Integrated Assessment of Soil Structural Quality

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Integrated assessment of soil structural quality

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To the most wonderful people in my life,
My Family

How is the soil? Is it fertile or poor? Are there trees in it or not? Do your best to bring back some of the fruit of the land.

Numbers 13:20, New International Version

It had been planted in good soil by abundant water so that it would produce branches, bear fruit and become a splendid vine.

Ezekiel 17:8, New International Version

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List of contents

List of figures

List of tables

List of abbreviations

Abbreviation	*Description*	*Unit*
AC	Air capacity	cm^3 cm^{-3}
ANOVA	Analysis of variance	
au	Arbitrary units	
B1-B4	'Temperate' studied soils from Belgium	
BD	Bulk density	Mg m^{-3}
CC	Correlation coefficient	
CCI	Correctly classified instances	%
CEC	Cation exchange capacity	$cmol_c$ kg^{-1}
CM	Cereal monoculture	
CV	Coefficient of variation	
dLdB	De Leenheer and De Boodt (1959) method of aggregate stability	
EC	Electrical conductivity	dS m^{-1}
FA	Fulvic acids	g kg^{-1}
FC	Field capacity	cm^3 cm^{-3}
FW	Fast wetting	
HA	Humic acids	g kg^{-1}
HD	Humification degree	
HF_c	Heavy fraction of soil organic matter associated with coarse particle of soils	%; g kg^{-1}
HF_f	Heavy fraction of soil organic matter associated with fine particle of soils	%; g kg^{-1}
HI	Humification index	
HR	Humification rate	
IS	Instability index	
K	Cohen's Kappa coefficient	
$K_{(h)}$	Unsaturated hydraulic conductivity	cm h^{-1}
K_a	Air permeability	μm^2
KR	Kemper and Rosenau method of aggregate stability	
K_s	Saturated hydraulic conductivity	cm h^{-1}
LB	Le Bissonnais (1996) method of aggregate stability	
LB1	Treatment one of Le Bissonnais (fast wetting)	
LB2	Treatment two of Le Bissonnais (slow wetting)	
LB3	Treatment three of Le Bissonnais (mechanical breakdown by shaking after pre-wetting)	
LF	Light fraction	%; g kg^{-1}
LP	Laboratory permeameter	
MacP	Large macropores	cm^3 cm^{-3}

MASL	Metres above mean sea level	m
MicP	Micropores	$cm^3\ cm^{-3}$
MWD	Mean weight diameter	mm
NE	Number of earthworms	individual m^{-2}
NH	Non-humic substances	$g\ kg^{-1}$
PAWC	Plant available water capacity	$cm^3\ cm^{-3}$
PCF	Pruning confidence factor	
PP	Permanent pasture	
PTF	Pedotransfer functions	
PWP	Permanent wilting point	$cm^3\ cm^{-3}$
r	Coefficient of correlation	
R^2	Coefficient of determination	
RETC	Retention Curve programme	
RMSE	Root mean squared error	
RWC	Relative water capacity	$cm^3\ cm^{-3}$
S	Modulus of the slope at the inflection point of the soil water release curve	
SI	Stability index	
SOC	Soil organic carbon	$g\ kg^{-1}$
SOM	Soil organic matter	$g\ kg^{-1}$
SPQ	Soil physical quality	
Sq	Structural quality score	
SQIs	Soil quality indicators	
SQSP	Soil quality scoring procedure	
StI	Structural stability index by Pieri (1992)	%
SW	Slow wetting	
SWRC	Soil water release curve	
TE	Total extract	%
TI	Tension infiltrometre	
TPV	Total pore volume	$cm^3\ cm^{-3}$
Tyagg	Visual type of aggregate index	
V1-V6	'Tropical' studied soils from Venezuela	
VESS	Visual evaluation of soil structure	
VS	Visual score	
VSA	Visual soil assessment	
WSA	Water stable aggregates	%
XRD	X-ray diffraction	

Chapter 1

Introduction

1.1. Land degradation: deterioration of soil quality

Land degradation, defined as 'a decline in land quality caused by human activities', has been a matter of concern since the 20th century and it remains up to date (Eswaran et al., 2001). According to the authors, this is justified on the fact that land degradation has an impact on world food security and quality of the environment. Indeed, the Food and Agriculture Organization of the United Nations (FAO), states that in 2008 thirty seven countries faced food crisis and 1.5 billion people living in degraded lands were at risk of starvation (Cribb, 2010).

Recently statistics show that 38% of the used land (agricultural areas, permanent pasture, and forests) of the earth can be considered as degraded. In places such as Africa, South America, Asia and Europe the proportion of degraded agricultural areas are 65, 45, 38 and 25%, respectively (Osman, 2013).

Of the degradation processes causing land degradation, soil degradation has a high importance in agricultural areas. FAO (http://www.fao.org/soils-portal/soil-degradation-restoration/en/) defines soil degradation as 'a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries'. Therefore, the decline in food production and rise of people's needs in the world can in part be directly associated to soil degradation as such.

Deforestation and overexploitation of vegetation, shifting cultivation, overgrazing, indiscriminate use of agrochemicals, lack of soil conservation practices, and overextraction of ground water are some anthropogenic causes of soil degradation (Osman, 2013). Any of these activities generates several physical, chemical and biological processes that restrict the soil to perform its functions (Karlen et al., 2003). Therefore, soil degradation causes adverse effects on soil health and soil quality.

1.2. Soil quality and soil quality indicators

Soil quality is defined as 'the capacity of a soil to function within the ecosystem boundaries and to interact positively with surrounding ecosystems' (Larson and Pierce, 1991). The capacity of soil to function can be reflected by soil properties, also known as soil quality indicators (Shukla et al., 2006).

Ideally a diverse group of indicators, or minimum data set of indicators, should be used for soil quality assessment, because the use of individual indicators cannot represent the interaction among several soil properties and processes involved (Carter et al., 1997; Andrews et al., 2004).

It must be emphasized that there is no standard minimum data set of indicators that can be applied for a whole country or universally. Instead a series of indicators must be defined or selected for specific circumstances such as region or scale of study. In fact, many examples of minimum data sets of > 20 to < 5 indicators have been established by several authors (Doran and Parkin, 1996; Lilburne et al., 2004; Lima et al., 2013).

In any case, the selection of indicators for developing soil quality indices and frameworks should be conducted in such a way so that they: (i) integrate soil physical, chemical and/or biological properties and processes, (ii) apply under diverse field conditions, (iii) complement either existing databases or easily measurable data, and (iv) respond to land use, management practices, climate and human factors (Doran and Parkin, 1994). The selection of proper soil quality indicators should therefore be based on the soil functions of interest, the defined management goals for the system and the sensitivity of the indicator to detect changes in soil functions (Andrews et al., 2002; Arshad and Martin, 2002).

1.3. Soil physical quality: deterioration of soil structure as a common factor

According to Topp et al. (1997) a 'good' soil physical quality is considered when the soil is 'strong' enough to provide adequate plant support and stable soil structure, but 'weak' to allow fluid transmission and storage, unrestricted root development and favourable faunal population and activity.

On the contrary, a 'poor' soil physical quality is manifested through physical problems such as poor water infiltration, run-off, hard-setting, poor aeration, poor rootability, and poor workability. A poor soil structure is the common cause of these physical problems that can occur simultaneously in the soil (Dexter, 2004a; Pagliai et al., 2004). The degradation of the soil structure is a complex process in which many factors are involved, but it is mainly associated with a deterioration of the pore system (An et al., 2010). Soil structure, defined hereafter, affects therefore physical, chemical and biological processes that support soil's life functions (Eswaran et al., 2001; Osman, 2013). This is the main reason to consider soil structure as the basis of soil physical quality assessment and the main context of this dissertation.

1.4. Soil structure: concepts and importance

Many definitions, terminologies and approaches have been given to soil structure, some of which are summarized below. According to McKeague et al. (1986) definitions of soil structure fall mainly into two groups: those related to the size, shape and arrangement of solid soil constituents, and those including the size, shape and arrangement of both solid soil constituents and pores. An example of the first of these definitions is the concept of soil structure by Day (1983), who refers to this property as 'the aggregation of primary soil particles into compound particles, which are separated from adjoining aggregates by planes of weaknesses'. This concept still prevails in the United States, with the Soil Science Society of America defining soil structure in its glossary of soil science terms as, 'the combination or arrangement of primary soil particles into secondary units or peds' (Soil Science Society of America, 2008).

The second definition, including pores as an aspect of soil structure, has been considered by many other authors. Emerson et al. (1967) already pointed out interactions between soil structure, water movement, soil aeration and root growth. Thus, authors such as Lal (1991) referred to soil structure as 'the size, shape and arrangement of solids and voids, continuity of pores and voids, their capacity to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development'. Others like Horn and Smucker (2005) simplified this approach defining soil structure as 'the arrangement of single mineral particles and organic substances into greater units known as aggregates and the corresponding inter-aggregate pore system'.

In a wider concept, soil structure controls the interaction between three phases in the soil, i.e., liquid, gaseous and solid. It thus becomes the common factor between the five soil functions mentioned by Karlen et al. (1997):

(i) 'Sustaining biological activity, diversity, and productivity',
(ii) 'Regulating and partitioning water and solute flow',
(iii) 'Filtering and buffering, degrading, immobilizing, and detoxifying organic and inorganic material',
(iv) 'Storing and cycling nutrients and other elements within the earth's biosphere', and
(v) 'Providing support of buildings and others structures as well as protection for archaeological treasures associated with human habitation'.

Consequently, favourable soil structure is important to improve soil fertility, increase agronomic productivity, enhance porosity and soil quality, as well as to decrease erodibility (Bronick and Lal, 2005), soil degradation and land degradation.

Dexter (1988) mentioned that soil structure, defined as 'the spatial heterogeneity of the different components or properties of soil', involves the different aspects that are manifest at many different size scales in soil. These aspects are: the arrangement of colloidal clay particles in a floccule; the arrangement of clods on the surface of a tilled layer; an array of earthworm burrows; and the variability of soil strength. The soil structure concept by Dexter (1988) suggests that 'spatial heterogeneity = spatial variability = structure', thefore the range of size scales involved in soil structure is very wide, ranging from a few Å to several cm. In this context, Carter (2004) states that soil structure can be described from the level of clay particles and clay–organic matter complexes to the spatial arrangement of peds and clods in the soil profile (Figure 1-1).

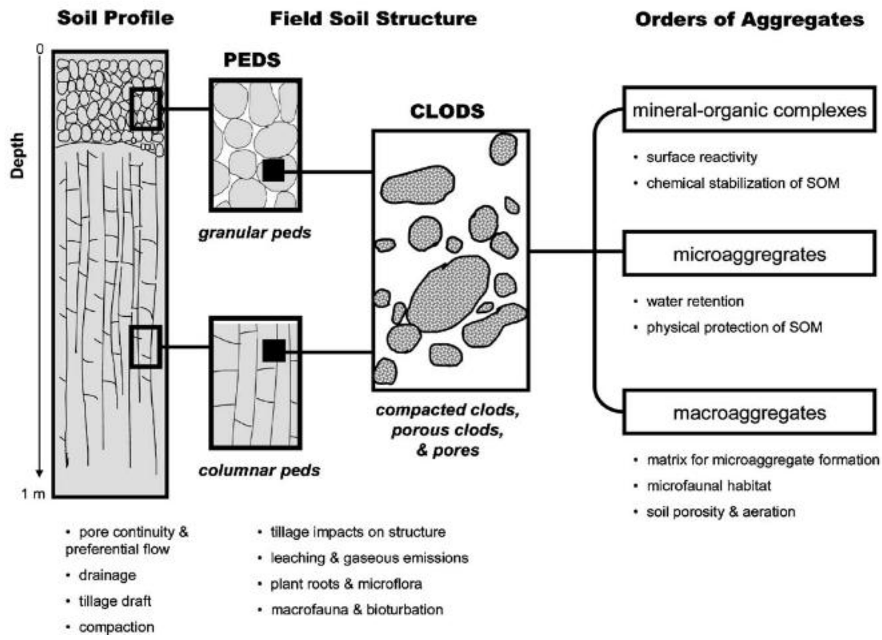


Figure 1-1 The range of size scales (from <µm to >cm) involved in soil structure assessment: from soil profile in the field to microscopic level in the laboratory (Source: Carter, 2004).

The range of scales involved in soil structure and its dynamic nature are the principal reasons for the complexity of this soil property (Lal and Shukla, 2004). The authors state that soil attributes observed at any given time are results of varying interacting factors and processes. Consequently, structural attributes can vary in time and space. Apart from the natural pedogenesis that has an impact on structure-related processes, in agricultural soils; the soil structural complexity is also affected in nearly all range of scales by soil and plant management (Carter, 2004).

For these reasons, soil structure does not have a universally accepted definition (Hillel, 1998). Despite the numerous studies on and related to soil structure, it 'remains to be the most complex, the least understood, and among the most important soil physical properties' (Lal and Shukla, 2004). However, Baveye (2006) emphasized that 'more factual knowledge about soil structure has emerged, concerning its development over time under specific conditions, the binding agents responsible for aggregation, the biotic and abiotic factors that control this aggregation, and the environmental impact of soil structure'.

The complexity in defining soil structure is hence related to the many factors and processes involve in soil structure formation. In general, soil structure is developed from single grain or massive materials. The main factors that have an effect on the genesis of the soil structure are: the effect of the cations (ionic bonds), the interaction between clay particles (adhesion between clay-water particles, electrostatic attraction between the positives edges and negative faces of clay lattices), the effect of soil organic matter (organic bonds) and biological activity (roots development, soil micro and microorganisms activity) (Lal and Shukla, 2004). Therefore, aggregate formation, as the first step in development of soil structure, can result from different bonding agents. In fact, at each stage of aggregation a different binding agent can be involved (transient, temporary and persistent). Additionally, other factors involved in the formation of soil structure, such as land use, soil management and drying and wetting, can play an important in soils under agriculture. Consequently, in agricultural soils, the soil organic matter-aggregation interaction is a critical factor in understanding soil structure formation (Six et al., 2004.)

1.5. Assessment of soil structure

It is unlikely that any single soil physical process will be applicable over the whole range of size scales that soil structure implies (Dexter, 1988). For these reason, there is also disagreement on the methods applied for soil structure characterization and the evaluation of its dynamic. However, a useful approach to assess soil structure in agricultural soils is its characterization according to three aspects, viz. structural form (geometrical aspect), structural stability and structural resilience (Lal and Shukla, 2004; Ball et al., 2007). As a result of this wide approach, several methods and indices for soil structure assessment have been proposed and tested around the world. In general, methods of soil structure assessment outlined in Figure 1-2 can be divided in direct and indirect methods.

Direct methods involve measuring aggregate size and stability, visual examination of structural form, and observation of morphological structural features by microscopy or analysis of images (e.g., CT scans, electrical resistivity tomography, thin sections) (Young et al., 2001; Lal and Shukla, 2004; Pagliai et al., 2004; Boizard et al., 2005). Indirect characterization of soil structure includes its estimation from soil properties such as hydraulic conductivity, infiltration rate, bulk density (BD) and pore-size distribution among others (Pagliai et al., 2004; Reynolds et al., 2009; Kodesova et al., 2011). The indirect measurement of soil structure is based on the effect of soil structure on soil physical properties such as porosity, soil strength, water retention, water transmission and aeration (Pagliai et al., 2004; Kodesova et al., 2011). Indirect evaluation of soil structure is also conducted using modelling techniques such as Boolean models, neural networks, pedotransfer functions, cellular automata techniques, fractal theory and network models (Young et al., 2001).

Among the methods implied in soil structure assessment, this dissertation will mainly focus on the use of two of those direct methods, viz. aggregate stability and visual examination, as well as some soil physical properties as indirect methods.

1.5.1. Assessing aggregate stability

There are different methods for measuring aggregate stability, which may explain: (i) the existence of different mechanisms that cause destabilization, (ii) different scales at which stability can be determined, and (iii) methodological reasons (Amezketa, 1999).

According to Amezketa (1999) and Lal and Shukla (2004) aggregate stability methods can be grouped into three categories:

(i) Ease of dispersion by turbidimetric techniques.
(ii) Assessment of aggregation and aggregate size distribution using wet sieving, and
(iii) Evaluation of aggregate strength in relation to raindrop impact.

Focusing on different purposes, some authors have compared various methods and methodologies of the three categories listed above (Pojasok and Kay, 1990) and all methods showed advantages and disadvantages. Amezketa (1999) in his review about soil aggregate stability, states that several authors agree with the fact that the wet sieving methods are simpler and less time-consuming than the turbidimetric technique. However, the latter is considered to be practical and convenient when only limited amounts of sample are available. The author also emphasized that turbidimetric techniques have been mentioned as useful for comparing treatments of the same or similar soils, but are not suitable for comparing soils that differ in texture.

Regarding wet sieving methods, they include procedural variations that can be critical for interpreting data (Beare and Bruce, 1993). This comprises pre-treatments that control the severity of the disruption. Márquez et al. (2004) mention that in some cases, the pre-treatment consists in wetting soil aggregates by capillary before wet sieving in order to produce minimal aggregate disruption avoiding increasing air pressure in the pores. Other methods involve a slaking pre-treatment (fast wetting). This causes considerable disruption because air-dried aggregates are submerged in water causing a rapid displacement of the trapped-air with water.

The limit of aggregate sizes used in wet sieving tests varies greatly from one author to another. This affects results, because the size of soil aggregates determines their physical properties (Niewczas and Witkowska-Walczak, 2003). Macro-aggregates as compared to micro-aggregates display little resistance to mechanical action and reduced resistance to water action (Vermang et al., 2009).

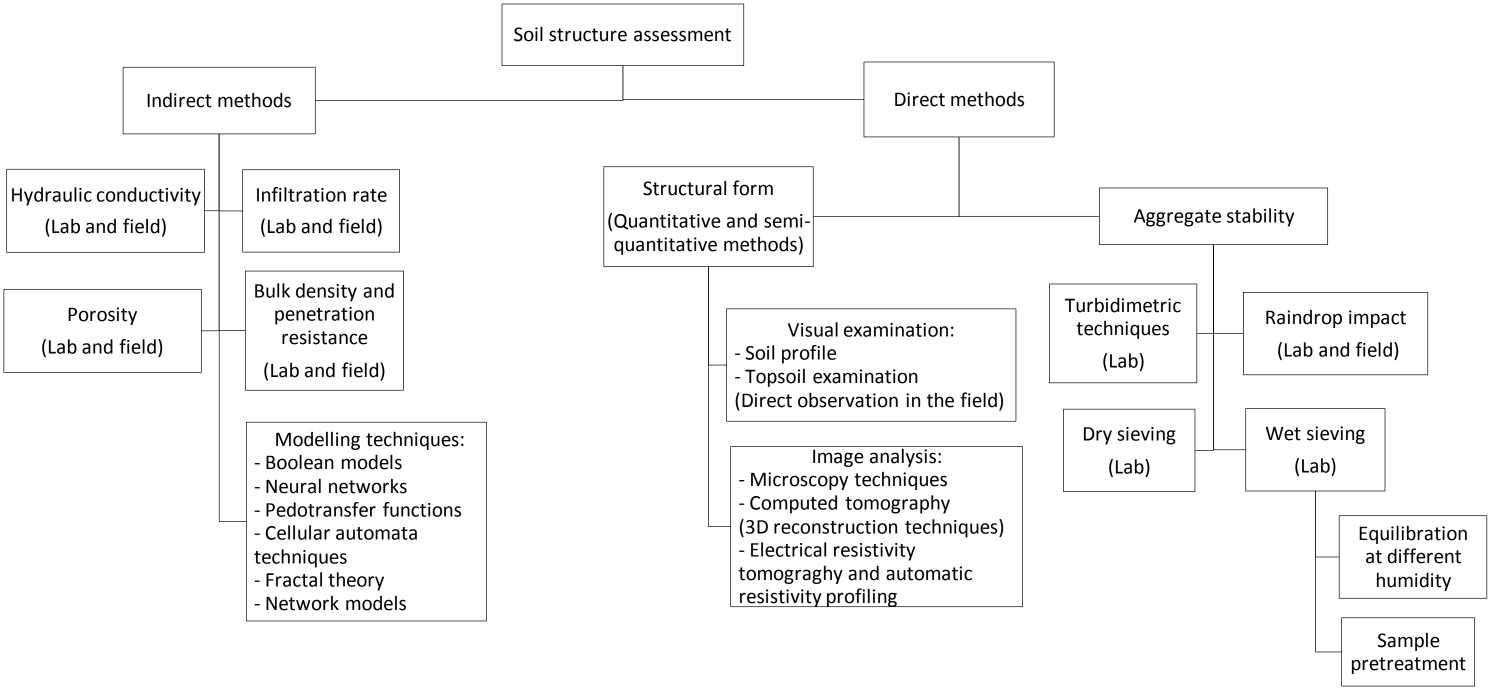


Figure 1-2 Methods of soil structure assessment (Young et al., 2001; Pagliai et al., 2004; Lal and Shukla, 2004; Boizard et al., 2005; Reynolds et al., 2009; Kodesova et al., 2011).

Other differences in pre-treatment are the use of a single sieve or a nest of sieves (De Leenheer and De Boodt, 1959; Beare and Bruce, 1993; Le Bissonnais, 1996), the different intensities of disruptive mechanical energy to the sample (Amezketa, 1999) and the liquid used to immerse the sample. Commonly, wet sieving involves immersion of samples in distilled water (Yoder, 1936) but other authors use liquids such as ethanol (Henin et al., 1958; Le Bissonnais, 1996) or benzene (Henin et al., 1958) to prevent clay dispersion.

Additionally, the different expressions of aggregate stability results also complicate the comparison among them. Various indices have been proposed for expressing the distribution of aggregate sizes and they are still well accepted and in use (Amezketa, 1999): the mean weight diameter, the geometric mean diameter, the coefficient of aggregation, the weighted mean diameter, the change in mean weight diameter, and the slaking loss.

These indices have often been used for different purposes such as (Chisci et al., 1989):

(i) 'To combine data from different size distributions',
(ii) 'To express the data in a comparable form for different soils',
(iii) 'To interpret the data of structure analysis for specific purposes', and
(iv) 'To improve the interpretation of soil structure analysis from laboratory test to field conditions'.

Because the comparison of aggregate stability from different procedures is very difficult, many researchers have tried to describe the factors that influence structure stability (Barthès et al., 2008; Bronick and Lal, 2005; Six et al., 2004; Idowu, 2003), and to establish indices through the comparison of methods (Beare and Bruce, 1993; Amezketa, 1999; Le Bissonnais, 1996). The diversity in aggregate stability measurement techniques is partially because these indices and methods, proposed by different authors, have been developed under different management practices, soil type and climate. Reasons why aggregate stability in some cases did not express association with other soil structure indicators (Kay et al., 1988).

Therefore, any research on or related to aggregate stability must describe very carefully the experimental methodology applied. Only in this way, results can be interpreted and compared with others. In Part I of this dissertation, Chapter 3, Chapter 4 and Chapter 5, soil structure is evaluated in terms of aggregate stability and factors related to aggregate stability and aggregation.

1.5.2. Assessing soil structural form

Visual examination of soil structural form made directly in the field provides a rapid and immediate assessment of the quality of the soil structure. This is of importance to farmers and consultants in soil management decisions, as well as to soil scientists for planning sampling in punctual assessments or monitoring campaigns (Ball et al., 2007).

Visual examination methods have been shown to detect small but significant changes in soil physical conditions and to relate well to crop growth and soil aeration, strength and density measurements (Ball and Douglas, 2003). Therefore, for whatever purpose or under whatever condition, properties that can be determined in the field by sight or by handling the soil have an important part to play in soil physical analysis (Batey, 2000).

The different methods used to assess soil structural quality directly in the field can be grouped into methods based on soil profile evaluation and those based on topsoil examination (Table 1-1 and Table 1-2). When comparing both procedures, it is evident that soil profile evaluations are more destructive. This is because a pit or trench is required to expose the profile face, which is not suitable for assessment of small plot experiments (Boizard et al., 2005). On the contrary, the disturbance of the land is minimal when a topsoil examination method is used. The principal limitation of topsoil examination is the requirement for moist soil conditions at the time of sampling and examination, since applying it is difficult when soils are very dry or very wet (Ball and Douglas, 2003; Ball et al., 2007; Guimarães et al., 2011).

Both the time spent and the degree of detail have been mentioned as important aspects of the visual examination methods (Batey, 2000; Ball and Douglas, 2003; Boizard et al., 2005; Ball et al., 2007). They depend on the purposes for which the examination or description of the soil structure is made and on the skill and experience of the user of the method (McKeague et al., 1986). Besides, as has been mentioned by Boizard et al. (2005) 'each method of field assessment had been developed for a specific purpose and the selection of one of these depends on the user and the purpose'.

Three basic steps have to be considered in the visual examination of soil structure, in order to avoid erroneous evaluation of soil condition (McKeague et al., 1986):

(i) 'Purpose for describing soil structure'. This step is important because the decision why soil structure is to be assessed affects the decisions on where and how.
(ii) 'Choosing a site or sites at which to assess the soil'. The site should avoid locations likely to have atypical soil properties and make representation of the variability. The variability is taken into account by the number of replicates or the depth of a profile pit.
(iii) 'Deciding upon the operations to follow in the assessment'. This refers to the kind and degree of detail of the evaluation, which are involved in the method selected. It should include information on the different layers and depth of evaluation, but it is also depending on the purpose of the work.

In order to decide the operations to follow in the assessment of soil structure, it is necessary to know the differences between the methods developed for this purpose. The section below summarizes the currently available methods of visual field assessment of soil structure.

1.5.2.1. Methods based on soil profile evaluation

The systems outlined by soil survey organizations such as the United States (Soil Survey Staff, 2010), Australia (Raymond, 2002), Canada (Day, 1983), United Nations (FAO, 2006), and developed for soil survey applications, have been evaluated for describing and interpreting soil structure. They require description of the morphology of a modal pedon, which generally implies a large soil pit or trench of 1.5 to 2 m deep. They could thus be used as well to assess the physical condition of the soil surface when the evaluation is focused on the surface as a seedbed for crops (McKeague et al., 1986).

Recently, three methods based on soil survey description have been developed to assess soil structure in agricultural soils, viz. the 'Whole Profile Assessment', the 'Soilpak Scoring Procedure', and 'Le Profil Cultural' (Table 1-1). These methods focus on detecting soil physical evidence of degradation processes as product of soil management.

The 'Whole Profile Assessment' developed by Batey (2000) is a soil profile description and land evaluation technique to assess land capability and particularly for the diagnosis of crop problems related to soil physical quality. This method was developed to be used in soils under any land use, to detect slight changes in physical conditions, to evaluate the capacity of the soil and to assess the potential limiting layers for plant growth (Boizard et al., 2005).

Other methods like the 'SOILpak Scoring Procedure' by McKenzie (2001) or 'Le Profil Cultural' by Roger-Estrade et al. (2004) are more advanced and provide detailed information on the complete soil profile (Mueller et al., 2009). The 'SOILpak Scoring Procedure' was designed originally to assess compaction under irrigated cotton on Vertisols. However, a revised 'SOILpak Scoring Procedure' for assessing soil 'structural form' was developed to be used on a wide range of soils for root growth relevance. (McKenzie, 2001). It was shown to be flexible and sensitive with a wide range of criteria (Boizard et al., 2005).

'Le Profil Cultural' estimates the effects of cultural operations on soil structure and plant growth. The method is useful for analysing spatial and temporal variation in aggregate shape and porosity. It also comprises vertical and lateral stratification of the soil structure, which enable identification of the location of very highly compacted areas and the internal structural states of the soil profile. The method has been reported as a tool that allows directly linking the cultivation operations with soil structure dynamics, considering the spatial variation of soil structure as an element of the interpretation. However, the method is time consuming and requires a high degree of scientific knowledge (Roger-Estrade et al., 2004).

Table 1-1 Methods of field assessment of soil structure based on profile evaluation (Adapted from Boizard et al., 2005).

Method, author and country	Objective	Key criteria	Basis	Scale of scoring
Whole profile assessment by Batey (2000) Scotland	To evaluate the inherent capability of the soil to determine its potential for cropping To identify any limitations of crop growth as a result of soil management	To evaluate the soil potential for cropping: texture, colour and potential rooting depth. For the assessment of potential limiting layers: colour, development, strength and stability of structure; dense and compacted soil and degree of fissuring; the formation of saturated zones, anaerobic zones and the pattern of roots.	Description	Soil structure score system based on Peerlkamp (1959) 1 = worst, 10 = best
SOILpak Scoring Procedure of Daniells and Larsen (1991) modified by McKenzie (1998; 2001) Australia	To assess compaction under wide range of soil types and cropping systems	Soil structural shape, structural stability in water and structural resilience: crop root growth.	Description	21 point scale: 0.0 = severely compacted, 2.0 = excellent structure for root growth
Le profil cultural by Gautronneau and Manichon (1987) modified by Roger-Estrade et al. (2004) France	To estimate the effects of cultural operations on soil structure and crop growth To conduct field studies on water transfer modelling and on denitrification	Transition between the tilled layers; internal structural state of clods or zones; type of structural state	Description	Qualitative assessment: areas with severe compaction; or areas without any change in clod structure Γ = clod with high eye-visible porosity Δ = clod with no eye-visible porosity Φ = clod with cracks due to weathering

1.5.2.2. Methods based on topsoil examination

Methods related to topsoil examination are focused on the top 20 to 30 cm of soil and describe the status or condition of a specific soil due to relatively recent land use or management decisions. Several topsoil examination methods have been proposed (Table 1-2), differing in aspects such as depth of the soil under consideration, handling the soil prior to assessment, emphasis placed on particular features of soil structure, and application of size, increments and direction of scoring scales (Mueller et al., 2009). In spite of these differences, they have been well accepted because they are quick, straightforward and widely applicable (Mueller et al., 2009; Guimarães et al., 2011; Mueller et al., 2013).

One of the most widely accepted topsoil examination methods is that of Peerlkamp (1959). This method was developed to assess the soil physical characteristics in a systematic way by numerically assessing the soil structure quality within the topsoil or tilled layer (Boizard, et al., 2005). Some modifications to the Peerlkamp method have been proposed and have been compared with the original (Batey, 2000; Ball and Douglas, 2003; Ball et al., 2007).

Ball et al. (2007) revised and updated the Peerlkamp method, and proposed the Visual Evaluation of Soil Structure (VESS). The proposed method involves the use of a visual key with well-defined descriptions of criteria for each category. VESS includes soil layering, which constitutes the main improvement from the original method. However, according to Mueller (2009), modifications of the Peerlkamp method are very fast in handling but prone to subjective scorings. If one or more features are not present for this description, the operator can underestimate the structural quality.

Based on the previous modifications proposed by Ball et al. (2007), Guimarães et al. (2011) developed improvements on VESS. Although some researchers suggest subjectivity in the way of breaking up the soil block, they showed that breaking up a soil block by hand or by dropping results in the same soil quality score. They also found that reducing large aggregates to 1.5-2.0 cm fragments and describing their shape and porosity, helps to identify visual score particularly in the middle range of soil quality. Furthermore, modifications proposed to this technique, tested in soils from Scotland and Brazil, suggest that the modified version is a more practical and objective evaluation of soil structural quality compared to the original one (Guimarães et al., 2011).

Other methods including fertility determinant aspects such as root growth, organic residues or fauna within individual layers in the topsoil are those of Beste (1999) and Munkholm (2000). Beste´s system is not as detailed as Munkholm´s but it is extended with the quantitative determination of some soil physical properties. Beste´s system originates from the method of 'The Spade Diagnosis' developed by J. Görbing in about 1930. According to Beste (1999), this method is 'based on farmers' knowledge and combines the actual comprehensive and qualitative impression of soil condition in the field with exact and quantitative data information about soil parameters from same location'.

Table 1-2 Methods of field assessment of soil structure based on topsoil examination (Adapted from Boizard et al., 2005)

Method, author and country	Objective	Key criteria	Basis	Scale of scoring
Visual method of soil structure evaluation by Peerlkamp (1959) the Netherlands	To assess the soil physical characteristics systematically in terms of numeric assessment of the soil structure quality within the topsoil or tilled layer	Size and shape of aggregates, cohesion of soil particles, porosity, root development, dispersion of the soil surface	Description scale	1 = worst, 10 = best
Visual Soil Assessment (VSA) by Shepherd (2000, 2009) New Zealand	To assess and monitor soil quality and plant performance	Soil texture, size of aggregates, porosity feature, soil colour, earthworms, potential rooting depth, soil surface	Guideline photographs	For each indicator: 0 = poor, 2 = good For overall index: < 20 for poor SQ, > 37 for good SQ
Visual soil assessment - spade analysis by Munkholm (2000), Denmark	To assess soil quality in the 0-30 cm soil layer regarding soil structure and rooting characteristics and relate to past management practices	Ground cover; soil layering; moisture; texture; structural elements, macropores, root growth, soil fauna, decomposition of soil matter	Description	
Soil Quality Scoring Procedure (SQSP) by Ball and Douglas (2003) Scotland	To assess soil quality from a soil and root assessment procedure.	Soil structure, rooting and soil surface condition	Description	1 = worst, 5 = best
Visual Evaluation of Soil Structure (VESS) by Ball et al. (2007) based on Peerlkamp method Scotland	To incorporate simplified structural descriptions into a scale of structural quality	Size, shape and strength of aggregates, porosity, colour and roots	Guideline photographs	1= good, 5= poor

The Soil Quality Scoring Procedure (SQSP) developed by Ball and Douglas (2003) is presented as a semi-quantitative visual and tactile method for assessing soil physical fertility in terms of soil structure, root growth and soil surface condition based on Munkholm (2000) and ranks soils according to a marking scheme similar to that of Beste (1999). According to Ball and Douglas (2003), the SQSP has as advantage that a brief, standardized description of the soil is provided which is summarized into three ranks of soil condition. The method implies layering of the soil sample evaluated and scores for structure and rooting conditions are weighted to the thickest apparent layer.

For New Zealand soils, Shepherd (2000) developed the Visual Soil Assessment (VSA) method, based on the visual assessment of key soil state and plant indicators of soil quality, presented on a score card. Each indicator used by VSA is considered as a separate entity. In this way each indicator is a useful early warning of changes in soil conditions. For an overall score of the soil condition each indicator is weighted by a factor of importance. VSA is considered to provide a valid semi-quantitative assessment of soil quality, in terms of the criteria defined, and it can therefore be used in conjunction with, and complement, quantitative laboratory measurements (Shepherd and Park, 2003; Shepherd, 2009).

Due to many early and new methods developed to assess soil structure directly in the field, the Working Group F 'Visual Soil Examination and Evaluation' of the International Soil & Tillage Research Organisation (ISTRO) promoted a field meeting in northern France during which several methods were compared, including those mentioned above (Boizard et al., 2005). The results of each test were presented to the whole group, which was able to question and discuss the findings. They concluded that:

(i) 'Each method has been developed to answer a specific question in a specific locality',
(ii) 'Any transfer of techniques from one area to another must be done with care and sensitivity', and
(iii) 'The selection of one or different methods to assess soil structure depends on why and who will perform the test'.

Until now, field assessment methods have been tested and compared by researchers in pasture and crop areas of some 'temperate' and 'subtropical' soils, but the evaluation and comparison of these methods under 'tropical' soils is still missing. In this context 'tropical soil' refers to all those soils geographically located within the Tropic of Capricorn and Tropic of Cancer without any distinction in evolution state. Similarly, evaluation of the suitability of these methods in soils under different land uses or in soils under different conditions in a more comprehensive approach with respect to other soil physical indicators is also requested. In part II of this dissertation, Chapters 6, 7 and 8, the use of visual examination methods for assessing soil structural quality is addressed.

1.6. Linking and interpreting soil structural quality using an integrated framework

Soil properties that have been used as the most important indicators for evaluating soil physical quality are bulk density (BD), porosity, air capacity (AC), field capacity (FC), plant available water capacity (PAWC), soil organic matter (SOM), hydraulic conductivity, aggregate stability and penetration resistance (Karlen et al., 1998, Reynolds et al., 2002, 2007; Shukla et al., 2006; Osman, 2013). They provide direct quantitative estimations of the ability of a soil to store and transmit root zone water and grow crops.

Internationally, there are several indices of soil physical quality, soil quality kits and frameworks that comprise different indicators (Karlen et al., 2003), most of them including those mentioned above. But not many include structural form description as indicators. This leads to a separated indirect and direct evaluation of the structural quality, which does not follow the ideal evaluation of the soil structure (structural form, aggregate stability and resilience). However, Carter (2004) states that research focussed on structural complexity in agricultural soils are 'ongoing to provide an improved understanding of soil structure and structure mediated processes and to develop or modify appropriate soil structure methodology'.

This point is sustained by the work of Pachepsky and Rawls (2003) who found that qualitative morphological observations of soil could be translated into quantitative soil parameters and used in an integrated framework. Many others have tested the inclusion of structural form indicators as potential independent variables for predicting other structure-related properties (Lilly et al., 2008; Vereecken et al., 2010; Nguyen et al., 2014). The use of a data-driven statistical technique for integrating quantitative and qualitative evaluations of soil structure is the main focus of Chapter 9 of this dissertation.

On the other hand, the interest in developing 'unique' indicators for soil structure and soil quality assessment, which is a simplistic approach, can be found in the literature as well. Examples include indices of soil structure based on soil characteristics related to this property such as particle size distribution and soil organic matter (SOM) such as the instability index (Henin et al., 1958), the index of crusting (FAO, 1980), and the structural stability index (Pieri, 1992). These indices involve SOM content *per se*, from which in some cases, differences in soil classifications according to their structure stability or quality become evident.

Generally, SOM promotes aggregate stability because it reduces aggregate swelling, and increases the intrinsic strength of aggregates (Fortun and Fortun, 1989).The effectiveness of SOC forming stable aggregates is related to its decomposition rate, which in turn is influenced by physical and chemical protection to microbial action (Bronick and Lal, 2005). However, inconsistencies in proportional relationship between SOM content and structural quality (mainly aggregate stability) has also been mentioned. Therefore, aggregate stability may depend more on the type of SOM and its provisions relating to the mineral particles (Fortun and Fortun, 1989; Holeplass et al., 2004). The SOM constituents link the primary particles in aggregates physically and chemically (Lado et al., 2004). Therefore, content and distribution of the stable and unstable aggregates in soil have close association with SOM dynamics and soil quality, hence, the soil degradation problems could be evaluated studying the proportion of stable aggregates (Márquez et al., 2004). It is however, important to emphasize that many other factors, apart from SOM, are related to structural stability. Recently, it has been suggested that 2:1 clay minerals contribute to the formation and stabilization of different aggregate-size classes differently (Fernández-Ugalde et al., 2013).

Another example of simplistic approaches is the soil physical quality index S (Dexter, 2004a), which is the slope of the soil water release curve (SWRC) at its inflection point. Although this index was developed based on the idea of integrating observations of a range of soil properties to obtain an overall assessment, it only represents a particular value of the SWRC. S index has been criticised as providing inconsistent designations of soil physical quality and lacking consistency with other physical indicators for some soils (Reynolds et al. 2009; Van Lier, 2014). When the objective is to use an indicator to predict specific soil property or soil function, then the existence of the complexity of the soil structure is neglected. The use of simpler approaches is discussed in Chapter 10 of this dissertation.

Despite the numerous methods for characterizing soil structure, none of these have been accepted universally. In each case, the choice of the method to be used depends on the problem, the soil and the equipment available (Hillel, 1998), but also on the scale and scope of the study.

According to Eswaran et al. (2001), 'soil scientists have an obligation not only to show the spatial distribution of stressed systems but also to provide reasonable estimates of their rates of degradation'. This justifies the efforts of several researchers in their emphasis for selecting the most suitable warning indicators of soil degradation. Indicators of soil degradation or soil quality judiciously selected can play a significant role in assisting national decision-makers to develop appropriate land use and conservation policies.

1.7. General and specific objectives

Beyond the selection of potential indicators for assessing and monitoring soil structural quality, the performance of the method applied to measure these indicators is a critical criterion to take into account. Therefore, the overall aim of this dissertation is to test and develop soil structural quality indicators, based on the comparison of different methods, for the improvement of frameworks for assessing soil quality (from an agricultural perspective) to contribute to soil conservation and sustainable agriculture approaches.

To achieve the above mentioned main aim the following specific objectives are addressed:

(i) To select appropriate aggregate stability methods that enable evaluation of soil physical quality of medium textured soils from both 'tropical' and 'temperate' regions.

(ii) To evaluate the use of chemical and physical fractions of SOM, rather than SOM *per se*, as better indicators of soil quality based on their effect on soil aggregate stability.

(iii) To test whether there are measurable differences in clay mineralogy among aggregate sizes. And to test the influence of the disaggregation mechanisms on the composition of clay mineralogy in the different aggregate sizes.

(iv) To compare the performance of the SQSP, VESS, and VSA methods in assessing the soil structural quality on Venezuelan 'tropical' soils with contrasting soil type and land use.

(v) To evaluate the use and the ability of visual examination methods for assessing soil structural quality in soils with contrasting texture and land use by comparing them to soil physical and hydraulic properties related to function of the soil.

(vi) To evaluate how responsive visual examination methods are to detect significant changes on soil structural quality related to soil management over a given sampling interval.

(vii) To identify soil morphology related parameters that may be linked to soil quality at different geographic areas and to test the potential power of using decision trees in setting up a framework for soil structural quality assessment.

(viii) To compare the suitability of the index S in identifying the soil physical quality of different 'tropical' and 'temperate' soils against the more frequently used soil physical and hydraulic properties on the one hand and visual examination methods on the other.

1.8. Outline of the dissertation

After an introductory chapter, Chapter 2 reviews the reasoning behind the selection of the study fields and the general characteristics of the selected fields and soils. Hereafter, based on the objectives mentioned above, this dissertation is divided into three parts:

(i) Soil physical quality assessment based on aggregate stability (Chapters 3, 4 and 5)

(ii) The use of visual examination methods for assessing soil structural quality (Chapters 6, 7 and 8)

(iii) Integrated and simple approaches for assessing soil structural quality (Chapters 9 and 10)

In Part I, Chapter 3 focuses on the influence of wet sieving methods on soil physical quality assessment. Chapter 4 discusses the use of chemical and physical fractions of SOM as indicators of soil physical quality instead of SOM *per se*. Chapter 5 presents an evaluation of the mineralogical composition of the clay fraction among aggregate sizes and the influence of the disaggregation mechanisms on the distribution of the mineralogical composition of the clay fraction of different aggregate sizes.

In Part II, Chapter 6 presents the assessment of the performance of visual examination methods in ‘tropical’ soils. Chapter 7 focuses on the validation of morphological approaches using measurements for assessing soil physical quality. Chapter 8 examines the use of visual examination methods for assessing changes in soil physical quality related to soil management.

In Part III, Chapter 9 examines the use of data-driven analysis of soil quality indicators using limited data. And Chapter 10 discusses the suitability of water release-related indicators for assessing soil physical quality.

The final chapter comprises an overall discussion of the main findings of this dissertation, the general conclusion and recommendations for further research.

Chapter 2

Selection of study sites

2.1. Introduction

Land degradation, including soil degradation, involves direct and indirect processes that affect ecosystem functions and services. Consequently, its impact is experienced on a local, regional and global scale. This fact justifies the starting of soil protection or soil conservation related policies in many countries.

Recently, the Rio+20 United Nations Conference on Sustainable Development in 2012 confirmed 'urgency for international soil conservation commitments'. It also emphasized 'the necessity of improvements and harmonisation of soil monitoring systems, promotion of sustainable soil management practice, and encouraged knowledge transfer in related fields' among other aspects (Camarsa et al., 2014).

As this dissertation was conducted in two contrasting geographical areas, one in Venezuela in the tropics and one in the temperate Flanders Region of Belgium, a brief description of the policies regarding soil protection in these regions is given.

The current Environmental Organic Law of Venezuela, implemented in 2006, states that:

(i) The use and exploitation of the soil and subsoil have to be done according to its natural suitability, availability and access to environmental safe technologies, in order to avoid degradation.
(ii) It is obligatory to adopt measures to prevent and correct any activity that leads to erosion, salinization, desertification or modification of the topography and other forms of soil and land degradation.

Policies on soil conservation are not that new in Venezuela. Actions on evaluating land use and conservation strategies in agricultural areas of Venezuela were initiated in 1943 with the collaboration of the former United States Soil Conservation Service. Consequently, a conservation subsidy for farmers was developed in 1958; however, it was only applied until 1970. Since that moment, the national policy interest turned into reforestation and watershed protection (Pla, 1990). Currently, the education of farmers in monitoring soil quality and applying conservation practices is very little. However, studies focusing on soil conservation, hence on the selection of capable indicators for assessing soil quality under crop lands, are in harmony with article 63 of the current Environmental Organic Law of Venezuela, which decrees that for the purposes of conservation, prevention, control of pollution and degradation of soils and groundwater, environmental authorities shall ensure the conduction of research and soil conservation studies.

