Soil Use and Management

Soil Use and Management, June 2018, **34,** 187–196 doi: 10.1111/sum.12414

Using soil organic matter fractions as indicators of soil physical quality

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Abstract

The objective of this study was to evaluate the use of chemical and physical fractions of soil organic matter (SOM), rather than SOM *per se*, as indicators of soil physical quality (SPQ) based on their effect on aggregate stability (AS). Chemically extracted humic and fulvic acids (HA and FA) were used as chemical fractions, and heavy and light fractions (HF and LF) obtained by density separation as physical fractions. The analyses were conducted on medium-textured soils from tropical and temperate regions under cropland and pasture. Results show that soil organic carbon (SOC), SOM fractions and AS appear to be affected by land use regardless of the origin of the soils. A general separation of structurally stable and unstable soils between samples of large and small SOC content, respectively, was observed. SOM fractions did not show a better relationship with AS than SOC *per se*. In both geographical regions, soils under cropland showed the smallest content of SOC, HA and carbon concentration in LF and HF, and the largest HF/LF ratio (proportion of the HF and LF in percent by mass of bulk soil). With significant associations between AS and SOC content (0.79**), FA/SOC ($r = -0.83^{*}$), HA/FA ($r = 0.58^{*}$), carbon concentration of LF ($r = 0.69^{*}$) and HF ($r = 0.70^{*}$) and HF/LF ratio ($r = 0.80^{*}$), cropland showed lowest AS. These associations indicate that SOM fractions provide information about differences in SOM quality in relation to AS and SPQ of soils from tropical and temperate regions under cropland and pasture.

Keywords: Aggregate stability, soil quality, chemical and physical fractions

Introduction

The quality of agricultural soils can be assessed using soil properties as indicators of quality, which allow comparisons among different soils, land uses or agricultural practices (Duval *et al.*, 2013). In agricultural soils, a decrease in soil organic matter (SOM) content is generally associated with loss of aggregate stability (AS) (Abid & Lal, 2008), indicating soil structural degradation and consequently a reduction in soil physical quality (SPQ).

Loveland & Webb (2003) argued that it is difficult to draw a conclusion on the effect of agricultural practices on AS and changes in SOM because (i) there is not uniform methodology and size range of aggregates for determining AS; (ii) the general assumption of a linear relationship between SOM and AS; meanwhile, nonlinear relationships or nonsignificant relationships have also been found; (iii) the sampling depth; and (iv) the wide variation in AS within the same soil depending on the type and amount of SOM.

Haynes (2000) showed that increasing inputs of organic matter under short-term pasture could result in significant increases in AS without a measurable change in SOM content. In contrast, different fractions and fractionation methods for SOM are used to evaluate the effect of different agronomic practices on the dynamics of soil organic carbon (SOC) and to assess soil quality. These SOM fractions have been found to be more effective than using SOM or SOC *per se* (Guimarães *et al.*, 2013; Nascente *et al.*, 2013). This is because particular fractions of SOM are associated with specific mineral particles and clay mineralogy (Jindaluang *et al.*, 2013) and consequently to certain aggregate sizes (Lee *et al.*, 2009).

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Received May 2017; accepted after revision March 2018

Soil organic matter fractions are mainly obtained by chemical and physical methods. Chemical fractionation provides information about the type and quantity of components in SOM (Schnitzer, 1999). The chemical composition of each fraction is believed to determine its stability and turnover time (Poeplau *et al*., 2013) and to play an important role in the formation and stabilization of aggregates (Six *et al*., 2000). In contrast, physical fractionation gives information on how the SOM is bound within the soil matrix (Elliott & Cambardella, 1991) and it is used to separate partially decomposed fractions from those associated with mineral particles (Christensen, 2001). This allows establishment of the role of organic materials in processes, such as aggregate stabilization, and uncovering the biological and environmental importance of SOM in organomineral complexes (Lützow *et al*., 2006).

Many chemical and physical methods and combinations of both are used effectively to characterize and isolate SOM fractions (Barrios *et al*., 1996; Zimmermann *et al*., 2007). Chemical fractions are separated by extracting SOC using different solutions, and physical fractions are separated by different degrees of disaggregation, dispersion, density fractionation or particle size separation (Poeplau *et al*., 2013). In the present study, the classical SOM chemical fractionation by Ciavatta & Govi (1993) was selected to isolate the chemical components and the Anderson & Ingram (1993) density separation was applied as a physical fractionation method. The latter has the advantage of using water as dispersant (a noncontaminating and a low-cost component) and has been successfully used for characterizing SOM in soils of the tropics (Pulido-Moncada *et al*., 2010; Lozano *et al*., 2011).

The objective of this study was to evaluate the use of chemical and physical fractions of SOM, rather than SOM *per se*, as indicators of SPQ based on their effect on AS. It was hypothesized that the different SOM fractions analysed would be more sensitive indicators than SOM for the evaluation of land-use effects under soils in different climatic conditions.

