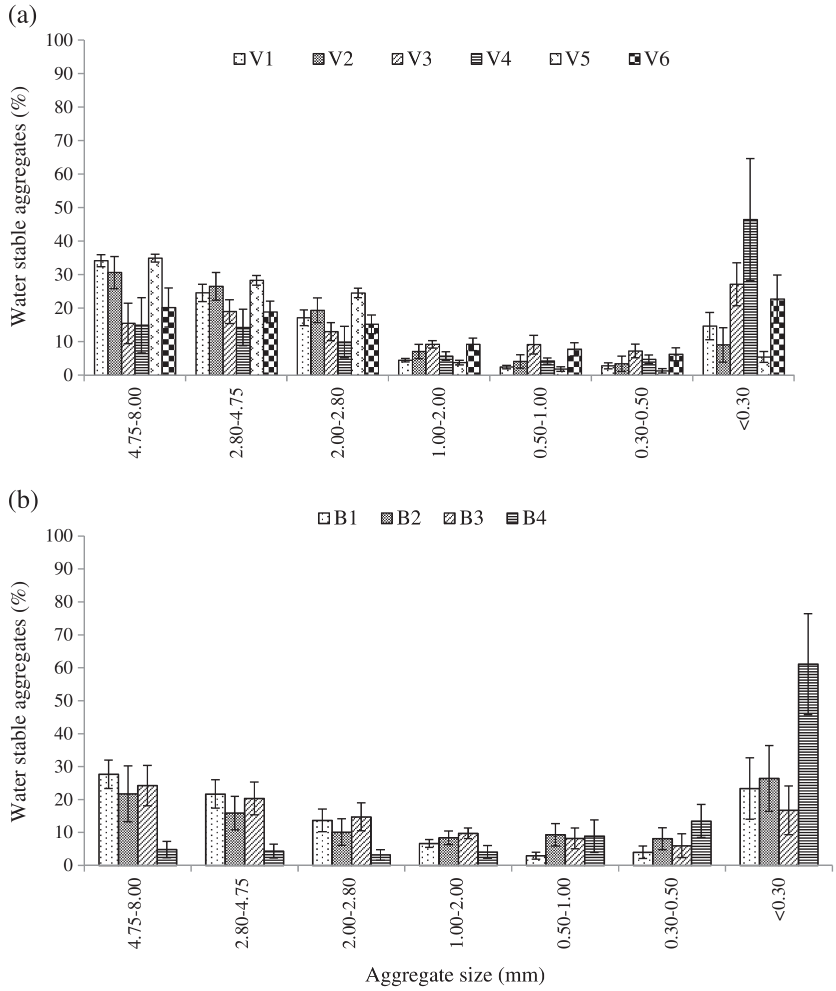

Figure 1. Distribution of the aggregate size fractions of the 0 to 20 cm layer according to the de Leenheer & de Boodt method (1959) for soils from tropical (V1–V6; Venezuela) (a) and temperate (B1–B4; Belgium) (b) environments.

between unstable soils is obtained when LB2 is applied. Soils B1 and B2 were very stable when slaking was prevented.

The results obtained from the KR method, were expressed in terms of WSA and MWD. With respect to WSA, the soils can be classified in terms of stability after FW as: V1, V2 and V5 being very stable soils; V6 is a stable soil; and the other soils are considered unstable (Table II). The reduction of MWD using FW of aggregates 2 to 1 mm in diameter was 30% for V5, between 50 and 60% for V1, V2, and V6 soils and >70% for the other soils. When comparing with the reduction of the initial MWD considered in the previous methodologies, the 2 to 1 mm size fraction is less resistant to breakdown after wet sieving when an FW was applied, except for V5.

Table II shows that when slowly prewetted aggregates were used, all the soils appeared as very stable. Between 70 and 90% of aggregates remained on the sieve after wet sieving. The results show a reduction of MWD_{KRSW} with less than 30% for all soils. Consequently, when SW at a matric potential of −3 cm for 30 min is used to prevent slaking, all soils expressed a high stability after shaking. This shows that the aggregate stability of our medium-textured soils was strongly affected by the moisture content of the aggregates before wet sieving.

The variability of the scores and the relationship between methods

Analysis of the differences between coefficients of variation was performed with the purpose of comparing the variability in the scores between the different methods of aggregate stability (Table III). Differences in variability were found between methods ($p < 0{\cdot}01$) for both tropical and temperate soils.