On a European level, the Roadmap to a Resource Efficient Europe proposes that by 2020 European Union policies take into account their direct and indirect impact on land use in the European Union and globally (Camarsa et al., 2014). In this perspective, reduced farm fertility and off-site problems caused by soil and land degradation in populated areas of Flanders in Belgium, stimulated the consciousness of farmers, policy makers and scientists in the mid 1990's. Therefore, the Mid Term Review, implemented in the local regulation of the Flemish government of Belgium, recommends farmers to comply with standards to maintain good agricultural and environmental conditions, known as cross-compliance. Only farmers who fulfil the cross-compliance are allowed to receive European Union support. Those who are willing to go beyond the standards and implement Agri-Environmental Schemes on a voluntary base, receive a subsidy (Vermang, 2012). The combination of recommended cross-compliance and voluntary Agri-Environmental Schemes aimed at a conversion of conventional tillage to reduced tillage or no-till system in Flanders. However, there are concerns whether the subsidy for reduced tillage or no-till systems applications should be continued or not.

The policy contexts described above constitute a basis to support the two geographical areas, central northern part of Venezuela and Flanders Region of Belgium, as cases for evaluating soil structural quality indicators. To ensure an adequate land use with low risk of soil degradation, development of unified soil quality frameworks is required for evaluating and monitoring the soil condition of these agricultural areas. Therefore, judicious selection of soil quality indicators is needed.

These soil quality frameworks, based on scientific research, should be available for the use of both policy makers and land users to identify future policies and practices that control the development of soil degradation, and to contribute to soil conservation and sustainable agricultural approaches.

2.2. Selection of study sites and soils

The studied soils were mainly medium textured and collected from two different geographical locations; in the tropics (Venezuela) and in a temperate area (Belgium). The selection of these two geographical areas under different climatic conditions, is justify as the majority of methods for assessing soil structure have been developed for soils under temperate conditions and its applicability to soils under other climatic condition should be conducted. This will help in the improvement of frameworks for assessing soil quality from an agricultural perspective. Heavy and coarse textured soils were not included in this survey because they are not representative of the studied areas, as well as they have different physical behaviour compared to medium textured ones. Additionally, this survey was conducted on a range of soil types of varying age, parent material, climate and topography. The sampled soils also include different land uses such as natural savannah, fruit cropping, permanent pasture, and cereal monoculture, as well as different management practices. The variation in environmental factors, including land use and management, ensured counting with a wide range of soil quality for this survey. Hence, a proper scenario for testing and comparing the reliability of the methods selected for an integrated assessment of soil structure, and the selection of minimum dataset of indicators of soil structural quality.

Soils sampled in the central-northern part of Venezuela, are representative of the area where a large part of the country's cereal and vegetable production takes place. Correspondingly, soils collected in the Flanders Region of Belgium are representative for the loess belt in the western and eastern Flanders. Soils from the central-northern part of Venezuela were denoted as V1-V6 and those from Flanders Region of Belgium as B1-B4 (Table 2-1). To emphasize the difference in climate condition between the two geographical areas, they are also termed further in the manuscript as 'tropical' and 'temperate' soils. The term 'tropical' soil does not imply highly weathered soil.

2.2.1. Tropical environment: central-northern part of Venezuela

2.2.1.1. Geographical location

Venezuela is located in northern South America at 1-12° N and 59-73° W, bordering the Caribbean Sea and the North Atlantic Ocean, between Colombia and Guyana. Venezuela has a total area of 916,445 km^2 and a land area of 882,050 km^2.

2.2.1.2. Climate

Although the country lies entirely within the tropics, its climate varies from arid to tropical rainforest, depending upon the topography of the area. In the country rainfall varies from less than 400 mm per year on the coastline to more than 4000 mm per year in the south. Mean daily temperatures are ranging from 28 °C (coastline and plain areas) to less than 0 °C (Páramos in the Andean area). Seasonal variations are marked less by temperature than by rainfall. Most of the country has a distinct rainy period and a dry period influenced by the Intertropical Convergence Zone (Andressen, 2007). The central-northern area of Venezuela has mainly a tropical savannah climate (Aw) according to the Köppen-Geiger classification.

2.2.1.3. Soils

The territory of Venezuela is characterized by a wide pedo-diversity, partly linked to the geology of each region. In fact, 10 out of the 12 orders and 35 out of the 64 suborders established by Soil Taxonomy of the Soil Survey Staff (2010) in the country have been identified. Major orders that have been identified in Venezuela are Ultisols (42% of the territory) and Inceptisols (22% of the territory). Specifically in the central-northern part of Venezuela, the dominant orders are Inceptisols, Mollisols, Alfisols, Ultisols and Vertisols (Comerma, 1971). In general, agricultural use of soils is constrained by a number of limitations: 4% of the territory is arid, 18% has drainage limitations, 32% are soils of low fertility, and 44% are on steep slopes, thus leaving only 2% without limitations (Comerma and Paredes, 1978).

The six soils sampled in Venezuela were taken from different agricultural areas located in the central coast range and the plain area in the north of the Orinoco River (central-northern part of Venezuela, Figure 2-1). In general, V1, V2 and V3 belongs to a region formed over a geological material comprised by metamorphic rocks in association with igneous rocks, whereas V4, V5 and V6 are situated in a region which has been formed over geological material where sedimentary rocks and sediments prevail, or intrusive igneous rocks (Elizalde et al., 2007).

The soil V1 is located in La Colonia Tovar community (10° 22’ N and 67° 12’ W) at 1861 MASL. The climate of the area is characterized by a mean annual temperature of 17 °C and a mean annual rainfall of 1154 mm. The dominant soil type in the area is classified as Typic Kandiustult (Soil Survey Staff, 2010). The plot from where V1 was collected is characterized by a top layer having sandy clay loam texture, a strongly acid pH (KCl) and high content of SOM. The main land use in the agricultural area of La Colonia Tovar is vegetable and fruit production under no-till. At the time of sampling the V1 soil was under permanent trees (*Prunus persica* (L.) Batsch) and grass between tree rows. Chicken manure is applied without any specific criterion.

V2 soil is located in Maracay city in the plain area of the Guey River (10° 15’ N and 67° 37’ W at 436 MASL), where the climate is characterized by a mean annual temperature of 25 °C and mean annual rainfall of 979 mm. The studied soil is developed in colluvial materials derived from metamorphic rocks that contain abundant quartz, mica and some plagioclase (Gonzalez de Juana, 1980). The dominant soil type of the sampled area is classified as a Fluventic Haplustoll (Soil Survey Staff, 2010). The plot where V2 was sampled is in foot slope position and its top soil layer is characterized by a clay loam texture, a pH_{KCl} equal to 7.67 and high SOM content. V2 soil was under permanent pasture (*Morus* spp and *Cynodon nlemfuensis*) with no-till at the time of sampling.

Table 2-1 Description and characteristics of the 'tropical' (V1-V6; Venezuela) and 'temperate' (B1-B4; Belgium) soils.

Soil	Textural class	Soil Taxonomy (Soil Survey Staff, 2010)	Geographic coordinates	Drainage status [a]	Soil use and management [b]	Clay [c]	Silt	Sand	SOC	pH_{KCl}
						(g kg^{-1})				
V1	Sandy clay loam	Typic Kandiustult	10° 22' N 67° 12' W	Well drained	Fruit cropping with no-till	285	199	516	42.6	3.65
V2	Clay loam	Fluventic Haplustoll	10° 15' N 67° 37' W	Well drained	Ungrazed grassland with no-till	291	282	427	24.4	7.67
V3	Loam	Typic Endoaqualf	10° 21' N 68° 39' W	Imperfectly drained	Maize mono-cropping, conventional tillage	173	351	476	7.5	4.90
V4	Loam	Aquic Haplustoll	8° 46' N 67° 45' W	Moderately well drained	Grassland with trampling and no-till	229	486	285	20.3	5.19
V5	Silt loam	Typic Rhodustalf	9° 0' N 67° 41' W	Moderately well drained	Cereal crops with fallow periods, conventional tillage	261	583	156	29.1	4.84
V6	Silty clay	Aquic Haplustalf	9° 02' N 67° 41' W	Moderately well drained	Grassland with natural vegetation, trampling	423	501	76	16.1	4.67
B1	Sandy loam	Dystric Eutrudept	50° 59' N 3° 31' E	Well drained	Cereal mono-cropping with conventional tillage	136	120	744	11.6	5.96
B2	Silt loam	Aquic Hapludalf	50° 46' N 3° 35' E	Moderately well drained	Cereal mono-cropping with conventional tillage	164	628	208	13.4	6.76
B3	Silt loam	Aquic Hapludalf	50° 47' N 3° 25' E	Moderately well drained	Rotation of corn and winter wheat with conventional tillage	125	658	217	9.4	6.22
B4	Loam	Dystric Eutrudept	50° 47' N 2° 49' E	Well drained	Rotation of cereal and grass, reduced tillage	98	532	370	9.6	6.52

[a] The soil drainage class indicates the possibility to evacuate excess of water from a soil based on the soil unit's classification name. The FAO soil drainage classes are: not applicable; excessively drained; soils extremely drained; well drained; moderately well drained; imperfectly drained; poorly drained; very poorly drained; water bodies.
[b] Current and over the last 10 years.
[c] Particle size distribution, soil organic carbon (SOC) and pH values correspond only to analyses conducted on samples taken from 0-20 cm depth.

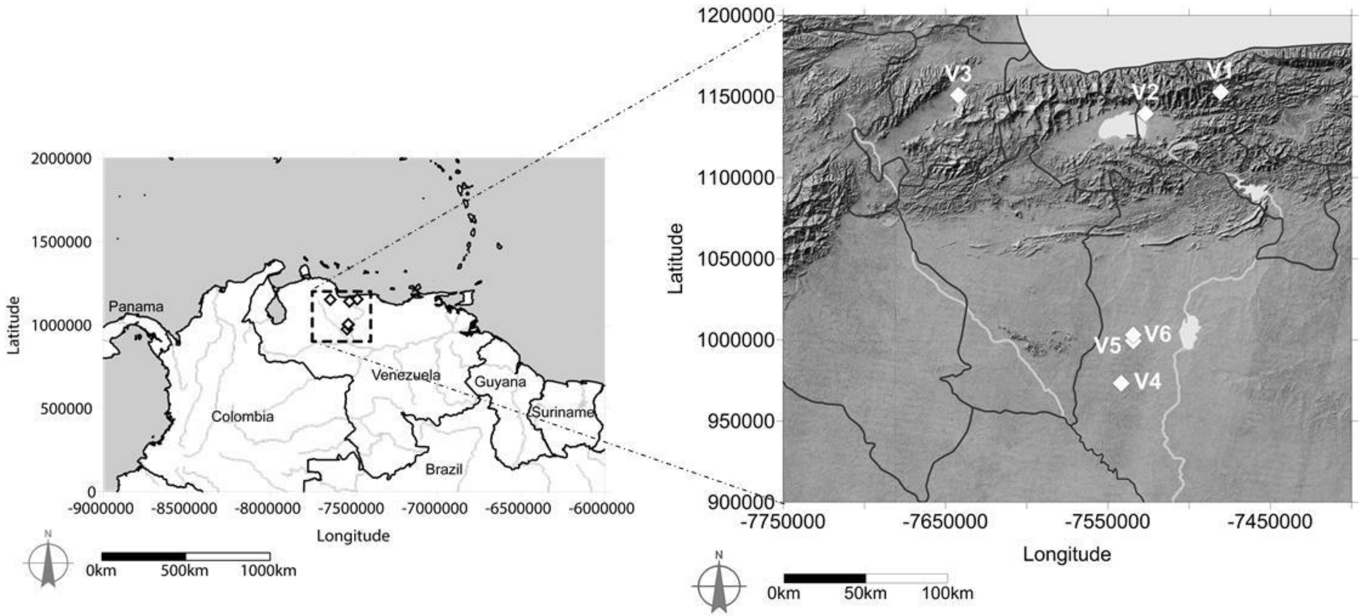
The soil denoted as V3 was sampled in the experimental field of the 'Fundación Danac' research station of Empresas POLAR S.A. This is located in the community of San Felipe in Yaracuy state (10° 21' 52.38" N; 68° 39' 17.18" W) at 320 MASL. The climate of the area is characterized by a mean annual temperature of 27 °C and annual rainfall of 1212 mm. The soil is classified as Typic Endoaqualf (Soil Survey Staff, 2010). Its parental material is associated with alluvial material, derived from micaceous schist, gneiss, and sandstone. It is an imperfectly drained soil. V3 samples were taken from the surface layer of a plot characterized by acid pH (KCl), with loam texture and a low content of SOM. The plot where V3 was sampled has < 3 % of slope and is under a long term cereal monoculture (*Zea mays* L.) with conventional tillage. Conventional tillage in this area of Venezuela can be described as ploughing and multiple passes of the harrow and during each cultivation period as well as a yearly subsoiling (0.4 m depth).

Soils V4, V5 and V6 were selected from the agricultural area of the Tiznados River in the Guardatinajas community, Guárico state, located at 120 MASL. The mean annual rainfall in the area is about 1336 mm. A yearly mean temperature varies between 27 °C and 29.4 °C. The area consists of alluvial depositions of the Tiznados River of quaternary age (Pleistocene) and recent (Holocene). This alluvial plain area (< 1 % of slope) has very few differences in relief. In general two landforms can be distinguished, one with medium textured soils and well drained and another with fine texture soils and surface flooding. In general, the land use in this area is cattle grazing, but there are also areas with corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.), and smaller areas with vegetable production.

V4 soil classified as Aquic Haplustoll (Soil Survey Staff, 2010) is located in *'La Fundación' commercial farm* at 8° 46' N and 67° 45' W. Drainage class is moderately well drained. In the surface layer this soil is acid (pH_{KCl}), with a loam texture and high content of SOM. At the time of sampling V4 soil was under pasture (*Brachiaria brizantha*) with no-till.

V5 soil classified as Typic Rhodustalf (Soil Survey Staff, 2010) is located in *'El Cujicito' commercial farm* (9° 0' N and 67° 41' W). Red colours dominate the matrix in the whole soil profile. In general, this soil was characterized in the top layer as having silt loam texture, a very strongly acid pH (KCl), low content of macronutrients, and a medium SOM content. At the time of sampling, this soil was in fallow with natural vegetation.

V6 soil is located in '*Las Nubes' commercial farm* at 9° 02' N and 67° 41' W. The soil is classified as Aquic Haplustalf (Soil Survey Staff, 2010). The soil texture is silty clay in the upper layer and clay at greater depth. In general this soil has a medium fertility level. The top layer was characterized as strongly acid, medium SOM content and low content in macronutrients. The main land use in the area is grassland (natural vegetation) with permanent cattle.



Source: Jan De Pue, Soil Physics Research Unit, Ghent University. Software used: Surfer v11.1.719 (Golden Software, Inc., Golden, CO). The used projection is WGS84 / Mercator projection (EPSG 3395).

Figure 2-1 Location of the studied soils in Venezuela (V1-V6).

2.2.2. Temperate environment: Flanders Region of Belgium

2.2.2.1. Geographic location

Belgium is a federal state located in Western Europe, bordering the North Sea and shares borders with France, Germany, Luxembourg and the Netherlands. It lies between latitudes 49°30’ and 51°30’ N, and longitudes 2°33’ and 6°24’ E. The country comprises the regions of Flanders, Wallonia and Brussels.

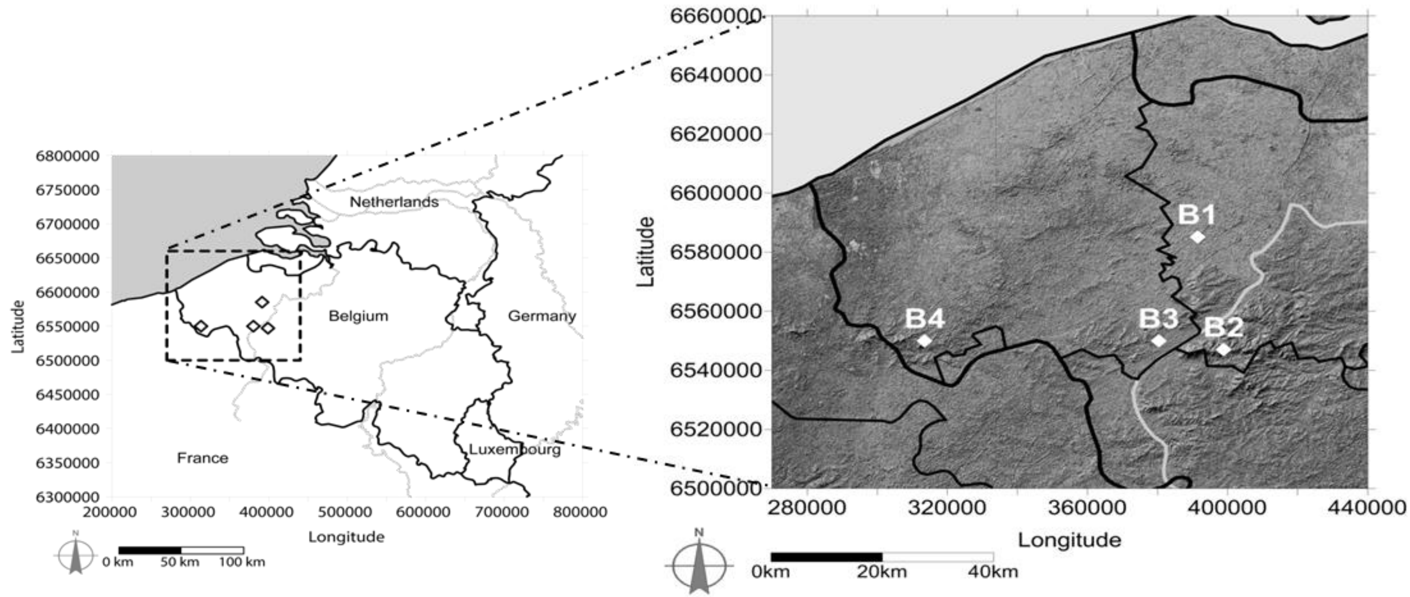
2.2.2.2. Climate

Belgium has temperate climate without dry season (Cfb, Köppen-Geiger classification). The Flanders area has a mean annual precipitation of 780 mm and a mean yearly temperature of 9.8°C. However, significant deviations from the long-term average (30 years) rainfall (690 mm in 2003 and 914 mm in 2004) and temperature (11.1°C in 2003, 10.7°C in 2004 and 11.0°C in 2005) have been observed in recent years (D’Haene et al., 2008).

2.2.2.3. Soils

Soils B1 - B4 are located in the Flanders Region of Belgium, specifically in the loess belt of Belgium (Figure 2-2). This area drains to the Scheldt River. The elevation ranges from 10 m at the borders of the Scheldt River up to 157 m at the top of the Pottelberg. Most slopes in the area range between 0 and 20%. In this area the quaternary period was characterized by a sequence of glacial and interglacial periods. During the last ice age Flanders was covered by Aeolian deposits, originating from the North Sea plain: the coarse sand fractions were mainly deposited in the northern part, while the loess was transported over longer distances and deposited mainly in the southern region of Flanders. In these aeolian deposits the current soils were formed (Schiettecatte et al., 2012).

The soil denoted as B1 is a Dystric Eutrudept (Soil Survey Staff, 2010) located in the community of Kruishoutem (50° 55´N; 3° 31´E) on a southwest facing slope of 5.5% on a mid-slope position. The top layer of B1 is characterized by a sandy loam soil texture and a moderately acid pH (KCl). In this soil two plots of 810 m² (18 m x 45 m) were selected, one under cereal mono-cropping (*Zea mays* L.) with conventional tillage (CM) and another under permanent pasture (PP). Conventional tillage consisted of primary tillage with mouldboard plough with 4 shares (30 cm depth), and a secondary tillage with harrow + seed drill (5-10 cm depth). PP is used in this area to protect the soil surface against erosion and is free of grazing.



Source: Jan De Pue, Soil Physics Research Unit, Ghent University. Software used: Surfer v11.1.719 (Golden Software, Inc., Golden, CO). The used projection is WGS84 / Mercator projection (EPSG 3395).

Figure 2-2 Location of the studied soil in Belgium (B1-B4).

B2 soil is located in Nukerke at 50° 46´N, 3° 31´E in the municipality of Maarkedal in the Flemish Ardennes. It shows a steep, slightly convex topography with an average slope of 13%. Due to its soil properties and topography, soils in this area are highly susceptible to soil erosion. The dominant soil type in this area is classified as an Aquic Hapludalf (Soil Survey Staff, 2010). The sampled plot has in the top layer a silt loam soil texture, a slightly acid pH (KCl), and a medium SOM content. The field is tilled using a mouldboard plough, followed by harrowing and sowing. At the moment of sampling, it was under cereal mono-cropping (maize).

The soil denoted as B3 is located in the community of Heestert (50° 48´ N; 3° 25´E) on a slope of 4.5% on a mid-slope position facing southeast. Drainage class is moderately well drained. The dominant soil type in this area is classified as Aquic Hapludalf (Soil Survey Staff, 2010). In the surface layer B3 is slightly acid (pH_{KCl}), with silt loam texture and low content of SOM. In this soil, as in the case of B1, two plots of 810 m^2 (18 m x 45 m) were selected: one under rotation of maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) with conventional tillage, and the other under PP with the constant presence of cattle (7.5 animals per ha). The plot under crop production is under conventional tillage, which comprised primary tillage with cultivator (5-10 cm depth) + mouldboard plough with 15 shares (30 cm depth), followed by secondary tillage with harrow and seed drill (5-10 cm).

Finally, B4 soil is a Dystric Eutrudept (Soil Survey Staff, 2010) located in the alluvial plain of the river Leie in the municipality of Heuvelland in West Flanders (50° 47´ N; 2° 49´E). The topsoil of B4 is characterized by loam texture, slightly acid pH (KCl) and low SOM. At sampling moment B4 was under grass. The land use is mainly rotation of cereal and grass with reduced tillage.

Part I

Soil physical quality assessment based on aggregate stability

Chapter 3

The influence of wet sieving methods on soil physical quality assessment[#]

3.1. Introduction

Soil aggregate stability is the ability of the soil to retain its arrangement of solids and pore space 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 (An et al., 2010; Horn et al., 1994).

There are different methods for measuring aggregate stability that are based on the fragmentation of the soil samples after applying mechanical stresses (Amezketa, 1999). As was mentioned in the introductory Chapter, the most frequently applied method is the wet sieving.

From the wet sieving method, many methodologies have been developed (Le Bissonnais, 1996), which differ in one or more of the following aspects:

(i) The pre-wetting techniques (Beare and Bruce, 1993);
(ii) The limit of the aggregate sizes, which determines their physical properties (Niewczas and Witkowska-Walczak, 2003);
(iii) The use of a single sieve or a nest of sieves (De Leenheer and De Boodt, 1959; Beare and Bruce, 1993; Le Bissonnais, 1996),
(iv) The different intensities of disruptive mechanical energy to the sample (Amezketa, 1999); and

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(v) 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 simpler and more advanced methods, such as visual aggregate stability (Mueller et al., 2013; Beste, 1999) and aggregate stability measurements by laser granulometry with sonication (Rawlins et al., 2013) have been also developed to monitor the aggregate stability. There are also several indirect indicators of soil structure used as soil physical quality (SPQ) indices, which are aggregate stability-related. For instance, the relationship between the particle size distribution and the SOM (Lal and Shukla, 2004), BD, porosity, AC, FC and PAWC (Reynolds et al., 2009; Reynolds et al., 2007).

Aggregate stability 'function' in terms of soil strength, the storage and transmission of water and air can be estimated by the parameters mentioned above and hence the aggregate stability can be tested through the comparison against other indicators.

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 (Rawlins et al., 2013, Arshad and Coen, 1992).

The objective of this Chapter was to evaluate appropriate aggregate stability methods that enable evaluation of the SPQ condition of both 'tropical' and 'temperate' medium textured soils. Additionally, the evaluation of selected methods by comparing them with other indicators of SPQ was conducted with the purpose of using aggregate stability as a dependable indicator of the soil structural quality. This Chapter only focuses on standard methods to measure aggregate stability involving wet-sieving.

3.2. Materials and Methods

3.2.1. Soils description and soil sampling

Ten fields with representative soils were selected, with six located in a tropical environment (V_1-V_6; central northern Venezuela) and four in a temperate one (B_1-B_4; Flanders, Belgium). The soils were described in Table 2-1 of Chapter 2. In the 'temperate' soils, B1 and B3, aggregate stability assessment was only conducted under cropland plots. In all fields, plots having homogeneous texture were demarcated. The plot's area in the different fields varied from 810 m^2 to 2000 m^2. Within the plots three transects of variable length were randomly laid out at least 15 m from the edge of the field in order to minimize edge effects. Samples were taken at the centre points of each half of each transect (at 25 and 75% of its length).

At each sampling point, 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 and Or, 2002), soil organic carbon (SOC) measured by wet oxidation (Walkley and 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 samples per soil. Saturated hydraulic conductivity (K_s), SWRC and BD were determined on the core samples.

3.2.2. Saturated hydraulic conductivity, soil water release curve and soil bulk density

The K_s was determined using the constant head method with a closed laboratory permeameter system (Eijkelkamp Agrisearch Equipment, the Netherlands).

The SWRC data were determined from the wet to the dry range at eight different matric potentials: -1, -3, -5, -7, -10, -33, -100, and -1500 kPa. For the matric potentials ranging from -1 to -10 kPa, the sand box apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used, whereas for matric potentials between -33 and -1500 kPa, pressure chambers (Soil Moisture Equipment, Santa Barbara, C.A., USA) were used. The procedure followed is described by Cornelis et al. (2005). The coupled matric potential-water content pairs represent single measurements on individual samples.

Soil physical properties such as air capacity (AC, $\theta_{\psi= 0\ kPa}$ - $\theta_{\psi= -10\ kPa}$), plant available water capacity (PAWC, $\theta_{\psi= -33\ kPa}$ - $\theta_{\psi= -1500\ kPa}$), and relative water capacity (RWC, $\theta_{\psi= -33\ kPa}$/ $\theta_{\psi= 0\ kPa}$) were calculated from the SWRC data, with $_\psi$ denoting matric potential. The RWC 'expresses the soil's capacity to store water (and air) relative to the soil's total pore volume' (Reynolds et al., 2007). Soil BD was determined based on the core method. Shrinkage was observed in some of the rings as well as some rock fragments; hence, a correction on the volume was made for the calculation of BD. Furthermore, the volume of the rock fragments was determined by Archimedes' principle.

3.2.3. Aggregate stability

Aggregate stability was measured on air-dried soil samples using three different methods:

(i) The wet sieving method with multiple sieves proposed by De Leenheer and De Boodt (1959) and adjusted by Hofman (1973)
(ii) The three treatments of the method by Le Bissonnais (1996)
(iii) The wet sieving method using a single sieve based on Kemper and Rosenau (1986).

All analyses were replicated three times for each sample. For the method of De Leenheer and De Boodt (1959), abbreviated here as dLdB, 100 g of aggregates divided in three fractions were used. The aggregate fractions of 40 g with diameter between 4.75 – 8.00 mm, 32 g of 2.80 - 4.75 mm and 28 g of 2.00-2.80 mm, were prewetted to field capacity by drops falling from a height of 50 cm. Raindrops are formed at 5 mm tip of a capillary tube with inner diameter of 0.4 mm.

After pre-wetting, the different aggregate size fractions were incubated for 24 h at 20 °C and 98-100% relative humidity. Finally, each aggregate size fraction was placed on its corresponding sieve. Three extra sieves with mesh sizes of 1, 0.5 and 0.3 mm were added and all the sieves were gently shaken under water at a constant speed (automatically controlled) for 5 min. The aggregates remaining on each sieve were washed off the sieve and weighed after drying.

The results were expressed in terms of the mean weight diameter (MWD) and the stability index (SI):

$$\mathrm{MWD\,(mm)} = \frac{\sum_{i=1}^{i=n} m_i d_i}{m_t} \qquad (3\text{-}1)$$

where m_i = mass of the stable aggregate fraction i; d_i = mean diameter of fraction i; m_t = total weight of the sample.

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

$$SI = \frac{1}{IS} \qquad (3\text{-}2)$$

Classification of the aggregate stability based on SI (De Leenheer and De Boodt, 1959), for medium-textured Belgian soils includes the following rating: >1 = excellent; 0.8 - 1 = very good; 0.66 - 0.8 = good; 0.5 - 0.66 = unsatisfactory; and < 0.5 = bad.

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 pre-wetting (LB3). Briefly, air dried aggregates of 3-5 mm in diameter, were calibrated by putting them in the oven at 40 °C for 24 h.

LB1 involves the immersion of 5 g of calibrated aggregates in 50 ml of deionized water for 10 min. Then the water was cautiously extracted and the soil material was transferred to a 50 µm sieve for wet-sieving in ethanol (gently moved five times) in order to measure the fragment size distribution. For LB2 the 5 g of calibrated aggregates were put on a filter paper on a tension table at a matric potential of -0.3 kPa for 30 min and then transferred to the 50 µm sieve immersed in ethanol.

In the case of LB3, 5 g of calibrated aggregates were immersed in 50 ml of ethanol for 10 min. After this, the ethanol was extracted and the soil material was transferred to a flask with 200 ml of deionized water and agitated end over end 20 times. The mixture of water and soil was left for 30 min for sedimentation, then the water was extracted and the soil material was transferred to the 50 µm sieve immersed in ethanol as the other treatments of LB.

After wet-sieving in ethanol, the > 50 µm soil material was collected, oven-dried and gently dry-sieved by hand on a set of six sieves: 2.0, 1.0, 0.5, 0.2, 0.1 and 0.05 mm. The mass percentage of each size fraction was then calculated; the fraction < 50 µm was the difference between initial mass and the sum of the six other fractions.

The aggregate stability resulted from the three treatments was expressed by calculating MWD and SI from equations (3-1) and (3-2), respectively. Le Bissonnais (1996) suggested the following classes of stability according to 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.

Finally, the Yoder method modified by Kemper and Rosenau (1986), denoted here as KR, calls for air-drying and rewetting the soil samples prior to wet sieving in deionized 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 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 – 0.33 kPa for 30 minutes. For both pre-treatments, 1 - 2 mm air-dried aggregates were wet sieved in deionized water for 3 minutes at a constant, automatically controlled speed. After mechanical shaking, the soil sample that remains on the sieve (0.25 mm) was shaken again in a solution of sodium metaphosphate until the aggregates were fully dispersed. This was in order to conduct the correction of sand fraction. Results were expressed as MWD.

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 remained on the sieve of 0.5 mm and those above it. 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%.

3.2.4. Structural stability index

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

$$\text{StI} = \frac{1.724 \times \text{SOC}}{\text{Clay} + \text{Silt}} \times 100 \qquad (3\text{-}3)$$

Where StI is the structural stability index expressed in %, SOC is the soil organic carbon content (%) and Clay + Silt is the soil's combined clay and silt content (%). StI < 5% indicates a structurally degraded soil; 5% < StI < 7% indicates high a 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.

3.2.5. Statistical data analysis

Differences between coefficients of variation (CV) of the aggregate stability methods were determined with an analysis of variance, with methods as factor, on the ratio 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 standardized 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).

3.3. Results

3.3.1. Comparison of methods for measuring aggregate stability

3.3.1.1. Similitudes of the methods in assessing aggregate stability

The results from the three aggregate stability methods were expressed in terms of MWD, as a common index. Others such as WSA and SI were selected according to the methodology used. Method abbreviations are shown in Table 3-1.

The difference between initial MWD and final MWD represents a comparison of the aggregate status after dry and wet sieving (IS). 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} = 0.68) and the other soils showed a low SI_{dLdB} (≤ 0.66, unsatisfactory).

As illustrated in Figure 3-1, > 70% of WSA comprises the size fractions between 2 - 8 mm in diameter of the soils V1, V2 and V5, and between 50 - 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 3-2 displays the aggregate size distributions of the 0 - 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 2-5 mm with the three treatments. The other soils, after treatment LB1 > 50% of aggregates (in terms of mass) was retained between the sieves of 0.05 and 0.5 mm, and between 40 - 50% of aggregates was retained in between 0.2-2 mm after treatments LB2 and LB3.

Table 3-1 Mean of the aggregate stability indices values for soils from tropical (V1-V6; Venezuela) and temperate (B1-B4; Flanders) environments

	V1	V2	V3	V4	V5	V6	B1	B2	B3	B4
MWD_{dLdB}	3.63	3.58	2.29	1.93	3.97	2.62	2.11	1.71	2.92	0.82
	(0.06)	(0.15)	(0.31)	(0.70)	(0.08)	(0.50)	(0.22)	(0.33)	(0.33)	(0.17)
SI_{dLdB}	1.22	1.15	0.46	0.40	2.07	0.55	0.43	0.37	0.68	0.28
	(0.10)	(0.21)	(0.07)	(0.15)	(0.31)	(0.16)	(0.04)	(0.04)	(0.14)	(0.01)
MWD_{LB1}	1.78	1.86	0.51	0.79	2.99	0.93	0.73	0.67	0.53	0.33
	(0.19)	(0.22)	(0.06)	(0.33)	(0.09)	(0.17)	(0.10)	(0.09)	(0.07)	(0.06)
MWD_{LB2}	3.46	3.37	1.64	1.99	3.46	1.89	3.25	2.85	1.60	2.04
	(0.01)	(0.05)	(0.16)	(0.44)	(0.02)	(0.33)	(0.05)	(0.37)	(0.17)	(0.27)
MWD_{LB3}	3.15	3.18	1.50	1.82	3.38	1.99	0.65	1.98	0.71	0.80
	(0.12)	(0.06)	(0.10)	(0.43)	(0.02)	(0.34)	(0.08)	(0.18)	(0.03)	(0.08)
MWD_{KRFW}	0.73	0.61	0.18	0.42	1.00	0.58	0.46	0.41	0.40	0.38
	(0.05)	(0.07)	(0.02)	(0.11)	(0.02)	(0.07)	(0.10)	(0.10)	(0.08)	(0.12)
MWD_{KRSW}	1.02	0.82	0.77	0.68	1.01	0.84	0.84	0.90	0.83	0.76
	(0.03)	(0.03)	(0.05)	(0.02)	(0.02)	(0.03)	(0.02)	(0.17)	(0.01)	(0.04)
WSA_{KRFW}	70.8	82.2	37.1	43.1	93.4	57.3	44.9	37.9	34.5	39.6
	(4.67)	(5.39)	(4.37)	(10.43)	(1.47)	(5.97)	(8.34)	(9.95)	(7.17)	(11.46)
WSA_{KRSW}	92.7	99.3	91.1	68.9	97.7	83.6	82.3	83.7	77.2	74.4
	(1.70)	(0.42)	(0.88)	(0.87)	(0.24)	(0.24)	(1.00)	(0.75)	(0.62)	(3.21)

MWD_{dLdB} = mean weight diameter (mm) after drop impact and wet sieving using the De Leenheer and De Boodt method, SI_{dLdB} = stability index after drop impact and wet sieving using dLdB method, MWD_{LB1} = mean weight diameter (mm) after LB1, MWD_{LB2} = mean weight diameter (mm) after LB2, MWD_{LB3} = mean weight diameter (mm) after LB3, MWD_{KRFW} = mean weight diameter (mm) after fast wetting using Kemper and Rosenau method, MWD_{KRSW} = mean weight diameter (mm) after slow wetting using KR method, WSA_{KRFW} = per cent of water stable aggregates after fast wetting using KR method, WSA_{KRSW} = per cent of water stable aggregates after slow wetting using KR method.
Standard deviation for each index is given in parenthesis (±).

In the ‘temperate’ soils (B1 to B4) the trend in aggregate distribution between the three treatments of LB was different compared to 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 2-5 mm, which was not the case of B3 and B4. When LB3 was applied, fractions between 0.5 and 2 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 2-5 mm.

These differences between LB treatments were also evidenced in the values of MWD. The MWD obtained after the different treatments 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 to 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 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 3-1). The reduction of MWD using FW of aggregates 1 - 2 mm in diameter was 30% for V5, between 50 - 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 1 - 2 mm size fraction is less resistant to breakdown after wet sieving when a FW was applied, except for V5.

Table 3-1 shows that when slowly pre-wetted aggregates were used, all the soils appeared as very stable. Between 70 - 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 -0.3 kPa for 30 min is used to prevent slaking, all soils expressed a high stability after shaking. This shows that the aggregate stability of the studied medium textured soils was strongly affected by the moisture content of the aggregates before wet sieving.

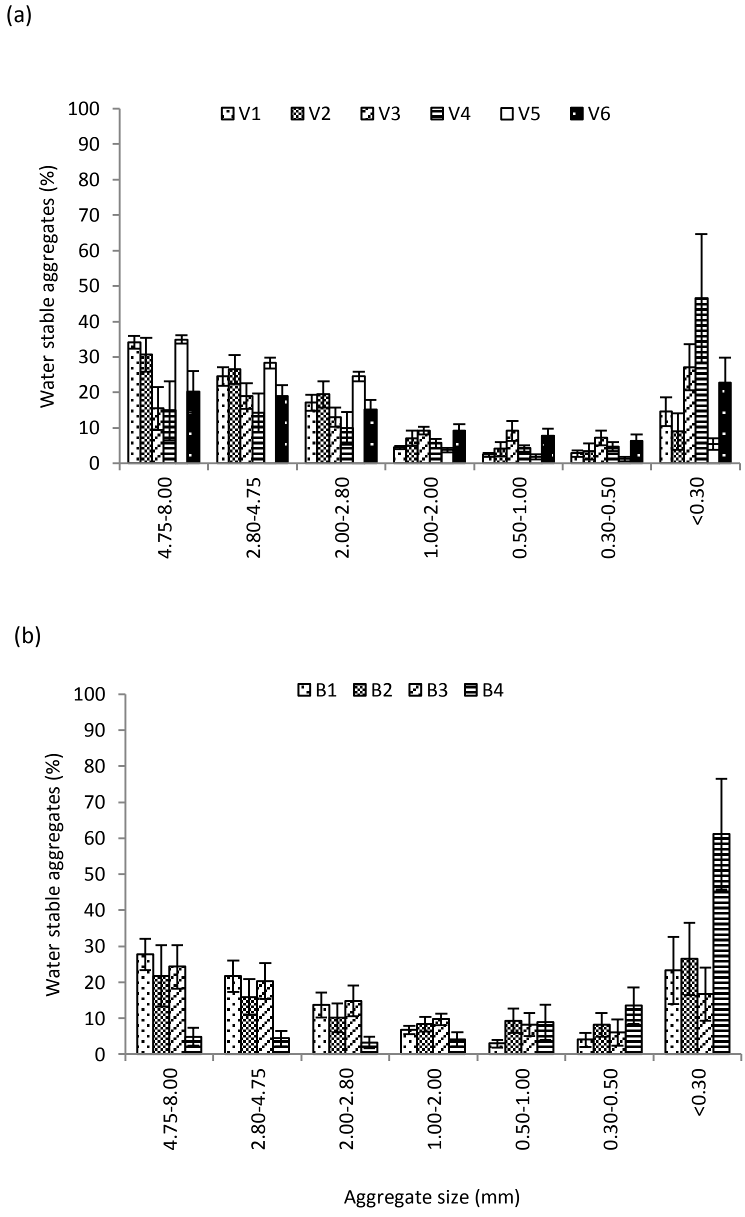


Figure 3-1 Distribution of the aggregate size fractions of the 0-20 cm layer according to the De Leenheer and De Boodt method (1959) for soils from tropical (V1-V6; Venezuela) (a) and temperate (B1-B4; Flanders) (b) environments.

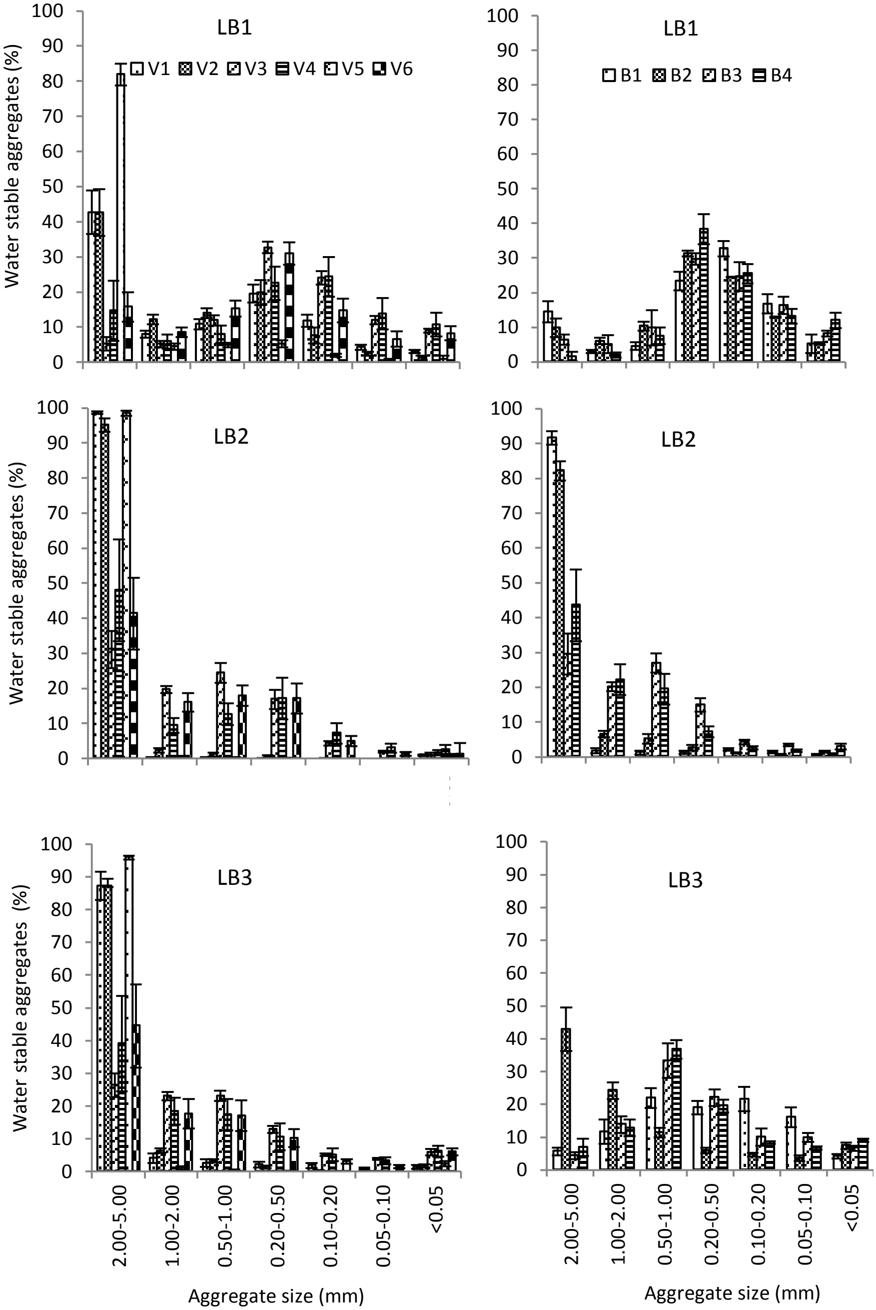


Figure 3-2 Distribution of the aggregate size fractions of the 0-20 cm layer from the Le Bissonnais method (1996) (LB1, LB2, and LB3) for soils from tropical (V1-V6; Venezuela) and temperate (B1-B4; Belgium) environments.

3.3.1.2. The variability of the MWD values and the relationship between methods

Analysis of the differences between CV was performed with the purpose of comparing the variability in the values of MWD between the different methods of aggregate stability (Table 3-2). Differences in variability were found between methods ($P < 0.01$) for both ‘tropical’ and ‘temperate’ soils.

Table 3-2 shows that in the ‘tropical’ soils from Venezuela, two groups of comparable methods are formed, MWD_{KRFW} and MWD_{LB1} as one group, and MWD_{LB2} and MWD_{LB3} as another. LB2 and LB3 are expected to give a better SPQ class when aggregate stability is used as an indicator ($P < 0.01$). MWD_{LB2} and MWD_{KRSW} are distinct in classifying the SPQ condition of soils associated with a greater variability ($P < 0.01$). For these ‘tropical’ 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 input energy by slaking and shaking over dry aggregates is more aggressive than pre-wetting the aggregates prior to wet sieving.

Table 3-2 Summary statistics for stability indices related to tropical (V1-V6; Venezuela) and temperate (B1-B4; Flanders) soils.

Method	Index		Venezuelan soils					Belgian soils				
			Mean	SD	CV*	Min	Max	Mean	SD	CV*	Min	Max
dLdB	MWD	MWD_{dLdB}	3.00	0.88	29 c	0.95	4.12	1.83	1.32	72 b	0.15	3.67
	SI	SI_{dLdB}	1.07	0.74	69	0.29	3.03	0.52	0.30	57	0.23	1.29
LB	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
KR	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		

dLdB is the De Leenheer and De Boodt method; LB is the Le Bissonnais method; and KR is the Kemper and Rosenau method. MWD = mean weight diameter of the aggregates in mm; SI = stability index; WSA = per cent of water stable aggregates. *Homogeneous subsets of Levene’s test of the coefficient of variation (CV) among MWD of the different methods. SD = standard deviation. Min and Max are minimum and maximum value. See also legend of Table 3.1 for abbreviations.