Materials and methods

Site description and soil sampling

Ten soils were selected, of which six were located in a tropical environment in the central-northern part of Venezuela (V1–V6) and four (two soil types, each with two locations having contrasting management histories, i.e. permanent pasture, PP, and cropland, CP) found in a temperate environment in the Flemish Region of Belgium (B1–B2) (Table 1). The terms tropical and temperate soils are used hereafter to emphasize the climatic difference between the two geographical regions. The term tropical does not imply a highly weathered soil. The climate of the tropical area is characterized by a mean annual temperature of 17, 25 and 27 °C and a mean annual rainfall of 1154, 979 and 1212 mm, for V1 (1861 metres above sea level, MAMSL), V2 (436 MAMSL) and V3 (320 MAMSL), respectively. Soils V4, V5 and V6 are located in the same geographical area at 120 MAMSL, with 27 °C of mean annual temperature and 1336 mm of mean annual rainfall. The Flemish Region (47–55 MAMSL) has a mean annual temperature of 10 °C and a mean annual rainfall of 780 mm.

The selection of these two geographical regions under different climatic conditions is because most studies related to SOM–AS relationships have been conducted in temperate conditions, whereas it is well known that the decomposition rate of the different SOM fractions is faster in the tropics compared to temperate regions. Soils sampled in the central-northern part of Venezuela represent the dominant soils in this agricultural area, where a large part of the country's cereal and vegetable production takes place. Likewise, the soils collected in the Flemish Region of Belgium are representative for the loess belt that stretches from west to east, with land primarily under crop production and pasture.

The selection of sites that differed in terms of climate, soil type, land use and soil management practices (Table 1) provided a wide range of SPQ (see Pulido-Moncada *et al*., 2014, 2017, for more details) and enabled testing of the indicators used in this study. The plot size for the different soils ranged from 810 to 2000 m^2. In both geographical regions, for each soil, three transects of variable length were randomly laid out avoiding edge effects. Samples were taken at the centre points of each half of the transects, a total of six sampling points per plot. At each sampling point, a disturbed composite sample and three 100-cm^3 core samples were taken at 0–20 cm depth.

Soil organic matter analysis

Air-dried 2-mm soil samples were used to determine SOC, as well as chemical and physical fractions of SOM (described below). SOC was measured by wet oxidation (Walkley & Black, 1934).

Chemical fractionation of SOM

The chemical fractionation of SOM was conducted by the sequential extraction procedure of Ciavatta & Govi (1993), which seeks to separate humic (alkali-extractable) and nonhumic substances. In a first stage, SOM was extracted with 0.1 M $NaOH/Na_4P_2O_7$. The resulting SOM extract was further fractionated into humic acids (HA) and fulvic acids (FA) according to the methodology proposed by Schnitzer & Schuppli (1989). Then, the purification of the fulvic fraction from the nonhumic substances (NH) was achieved by applying the insoluble polyvinylpyrrolidone method (Ciavatta & Govi, 1993).

Table 1 Description and characteristics of the 'tropical' (V1–V6; Venezuela) and 'temperate' (B1, B2; Belgium) soils

Soil	Textural class	Soil taxonomy	Geographic coordinates	Land use[a]	Soil management[a]	CEC cm_c /kg	Clay (<2 μm)[b]	Silt (2–50 μm)	Sand (50–2000 μm)	pH_{KCl}
							(g/kg)			
V1	Sandy clay loam	Typic Kandiustult	10°22'N 67°12'W	Fruit cropping (*Prunus persica* L.)	No-till	9.5	285	199	516	3.65
V2	Clay loam	Fluventic Haplustoll	10°15'N 67°37'W	Grassland (*Morus* spp. and *Cynodon nlemfuensis)*	No-till, no trampling	20.8	291	282	427	7.67
V3	Loam	Typic Endoaqualf	10°21'N 68°39'W	Maize mono-cropping (*Zea mays* L.)	Conventional tillage	12.0	173	351	476	4.90
V4	Loam	Aquic Haplustoll	8°46'N 67°45'W	Grassland (*Brachiaria brizantha)*	Trampling	11.7	229	486	285	5.19
V5	Silt loam	Typic Rhodustalf	9°0'N 67°41'W	Cereal crops with fallow periods[c]	Conventional tillage	13.9	261	583	156	4.84
V6	Silty clay	Aquic Haplustalf	9°02'N 67°41'W	Grassland with natural vegetation	Trampling	17.2	423	501	76	4.67
B1CP	Sandy loam	Dystric Eutrudept	50°59'N 3°31'E	Maize mono-cropping (*Zea mays* L.)	Conventional tillage	7.58	136	120	744	5.96
B1PP	Sandy loam	Dystric Eutrudept	50°59'N 3°31'E	Permanent pasture	No trampling	-	102	155	743	4.60
B2CP	Silt loam	Aquic Hapludalf	50°47'N 3°25'E	Rotation of maize (*Zea mays* L.) and winter wheat (*triticum aestivum* L.)	Conventional tillage	6.6	125	658	217	6.22
B2PP	Silt loam	Aquic Hapludalf	50°47'N 3°25'E	Permanent pasture	Trampling	-	142	646	212	5.58