Table III shows that in our tropical soils, two groups of comparable methods are formed ($\alpha = 0{\cdot}05$), MWD_{KRFW} and MWD_{LB1} as one group, and MWD_{LB2} and MWD_{LB3} as another. The latter group is expected to give a better SPQ class when aggregate stability is used as an indicator ($p < 0{\cdot}01$). MWD_{LB2} and MWD_{KRSW} are distinct in classifying the SPQ condition of soils associated with a greater variability ($p < 0{\cdot}01$). For these soils, the different groups formed confirm that the procedures used in each method destroy the aggregates with a different intensity. In case of MWD_{dLdB}, MWD_{KRFW}, MWD_{LB1} and MWD_{LB3}, the

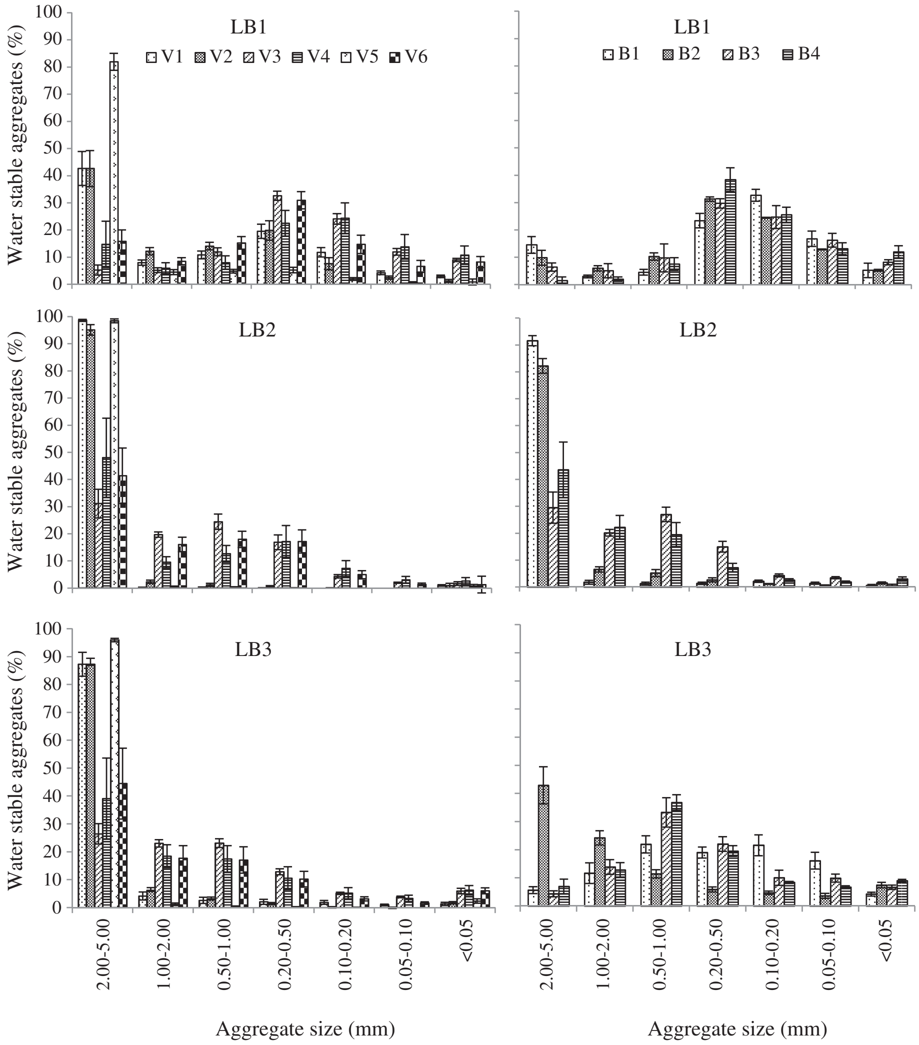

Figure 2. Distribution of the aggregate size fractions of the 0 to 20 cm layer from the Le Bissonnais method (1996) for soils from tropical (V1–V6; Venezuela) and temperate (B1–B4; Belgium) environments.

input energy by slaking and shaking over dry aggregates is more aggressive than prewetting the aggregates prior to wet sieving.

Both methods for determining MWD_{LB2} and MWD_{KRSW} start with removing the air from the aggregates (prewetting with water at a given matric head and with ethanol, respectively) before the energy is applied (hand or mechanical shaking). The different results found between the methods can be attributed to LB2 having a shorter wet sieving duration than KR, the immersion of the aggregates into different liquids for wet sieving and the aggregate size used.