Both methods for determining MWD_{LB2} and MWD_{KRSW} start with removing the air from the aggregates (pre-wetting with water at a given matric potential 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 different aggregate size used.

On the other hand, there were high correlation coefficients with most of the methods applied on 'tropical' soils (Table 3-3). 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 by the same degradation mechanics. The degradation mechanics have a similar impact on the different sizes of aggregates used by the two methods.

In case of 'temperate' soils, the efficiency of the MWD_{KRFW}, MWD_{LB3} and MWD_{LB1} methods was similar for measuring aggregate stability as a SPQ indicator. SPQ can be different classified 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} ($P < 0.01$). 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 3-3).

Table 3-3 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 (n = 36) and the ones in the lower left part to the 'temperate' dataset (n = 24)
$^{*}P < 0.05$, $^{**}P < 0.01$; $^{***}P < 0.001$; ^{NS} not significant
See also legend of Table 3-1 for abbreviations.

3.3.2. Association of aggregate stability with other soil physical quality indicators

In order to select an appropriated aggregate stability method for the 'tropical' and 'temperate' soils, it was tested their validity through their association with SPQ indicators mentioned by Reynolds et al. (2009). The mean of the SPQ indicators (Table 3-4) were compared with the 'optimal' values used by Reynolds et al. (2009), except for BD. This was evaluated against critical BD values that limit root growth proposed by Pierce et al. (1983).

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

This quality designation was based on the following analysis. With the exception of V1, V2 and V5, the SOC content of the soils was lower than 23.2 g kg^{-1}, which is the target value for Venezuelan soils (Gilabert et al., 1990). Based on 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 V3, V5 and V6 have a BD higher than the 'critical' values (1.48 Mg m^{-3}) for causing reduction in root growth. The other soils have a mean BD in the optimum range for root growth.

Table 3-4 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	42.6	24.4	7.5	20.3	29.1	16.1	11.6	13.4	9.4	9.6
	(3.1)	(5.6)	(0.6)	(5.4)	(5.3)	(3.7)	(1.5)	(1.0)	(0.5)	(0.7)
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	0.08	0.10	0.08	0.04	0.05	0.13	0.07	0.09	0.09
	(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)
K_s	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 (g kg^{-1}); StI = structural stability index by Pieri (%); BD = bulk density (Mg m^{-3}); AC = air capacity (m^3 m^{-3}); PAWC = plant available water capacity (m^3 m^{-3}); RWC = relative water capacity (m^3 m^{-3}); K_s = saturated hydraulic conductivity (geometric means, cm h^{-1}).
Standard deviation for each index is given in parenthesis (±).

V1 has 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 sub-optimal with respect to root growth/function and resistance to drought. The values of K_s in V3, V4, and V5 are below the optimal range (18 cm h^{-1} to 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 K_s showed a similar tendency 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 had a contrasting condition when aggregate stability and SPQ provided by the other indicators were compared.

The 'temperate' soils, also with medium texture, showed SOC values below the lower critical limit (12.0 g kg^{-1}, Vanongeval et al., 2000) 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 m^{-3} ≤ AC; 0.6 m^3 m^{-3} ≤ RWC) except for soil B1. The K_s was very low for B4. These indicators gave an indication of 'limited' SQP for the Belgian soils. As was mentioned above, the '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}).

A multidimensional scaling analysis presented in Figure 3-3 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 Euclidean distance between the parameters, the higher the similarity in SPQ condition they provide. For the 'tropical' soils dataset (Figure 3-3a), MWD_{KRFW}, MWD_{LB3}, 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 3-3b, MWD_{KRFW}, MWD_{LB1} and MWD_{LB3} were closely associated with SOC. Methods having a larger distance from this cluster were applying pre-wetting (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). K_s 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 3-3c), then MWD_{KRFW} and MWD_{LB1} are considered as the most similar methods. The isolated condition of MWD_{KRSW} and MWD_{LB2} is still evident. The closest SPQ indicator with respect to MWD_{KRFW} and MWD_{LB1} is SOC.

3.4. 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 can be 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 non-comparable, 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 3-2). 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 and 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 binding agents. However, our ‘temperate’ medium textured soils are only comparable with methods MWD_{LB1} and MWD_{LB3} ($P > 0.05$).

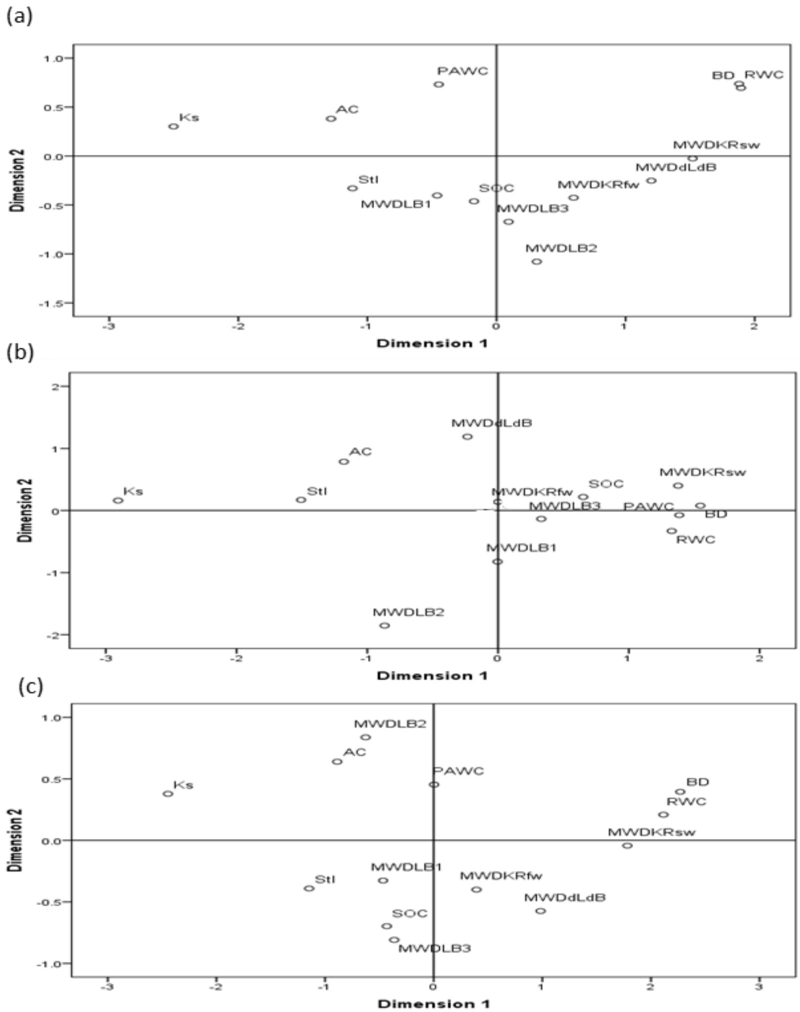


Figure 3-3 Euclidean distance model of mean weight diameter (MWD) and the other physical soil indicators for tropical (n = 36) (a) and temperate (n = 24) (b) soils and for the complete dataset (n = 60) (c). See also legend of Tables 3-1 and 3-4 abbreviations.

Furthermore, Deviren Saygin et al. (2012) suggested that dLdB method could work much better, compared to LB and KR methods, to evaluate aggregate stability of coarse textured soils. This is not the case in the studied medium textured soils, because dLdB displayed an isolated position with respect to the other aggregate stability methods and the SPQ indicators evaluated (Figure 3-3b). In both 'temperate' and 'tropical' soils when dLdB was applied, the reduction in MWD after wet sieving was lower compared to 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' soils, MWDKRFW and MWDLB1 are comparable. Comparison of aggregate stability of different soils is possible if any of these two methods is used. Rohošková and 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. Seybol and Herrick (2001) have mentioned that applying FW is a better indicator for detecting changes in aggregate stability as a result of management.

The homogeneous group of comparable methods also includes MWDLB3. The LB3 includes the use of ethanol, which according to Nimmo and Perkins (2002), preserves aggregate structure in dry condition. However, the similarity found among KR using FW, LB1 and LB3, suggests that for the evaluated 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 dependent 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 K_s.

Nevertheless, SOC appeared to be an indicator well associated with aggregate stability (FW of KR and LB1), at least in the studied medium textured soils. SOC and aggregate stability have been reported as dynamic soil quality indicators, which are able to vary with management practice (Shukla et al., 2006). Therefore, in order 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 stabilizing agent (Pulido Moncada et al., 2009). This aspect is further discussed in Chapter 4.

3.5. 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 dLdB, LB2 and KRSW are not suitable in terms of SPQ condition to distinguish differences between MWD of the studied soils. Methods involving prewetting should be avoided when the aim of the survey is to make comparison among different soil types under different land use and management. If a simple and rapid analysis of the structural stability quality is needed, single tests such as MWD_{KRFW} or MWD_{LB1} can be used.

Chapter 4

Soil organic matter and its fractions as indicators of soil structural stability

4.1. Introduction

The quality of arable soils can be assessed by soil properties that are indicators of quality and which allow comparisons among different soils or between different soil management types (Duval et al., 2013). In agricultural soils, a decrease in SOM content is frequently associated with a decrease in aggregate stability (Abid and Lal, 2008), hence with structural degradation and consequently with a loss of soil physical quality.

Loveland and Webb (2003) summarised a number of studies of 'temperate' soils where the effect of agricultural practices on aggregate stability and associated changes in SOM has been evaluated. These authors mention that drawing a statement about the relationship between these two properties is difficult because of different aspects including: (i) the absence of uniformity in the choice of methods and size range of aggregates for determining aggregate stability; (ii) the general assumption of a linear relationship between SOM and aggregate stability, while non-linear relationships or no significant relationships have been found; (iii) the depth of sampling, which can be a key factor in the study of SOM-aggregate stability relationship; and (iv) the wide variation in aggregate stability within the same soil depending on the type and amount of SOM added to the soil, as well as the time of sampling.

Therefore, although SOM *per se* has been suggested as an indicator for monitoring soil quality changes (Shukla et al., 2006), inconsistencies in the proportional relationship between SOM and aggregate stability have also been mentioned. For instance, Haynes (2000) showed that increasing inputs of SOM under short-term pasture could result in significant increases in aggregate stability without a measurable change in SOM content occurring. Not surprisingly, structural stability indices that involve SOM *per se* as contributing factors to soil structure such as the StI (Pieri, 1992) and the crusting index

(FAO, 1980), among others, do not always reflect the structural conditions of the soils (Pulido Moncada et al., 2014). In contrast, the use of SOM fractions to evaluate the effects of different agronomic practices and changes in soil C dynamics due to agricultural use, as well as to assess soil quality, is more effective than the use of total SOM (Guimarães et al., 2013; Nascente et al., 2013). This is because specific fractions of SOM are associated with specific mineral particles and clay mineralogy (Jindaluang et al., 2013), and consequently to specific aggregate sizes (Lee et al., 2009).

Characterization of SOM is mainly conducted by physical and chemical fractionation. Chemical fractionation provides information about the type of SOM present in the soil, whereas the physical fractionation gives information about how the SOM is set in the soil matrix (Elliot and Cambardella, 1991). The conventional chemical fractionations of SOM seek for the separation of humic and non-humic substances. The humic substances are bound to mineral particles in different ways and play an important role in the formation and stabilization of aggregates. On the other hand, physical fractionation of SOM is used to separate partially decomposed fractions from those associated to mineral particles. This allows establishing the role of the organic materials on processes such as aggregate stabilization, as well as founding the biological and environmental importance of the SOM in organo-mineral complex (Evans et al., 2001; Lützow et al., 2006).

The objective of this chapter was to evaluate the use of chemical and physical fractions of SOM, rather than SOM *per se*, as indicators of soil quality based on their effect on soil aggregate stability. It was hypothesised that the evaluated fractions of SOM would give a better understanding of the aggregate stability of different soil types and under different land use and management.

4.2. Materials and Methods

4.2.1. Site description and soil sampling

Eight soils were selected, with six located in a tropical environment in the central-northern part of Venezuela (V_1-V_6) and two in a temperate environment (B_1 and B_3, Flanders Region of Belgium). The soils are described in Table 2-1 of Chapter 2. The eight soils sampled include different land uses such as natural savannah, fruit cropping, permanent pasture, and cereal monoculture. Soil samples were taken as described in Section 3.2.1 of Chapter 3. In the 'temperate' soils, B1 and B3, characterization of SOM was conducted under two land uses, cropland and pasture. More details about soils and land use are given in Chapter 2.

4.2.2. Soil organic matter analysis

Soil samples were air-dried and sieved through a 2 mm sieve. For SOM analysis, the total SOC, SOC stock, chemical and physical fractionation of SOM were determined. SOC was measured by wet oxidation (Walkley and Black, 1934). The SOC stock (Mg ha^{-1}) was calculated:

$$SOC_{stock} = \left(\frac{x}{100}\right) BD\, d\, 10^4 \tag{4-1}$$

where x is the content of SOC in per cent (%), BD is the soil bulk density (Mg m^{-3}) and d is the thickness (m) of the soil layer.

Soil BD was determined from the core method, as described in Chapter 3. Mean BD values for 'tropical' and 'temperate' soils are given in Table 3-4 of Chapter 3.

4.2.3. Chemical fractionation of soil organic matter

Because of the complexity of the structure of the humic substances, many procedures are used to conduct an effective fractionation and characterization of the chemical fractions of SOM. In this Chapter, the chemical fractionation of SOM was conducted by the sequential extraction procedure described by Ciavatta and Govi (1993). 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 and Schuppli (1989). Then, the purification of the fulvic fraction from the non-humic substances (NH) was achieved by applying the insoluble polyvinylpyrrolidone (PVP) method (Ciavatta and Govi, 1993). The organic carbon (OC) of each fraction was measured by Walkley and Black (1934) method. None of the soils considered in the study were calcareous, so no attempt was made to correct for inorganic carbon content of the soils analysed by combustion method.

The humification parameters proposed by Sequi et al. (1986) and Ciavatta et al. (1990) were determined: (i) the humification index (HI), which refers to the relative ratio of non-humic substances and humified constituents (HI= NH/(HA+FA)), (ii) the humification degree (HD), corresponding to the relative amount of C present in HA and FA relative to the C in the total $NaOH/Na_4P_2O_7$ extract (TE) (HD= ((HA+FA)/TE)*100), and (iii) the humification rate (HR), i.e. the amount of C present in HA and FA relative to the total SOC content (HR=((HA+FA)/TOC)*100).

4.2.4. Physical fractionation of soil organic matter

The modified Anderson and Ingram (1993) test for soil litter separation was used to obtain a physical fractionation of SOM (Hernández-Hernández and López-Hernández, 2002). This test has the advantage of using water as dispersant, which is a non-polluting and a low cost component, and it has been successfully used for characterizing SOM in soils from the tropics. Three fractions of SOM were obtained using separation density, 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 (HF_c).

Briefly, the procedure consisted in mixing 150 g of air-dried and sieved (< 2 mm) soil with deionized water. The amount of water added to the soil sample was enough to have a layer of water of approximately 1 cm over the solid material. The soil sample was stirred manually for 30 minutes. After sedimentation of coarse soil particles (40 sec), 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 g cm^{-3}) and that was retained on the sieve (> 0.25 mm). The non-floating organic material, which passed through the 0.25 mm sieve and remain in suspension together with silt and clay particles, corresponded to HF_f. The remaining organic material that settled on the bottom of the plastic 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 SOC of each physical fraction was also measured by Walkley and Black (1934) method.

4.2.5. 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 siphoning of supernatant clay suspensions after dispersion of clay using Na_2CO_3. NaCl was used as the flocculating agent. The recovered clay fraction was thoroughly washed to remove excess Cl^- (until testing negative with $AgNO_3$), while centrifuging at 3500 rpm after each step. The total <2 µm fraction was saturated with Ca^{2+}. Excess electrolytes were removed by washing twice with deionized water and centrifugation after which they were transferred to a dialysis tube and placed in a beaker with distilled water. Dialysis was continued until no more Cl^- could be detected using $AgNO_3$, after which the samples were transferred to a beaker and dried.

Oriented samples of all clay fractions were prepared by transferring a suspension using a pipette on glass slides. The suspension was prepared as such that the surface density of the sample on the glass slide was at least 10 mg cm^{-3} and by ensuring adequate dispersion using an ultrasonic probe. For each slide, an X-ray diffraction (XRD) pattern was recorded in air-dried and glycolated state. XRD patterns were obtained by using a Philips X'PERT SYSTEM with a PW 3710 based diffractometer equipped with a Cu tube anode, a secondary graphite beam monochromator and a proportional xenon filled detector. The incident beam was automatically collimated. The secondary beam side comprised a 0.1 mm receiving slit, a soller slit, and a 1° anti-scatter slit. The tube was operated at 40 kV and 30 mA, and 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 seconds per step.

4.2.6. Aggregate stability determination

Aggregate stability was measured on air-dried soil samples using three different methods: (i) the wet sieving method with multiple sieves proposed by De Leenheer and De Boodt, dLdB (1959); (ii) the three treatments of the method by Le Bissonnais, LB (1996); (iii) the wet sieving method using one single sieve based on Kemper and Rosenau, KR (1986). The procedure followed in each method was well described in the Materials and Methods Section of Chapter 3. The results were expressed in terms of the MWD.

4.2.7. Statistical analyses

To ensure the efficiency of the analysis, normality of the observations was tested by Q-Q plot 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, a non-parametric alternative to the paired t test (Wilcoxon), was conducted to test for significant differences between fractions of each soil. In order to evaluate the associations between the SOM fractions and aggregate stability, a Spearman correlation analysis was conducted. A criterion of $P < 0.05$ was selected to represent statistical significance. All data were analysed using the SPSS 17.0 statistical software package.

4.3. Results

4.3.1. Chemical characterization of soil organic matter

As expected, the total SOC was lower in soils under conventional tillage compared to those soils under no-till in both geographic areas (Table 4-1). Soils were ranked in a decreasing order of total SOC as V1 > V5 > V2 > V4 > V6 > V3 and B3PP > B1PP > B1CM > B3CM. In both environments, the values of SOC_{stock} in 0-20 cm showed the same trend than the total SOC content.

Humified constituents (HA and FA) represented the major part of SOM in all soils. The 'tropical' soils had a significantly higher content of HA than of FA ($P < 0.05$). In the 'temperate' soils this was true only for the silt loam soil under both land uses, the sandy loam soil showed similar content of HA and FA under CM ($P > 0.05$), but higher HA than FA under PP ($P < 0.05$). In both environments, the concentration of HA and FA was lower under conventional tillage compared to soils under no-till. Differences in the NH fraction were less evident with land use and soil management.

Regarding the humification parameters, the highest value of HI was present in V6 for the 'tropical' soils. No clear differences in HI were observed among the soils with respect to land use and management. In 'temperate' soils, the HI was higher under PP than CM in the sandy loam soil (B1), whereas the opposite was observed in the silt loam soil (B3). The HD of most 'tropical' soils (except V6) exceeded the HD (79-97%) of the two 'temperate' soils (63-77%). The HR of the 'tropical' soils also exceeded (24% to 65%) that of the 'temperate' soils. Regardless of the texture both 'temperate' soils had a comparable HR varying from 16-26%.

4.3.2. Physical fractionation of soil organic matter

In 'tropical' soils the per cent of LF ranged from 1.1 to 2.8%, except for V3 where it was 0.6%. In the 'temperate soils' LF was 0.2% in both soils under CM. Under PP the LF was 2 and 4 times higher in relation to the CM in the sandy loam and silt loam (0.5 and 1.0%), respectively. The HF_f was higher in soils V1, V2 and V3 (22-38%) compared to soils V4, V5 and V6 (1-4%) where there was a low per cent of this fraction. In 'temperate' soils, HF_f was lower in relation with the 'tropical' soils (0.8-4.4%). The lowest value was present in B3CM. In both geographical areas the dominant physical fraction of SOM was HF_c, which ranged between 43-65% and 86-89% in 'tropical' and 'temperate' soils, respectively. The distribution of the physical fractions of SOM was in the following order $HF_c > HF_f >$ LF. The highest relative carbon concentration was present in the HF_f and HF_c for soils V1, V2 and V3, but only in the HF_c for V5, V6, B1 (CM and PP) and B3 (CM and PP).

Table 4-1 Soil organic carbon content and stock, distribution of C over three chemical fraction (humic acids, fulvic acids and non-humic substances) and derived humification parameters.

Soil	SOC ($g\ kg^{-1}$)	SOC_{stock} ($Mg\ ha^{-1}$)	HA ($g\ kg^{-1}$)	FA ($g\ kg^{-1}$)	NH ($g\ kg^{-1}$)	HI	HD (%)	HR (%)
V1	42.6	94.41	11.7	2.6	2.3	0.16	81	34
	(3.1)	(10.7)	(0.08)	(0.02)	(0.02)	(0.01)	(3.0)	(4.0)
V2	24.4	67.01	7.8	1.3	0.5	0.05	97	65
	(5.6)	(17.3)	(0.05)	(0.01)	(0.01)	(0.01)	(4.5)	(13.2)
V3	7.5	23.36	1.9	1.3	0.4	0.13	79	42
	(0.6)	(2.4)	(0.02)	(0.01)	(0.00)	(0.01)	(7.9)	(2.4)
V4	20.3	54.63	7.2	1.5	1.1	0.12	84	45
	(5.4)	(15.8)	(0.03)	(0.01)	(0.04)	(0.04)	(7.2)	(9.1)
V5	29.1	96.15	5.9	1.3	1.2	0.17	80	26
	(5.3)	(18.9)	(0.05)	(0.03)	(0.01)	(0.02)	(3.5)	(5.7)
V6	16.1	48.80	2.6	1.1	1.3	0.34	64	24
	(3.7)	(10.4)	(0.02)	(0.01)	(0.03)	(0.08)	(3.9)	(3.8)
B1CM	11.1	28.62	1.4	1.4	0.5	0.19	69	26
	(1.5)	(6.9)	(0.03)	(0.01)	(0.00)	(0.02)	(6.05)	(6.05)
B1PP	22.7	64.48	2.1	1.6	1.0	0.29	70	16
	(3.6)	(11.4)	(0.03)	(0.02)	(0.04)	(0.16)	(10.8)	(3.7)
B3CM	9.4	28.76	1.1	1.4	0.8	0.32	63	26
	(0.5)	(4.19)	(0.01)	(0.03)	(0.03)	(0.16)	(5.2)	(5.1)
B3PP	37.1	81.1	6.2	1.8	2.0	0.25	77	23
	(1.0)	(17.5)	(0.07)	(0.0)	(0.06)	(0.06)	(5.7)	(5.9)

V1-V6 are soils from Venezuela; B1 and B3 are soils from Belgium; CM = cereal monoculture; PP = permanent pasture; SOC = total soil organic carbon; SOC_{stock} = soil organic carbon stock; HA = humic acids; FA = fulvic acids; NH = non-humic substances; HI = humification index; HD = humification degree, HR = humification rate. Standard deviation for each parameter is given in parenthesis (±).

Table 4-2 Per cent of the different physical fractions of soil organic matter (SOM) and the amount of organic carbon in each fraction of SOM.

Soils	Fraction distribution (%)			Carbon concentration (g kg^{-1} soil)			Total physical fraction (%)	Total C (g kg^{-1})
	LF	HF_f	HF_c	LF	HF_f	HF_c		
V1	2.1	38.6	43.3	2.18	15.54	12.37	84	30.10
V2	1.1	36.4	45.3	1.21	7.06	9.92	83	18.19
V3	0.6	22.8	54.2	0.64	1.46	1.48	78	3.58
V4	1.6	4.3	65.6	2.13	0.62	4.25	72	7.02
V5	2.8	1.6	55.6	3.73	0.48	13.44	60	17.66
V6	1.3	3.9	58.5	1.22	0.45	7.37	64	9.05
B1CM	0.2	4.4	88.2	0.24	0.26	6.36	93	6.87
B1PP	0.5	3.7	89.7	0.55	0.23	9.31	94	10.10
B3CM	0.2	0.8	87.3	0.29	0.11	7.06	88	7.47
B3PP	1.0	1.1	86.1	1.28	0.24	17.83	88	19.37

V1-V6 are 'tropical' soils from Venezuela; B1 and B3 are 'temperate' soils from Belgium; CM = cereal monoculture; PP = permanent pasture; LF = light fraction of SOM; HF_f = heavy fraction of SOM associated with fine mineral particles of the soil (silt and clay); HF_c = heavy fraction of SOM associated with coarse mineral particles of the soil (sand).

4.3.3. Clay mineralogy related to soil organic matter fractions dynamics

V1 was characterized by a clay mineralogy dominated by illite and kaolinite, whereas V2 was dominated by smectite and mica (muscovite). V3 had a clay dominance of both mica and smectite. In the other three 'tropical' soils, the mineralogical composition of the clay fraction was very similar, containing mostly smectite, illite and kaolinite. All clay fractions had an abundance of mixed-layer minerals. Soil V2 was different from the other samples due to the presence of two types of mica, which appear to have contributed to the formation of mixed-layers with smectite.

Concerning the proportions of the type of clay present in each soil, in these 'tropical' soils V1 and V3 contained more mica than the other soils. V4, V5 and V6 contained a higher proportion of kaolinite compared to the other soils. On the other hand, the two 'temperate' soils had a clay fraction dominated by smectite. Samples B1, B2, B3 and B4 have mineralogically very similar clay fractions composed of a mixture of mica and smectite and their mixed-layers, with minor additions of kaolinite. In both geographical areas, difference in the amount of chemical fractions of SOM seems to be less related to clay mineralogy. Regarding the physical fractions of SOM, in the smectite-rich soils HF_c ranged between 70- 97% of the total HF, except in V2 where it was 55%.

4.3.4. Soil organic matter and its interaction with soil aggregate stability

Aggregate stability was evaluated for the six 'tropical' soils and only for those 'temperate' soils under CM. Aggregate stability data were taken from Chapter 3, where three aggregate stability methods were compared for soil physical quality indicators. Briefly, results from dLdB method showed that only V1, V2, V5 and B3 were stable soils, hence they had a 'good' structural quality. When LB method was applied, MWD was different among LB treatments. In general, when using LB1 the aggregate stability of the soils V5, V1 and V2 was high, but medium for V6 and low for the other soils. On the contrary, all soils were classified as stable after LB2 and LB3, except B1 and B3 using LB3. The reduction of MWD using KR with fast wetting (KR_{FW}) was 30-44% for V5, between 50 - 60% for V1, V2 and V6 soils, and > 70% for the other soils.

The relationship between SOC and MWD varied among aggregate stability methods (Table 4-3). The r values established for the two parameters ranged between 0.4-0.6 (for KR_{SW} and dLdB) and 0.7-0.8 (for KR_{FW}, LB1, LB2, and LB3). From the correlation analysis no direct causality could be established for any combination of SOC and aggregate stability method. However, correlations allow to indirectly evaluating associations between variables.

In Chapter 3, it was demonstrated through a multidimensional scaling analysis that SOC is an indicator well associated with aggregate stability when KR_{FW} and LB1 methods are used to compare different soils in terms of their structural stability. Therefore, to evaluate the structural stability quality of the studied soils and its relationship to SOM content and type, results of aggregate stability from KR_{fw} were selected. This was justified on the fact that 1-2 mm aggregates were used for KR method and the fractionation of the SOM was conducted using < 2 mm sample.

Table 4-3 Correlation coefficients (r) among total soil organic carbon, soil organic matter fractions and aggregate stability (n = 60)

	SOC	SOC_{stock}	Carbon concentration ($g\ kg^{-1}$ soil)			HA	FA	NH
	($g\ kg^{-1}$)	($g\ kg^{-1}$)	LF	HF_f	HF_c	($g\ kg^{-1}$)	($g\ kg^{-1}$)	($g\ kg^{-1}$)
MWDdLdB	0.61**	0.66**	0.44**	0.32*	0.76**	0.46**	0.14	0.37**
MWDKRFW	0.79**	0.81**	0.53**	0.28*	0.82**	0.56**	0.05	0.48**
MWDKRSW	0.44**	0.48**	0.26	0.18	0.62**	0.19	0.18	0.44**
MWDLB1	0.80**	0.81**	0.64**	0.39**	0.76**	0.64**	0.11	0.44**
MWDLB2	0.75**	0.72**	0.48**	0.40**	0.74**	0.59**	0.34*	0.41**
MWDLB3	0.77**	0.83**	0.76**	0.58**	0.66**	0.76**	0.17	0.43**

SOC = total soil organic carbon; SOC_{stock} = soil organic carbon stock; LF = light fraction of SOM; HF_f = heavy fraction of SOM associated with fine mineral particles of the soil (silt and clay); HF_c = heavy fraction of SOM associated with coarse mineral particles of the soil (sand); HA = humic acids; FA = fulvic acids; NH = non-humic substances; MWD = mean weight diameter (mm); dLdB = De Leenheer and De Boodt method; KRFW = Kemper and Rosenau method using fast wetting of the aggregates; KRSW = 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. ** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level.

When comparing the aggregate stability values from KR_{FW} method among the soils (see Table 3-1 in Chapter 3), a clear trend was observed with soils under no-till showing a 'good' structural stability quality, and the opposite when under conventional tillage. Higher values of MWD and water stable aggregates > 250 µm are considered to be indicator of 'good' structural stability quality.

Additionally, a correlation analysis was conducted among content of C in the various isolated SOM fractions and aggregate stability determined by different methods (Table 4-3). The intention was to evaluate individual SOM fractions rather than SOM *per se* as predictors of aggregate stability or structural stability condition. Results showed that there were significant correlations ($P < 0.01$) between LF, HF_c, HA and NH contents and MWD.

4.4. Discussion

4.4.1. Distribution of soil organic matter over different fractions

Although soils differ in texture, results show that SOC content and SOM fractions appear to be more influenced by soil use and management than soil texture. Loveland and Webb (2003) mentioned that there is a proportional relationship between SOC and clay content, under comparable land-use and management practices. Similarly, Duval et al. (2013) stated that SOC content increases when clay content increases and particulate organic matter became less abundant than in coarse textured soils.

However, in the studied soils, neither the SOM fractions nor the total SOC content were significantly correlated with clay content ($P > 0.05$). Therefore, it appears that in the studied soils, texture is not determinant for the SOM content and quality. Differences in SOC content and SOM fractions among the soils appeared to be more related to land use and soil management practices. For instance, although different dynamics were found between soils from Venezuela and Belgium, results showed that the total SOC, SOC_{stock}, LF and HA varied with the type of land use and soil management applied in both environments.

No clear differences were found among the studied soils when the humification parameters were considered. It should be expected that soils susceptible to degradation, with low structural stability quality, present high values of HD and HR, but low values of HI. However, relationships between the different SOM fractions (HA/FA, FA/TOC and HF/LF) were better indicators of the effect of soil management on the SOM dynamic of the studied soils.

For the 'tropical' soils, the lowest value of HA/FA (1.38) and the highest values of FA/TOC (0.18) and HF/LF (129.34) were present in V3 soil. According to Lozano et al. (2011) these relationships are sensitive indicators for detecting changes in SOM as a consequence of agricultural activities. These authors stated that HA/FA is an index that allows detecting differences in humic substances. Soils with low values of HA/FA show low humification, because FAs are more susceptible to soil management. High FA/TOC indicates that the SOM has constituents that are more susceptible to be degraded by soil management. And high values of HF/LF are related to low diversity of crop residues. Therefore, these relationships made a clear distinction between the most unstable soil (V3), which is under mono cropping and conventional tillage, and the others.

In the ‘temperate’ soils, the content of total SOC, SOCstock and chemical and physical fractions of the SOM was higher in soils under PP compared to those under CM. As in the case of the ‘tropical’ soils, the humification parameters did not show clear differences between land uses in the ‘temperate’ soils. But the values of HA/FA, FA/TOC and HF/LF allow differentiation. For instance, in soils B1 and B3 under CM, values of FA/TOC (0.15 and 0.12, respectively) were higher than under PP (0.05 and 0.07, respectively). The opposite was evident for HA/FA (B1CM= 0.81, B1PP= 3.49, B3CC= 0.99, B3PP= 1.30). Similarly, for HF/LF high values were found under CM (B1CM= 412.02, B3CM= 344.04), compared to PP (B1PP= 182.83, B3PP= 83.07). These differences are evidence that in soils under conventional tillage and monoculture, the quality of the SOM was affected and consequently, SOM-related properties such as structural stability were also affected.

The dominance of HA in soils under no-till is explained by the fact that in absence of mechanization large humic molecules are protected from breaking, so the formation of HA is favored (Novotny et al., 1999). Nascente et al. (2013) found that no-till results in higher accumulation of LF compared to conventional tillage. These authors justify the differences in LF between different farming systems on the effect of decomposition stage of the residue and type of soil management among others. They also mentioned that HF usually dominates the SOC pool and involves a high amount of C, because of high degradation rate of SOM.

In Table 4-2, results showed that the dominance of HF per cent and relative carbon concentration was true for all the studied soils under ‘tropical’ and ‘temperate’ environments. In the ‘tropical’ soils the lowest value of relative carbon concentration of LF and HFc was present in V3 soil. Similarly, soils under CM in the ‘temperate’ environment had a lower value of these variables compared to those under PP.

Although clay mineralogy is believed to play an important role on SOM dynamics and the stability of the aggregates, a clear trend of SOM dynamic in relation to clay mineralogy was apparently absent. This suggests an interaction of other factors or the action of a more influential factor in SOM fractions. In the studied soils, the effect of clay mineralogy on the variation of the SOC content and SOM fractions appear to be most likely overshadowed by other factors such as soil use and management.

4.4.2. Relationship between soil organic matter and aggregate stability

Separation of stable and unstable soils, using results from KR_{FW}, was achieved between samples of high and low SOC. On the contrary, aggregate stability from KR_{SW} could not separate soils in terms of structural stability between soils when using tension-rewetted samples. These results are in correspondence with Haynes (2000).

SOC has been referred to as a factor highly related to aggregate stability (Loveland and Webb, 2003). Both SOM and aggregate stability have been mentioned as dynamic indicators to evaluate soil physical quality (Pieri, 1992; Lal and Shukla, 2004). Nevertheless, the relationship between these two properties has been part of discussion by several authors as was summarised by Loveland and Webb (2003).

Because of the high variability between the methods used for aggregate stability assessment, differences in relationship between SOC and MWD were evident (Table 4-3). In fact, the associations shown in Table 4-3 lead to agreement with Haynes (2000), who demonstrated that the relationship between these two properties could be significantly influenced by the method, by which aggregate stability is measured. Factors such as size of aggregate, moisture content, and mechanism of dispersion all influence the results of aggregate stability assessment (Amezketa, 1999).

The absence of strong association ($r > 0.75$) between these two variables suggests the influence of other factors rather than only SOC in the structural stability of the soils. Indeed, it is very well known that soil structural stability is affected by the complex interaction of different internal soil characteristics and external factors (Barthes et al., 2008; Martínez-Gamiño and Walthall, 2000; Six et al., 2004). Among the internal factors are SOM, texture, clay mineralogy, cation exchange capacity, oxides and hydroxides of Fe and Al, $CaCO_3$, Mg and gypsum (Lado et al., 2007; Wakindiki and Ben-Hur, 2002). External factors that have received attention include soil management, intensity of the rainfall among others. The formation and stability of aggregates are therefore mainly affected by a complex interaction of soil characteristics and properties.

Contradictory results reported in many studies suggest that the aggregate stability/soil properties relationship differs with climatic zones and with different types of soils. However, among the different studied soils, there was a general strong effect of the land use and management on aggregate stability which explained most of its variation over the other factors.

According to Bronick and 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 action. Therefore, the quality of the SOM measured through its fractions, is considered as fine indicator of soil quality that influenced soil function in specific ways (Haynes, 2005). This author stated that 'they are typically much more sensitive to changes in soil management practice than total soil organic matter content'.

Because relationships between SOM fractions and aggregate stability differed depending on the size of the aggregates (Boix-Fayos et al., 2001), for further comparison between these properties only MWD from KR_{FW} was considered. Results show that there was a significant positive correlation among carbon in the LF ($r = 0.53^{**}$), carbon in the HF_c

(r = 0.82**), HA (r = 0.56**) and NH (r = 0.48**) with MWD. It is also important to highlight that correlations among aggregate stability and FA/TOC (r = -0.83**), HA/FA (r = 0.58**) and HF/LF (r = -0.56**) confirmed the differences found among the soils in relation to land use and soil management. No significant correlations (P > 0.05) were found among aggregate stability and humification parameters (HI, HD, HR). These associations cannot be seen as causal relationships, but they confirm the existence of a link between them.

For instance, the SOC associated with sand-size fraction has been considered to be strongly affected by management (Sleutel et al., 2007; Sleutel et al., 2010). In the results of this Chapter, the lowest amount of SOC in HF_c was present in the soils under conventional tillage and monoculture. An effect of soil management on the SOM fractions and aggregate stability among the studied soils, was therefore supported by the associations found between HF_c and MWD, as well as HF/LF and MWD.

Regarding chemical fractions of SOM, predominance of HA might indicate that the SOM type present in the soils does not contribute to macroaggregate stability, since humic materials of less molecular weight (FA) are associated with the macroaggregates (>250 µm) and those of greater molecular weight (HA) to microaggregates (< 250 µm) (Fortun and Fortun, 1989; Puget et al., 1995; Six et al., 2000). Although, in the evaluated soils, the organic matter type was assessed in bulk samples and not per aggregate fractions, higher content of HA correspond to higher proportion of aggregates > 250 µm. High correlation has been found between SOM content and aggregate stability (Haynes et al., 1997) because of the linking action of the humic substances and other products generated by microbial activity (Shepherd et al., 2001).

In this Chapter, results suggested that structural stability among different soils could be evaluated either by the total SOC or some of the SOM fractions such as HA, NH, LF and HF_c. This is because SOM fractions did not correlate better than the SOC content with aggregate stability (Table 4-3). However, the advantages in terms of cost and time of measuring total SOC over the chemical and physical fractions lead to suggest this property as an indicator of structural stability when soil physical quality assessments are conducted among different soils.

Nevertheless, as SOM fractions are considered as more sensitive indicators to changes in soil management practices than total SOM content (Haynes, 2000), they will be preferred when farming systems vary in the same soil type. Additionally, specific fractions of SOM seem to be better indicators to detect early changes in SOM quality that will affect the structural quality of the soils in time (Duval et al., 2013).

From the evaluated data set, it was difficult to separate the effect or contribution of the different measured characteristics on the aggregate stability of the soils, but clearly low values of SOC, LF, and HA were related to a degraded structural stability quality of those soils affected by mechanical or animal compaction.

As it was mentioned before, clay mineralogy is another key factor in aggregate stability, though, a link between clay mineralogy and structural stability (via changes in

SOM) was apparently absent. However, it has been found that kaolinitic soils have the capacity to form more stable aggregates through electrostatic binding between the minerals (Denef and Six, 2005; Barthes et al., 2008). This makes aggregates less dispersible and more flocculative, preventing soil degradation processes (Wakindiki and Ben-Hur, 2002; Lado et al., 2004). On the contrary, high smectitic clay content increases the susceptibility to dispersion, slaking and swelling, and promotes seal formation, runoff and erosion (Levy and Mamedov, 2002; Lado et al., 2007).

Importantly, SOM-mineralogy-aggregate stability interactions have to be considered when agricultural soils are being assessed as crop growth medium. This is because in soils where Fe/Al oxides are abundant the loss of SOM by soil management should have minimal impact on aggregate stability (Jindaluang et al., 2013). In contrast, in soils poor in Fe/Al oxides, SOM dynamics could be a key factor in the stability of the aggregates.

As was demonstrated in this Chapter, the change of the land use in the 'temperate' soils, has affected the SOM content and quality, and consequently the structural stability. The most stable soils were found under no-till and unstable soils under conventional arable cropping, supporting the results of Amezketa (1999) and Pagliai et al. (2004). The evaluation of the soil structural stability, as an important aspect of the soil physical quality, can be evaluated by the capacitive indicators of amount of SOM and the distribution of the SOM fractions. However, the absence of similarity between aggregate stability methods requests for a 'pre-selection' of the most appropriate method of evaluation and the consideration of criteria such as scope of the study, type of soil and history of the agricultural activities of the soils.

4.5. Conclusion

The similarities in relationships found between SOM *per se* and SOM fractions with the aggregate stability of the evaluated soils, allow concluding that SOM content is an indicator sensitive enough to differentiate soils in terms of structural stability. SOM fractions did not correlate any better with aggregate stability than SOC content. With the results obtained, it is also possible to conclude that there are differences in aggregate stability/SOM quality between the different soil types and geographical areas; however a clear effect of soil management exists. Although SOM fractions have been mentioned as more sensitive indicators of changes in SOM, which is related to soil structural quality, their determination is more expensive in time and cost than SOM *per se*. However, these indicators in conjunction with the history of soil management, type of vegetation and soil type are factors to be considered for obtaining more insight in the characterization of SOM present in the different studied soils and the contribution of the different SOM fractions in the aggregate hierarchy.

Chapter 5

Is the mineral composition of the clay fraction of aggregates an indicator of aggregate stability?

5.1. Introduction

According to Young et al. (2001) 'measurements related to soil structure tend to be dependent upon the method of measurement and have little to do with soil structure as defined'. This dependence on the measurement method was demonstrated in Chapter 3, where results of aggregate stability of different soils varied among the method applied.

The dynamic of the soil structure assessed by the variation of size and stability of the aggregates is related to the different levels of weaknesses of binding agents to mechanisms of disaggregation. This supports the hierarchical arrangement of soil structure proposed by several authors (Young et al., 2001; Diaz-Zorita et al., 2002).

In a hierarchical order, aggregates are mainly classified as macro- and microaggregates. The formation and stabilization of the different aggregate sizes is attributed to different factors. The formation of soil aggregates occurs mainly as a result of physical forces, while the stabilization of soil aggregates is caused by a number of factors, in particular the quality and quantity of organic and inorganic stabilizers (Amézketa, 1999). Size and stability of macroaggregates have been attributed to biological processes. However, correlation between aggregate sizes and binding agents or stabilization processes differs among different aggregation scale, soil texture and clay mineralogy (Six et al., 2004; Denef and Six, 2005).

Among these factors, the clay minerals exert a key influence on aggregate stability as well as on other soil chemical and physical properties, and consequently play an important role in soil susceptibility to degradation (Wakindiki and Ben-Hur, 2002, Lado et al., 2007). This is because of their high exchange capacities, small particle sizes, and high specific surface areas (Hubert et al., 2012).

Aggregate hierarchy has been reported in soils dominated by 2:1 clay minerals, but less expressed in those dominated by low-activity clays (kaolinite and Fe oxides) (Six et al., 2000). The authors also found a clear relationship between loss of soil structure and loss of SOM in the soils that expressed aggregate hierarchy (2:1 clay dominance), but in 1:1 clay soils, aggregates were stabilized by electrostatic bonds or physical forces, rather than by organic cementing agents.

Denef and Six (2005) supported the previous statement based on an experiment conducted on a kaolinitc soil and an illitic soil. They found that large macroaggregate formation is less related to biological processes, associated with residues or root derived organic matter inputs, in the kaolinitic soil than in the illitic soil. Also, they mentioned that the illitic soil had an overall greater capacity to stabilize more large macroaggregates in the longer term than did the kaolinitic soil.

Therefore, as was stated by Baveye (2006) 'any discussion on the nature of chemical compounds that enhance aggregate stability should explicitly identify the scale of observation and the level in the hierarchy at which each compound is believed to have an effect'. Assessment on organo-mineral complexes has been conducted by researchers in microaggregates and at clay-size scale, for more insight of the interactions between soil minerals and SOM and their contribution to soil aggregation (Chenu and Plante, 2006).

More recently, authors such as Fernández-Ugalde et al. (2013) have attempted to evaluate the contribution of different clay mineral types to aggregation in a 'temperate' soil using its intrinsic mineral heterogeneity. They found that different 2:1 clay minerals contribute differently to the formation and stabilization of different aggregate-size classes, and suggested a clay-mineral-based evidence for the aggregate hierarchy. Authors' perspective in the use of mineralogical indicators of structural stability attempts to encourage researchers to explore on selective contribution of clay composition in aggregate sizes.

Based on the statements given in the Fernández-Ugalde et al. (2013) article, the aims of this Chapter were (i) to test whether there are measurable differences in clay mineralogy among aggregate sizes, which could be used as indicator of structural stability, and (ii) to test the influence of the disaggregation mechanisms on the composition of clay mineralogy in the different aggregate sizes, when aggregate sizes are obtained by aggregate stability methods frequently used in soil quality assessment.

5.2. Materials and Methods

5.2.1. Study site and data collection

Three out of the six 'tropical' soils from Venezuela, with different degree of weathering, were selected to achieve the aims of this Chapter, viz. V1 (Typic Kandiustult), V2 (Fluventic Haplustoll) and V5 (Typic Rhodustalf). Description and characteristics of these soils were detailed in Chapter 2. They were selected based on their differences in soil type and parent material. These criteria guarantee to work with soils that differ in the mineral composition of the clay fraction.

Soil samples, taken as described in Chapter 3, involved six replicates per soil. Aggregate fractions obtained for each replicate were mixed thoroughly to form a bulked sample per each aggregate size class per soil. On each aggregate size class the mineral composition of the clay fraction, SOC and particle size distribution were determined.