CEC, cation exchange capacity; CP, cropland; PP, permanent pasture. [a]Current and over the last 15 yrs under the same soil management. Conventional tillage in Venezuela can be described as ploughing and multiple passes of a harrow during each cultivation period as well as yearly subsoiling. Conventional tillage in B1 consisted of primary tillage with mouldboard plough with four shares (30 cm depth), and a secondary tillage with harrow + seed drill (5–10 cm depth). Conventional tillage in B2 soil comprised primary tillage with cultivator (5–10 cm depth) + mouldboard plough with 15 shares (30 cm depth), followed by secondary tillage with harrow + seed drill (5–10 cm). [b]Particle size distribution, CEC and pH values correspond only to analyses conducted on samples taken from 0 to 20 cm depth. [c]V5 soil was under fallow with natural vegetation at sampling moment.

The humification parameters proposed by Sequi *et al.* (1986) and Ciavatta *et al.* (1990) were determined, that is (i) the humification index (HI), which refers to the ratio of nonhumic substances and alkali-extractable compounds (HI = NH/(HA+FA)), (ii) the humification degree (HD), corresponding to the relative amount of OC present in HA and FA relative to OC in the total $NaOH/Na_4P_2O_7$ extract (TE) (HD = ((HA+FA)/TE)*100), and (iii) the humification rate (HR), representing the amount of OC present in HA and FA relative to SOC content (HR = ((HA+FA)/SOC)*100).

Physical fractionation of SOM

The modified Anderson & Ingram (1993) test for soil litter separation was applied to obtain three physical fractions of SOM using separation density (Hernández & López-Hernández, 1998), viz. light fraction (LF), heavy fraction associated with the fine mineral particles of the soil (silt and clay) (HF_f) and heavy fraction associated with the coarse mineral particles of the soil (sand) (HF_c). Briefly, the procedure involves mixing 150 g of soil (<2 mm) with deionized water in a plastic tray ensuring a layer of water of ~1 cm over the solid material. The soil sample was stirred manually for 30 min. After sedimentation of coarse soil particles (40 s), water with floating material was decanted onto a 0.25 mm sieve.

The LF was defined as the organic material that floated in the water (density < 1.0 Mg/m^3) and that was retained on the sieve. The nonfloating organic material, which passed through the sieve and remained in suspension together with silt and clay particles, corresponded to HF_f. The remaining organomineral material that settled on the bottom of the tray, together with the sand particles, was considered as the HF_c. Each collected fraction was oven-dried at 50 °C to constant weight. The proportion and OC concentration of each physical fraction were measured. The HF/LF ratio was calculated using the proportion of HF (HF_f + HF_c) and LF in per cent by mass of bulk soil.

Clay mineralogy analysis

The sand fraction (63–2000 μm) was separated from the silt and clay fraction by wet sieving, and the silt fraction (2–63 μm) was separated from the clay fraction (<2 μm) by successive sedimentation using repeated syphoning of supernatant clay suspensions after the dispersion of clay using Na_2CO_3. The clay fraction was saturated with Ca^{2+}. Excess electrolytes were removed by washing twice with deionized water and centrifugation, after which dialysis was used. Oriented samples were prepared by transferring ultrasonically dispersed suspension of all clay fractions on glass slides. X-ray diffraction (XRD) patterns were recorded in air-dried and glycolated state using a Philips X'PERT SYSTEM with a PW 3710 based diffractometer equipped with a Cu tube anode. The XRD data were collected in a θ, 2θ geometry from 3.00' onwards, at a step of 0.020° 2θ and a count time of 5 s per step.

Aggregate stability determination

AS data were taken from Pulido-Moncada *et al.* (2015), who compared three AS methods to derive SPQ indicators: (i) the wet sieving method with multiple sieves proposed by De Leenheer & De Boodt (1959) (dLdB); (ii) the three treatments of the method by Le Bissonnais (1996) with fast wetting (LB1), slow wetting (LB2) and mechanical breakdown by shaking after prewetting (LB3); and (iii) the wet sieving method, using one single sieve, based on Kemper & Rosenau (1986), with slow and fast wetting (KR_{SW} and KR_{FW}, respectively).