On the other hand, there were high correlation coefficients with most of the methods applied on tropical soils (Table IV). The Spearman Rho was used as a numerical expression of the degree of correlation between the stability indices of the different methods providing similar parameters. The higher correlation between MWD_{LB1} and MWD_{KRFW} confirms the comparison of their results. These methods simulate aggressive forces, which promote breakdown of the unstable aggregates. Even if they include different sizes of aggregates, they produce the same degradation mechanics on the aggregates.

In case of temperate soils, the efficiency of the MWD_{KRFW}, MWD_{LB3} and MWD_{LB1} methods was similar for measuring aggregate stability as an SPQ indicator ($\alpha = 0{\cdot}05$). A different classification in SPQ condition is expected when results of aggregate stability determined by MWD_{KRSW}, MWD_{dLdB} and MWD_{LB2} are compared between them and against MWD_{KRFW}, MWD_{LB3} and MWD_{LB1} ($p < 0{\cdot}01$). However, in contrast with the Venezuelan soils, no significant correlation was found between most of the MWD of the aggregate stability methods for Belgian soils (Table IV).

Association of aggregate stability with other SPQ indicators

To select an appropriated aggregate stability method for the tropical and temperate soils, we tested their validity through their association with SPQ indicators mentioned by Reynolds *et al.* (2009). The mean of the SPQ indicators (Table V) were compared with the ‘optimal’ values used by Reynolds *et al.* (2009), except for BD, which was evaluated against critical BD values that limit root growth for various soils proposed by Pierce *et al.* (1983).

Table III. Summary statistics for stability indices related to tropical (V1–V6; Venezuela) and temperate (B1–B4; Belgium) soils

Methods	Methods of expressing	Methods abbreviation	Venezuelan soils					Belgian soils				
			Mean	StDev	C. V.*	Min	Max	Mean	StDev	C.V. *	Min	Max
de Leenheer & de	MWD	MWD_{dLdB}	3·00	0·88	**29 c**	0·95	4·12	1·83	1·32	**72 b**	0·15	3·67
Boodt	SI	SI_{dLdB}	1·07	0·74	69	0·29	3·03	0·52	0·30	57	0·23	1·29
Le Bissonnais	MWD	MWD_{LB1}	1·47	0·87	**59 b**	0·32	3·18	0·58	0·19	**33 bc**	0·24	1·06
		MWD_{LB2}	2·63	0·86	**33 a**	1·16	3·53	2·47	0·82	**33 a**	0·00	3·45
		MWD_{LB3}	2·50	0·79	**31 a**	1·13	3·42	1·06	0·61	**57 c**	0·46	2·47
Kemper & Rosenau	MWD	MWD_{KRFW}	0·59	0·26	**45 b**	0·14	1·04	0·41	0·11	**26 c**	0·24	0·69
		MWD_{KRSW}	0·86	0·13	**15 d**	0·61	1·07	0·83	0·06	**7·2 d**	0·69	0·93
	WSA	WSA_{KRFW}	64·03	21·27	33	33·67	95·50	39·28	9·55	24	24·00	60·17
		WSA_{KRSW}	88·76	11·40	12	54·75	99·33	79·44	6·01	7·5	67·67	88·58
Between methods	MWD	*p*-value	—	—	0·00	—	—	—	—	0·00	—	—

*Homogeneous subsets of Levene's test of the coefficients of variation (C.V.) among MWD of the different methods.
See also legend of Table II for abbreviations.

Within tropical soils, with medium to fine texture, the SPQ indicators except for S index enabled to distinguish two groups of SPQ within their respect ranges, that is, an optimal range for soils V1, V2 (good SPQ) and V3 (moderately good SPQ) as well as 'limited' range for V4 (moderately poor SPQ), V5 and V6 (poor SPQ).

This quality designation was based on the follow analysis. With the exception of V1, V2 and V5, the SOC content of the soils was lower than 2·3% (3·5% soil organic matter), which is the lower critical limit proposed by Greenland (1981) for maintaining soil structure in tilled soil. On the basis of the StI ranking proposed by Pieri (1992), soil V1 is considered as having a stable structure and V2 has a low risk of structural degradation. In contrast, the other soils are structurally degraded. Soils V5 and V6 have a BD higher than the 'critical' values (1·67 and 1·49 Mg m^{-3}, respectively) for causing reduction in root growth. The other soils have a mean BD in the optimum range for root growth.

V1 and V3 have an AC > 0.10 m^3 m^{-3}, a value required for good crop production and for adequate root zone aeration in sandy loam to clay loam soils. The other soils were not well aerated. A similar classification was obtained for the RWC indicator. With respect to PAWC, only V1, V5 and V6 fell into the limited category, which is suboptimal with respect to root growth/function and resistance to drought. The values of Ksat in V3, V4 and V5 are below the optimal range (18–1·8 cm h^{-1}), which might evidence a poor condition for water movement.