5.2.2. Aggregate size fractionation

The aggregate size distribution data used in this Chapter corresponded to that obtained from De Leenheer and De Boodt (1959) method as well as the fast wetting treatment of the Le Bissonnais (1996) method in Chapter 3. These methods were previously abbreviated as dLdB and LB1, respectively. The procedure conducted for these two methods of aggregate stability assessment was fully described in the Materials and Methods Section (Chapter 3).

5.2.3. Extraction of the clay fraction and the X-ray diffraction analysis

The mineral composition analysis was conducted based on standard methods described by Van Reeuwijk (1993) and Van Ranst et al. (1999). Briefly, for sample preparation, each aggregate fraction was individually grinded and used for analyses. SOC, clay, silt and sand concentration were determined in each fraction. The SOC in isolated aggregate fractions was measured by Walkley-Black (1934) method.

The particle size distribution was determined by sieving and successive sedimentation. The sand fraction was separated from silt and clay fractions by wet sieving (63 µm) after removing organic carbon by sodium hypochlorite (NaOCl) oxidation method. The silt fraction (2-63 µm) was separated from the clay fraction (< 2 µm) by successive sedimentation using repeated siphoning of supernatant clay suspensions after dispersion of clay using Na_2CO_3 2% dispersant. NaCl served as flocculation agent, and washing by dialysis was continued until testing negative for Cl^- with $AgNO_3$.

Na^+ saturated samples of clay fractions, in each aggregate size, were prepared by transferring a suspension on glass slides (surface density of at least 10 mg cm^{-3}). For each slide, samples of the clay fraction were then saturated with Mg^{2+} and K^+ by repeated washing with 1N solutions of $MgCl_2$ and $Mg(OAc)_2$ or KCl and KOAc, respectively. The excess of the saturating solution was washed with acetone and alcohol until free of Cl^-. Ethylene glycol solvation of the Mg^{2+} saturated samples was conducted in vacuum with ethylene glycol vapour during 24 hours. The different heat treatments (350° and 550°C) of the K^+ saturated samples were always made during 2 hours.

The mineral composition of the clay fraction was studied by X-ray diffraction (XRD) analysis. A Philips X'PERT SYSTEM apparatus 'PW 3710' with Cu-Kα radiation was used to obtain the XRD patterns of micronized powder samples and oriented clay samples before and after specific treatments. For the analysis, the tube was operated at 40 kV and 30 mA, and 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 1 second per step.

5.2.4. Data analysis

The evaluation of the contribution of the clay mineralogical composition to aggregate hierarchy was conducted by measuring and comparing the peak intensities of the XRD patterns among aggregate sizes as Fernández-Ugalde et al. (2013). The peak intensity is known to be proportional to the concentrations of the different minerals present (Ouhadi and Yong, 2003).

Each pattern was scaled relatively to each other in order to make the 001 reflection of kaolinite (at about 0.71 nm) overlap. This peak was chosen because kaolinite is unaffected by saturations and has little or no overlap with other peaks (e.g. from smectites and illites) that might be influenced by saturations and external conditions. For each peak the maximum intensity was determined after scaling the patterns to assess the relative changes in concentration. These values were rounded to 5 arbitrary units (au).

5.3. Results

5.3.1. Aggregate size distribution in the studied soils

Figure 5-1 displays results of aggregate size distribution, from the dLdB and LB1 methods, of the studied 'tropical' soils from Venezuela. Results from both methods showed that aggregates > 2 mm dominated the aggregate-size distribution in the three studied soils. In Chapter 3, these soils (V1, V2 and V5) were classified in terms of structural stability as very stable after the dLdB (> 70% of WSA remained on the sieve of 0.5 mm and those above it) and LB1 (the highest proportion of aggregate was present in the 5-2 mm fraction) fractionations. In general, after both fractionation methods a similar distribution in aggregate sizes was observed in the three studied soils (Figure 5-1a and b).

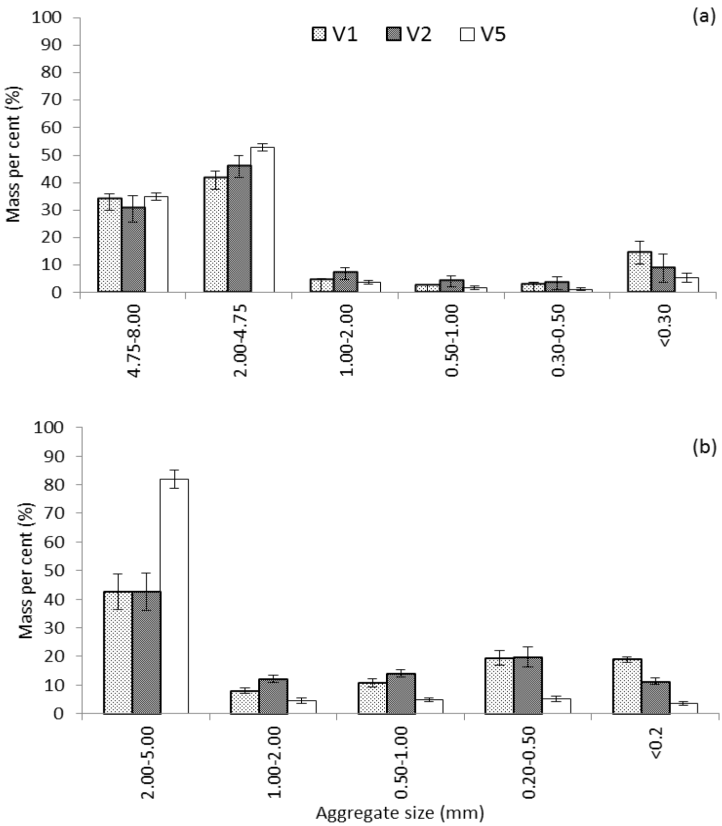


Figure 5-1 Aggregate size distribution of the studied 'tropical' soils from Venezuela, V1 is a Typic Kandiustult, V2 is a Fluventic Haplustoll and V5 is a Typic Rhodustalf; (a) displays results from the De Leenheer and De Boodt method and (b) displays results from Le Bissonnais method.

5.3.2. Mineral particle size distribution and organic carbon concentration within the aggregate sizes

Because of the limited data used in this Chapter, none statistical analysis were conducted. However, the differences in mineral particles and organic carbon expressed throughout this Chapter only refer to the tendency observed among the values. The clay, silt and sand content did not vary among the different aggregate sizes in the three evaluated soils (Table 5-1). A very narrow range was observed in the clay content within aggregate sizes in the V1 (377 - 391 g kg^{-1}), V2 (288 - 324 g kg^{-1}) and V5 (321 - 332 g Kg^{-1}) soils. This was also the case for silt and sand content. In V5, the narrow range in mineral particle content within aggregate sizes was evident after both fractionation methods (dLdB and LB1).

The distribution of organic carbon varied among the aggregate sizes in the three studied soils. The organic carbon concentration decreased with decreasing aggregate size. This trend was less marked in V5, where the range was very narrow, in both dLdB (21.0-26.7 g kg^{-1}) and LB1 (23.3-29.6 g kg^{-1}) methods.

Table 5-1 Soil organic carbon concentration and mineral particle size distribution among aggregate sizes in the studied soils.

Soil	Fractionation method	Aggregate sizes (mm)	Organic carbon	Sand	Silt	Clay
			g kg^{-1}			
V1	dLdB	8.0-4.75	47.1	397	214	389
		4.75-2.8	49.5	400	213	387
		2.8-2.0	44.7	384	226	391
		2.0-1.0	33.7	390	233	377
		1.0-0.5	36.4	367	245	388
		0.5-0.3	30.3	362	247	391
V2	dLdB	8.0-4.75	34.2	459	226	315
		4.75-2.8	28.0	449	237	314
		2.8-2.0	26.8	423	253	324
		2.0-1.0	22.6	484	223	293
		1.0-0.5	20.7	425	287	288
		0.5-0.3	23.7	434	242	323
V5	dLdB	8.0-4.75	26.7	89	581	330
		4.75-2.8	26.8	95	574	331
		2.8-2.0	28.5	98	570	332
		2.0-1.0	25.2	92	587	321
		1.0-0.5	21.7	79	595	326
		0.5-0.3	21.0	95	584	321
	LB1	5.0-2.0	29.6	93	573	334
		2.0-1.0	23.6	86	586	328
		1.0-0.5	23.4	73	599	328
		0.5-0.2	23.3	96	575	329

V1, V2 and V5 are 'tropical' soils from Venezuela classified as Typic Kandiustult, Fluventic Haplustoll and Typic Rhodustalf, respectively. dLdB is the De Leenheer and De Boodt method. LB1 is the fast wetting treatment of the Le Bissonnais method.

5.3.3. Mineral composition of clay fraction among aggregate sizes

Figures 5-2, 5-3 and 5-4 show the XRD patterns of the clay fraction of the different aggregate sizes for the three studied soils.

The XRD patterns of the clay fraction of soil V1 (Figure 5-2), Typic Kandiustult, contained diffraction peaks typical of illite (1.0, 0.50 and 0.333 nm), kaolinite (0.71, 0.357 and 0.237 nm), and gibbsite (0.482 nm). Additional reflections were attributed to minor quantities of feldspars (0.319 nm) and quartz (0.424, 0.333 and 0.214 nm). Among the different aggregate fractions the same mineralogical composition of the clay fraction was observed (Figure 5-2). The variation of the peak intensity of each mineral had a narrow range among the aggregate sizes. For instance the 1.15 nm peak ranged from 155 to 165 au, the 1.0 nm peak from 175 to 195 au and the 0.71 nm peak from 115 to 125 au. Therefore, no evidences of variation in peak intensity of specific minerals in a specific aggregate size fraction were observed.

For the Fluventic Haplustoll (V2), the XRD patterns of the clay fraction of the aggregate sizes showed that the clay fraction of this soil is dominated by mica, most probably muscovite, (1.0, 0.50 and 0.332 nm) and smectite (1.41 nm peak in the Mg^{2+} saturated sample shifting to 1.76 nm after ethylene-glycol solvation) (Figure 5-3). The swelling clay mineral and mica were observed in each aggregate fraction, indicated by characteristic peaks with similar intensity in the different aggregate fractions.

This behaviour was also observed for the other minerals present with lower abundance in the clay fraction such as kaolinite (0.71 and 0.355 nm), goethite (0.417 nm) and feldspars (0.320 nm). For this soil the range of the peak intensity among the aggregate sizes was also very narrow, e.g. the 1.42 nm peak ranged from 240 to 250 au, the 1.0 nm peak ranged from 305 to 330 au, the 0.985 nm peak ranged from 165 to 180 au, the 0.71 nm peak ranged from 95 to 100 au. Results from V2 showed the absence of a clear link between the type of clay and the aggregate sizes in the soil.

The third studied soil, a Typic Rhodustalf (V5), had a dominance of smectite (1.42 nm shifting towards 1.73 nm after glycolation of the Mg^{2+} saturated sample), illite (1.0, 0.50 and 0.334 nm) and kaolinite (0.71 and 0.357 nm) in the clay fraction of the aggregate sizes. Quartz (0.424 and 0.334 nm) was also observed in the XRD patterns (Figure 5-4). In comparison with the V1 soil, the intensity of the peak of illite in the glycolated XRD pattern was smaller in V5. This was an indicator for a lower abundance of illite in V5. When comparing the diffractograms among the aggregate sizes, an absence of variation in peak intensity of mineral constituents in the clay fraction was observed. The 1.42 nm peak ranged 215-235 au, the 1.0 nm peak ranged 110-120 au and the 0.71 nm peak ~155 au.

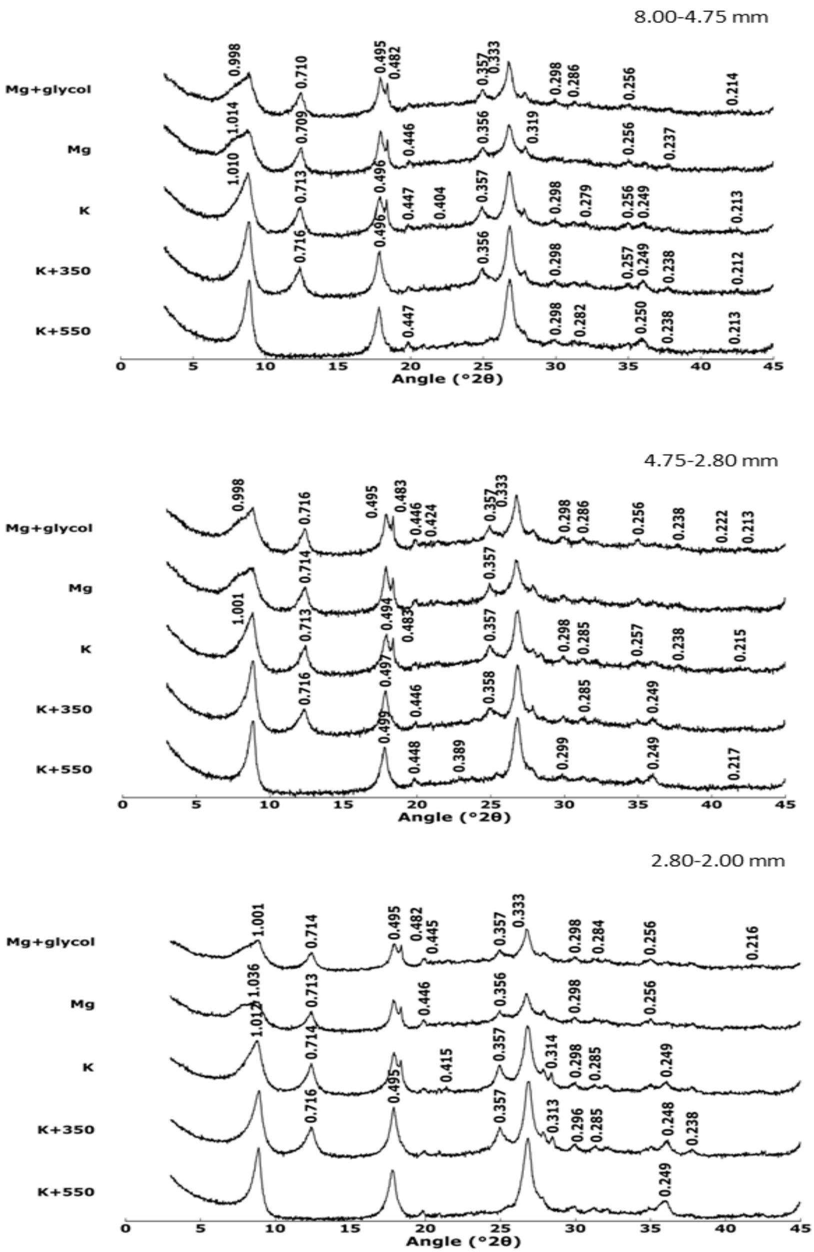


Figure 5-2 X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Typic Kandiustult soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

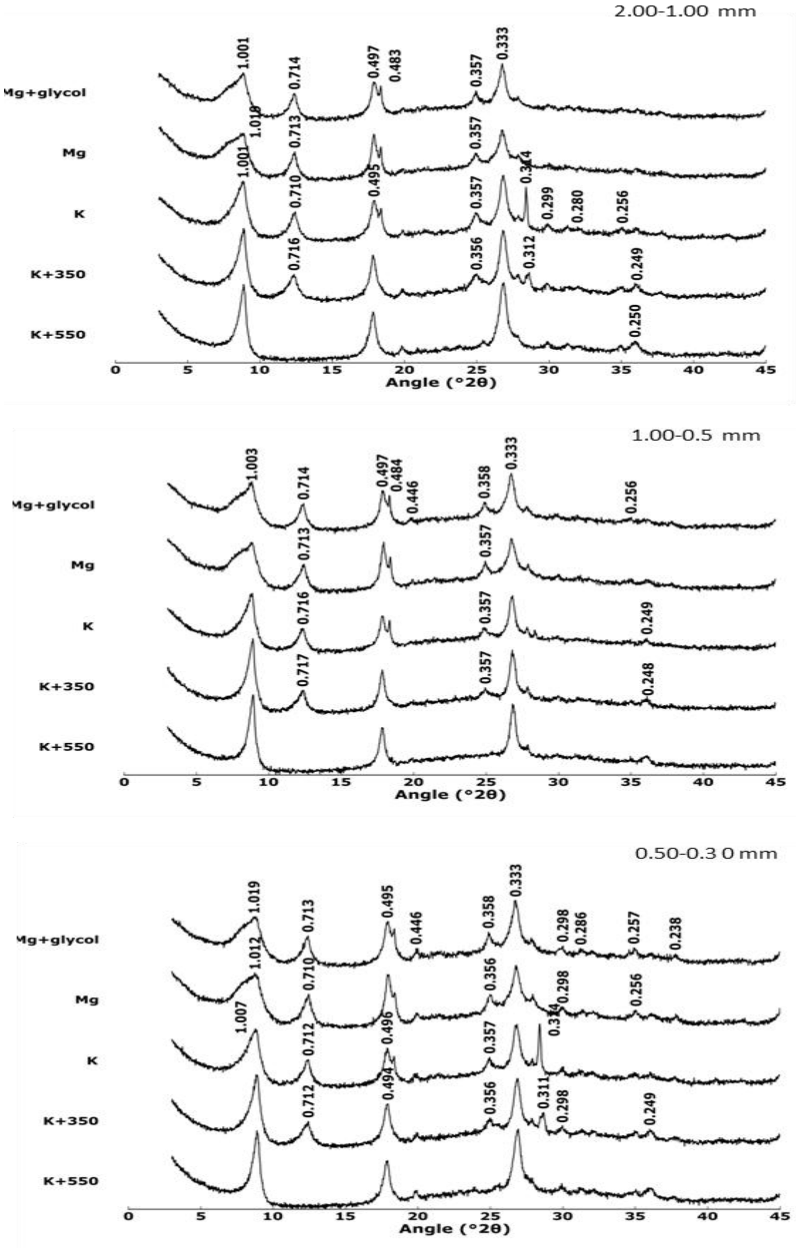


Figure 5-2 **(continued)** X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Typic Kandiustult soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

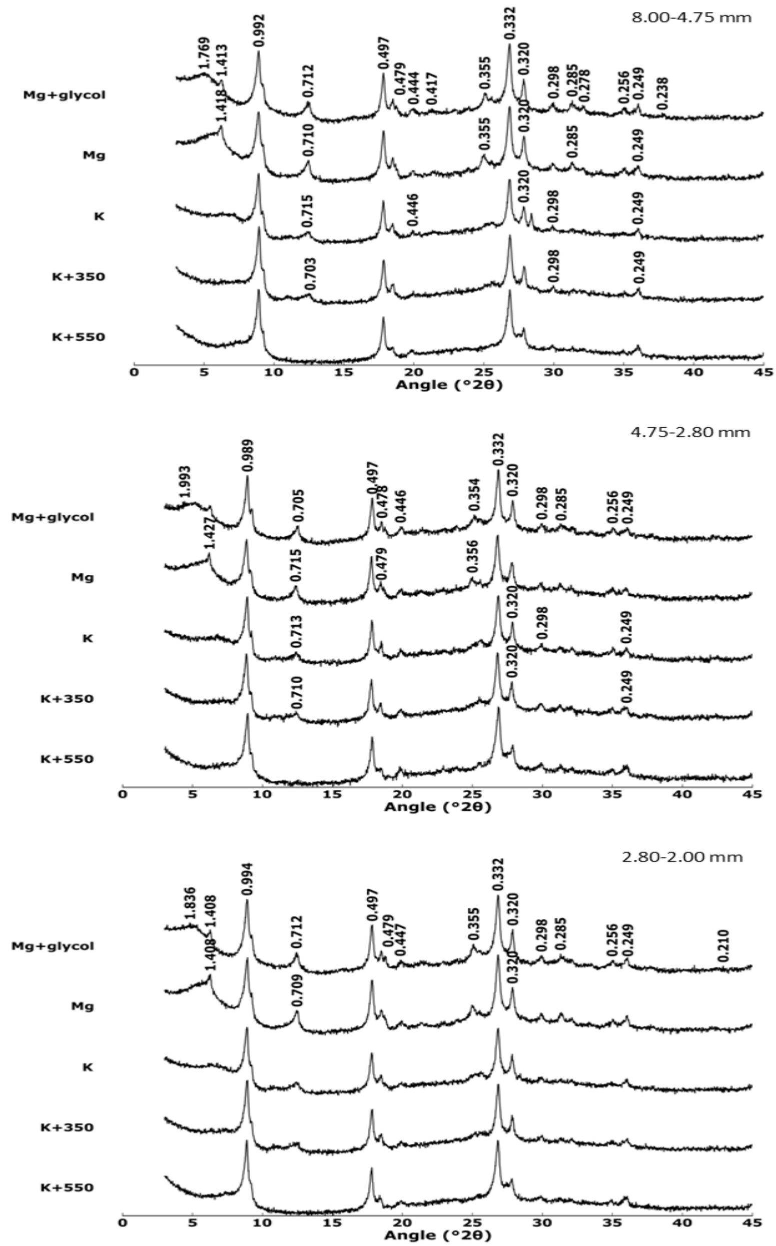


Figure 5-3 X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Fluventic Haplustoll soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

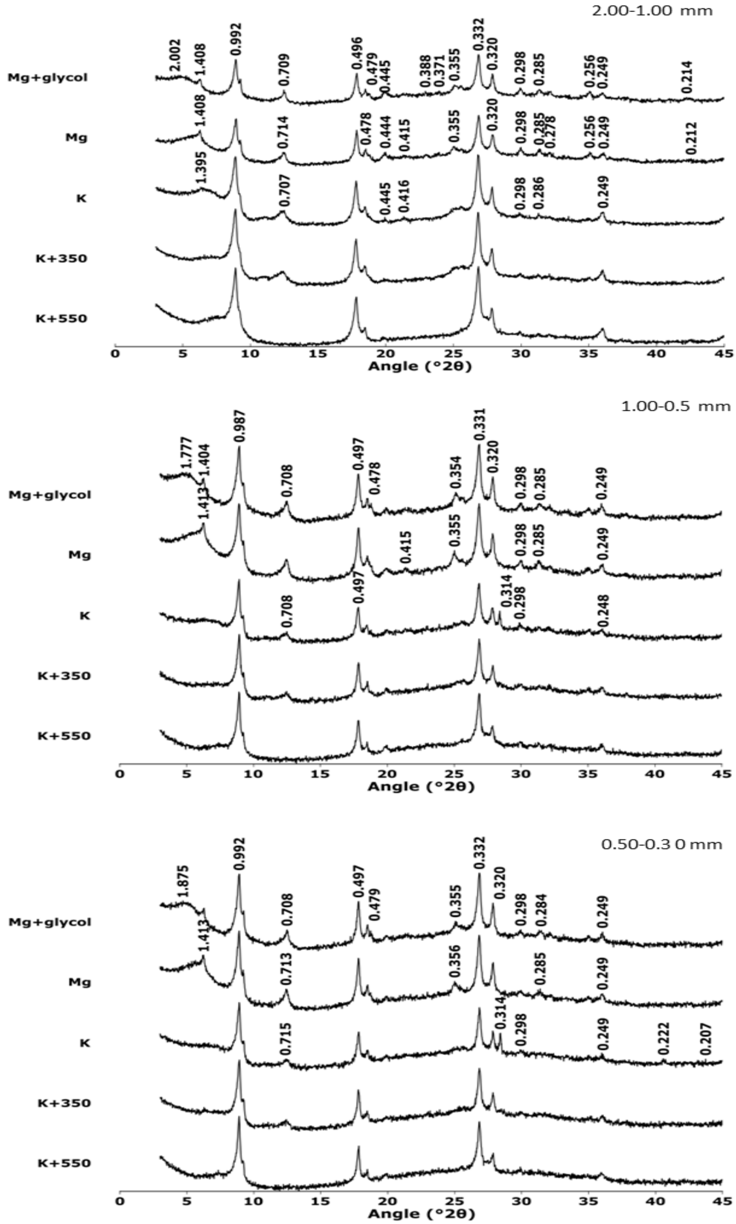


Figure 5-3 **(continued)** X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Fluventic Haplustoll soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

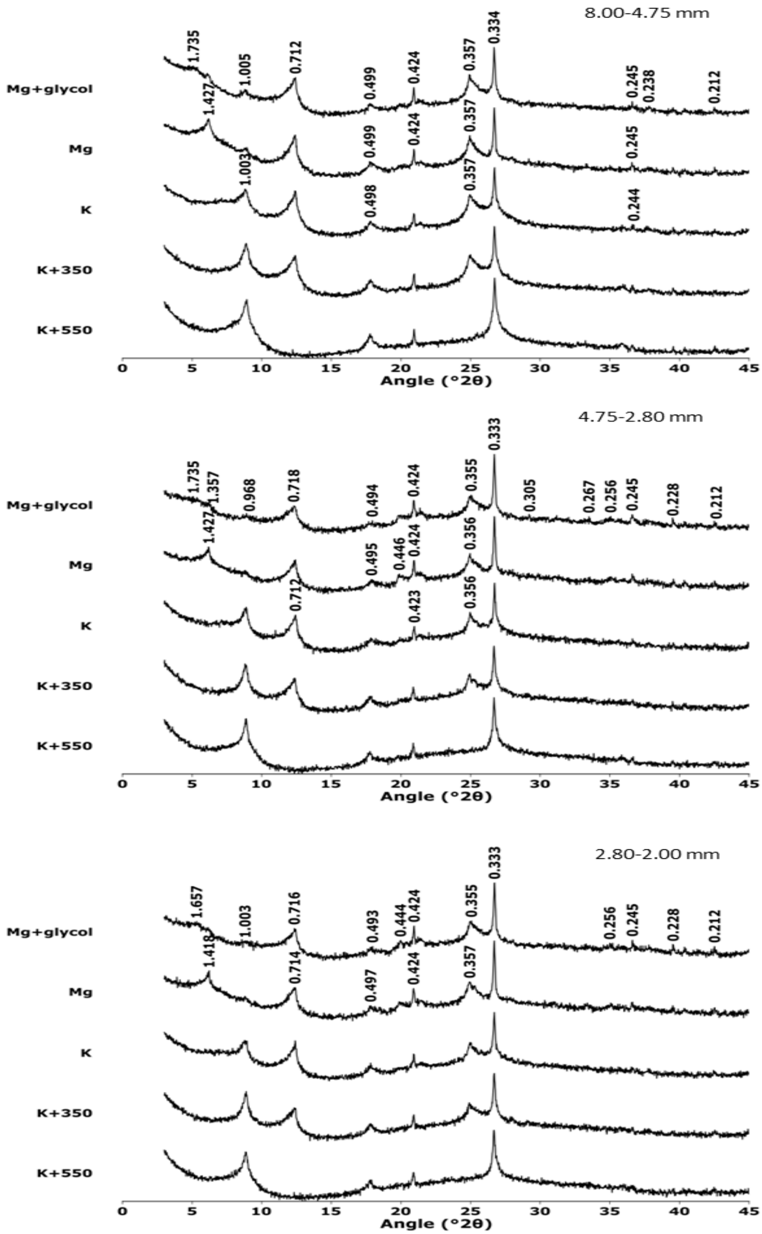


Figure 5-4 X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Typic Rhodustalf soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

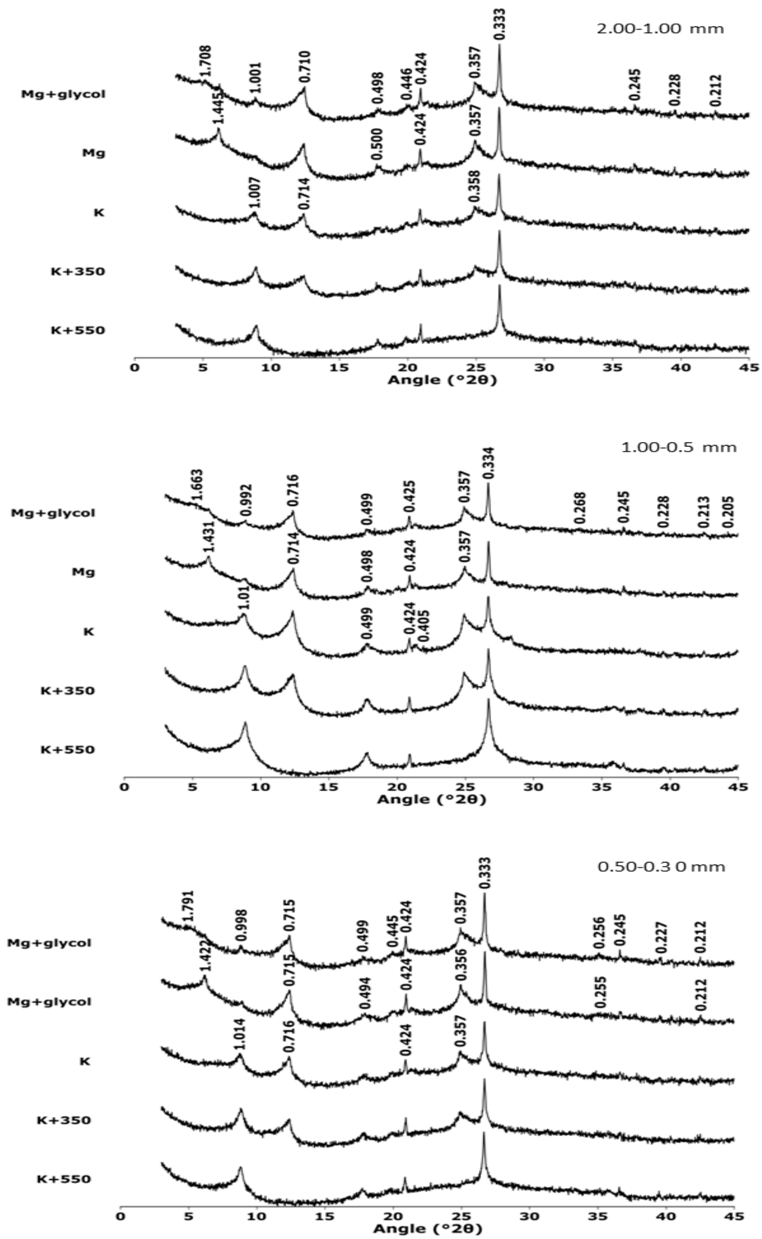


Figure 5-4 **(continued)** X-ray diffraction patterns for the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) in a Typic Rhodustalf soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

5.3.4. Mineral composition of clay fraction among aggregate fractions obtained by two different aggregate stability methods

Figures 5-4 and 5-5 display the results of mineralogical composition of the clay fraction of the aggregate sizes of the Typic Rhodustalf (V5) obtained by dLdB and LB1 method, respectively. Comparable aggregate sizes between dLdB and LB methods showed no evidence of variation in mineral composition of the clay among the aggregates and between the methods. For both fractionation methods, the XRD patterns showed no noticeable differences in intensity for the mineral reflections; hence XRD patters were very similar in terms of type and intensity of peaks.

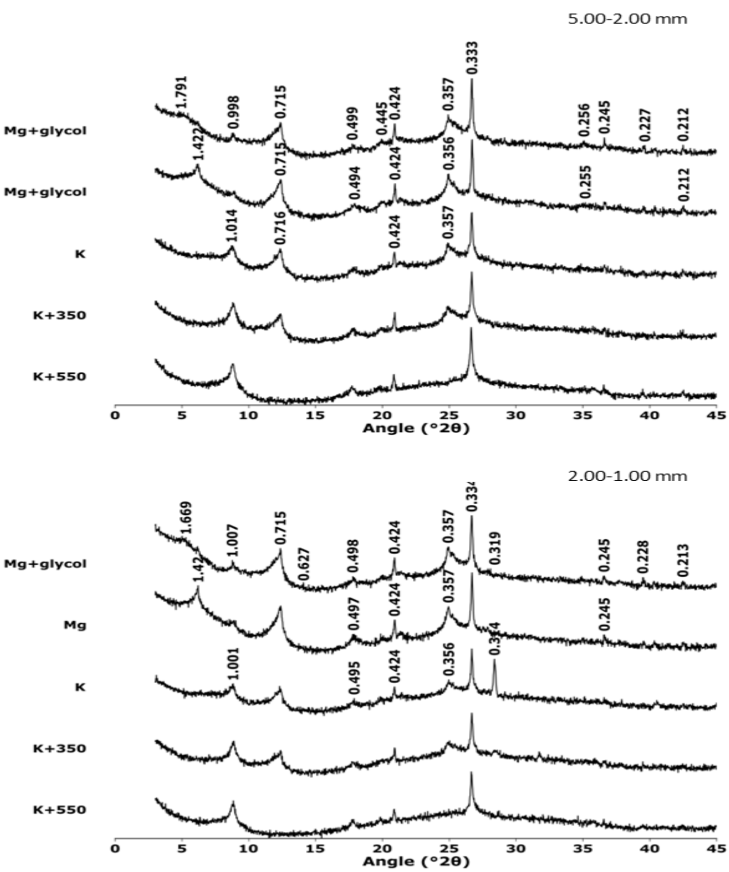


Figure 5-5 X-ray diffraction patterns for the clay fraction of the different aggregate sizes (fast wetting of Le Bissonnais fractionation method) in a Typic Rhodustalf soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

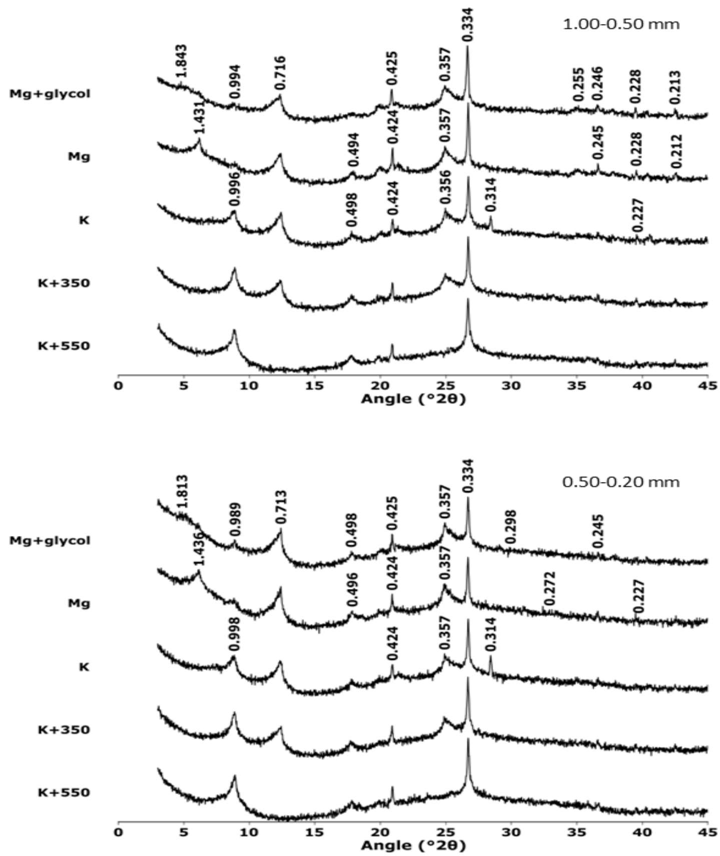


Figure 5-5 **(continued)** X-ray diffraction patterns for the clay fraction of the different aggregate sizes (fast wetting of Le Bissonnais fractionation method) in a Typic Rhodustalf soil from Venezuela. The figure shows the XRD for clay fraction saturated with Mg^{2+} and K^{+}, Mg^{2+} saturated after glycolation, and K^{+} saturated after heat treatments (350 and 550°C). Spacing of important 001 reflections are in nm.

5.4. Discussion

5.4.1. Does the mineralogical composition of the clay fraction vary among aggregate sizes?

The XRD patterns of the clay fractions showed that the three different studied soils contained different types of clay minerals. Their mineral composition confirms their taxonomical order. The Ultisol (V1) was characterized by illite, kaolinite and gibbsite, which is indicating advanced weathered clay. The Mollisol (V2) was characterized by a considerable amount of illite and smectite, and in the case of the Alfisol clearly smectite and mixed layers with a swelling component dominate the clay fraction.

The contribution of the clay mineral composition to aggregate stability was semi-quantitatively sought (based on peak intensity) by comparing the XRD patterns of the clay within the different aggregate sizes (Figure 5-6). The aggregate size fractionation, based on the dLdB method, involves aggregate fractions ranging from 0.30 to 8.00 mm. The three studied soils were considered stable because > 50% of the aggregates was > 0.5 mm. It should be noted that it was difficult to observe differences in mineral composition of the clay fraction among the range of aggregate sizes studied in the three soils. The peak intensity of mineral constituents present in the clay fraction did not change (very narrow range) with aggregate sizes (Figures 5-6). However, this was not surprising, because the different aggregates present in each soil, were formed from the same mineral material, with a specific clay composition.

Fernández-Ugalde et al. (2013) found qualitative variation in clay mineralogy in aggregate size classes (ranging from < 0.002 to 5.0 mm). The authors stated that the formation of microaggregates (0.05-0.25 mm) in a temperate Luvisol (Alfisol) is a consequence of the higher concentration of swelling clay and their reactivity in this size of aggregates. Using the peak intensity in the low-angle region of the XRD patterns as a mineralogical indicator, the authors suggested that there is a mineral selection in aggregate fractions, which constitute a clay-mineral-based evidence for the aggregate hierarchy.

It is important to emphasize that even if the authors mentioned that 'significant' differences in peak intensity were found within aggregates, no real quantification of the proportion of the minerals present in the clay fraction was conducted. In any case, the interpretation in terms of quantity should be combined with chemical analysis, e.g. total elemental analysis. This would make it a more accurate way for quantification of mineral composition.

However, even if there are differences in the peak intensities in the low-angle region of the XRD patterns, caution needs to be taken when interpreting them as a result of compositional differences. It is well known that the low-angle region of XRD patterns is highly influenced by surface characteristics (reflectivity) and the orientation of the phyllosillicates (Reynolds, 1986; Zevin and Viaene, 1990), which makes an unambiguous interpretation very difficult.

Quantitative analysis of clay mineralogy based on peak height of the mineral present in a sample has been considered to cause overestimation or underestimation of the quantity of clay minerals (Ouhadi and Yong, 2003). This is a reason why it cannot be considered as a quantitative indicator of mineralogical composition. On the contrary, XRD is a primary tool for analysing mineral composition of soils, which only allow comparison between soils or horizons.

Accurately quantification of the mineralogical composition of the clay fraction has been considered as a difficult task because of the complex nature of the clay mineral composition in soils, but it has been the main focus of several researchers (Kahle et al., 2002; Hubert et al., 2012; Dumon et al., 2014).

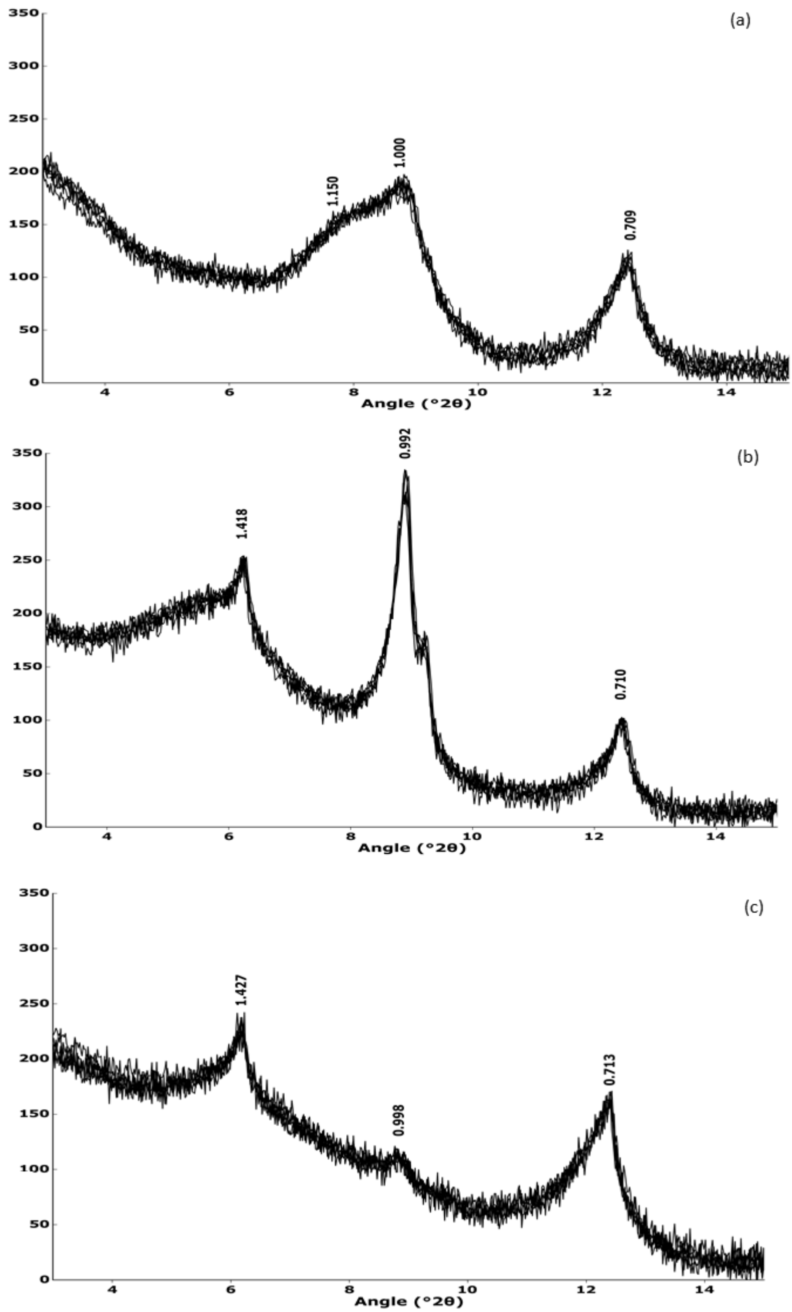


Figure 5-6 Mg^{2+} saturated X-ray diffraction patterns, normalized by the kaolinite peak, of the clay fraction of the different aggregate sizes (De Leenheer and De Boodt fractionation method) for the studied soils from Venezuela. (a) Typic Kandiustult, (b) Fluventic Haplustoll, and (c) Typic Rhodustalf.

Analysis of discriminative composition of clay mineralogy has been applied within different fraction sizes at the level of < 2 µm. Hubert et al. (2012) stated that XRD patterns of sub-fractions (< 0.05, 0.05-0.1, 0.1-0.2 and 0.2-2 µm) of the clay fraction can provide information on the respective discriminative composition of clay minerals in each sub-fraction and their respective mass contribution to the overall bulk < 2 µm fraction. Similarly, Dumon et al. (2014) observed differences in mineralogy of the total < 2 µm fraction between different horizons mainly attributed to the different proportions of the sub-fractions of the < 2 µm fraction.

Soil aggregation at clay-sized fraction scale has been suggested as the major sites of SOM stabilization and to control the accessibility of SOM to microbial decomposers (Chenu and Plante, 2006). However, as the authors emphasized, to observe organo-mineral complexes at this very small microaggregate sizes request for isolation of the clay content by mechanical means and using chemical dispersant, which is meaningless in natural systems.

These statements suggest that differences in mineral composition in the different sub-fractions of the clay exist, but specific contribution of the mineralogical composition of a specific sub-fraction in the aggregate hierarchy is less probable. In this Chapter, the clay content of each aggregate size was similar; hence contribution of the whole bulked clay fraction to aggregation is expected. The aggregate sizes evaluated, were those frequently considered by soil scientists when aggregate size distribution is applied as an indicator of soil structural quality. Therefore, insights at clay-sized fraction scale appear to be meaningless to aggregate hierarchy in the studied soils.

The absence of a clear contribution of clay mineral composition to the distribution of the different sizes of aggregates indicates that other factors such as biological activities or properties are the most important factor for aggregation of the studied aggregate sizes in these ‘tropical’ soils. For the three studied soils, the organic C concentration in the aggregate fractions showed a trend to increase with increasing size of aggregates (Table 5-1). Regarding the mineral particle concentration of each aggregate fraction no variation among the aggregate sizes was observed.

Therefore, for the studied ‘tropical’ soils from Venezuela the aggregation hierarchy of aggregates from 8.00 to 0.30 mm appears to be influenced neither by the distribution of the mineral composition of the clay fraction nor by particle size distribution but by SOM and its constituents.

5.4.2. Are the results of the mineral distribution of the clay fraction among the aggregate sizes influenced by the method applied for aggregate stability determination?

Fernández-Ugalde et al. (2013), based on the fact that several methods for aggregate stability and size distribution assessment have been developed, suggested that ‘the results of clay mineral distribution among aggregate-size classes may be influenced by the physical dispersion protocol'. This statement was the basis for the second objective of this Chapter.

It can be observed in Figures 5-6c and 5-7 that the low-angle region in the XRD patterns for the different aggregate sizes of the Typic Rhodustalf soil was similar after both dLdB and LB1 fractionations. No differences in mineralogical composition and distribution of the clay fraction were observed when the XRD patterns of the different aggregate fractions were overlaid (Figures 5-6c, 5-7, and 5-8). Based on the results, it can be stated that for the Typic Rhodustalf, the different mechanisms of fragmentation involved in both methods used for assessing aggregate size distribution do not have an effect on the mineral distribution of the clay fraction among the studied aggregate sizes (Figure 5-8).