Statistical analyses

To ensure the efficiency of the analysis, normality of the data was tested by Q-Q plots and the Kolmogorov test, and homogeneity was checked by Levene's test (homogeneity of variance test). As the majority of the SOM fractions did not fulfil the assumptions, log-transformed variables were used in the pairwise comparison of means. Scheffe's test was conducted to test for homogeneous subsets between fractions of each soil. Spearman's rank correlation analysis was conducted to evaluate the associations between the SOM fractions and AS. A criterion of $P < 0.05$ was selected to represent statistical significance. All data were analysed using the SPSS 24.0 statistical software package.

Results

Chemical fractionation of SOM

Among the studied soils, V3 showed the smallest values of SOC (Table 2). From the classical alkali-extractable compounds of SOM, HA and FA represented major parts in all soils (Table 2). The 'tropical' soils had a significantly larger content of HA than of FA ($P < 0.05$). In the 'temperate' soils, this was true only for B2PP; but B1CP, B1PP and B2CP showed similar content of HA and FA ($P < 0.05$). In general, in the 'tropical soils', NH fraction showed similar content to FA, but in the 'temperate' soils, NH was significantly less than HA or FA.

For the humification parameters, the largest value of HI appeared to be present in V6 of the 'tropical' soils. In the 'temperate' soils, HI was larger under PP than CP in B1, whereas the opposite was observed in B2. HD of 'tropical' soils, except V6 (79–97%) exceeded that of the 'temperate' soils (63–77%). HR of the 'tropical' soils also exceeded (except V5 and V6) (34–65%) that of the 'temperate' soils

Table 2 Soil organic carbon content, distribution of OC over three chemical fractions (humic acids, fulvic acids and nonhumic substances) and derived humification parameters (n = 60)

Soil	SOC (g/kg)	HA (g/kg)	FA (g/kg)	NH (g/kg)	HI	HD (%)	HR (%)	FA/SOC	HA/FA
V1	42.6 A	11.7 A a	2.6 A b	2.3 A b	0.16	81	34	0.06 B	4.58 B
	(1.2)	(0.32)	(0.08)	(0.09)	(0.007)	(1.2)	(1.6)		
V2	24.4 AB	7.8 B a	1.3 BC b	0.5 DE c	0.05	97	65	0.06 B	6.09 A
	(2.2)	(0.21)	(0.07)	(0.04)	(0.004)	(1.8)	(5.4)		
V3	7.5 D	1.9 D a	1.3 BC b	0.4 E c	0.13	79	42	0.18 A	1.38 E
	(0.2)	(0.10)	(0.05)	(0.01)	(0.005)	(3.2)	(1.0)		
V4	20.3 C	7.2 B a	1.5 BC b	1.1 BCD b	0.12	84	45	0.08 B	4.83 B
	(2.1)	(0.14)	(0.05)	(0.18)	(0.020)	(2.9)	(3.7)		
V5	29.1 B	5.9 B a	1.3 BC b	1.2 ABC b	0.17	80	26	0.05 B	4.56 B
	(2.1)	(0.24)	(0.12)	(0.06)	(0.010)	(1.4)	(2.3)		
V6	16.1 C	2.6 C a	1.1 C b	1.3 ABC b	0.34	64	24	0.07 B	2.42 D
	(1.5)	(0.09)	(0.05)	(0.15)	(0.035)	(1.6)	(1.5)		
B1CP	11.1 C	1.4 E a	1.4 BC a	0.5 DE b	0.19	69	26	0.12 A	0.99 E
	(0.9)	(0.15)	(0.05)	(0.04)	(0.011)	(2.4)	(2.4)		
B1PP	22.7 C	2.1 CD a	1.6 B a	1.0 BCDE b	0.29	70	16	0.07 B	1.30 E
	(1.4)	(0.15)	(0.08)	(0.20)	(0.066)	(4.4)	(1.5)		
B2CP	9.4 AB	1.1 E a	1.4 BC a	0.8 CDE b	0.32	63	26	0.15 A	0.81 E
	(0.5)	(0.04)	(0.12)	(0.14)	(0.067)	(2.1)	(2.1)		
B2PP	37.1 C	6.2 B a	1.8 B b	2.0 AB b	0.25	77	23	0.05 B	3.49 C
	(4.4)	(0.29)	(0.01)	(0.24)	(0.028)	(2.3)	(2.4)		

CP, cropland; FA, fulvic acids; HA, humic acids; HD, humification degree; HI, humification index; HR, humification rate; NH, nonhumic substances;PP, permanent pasture; SOC, soil organic carbon. V1–V6 are soils from the tropics in the central-northern part of Venezuela; B1 and B2 are soils from a temperate area in the Flemish Region of Belgium. Standard errors for each parameter are given in parentheses (±). Means followed by the same uppercase letter in a column are not significant different at $P < 0.05$. Means followed by the same lowercase letter in a row are not significant different at $P \leq 0.05$.

(16–26%). Regardless of texture, both ‘temperate’ soils had a comparable HR varying from 16 to 26%.