Note also that the optimal to limited SPQ groups provided by the indicators SOC, StI, BD, AC, RWC, PAWC and Ksat were consistent with the results of the aggregate stability tests expressed as MWD_{dLdB}, MWD_{KRFW} and MWD_{LB1} for soils V1, V2 (stable aggregates) and V3,V4 and V6 (moderately to unstable aggregates). In contrast, V5 has a contrasting condition when aggregate stability and SPQ provided by the other indicators are compared.

The temperate soils, also with medium texture, showed SOC values below the lower critical limit (≤2·2%) and StI values below 5%, except B1, which indicate a structurally degraded soil. BD was in the optimal range (1·33 Mg m^{-3} ≤ BD ≤ 1·48 Mg m^{-3}) with exception of B3. The PAWC values were limited for B1 and B3 (0·10 ≤ PAWC ≤ 0·15) and within the good range (0·15 ≤ PAWC ≤ 0·2) for B2 and B4. AC and RWC were below their minimum (0·10 m^3

Table IV. Correlation matrix (Spearman Rho) of the methods used for evaluating aggregate stability

	MWD_{dLdB}	MWD_{LB1}	MWD_{LB2}	MWD_{LB3}	MWD_{KRFW}	MWD_{KRSW}
MWD_{dLdB}	**1·00**	0·92**	0·85**	0·90**	0·91**	0·73**
MWD_{LB1}	−0·74**	**1·00**	0·89**	0·94**	0·98**	0·63**
MWD_{LB2}	−0·74**	0·86**	**1·00**	0·90**	0·86**	0·70*
MWD_{LB3}	−0·38^{NS}	0·12^{NS}	−0·03^{NS}	**1·00**	0·93**	0·66**
MWD_{KRFW}	0·34^{NS}	0·10^{NS}	0·00^{NS}	0·07^{NS}	**1·00**	0·64**
MWD_{KRSW}	0·19^{NS}	−0·33^{NS}	−0·42*	0·33^{NS}	0·18^{NS}	**1·00**

Values on the upper right side of the table correspond to the tropical dataset and the ones in the lower left part to the temperate dataset.
*$p < 0·05$.
**$p < 0·01$.
***$p < 0·001$.
^{NS}not significant.
See also legend of Table II for abbreviations.

Table V. Mean overall SPQ indicators for soils from tropical (V1–V6; Venezuela) and temperate (B1–B4; Belgium) environments

Indicators	V1	V2	V3	V4	V5	V6	B1	B2	B3	B4
SOC	4·26	2·44	0·75	2·03	2·91	1·61	1·16	1·34	0·94	0·96
	(0·31)	(0·56)	(0·06)	(0·54)	(0·53)	(0·37)	(0·15)	(0·10)	(0·05)	(0·07)
StI	15·25	7·32	2·48	4·97	5·94	2·98	7·79	2·91	2·08	2·63
	(1·95)	(1·67)	(0·16)	(1·69)	(1·09)	(0·63)	(1·03)	(0·21)	(0·14)	(0·20)
BD	1·10	1·41	1·55	1·34	1·65	1·53	1·33	1·44	1·51	1·46
	(0·08)	(0·09)	(0·09)	(0·05)	(0·06)	(0·11)	(0·09)	(0·11)	(0·09)	(0·10)
AC	0·16	0·12	0·08	0·05	0·04	0·05	0·17	0·07	0·09	0·05
	(0·05)	(0·04)	(0·01)	(0·02)	(0·02)	(0·01)	(0·01)	(0·03)	(0·04)	(0·01)
PAWC	0·13	0·17	0·13	0·18	0·13	0·13	0·17	0·17	0·16	0·18
	(0·03)	(0·08)	(0·01)	(0·02)	(0·01)	(0·02)	(0·01)	(0·02)	(0·01)	(0·01)
RWC	0·66	0·65	0·68	0·78	0·82	0·82	0·49	0·72	0·65	0·73
	(0·07)	(0·10)	(0·03)	(0·04)	(0·05)	(0·04)	(0·02)	(0·07)	(0·07)	(0·03)
S index	0·048	0·047	0·047	0·057	0·038	0·038	0·086	0·059	0·057	0·061
	(0·015)	(0·01)	(0·002)	(0·005)	(0·003)	(0·005)	(0·010)	(0·009)	(0·008)	(0·003)
Ksat	53·82	25·97	0·88	0·87	0·75	2·30	77·00	11·11	18·90	0·36
	(416·9)	(16·87)	(1·62)	(1·18)	(3·49)	(117·2)	(102·5)	(224·1)	(31·31)	(9·64)