Caution must be taken when methods of aggregate fractionation involve dispersion by centrifugation or sonication. These treatments could separate different fractions of clay, which could probably result in differentiating clay mineral distribution among aggregate sizes. These techniques are mainly applied when more fundamental science is aimed. Aggregate fractionation methods used in this dissertation are those frequently applied for aggregate size distribution assessment related to soil structural quality.

The different organic cementing agents (SOM constituents) involved in aggregation are more susceptible to the different mechanisms of disruption when determining aggregate size distribution than electrostatic bonds or physical forces (Six et al., 2000). Therefore, the absence of variation in mineralogical composition of the clay fraction found between fractionation methods in this Chapter, suggests that the differences in mass per cent of the different aggregate sizes among soils obtained in Chapter 3 are only attributed to the breakdown of organic bonds. Consequently, the size aggregate distribution depends on the different levels of weaknesses of organic binding to mechanisms of disaggregation. The use of different fractionation methods is expected to have a higher effect on the aggregate size distribution in soils with aggregation hierarchy than in those with no hierarchy.

According to Young et al. (2001) aggregate stability methods are useful when examining the presence/absence of components across aggregate sizes, but significant problems arise if it is attempted to relate functional traits of aggregates to undisturbed soil profiles. These authors emphasized that it 'is important to distinguish between the process of particle aggregation in soil, which contributes to structure formation, and the concept of a soil aggregate'. This because aggregates are relevant to soil structure in soils with high aggregate stability and where the individual aggregate units are preserved. On the other hand, the used of separated aggregates fractions or aggregate distribution lack of meaning when soil structure is thought of as a framework. The effect of the methodology applied for assessing aggregates sizes/stability should be more the focus for classifying soil quality and understanding the influence of tillage practices than for more insight in permanent binding agent in aggregation.

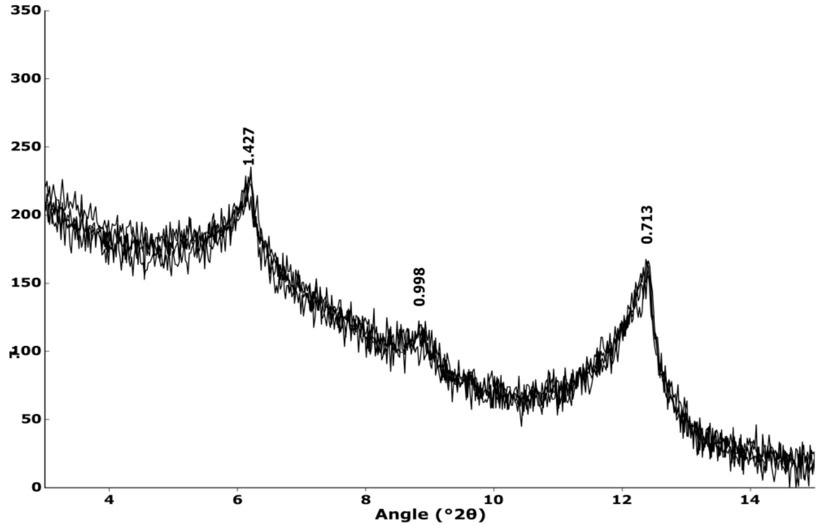


Figure 5-7 Mg^{2+} saturated X-ray diffraction patterns, normalized by the kaolinite peak, of the clay fraction of the different aggregate sizes (fast wetting treatment by Le Bissonnais fractionation method) for a Typic Rhodustalf from Venezuela.

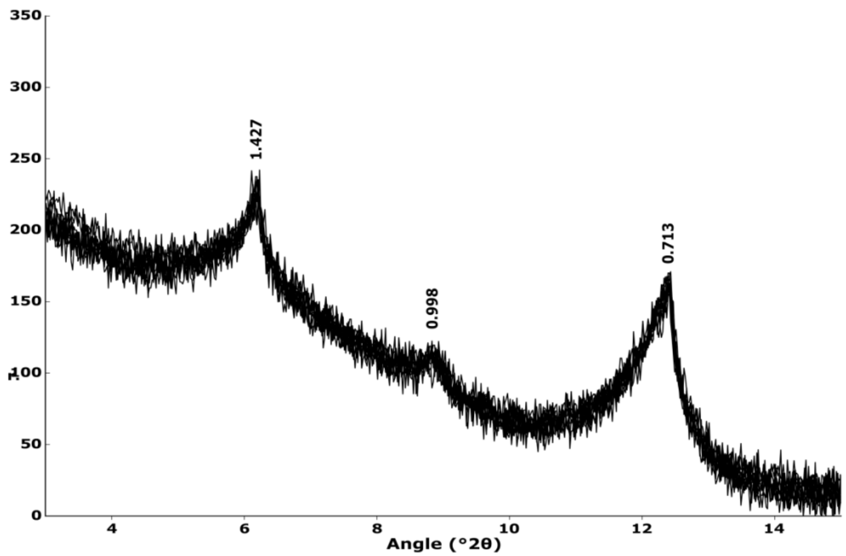


Figure 5-8 Mg^{2+} saturated X-ray diffraction patterns, normalized by the kaolinite peak, of the clay fraction of the different aggregate sizes (obtained by both De Leenheer and De Boodt method and the fast wetting treatment by Le Bissonnais) for a Typic Rhodustalf from Venezuela.

5.4.3. Are mineralogical indicators capable of evaluating aggregate stability as a key aspect of structural quality?

In soil structural quality the abundance of macroaggregates is linked to an optimal structural condition. Therefore, mineral selection in microaggregates and clay-size fraction or its sub-fractions could be less important at the macroaggregate scale for soil quality assessment.

The absence of mineral selection among the aggregate sizes observed in the studied soils, suggests that the mineralogical indicator of aggregate hierarchy proposed by Fernández-Ugalde et al. (2013) is not generally valid for the aggregation hierarchy of aggregates larger than clay-size fraction. It could be however more related to specific stage of the aggregation processes at smaller scale. Additional research in this aspect is needed, but taking into consideration more accurate quantitative method together with elemental analysis as mentioned above. Mineralogical composition of the clay fraction still remains as an important indicator of aggregate stability and structural shape when assessing different soils or horizons.

As aggregate stability is considered one of the key factors in the assessment of soil structure, quantification of the interaction between factors that affect this soil property at different scales remains an aspect of interest. Six et al. (2004) mentioned that researches focusing on aspects such as (i) integrating aggregation measurements with morphological characterization, (ii) viewing aggregates as dynamic entities and (iii) exploring novel statistical techniques, are attempted to contribute to the knowledge of this complex property. Importantly, structural stability and the related features/properties of soils must be seen as dynamic factors. Therefore, the presence of distinct aggregates within a soil profile can vary with time; this implies that the aggregate hierarchy described at certain moment is not a unique feature that describes a particular soil in a particular state.

5.5. Conclusion

Results did not allow drawing conclusion on clay-mineral-based evidence for the aggregate hierarchy in the three studied soils from Venezuela. Although the results of this Chapter are based on a limited amount of data, no evidences were found to suggest that clay mineral distribution within aggregates of 5.0 to 0.2 mm is influenced by the physical dispersion method applied for aggregate fractionation. The mineralogical composition of the clay fraction of the studied soils, which differ in weathering degree, contributed equally to the formation and stabilization of different aggregate sizes. The aggregate hierarchy present in these soils seems to be more correlated with biological agents, mainly SOM constituents. This Chapter attempts to encourage searching for more accurate quantitative mineralogical indices for seeking clay-mineral-based evidence for the aggregate hierarchy.

Part II

The use of visual examination methods for assessing soil structural quality

Chapter 6

The performance of visual examination methods in 'tropical' soils#

6.1. Introduction

The use of aggregate stability for assessing soil structure status was emphasized in Part I. In order to assess soil structure in a wider scope, visual examination of structural form is now the main focus of Part II.

According to Batey (2000), the advantages of making assessment of soil physical quality including soil structure directly in the field are: (i) the relatively short time consumed and the immediate availability of the results, (ii) the use of simple equipment, (iii) the observation of slight changes in physical conditions that may be difficult to determine by other means, and (iv) the flexibility to deal with a wide range of situations.

On the other hand, some of the disadvantages of the visual soil examinations are: (i) they demand field training and some experience for effective use, (ii) cross-checking of the results by two or more assessors is necessary when there is an absence of confidence for accurate evaluation, and (iii) the process of sample extraction requires destruction of significant area in experimental plots (Giarola et al., 2013; Kerebel and Holden, 2013).

Several studies about the use and the refinement of visual soil examinations have been published (Munkholm, 2000; Mueller et al., 2009, 2013; Guimarães et al., 2011, 2013; Boizard et al., 2013; McKenzie, 2013; Munkholm et al., 2013; Murphy et al., 2013). However, it must be emphasized that the main focus of these publications has been mainly for 'temperate' soils where the visual examinations have been developed. Consequently, there is scant information about the applicability of these techniques to

This Chapter is based on:
Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, B. J. C., Cornelis, W. M., 2014. Visual field assessment of soil structural quality in tropical soils. Soil & Tillage Research 139, 8-18.

'tropical' soils. Giarola et al. (2013) tested the method described by Ball et al. (2007) in a sub-tropical area with a humid climate in Brazil. These authors described the method as sufficiently sensitive to identify changes in structural quality of Oxisols under different soil managements. Moreover, other similar methods such as 'Le profil cultural' method by Roger-Estrade et al. (2004) were tested for soil physical evaluation under 'tropical' environments (Tavares et al., 1999).

Three widely used methods that have been evaluated on different 'temperate' soils but not on tropical areas are the soil quality scoring procedure (SQSP), the visual evaluation of soil structure (VESS) and the visual soil assessment (VSA). These visual examination methods could be used as alternatives to or complementing the most frequently used soil physical properties for evaluating soil structure. However, before these visual examinations of soil structural quality can be applied under tropical environments, validation is needed.

The hypothesis assessed in this Chapter was that the SQSP, the VESS and the VSA methods are applicable on 'tropical' soils and they are related to quantitative soil physical properties. The objective was therefore to compare the performance of the SQSP, VESS, and VSA methods in assessing the soil structural quality on Venezuelan 'tropical' soils with contrasting soil type and land use. Additionally, soil physical properties were measured and correlated with the soil structure scores.

6.2. Materials and Methods

6.2.1. Soil sampling

The six soils (V1-V6) from the central-northern part of Venezuela were selected. As was described in Chapter 2, they differ in factors that affect soil quality such as soil type, soil management and vegetation type. This provided a wide range of soil quality, which enables testing of the three visual soil examinations. Soil use and management, soil taxonomy and general characterization were detailed in Table 2-1 of Chapter 2.

Sampling was conducted as described in Chapter 3. In each soil disturbed and undisturbed samples were taken. For the visual field assessment two blocks of soil (20 cm deep, 10 cm thick and 20 cm long) were taken at each sampling location. One block was broken by hand and the other by dropping one to three times from a height of 1 m into a plastic tray. The water content at sampling was near FC, except for V1: 0.40, 0.20, 0.18, 0.27, 0.23 and 0.22 kg kg^{-1} for soils V1-V6, respectively.

6.2.2. Visual soil structure assessment

The visual field assessment of soil structural quality was conducted by three methods: the SQSP (Ball and Douglas, 2003), the VESS (Ball et al., 2007), and the VSA (Shepherd, 2009).

6.2.2.1. The Soil Quality Scoring Procedure (SQSP)

The SQSP was performed by describing the condition of the soil block broken by hand and the condition of the soil surface. The horizontal layers of contrasting structure present in each soil block were identified and depth of each layer was measured. The degree of firmness was the criterion used to identify the contrasting layers present in the soil block. In each layer, soil structure (type, size and rupture resistance of aggregates) and rooting (quantity, distribution, bending and thickness) were evaluated using the explanatory notes proposed by Ball and Douglas (2003), as well as the soil surface condition (vegetation and surface soil relief) where the soil blocks were extracted.

The criteria used by the method are presented in Tables 6-1, 6-2 and 6-3. When layering was present in the soil block, an average weighted score for the depth of each layer was calculated for the whole soil block (block score). Individual score of each layer was multiplied by its thickness, and then the sum of these products was divided by the total depth of the soil block. The scale of scoring (semi-quantitative evaluation of soil physical quality and rooting) was ranked from 1 to 5, where scores of 1 and 2 represent incoherent or poorly developed structure and scores of 3 to 5 refer to distinct aggregates and good physical condition for root growth.

Table 6-1 Evaluation of soil surface from vegetation and surface soil relief (Source: Ball and Douglas, 2003).

Surface score	Vegetation	Surface soil relief
5	Decomposing mat 2±4 cm thick	Not visible
3	Surface vegetation of stalks and weeds, possibly mossy	Rough, crumbly or smooth with ridges
1	Little or no vegetation	Smoothed, sealed or crusted

Table 6-2 Evaluation of soil structure applicable to sandy and loamy soils (Source: Ball and Douglas, 2003).

Soil structure score	Descriptor	Types and sizes of peds	Ped rupture resistance
5	Loose soil	Range between crumb and coarse blocky, ~ 75% of peds are crumbs	Friable/firm
4	Loose	Wide size range, including very coarse blocky	Firm/friable
3	Firm	Massive/single grain which breaks down readily to mainly crumb ± medium blocky	Firm/friable
2	Firm	Massive/single grain which breaks into crumb - coarse blocky or coarse subangular blocky	Firm
1	Compact	Massive which breaks into mostly very coarse subangular blocky, or to platy with horizontal failure planes	Extremely firm

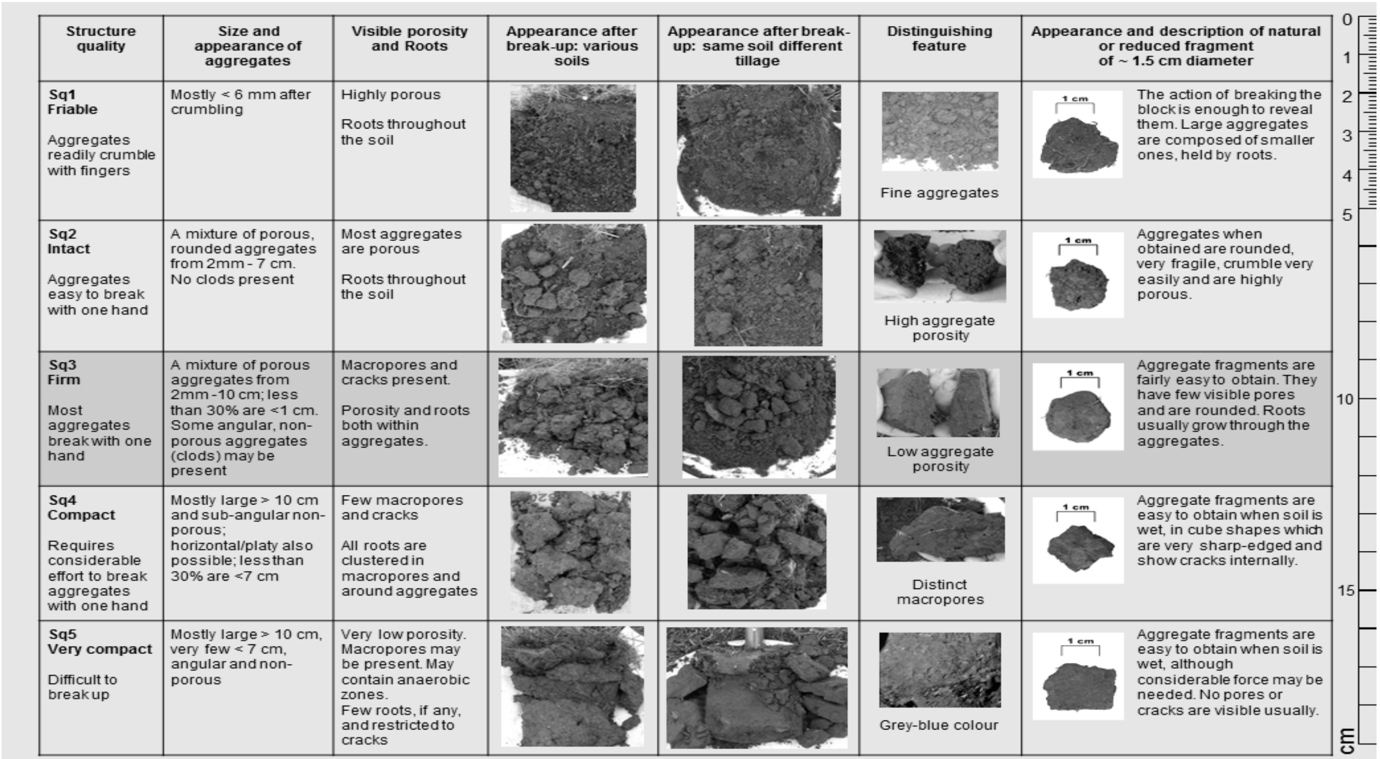
Table 6-3 Evaluation of rooting (Source: Ball and Douglas, 2003).

Rooting score	Quantity	Distribution	Bending and Thickening
5	Many or common	Appears evenly distributed	None - no restriction to roots
4	Common or few	Appears evenly distributed	None - no restriction to roots
3	Common or few	Some clustering between larger aggregates, around stones and in residues. Some are horizontally oriented	Minor or weak
2	Few	Mostly clustered around peds, stones or in residues, macropores and loose soil zones. Some are horizontally oriented	Moderate or strong, restricting roots
1	Few	Limited to clusters in macropores and cracks, confining direction of growth	Moderate or strong significantly restricting roots

6.2.2.2. The Visual Evaluation of Soil Structure (VESS)

The VESS was simultaneously conducted with the SQSP, meaning that the same soil block was used to perform both methods. The evaluation of the soil blocks was conducted according to the method described by Ball et al. (2007), which allows to assess the soil structural quality based on a visual key linked to criteria chosen to be as objective as possible. This method consists of identifying any layers of contrasting structure and giving a structural quality score (Sq) by comparing the appearance of the soil block after hand breaking with a visual key proposed by Guimarães et al. (2011) (Figure 6-1).

In this visual key the attributes evaluated are size and appearance of aggregates, visible porosity and roots, appearance after break up, distinguishing features, as well as appearance and description of natural or reduced fragment of 15 mm in diameter. The blocks of soil were graded on a scale from Sq1 to Sq5 where 1 was best. Scores were fitted between structural quality categories when the soil block had the properties of both. The assigned score was confirmed or increased from factors such as difficulty in extracting the soil block, aggregate shape and size, presence of large worm holes, root clustering, thickness and deflections, soil colour and smell, and the necessity to break large aggregates to small fragments to reveal their type. When layering was present in the soil block, an average weighted score for the whole soil block was calculated as described above. Soils with scores of Sq1 - Sq3 have acceptable condition of soil structure whereas those with scores of Sq4 - Sq5 have a limiting condition and require change of management.



Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 Friable Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			Fine aggregates	1 cm The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 Intact Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous Roots throughout the soil			High aggregate porosity	1 cm Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 Firm Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			Low aggregate porosity	1 cm Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 Compact Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			Distinct macropores	1 cm Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	1 cm Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

Figure 6-1 Chart describing the structural soil quality scores (Sq) of the Visual Evaluation of Soil Structure (VESS) test (Source: Guimarães et al., 2011).

6.2.2.3. The Visual Soil Assessment (VSA)

The soil block broken by dropping was used in order to conduct the VSA as described by Shepherd (2009). This method was performed following the visual assessment of the key indicators (soil texture, soil structure, soil porosity, number and colour of soil mottles, soil colour, number of earthworms (NE), soil smell, potential rooting depth, surface ponding, surface cover, surface crusting, and soil erosion) presented on the scorecard suggested by the author (see Appendices 1 and 2). For the soil structure evaluation, the soil blocks were individually dropped three times as mentioned above. After dropping the soil fragments were arranged from coarse to fine fractions over a plastic bag. The aggregate/fragments-size distribution was then compared with the photographs and criteria given in the field guide (Figure 6-2).

The fresh face of three of the large clods from the soil structure test, as well as a fresh spade slice of soil, were examined for soil porosity by comparing it with the reference photographs from the field guide manual. Pores visible to the naked eye and earthworm burrows were also considered before giving a visual score (VS) for soil porosity (Figure 6-3). Criteria for how to assess the other soil indicators such as soil texture, number and colour of soil mottles, soil colour, earthworms, soil smell, potential rooting depth, surface ponding, surface cover, surface crusting, and soil erosion, are given in Appendix 3. It is important to mention that earthworms were counted by hand, sorting through the soil sample after dropping. In each studied soil the visual field assessment was conducted when the soils were near FC, moist or suitable for grazing or cultivation, and when the temperature was low compared to the maximum peak at noon time. Such conditions are necessary to obtain a good evaluation of NE according to Araujo and López-Hernández (1999) and Shepherd (2009). In the case of potential rooting depth, the assessment was conducted simultaneously with the examination for the presence of a strongly developed tillage or plough pan by evaluating the penetration resistance to the knife of soil profile.

Each indicator was given a VS of 0 (poor), 1 (moderate), 2 (good), or an in-between score (0.5 = moderately poor and 1.5 = moderately good), based on the soil quality observed when comparing the soil with the description of the indicator and the photographs in the field guide manual (e.g. Figures 6-2 and 6-3). The score of each indicator was then multiplied by a weighting factor of 1, 2 or 3 (see appendices 1 and 2) and summed up to derive a final overall score for soil quality. The field guide manual for cropping land was used in soils V1 and V3, whereas in the other soils that for pastoral grazing was applied. Soils with a sum of visual scores ranking < 20 (under both grazing and cropping) have a poor soil quality, and soils with values > 35 (under grazing) or > 37 (under cropping) have a good soil quality. Values between these ranges are considered to be of a moderate soil quality.

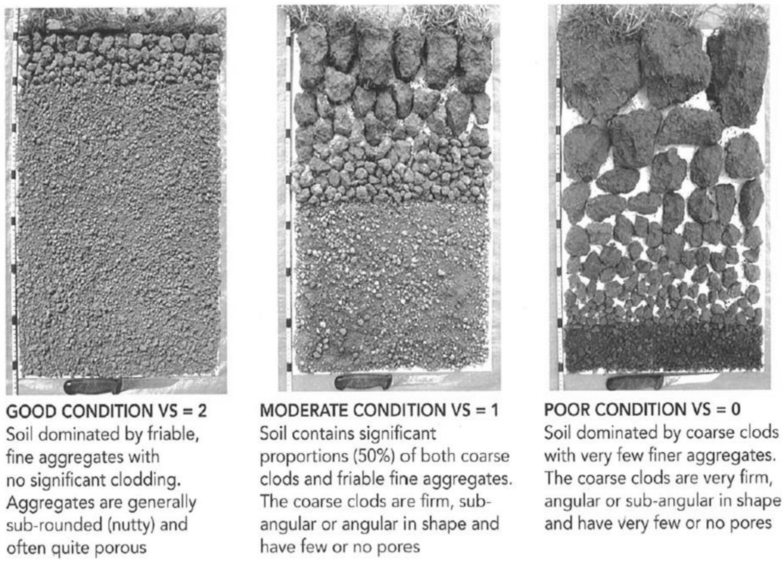


Figure 6-2 Visual scoring of the soil structure using visual soil assessment method (Source: Shepherd, 2009).

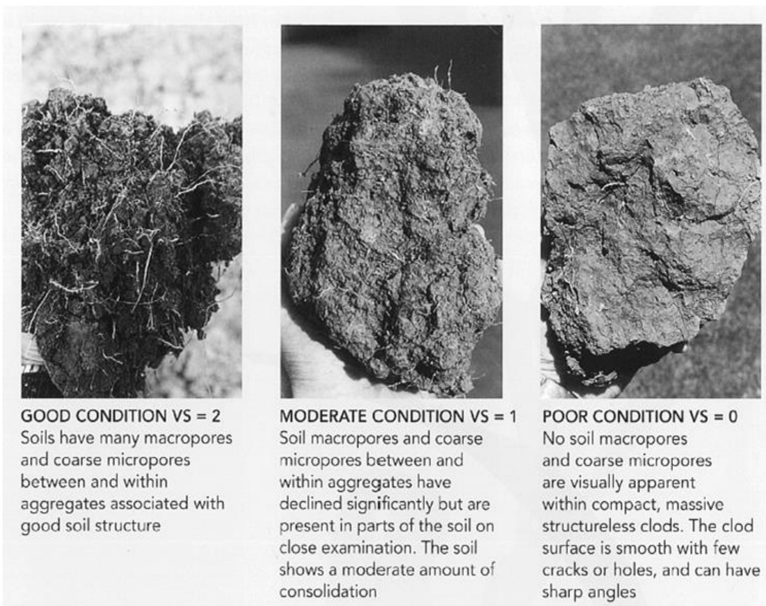


Figure 6-3 Visual scoring of the soil porosity using visual soil assessment method (Source: Shepherd, 2009).

6.2.3. Soil physical analysis

The soil physical properties such as K_s, SWRC, BD and StI were determined as described in Chapter 3.

Total porosity ($\theta_{\psi= 0\ kPa}$), AC ($\theta_{\psi= 0\ kPa}$ - $\theta_{\psi= -10\ kPa}$), FC ($\theta_{\psi= -33\ kPa}$), permanent wilting point (PWP, $\theta_{\psi= -1500\ kPa}$), PAWC ($\theta_{\psi= -33\ kPa}$ - $\theta_{\psi= -1500\ kPa}$), and RWC ($\theta_{\psi= -33\ kPa}$/ $\theta_{\psi= 0\ kPa}$) were calculated from SWRC data.

These soil physical properties were compared with the score of the visual examination methods. This comparison was performed with the aim to establish relationships between simple visual assessments and quantitative indicators of soil quality, which can demonstrate the strengths and weaknesses of the methods (Mueller et al., 2009; Guimarães et al., 2013).

6.2.4. Data analysis

An evaluation of individual indicators and indices of the visual examination was simultaneously conducted on each soil. Methods were compared from score data of all soils. To test the relationships between the visual examination scores and soil physical properties measurements, correlation coefficients were calculated using Spearman's statistic for mean rank data. A criterion of $P < 0.05$ was selected to represent statistical significance. If a visual field method was consistently correlated with all the soil physical properties measured, then this method was seen as an adequate indicator of the soil structural quality. Regressions between variables were conducted in order to postulate thresholds of soil physical properties that correspond to a deterioration of the soil structural quality (visualised). These analyses were performed using the statistical package SPSS (version 15.0, SPSS Inc., USA).

6.3. Results

6.3.1. Soil structural quality as evaluated by different visual field assessment

6.3.1.1. Soil quality scoring procedure (SQSP)

In general, the absence of roots or the low density of plants in soils under fallow (natural vegetation) made the evaluation of rooting in the SQSP (Ball and Douglas, 2003) difficult. The identification and description of the different indicators and features used in this method are summarised in Tables 6-4 and 6-5.

6.3.1.1.1. Surface condition

Soils V1, V2, V4 and V5 did not show evidence of crusting and sealing, neither of visible nor slight micro relief, but decomposing vegetation was present on the soil surface, which provides a ‘good’ surface score for these soils (Table 6-4). In contrast, soils V3 and V6 had a ‘bad’ surface score. The soil surface of these soils had little vegetation, mossy spots, and soils crusting along the plot. These are features commonly present in soils with a ‘poor’ physical quality.

6.3.1.1.2. Structure block score

All soils had two visible layers to a depth of 200 mm. V1 and V5 had an upper layer of 50 mm in depth. But for V2 the blocks of soils had an upper layer of 100 mm and for the other soils a layer between 50 and 100 mm. The features used to differentiate the contrasting layers were the type, size, and rupture resistance of the aggregates. Results in Tables 6-4 and 6-5 showed that the quality of the soil structure was ‘good’ in soils V1 and V2. This is attributed to the dominance of a fine crumbly structure with low resistance to rupture in the upper layer (0 to 50 mm and to 100 mm, respectively) and the friable sub-angular blocky structure underneath.

In V4 and V5 soils, the dominance of friable, sub-angular or angular blocky aggregate types with visible macropores in the upper layer as well as the prevalence of firm angular blocky structure in the under layer (50 or 100 mm to 200 mm), result in a ‘moderate’ soil structure score for these soils. In some blocks, macropores were not visible to the naked eye, but few earthworm burrows were present. A ‘bad’ soil structure score was given to V3 and V6 soils because of the dominance of angular blocky structure type, the high resistance against rupture of the field moist aggregates, and the low porosity observed in the faces of the aggregates (non-visible porosity).

6.3.1.1.3. Rooting block score

The amount of roots, distribution and bending were important features to designate scores in each soil block. Reference photographs are given in Figure 6-4. The root distribution was uniform along the soil blocks in V1 and V2, the root growth was not restricted. In the V3 and V6 soils, however, roots were concentrated in the upper layer (0 to 100 mm) of the soil blocks as evidenced by a compacted layer underneath (approx. 100 to 200 mm).

In the V4 and V5 soils, the evenness of the root distribution and the absence of thickening and bending indicated that roots were not restricted by unfavourable soil structure (Table 6-5). However, the vegetation present in V5 and V6 soils was heterogeneous and had a poor root density making it difficult to describe the distribution of the roots and the other specific features such as thickening and bending.

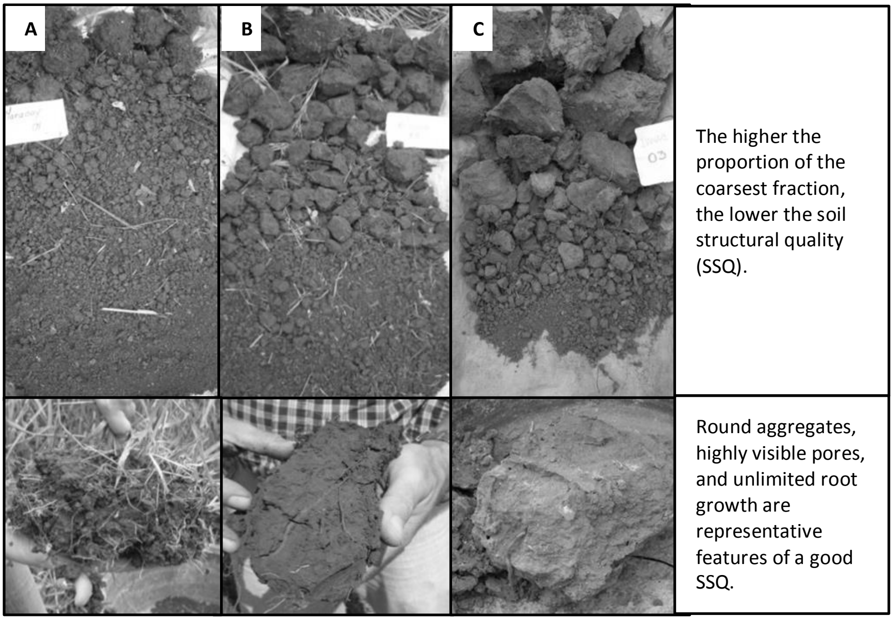


Figure 6-4 Three soils with different soil structural quality classes. From left to right, the photographs show ‘good’, ‘moderate’ and ‘poor’ soil structural quality. (A) is from a clay loam-Mollisol under permanent pasture, with high soil organic matter (SOM,) no-till and no-trampling, (B) is from a loam-Mollisol under pasture, with medium SOM, and permanent trampling, and (C) is from a loam-Alfisol, under cereal growth, conventional tillage and with low SOM.

6.3.1.1.4. Block score

The ‘block score’, from the soil structure score and soil rooting score, was ‘good’ for V1, V2 and V4 soils; ‘moderate’ for V5 soil; and ‘bad’ for V3 and V6 soils (Table 6-5). This means that the interaction between the soil use and management with the soil features prevalent in each soil, contributes in maintaining a ‘good’ quality of soil structure. No physical limitations were present for plant growth in V1, V2 and V4 soils. In V3 soil, the ‘block score’ revealed a ‘poor’ soil structural quality. Evidence of soil compaction, soil crusting and soil erosion were present in this soil. The degradation condition of this soil restricts the root development of the crop. In the clayey soil, V6, the ‘block score’ suggests that this soil has a ‘poor’ soil structural quality condition as well. This can result in a high risk of water logging. Soil V5 under fallow condition had a ‘moderate’ soil structural quality, suggesting that action should be taken to improve the soil condition for the functioning of soil.

Table 6-4 Mean values of the scores given to the indicators and index of the three field assessment methods for the soils under study.

Soil	SQSP				VESS	VSA		
	Surface condition	Structure score	Rooting score	Block score		Soil structure	Soil porosity	Soil quality
V1	3 (0)*	3.5 (0.4)	3.7 (0.4)	3.0 (0.2)	2.5 (0.5)	1.3 (0.5)	1.6 (0.2)	35 (2.0)
V2	4 (0)	4.0 (0.0)	4.1 (0.5)	4.1 (0.3)	2.0 (0.0)	1.6 (0.2)	1.9 (0.2)	40 (1.3)
V3	2 (0)	1.3 (0.4)	1.6 (0.8)	1.5 (0.6)	4.2 (0.4)	0.0 (0.0)	0.2 (0.3)	15 (1.2)
V4	4 (0)	2.3 (0.1)	3.7 (0.4)	3.0 (0.2)	3.3 (0.4)	0.7 (0.3)	1.1 (0.2)	31 (2.3)
V5	3 (0)	2.6 (0.4)	3.0 (0.0)	2.8 (0.2)	3.5 (0.3)	1.0 (0.0)	1.4 (0.2)	27 (0.9)
V6	2 (0)	2.0 (0.0)	2.0 (0.0)	2.0 (0.0)	4.4 (0.4)	0.3 (0.4)	0.3 (0.3)	11 (2.7)

*Standard deviation is given in parenthesis (±); SQSP = soil quality scoring procedure; VESS = visual evaluation of soil structure; VSA = visual soil assessment.

Table 6-5 Global comparison of indicators and indices of the three methods of visual field assessment for soils under study.

Soil	SQSP				VESS	VSA		
	Surface condition	Structure Score	Rooting Score	Block Score		Soil structure	Soil porosity	Soil quality
V1	No relief/ smooth	Firm / friable	None restriction	Good structural development	Intact / firm	Moderately high	Moderately high	Moderately good
V2	No relief	Friable / firm	None restriction	Good structural development	Intact	Moderately high	Moderately high	Good
V3	Crusting	Firm / extremely firm	Restricting roots	Structure deteriorated	Compact	Poor	Poor	Poor
V4	No relief	Firm / friable	Weak restriction	Good structural development	Firm	Moderately poor	Moderate	Moderate
V5	Rough/ high covert	Firm / friable	Weak restriction	Moderate structural development	Firm/ compact	Moderate	Moderately high	Moderate
V6	Smooth with ridges	Firm	Restricting roots	Structure deteriorated	Compact	Poor	Poor	Poor

SQSP = soil quality scoring procedure; VESS = visual evaluation of soil structure; VSA = visual soil assessment.

6.3.1.2. Visual evaluation of soil structure (VESS)

The visual key of VESS (Guimarães et al., 2011) was very practical and made the evaluation of the soil structural quality less time-consuming. Low scores in the visual key, Sq = 1 and Sq = 2, refer to a high soil quality. A crucial factor to identify the score in some soil blocks was the shape of the aggregate fragments (photographically evaluated); e.g., this factor provides in most of the cases Sq = 4 to soils where the other attributes such as size of aggregates and visible porosity match with the description of Sq = 3.

In the clayey soil (V6), it was difficult to test the methods SQSP and VESS. Much effort was needed to extract the block and break up the aggregates. In this soil the features such as massive structure, absence of roots, abundance of soil mottles and visible cracks, match with the Sq = 5 description of the visual key, which means a low physical quality for crop production.

In the upper layer (0 to 100 mm) of V3 the seedbed created by tillage had Sq = 3, but an abrupt change was observed in the under layer (approx. 100 to 200 mm) where Sq = 5 (Table 6-4). The whole block had a degraded quality despite the condition of the upper layer. The compacted layer had evidences of restricted root growth and water movement (deformed roots and mottled soil).

In V4 and V5 soils, the aggregate fragments were easily obtained. Most aggregates were round-shaped in the upper layer (0 to 100 mm in V4, and 0 to 50 mm in V5) and cube-shaped in the under layer. The evidence of earthworm burrows in soil V5 and the evenness of root distribution in soil V4 were considered as positive features in the description of porosity and roots. But the few visible pores and the cube-shaped in the aggregate fragments of the under layer (approx. 100 to 200 mm) of the blocks soils were features for increasing the scores. Therefore, the structural quality of these soils was between Sq = 3 and Sq = 4 (Table 6-4).

The differences in size and appearance of aggregates in soil V1 were the most important features to designate Sq as visual key. This soil had Sq = 2.5 (moderate quality). In soil V2 the majority of the aggregates obtained were fragile, round and in most of the cases were held together by roots. No clods were present, most aggregates were porous and roots were well distributed along the block. Consequently, this soil had Sq = 2 (Table 6-4).

6.3.1.3. Visual soil assessment (VSA)

The indicators of the score card were identified in the soils using the comparative photographs of the field guide manual proposed by Shepherd (2009). Dropping of the soil block was difficult to do with compacted and heavy soils. Dropping the soil block and arranging the distribution of aggregates for the VSA method consumed more time than breaking up the soil block by hand as was conducted in the other methods. However, from a visual point of view, VSA was the easiest method to provide soil quality scores to the indicators such as soil structure, soil porosity and surface condition, because of the three reference photographs and the criteria given in the field guide. The overall soil quality index (Tables 6-4 and 6-5) and the soil quality of specific indicators were evaluated as summarised (Table 6-6).

Table 6-6 Summary of the visual scores given to the indicators of the Visual Soil Assessment (VSA) method for each 'tropical' soil from Venezuela (V1-V6).

Visual indicator of soil quality	V1	V2	V3	V4	V5	V6
Soil texture	1	2	1	2	1	0
Soil structure	1	2	0	1	1	0
Soil porosity	2	2	0	1	2	0
Number and colour of soil mottles	2	2	1	1	2	1
Soil colour	1	2	0	1	2	1
Earthworms	0	0	0	0	0	0
Soil smell	2	2	1	2	2	1
Potential rooting depth	2	2	0	2	2	1
Surface condition	2	2	1	2	1	0

0 = average from ≥ 0 - ≤ 0.5 (condition from poor to moderately poor); 1 = average from > 0.5 - < 1.5 (condition from moderately poor to moderately good); 2 = average from ≥ 1.5 - 2 (condition from moderately good to good).

6.3.1.3.1. Soil structure

The soil fragments obtained after dropping the soil block were used to visually describe the aggregate size distribution (Table 6-4, Figure 6-4). In soils under grass, large fragments remained after the second or the third drop because they were held together by roots and no force was applied to separate them. In the tilled soil (V3) and the clayey soil (V6) most of the soil blocks did not break apart in more than three or four parts after being dropped. The coarsest fraction (firm and angular in shape) of the aggregates was larger than the finest fraction (friable and rounded or sub-angular) in soils V5, V4, V3 and V6 (50, 60, 70 and 90%, respectively). The higher the proportion of the coarsest fraction, the lower the quality of the soil structure. Hence structure in V1 and V2 soils was 'moderately-good', in V5 'moderate', in V4 'moderate-poor' and in V3 and V6 soils was 'poor' (Table 6-5).

6.3.1.3.2. Soil porosity

Soil V2 showed 'good' porosity (VS = 2), V1 and V5 soils had 'moderate-good' porosity (VS = 1.6 and VS = 1.4, respectively), V4 soil had 'moderate' porosity (VS = 1.1) and V3 and V6 soils had 'poor' porosity (VS = 0.3 and VS = 0.2, respectively) (Tables 6-4 and 6-5). In V1, V2, V4 and V5 soils, the presence of bio-pores (formed by roots or fauna activities) in the majority of the blocks contributed to a higher score for soil porosity than when they were not visible.

6.3.1.3.3. Soil quality

After dropping of the soil block, the contrasting layers present in the soil block could not be observed. But, an overall estimation of the soil quality over the entire soil block could be obtained immediately. The advantage of this is that the 'score' is the interpretation of the physical and biological properties in the first 200 mm of the soil as well as the soil surface condition.

With the VSA, the features most difficult to evaluate and with the lowest score along the soils were the potential rooting depth and the earthworm numbers respectively. These are indicators with a high weighting factor in the scorecard. Identifying the potential rooting depth requires digging very deep, at least to a depth of 800 mm that is the range established by Shepherd (2009) for a 'good' condition. This demands much effort and time especially in clayey soils. With respect to earthworm number, all soils were classified as having a 'poor' condition (Table 6-6). This score did not significantly correlate with any of the visual scores or soil physical properties (Tables 6-7 and 6-8).

6.3.2. Overall assessment of each soil

Table 6-5 shows the description of the scores given to all soils under study. Soil structural quality was unfavourable in soils V3 and V6, where SQSP scores ranged between 1 (extremely firm) and 2 (firm), VESS scores ranged from 4 (compact) to 5 (very compact), and VSA scores were between 0 (poor) and 0.5 (moderately poor). For the other soils, the structural status was favourable or moderate with slight restrictions for root growth according to the three methods. Photographs of investigated soil structure are provided in Figure 6-4.

However, in soil V4 a different rating was given for SQSP compared to VESS and VSA. The shape and the distribution of the aggregates were the features that mainly influenced the rating of 'moderate' soil quality using VESS and VSA criteria. On the contrary, the overall classification of SQSP method was 'good structural development' for these soils, in spite of 'smooth', 'firm/friable' or 'weak restriction' conditions described by the indicators of SQSP. This method comprises a wide range of 'good' quality, from 3 to 5, and soil V4 received a score equal to 3 (Tables 6-4 and 6-5). Consequently, for soils with 'moderate' soil quality as determined by VESS and VSA, the SQSP tends to overestimate the soil quality. Regardless of the differences in rating found for soil V4, relation between the methods applied was found when all soils were considered (Figure 6-5, Table 6-7).

Soil taxonomy allows comparison of the structural quality within soil orders. Irrespective of differences in factors such as texture, drainage, land use and management, all three visual soil examinations indicated a compacted or poor condition of soil structure of the Alfisols (soils V3, V5 and V6). When Mollisols were considered (V2 and V4), a better condition of soil structure was observed. However, weak restrictions for rooting and evidence of deterioration in shape and size of aggregates were observed in the Mollisol that was only under one pasture species and subjected to trampling (V4).

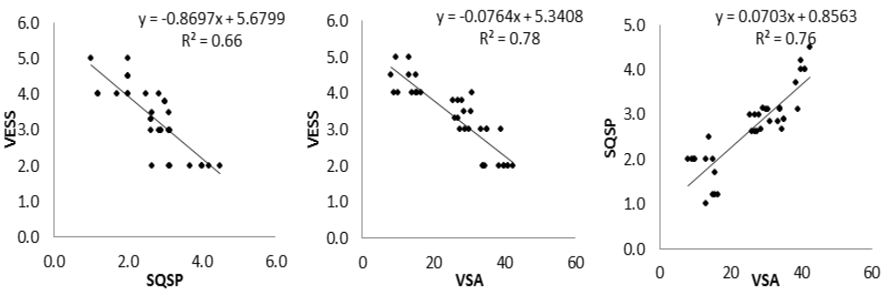


Figure 6-5 Relationship between scores of the visual field assessments from collected data in 'tropical' Venezuelan soils (V1–V6). SQSP = soil quality scoring procedure; VESS = visual evaluation of soil structure; VSA = visual soil assessment.

Table 6-7 Correlation matrix (Spearman ρ) of the visual field assessment methods at all soils[a] (n = 36).

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
M1	1									
M2	0.71**	1								
M3	0.87**	0.81**	1							
M4	0.86**	0.88**	0.94**	1						
M5	-0.75**	-0.84**	-0.85**	-0.84**	1					
M6	0.66**	0.88**	0.75**	0.82**	-0.77**	1				
M7	0.72**	0.88**	0.78**	0.82**	-0.88**	0.89**	1			
M8	0.74**	0.83**	0.77**	0.81**	-0.85**	0.83**	0.87**	1		
M9	0.00	0.13	-0.01	0.02	-0.11	-0.01	0.14	0.17	1	
M10	0.83**	0.87**	0.87**	0.86**	-0.90**	0.84**	0.89**	0.84**	0.09	1
$M9_{mod}$	0.42**	0.73**	0.45**	0.54**	-0.67**	0.59**	0.74**	0.72**	0.45**	0.62**
$M10_{mod}$	0.81**	0.88**	0.86**	0.85**	-0.90**	0.84**	0.84**	0.85**	0.12	0.98**

[a] M1 = surface condition (soil quality scoring procedure, SQSP), M2 = structure score (SQSP), M3 = rooting score (SQSP), M4 = block score (SQSP), M5 = structure quality (visual evaluation of soil structure, VESS), M6 = soil structure (visual soil assessment, VSA), M7 = soil porosity (VSA), M8 = Soil colour, M9 = earthworms score, M10 = soil quality (VSA), $M9_{mod}$ = visual score given to earthworms number based on criteria showed in Table 6-10, $M10_{mod}$ = overall score of VSA including $M9_{mod}$. ** Correlation is significant at the 0.01 level.