Physical fractionation of SOM

Light fraction ranged from 0.1 to 1.1% by bulk soil mass for the ‘tropical’ soils (Table 3). In the ‘temperate’ soils, LF was 0.07 to 0.2% under CP, but two and seven times larger under PP in B1 and B2 (0.4 and 0.5%), respectively.

HF_f was larger in soil V6 (50.3%) compared to the other ‘tropical’ soils, where values ranged from 27 to 39%. Within this group of soils, V3 had the smallest percentage of HF_f (27%). HF_f was smaller in ‘temperate’ soils compared to the ‘tropical’ soils (7.2–20.7%), and the largest value was present in B2CP. The dominant physical fraction of SOM was HF_c, with ranges of 46–71% and 81–88% in ‘tropical’ and ‘temperate’ soils, respectively.

In general, OC concentration was larger in HF than in LF in both geographical regions and among the different soil conditions and land uses. OC concentration in HF_f was larger than HF_c and LF for soils V1, V2, V3, V6 and B1CP (28.6, 22.1, 5.8, 14.2 and 6.8 g/kg soil, respectively). On the contrary, OC concentration was larger in HF_f and HF_c of V4, V5, B1PP and B2CP compared to LF, but in HF_c of B2PP compared to the others two physical fractions (Table 3).

Clay mineralogy of the studied soils

Soil V1 was characterized by a clay mineralogy dominated by illite and kaolinite, whereas V2 was dominated by smectite and mica (muscovite). Soil V3 had a clay dominance of both mica and smectite. In the other three ‘tropical’ soils, the clay mineralogical composition was similar, containing mostly smectite, illite and kaolinite. Soil V2 differed from the other samples by the presence of two types of mica, which appeared to have contributed to the formation of mixed-layers containing smectite. Regarding the proportions of the type of clay minerals present in each soil, the ‘tropical’ soils V1 and V3 contained more mica than the other soils. Soils V4, V5 and V6 contained a larger proportion of kaolinite compared to the other soils.

The two ‘temperate’ soils had a clay fraction dominated by smectite. Samples B1 and B2 have mineralogically very similar clay fractions, composed of a mixture of mica and smectite and their mixed layers, with minor amounts of kaolinite.

Table 3 Proportion of the different physical fractions of soil organic matter (SOM) (per cent by mass of whole soil) and the determined organic carbon concentration (n = 60)

	Fraction distribution (%)			Carbon concentration (g/kg soil)			
Soils	LF	HF_f	HF_c	LF	HF_f	HF_c	HF/LF
V1	0.8 c	33.1 b	64.0 a	2.5 A c	28.6 A a	15.5 AB b	127
	(0.12)	(1.1)	(1.3)	(0.35)	(3.3)	(1.9)	
V2	0.7 c	39.3 b	57.9 a	2.1 AB c	22.1 AB a	6.8 BC b	144
	(0.11)	(1.3)	(1.2)	(0.32)	(0.7)	(1.5)	
V3	0.1 c	27.4 b	71.5 a	0.5 CD c	5.8 D a	2.6 D b	685
	(0.01)	(2.1)	(2.2)	(0.06)	(0.5)	(0.2)	
V4	0.4 c	34.1 b	63.9 a	1.6 AB b	11.9 BC a	9.8 ABC a	244
	(0.07)	(2.5)	(2.4)	(0.33)	(0.6)	(2.0)	
V5	1.1 c	30.3 b	67.0 a	3.5 A b	12.6 BC a	17.9 A a	92
	(0.14)	(2.6)	(2.7)	(0.44)	(1.1)	(1.9)	
V6	0.7 b	50.3 a	46.7 a	2.7 A c	14.2 BC a	7.6 ABC b	131
	(0.09)	(3.6)	(3.3)	(0.24)	(2.9)	(0.4)	
B1CP	0.2 c	11.9 b	85.8 a	0.3 DE c	6.8 CD a	4.8 CD b	987
	(0.01)	(0.9)	(0.9)	(0.03)	(0.5)	(0.6)	
B1PP	0.4 c	7.2 b	88.8 a	0.5 CD b	7.9 CD a	6.9 ABC a	1127
	(0.06)	(1.6)	(0.8)	(0.06)	(0.3)	(0.9)	
B2CP	0.07 c	20.7 b	81.7 a	0.2 E b	4.8 D a	4.7 CD a	3476
	(0.03)	(1.3)	(2.3)	(0.06)	(0.2)	(0.3)	
B2PP	0.5 c	14.1 b	84.4 a	0.9 BC c	8.8 CD b	17.8 A a	314
	(0.04)	(0.7)	(1.0)	(0.11)	(2.6)	(2.4)	

CP, cropland; HF_c, heavy fraction of SOM associated with coarse mineral particles of the soil (sand); HF_f, heavy fraction of SOM associated with fine mineral particles of the soil (silt and clay); LF, light fraction of SOM; PP, permanent pasture. V1–V6 are soils from the tropics in the central-northern part of Venezuela; B1 and B2 are soils from a temperate area in the Flemish Region of Belgium. HF/LF ratio was calculated using the proportion of the HF ($HF_f + HF_c$) and the LF in per cent by mass of whole soil. Standard errors for each parameter are given in parentheses (±). Means followed by the same uppercase letter in a column are not significant different at $P \leq 0.05$. Means followed by the same lowercase letter in a row (for a given parameter) are not significant different at $P \leq 0.05$.