SOC, soil organic carbon (%); StI, structural stability index by Pieri (%); BD, bulk density (Mg m^{-3}); AC, air capacity of total soil (m^3 m^{-3}); PAWC, plant available water capacity (m^3 m^{-3}); RWC, relative water capacity (m^3 m^{-3}); S index, inflection point in the SWRC by Dexter; Ksat, saturated hydraulic conductivity (geometric means, cm h^{-1}).
Standard deviation for each index is given in parenthesis (±).

$m^{-3} \leq$ AC; 0·6 m^3 $m^{-3} \leq$ RWC) except for soil B1. The Ksat was very low for B4.

These indicators gave a consistent indication of 'moderately good' SPQ for B1 and B2, and limited SQP for B3 and B4. As was mentioned previously, our temperate soils were designated as unstable soils concluded from the mean values of MWD_{dLdB}, MWD_{KRFW}, MWD_{LB1} and MWD_{LB3} (except B2 and B3 in MWD_{LB3} and MWD_{dLdB}).

With respect to the S index, in both groups of soils, tropical and temperate, values were higher than 0·035, designating an optimal SPQ condition (Dexter 2004a). This index did not enable to distinguish differences in soil quality conditions among the soils as with the other indicators. Apparently, the S index ranking given by Dexter (2004c) is not generally valid and does not apply for the soil conditions in our study.

A multidimensional scaling analysis presented in Figure 3 gives a visual impression of the similarity between the methods in terms of MWD and other SPQ indicators for tropical and temperate soils. The closer the Eucledian distance between the parameters, the higher the similarity in SPQ condition they provide. For the tropical soils dataset (Figure 3a), MWD_{KRFW}, MWD_{LB3}, MWD_{LB2} and MWD_{LB1} were closest with SOC.

Methods more distant from this cluster were MWD_{KRSW} and MWD_{dLdB}. With respect to temperate soils, as can be seen in Figure 3b, MWD_{KRFW}, MWD_{LB1} and MWD_{LB3} were closely associated with SOC and S index. Methods having a larger distance from this cluster were applying prewetting (MWD_{dLdB}, MWD_{KRSW} and MWD_{LB2}). Indicators such as StI, AC, RWC, BD and PAWC were located away from the comparable aggregate stability tests (FW of KR, LB1 and LB3). Ksat had an isolated position in this distance matrix. This might be associated with the high variation coefficient of this soil physical property.

When a multidimensional scaling was plotted with all the soils, both tropical and temperate soils datasets (Figure 3c), then MWD_{KRFW} and MWD_{LB1} are considered as the most similar methods. The isolated condition of MWD_{KRSW} and MWD_{LB2} and the SPQ indicators such as Ksat, AC, PAWC, S index, BD and RWC is still evident. The closest SPQ indicator with respect to MWD_{KRFW} and MWD_{LB1} is SOC.

DISCUSSION

The large differences in aggregate stability estimation between the SW in KR and LB2 with the other methods confirm that aggregate stability increased with increasing degree of soil wetting. This is attributed to a decrease in the volume of entrapped air resulting in lower compression forces acting on the aggregates during fast wetting (Vermang *et al*., 2009). However, the absence of similarity, in terms of soil structure status, between MWD_{KRSW} and MWD_{LB2}, suggests that the results from these two methods are noncomparable, neither for tropical soils nor for temperate soils.

Differences in distribution of aggregate size fractions with the three treatments of LB were higher in temperate soils than in tropical soils (Figure 2). Such differences with these treatments of LB have also been reported for temperate soils by other authors (D'Haene *et al*., 2008; Leroy *et al.,* 2008). Although Rohošková & Valla (2004) have mentioned that the three treatments of LB allow distinction between the particular mechanisms of aggregate breakdown, which is an advantage for evaluating bonding agents, our temperate medium-textured soils are only comparable with methods MWD_{LB1} and MWD_{LB3} ($p > 0·05$).