6.3.3. Relationships between the visual field assessment scores and indicators of soil physical quality

When comparing the scores of the indices and indicators of the visual soil examinations with soil physical properties determined in the laboratory, significant correlations were found (Table 6-8), but not all correlations were strong ($P > 0.01$, $r < 0.7$). This significant correlation indicates that most indices and indicators of the visual soil examinations refer to diagnostic features, e.g. soil compaction. The visual soil examinations, based on the arrangement of soil structure, consider a low mass/volume relation as a ‘good’ quality condition. Results showed soils with low BD, high SOC, and high AC had high NE (reflect pores visible to the naked eye), abundant small round-shaped aggregates and no-limitation of root growth, which represent a ‘good’ visual soil structural quality.

Table 6-8 shows, that there were significant correlations ($P < 0.01$) between the overall visual scores and BD, porosity, SOC, and K_s. Besides, the overall score of VESS and VSA were significantly correlated with porosity, AC and RWC. For the studied soils, with a silt and clay content ranging from 20 to 58% and from 23 to 42%, respectively, significant correlations were found between silt content and indicators of the visual soil examinations, except with the SQSP overall score. This confirms that the SQSP tends to overestimate the soil quality of the studied soils. On the other hand, no correlations were found with clay content. This indicates that the higher the content of silt, the lower the soil structural quality in the evaluated soils.

Table 6-8 Correlation coefficient between scores of the field assessment methods and soil physical parameters of soil quality (n = 36).

	BD	TPV	AC	PAWC	RWC	SOC	K_s	Clay	Silt	Sand	NE	StI
M1	-0.46**	0.29	0.12	0.47**	-0.13	0.44**	0.39*	-0.05	-0.12	0.13	0.46**	0.57**
M2	-0.52**	0.43**	0.22	0.04	-0.17	0.75**	0.73**	0.29	-0.44**	0.30	0.68**	0.84**
M3	-0.62**	0.49**	0.26	0.20	-0.25	0.57**	0.55**	0.06	-0.38*	0.32	0.44**	0.72**
M4	-0.49**	0.37*	0.13	0.23	-0.11	0.58**	0.58**	0.12	-0.30	0.21	0.51**	0.71**
M5	0.60**	-0.43**	-0.39*	-0.07	0.39*	-0.66**	-0.68**	-0.07	0.49**	-0.46**	-0.64**	-0.80**
M6	-0.37*	0.28	0.11	-0.07	-0.15	0.68**	0.64**	0.18	-0.34*	0.26	0.55**	0.75**
M7	-0.40*	0.23	0.14	-0.02	-0.22	0.74**	0.65**	0.15	-0.34*	0.29	0.71**	0.82**
M8	-0.38*	0.30	0.10	-0.02	-0.09	0.62**	0.67**	0.29	-0.29	0.19	0.68**	0.70**
M9	-0.08	0.07	0.07	-0.04	0.00	0.28	0.24	0.08	-0.04	0.04	0.41*	0.19
M10	-0.62**	0.43**	0.41*	0.18	-0.43**	0.59**	0.68**	-0.02	-0.53**	0.51**	0.66**	0.75**
$M9_{mod}$	-0.22	0.13	0.08	-0.13	-0.12	0.60**	0.60**	0.32	-0.32	0.22	0.94**	0.62**
$M10_{mod}$	-0.60**	0.42**	0.38*	0.10	-0.40*	0.63**	0.72**	0.03	-0.52*	0.49**	0.72**	0.76**

BD = bulk density; TPV = total pore volume; AC = air capacity; PAWC = plant available water capacity; RWC = relative water capacity; SOC = soil organic carbon; K_s = saturated hydraulic conductivity; NE = number of earthworms; StI = structural stability index. **Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level. See Table 6-5 for abbreviations.

The relationships between the visual field assessment scores and some of the soil physical properties are presented in Figure 6-6 and Table 6-9. These relationships based on the data set of all soils were in many cases significant. The strongest relationships were those between VESS and VSA with the soil physical properties such as porosity, BD, SOC, and K_s as well as StI.

Table 6-9 Relationships between field assessment scores and the structural stability index (StI), which has been used as soil quality indicator.

Relationship	Equation	R^2	Significance	n
StI vs. SQSP	$StI = 1.5082e^{0.4621SQSP}$	0.40	P < 0.01	36
StI vs. VESS	$StI = 28.476e^{-0.507VESS}$	0.55	P < 0.01	36
StI vs. VSA_{mod}	$StI = 1.7081e^{0.0404VSA}$	0.59	P < 0.01	36

SQSP = soil quality scoring procedure; VESS = visual evaluation of soil structure; VSA_{mod} = visual soil assessment modified (see footnote Table 6-7).

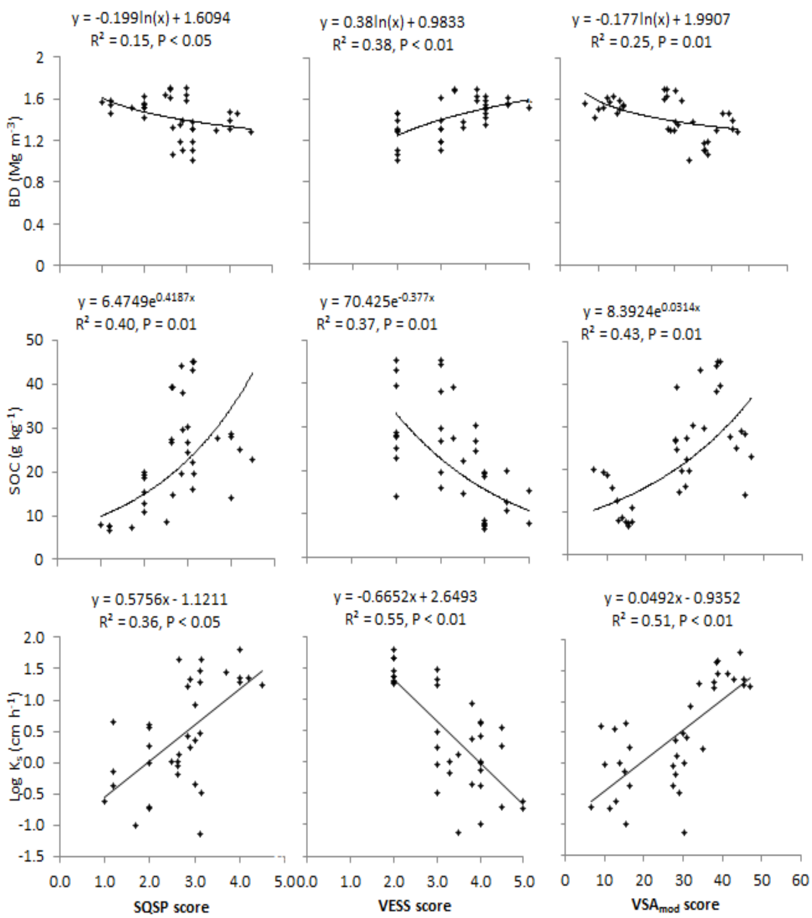


Figure 6-6 Relationships between the visual field assessment scores (SQSP, VESS and VSA_{mod}) and the soil physical properties measured in the laboratory: bulk density (BD), soil organic carbon (SOC), and saturated hydraulic conductivity (K_s).

6.4. Discussion

6.4.1. Comparison of visual soil quality classification

It is important to emphasize that land use and soil type are not considered as factors in this Chapter, but are mentioned because they refer to the condition of the soil at the time of sampling.

Overall the three visual soil examinations enabled detecting the different soil structural quality classes present at the evaluated soils, which is in agreement with the hypothesis. From the aspect of soil quality, sandy clay loam and clay loam soils (V1 and V2) were the best. Both soils V1 and V2 had high SOC and no-till management. The worst soil quality was found on a loamy soil (V3), characterized by continuous cereal growth, conventional tillage and low SOC, as well as on silty clay soil (V6) under natural vegetation and cattle production (Figure 6-4). This indicates that no matter the differences in texture and other factors, these Alfisols (V3 and V6) are susceptible to compaction by mechanical or animal traction. These results corresponded with those reported by Mueller et al. (2013). They found the worst structure status on soils characterized by imperfect land drainage, continuous cereal growth, high intensity of tillage and traffic. Best scores of the visual structure were given for properly managed soils with reduced tillage, crop rotation, and low traffic intensity.

In this dissertation it was confirmed that simple indicators allow the evaluation of the compaction status of soils. Those indicators were the presence of clods, high rupture resistance, lower porosity into aggregate’s faces, limitation of root growth, change in aggregate shape as well as the difficulty to extract the soil block and to break down the soil block into aggregates. The three visual soil examinations were capable to differentiate between compacted soils and well-structured soils (Table 6-5). This supports that the identification of soil compaction can be conducted directly in the field as was mentioned by Batey and McKenzie (2006).

In general, the VESS and VSA scores indicated that the samples of soils under no-till had a ‘good’ soil structural quality (Tables 6-4 and 6-5). On the other hand, soils under conventional tillage or trampling showed a detrimental impact on soil structure. In all cases, VESS scores indicated a better soil structural quality in the upper layer (0 to 50 or 100 mm). This is consistent with a general understanding of the influence of the agricultural activities on soil structural quality. Differences in structural quality of layers and under different soil tillage have been mentioned by other authors (Shukla et al., 2003; Askari et al., 2013).

Conclusions about the effects of land use, vegetation type, root growth stage and soil management cannot be drawn from the data set presented in this dissertation because of differences in other factors that affect soil structural quality such as drainage, climate, pedogenesis, as well as the possible interaction between them. However, the study demonstrates the utility of field assessment for visually identifying soil structural quality.

6.4.2. Validity of the methods based on their relationships with soil physical properties of soil structure

Results confirm the hypothesis that in these 'tropical' Venezuelan soils, there are also associations between the visual scores and soil physical properties as have been reported for 'temperate' soils (Mueller et al., 2009; Guimarães et al., 2011; Mueller et al., 2013; Murphy et al., 2013). In this Chapter, significant relations between porosity, BD, SOC, and K_s with SQSP, VESS and VSA were found. However, it should be emphasized that these relationships were stronger ($P < 0.01$, $r > 0.4$, $R^2 > 0.4$) with the VESS and VSA (Table 6-8 and Figure 6-6) than with the SQSP method.

These relationships indicate that the visual soil examinations can evaluate soil structure degradation by compaction, which is related to a decrease in SOC, an increase in BD and consequently decreasing in continuity of soil pores and reduction in permeability (K_s). It can be postulated that from comparing the different graphs of Figure 6-6, the evaluated soils presented deterioration of the soil structure when the BD is higher than 1.4 Mg m^{-3}, SOC is lower than 25 g kg^{-1}, and $\log K_s$ is lower than 0.5 cm h^{-1}.

Under temperate conditions, Mueller et al. (2009) also found similarity between soil physical properties (SOC, BD, AC and penetration resistance) with soil scores of visual soil examinations based on the Peerlkamp method (Ball and Douglas, 2003), VSA and FAO description (FAO, 2006). Shepherd and Park (2003) found close correlations between the VSA score of soil structure and soil properties such as dry aggregate size distribution, K_s, air permeability, macropores, BD and aggregate stability, which made them to conclude that 'we can see what we measure'. Results from this study suggests that in the studied 'tropical' and 'temperate' soils visual soil examinations are similar to measured BD, SOC and K_s.

According to Newell-Price et al. (2013), the advantage of visual soil examinations is that it is possible to summarise in a simple score the overall soil structure condition of a block of soil, as well as to rapidly identify restrictive layers. Visual soil examinations provide more information than quantitative methods such as BD, porosity and air permeability. On the other hand, measuring these soil physical properties have the advantage of providing quantitative data at specific depths, which would be difficult to obtain using visual evaluation alone.

Visual scores were well associated with the relation SOC-texture present in the soils (StI). Evidence of this is the significant exponential relations (Table 6-9) and strong correlations (Table 6-8) between the visual scores and the StI. However, no-relations were found when visual scores and indicators calculated from SWRC, such as AC, RWC, and PAWC, were compared. Results suggest that the visual soil structural quality of the soils under study is more related to water movement than water retention parameters.

For revealing the pore network in its entirety, Boizard et al. (2013) stated that a micro-morphological assessment (analysis of images) enables obtaining detailed information about characterization of cracks and the macropore network for a more effective description of the functioning of soil and root growth.

6.4.3. Adjustment of the visual assessments for 'tropical' soils

When VSA was used for assessing the soil quality of the Venezuelan 'tropical' soils, constraints were found when using the rating of NE of the method. The 'poor' visual scores (Table 6-6) given to the NE found in the Venezuelan 'tropical' soils, and the no significant correlation between the NE scores with all the overall scores of visual assessments as well as with the soil physical properties (Tables 6-7 and 6-8), suggest that the scores given by Shepherd (2009) based on conditions in New Zealand, are not necessarily generally valid, and do at least not apply for the tropical conditions in the Venezuelan studied soils.

According to the values of NE reported for savannah (30 individual m^{-2}) and agricultural organic systems in savannah (145 individual m^{-2}) in Venezuela (Araujo and López Hernández, 1999), V1 and V2 present a large NE. Table 6-10 shows a modified ranking of NE proposed for the Venezuelan soils, based on the density of earthworms found in the studied soils, which provides a significant correlation of the modified visual score of NE with other indicators (Table 6-7). However, there is no a noticeable increase in the relationship of the soil physical properties and the recalculated overall score of the VSA ($V9_{mod}$ and $V10_{mod}$ in Table 6-7).

Table 6-10 Earthworm numbers and species present in the soil blocks evaluated for Venezuelan tropical soils.

Soils	Density of earthworms (individual m^{-2})				Number of species [b]	Visual score of VSA	Modified visual score of VSA [c]
	Mean	Standard deviation	Max [a]	Min [a]			
V1	196	196	525	0	1	0	1.0
V2	196	58	250	125	1	0	1.3
V3	8	13	25	0	1	0	0
V4	13	14	25	0	1	0	0
V5	117	133	375	0	1	0	0.8
V6	0	0	0	0	0	0	0

[a] Max and Min = the largest and the smallest values of the number of earthworms in the first 20 cm of soil.
[b] Only one species was present in each soil or at least earthworms with the same colour and appearance.
[c] Visual scores given by using ranking of earthworm numbers per block of soil based on the density of earthworms present in the evaluated soils. Visual scores: 2 = >10, 1.5 = 8-10, 1= 5-7, 0.5= 4-2, 0= <2.
VSA= Visual Soil Assessment

The results in terms of soil quality from the SQSP method were not generally supported by the other visual methods and measured soil physical properties (Tables 6-5, 6-7 and 6-8). This method required modification for evaluating structural condition of soils under fallow or natural vegetation because of the difficulty in evaluating the root system. Regarding the VSA, this comprises the evaluation of the potential rooting depth in spite of the root system condition (distribution, quantity, bending and thickening), which on the one hand is an advantage, compared to the SQSP, when the field assessment is conducted at an early crop stage or in soils without crop production where the evaluation of the rooting system is not possible. But on the other hand, the evaluation of the potential rooting depth in the VSA needs more effort and time, especially in heavy soils. For a more accurate evaluation of the root development directly in the field, the use of other well-known indicators such as the root length density (Tennant, 1975) or the root distribution (profile wall method by Bohm, 1979) could be recommended.

Finally, from the practical point of view, the time to perform each method is variable. This depends on the difficulty in extracting and breaking up the soil block as well as the identification of the features. The quickest method was VESS, followed by SQSP and VSA. The lower the number of features present in the soil, the less the time needed.

6.5. Conclusions

The SQSP, VESS and VSA were suitable for differentiating the soil structural quality of different agricultural tropical soils. For some soil conditions, the SQSP tends to overestimate the soil structural quality, and it is not sensitive enough when limitations in the evaluation of rooting system are present. In order to improve the accuracy of the VSA under tropical conditions, the rating of biological parameters such as earthworm number has to be adapted to the local condition. The scores obtained by the visual methods showed relationships with physical properties or indicators of soil quality measured in the laboratory such as bulk density, soil organic carbon and saturated hydraulic conductivity. This provided evidence of ‘poor’ or ‘good’ condition of soil structure to soil functioning from simple visual observations. In conclusion, the acceptable performance of these visual soil examinations on ‘tropical’ Venezuelan soils with contrasting soil type and land use allows suggesting them as alternative complementary rapid field methods for assessing structural quality of ‘tropical’ soils.

Chapter 7

Validation of morphological approaches for assessing soil structural quality[#]

7.1. Introduction

In agricultural soils, tillage practices modify soil properties and quality and hence affect crop production and the environment (Batey and McKenzie, 2006). Machinery traffic, tillage and loss of SOM have adverse effects on soil structural quality (Guimarães et al., 2013) and are generally resulting in soil compaction (Batey, 2009). Loss of integrity of soil structural units, decrease in soil volume, increase in BD, decrease in porosity and a reduction in hydraulic conductivity are the principal consequences of soil structure degradation and soil compaction (Newell-Price et al., 2013).

Soil structure is the property most frequently evaluated when determining soil quality under different land uses and tillage practices. As mentioned before, soil structure is usually evaluated in an indirect way from properties such as SOC content, BD, porosity, SWRC, soil resistance to root growth, K_s, and infiltration rate (Lal and Shukla, 2004). These properties, which can be used as indicators of SPQ (Reynolds et al., 2009), are usually evaluated by classical tests, which refer in here to those laboratory and field measurements frequently used to characterize and monitor physical condition of soils.

Despite the many instruments or techniques available to measure properties related to soil structure, there are many circumstances where such tests cannot be conducted or the number of samples has to increase to adequately capture the spatial and temporal variability (Batey, 2000). According to this author in some cases, specific

[#] This Chapter is based on:
Pulido Moncada, M., Helwig Penning, L., Timm, L. C., Gabriels, D., Cornelis, W. M., 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil & Tillage Research 140, 20-28.

instruments or devices may not be available, the cost of the analysis is high, sampling can damage a considerable part of the crop, layers with dissimilar properties can be present and there might be lateral distribution of a particular soil physical condition that needs to be determined.

Facing those limitations, the direct evaluation of morphological structural properties in the field is a possible alternative (Boizard et al., 2005). In recent years, several methods of visual field examination have been developed to provide a direct description of soil structure, helping farmers to take rapid decisions in order to improve the soil structural quality, and thus ensuring the soil's capacity of sustainable production. The importance of visual field examination of soil quality has been widely recognized as it plays a particularly important role in providing rapid semi-quantitative data on physical soil quality (Shepherd, 2000; Mueller et al., 2009; Garbout et al., 2013).

The morphological properties comprised in these methods are used in classical soil survey and classification. They are not competing with but rather complementary to soil physical properties measurements (Karlen et al., 2003). Morphological descriptions of soil structure also provide information that cannot easily be obtained by other methods, such as the shape and strength of aggregates, type of macropores, and macropores continuity and connectivity (Lin et al., 1999a; Batey and McKenzie, 2006). These are properties that reveal differences in quality between land use types and detect harvest compaction in cereal crops (Guimarães et al., 2013).

Visual examination methods are now being used in several countries and have shown value in explaining differences in crop performance and yield resulting from soil management and type (Ball et al., 2013). To provide similar information through other measures of soil physical condition such as BD, penetration resistance, porosity, water retention or hydraulic conductivity, requires several measurements and can be costly and time consuming (Newell-Price et al., 2013). Comparisons of visual examination of soils under different land uses and with contrasting textures, and their relationships with physical and hydraulic properties are not well documented in literature. Therefore, to encourage researchers, farmers and other stakeholders to use simple but accurate indicators for evaluating and monitoring the soil structural quality and soil degradation, there is a need to extend the validation of simple visual examinations.

This Chapter examines the applicability and validation of proposed visual examinations for soil structural quality assessment and the use of new visual indices such as the assessment of the type of aggregates. The main objective of this Chapter was therefore to evaluate the use and the ability of visual field examinations for assessing soil structural quality in soils with contrasting texture and land use by comparing them to soil physical and hydraulic properties related to a function of the soil.

7.2. Materials and Methods

7.2.1. Soil sampling

The survey was conducted in the Flanders Region of Belgium, on the sandy loam (B1) and the silt loam soil (B3) (see Chapter 2, Table 2-1). In each soil, two plots under different land use were sampled. As mentioned in Chapter 2, in the sandy loam soil, one plot was under cereal mono-cropping (*Zea mays* L.) with conventional tillage (CM) and another was under permanent pasture (PP). In the silt loam soil one plot was under rotation of corn (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) with conventional tillage, and another under PP with constant presence of cattle. Characteristics of the two plots sampled in both sandy loam and silt loam soils are shown in Table 7-1.

In each plot, six sampling points were randomly selected and soil cores in triplicate were taken simultaneously with visual field examination of soil structure (see Materials and Methods of Chapter 3 and 6, respectively). The water content at sampling was near FC (-33 kPa).

Table 7-1 Characteristics of the sandy loam and the silt loam soils under cereal monoculture (CM) and permanent pasture (PP).

Soils	Land use	Clay	Silt	VFS	FS	MS	CS	VCS	SOM	pH_{KCl}	EC
		(g kg^{-1})									(dS m^{-1})
Sandy loam	CM	136	120	426	272	38	6	2	23.2	5.96	0.10
	PP	102	155	379	307	39	11	7	26.8	4.60	-
Silt loam	CM	125	657	128	74	13	2	1	18.9	6.22	0.18
	PP	142	646	113	82	12	3	2	55.6	5.58	-

VFS= very fine sand, FS= fine sand, MS= medium sand, CS= coarse sand, VCS= very coarse sand, SOM= soil organic matter.
pH and EC (soil electrical conductivity) were determined in 1:2.5 soil solution ratio.

7.2.2. Soil physical and hydraulic properties for assessing soil structural quality

The soil physical properties evaluated were aggregate stability, BD, porosity (total pore volume (TPV), AC, large macropores (MacP, 0.3 mm equivalent pore diameter) and micropores (MicP, < 30 µm equivalent pore diameter)), PAWC and unsaturated (K_h) and saturated (K_s) hydraulic conductivity. Also, particle size distribution by sedimentation using the pipette method (Gee and Or, 2002), SOC by wet oxidation (Walkley and Black, 1934), gravimetric soil water content, pH and EC (soil electrical conductivity) were determined.

For this assessment, K_s was obtained by using two methods: i) on soil cores with the constant-head method (Klute and Dirksen, 1986), using a laboratory permeameter (LP), and ii) in the field with a tension infiltrometer (TI), similar to that described by

Reynolds and Elrick (1991). Geometric means of the three values per sampling point were determined.

In case of the use of LP the undisturbed core samples were placed in a closed permeameter (Eijkelkamp Agrisearch Equipment) after saturation. A constant water head was obtained by creating a difference in water pressure on both sides of the saturated soil sample so that a water flow was passing through the soil sample. The flow was measured until a constant water flux was observed and K_s was then determined using Darcy's equation.

$$K_s = \frac{QL}{A\Delta H} \tag{7-1}$$

where *Q* is the outflow through the soil core (cm^3 h^{-1}), *L* is the length of the soil core (cm), *A* is the cross-sectional area of the soil core (cm^2), and ΔH is the applied hydraulic head (cm).

The TI method (Soilmoisture Equipment) was applied in a relatively levelled spot where local surface irregularities were covered with a fine layer of ~5 mm of sand (0.5–0.10 mm in diameter) to ensure a good hydraulic contact between the disc and the soil surface. Apparent steady-state infiltration rates were measured at sequential supply water potentials of -10, -6, -3 and -1 cm. It was assumed, based on the capillary theory, that these water potentials exclude pores of diameter or fissures of width greater than 0.30 mm, 0.5 mm, 1 mm, and 3 mm, respectively from participating in the water flow.

The non-linear regression method (Logsdon and Jaynes, 1993) based on the theoretical analysis of the steady-state water flux under the infiltrometre (Wooding, 1968) was used to calculate soil K_h and α according to:

$$\frac{Qx(h)}{\pi R^2} = K_s \exp(\alpha h) + \frac{[4K_s \exp(\alpha h)]}{\pi R \alpha} \tag{7-2}$$

where, Qx(h) is the steady infiltration rate under pressure head of h (-m), R is the radius of the disc, and α is the Gardner constant which characterizes the soil pore size distribution. The parameter K_s and α were determined by curve-fitting, using the Levenberg-Marquardt algorithm, allowing to determine hydraulic conductivity (K_h) under any other pressure head h from Gardner's exponential function:

$$K_h = K_s \exp(\alpha h) \tag{7-3}$$

7.2.3. Visual examination of the soil structural quality

The visual examination of the soils was conducted by using two different methods: the VESS by Ball et al. (2007) and the VSA by Shepherd (2009). Both methods were previously described in Chapter 6. As mentioned before, additionally two other indices for visually assessing soil structural quality were tested simultaneously in this Chapter, viz. visual type of aggregates index and visual assessment of the aggregate stability. Details are given below.

7.2.4. Visual soil structural quality assessment based on type of aggregates

The type of aggregates, in terms of form, was considered as an individual morphological index of soil structural quality, namely visual type of aggregates index. After hand breaking of the soil for the visual soil evaluation, aggregates of 1-2 cm in diameter were described in terms of shape according to FAO (2006).

The abundance of rounded aggregates was considered as an indicator of ‘good’ quality for crop growth, and the abundance of sharper edge aggregates as ‘poor’ quality. The abundance of a certain type of aggregates was graded on a scale from 1 to 5, where 1 was the best (Table 7-2). This scale was based on the appearance of small aggregates as is considered in the key of VESS described by Guimarães et al. (2011).

Table 7-2 Criteria used to score the type of aggregates and soil structural quality.

Type of aggregate	Abundance	Score	Soil structural quality class
Rounded and crumbly	100% round	1	Good
Sub angular blocky	100% sub angular	2	Moderately good
Sub angular and angular blocky	> 50% sub angular	3	Moderate
Angular and sub angular blocky	> 50% angular	4	Moderately poor
Angular blocky	100% angular	5	Poor

7.2.5. Visual soil structural quality assessment based on aggregate stability

Soil structural quality was also assessed by evaluating the aggregate stability in water. Two methods were used: wet sieving, and visual evaluation of the degree of fragmentation and dispersion of aggregates. The wet sieving test was conducted using the Yoder method modified by Kemper and Rosenau (1986) as described in Chapter 3.

The visual assessment of the aggregate stability was conducted by visually evaluating the ability of the aggregate in maintaining its initial shape and size after immersion in water. The modified Emerson test described by Field et al. (1997) was used as reference. Per sampling point, 12 aggregates of 1-2 cm in diameter were placed in a ceramic plate with separated cavities. Each cavity was filled with deionized water so that the aggregates were completely immersed. Visual assessment of the degree of fragmentation and dispersion was made 5 and 10 min after immersion of the aggregates. This measurement was done both on aggregates at sampling water content, near field capacity, and air-dried.

A visual appraisal of the aggregates appearance was made according to the graphical scheme of aggregate stability test of Beste (1999) (Figure 7-1). An overall score between 0 and 2 was assigned. A score of 2 indicates no or slight fragmentation and dispersion, 1 indicates fragmentation in more than two fragments and moderate dispersion; and a score of 0 indicates strong dispersion and muddy water. Scores were individually given to each aggregate, and an average score was given afterwards for each sample.

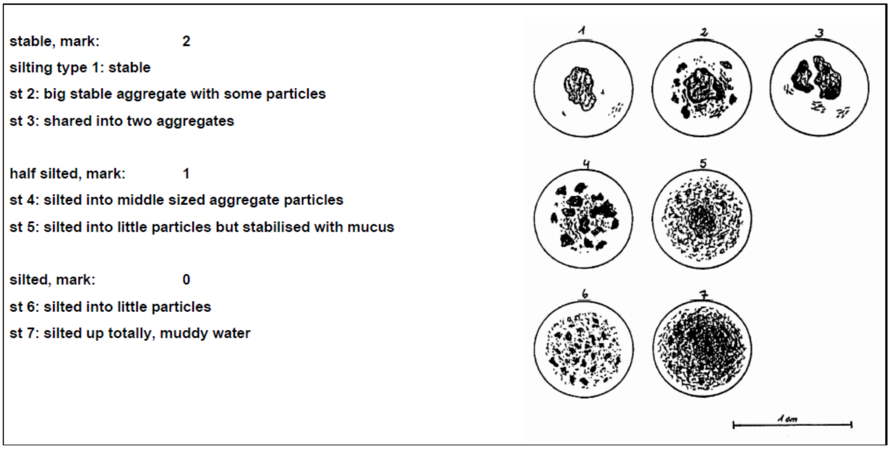


Figure 7-1 Visual assessment of the degree of fragmentation and dispersion of aggregates after immersion in water (Source: Beste, 1999).

7.2.6. Data analysis

In this research, a strip design (with six measurements taken randomly within strip) was conducted instead of a complete randomized block design. This was based on the spatial homogeneity of soil texture present on each study area (Saey et al., 2008). As spatial variability was taken into account, part of the variability determined by a randomized block design was also accounted for (Fagroud and Van Meirvenne, 2002). ANOVA was used as a tool to discuss significant differences in soil structural quality indicators. However, significant differences found have to be seen within the limitations of the experimental design and therefore are rather considered as tendencies. Nonparametric Kruskal-Wallis rank sum tests were conducted to detect statistical differences among land use in both soils for each measured variable. Further, Spearman correlation tests were conducted to measure the association between each pair of variables.

A Levene's test (Schultz, 1985) was applied to compare the variability in the scores between the different methods (VESS and VSA). The Levene's test was conducted by performing an analysis of variance on the CV with methods as a factor, and on the ratio of the absolute deviations associated with each observation from its respective group mean divided by the group mean. All tests were conducted at the 5% significance level. With the aim of assessing the tendency of the relationships between soil physical indicators and the visual examination of soil structural quality for both soils, analyses of simple regression were performed. All analyses were performed using the statistical package SPSS 17.0.

7.3. Results

7.3.1. Comparison of soil structural quality evaluated by visual examinations and by soil physical properties

In the sandy loam soil, the difference in scores of the visual examination methods, VSA and VESS, was statistically not significant ($P > 0.05$) under CM and PP. Both VSA and VESS methods indicated 'moderate' soil structural quality for crop growth and root penetration under both land uses (Table 7-3). Regarding the silt loam soil, both VSA and VESS were able to distinguish a poorer condition in terms of soil quality for the PP plot under permanent grazing. Significant differences were found between land uses for VSA and VESS scores ($0.01 < P < 0.05$).

Table 7-3 Soil structural quality of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP) using VSA and VESS. With VSA, lower values refer to poorer soil quality, whereas with VESS lower values indicate better soil structural quality

Soils	Land use	VSA						VESS	
		Soil structure		Soil porosity		Soil quality			
		Score	Class	Score	Class	Score	Class	Score	Class
Sandy loam	CM	1.5 a	Good	1.1 a	Moderate	31 a	Moderate	3.0 a	Moderate
		(0.3)		(0.2)		(2.9)		(0.8)	
	PP	1.7 a	Good	1.0 a	Moderate	32 a	Moderate	2.8 a	Moderate
		(0.4)		(0.0)		(1.4)		(0.5)	
Silt loam	CM	1.4 a	Moderate	1.2 a	Moderate	35 a	Moderate	2.7 a	Moderate
		(0.2)		(0.2)		(2.7)		(0.3)	
	PP	1.1 a	Moderate	1.0 a	Moderate	31 b	Moderate	3.4 b	Poor
		(0.3)		(0.0)		(1.6)		(0.1)	

Standard deviation for each index is given in parenthesis (±)
Values in a column followed by the same letter are not significantly different at $P > 0.05$

In the sandy loam soil, VESS revealed a higher variability (21.3%) than VSA (5.5%) ($P < 0.01$). Whereas, in the silt loam soil, differences in CV (VESS = 17.2%, VSA = 8.7%) were not found ($P > 0.05$). This suggests that in sandy soils, VSA is less sensitive for revealing slight spatial variation, in contrast with the silt loam soil for which both methods showed a response to differences in soil quality condition. Conversely, Spearman correlations indicated high and significant correlations between both methods (r = -0.83).

Results from VSA and VESS methods were compared to soil physical properties results (Table 7-4) in terms of soil quality class. Soil BD did not reflect the differences in soil quality ($P > 0.05$), among soils and land uses, shown by the visual field examination methods. BD values were lower than 1.63 Mg m^{-3} and 1.49 Mg m^{-3}, which are according to Pierce et al. (1983), critical values for adequate aeration and unlimited root elongation for sandy loam and silt loam, respectively.

When SOC was considered for comparison. Critical limits of SOC content established by the Soil Service of Belgium (Vanongeval et al., 2000) were used. The PP plot in the sandy loam had a SOC content within the target zone and in the silt loam the SOC was moderately high class content. The plots under CM were classified as moderately low (sandy loam) and low (silt loam) in SOC content. A value of 23 g kg^{-1} of SOC is considered the lower critical limit for maintaining a good soil structure in tilled soil (Greenland, 1981). The SOC values were higher in PP than CM ($0.01 < P < 0.05$) in both soils, which indicates better soil quality. This is distinct with respect to the soil quality of the visual examination results (VSA and VESS).

Table 7-4 Soil properties of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP)

Soil	Land use	SOC (g kg^{-1})	BD (Mg m^{-3})	TPV	MacP	MicP	AC	FC	PWP	PAWC
				(cm^3 cm^{-3})						
Sandy loam	CM	11.6 b	1.29 a	0.51 a	0.05 a	0.36 b	0.16 a	0.20	0.02	0.18 a
		(1.5)	(0.07)	(0.03)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
	PP	13.4 a	1.31 a	0.51 a	0.04 a	0.39 a	0.12 b	0.28	0.08	0.20 a
		(1.1)	(0.03)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.02)
Silt loam	CM	9.4 b	1.34 a	0.50 b	0.10 a	0.32 b	0.17 a	0.26	0.11	0.15 b
		(0.5)	(0.09)	(0.03)	(0.04)	(0.02)	(0.05)	(0.02)	(0.02)	(0.02)
	PP	27.8 a	1.25 a	0.55 a	0.02 b	0.51 a	0.04 b	0.45	0.15	0.31 a
		(4.1)	(0.04)	(0.02)	(0.01)	(0.01)	(0.01)	(0.02)	(0.03)	(0.04)

SOC = soil organic carbon, BD = bulk density, TPV = total pore volume, MacP = large macropores, MicP = micropores, AC = air capacity, FC = field capacity, PWP = permanent wilting point, PAWC = permanent available water capacity; Standard deviation for each soil property is given in parenthesis (±); Values in a column followed by the same letter are not significantly different at $\alpha = 0.05$ between land uses in a given soil.

Regarding the individual score for the most critical indicators of VSA method, i.e., soil structure and soil porosity, the best soil structure condition (higher score) was found in the sandy loam soil. Differences in visual structure and porosity conditions were not found among land uses under the different soils (Table 7-3). However, the lowest scores for soil structure and porosity were found in the PP with permanent grazing in the silt loam soil, which is in correspondence with the values of the soil porosity indicators. In this plot, values of MacP, MicP and AC (Table 7-4) felt in a 'poor' soil quality class based on the threshold value proposed by Reynolds et al. (2007). In contrast, in both soils and land uses the PAWC values were > 0.10 $m^3\ m^{-3}$, which can be considered as a 'good' quality for maximum root growth and adequate to store and provide water to plant roots (Reynolds et al., 2007).

7.3.2. Comparison of soil structural quality evaluated by visual type of aggregates index and by water flow

The abundance of a certain type of aggregates was tested as a new index of soil structural quality (Table 7-5). Subangular blocky aggregates were abundant in the sandy loam soil, but in 5 out of the 12 soil blocks evaluated aggregates with sharper edges and a firmer consistence were present in the second layer (5 to 20 cm) of the 20 cm soil blocks. The overall visual type of aggregates index score given to this soil, corresponded to a 'moderate' soil structural quality condition and no differences were found between land uses (P > 0.05). Most aggregates present in the silt loam soil were subangular blocky in shape, for both CM and PP land uses (P > 0.05), which correspond to a 'moderately good' soil quality. No-angular aggregates were found in the PP plot under permanent grazing in this soil, meaning that the visual type of aggregates index does not reveal the poorer condition described by the previous indicators in this plot.

Table 7-5 Soil structural quality based on the visual type of aggregates index of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP).

Soils	Land use	θ ($cm^3\ cm^{-3}$)	Aggregate form	Score	Class
Sandy loam	CM	0.21	Subangular and angular blocky	2.8 (1.2) a	Moderate
	PP	0.17	Subangular and angular blocky	2.8 (1.1) a	Moderate
Silt loam	CM	0.28	Subangular blocky	2.4 (0.3) a	Moderately good
	PP	0.30	Subangular blocky	2.3 (0.5) a	Moderately good

θ = volumetric soil water content at sampling
Standard deviation of the mean value is given in parenthesis (±)
Values in a column followed by the same letter are not significantly different at P > 0.05

The soil structural quality classes based on the visual type of aggregates index were compared to the water flow measurements. Despite not finding any significant differences in K_s ($P > 0.05$) between the land uses for both LP and TI measurements at the two sites (Figure 7-2), measurements in the sandy loam soil with LP displayed 'moderate' and 'moderately slow' permeability classes in CM and PP, respectively (NRCS, 2003). In the silt loam soil, K_s values in CM and PP were classified as 'moderately rapid' and 'moderate' permeability, respectively. This demonstrates that the aggregates with sharper edges and a firmer consistence found in the sandy loam soil could restrict the water flow. Regarding the K_s values estimated from TI measurements, the NRCS permeability classification is not appropriate since it was based on vertical flow (ring samples) while in TI there is also lateral flow.

Figure 7-3 shows, for both soils and land uses, a decreasing trend in K_h from the pressure head at -1 cm (corresponding with pores of 3 mm in diameter) to the pressure head at -10 cm (representing a pore size of 0.3 mm in diameter). In the sandy loam soil, K_h was higher for CM than for PP, whereas an opposite trend was observed in the silt loam soil. No significant differences were found between the land uses ($P > 0.05$), which correspond to the results from the visual type of aggregates index.

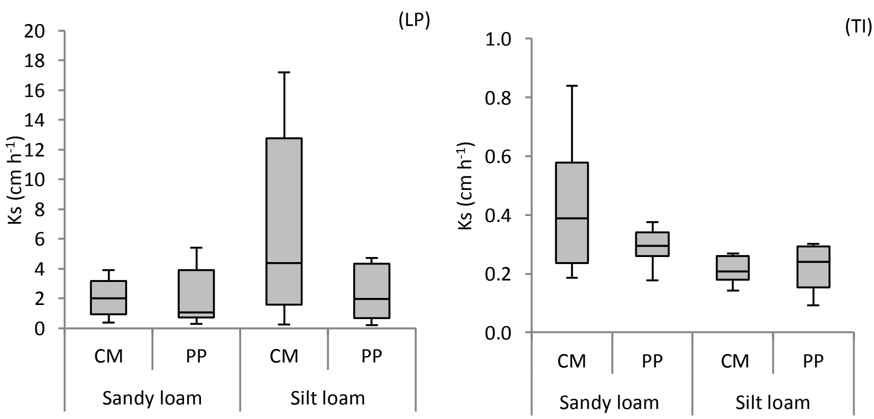


Figure 7-2 Saturated soil hydraulic conductivity (K_s) values of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP) obtained from the laboratory permeameter (LP) and the tension infiltrometer (TI) methods. Error bars indicate standard deviations. Values shown are based on 18 (LP) and 6 (TI) samples.

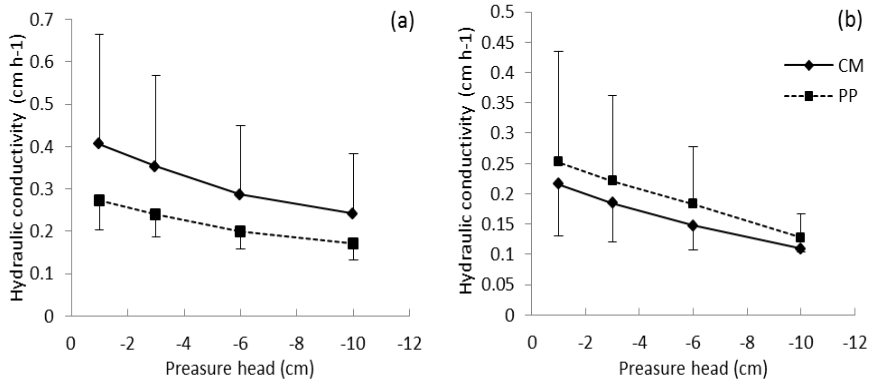


Figure 7-3 Geometric mean of unsaturated hydraulic conductivity values at pressure heads of -10, -6, -3 and -1 cm, obtained from six measurements with the tension infiltrometer for a sandy loam (a) and a silt loam (b) soil under cereal monoculture (CM) and permanent pasture (PP).

7.3.3. Comparison of soil structural quality evaluated by water aggregate stability

Aggregate stability was evaluated using the classical test of wet sieving and a visual examination method (Table 7-6). Concerning wet sieving, the reduction of MWD using fast wetting of air-dried aggregates of 1-2 mm in diameter was > 50% for CM and < 30% for PP for both soils. The wet sieving test showed that there was an effect of the land uses on aggregate stability for both soils. Aggregates from PP were more resistant to breakdown after wet sieving when fast wetting was applied ($P < 0.05$).

Table 7-6 Soil structural quality based on water aggregate stability of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP).

Soils	Land use	Visual assessment: Aggregates at sampling moisture Θ (cm^3 cm^{-3})	5 min	10 min	Class	Air-dried aggregates 5 min	10 min	Class	Wet sieving: MWD (mm)	Class
Sandy loam	CM	0.21	1.9	1.5 b	Mod-good	1.2	0.9 b	Mod- bad	0.46 b	Poor
			(0.1)	(0.4)		(0.5)	(0.5)		(0.1)	
	PP	0.17	2.0	2.0 a	Good	2.0	2.0 a	Good	0.83 a	Good
			(0.0)	(0.0)		(0.0)	(0.1)		(0.1)	
Silt loam	CM	0.28	1.7	1.5 b	Mod-good	0.6	0.2 b	Poor	0.40 b	Poor
			(0.3)	(0.3)		(0.5)	(0.2)		(0.1)	
	PP	0.30	2.0	2.0 a	Good	1.9	1.9 a	Good	1.0 a	Good
			(0.0)	(0.0)		(0.1)	(0.1)		(0.0)	

θ = volumetric soil water content at sampling; Mod = moderately; Standard deviation for each soil indicator is given in parenthesis (±); Values in a column followed by the same letter are not significantly different at α = 0.05.

Regarding the visual evaluation of aggregate stability, when field moist aggregates (near FC) were immersed in deionized water, no changes in type and size of aggregates were observed. On the contrary, when aggregates were air-dried, fragmentation of the aggregates and dispersion of particles were observed for both soils under CM ($P < 0.01$). Consequently, when air-dried aggregates were used, the soil structural quality of the sandy loam and silt loam soils under CM was visually classified as 'moderate' and 'poor', respectively.

These results reveal an effect of slaking, when the aggregates collapse because of entrapped air, resulting from poor pore arrangement and weak bonds. Conversely, PP for both soils resulted in 'good' soil structural quality by this measure, irrespective of the antecedent moisture status of the samples. Like the wet sieving test, the visual evaluation of aggregate stability was able to distinguish differences in soil structural quality between land uses in both soils. An example of the appearance of the aggregates after immersion in water is given in Figure 7-4.

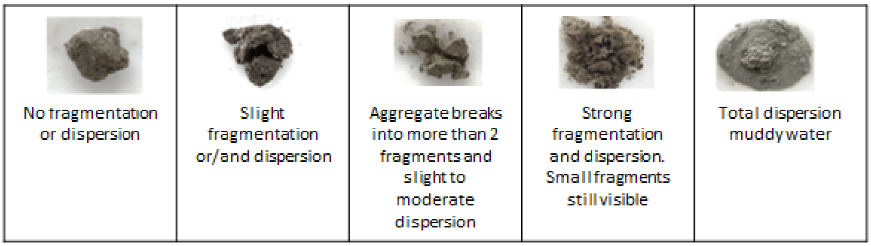


Figure 7-4 Appearance of soil aggregates after immersion in water. From left to right stable and unstable aggregates.

7.3.4. Relationships between morphological scores and values of soil physical and hydraulic properties

Besides searching for the similarities found between the morphological evaluations and the soil physical and hydraulic properties in classifying the soil structural quality of the soil, we also sought statistical relationships between them. Table 7-7 shows those regression equations that were significant at $\alpha = 0.05$, with soil physical and hydraulic properties as dependent variable and the scores obtained from the various visual examination methods as independent variable.

A relationship between VSA and BD was observed in sandy loam soil, with $R^2 = 0.50$. Relationships between VSA and SOC, MacP, MicP, AC, PAWC and MWD were observed in silt loam soil, with R^2 values ranging from 0.35 to 0.50. Whereas, VESS was only related to SOC ($R^2 = 0.51$), MicP ($R^2 = 0.47$), TPV ($R^2 = 0.47$), PAWC ($R^2 = 0.35$) and MWD ($R^2 = 0.47$). In the sandy loam soil, VESS was only related to K_h at different pressure heads (0, -1, -3 and -10 cm), with R^2 values ranging from 0.37 to 0.43. The individual scores given for the soil structure and the soil porosity according to the VSA method were not correlated with any of the soil physical and hydraulic properties.