Soil aggregate stability and its interaction with SOM

AS was evaluated for the six 'tropical' soils and only for 'temperate' soils under CP by Pulido-Moncada *et al.* (2015; Table 4). Briefly, results from the De Leenheer and De Boodt method (dLdB) showed a reduction of less than 20% of the initial mean weight diameter (MWD) only by V1, V2, V5 and B2, which were classified as structurally stable soils. In the case of LB test (following classes of stability according to Le Bissonnais, 1996), when using LB1 soils, V1, V2 and V5 were classified as structurally stable soils, V6 as moderately stable and the other soils as unstable. On the contrary, all soils were classified as structural stable after LB2 and LB3, except B1 and B2 using LB3. The reduction in MWD of aggregates 1–2 mm in diameter using KR_{FW} was 30–44% for V5, 50–60% for V1, V2 and V6 soils, and >70% for the other soils. When KR_{SW} was used, all soils expressed high AS. More details about AS of the studied soils and the criteria for classes of stability based on the aggregate stability methods used are given in Pulido-Moncada *et al.* (2015).

The relationship between MWD and SOC varied among AS methods (Table 5). The r value ranges were 0.44–0.61 (for KR_{SW} and dLdB) and 0.75–0.80 (for KR_{FW}, LB1, LB2, and LB3). When comparing AS values from KR_{FW} among the soils (Table 4), soils under cereal mono-cropping showed a 'poor' structural stability, and the opposite was observed when under other land uses. The KR_{FW} method was selected by Pulido-Moncada *et al.* (2015) as a dependable indicator of AS status for comparing soils.

Additionally, a correlation analysis was conducted among OC contents in the various isolated SOM fractions and MWD determined by different methods (Table 5). The intention was to evaluate individual SOM fractions rather than SOM *per se* as predictors of structural stability. Results show that there was a significant positive correlation among OC in LF ($r = 0.69^{**}$), HF_f ($r = 0.70^{**}$), HF_c ($r = 0.71^{**}$), HA ($r = 0.56^{**}$), NH ($r = 0.48^{**}$), FA/SOC ($r = -0.83^{**}$) and HA/FA ($r = 0.58^{**}$) with MWD for KR_{FW}. However, these relationships did also vary among the methods. Values of r were smaller when using MWD obtained by dLdB and KR with slow wetting procedure compared to LB and KR_{FW}.

Discussion

Distribution of SOM over different fractions

Although different SOC contents were found between soils from Venezuela and Belgium, results suggest that SOC content and SOM fractions were influenced by land use, with SOC, LF and HA being smaller in soils under cereal mono-cropping and conventional tillage compared to soils under other land uses (Tables 2 and 3). Dominance of HA in soils under permanent pasture or grassland has been explained by the protection of large humic molecules from breaking in the absence of mechanization, thereby favouring the formation of HA (Novotny *et al*., 1999). No clear differences were found for the studied soils when the humification parameters were considered. It would be expected that soils susceptible to degradation, with low structural stability, show large values of HD and HR, but small values of HI (Lozano *et al*., 2011). However, ratios between the different SOM fractions (HA/FA, FA/SOC and HF/LF) were better indicators of land-use effect on SOM quality of the studied soils (Tables 2 and 3).

For the 'tropical' soils, the smallest value of HA/FA (1.38) and the largest values of FA/SOC (0.18) and HF/LF (684.7) were present in soil under maize mono-cropping (V3) (Tables 2 and 3). According to Lozano *et al*. (2011), these relationships can be interpreted as follows: (i) small values of HA/FA show slow humification because FA is more susceptible to agricultural activities, (ii) large FA/SOC values indicate that SOM has constituents that are more susceptible to be degraded by agricultural activities, and (iii) large values of HF/LF are related to low diversity of crop residues. Therefore, in the present study, these relationships made a distinction between the most unstable soil (V3), which is under mono-cropping and conventional tillage, and the more structurally stable soils of the 'tropical' group.