Furthermore, Deviren Saygin *et al*. (2012) suggest that dLdB method could work much better, compared with LB and KR methods, to evaluate aggregate stability of coarse textured soils. This is not the case in our soils, because

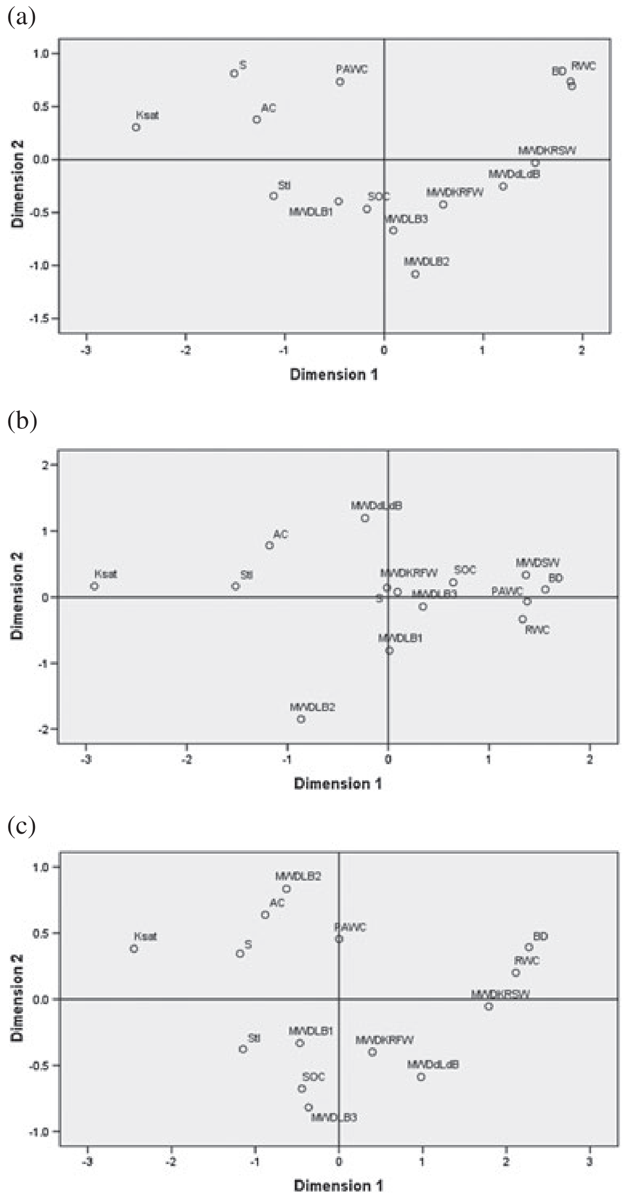

Figure 3. Euclidic distance model of MDW and the other physical soil indicators for tropical (a) and temperate (b) soils and for the complete dataset (c). See also legend of Tables 2 and 5 for abbreviations.

dLdB displayed an isolated position with respect to the other aggregate stability methods and the SPQ indicators evaluated (Figure 3b). In both temperate and tropical soils when dLdB was applied, the reduction in MWD after wet sieving was lower compared with the other methods. This can be attributed to the size range of aggregates used (Gijsman, 1996), but also to the low energy of the drop impact applied and the initial moisture content of the aggregates before wet sieving (Cerdà, 2000).

Under both tropical and temperate conditions, MWD_{KRFW} and MWD_{LB1} are comparable ($\alpha = 0{\cdot}05$). Comparison of aggregate stability of different soils is possible if any of these two methods is used. Rohošková & Valla (2004) also found that LB1 and KR using FW are comparable methods in terms of aggregate stability for reclaimed dumpsite soils. Both LB1 and KR methods involve FW of air-dried soil. Seybold & Herrick (2001) have mentioned that applying FW is a better indicator for detecting changes in aggregate stability as a result of management.

In temperate soils the homogeneous group of comparable methods also include $MWD_{LB3.}$ The LB3 includes the use of ethanol, which according to Nimmo & Perkins (2002), preserves aggregate structure in dry condition. However, the similarity found among KR, LB1 and LB3 suggests that for the temperate soils, the wet mechanical cohesion of aggregates appears to be similar, whether or not under presence of slaking. In spite of this, the methodology applied to obtain MWD_{KRFW} is less time-consuming than LB3.

The absence of similarity between the comparable aggregate stability methods and the common SPQ indicators illustrate the complexity of soil structure. This can be related to site-specific relationships. Similarities between these SPQ indicators and parameters directly related to soil structure have been reported as site-specific dependents by Mueller *et al*. (2009). The inconsistency between aggregate stability comparable methods and other SPQ indicators can also indicate that a combination of ‘unsuitable’ soil physical characteristics with ‘suitable’ aggregate stability or vice versa may occur, for instance soils with high proportion of water-stable aggregates and high BD and low Ksat.