The visual type of aggregates index was only related to K_h at different pressure heads in both soils. The strongest relationships were between the visual type of aggregates index and K_s estimated from TI measurements ($R^2 = 0.40$) in the sandy soil, and with K_h at -10 cm ($R^2 = 0.56$) in the silt loam soil. Although significant relationships ($P < 0.05$) were found between the morphological scores and the soil physical and hydraulic properties, R^2 values remained low and could only explain < 56% of the variation of the VSA, VESS and visual type of aggregate index scores of both the sandy loam and the silt loam soils. On the other hand, with regards to the visual score of the aggregate stability, strongest relationships were found with the soil physical and hydraulic properties. In the silt loam soil, there were significant relationships between the visual score of aggregate stability and SOC ($R^2 = 0.89$), MacP ($R^2 = 0.71$), MicP ($R^2 = 0.95$), TPV ($R^2 = 0.49$), AC ($R^2 = 0.80$), PAWC ($R^2 = 0.91$) and MWD ($R^2 = 0.94$). For the sandy loam soil relationships were evidenced with AC ($R^2 = 0.65$) and MWD ($R^2 = 0.59$), and with K_h at different pressure heads ($0.33 < R^2 < 0.43$).

7.4. Discussion

The visual examinations used in this dissertation, reflect the different conditions related to the complexity of the soil structure: i) VESS method in the silt loam soil was able to reveal the compaction present in the PP plot under permanent grazing; ii) the visual type of aggregates index indicated a poorer condition in the sandy soil, where a more angular type of aggregates was found; iii) the visual aggregate stability showed the effect of tillage on aggregate stability of CM. This is in accordance with Mueller et al. (2013) who showed the feasibility and reliability of visual examination methods such as VSA and VESS, for giving scores and classes characterizing the soil potential for cropping.

When numerical quantification of these visual examinations was used as a factor in the estimation of soil physical and hydraulic properties, simple relationships were found. These relationships suggest that for our soils a visual quality is associated with at least one quantitative quality. In the silt loam soil, the visual examinations were most related to properties such as SOC, PAWC, MWD and porosity, whereas in the sandy loam soil they were most associated with water flow properties (Table 7-7).

In the silt loam soil, the soil structural quality of the different plots was classified similarly by SOC (as an individual indicator) and water stability tests. Whereas a dissimilar classification was given by SOC when compared to VSA, VESS, MacP, MicP and AC. In this soil, the permanent presence of cattle on PP results in a constant addition of manure, which increases SOC content. But also in soil compaction from the cattle trampling that counteracted the possible positive effect of SOC on soil structure. This opposite trend has been also mentioned by Newell-Price et al. (2013). Results suggest that caution should be taken when using SOC as a sole soil quality indicator in some conditions, as is often suggested when deriving minimal data sets for soil quality evaluation (e.g. Shukla et al., 2006). On the other hand, morphological evaluations could give an immediate idea about properties that are time-consuming in laboratory measurements, such as PAWC, MicP and MacP. Subsequently, some inferences could be drawn for plant growth and agricultural practices.

The higher aggregate stability found in soils under PP ($P < 0.01$, Table 7-6) can be attributed to the presence of a higher density of roots (visually evaluated) and a higher SOC content, which can keep mineral particles together against destructive forces (Bronick and Lal, 2005).

Table 7-7 Relationships between soil physical and hydraulic properties and the visual examination of soil structural quality of a sandy loam and silt loam soils. These relationships are based on the 12 observation points at each soil.

Sandy loam Soil			Silt loam soil		
Equation	R^2	P	Equation	R^2	P
BD= -0.0131 (VSA) + 1.7266	0.53	0.00	SOC= -0.232 (VSA) + 9.53	0.45	0.01
K_s (TI)= -0.50 (VESS) + 0.3239	0.43	0.02	MacP= 0.01 (VSA) – 0.281	0.35	0.04
$K_{(h=-1cm)}$= -0.476 (VESS) + 0.18	0.41	0.02	MicP= - 0.023 (VSA) + 1.165	0.45	0.01
$K_{(h=-3cm)}$= -0.4301 (VESS) – 0.0724	0.38	0.03	AC= 0.018 (VSA) – 0.48	0.42	0.02
$K_{(h=-10cm)}$ = -0.3673 (VESS) – 0.5927	0.37	0.03	PAWC= -0.02 (VSA) + 0.877	0.43	0.02
K_s (TI)= 0.2721 (Tagg) – 1.9808	0.40	0.02	MWD= -0.079 (VSA) + 3.304	0.50	0.01
$K_{(h=-1cm)}$= -0.26 (Tagg) – 0.448	0.39	0.02	SOC= 1.364 (VESS) – 2.265	0.51	0.00
$K_{(h=-3cm)}$= -0.234 (Tagg) – 0.6468	0.36	0.03	MicP= 0.128 (VESS) + 0.03	0.47	0.01
K_s (TI)= -0.4258 (VSt) – 0.5018	0.33	0.03	TPV= 0.051 (VESS) + 0.366	0.47	0.00
$K_{(h=-1cm)}$= -0.434 (VSt) – 0.553	0.37	0.03	PAWC= 0.10 (VESS) – 0.077	0.35	0.03
$K_{(h=-3cm)}$= -0.3992 (VSt) – 0.7314	0.38	0.03	MWD= 0.422 (VESS) – 0.572	0.47	0.01
$K_{(h=-6cm)}$= -0.394 (VSt) – 0.92	0.41	0.02	$K_{(h=-3cm)}$= -0.659 (Tyagg) – 0.146	0.35	0.03
$K_{(h=-10cm)}$= -0.3747 (VSt) – 1.106	0.43	0.02	$K_{(h=-6cm)}$= -0.602 (Tyagg) – 0.459	0.41	0.02
AC= -0.0294 (VSt) + 0.1823	0.65	0.00	$K_{(h=-10cm)}$= -0.434 (Tyagg) – 1.144	0.56	0.00
MWD= 0.2633 (VSt) + 0.2641	0.59	0.00	SOC= 1.061 (VSt) + 0.739	0.89	0.00
			MacP= -0.047 (VSt) + 0.107	0.71	0.00
			MicP= 0.107 (VSt) + 0.304	0.95	0.00
			TPV= 0.030 (VSt) + 0.49	0.49	0.01
			AC= -0.0775 (VSt) + 0.187	0.80	0.00
			PAWC= 0.0939 (VSt) + 0.129	0.91	0.00
			MWD= 0.345 (VSt) + 0.3372	0.94	0.00

P-value; BD = bulk density (Mg m^{-3}); K_s (TI) = $\log_{10}$ of saturated hydraulic conductivity (cm h^{-1}) estimated from tension infiltrometer data; K_h = $\log_{10}$ of unsaturated hydraulic conductivity (cm h^{-1}) determined by tension infiltrometer; AC = air capacity (cm^3 cm^{-3}); MWD = mean weight diameter (mm); SOC = soil organic carbon (g kg^{-1}); MacP = large macropores (cm^3 cm^{-3}); MicP = micropores (cm^3 cm^{-3}); PAWC = plant available water capacity (cm^3 cm^{-3}); TPV = total pores volume (cm^3 cm^{-3}); VSA = overall visual soil assessment score; VESS = overall visual evaluation of soil structure score; Tyagg = visual type of aggregate index score; VSt = visual evaluation of aggregate stability score (air-dried aggregates).

Although several authors have mentioned relationships between the overall score of VSA and VESS with soil properties under different conditions (Shepherd, 2000, 2009; Mueller et al., 2009; Guimarães et al., 2013; Mueller et al., 2013), some disadvantages of these methods have been mentioned. For instance, Newell-Price et al. (2013) have appointed some weaknesses of using VSA in grassland systems, where distinct contrasting layers can be found, ensuring that the scores of the poorest layer within the topsoil could provide a better indication of physical soil quality than a weighted average score for the whole topsoil layer. This could be considered in the case of the sandy loam soil, where unfavourable soil structure (angular aggregates) was only described in the sub layer present in some of the blocks of soil.

The relationships between the visual type of aggregates index and the soil physical and hydraulic properties showed that the water flow was facilitated when a higher amount of rounded aggregates was present in both the sandy loam and the silt loam soils. Sandy soils are expected to have a higher saturated hydraulic conductivity when no limitations of flow are present based on the visual type of aggregate index. Generally, well-structured soils with rounded aggregates tend to drain more easily than soils with a poor structure or angular aggregates (Hu et al., 2009). According to Alvarez et al. (2012) the lower roughness of the aggregates results from the pressure exerted by farming and mutual friction.

In this Chapter, as was mentioned before, the unfavourable soil structure under the silt loam soil was not in correspondence with the visual type of aggregates index. The interaction between the root system and the higher SOC in this plot could have had a higher effect on the shape of the aggregates.

Morphological characteristics evaluated in the field have been referred to as important tools in the classification of the soil K_s values, therefore they can be considered as factors to be incorporated into hydraulic models (Ingelmo et al., 2011). Results showed the existence of single relationships between soil hydraulic conductivity measurements using TI and different soil properties. These relationships confirm that the quantification of soil morphology can be incorporated as soil structural information into the hydraulic models. However, limitations are presented when there is an absence of a proper means for quantifying soil morphology (Lin et al., 1999a).

Classification criteria have to be well defined before quantifying morphological characteristics; hence the VSA and VESS protocols, visual type of aggregates index and visual aggregate stability are possible alternatives. Note that the relations between morphological test scores and hydraulic conductivity were dominantly present in the sandy soil, which suggests a more uniform pore system (homogeneous pore size distribution) in the sandy loam soil compared to the silt loam soil.

Moreover, K_s measured with LP was not correlated with any of the morphological evaluations, most probably because of the high variability in K_s. Differences in K_s using LP, and K_h using TI demonstrate the variation in values according to the method used (Verbist et al., 2013), but also the importance of the sizes of the pores participating in the water flow. Our results are supported by those of Reynolds et al. (2000) and Verbist et al. (2013) who found that TI values are significantly lower than any other method. K_s values estimated from the TI measurements showed lower variability (57%) than LP values (125%).

When determining K_s from TI measurements, only water flow in pores smaller than 3 mm in diameter is considered, whereas in case of LP all pores of the soil medium in the core samples contribute to water flow, including the larger pores due to burrows made by earthworms, which typically show a high variability (Hu et al., 2009). Macroporosity is an integral part of soil structure, which is deficiently reflected by single soil physical and hydraulic properties. Therefore, morphological indices of soil structure are crucial in characterizing the hydraulic behaviour in the MacP flow region (Lin et al., 1999b).

Caution is required in using these relationships, which were developed under the evaluated conditions, to other soil conditions because of the site-specific relationships found and the limited data set used. However, it must be emphasized that those could be used as support for the validity of the use of the visual examination for evaluating soil structural quality. Evaluation of root density and type of soil organic matter present in the soils should be included in further studies to better understand the relationships found.

7.5. Conclusions

Moderate to good relationships were found between visual examinations and values of soil physical and hydraulic properties. This supports their use as reliable semi-quantitative methods to assess soil structural quality. The VSA, the VESS, the visual type of aggregates index and the visual assessment of aggregate stability could be considered as encouraging visual estimators of soil physical properties. Because of the differences in the relationships demonstrated in this study for soils under contrasting texture and land use, further studies in correlating morphological evaluations and quantitative soil physical properties could be conducted in other soil textures and management systems. Finally, two aspects should be emphasized: i) relationships between visual examinations and hydrophysical properties are promising; therefore morphological properties could be worth considering for predicting hydrophysical soil properties; and ii) from the dissimilarities in terms of soil quality found between the visual examination of soil structure and the amount of SOC, SOC should be used cautiously as a sole indicator for soil structural quality as has been proposed in literature, because SOC *per se* is not always well related to the soil structural quality classes.

Chapter 8

Assessing changes in soil structural quality

8.1. Introduction

In soil structure quality assessment, an important consideration is the dynamic nature and the spatial variability of the soil structure (Lal and Shukla, 2004). The attributes used when observing soil structure at any given time reflect the net effect of numerous interacting factors which may change at any moment. Therefore, soil structure variation is a key point to consider for evaluating soil quality. Soil structure is strongly affected by changes in climate, biological activity, land use and soil management practices among others (Hillel, 1998). In croplands, new conditions for soil structure dynamics are created by the diversification of tillage practices (Roger-Estrade et al., 2009).

Tillage practices modify soil structural quality and hence affect crop production and the environment (Batey and McKenzie, 2006). Soil tillage usually decreases aggregate size and stability, water content, infiltration rate and increases BD (Alvarez and Steinbach, 2009), as a result of soil compaction through compression or smearing (Scholefield et al., 1985). In contrast, no-till management promotes conditions for aggregate formation related to greater SOM accumulation (Abid and Lal, 2008). When soils are exposed to changes in land use, the soil's physical and biological properties are affected by changes in SOM quality (amount and composition) and by intensive soil management (Pulido Moncada et al., 2010). For instance, in a study conducted on a group of soils from different land uses such as crop, pasture and forest, Dexter and Horn (1988) demonstrated that soil structure is strongly influenced by land use, and hence directly affects soil workability.

As soil structure is one of the indicators most frequently evaluated to determine changes in soil quality, Ball et al. (2007) suggested including elements of soil properties such as form, stability and resilience when evaluating soil structural quality. To embrace such an approach and the complexity of soil structure, multiple indicators are often used to provide a more complete measurement of soil quality. In this sense, visual soil examinations involve the assessment of different soil structure-related indicators (e.g. shape and strength of aggregates, macro porosity, root development, soil fragment size distribution, aggregate stability, and soil texture) that are summarised in a score. On the other hand, the interpretation of laboratory measurements (indirect evaluation of soil structure) in conjunction with visual examinations could provide a more integrated assessment of soil structure dynamics as was demonstrated in Chapters 6 and 7.

The objective of this Chapter was to evaluate whether visual examination methods are sensitive enough to detect significant changes in soil structural quality related to soil management over a given sampling interval, and to select a minimum data set of indicators for soil structure changes assessment by interpreting and integrating visual examination and laboratory measurements. This Chapter presents results of a characterization of the effect of CM (under conventional tillage) and PP on soil structural quality in a sandy loam and a silt loam soil, with a focus on morphological parameters visually evaluated in an agricultural cycle, before flowering and after harvesting.

8.2. Materials and Methods

8.2.1. Sites and soil sampling

The survey was conducted in the sandy loam (B1) and the silt loam soil (B3) located in the Flanders Region of Belgium, which were described in Chapter 2. Characteristics of the two plots sampled in both soils are shown in Table 7-1 (Chapter 7). In this Chapter, the soil structural quality was evaluated at one sampling interval in an agricultural cycle. The first evaluation was conducted in August 2012, which corresponds to the period before flowering of the maize on the sandy loam and the winter wheat on the silt loam. The second evaluation was conducted in November 2012, after cereal harvesting. For the first period of evaluation all samples were taken as described in Materials and Methods Section of Chapter 3. For the second evaluation (after harvesting), in the plots under CM, same number of samples were taken within the zone under the wheel track. Description of the tillage implements used in the CM plots is given in Chapter 2. In B1, the harvesting is conducted by using combine harvesters. Standard tires are used in dry condition, but when wet 3-wheel tracks are utilised. In the case of B3, harvesting is conducted only with combine harvester with wheels 48 cm wide and 3 meters apart.

8.2.2. Soil measurements

Soil structure assessment was conducted by structural form (VESS, VSA, the visual type of the aggregates index) and aggregate stability (visual assessment of aggregate stability and wet sieving) evaluation using the methods described in the Chapter 7. From the indicators listed in the score card of VSA given by Shepherd (2009) only soil texture, soil structure, soil porosity, number and colour of soil mottles, soil colour, earthworms, and soil smell were evaluated in this Chapter. The ratings for each indicator were also weighted and summed, resulting in a final score for the soil structural quality (maximum score 36, soils with score < 18 were considered having a bad soil structural quality). Because of the rather low temperatures in November 2012, the second evaluation was conducted on smaller soil block samples (15x10x12 cm) in the laboratory and not in the field. The results were not affected by the size of the sample as observed and confirmed by previous tests in the field.

For a more integrated assessment of soil structure, results from structural form description and aggregate stability were interpreted and integrated with soil physical properties such as BD, MacP (large macropores), AC, PAWC, SOC, air and water permeability. These properties were measured as described in Chapter 7. Air permeability (K_a) was determined on the 100 cm^3 core samples. The method used was based on the steady-state method proposed by Grover (1955), where K_a was measured in a core enclosed within two metal cylinders. The core sample was enclosed by a rubber stopper at the bottom of a cylinder to prevent leakage of air from the apparatus. Air contained in the metal cylinder flows through the soil sample after loosening the counterweight. The flow readings were taken from timing the fall of the air cylinder over a given distance. Measurements were repeated twice for each sample. The soil samples were previously equilibrated to -10 kPa matric potential. The following equation was used to determine K_a.

$$K_a = \frac{q \eta_{air} l_{sample}}{\Delta P} \quad (8\text{-}1)$$

where K_a is the air permeability (μm^2), q is the flux ($m^3\ m^{-2}\ s^{-1}$), η_{air} is the air viscosity (Pa s or kg $m^{-1}\ s^{-1}$), l_{sample} is the length of the soil sample (m), and ΔP is the pressure head difference across the sample (m).

8.2.3. Data analysis

A multi-factor analysis of variance (ANOVA) was conducted to detect statistical differences among the land uses and the two evaluation periods in both soils for each measured property. Further, Spearman correlation test was conducted between each pair of variables. All tests were conducted at the 5% significance level. These analyses were performed using the statistical package SPSS (version 17.0, SPSS Inc., USA).

8.3. Results

8.3.1. Dynamics of soil structure within an agricultural cycle: structural form assessment

The results for structural form assessment by VSA and VESS methods are shown in Table 8-1. For evaluating the quality of the soil structure by VSA in the sandy loam soil, ANOVA results qualify the F-ratio as significant at a probability level of 0.01 for land use x evaluation period. The best soil structural quality was found for PP in August before flowering and the worst for CM, in November after harvesting of maize. No differences were found between land uses for VSA-soil structure (P > 0.05), expressed in terms of size distribution of soil fragments, though differences were observed between the two evaluation periods (P < 0.01) for both land uses.

VSA-porosity was affected by the period of evaluation and land use (P < 0.01), with a lower value under CM after harvesting. The lower the value obtained using VSA, the lower the quality of the condition evaluated. This suggests that a decrease in soil structural quality of sandy loam over the agricultural cycle was the result of the formation of coarse fragments with low porosity due to the re-arrangement of the particles, which indicates soil compaction. On the other hand, when VESS was used, the effect of the two land use and changes in soil structural quality over the agricultural cycle could not be differentiated on the sandy loam soil.

Regarding the silt loam soil, significant interaction between land use and evaluation periods was found on scores from VSA-soil structure, VSA-soil porosity, and VSA-soil quality (P < 0.01), but not for VESS scores (P > 0.05). With the VSA approach, the worst quality of soil structure and soil porosity was found under CM after harvesting. VESS score did not respond to slight changes of soil structural quality over the agricultural cycle, but was able to discriminate between the two land uses (P < 0.01) (Table 8-1). The highest score, which indicates the poorer soil quality, was found under PP in August but under CM in November. These results suggest that there was a development of soil compaction under CM after harvesting. Two types of aggregates were observed in all plots during the study periods, subangular blocky and angular blocky corresponding within round and sharper edged aggregates, respectively (Table 8-2). In the sandy loam soil, there was no effect of land use or evaluation period on the visual type of aggregates index (P > 0.05). In this soil, the abundant aggregate type was subangular blocky over angular blocky. In contrast, the silt loam soil, showed changes (P < 0.05) in aggregate type for land use x evaluation period. In silt loam soil was observed a higher number of sharper edge aggregates after harvesting than before flowering under CM plot.

8.3.2. Aggregate stability changes within an agricultural cycle

Results of visual assessment of aggregate stability showed that for sandy loam no interaction was found between land use and evaluation periods (Table 8-3). In case of field moist aggregates no significant differences were found between evaluation periods (P > 0.05), but CM showed significantly lower aggregate stability compared to PP (P < 0.01) at each evaluation period. When air-dried aggregates were used, a decrease of aggregate stability over the agricultural cycle was obtained (P < 0.01). The effect of land use was also evident on air-dried aggregates showing the lowest aggregate stability under CM (P < 0.01). The wet sieving test also showed a significant higher stability of the 1-2 mm aggregates under PP of the sandy loam soil (P < 0.01) (Table 8-3). But higher values of MWD were found for both land uses after harvesting, which corresponds neither with the results from the visual assessment of aggregate stability nor with those from VSA.

Table 8-1 Visual assessment of the soil structural quality before flowering and after harvesting based on the visual soil assessment (VSA) and the visual evaluation of soil structure (VESS) examinations of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP). With VSA, lower values refer to poorer soil quality, whereas with VESS lower values indicate better soil quality.

		VSA, soil structure score[a]			VSA, soil porosity score[a]			VSA, final score[b]			VESS score[c]		
Soils	Land use	Before flowering	After harvesting	*Interaction*	Before flowering	After harvesting	*Interaction*	Before flowering	After harvesting	*Interaction*	Before flowering	After harvesting	*Interaction*
Sandy loam	CM	1.5 aA (0.3)	0.9 bA (0.3)	NS	1.1 A (0.2)	0.6 B (0.2)	P < 0.01	20 AB (1.9)	15 C (0.7)	P < 0.01	3.0 (0.8)	3.4 (0.2)	NS
	PP	1.7 aA (0.4)	1.3 bA (0.2)		1.0 AB (0.0)	1.1 A (0.3)		21 A (1.1)	19 B (2.0)		2.8 (0.5)	2.6 (0.4)	
Silt loam	CM	1.4 A (0.2)	0.6 B (0.3)	P < 0.01	1.2 A (0.2)	0.6 B (0.2)	P < 0.01	24 A (1.5)	17 C (1.1)	P < 0.01	2.7 aB (0.3)	3.8 aA (0.0)	NS
	PP	1.1 AB (0.3)	1.2 A (0.2)		1.0 A (0.0)	0.9 AB (0.2)		24 A (1.1)	20 B (1.5)		3.4 aA (0.1)	3.3 aB (0.2)	

[a] 0 (poor), 1 (moderate), 2 (good).
[b] < 18 (poor), 18-36 (moderate-good).
[c] 1-3 (good), 3-4 (moderate), 4-5 (poor).
Standard deviation for each soil indicator is given in parenthesis (±).
When interaction between land uses and evaluation periods is not significant (NS) then: values in a row followed by the same lowercase letters indicate no significant differences between evaluation periods (P > 0.05); and values in a column followed by the same uppercase letters indicate no significant differences between land uses (P > 0.05).
When interaction between land uses and evaluation periods is significant then values followed by the same uppercase letters indicate no significant differences between the combination groups.

Table 8-2 Soil structural quality over an agricultural cycle (before flowering and after harvesting) based on aggregate forms in a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP).

Soils	Land use	Water content (θ)		Type of aggregate		Score*		*Interaction*
		Before flowering	After harvesting	Before flowering	After harvesting	Before flowering	After harvesting	
Sandy loam	CM	0.21	0.29	Subangular and angular blocky	Subangular and angular blocky	2.8 (1.2)	3.2 (0.9)	NS
	PP	0.17	0.30	Subangular and angular blocky	Subangular blocky	2.8 (1.3)	2.3 (0.9)	
Silt loam	CM	0.28	0.30	Subangular blocky	Angular and subangular blocky	2.0 B (0.2)	4.3 A (0.4)	P < 0.05
	PP	0.30	0.44	Subangular blocky	Subangular and angular blocky	2.3 B (0.5)	3.7 A (0.8)	

* Lower values indicate better soil quality
Subangular and angular blocky = indicates abundance of subangular aggregates over angular aggregates
Angular and subangular blocky = indicates abundance of angular aggregates over subangular aggregates
θ = volumetric soil water content (m^3 m^{-3})
Standard deviation for each score is given in parenthesis (±)
NS = no significant differences
When interaction between land uses and evaluation periods is significant then values followed by the same uppercase letters indicate no significant differences between the combination groups.

Table 8-3 Soil structural quality over an agricultural cycle (before flowering and after harvesting) based on water aggregate stability of a sandy loam and a silt loam soil under cereal monoculture (CM) and permanent pasture (PP).

Soils	Land use	Visual assessment of aggregate stability*						Wet sieving		
		Field moist aggregates			Air-dried aggregates			Mean weight diameter (mm)		
		Score		*Interaction*	Score		*Interaction*	Before flowering	After harvesting	*Interaction*
		Before flowering	After harvesting		Before flowering	After harvesting				
Sandy loam	CM	1.5 aB	1.5 aB	NS	0.9 aB	0.0 bB	NS	0.46 bB	0.73 aB	NS
		(0.4)	(0.2)		(0.5)	(0.1)		(0.10)	(0.13)	
	PP	2.0 aA	1.7 aA		2.0 aA	1.2 bA		0.83 bA	0.94 aA	
		(0.0)	(0.2)		(0.1)	(0.5)		(0.11)	(0.04)	
Silt loam	CM	1.5 B	1.8 AB	P < 0.01	0.2 C	0.0 C	P < 0.01	0.40 aB	0.45 aB	NS
		(0.3)	(0.2)		(0.2)	(0.0)		(0.08)	(0.07)	
	PP	2.0 A	1.9 A		1.9 A	0.7 B		1.0 aA	0.99 aA	
		(0.0)	(0.2)		(0.1)	(0.5)		(0.05)	(0.05)	

* Higher values indicate better soil structural quality
See Table 2 for volumetric soil water content (m^3 m^{-3}) at the sampling moment
Standard deviation for each soil indicator is given in parenthesis (±)
When interaction between land uses and evaluation periods is not significant (NS) then: values in a row followed by the same lowercase letters indicate no significant differences between evaluation periods (P > 0.05); and values in a column followed by the same uppercase letter indicate no significant differences between land uses (P > 0.05)
When interaction between land uses and evaluation periods is significant then values followed by the same uppercase letters indicate no significant differences between the combination groups.

Regarding the silt loam, the visual stability in water of the aggregates differs between land uses with respect to the evaluation periods (Table 8-3). Field moist aggregates were visually less stable after water immersion, under CM before flowering ($P < 0.01$). But when aggregates were air-dried, aggregate disruption was significantly higher under CM at both evaluation periods ($P < 0.01$). The wet sieving test showed that for the silt loam soil, no changes over the agricultural cycle were found in any of the plots. Anyhow, consistently lower aggregate stability, in terms of MWD, was observed under CM as compared to PP ($P < 0.05$).

8.3.3. Indirect evaluation of soil structure changes within an agricultural cycle

The decline of the soil structural quality observed (structural form and aggregate stability) over the agricultural cycle under CM was not confirmed by the results from other soil physical properties (BD, AC, MacP and PAWC) evaluated in the laboratory on the sandy loam soil. No significant differences were found for any of these soil properties ($P > 0.05$), neither between land uses nor between periods of evaluation, except for the K_s, which showed that there was a higher conductivity when the soil was ploughed (CM before flowering, Figure 8-1).

In contrast to the sandy loam soil, deterioration of the soil structure over the agricultural cycle under CM revealed by VSA, type of aggregate and aggregate stability was supported by the soil physical properties results on the silt loam soil. Under CM, there was a higher BD and a lower AC and MacP after harvesting, and a markedly higher K_s, MacP and AC before flowering (Figure 8-1). This confirms a better initial quality of the soil structure before flowering under CM and the formation of soil compaction after harvesting. As regards PAWC, the highest value was obtained under PP plot in August.

In the sandy loam soil, SOC was affected by the land use and evaluation period. The highest value of SOC was obtained under PP in November ($P > 0.01$) (Figure 8-1). In the silt loam soil, no SOC content differences were found over the agricultural cycle ($P > 0.05$), though higher values were obtained under PP at both periods as compared to CM ($P < 0.01$) (Figure 8-1).

K_a, at -10 kPa matric potential, in CM had an average of 41.68 (± 29.28) μm^2 and PP of 72.77 (±41.15) μm^2 in the sandy loam soil with no significant differences between them ($P > 0.05$). In the silt loam soil significant differences in K_a ($P < 0.05$) were found between CM (0.37 ± 0.26 μm^2) and PP plot (2.84 ±2.14 μm^2). Overall, the results were in line with those obtained for VSA, VSA-porosity, and visual aggregate stability in both soils, PP > CM in terms of soil structural quality.

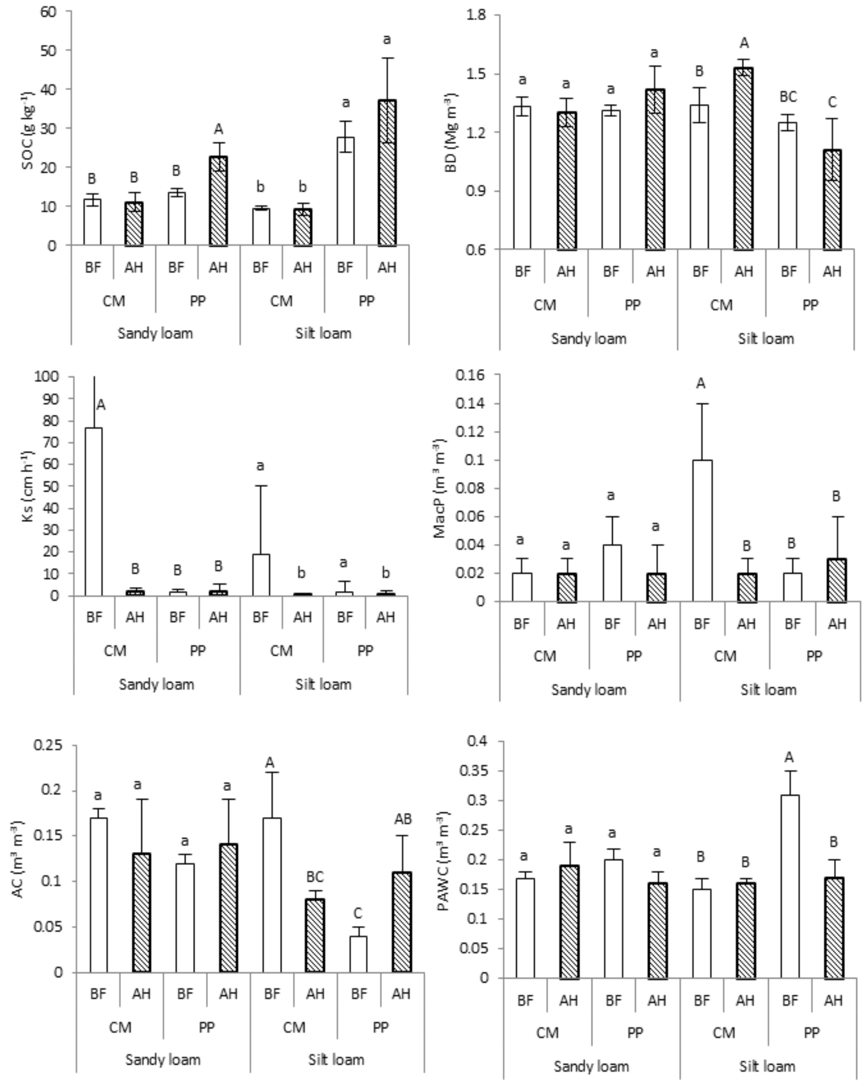


Figure 8-1 Mean values of soil properties among land uses and evaluation periods in a sandy loam and a silt loam soil. CM = cereal monoculture, PP = permanent pasture, BF = first evaluation before cereal flowering, AH = second evaluation after harvesting, SOC = soil organic carbon, BD = bulk density, K_s = saturated soil hydraulic conductivity, MacP = large macropores, AC = air capacity, PAWC = plant available water content. Error bars indicate standard deviations; same letter indicates no significant differences between evaluation periods and land uses ($P > 0.05$). Lowercase letters indicate differences between land uses, and uppercase letters indicate interaction between land use and evaluation periods.

8.4. Discussion

The changes in soil structural quality over the agricultural cycle under CM, where conventional agricultural practices in terms of tillage and harvesting was applied, are not surprising, as the soil might benefit from ploughing in the first stage of the crop cycle. But afterwards the soil is undergoing detrimental changes due to the use of harvesting machinery. Pagliai et al. (2004) mentioned that soil preparation before sowing can loosen the soil compaction resulting in a better initial quality, but with time and intensive use of machines, the deterioration of soil structure will intensify and will not allow a high sustainable crop production.

Soil compaction was visually evaluated (structural form and aggregate stability) after harvesting for both soils under CM, but more markedly in the silt loam soil. Results showed that assessing soil structural quality using structural form description gives reliable information on the degree of compaction on the soil surface after harvesting as was illustrated by Batey (2009) and Guimarães et al. (2013).

Discrepancy was found between VSA and VESS in detecting changes of soil structural quality over the agricultural cycle. Despite VESS being proven to be an efficient methodology for assessing soil physical quality in different soils (Guimarães et al., 2013; Munkholm et al., 2013), our results neither corresponded with those found with VSA nor with those from previous VESS studies on the effect of tillage on temperate soils (Garbout et al., 2013; Munkholm et al., 2013). Askari et al. (2013) using VESS for evaluating soil structural quality under different arable management systems commented that although VESS method worked well in a wide range of soils, difficulties in the applicability of the method were present on fine textured soils (silty clay). In this Chapter, results suggest that complications are also expected in coarse textured soils.

Although there was discrepancy between VSA and VESS, the degradation of the soil structure over time under CM was validated by the visual type of aggregates index only in the silt loam soil. In addition to, correlations were found between the visual type of aggregates index and the other soil physical properties such as K_s (r = -0.68), and MacP (r = -0.70). Although no relationship was found between the type of aggregate and BD and AC (Table 8-4), it can be seen from Figure 8-1 that, for the silt loam soil there was a higher BD and a lower AC when angular blocky aggregates were dominant in CM after harvesting.

In relation to K_a, values of this property were distinctly larger in the sandy loam than in the silt loam soil, indicating presence of larger or more continuous MacP in sandy loam associated with its configuration of particles (Dawidowski and Koolen, 1987). The K_a value obtained under CM of the silt loam soil was < 1 μm^2, a value that has been used as a reference for aeration restriction (McQueen and Shepherd, 2002). This suggests that soil structure deformation decreases the conductivity of soil pores (McQueen and Shepherd, 2002; Guimarães et al., 2013). Figure 8-2 shows that the type of aggregate scores was related to log K_a values (R^2 = 0.38, $P < 0.01$). This evidences that sharper aggregates result in lower K_a whereas rounded aggregates in higher, which hence confirms the link of soil management with changes in structural form (Alvarez et al., 2012), which at the same time demonstrates the dynamic nature of the soil structure in changing its form and consequently its arrangement.

The visualized decrease in aggregate stability over the agricultural cycle under CM (P > 0.01, Table 8-3), confirms the decline of soil structural quality showed by VSA and type of aggregate. When land use was considered, a higher aggregate stability was detected in the PP plots compared to CM under both soils. This can be related to the presence of a higher root density, which holds soil particles together, but also to the combination of the higher SOC content related to an increased vegetation residue level (Six et al., 2004).

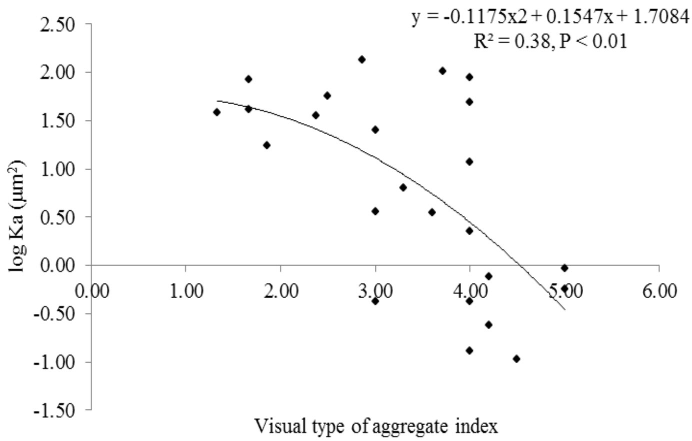


Figure 8-2 Relationship between the visual type of aggregates index and the air permeability (log K_a). Dataset comprises both sandy loam and silt loam soil values.

On the other hand, the disagreements found between visual aggregate stability and wet sieving results over the agricultural cycle in the sandy loam soil can be explained by the differences in aggregate sizes. In a study conducted on a typical Danish sandy loam soil, Daraghmeh et al. (2009) found that the fraction of aggregates > 2 mm decreased from initial high values to low values over time during an agricultural year, with an opposite trend in the fraction of 1-2 mm aggregates. They attributed the results to two factors: i) larger aggregates are thought to have more failure zones compared with 1-2 mm aggregates and may therefore be more prone to slaking upon wetting and ii) air drying pre-treatment prior to wetting decreases the stability of large aggregates and increase the stability of 1-2 mm aggregates.

Table 8-4 Correlation matrix (Spearman r) of the structural form, aggregate stability and soil physical properties as indicators of soil structural quality

		VSA	VSAst	VSAPor	VESS	Tyagg	VSt-FC	VSt-dry	K_s	SOC	BD	MacP	AC	PAWC
Sandy loam	K_s	0.09	0.07	0.37	0.18	-0.06	-0.24	-0.19	1					
	SOC	0.10	0.04	0.35	0.06	-0.31	0.35	0.40	-0.21	1				
	BD	0.17	0.12	0.18	0.01	-0.02	0.03	0.08	-0.03	0.25	1			
	MacP	0.31	0.33	0.21	-0.01	-0.28	0.22	0.23	0.1	0.37	-0.03	1		
	AC	-0.03	0.04	0.18	-0.02	-0.34	-0.28	-0.29	0.67**	-0.24	-0.30	0.42*	1	
	PAWC	0.09	-0.09	-0.31	-0.1	0.36	0.26	0.24	-0.39	-0.01	-0.05	-0.32	-0.59**	1
	MWD	-0.07	-0.11	0.05	-0.2	-0.38	0.07	0.19	-0.63**	0.72**	0.01	0.01	-0.42*	0.02
Silt loam	K_s	0.69**	0.46*	0.60**	0.07	-0.68**	-0.25	0.3	1					
	SOC	0.17	0.22	0.27	0.67**	-0.10	0.49*	0.67**	0.08	1				
	BD	-0.28	-0.42*	-0.36	-0.51**	0.31	-0.27	-0.59**	-0.18	-0.77**	1			
	MacP	0.60**	0.53**	0.65**	-0.14	-0.70**	-0.26	0.2	0.61**	0.03	-0.38	1		
	AC	-0.07	0.25	0.14	-0.38	-0.06	-0.45*	-0.49*	0.17	-0.24	-0.04	0.57**	1	
	PAWC	0.21	-0.07	-0.05	0.37	-0.09	0.23	0.52**	-0.07	0.27	-0.12	-0.38	-0.87**	1
	MWD	0.10	0.04	0.14	0.48*	-0.12	0.68**	0.69**	-0.1	0.72**	0.01	0.01	-0.42*	0.02

VSA = visual soil assessment, VSAst = visual assessment of soil structure by VSA protocol, VSAPor = visual assessment of soil porosity by VSA protocol, VESS = visual evaluation of soil structure; Tyagg = visual type of aggregate index; VSt-FC = visual evaluation of aggregate stability (field moist aggregates), VSt-dry = visual evaluation of aggregate stability (air-dried aggregates), K_s =saturated soil hydraulic conductivity, SOC = soil organic carbon, BD = bulk density, MacP = large macropores, AC = air capacity, PAWC = permanent available water capacity.

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level.

Regardless of the method applied for detecting changes in soil structural quality, the results suggest that the silt loam soil is more susceptible than the sandy loam to deformation of its structure by compaction by machinery or trampling. In November, after harvesting, the silt loam soil (0.44 m^3 m^{-3}) was wetter than in August (0.30 m^3 m^{-3}) (Table 8-2), which renders the soil more sensitive to compaction by harvesting machinery (Boizard et al., 2013).

Overall, mechanical destruction of soil structure changes the configuration of soil pores (Kutilek, 2004). These changes could be verified by the alteration in soil physical properties such as AC, MacP, and total porosity and consequently, by changes in saturated and unsaturated soil hydraulic conductivity. In the case of the sandy loam soil, there was a lack of significant relationships between K_s and any of the structural form and aggregate stability indicators, but with AC and MWD. In the silt loam soil, statistically significant interrelations were obtained between K_s and MacP, Tyagg and VSA (Table 8-4).

The lack of interaction between the evaluated properties over the agricultural cycle could be explained as follow. According to Horn and Fleige (2009), shearing processes, such as those induced by traffic, change the permeability of voids by structure deformation, which should not necessarily result in a change of the total volume/bulk density. Thus, it is understood that the complexity to cover all situations involving the soil structure dynamics, makes the soil structural quality assessment to demand for minimum data set of indicators, site-specific, and data mining techniques for an accurate evaluation.

Based on the sensitivity of the measured soil properties (ANOVA results) and the interaction between them (correlation analysis results), a minimum data set of indicators for detecting changes in soil structural quality over an agricultural cycle can be proposed for these two soils. A group comprised by VSA, visual aggregate stability, K_s, AC, MWD and SOC for the sandy soil, whereas VSA, aggregate stability, Tyagg, K_s, AC, MWD and K_a for the silt loam soil. However, developing a minimum data set for evaluating the complexity of temporal and spatial changes of soil structure should be designed in such a way that (i) the structural form, aggregate stability and soil physical properties could be integrated, and (ii) the reduction of data redundancy is involved. Several procedures have been proposed for developing minimum data set, most of them based on principal component analysis and scoring functions (Yemefack et al., 2006; Andrew et al., 2002). Another statistical technique that enables combining quantitative and qualitative variables is examined in Chapter 9.

Finally, two aspects must be emphasized in this Chapter. First the visual soil examinations used, except VESS, were capable for representing structural dynamic within an agricultural cycle, especially in the silt loam soil. This validates them for assessing and monitoring soil structural quality. However, because of the limited data used, the second aspect to be emphasized is the need of further evaluations in other conditions (different soil type, soil management and land use) and in time (several sampling intervals and agricultural cycles).

8.5. Conclusions

This Chapter demonstrated that the visual examination methods are responsive in evaluating the effect of land use on soil structural quality, and in identifying changes in soil structure related to soil management over an agricultural cycle. Based on the visual assessment of the structural form and aggregate stability, it was demonstrated that permanent pasture resulted in the best soil quality compared to cereal monoculture (under conventional tillage), whereas soil structural quality under cereal monoculture was better before cereal flowering than after harvesting. The results reveal that VESS is not always sensitive enough for detecting differences in soil quality when sandy loams are evaluated. Similarly, when comparing individually the soil physical properties measured there was not a clear tendency of the effect of soil management on the soil structural quality. Therefore an overall estimation must be preferred. Undoubtedly, quantifying the effect of land use and soil management on soil structural quality is essential to understand the dynamic of soil structure in agricultural soils.

Part III

Integrated and simple approaches for assessing soil structural quality

Chapter 9

Data-driven analysis of soil quality indicators using limited data[#]

9.1. Introduction

Soil quality is defined as 'the capacity of the soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Doran et al., 1996). The capacity of the soil to function can be reflected by measuring soil physical, chemical and biological properties, also known as soil quality indicators (SQIs) (Shukla et al., 2006).

Overall SQIs are intended to make complex information more accessible to decision makers. However, their applicability can be restricted not only to different soil types but also to multiple regions and management systems because of the site-specific nature of some SQIs (Andrews et al., 2003). Therefore, SQIs selected for evaluating soil functions must be truly representative of the complexity of the soil, and their selection should be based on integrated approaches.

The concept of the minimum data set of SQIs that reflects sustainable management goals and specific soil structure conditions is widely accepted, but has relied primarily on expert opinion to select minimum data set components (Larson and Pierce, 1991; Doran and Parkin, 1994; Karlen et al., 1997). The difficult question of which variables to include in an index or framework of soil quality may be simplified by statistical methods (Andrews et al., 2002). Soil structure, as a key factor in the functioning of soil (Mooney et al., 2006), is usually described in situ using classes or categories rather than continuous variables. Such soil structure classes cannot be used directly in classical statistical regressions for estimating soil properties from others (Pachepsky and Rawls, 2003), but techniques for developing tree-based models or decision trees enable to work

[#] This Chapter is based on:
Pulido Moncada, M., Gabriels, D., Cornelis, W. M., 2014. Data-driven analysis of soil quality indicators using limited data. Geoderma 235-236, 271-278.

with databases including categorical and numerical variables (Clark and Pregibon, 1992). These are exploratory techniques based on uncovering structure in data, and partition the samples to find both the best predictors and best grouping of samples. Decision trees derive knowledge rules from the data that subsequently can be used to estimate the impact of proposed measures (Pachepsky and Rawls, 2003).