For the 'temperate' soils, SOC, as well as chemical and physical fractions of SOM, was larger in B2 soil under PP compared to that under CP. The humification parameters

Table 4 Mean of the aggregate stability values for soils from tropical (V1–V6; Venezuela) and temperate (B1, B2; Flemish) environments. Aggregate stability data were taken from Pulido-Moncada *et al*. (2015)

	V1	V2	V3	V4	V5	V6	B1	B2
MWD_{dLdB}	3.63	3.58	2.29	1.93	3.97	2.62	2.11	2.92
MWD_{LB1}	1.78	1.86	0.51	0.79	2.99	0.93	0.73	0.53
MWD_{LB2}	3.46	3.37	1.64	1.99	3.46	1.89	3.25	1.60
MWD_{LB3}	3.15	3.18	1.50	1.82	3.38	1.99	0.65	0.71
MWD_{KRFW}	0.73	0.61	0.18	0.42	1.00	0.58	0.46	0.40
MWD_{KRSW}	1.02	0.82	0.77	0.68	1.01	0.84	0.84	0.83

MWD_{dLdB}, mean weight diameter (mm) after drop impact and wet sieving using the De Leenheer and De Boodt method; MWD_{LB1}, mean weight diameter (mm) after Le Bissonnais method using fast wetting. MWD_{LB2}, mean weight diameter (mm) after Le Bissonnais method using slow wetting. MWD_{LB3}, mean weight diameter (mm) after Le Bissonnais method using mechanical breakdown by shaking after prewetting. MWD_{KRFW}, mean weight diameter (mm) after fast wetting using Kemper and Rosenau (KR) method. MWD_{KRSW}, mean weight diameter (mm) after slow wetting using KR method. Le Bissonnais (1996) suggested the MWD values measured with the three treatments: >2 = very stable; 1.3–2 = stable; 0.8–1.3 = medium; 0.4–0.8 = unstable; and <0.4 = very unstable. B1 and B2 are only the soils under cropland.

Table 5 Spearman's correlation coefficients (*r*) among soil organic carbon, soil organic matter fractions and aggregate stability (*n* = 48) of soils from the tropics in the central-northern part of Venezuela and from a temperate area in the Flemish Region of Belgium

		Carbon concentration (g/kg soil)											
	SOC (g/kg)	LF	HF_f	HF_c	HA (g/kg)	FA (g/kg)	NH (g/kg)	HI	HD	HR	FA/SOC	HA/FA	HF/LF
MWD_{dLdB}	0.61**	0.53**	0.57*	0.54**	0.46**	0.14	0.37**	−0.13	0.27	−0.13	−0.60**	0.45**	0.63**
MWD_{LB1}	0.80**	0.74**	0.72**	0.69**	0.64**	0.11	0.44**	−0.15	0.32*	−0.18	−0.83**	0.66**	0.81**
MWD_{LB2}	0.75**	0.54**	0.71**	0.64**	0.59**	0.34*	0.41**	−0.18	0.33*	−0.12	−0.67**	0.52**	0.65**
MWD_{LB3}	0.77**	0.79**	0.72**	0.66**	0.76**	0.17	0.43**	−0.30*	0.48**	0.08	−0.78**	0.77**	0.81**
MWD_{KRFW}	0.79**	0.69**	0.70*	0.71**	0.56**	0.05	0.48**	−0.04	0.21	−0.31*	−0.83**	0.58**	0.80**
MWD_{KRSW}	0.44**	0.39**	0.43**	0.49**	0.19	0.18	0.44**	0.22	−0.11	−0.36	−0.35*	0.05	0.32*

dLdB, De Leenheer and De Boodt method; FA, fulvic acids; HA, humic acids; HD, humification degree; HF_c, heavy fraction of SOM associated with coarse mineral particles of the soil (sand); HF_f, heavy fraction of SOM associated with fine mineral particles of the soil (silt and clay); HI, humification index; HR, humification rate; KR_{FW}, Kemper and Rosenau method using fast wetting of the aggregates; KR_{SW}, the Kemper and Rosenau method using slow wetting of the aggregates; LB1, LB2 and LB3 are the three different treatments of the Le Bissonnais method; LF, light fraction of SOM; MWD, mean weight diameter (mm); NH, nonhumic substances; SOC, soil organic carbon. *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level.

did not show any tendency between land uses, as in the 'tropical' soils. Nevertheless, in soils B2 and B1 under CP, values of FA/SOC (0.15 and 0.12, respectively) were larger than under PP (0.05 and 0.07, respectively). The opposite was evident for HA/FA (B2CP = 0.81, B2P $P = 3.49$) (Table 2). For HF/LF, no clear trend was found for the 'temperate' soils in relation to land use.

The dominance of HF as a proportion of bulk soil mass and relative OC concentration was true for all the studied soils. The smallest value of OC concentration of LF was found in V3 and B2CP, soils under mono-cropping system and conventional tillage in both geographical regions. Nascente *et al.* (2013) found that no-till results in larger accumulation of LF compared to conventional tillage due to the effect of decomposition stage of the residue and type of soil use and management. They also mentioned that HF usually dominates the SOC pool and involves a large amount of OC, because degradation rate of SOM in this fraction is slower due to the mineral protection.

The differences shown by the SOM fraction relationships indicate that in general, in soils under cropland, the quality of the SOM and the structural stability were affected by land use.