Nevertheless, SOC appeared to be an indicator well associated with aggregate stability (FW of KR and LB1), at least in our medium-textured soils. SOC and WSA have been reported as dynamic soil quality indicators, which are able to vary with management practice (Shukla *et al*., 2006). Therefore, to assess the effect of changes in SOC content on soil structure condition, the aggregate stability by KR using FW or LB1 can be considered as a good indicator. Caution is required in using the SOC as an estimator of aggregate stability, because a specific fraction of the SOC can be the principal stabilising agent (Pulido Moncada *et al.,* 2009).

CONCLUSIONS

Among different methods tested to distinguish soil quality in terms of aggregate stability, only the wet sieving with a single sieve modified from KR (using FW) and LB1 rendered similar results for both tropical and temperate soils. The MWD value of both methods for assessing aggregate stability can be considered as a dependable indicator of the soil structure status for comparing soils. Because only one SPQ indicator supported the trend of these comparable aggregate stability methods, it was concluded that the aggregate stability should be used judiciously and in concert with other indicators for an overall assessing of SPQ condition. For medium-textured soils, aggregate stability assessment from MWD_{dLdB}, MWD_{LB2} and MWD_{KRSW} are not suitable in terms of SPQ condition to distinguish differences between different soils. Methods involving prewetting should be avoided when the aim of the survey is to make comparison among different conditions. If a simple and rapid analysis of the structure status is needed, single tests such as MWD_{KRFW} or MWD_{LB1} can be used.

ACKNOWLEDGEMENTS

This research was supported in part by the Consejo de Desarrollo Científico y Humanístico (CDCH) of the Universidad Central de Venezuela and with the cooperation of the laboratory of the Department of Soil Management, Ghent University, Belgium.

REFERENCES

Amezketa E 1999. Soil aggregate stability: a review. *Journal of Sustainable Agriculture* **14**: 83–151.

An S, Mentler A, Mayer H, Blum W. 2010. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. *Catena* **81**: 226–233.

Arshad MA, Coen GM. 1992. Characterization of soil quality: physical and chemical criteria. *American Journal of Alternative Agriculture* **7**: 25–32.

Beare MH, Bruce RR. 1993. A comparison of methods for measuring water-stable aggregates: implications for determining environmental effects on soil structure. *Geoderma* **56**: 87–104.

Bruce-Okine E, Lal R. 1975. Soil erodibility as determined by the raindrop technique. *Soil Science* **119**: 149–157.

Cerdà A 2000. Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia. *Soil and Tillage Research* **57**:159–166.

Cornelis WM, Khlosi M, Hartmann R, Van Meirvenne M, De Vos B. 2005. Comparison of unimodal analytical expressions for the soil–water retention curve. *Soil Science Society of America Journal* **69**: 1902–1911.

D'Haene K, Vermang J, Cornelis WM, Leroy BLM, Schiettecatte W, De Neve S, Gabriels D, Hofman G. 2008. Reduced tillage effects on physical properties of silt loam soils growing root crops. *Soil and Tillage Research* **99**: 279–290.

Deviren Saygin S, Cornelis WM, Erpul G, Gabriels D. 2012. Comparison of different aggregate stability approaches for loamy sand soils. *Applied Soil Ecology* **54**: 1–6.

Dexter AR. 2004a. Soil physical quality: part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* **120**: 201–214.

Dexter AR. 2004b. Soil physical quality: part II. Friability, tillage, tilth and hard-setting. *Geoderma* **120**: 215–225.

Dexter AR. 2004c. Soil physical quality: part III: unsaturated hydraulic conductivity and general conclusions about S-theory. *Geoderma* **120**: 227–239.

Diaz-Zorita M, Perfect E, Grove JH. 2002. Disruptive methods for assessing soil structure. *Soil and Tillage Research* **64**: 3–22.

Emerson WW. 1967. A classification of soil aggregates based on their coherence in water. *Australian Journal of Soil Research* **5**: 47–57.

Gee GW, Or D. 2002. Particle-size analysis. *In*:Dane JH, Hopmans JW. *(Eds.)* Methods of Soil Analysis Part 4 Physical Methods. SSSA Book Series 5'. Soil Science Society of America: Madison.

Gijsman AJ. 1996. Soil aggregate stability and soil organic matter fractions under agropastoral systems established in native savanna. *Australian Journal of Soil Research* **34**: 891–907.

Greenland DJ. 1981. Soil management and soil degradation. *Journal of Soil Science* **32**: 301–322.

Henin S, Monnier G, Combeau A. 1958. Methode pour l'etude de la stabilite structural des sols. *Ann. Agron.* **9**:73–92.

Hofman G. 1973. Kritische Studie van de Instabiliteit van Bodemaggregaten en de Invloed op Fysische Bodemparameters. Dissertation. Faculty of Agricultural Sciences, University of Ghent, Belgium.

Horn R, Taubner H, Wuttke M, Baumgartl T. 1994. Soil physical properties related to soil structure. *Soil and Tillage Research* **30**: 187–216.

Kemper WD, Rosenau RC. 1986. Aggregate stability and size distribution, *In*: Klute A *(Ed)*, Methods of Soil Analysis Part 1, Physical and Mineralogical Methods. Agronomy Monograph Nº 9 (2nd Edition), American Society of Agronomy, Inc., Madison, WI.

Lal R, Shukla MK. 2004. Principles of Soil Physics. Marcel Dekker, New York. ISBN 0-8247-5324-0.

Le Bissonnais Y. 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *European Journal of Soil Science* **47**: 425–437.

de Leenheer L, de Boodt M. 1959. Determination of aggregate stability by the change in mean weight diameter. *Mededelingen van landbouwhogeschool en de opzoekingstations van de staat te Gent* **24**: 290–300.

Leroy BLM, Herath HMSK, De Neve S, Gabriels D, Bommele L, Reheul D, Moens M. 2008. The application of vegetable, fruit and garden waste (VFG) compost in addition to cattle slurry in a silage maize monoculture: effects on soil physical properties. *Compost science & utilization* **16**: 43–51.

Mueller L, Kay BD, Hu C, Li Y, Schindler U, Behrendt A, Shepherd TG, Ball BC. 2009. Visual assessment of soil structure: evaluation of methodologies on sites in Canada, China and Germany part I: comparing visual methods and linking them with soil physical data and grain yield of cereals. *Soil and Tillage Research* **103**: 178–187.

Mueller L, Shepherd G, Schindler U, Ball BC, Munkholm LJ, Hennings V, Smolentseva E, Rukhovic O, Lukin S, Hu C. 2013. Evaluation of soil structure in the framework of an overall soil quality rating. *Soil and Tillage Research* **127**: 74–84

Niewczas J, Witkowska-Walczak B. 2003. Index of aggregates stability as linear function value of transition value of transition matrix elements. *Soil and Tillage Research* **70** 121–130.

Nimmo JR, Perkins KS. 2002. Aggregate stability and size distribution. *In*: Dane JH, Topp GC *(Eds.)* Methods of Soil Analysis, Part 4 Physical Methods. Madison, Wisconsin, Soil Science Society of America. 317–328.

Pierce FJ, Larson WE, Dowdy RH, Graham WAP 1983. Productivity of soils: assessing long-term changes due to erosion. *Journal of Soil Water Conservation* **38**: 39–44. http://www.fao.org/docrep/V9926E/v9926e04.htm#TopOfPage

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

Pulido Moncada M, Lobo LD, Lozano PZ. 2009. Association between soil structure stability indicators and organic matter in Venezuelan agricultural soils. *Agrociencia* **43**: 221–230.

Rawlins BG, Wragg J, Lark RM. 2013. Application of a novel method for soil aggregate stability measurement by laser granulometry with sonication. *European Journal of Soil Science* **64**: 92–103.

Reynolds WD, Drury CF, Yang XM, Fox CA, Tan CS, Zhang TQ. 2007. Land management effects on the near-surface physical quality of a clay loam soil. *Soil and Tillage Research* **96**: 316–330.

Reynolds WD, Drury CF, Tan CS, Fox CA, Yang XM. 2009. Use of indicators of pore volume-function characteristics to quantify soil physical quality. *Geoderma* **152**: 252–263.

Rohošková M, Valla M. 2004. Comparison of two methods for aggregate stability measurement – a review. *Plant Soil and Environment* **50** 379–382.

Seybold CA, Herrick JE. 2001. Aggregate stability kit for soil quality assessments. *Catena* **44**: 37–45.

Shukla MK, Lal R, Ebinger M. 2006. Determining soil quality indicators by factor analysis. *Soil and Tillage Research* **87**: 194–204.

Van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44**: 892–898.

Vermang J, Cornelis WM, Demeyer V, Gabriels D. 2009. Aggregate stability and erosion response to antecedent water content of a loess soil. *Soil Science Society of America Journal* **73**: 718–726.

Walkley A, Black IA. 1934. An examination of the Degtjareff method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* **63**: 251–263.

Yoder RE. 1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. *Journal of the American Society of Agronomy* **28**: 337–351.