Relationship between SOM and aggregate stability

Because of the high variability between the methods used for AS assessment, differences in relationship between SOC and MWD were evident (Table 5). This is in agreement with Haynes (2000), who demonstrated that the relationship between these two properties could be significantly influenced by the method used to determine AS. Factors such as size of aggregates, antecedent moisture content and mechanism of dispersion influence the results of AS assessment (Vermang *et al.*, 2009).

Contradictory results reported in many studies suggest that the AS/soil properties relationship differs according to climatic and edaphic conditions. However, among the different studied soils, there was a general effect of land use on AS which explained most of its variation, although other potential factors were not evaluated in this study.

According to Bronick & Lal (2005), the effectiveness of SOC in forming stable aggregates is related to its decomposition rate, which in turn is influenced by its physical and chemical protection from microbial decomposition. Therefore, the quality of SOM measured through its fractions is considered as an effective indicator of soil quality that influences soil function in specific ways (Haynes, 2000). Haynes (2000) stated that SOM fractions 'are typically much more sensitive to changes in soil management practice than total SOM content'.

Because relationships between SOM fractions and AS differed depending on the size of the aggregates (Boix-Fayos *et al.*, 2001), for further comparison between these properties, only MWD from the KR_{FW} method was considered. This was justified by the fact that 1–2 mm aggregates were used for KR method and the fractionation of the SOM was conducted using <2 mm samples. No significant correlations ($P > 0.05$) were found among AS and humification parameters (HI, HD, HR).

The associations found between AS and SOM fractions confirm the existence of a link between the variables. For instance, SOC associated with sand-size fraction can be strongly affected by management (Sleutel *et al.*, 2010). In the present study, amount of OC in HF_c did not generally decrease in soils under cropland in either geographical region.

Results suggest that structural stability among different soils could be evaluated either by SOC *per se* or some of the SOM fractions such as HA, NH, LF and HF_c, as evidenced by the large correlation coefficients among these variables (Table 5). Nevertheless, SOM fractions have been considered as more sensitive indicators to changes in agricultural practices than has SOM content *per se* (Haynes, 2000; Duval *et al.*, 2013) and therefore preferred when assessing farming systems within the same soil type.

From the evaluated data set, it is difficult to separate the effect of the different measured characteristics on AS of the soils, but small values of SOC, LF and HA were related to a degraded structural stability of those soils under cropland.

Although clay mineralogy is believed to play an important role in SOM content and AS, in the studied soils, a trend between the dominant clay mineralogy and the variation of the SOC, SOM fractions and AS (via changes in SOM) was not evident in either geographical region. This suggests an interaction of other factors or the action of a more influential factor in SOC and SOM fractions. Other authors have found that kaolinitic soils have the capacity to form more stable aggregates through electrostatic binding between the soil particles (e.g. Barthes *et al.*, 2008), making aggregates less dispersible and more flocculated (Wakindiki & Ben-Hur, 2002). In contrast, large smectitic clay content is considered to increase the susceptibility to dispersion, slaking and swelling, and to promote soil degradation processes (Levy & Mamedov, 2002; Lado *et al.*, 2007).

As was demonstrated in this study, two aspects must be highlighted. First, although isolated SOM fractions did not correlate better than SOM *per se* with AS, they showed their capacity as indicators of AS. Although the chemical fractionation used in this study might be questioned on its applicability to follow the dynamics of organic material in soils and its usefulness for SOM models (Hassink, 1995), the physical fractionation used could be considered as a desirable potential indicator. It is less destructive, and its fractions are more related to the structure and function of SOM *in situ*. Secondly, the dissimilarities between AS methods confirms the need for a 'preselection' of the most appropriate evaluation method and the consideration of criteria (Loveland & Webb, 2003; Pulido-Moncada *et al.*, 2015), such as scope of the study, type of soil and history of the agricultural activities of the soils.

Conclusion

The similarities in relationships between SOM *per se* and SOM fractions with aggregate stability of the evaluated tropical and temperate soils support the conclusion that SOM content is an indicator sensitive enough to differentiate the studied soils in terms of SPQ. SOM fractions did not correlate better with aggregate stability than SOC content. Nevertheless, HA, LF, HFc, HA/FA, FA/SOC and HF/LF were sensitive indicators for evaluating land-use impact on SPQ under both tropical and temperate conditions and might yield extra information in studies where land use was changed recently. Among the different existing soil fractionation procedures, the density fractionation used in this study showed advantages over the chemical fractionation due to its low cost, noncontaminant dispersant and capability to show differences in SOM related to soil structural quality.

Acknowledgements

Dr. Joanna Cloy and Dr. Lars J. Munkholm provided helpful comments. This research was partly supported by the CDCH of the Universidad Central de Venezuela and by the Department of Soil Management and the Department of Geology of Ghent University.

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