Decision trees are familiar to pedologists because the main output is similar to most soil classification schemes. These techniques have been successfully used to explore databases containing categorical and numerical variables in some branches of soil science (McKenzie and Jacquier, 1997). For instance, in agro-ecology, decision trees have been used to evaluate how population dynamics of soil organisms are affected by changes of different biological and physicochemical environmental attributes and agricultural practices (Debeljak et al., 2007).

In soil physics, the use of decision trees has been mainly restricted to predicting soil hydraulic properties. For instance, Pachepsky and Rawls (2003) found that qualitative morphological observations of soil could be translated into quantitative soil hydraulic parameters, using a classification tree (tree-based model). The authors also demonstrate from decision trees the usefulness of the grade of structure as a predictor of water retention, which indicates a potential for observed aggregate-size distribution to be used in pedotransfer functions (PTFs).

Despite the effort done to include morphological properties of soil structure as potential predictors of the soil hydraulic properties (Pachepsky and Rawls, 2003; Lilly et al., 2008; Vereecken et al., 2010), thus far no unified approach exists on how to best include structural properties in PTFs. According to Vereecken et al. (2010) soil structure predictors in particular can suffer from the absence of a uniform protocol or definition, or may depend on the experience of the observer. However, the visual examination and evaluation of soil structure methods (Ball et al., 2007; Mueller et al., 2009; Shepherd, 2009) could be considered for collecting dependable morphological data for predicting other soil properties.

We hypothesised that the use of such decision tree approaches that relate morphological, physical and chemical soil properties to soil structure, hence soil quality, enables the possibility of developing soil quality frameworks more capable of representing structural dynamics in specific environments.

The objective of this study was to identify soil morphology related parameters that may be linked to soil quality at different geographic areas and to test the potential power of using decision trees in setting up a framework for soil quality assessment, using a limited number of categorical and numerical variables from both ‘tropical’ and ‘temperate’ soils.

9.2. Materials and Methods

9.2.1. Study area and data collection

The ten soils described in Chapter 2 were selected, with six located in a tropical environment (V1-V6; central-northern part of Venezuela) and four in a temperate one (B1-B4; Flanders Region of Belgium). In the tropical area the data set was collected from the soil structural quality evaluation study described in Chapters 3 and 6. The temperate data set includes samples taken from soils in the Flanders Region (Chapters 3 and 7). For soils B1 and B3, data correspond only to cropland plots. As has been mentioned before, the soils selected differ in factors that affect soil quality such as soil type, soil management and vegetation type (Table 2-1, Chapter 2), which provide a wide range of soil quality.

9.2.2. Physical, chemical and morphological soil properties

In this Chapter, physical and chemical soil properties most frequently evaluated when assessing soil structural quality were selected as measured properties such as: BD, AC, PAWC, K_s, WSA, particle size distribution, SOC and cation exchange capacity (CEC). From Chapters 6 and 7, the overall score of the VSA by Shepherd (2009), in conjunction with the individual score of the soil structure, soil porosity and number of earthworms using the VSA protocol, and the visual type of aggregate index (Chapter 7) were selected as morphological properties of the soil.

9.2.3. Data analysis

To ensure the efficiency of the models principal assumptions were checked. The test of normality was performed using Kolmogorov test and Q-Q plot. From the data set the only variable not normally distributed was the K_s (geometric mean of each sampling observation); therefore a transformation to a $\log_{10}$ scale of K_s data was done.

Two different types of decision trees were used to analyse the relationships between morphological, physical and chemical soil properties with soil quality: classification trees and model trees. Briefly, classification trees predict the values of a discrete variable with a final set of nominal values, whereas model trees represent piecewise linear functions with linear equations as the leaves of the model (Debeljak and Džeroski, 2011).

In a first stage, soil quality of each geographical area was predicted from classification trees, in which morphological properties (soil quality class by VSA) were used as the response variable and soil physical and chemical properties as the explanatory variables (BD, AC, PAWC, WSA, K_s, clay, silt, sand, SOC and CEC). A combined data set, in which the data of both geographical areas were pooled, was used to construct mixed models. Secondly, model trees were used to estimate soil properties (i.e. hydraulic conductivity) based on a set of explanatory structural variables including morphological characteristics. K_s was selected for estimation because it is one of the properties most wanted to be determined. However, it is difficult to measure and has a high variability. This property was also a parameter identified in the classification tree from the 'tropical' data set.

Briefly, the steps followed for building of the trees are described as following. According to Debeljak and Džeroski (2011) trees are built in accordance with splitting rule, which performs the splitting of a learning sample into smaller parts. Tree construction involves successively splitting of the data set into increasing homogeneous subsets. At each step, the algorithm first checks if the stopping criterion is satisfied (e.g. all examples belong to the same class). If not, the training set is split into subsets that have as homogeneous class values as possible. The subsets are built based on the selection of the most informative input variable, which is called the root of the (sub) tree. During the tree construction, rules are generated that relate the predictor or explanatory variables (e.g. soil physical or chemical properties) with the response variables (e.g. soil quality class). Tree construction stops when all examples in a node are of the same class (or if some other stopping criterion is satisfied). Such nodes are called leaves and they are labelled with the corresponding value of a class (e.g. soil quality by VSA).

Trees are viewed as a hierarchy of clusters, with each node corresponding to a cluster. After tree construction, pruning is applied to reduce the size of a decision tree by removing sections of the tree (sub-trees) that are unreliable and do not contribute to the predictive performance of the tree. In this way, some of the ending sub-trees are pruned, and the node is replaced by a leaf. Therefore, pruning reduces the complexity of the final tree and achieves a better predictive accuracy (Debeljak and Džeroski, 2011).

All models constructed in a certain geographic area (Flanders-Belgium or central northern-Venezuela) were validated based on a 10-fold cross-validation (Witten and Frank, 2005). In 10-fold cross-validation, the original data is randomly partitioned into 10 subsamples of approximately equal size. Of the 10 subsamples, a single subsample is retained for testing the model, and the remaining 9 subsamples are used as training sets. The cross-validation process is then repeated 10 times (the folds), with each of the 10 subsamples used exactly once as the validation data. The results or figures from the 10 folds (testing sets) are averaged to produce an overall estimation of the performance on data. Cross-validation is particularly useful when only a limited number of data are available for training and validating the model (Goethals et al., 2007).

The procedure of cross validation is based on an optimal proportion between the complexity of the tree and the misclassification error. With the increase in size of the tree, the misclassification error is decreasing and in the case of maximum tree, the misclassification error is equal to zero. On the other hand, complex decision trees poorly perform on independent data sets (Debeljak and Džeroski, 2011).

The classification and model trees were built with the Waikato Environment for Knowledge Analysis (WEKA) using the J48 algorithm, a re-implementation of the C4.5 algorithm within the WEKA suite for classification trees and M5 algorithm for model trees

(Hall et al., 2009). For the data of both geographical areas, a pruning confidence factor (PCF) of 0.25 and binary splits were applied. To assess the model performance of the classification trees, the percentage of Correctly Classified Instances (CCI) and Cohen's Kappa coefficient (K) were evaluated. In order to reach a satisfactory model performance, CCI should be at least 70%, and K should be at least 0.4 (Manel et al., 2001; Gabriels et al., 2007). In the case of model trees the performance indices used were correlation coefficients and root mean squared error.

9.3. Results

9.3.1. Estimating changes in soil quality from physical and chemical soil properties

Table 9-1 shows details of the soil chemical and physical properties used for estimating changes of soil quality on the ‘tropical’ and ‘temperate’ soils. The classification trees built to estimate soil quality of the ‘tropical’ and ‘temperate’ areas are displayed in Figure 9-1. After selection by the algorithm, only four (K_s, WSA, SOC and PAWC) and one (PAWC) of the 10 variables were included in the model for ‘tropical’ and ‘temperate’ soils, respectively. For the tropical data set, a tree with five leaves and PCF = 0.25, K = 0.66, and CCI = 78% was constructed (Figure 9-1a).

As regards the ‘temperate’ soils, the structure of the tree (Figure 9-1b) was simpler than that of ‘tropical’ soils, with PAWC being the only discriminating variable. The model constructed had a PCF of 0.25, a K of 0.66, and showed 83% CCI. Soils with PAWC values > 0.16 $cm^3\ cm^{-3}$ are having ‘good’ soil quality, whereas those with PAWC values ≤ 0.16 $cm^3\ cm^{-3}$ have a lower visually evaluated soil quality. When pooling the data of the ‘tropical’ and the ‘temperate’ soils into one data set, the model accuracy did not increase (K = 0.62 and CCI = 78%) compared to the previous models. The explanatory variables selected for the combined data set include two chemical soil characteristics (SOC and CEC) and one physical characteristic (Clay) (Figure 9-2).

Table 9-1 Soil chemical and physical properties of the 'tropical' and 'temperate' soils used for estimating changes in soil quality

		Unit	Minimum	Maximum	Mean	Standard Deviation	n
Venezuela	BD	Mg m^{-3}	1.00	1.70	1.42	0.19	36
	AC	cm^3 cm^{-3}	0.00	0.17	0.08	0.05	36
	PAWC	cm^3 cm^{-3}	0.08	0.22	0.14	0.04	36
	WSA	%	33.67	95.50	64.03	21.27	36
	K_s	cm h^{-1}	0.07	1060.35	41.70	176.25	36
	CEC	$cmol_c$ kg^{-1}	8.28	22.84	14.19	4.16	36
	SOC	g kg^{-1}	6.5	45.3	23.3	11.8	36
	Clay	%	14.42	48.18	27.71	8.14	36
	Silt	%	18.21	62.94	40.03	13.97	36
	Sand	%	3.95	56.12	32.26	17.24	36
Belgium	BD	Mg m^{-3}	1.26	1.59	1.43	0.10	24
	AC	cm^3 cm^{-3}	0.04	0.19	0.10	0.05	24
	PAWC	cm^3 cm^{-3}	0.10	0.20	0.15	0.03	24
	WSA	%	24.00	60.17	39.28	9.55	24
	K_s	cm h^{-1}	0.02	568.95	60.44	127.68	24
	CEC	$cmol_c$ kg^{-1}	6.00	8.21	7.11	0.79	24
	SOC	g kg^{-1}	8.5	14.7	11.0	1.9	24
	Clay	%	9.06	19.04	13.10	2.67	24
	Silt	%	10.22	69.68	48.43	22.14	24
	Sand	%	18.91	75.46	38.47	22.28	24

BD = bulk density; AC = air capacity; PAWC = plant available water capacity; WSA = water stable aggregates; K_s = saturated hydraulic conductivity; CEC = cation exchange capacity; SOC = soil organic carbon.

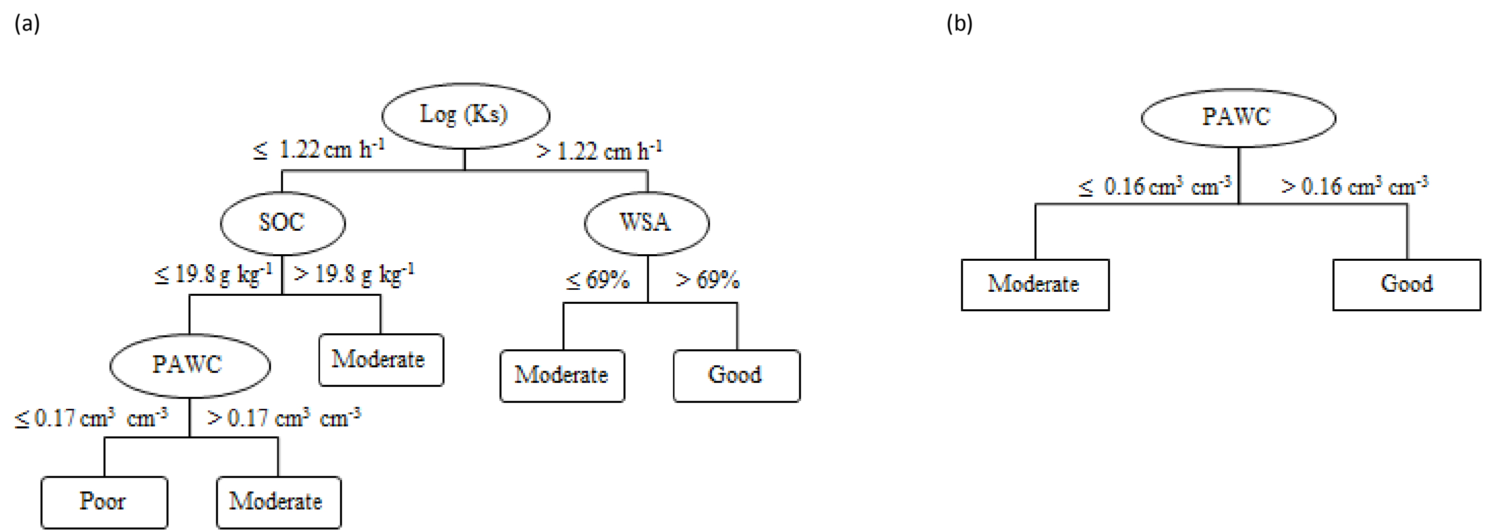


Figure 9-1 Classification tree predicting the soil quality in topsoil in (a) tropical (Pruning Confidence Factor = 0.25; Correctly Classified Instances = 78%; Cohen's Kappa = 0.65; total number of instance = 36) and (b) temperate environments (Pruning Confidence Factor = 0.25; Correctly Classified Instances = 83%; Cohen's Kappa = 0.66; total number of instance = 24). Ovals represent the nodes of the tree (discriminating variables) and the squared are the leaves (soil quality class). Log (K_s) = $\log_{10}$ scale of saturated hydraulic conductivity; WSA = water stable aggregates; SOC = soil organic carbon; PAWC = plant available water capacity. Good, moderate and poor are soil quality classes based on the visual soil assessment (Shepherd, 2009).

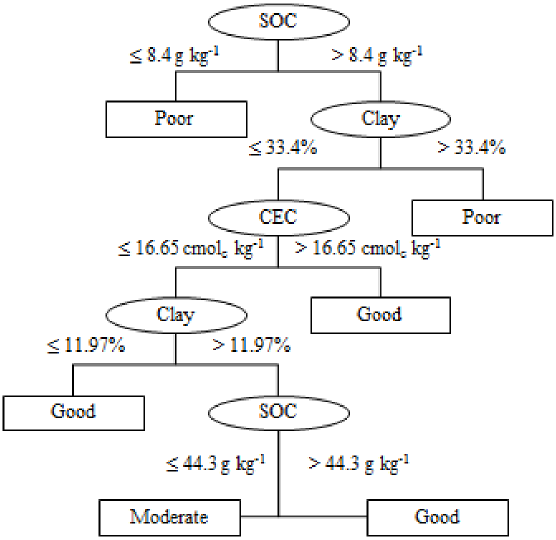


Figure 9-2 Classification tree predicting the soil quality in topsoil in combined dataset from tropical and temperate environments (Pruning Confidence Factor = 0.25; Correctly Classified Instances = 78%; Cohen's Kappa = 0.62; total number of instance = 60). Ovals represent the nodes of the tree (discriminating variables) and the squares are the leaves (soil quality class). SOC = soil organic carbon; CEC = cation exchange capacity. Good, moderate and poor are soil quality classes based on the visual soil assessment (Shepherd, 2009).

9.3.2. Estimating hydraulic conductivity from morphological, chemical and physical properties

Because of the relationships between soil morphological properties observable in the field assessment and the chemical and physical properties of the soil measured in the laboratory, it was tested whether K_s could be more accurately predicted by including morphological characteristics as predictor variables.

Figures 9-3a and 9-3b display the model trees built for the combined data set for the prediction of K_s. First, a model tree was built considering as predictor variables only physical and chemical characteristics measured in the laboratory (BD, AC, PAWC, WSA, clay, silt, sand, SOC and CEC). The model tree generated four linear equations for estimating K_s (Figure 9-3a); with a correlation coefficient (CC) of 0.61 and a root mean square error (RMSE) of 0.83 cm h^{-1}. The linear equations included six variables (i.e. BD, PAWC, WSA, silt, SOC, and CEC). The most important discriminating variables in the model tree were texture (silt and sand) and CEC, and depending on the values of these variables one specific linear model should be used (Table 9-2).

When morphological parameters were included as predictor variables such as type of aggregate, soil structure (VSA), soil porosity (VSA), number of earthworms (VSA), the model tree generated only two linear equations for estimating K_s (Figure 9-3b), with silt content (≤ or > 31.5%) as discriminator. Both models included six predictor variables, i.e. clay, silt, SOC, CEC, soil structure index, and earthworm number (Table 9-2).

(a) (b)

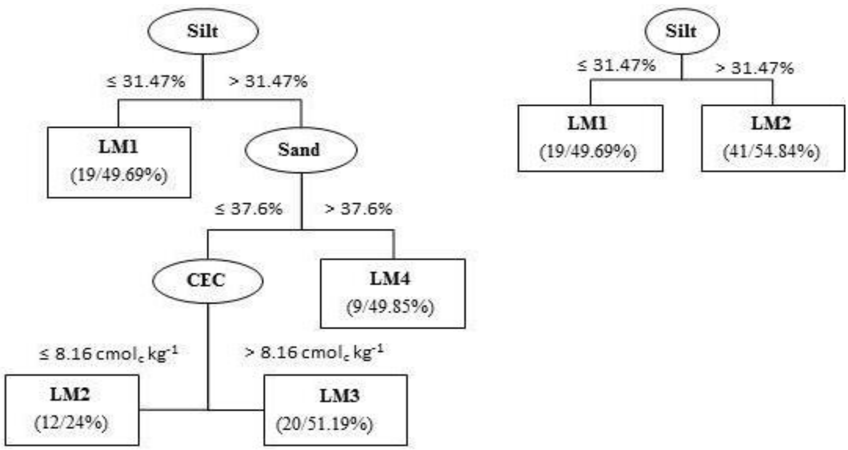


Figure 9-3 Model trees for predicting the $\log_{10}$ scale of saturated hydraulic conductivity only using chemical and physical characteristics as predictor variables (a) and including morphological characteristics (b). The additional information given in each leaf is the number of examples and relative root mean square error. Correlation coefficients 0.61 (a) and 0.75 (b); root mean squared errors 0.83 (a) and 0.67 (b); total number of instances 60. CEC = cation exchange capacity, LM = linear models (see Table 9-2).

9.4. Discussion

9.4.1. Merging measured and visual parameters for soil quality description

The models represent a clear link between physical and chemical properties on the one hand and visually evaluated soil quality on the other, as indicated by the relatively high values of the model performance indices CCI (> 70%) and K (> 0.4). Physical interpretation of Figure 9-1a suggests that soil quality is greater when the soil's permeability ($\log K_s$ > 1.22 cm h^{-1}) is at least moderately low (according to NRCS, 2003) and the stability of the aggregates (WSA > 69%), 2-1 mm in diameter, is high (Chapter 3). A 'good' soil quality can be visualized when soils show an adequate distribution and size of voids in the soil structure for water flow and the size of aggregates remains unalterable after water exposure.

Table 9-2 Detailed linear equations obtained based on the model trees showed in Figure 9-3a and b. Considering $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n$, each equation explains the response variable Y (log K_s values) by a vector of predictor variables $X = X_1 + X_2 + \ldots + X_n$ (BD = bulk density, PAWC = plant available water capacity, WSA = water stable aggregates, SOC = soil organic carbon, CEC = cation exchange capacity, clay, silt, SS = soil structure index, and NE = number of earthworm) and β_0 (as intercept) and $\beta = \{\beta_1, \ldots \beta_m\}$ as regression constants.

Rule	Linear model	Intercept	BD	PAWC	WSA	SOC	CEC	Clay	Silt	SS	NE
Only physical and chemical variables											
Silt < 31.5%	LM1	4.9223	-1.9368	-3.9272	0.0069	-0.123			-0.0251		
Silt > 31.5%, sand ≤ 37.6%, CEC ≤ 8.16 $cmol_c\ kg^{-1}$	LM2	2.1275	-1.5246	-2.3844	-0.0081	0.429	-0.015	0.0279	0.0074		
Silt > 31.5%, sand ≤ 37.6%, CEC > 8.16 $cmol_c\ kg^{-1}$	LM3	2.4559	-1.5246	2.3844	0.0042	-0.0752	-0.0116		0.0074		
Silt > 31.5%, sand > 37.6%,	LM4	2.2303	-1.8587	-2.3844	0.0042	-0.0752			0.0145		
Including morphological variables											
Silt < 31.5%	LM1	2.0388				-0.0826	0.0249	0.0178	-0.0413	0.2561	0.0434
Silt > 31.5%	LM2	0.1759				-0.0501	0.0151	0.0108	-0.0098	0.1555	0.0947

Different explanatory variables are involved in the left branch of the tree in Figure 9-1a. The first major distinction is based on SOC content. Soils with restricted water movement ($log_{10}K_s$ ≤ 1.22 cm h^{-1}) but high SOC are still having 'moderate' soil quality. Soils with SOC ≤ 19.8 g kg^{-1} are interestingly split based on the PAWC. Soils with deficits in PAWC (≤ 0.17 cm^3 cm^{-3}) have a degraded soil structure and consequently a 'poor' soil quality. Overall low SOC is associated with a decrease in soil quality with loss of soil pore size and consequently less water available to the plants.

In the temperate area (Figure 9-1b) the soil quality dynamic relates only with PAWC, which is a parameter very sensitive to changes in soil structure. The cluster displayed in Figure 9-1b ('temperate' soils) corresponds with the last node of the tree in Figure 9-1a ('tropical' soils) in the left branch. The threshold of PAWC selected in both geographic areas was very similar (0.16 – 0.17 cm^3 cm^{-3}). PAWC of the top layer of the soil might be useful for plant with shallow rooting systems.

The differences in the number of discriminating variables between the two geographic areas are not surprising because of site-specific differences due to soil, crop, climate and other factors (Andrews et al., 2004). The dissimilarity in variables identified from one geographic area to another, could be explained since in the tropical area, the soils sampled involve a higher variability of properties such as clay, SOC, WSA, and K_s (Table 9-1), compared to the 'temperate' soils. The variables selected by the algorithm can be suggested as those which better explain the total variance of the whole data set in each environment.

Another possible explanation could be the difference in texture classes, with a wider range of medium and finest textures in 'tropical' soil data set, while silt loam soils dominate in the 'temperate' soil data set. In the tropical area the clay content was higher than in soils from the temperate one, and a wider difference in soil quality was determined among soils. Besides this the expected differences in clay mineralogy between soils could contribute in the selection of the explanatory variables at each environment. The presence of more active clay types, even in small amounts, is a discriminating property and has an influence in hydraulic properties (Botula et al., 2013) and soil structure (Bronick and Lal, 2005).

Although limited data was used in our study, the variables (statistically) selected during pruning and thus for determining soil quality are in correspondence with other recent findings on the soil properties affecting the structural status. For instance, a study of 247 observations conducted in 'temperate' soils, revealed that unsuitable soil structure features like blocky structure and poor rooting were significantly associated with the soil drainage status, and with the compaction status in terms of increased densities (Mueller et al., 2013). Everaert et al. (2012) emphasize that in data mining it is often forgotten that maximizing mathematical indicators does not always result in the most optimal model. Therefore, a second criterion in evaluating decision models is to judge them against expert knowledge. Hence, the physical interpretation of the trees in Figure 9-1 enables consideration that the condition of the soil structure at each area is well represented by the models.

For the classification tree model of the combined data set, the strongest variable determining differences in soil quality was SOC. The selection of the SOC as the root of the tree is most likely due to the variability of the SOC present in 'temperate' and 'tropical' soil data sets, with soils from the tropical area having a wider range of SOC (0.65 - 4.53 g kg^{-1}), whereas a lower variance was presented in the soils sampled in the temperate area (0.85 - 1.47 g kg^{-1}). SOC varies among the soils collected in the tropical area as a consequence of a wider diversity of soil texture, land use, and soil management, compared to the temperate area.

The SOC has been proposed as an important key indicator in monitoring and evaluating soil quality (Shukla et al., 2006). Reynolds et al. (2009) used SQIs and pore volume-function characteristics to evaluate soil physical quality citing optimal ranges or critical limits of SOC as suggested by other authors (Greenland, 1981; Craul, 1999). However, limiting values of SOC developed under specific conditions have their limitations. Besides the idea that relationships between SOC and soil compaction or deterioration of soil structure are frequently based on BD (Hakansson and Lipiec, 2000), evidences of soil compaction are not always reflected by BD values. In this case, visual soil assessment (VSA) method have been referred as sensitive enough in demonstrating unfavourable changes in soil structure (Mueller et al., 2009; Munkholm et al. 2013; this dissertation Chapters 7 and 8). Therefore the qualitative data obtained by VSA could be more capable in determining more adequate thresholds of SOC for representing structural dynamics. Indeed, from Figure 9-2 it could be inferred that for the studied soils, those with ≤ 8.4 g kg^{-1} of SOC, soil structure is expected to be deteriorated or compacted. Soils with SOC < 44.3 g kg^{-1} can be evidence of a loss of soil structure. Hence, the quality of the studied soils can vary on the basis of clay content and CEC when the soils have a SOC ranging between 8.4 g kg^{-1} and 44.3 g kg^{-1}.

Andrews et al. (2004) mentioned that the expected range for each indicator will vary according to site-specific controlling factors, such as climate or inherent soil properties. Therefore, the structure of the tree in Figure 9-2 suggests that the effect of those controlling factors on the threshold values of the indicators is overcome when the grouping of the soils is based on the classes of the soil structure status (visually evaluated) as a response variable.

With reference to clay content and CEC as key indicators of soil quality of the combined data set (Figure 9-2), clay content has been described as an indicator that has an increasingly positive association with soil quality up to an optimal level beyond which soil quality decreases (Armenise et al., 2013). For our data set optimal level of clay content calculated by the classification tree is < 33.4%. On the other hand, CEC provides indications about the clay mineralogy of the soil, which is also responsible for the quality of the soil, as was mentioned above.

Further, Figures 9-1 and 9-2 illustrate the statistically significant relationships that exist between chemical and physical soil properties and structural quality (visually evaluated) of the evaluated soils. These relationships are promising in demonstrating that the dynamic nature of the soil structure requests different thresholds (or critical values) of the predicting variables at each specific area, rather than unique critical values as has been proposed or used for several authors such as Reynolds et al. (2009).

It must also be emphasized, that instead of reducing the number of SQIs to be evaluated in agricultural soils, a framework of key variables is more representative of their dynamic environment. According to Armenise et al. (2013) a SQI based on statistical techniques provides a valuable support for evaluating the interactions between soil quality indicators of different long-term soil managements. The potential of the SQIs, with specific reference to their ability to simplify complex data sets, would be better revealed when applied at regional and national scales.

Certainly, the explanatory variables of Figure 9-1a and b are dissimilar not only from each other but also from the combined data set tree. Further than referring these models as frameworks for each area, the value is the information generated. The models showed the necessity of judiciously selected dependable indicators (soil morphology related parameters) for soil quality evaluation under different environments. Decision trees appear to be adequate.

Morphological indicators from visual examination methods have been well related to crop yield (Mueller et al., 2013). Therefore, the inclusion of these parameters in predicting soil quality would be useful for identifying a minimum data set of indicators. The selected indicators should be the most significant variables that best represent the soil functions (crop productivity) associated with the selected goal (Armenise et al., 2013).

9.4.2. Morphological properties as parameters for estimation of hydraulic conductivity

In Figure 9-3a, the threshold silt and sand values of 31.47% and 37.6% indicate distinction in textural classes, i.e. fine, medium and coarse. The model tree reproduces the theoretical approach of having different parameters for estimating K_s according to soil texture (Lilly et al., 2008). On the other hand, when soil morphological properties were added as predictor variables, a simple tree was built (Figure 9-3b). Despite the tree's simplicity, the model performance was higher when morphological parameters were included (CC of 0.75 and an RMSE of 0.67 cm h^{-1}). This shows the potential of quantifying soil structure to explain hydraulic properties. Lin et al. (1999) demonstrated that pedality and porosity are crucial in characterizing hydraulic behaviour in the macropore flow region, and are better alternatives than the classical approach of using particle-size distribution, BD and SOC.

The model tree displayed in Figure 9-3b indicates that the soil structure index and the earthworm number are important parameters in the estimation of K_s for the soils studied. The soil structure index corresponds to the visual evaluation of the clods and aggregate size distribution by using the VSA method of Shepherd (2009). A higher proportion of coarse fragments represents poor soil structural condition. Overall coarse fragments are clods with high rupture resistance and low porosity, which limit the conductivity of the water. Earthworm number is a biological parameter that can be related to biopores between and within aggregates (earthworm burrows). The higher the number of earthworms the better the soil physical condition is expected in terms of soil porosity and hence water movement (Shepherd, 2009). Regarding the selection of the soil structure index as a predictor variable of K_s, authors such as Guber et al. (2003) have demonstrated that aggregate size distribution parameters can be useful in estimating parameters of soil water retention when using regression trees.

The models could adequately reproduce the effect of both the interaction between soil chemical and physical characteristics, and the arrangement of the soil fragments and the biological activity of the soil macro fauna on the K_s thresholds. Three out of the six variables selected by the models (SOC, soil structure index and earthworm number) (Table 9-2), are parameters highly affected by soil management and land use, which is physically meaningful in the estimation of K_s in agricultural soils.

These results are valuable in that they enable to identify morphological variables that are useful for prediction. The models presented here are encouraging because prediction of changes in soil structure and hydraulic conductivity, due to management and soil type, could be achieved with the collection of only a few variables.

Because a single rigorous means for quantifying soil structure does not really exist, Lin et al. (1999) proposed the use of soil profile description data as a major source of soil structural information for predicting hydraulic properties using PTFs. However, in those cases where the soil profile description data is not available or the study scale is more detailed, the data obtained by visual examination and evaluation methods (e.g. VSA) are capable in providing morphological information of the soil quality.

Andrews et al. (2004) mention that the analyses of integrated data in some cases can give more information than observed data alone. The information obtained from VSA, which summarised in a single score the whole evaluation of different indicators (i.e. texture, soil structure, soil colour, potential rooting depth, earthworms, among others); contributes to a more comprehensive evaluation of soil quality. Finally, the use of decision tree techniques that involve VSA data could be considered in further researches as a useful tool for the integration of soil management practices, soil physical properties and soil and plant processes.

The statistical technique applied in this Chapter is perhaps simpler than other frameworks presented by authors such as Karlen and Stott (1994), Andrews et al. (2004), and Armenise et al. (2013) for selecting important indicators of soil quality. However, it has the advantage of including categorical and numerical variables for evaluating soil quality.

9.5. Conclusions

Results demonstrate that the combination of soil physical and chemical properties with morphological evaluation of the soil quality using classification trees may provide reliable frameworks for soil quality evaluation under different environments. Classification trees could overcome the difficulties in using classified and numerical data together. This makes the selection of SQIs more flexible and allows integrated assessment of the soil quality status across different soil types, regions and management systems. Despite the limited database used in this study, physical reliable explanation was found in the models constructed. Predictions of K_s were improved when using morphological parameters such as soil structure index and number of earthworms, as explanatory variables. Decision trees are encouraging in the selection not only of well-developed SQIs, but also of the most influential morphological properties to be used in the prediction of key soil properties such as K_s. These statistical techniques appear to be helpful in future research directions for the evaluation of soil quality in relation to agricultural productivity. Visual soil assessment could be considered as dependable morphological data not only for predicting other soil properties, but also for developing soil quality frameworks (agricultural interest) more capable of representing structural dynamic to contribute to soil conservation and sustainable agriculture approaches.

Chapter 10

A comparison of S index with soil physical properties and visual examination for assessing soil physical quality[#]

10.1. Introduction

From the previous chapters it can be stated that it is unlikely that a sole ideal indicator can be used for assessing soil structural quality in any soil condition because of the multitude of properties involved and the dynamic condition of soils. Therefore, 'SQIs based decision tools that effectively combine a variety of information for multi-objective decision-making are needed' (Karlen and Stott, 1994). However, the use of unique indicators with the purpose to simplify the assessment of the SPQ has gained attention by some researchers.

In the context of SPQ assessment, an index that has been recently used by several authors is the S index proposed by Dexter (2004a). This SPQ index is defined as the slope of the SWRC on mass base at its inflection point on a logarithmic matric potential scale (Figure 10-1a). S index was proposed as an 'easy and unambiguous measure' based on the idea of integrating observations of a range of soil properties to obtain an overall assessment of SPQ (Dexter, 2004a).

The suitability of S in the diagnosis of SPQ has been studied by several authors. For instance, Dexter (2004a, b, c) suggested that S correlates with several important soil physical properties, which is supported by the ability of the van Genuchten (1980) equation to integrate over the whole SWRC and the corresponding pore size distribution (Dexter et al., 2008). Dexter (2004a) states that in the SWRC the pores that are smaller

[#] This Chapter is based on:
Pulido Moncada, M., Ball, B.C., Gabriels, D., Lobo, D., Cornelis, W.M., Evaluation of Soil Physical Quality Index S for Some "Tropical" and "Temperate" Medium Textured Soils. Soil Sci. Soc. Am. J., doi:10.2136/sssaj2014.06.0259.

than those corresponding with the inflection point represent textural pores, while pores larger than those corresponding with this point are mainly structural pores. The use of S as an indicator of SPQ is based on soil physical degradation being always related to an alteration in the structural pore distribution, which leads to a change in the shape of the SWRC and consequently to a change in the S value (Figure 10-1b).

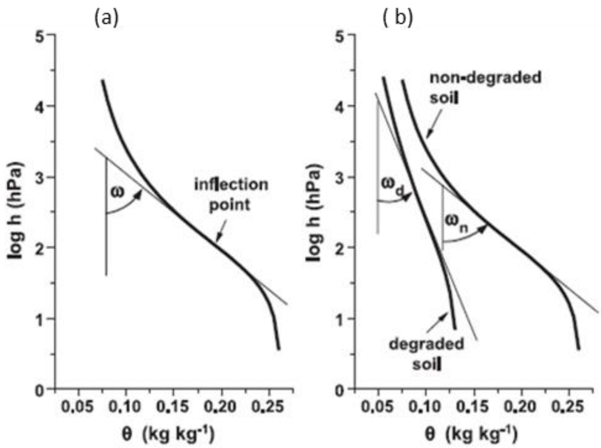


Figure 10-1 Soil water release curve (SWRC) showing the inflection point and the slope (a). Reduction of the slope of the SWRC at the inflection point when soil physical degradation occurs (b) (Source: Dexter, 2004a).

Dexter and Czyz (2007) stressed that there are two additional aspects supporting S as an adequate SPQ index. First, 'the same values of S have the same physical meaning in widely different soils, this is not the case with other soil physical properties, such as BD'. Secondly, S provides a more objective measurement with higher resolution (low coefficient of variation and standard error) compared to other measures such as subjective visual examination of the SPQ in the field. Nonetheless, in the literature there are very well-established critical values of BD for root growth developed for different soil textures, which enable evaluation of the physical condition of soils. With respect to the second assumption, the comparisons of the SPQ evaluation using visual examination methods and S have not yet been reported in the literature.

Another factor relevant to this discussion is the value of S = 0.035 proposed by Dexter (2004a) as a boundary value of soil degradation problems. This arbitrary value was established according to the experience of the author with temperate soils having a ranging of clay content from 4% to 73%, and based on relationships between S and other critical limits of different soil physical properties. Dexter and Birkas (2004) and Tormena et al. (2008) maintain that a value of S = 0.035 enables identification of variation in the soil physical condition among different soils. On the other hand, Van Lier (2012; 2014) mentions that S values at an order of magnitude higher than those described by Dexter (2004a) have been reported, as well as inconsistency in the use of S as an absolute indicator of SPQ.

Finally, it is important to stress that although Dexter (2004b) mentions that 'nearly every soil laboratory has the equipment necessary to determine the SWRC' and that the determination of soil properties related to soil structure are 'extremely costly in both time and money', there are many studies in the literature showing contrary arguments. For instance, Minasny and Hartemink (2011) pointed out that the information of soil water retention is usually missing in soil databases, especially in 'tropical' soils, since the direct method to determine SWRC is tedious and expensive in time and money. Therefore, several efforts have been dedicated to estimate SWRC from easily accessible soil properties using pedotransfer functions (Nguyen et al., 2014; Botula et al., 2013).

Although there is an acceptance of the S index in SPQ evaluations by some researchers, in this Chapter some constraints on its use are identified. The aim of this Chapter was to compare the suitability of S in identifying the SPQ condition of different 'tropical' and 'temperate' soils against the more frequently used soil physical and hydraulic properties on the one hand and visual examination methods on the other.

10.2. Materials and Methods

10.2.1. Study area and soil data set

The study was based on soil samples taken from nine soils, with five (V2-V6) located in a tropical environment (central-northern part of Venezuela) and four (B1-B4) in a temperate one (Flanders Region of Belgium). For soils B1 and B3, data correspond only to cropland plots. As mentioned in previous Chapters, the soils selected differ in factors that affect soil quality such as soil type, soil management, land use and vegetation type. This provided a wide range of SPQ, which enables testing of the different indicators that were selected for this study.

10.2.2. Methods and analysis

10.2.2.1. S index calculation and parameter estimation

The undisturbed samples collected at the different soils were used for constructing the SWRC. The SWRC data were determined from the wet to the dry range at eight different matric potentials: -1, -3, -5, -7, -10, -33, -100, and -1500 kPa. The procedure followed is described by Cornelis et al. (2005). The coupled matric potential-water content pairs represent single measurements on single samples.

The S index (Dexter 2004a) was calculated by fitting the soil water retention data to the mathematical model of van Genuchten (1980) with the m = 1 - 1/n constraint to the observed SWRC.

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \tag{10-1}$$

where θ_s is the gravimetric soil water content at saturation (kg kg^{-1}); θ_r is the residual gravimetric soil water content (kg kg^{-1}); h is the water suction (equal to the modulus of the matric potential in cm); α (cm^{-1}) as well as the dimensionless n and m are parameters respectively related to h and the curve's slope at its inflection point.

After the parameters of van Genuchten function were determined by fitting Equation (10-1) to the SWRC data, the slope at the inflection point, S, was calculated (Dexter, 2004a):

$$S = \frac{d(\theta_i)}{d(\ln h_i)} = -n\,(\theta_s - \theta_r)\left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n}-2\right)} \tag{10-2}$$

where θ_i and h_i are the water content and the water suction modulus of the water potential at the inflection point, Equations (10-3) and (10-4) respectively. Although S is always negative, the modulus of S is presented and discussed in this study.

$$\theta_i = (\theta_s - \theta_r)\left[1 + \frac{1}{m}\right]^{-m} + \theta_r \tag{10-3}$$

$$h_i = \frac{1}{\alpha}\left[\frac{1}{m}\right]^{\frac{1}{n}} \tag{10-4}$$

Since the S index depends on θ_r, it was necessary to set θ_r in equations (10-1) and (10-2) to zero to prevent negative fitted values being obtained (Dexter et al., 2008; Cornelis et al., 2005; Dexter, 2004b) and thereby allowing better comparison between the various soils. The estimation of the parameters θ_s, α and n was performed in the MatLab 8_1 environment (MathWorks, Inc., Hill Drive Natick, MA).

10.2.2.2. Physical soil properties

The physical soil properties selected for this study were BD, AC, PAWC, RWC, SOC, K_s, and WSA. The methodologies applied for measuring these soil properties have already been described at in the Materials and Methods Section of Chapter 3.

Additionally, pore volume distribution function was evaluated as suggested by Reynolds et al. (2009), hence the 'normalized' pore volume distribution function, S*(h) (-), was determined plotting the slope of the SWRC expressed as volumetric water content, θ_v (m^3 m^{-3}), versus ln(h), against equivalent pore diameter, d_e (µm), on a log_{10} scale.

$$S^*(h) = \frac{S_v(h)}{S_{vi}} \quad (10\text{-}5)$$

$$d_e = \frac{2980}{h} \quad (10\text{-}6)$$

where $S_v(h)$ is the slope of the θ(h)vs. ln(h) function, and S_{vi} the slope at the inflection point of the SWRC. Details on the derivation of Equations 10-5 and 10-6 are given in Reynolds et al. (2009). Equation (10-6) represents the capillary rise equation.

The pore volume distribution was characterized and compared using location and shape parameters (Blott and Pye, 2001), where the location parameters include the mode, median and mean d_e values, and shape parameters include, skewness (asymmetry) and kurtosis (peakedness) (Equations (10-7) to (10-9), Reynolds et al., 2009). The median d_e (d_{median}) occurs at a degree of saturation of 0.5 and the modal d_e (d_{mode}) corresponds to the relative water content or matric potential at the SWRC inflection. The d_{mode} also defines the most frequently occurring d_e value in the pore volume distribution.

$$d_\theta = \frac{2980\alpha}{(\theta^{-1/m} - 1)^{1/n}} \; ; 0 \le \theta \le 1 \quad (10\text{-}7)$$

$$d_{median} = d_{0.5} = \frac{2980\alpha}{(0.5^{-1/m} - 1)^{1/n}} \; ; \theta = 0.5 \quad (10\text{-}8)$$

$$d_{mode} = \frac{2980\alpha}{\left(\theta_i^{\;-1/m} - 1\right)^{1/n}} = \frac{2980\alpha}{m^{-1/n}} \quad (10\text{-}9)$$

Finally, the StI (Pieri, 1992), previously described in Chapter 3 (Equation 3-4), was also included as part of the physical soil properties.

10.2.2.3. Visual examination of soil structural quality

The evaluation of the macrostructure, in terms of SPQ, was conducted using the overall score of the VESS, and the VSA, in conjunction with the individual score of the soil structure using the VSA protocol (SS-VSA), and the Tyagg. More details about the methodology applied were described in the Material and Methods Section of Chapters 6 and 7.

10.2.3. Assessment of the soil physical quality

From the core samples values of S, BD, AC, PAWC, RWC and K_s were determined. These were used for comparison with the other SPQ indicators such as SOC, StI, WSA, VESS, VSA, SS_VSA and Tyagg. Soil quality designation provided by the different SPQ indicators was compared among soils. The optimal ranges or critical limits of the SPQ indicators are shown in Table 10-1. The relationships between S and the other SPQ indicators mentioned above were determined by simple regression models ($P < 0.05$). Differences between coefficients of variation of the indicators were determined with an analysis of variance, with indicators as factor, on the ratio 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 indicators.

10.3. Results and Discussion

10.3.1. Fitting parameters used for estimating S index

Table 10-2 shows details of the S index values together with the van Genuchten parameters used in its calculation for the different 'tropical' and 'temperate' soils. It should be noted that to allow comparison of the S index in different studies, Dexter (2004a, b, c) (i) expressed water content gravimetrically (kg kg^{-1}) in calculating the parameters of the van Genuchten equation, (ii) used the constraint $m = 1-1/n$, and (iii) set θ_r equal to zero, as was also done in this research. Although these premises should be assumed as fulfilled by researchers, studies can be found in the literature where the use of S and its critical value (Dexter 2004 a) is conducted without full consideration of these aspects (e.g, Calonego and Rosolem, 2011; Vizitiu et al., 2011; Silva Guedes et al., 2012).

Table 10-1 Critical limits of the soil physical quality indicators

Indicator	Critical limits	Reference
Bulk density, Mg m^{-3}	1.33, lower limit for soil compaction (medium-textured soils	Pierce et al. (1983)
	1.48, upper limit for soil compaction (medium-textured soils	
Air capacity, m^3 m^{-3}	> 0.10, adequate root zone aeration in sandy loam to clay loam soils	Reynolds et al. (2009)
Plant available water capacity, m^3 m^{-3}	≥ 0.15, good for roots growth and function	Reynolds et al. (2009)
	0.10 - 0.15, limited for roots growth and function	
	< 0.10, poor for roots growth and function	
Relative water capacity, m^3 m^{-3}	0.6 - 0.7, optimal range required for good crop production	Reynolds et al. (2009)
Soil organic carbon, g kg^{-1}	Venezuelan soils	Gilabert et al. (1990)
	medium textured soils	
	< 11.6, low	
	11.6 - 23.2, medium	
	> 23.2, high	
	fine textured soils	
	< 17.4, low	
	17.4 - 29.0, medium	
	> 29.0, high	
	Belgian soils (medium-textured soils)	Vanongeval et al. (2000)
	< 12.0, low	
	12.0 - 16.0, target zone	
	> 16.0, high	
Structural stability index, %	< 5, structurally degraded soil	Reynolds et al., (2009)
	5 – 7, high risk of soil structural degradation	
	> 9, sufficient soil organic carbon to maintain the structural stability	
Saturated hydraulic conductivity, cm h^{-1}	18 - 1.8, optimal range required for water movement	NRCS (2003)
	< 1.8, very low water movement	
Water stable aggregates, %	> 70, high aggregate stability	This dissertation Chapter 3
	< 50, low aggregate stability	

Table 10-1 (continued) Critical limits of the soil physical quality indicators

Indicator	Critical limits	Reference
Visual evaluation of soil structure	1-2, acceptable condition of soil structure	Ball et al. (2007)
	3, moderate condition of soil structure	
	4-5, limiting condition of soil structure and require change of management	
Visual soil assessment (VSA)	< 20, poor soil quality	Shepherd (2009)
	> 37, good soil quality	
Soil structure indicator of the VSA protocol	0, poor soil quality	Shepherd (2009)
	1, moderate soil quality	
	2, good soil quality	
Visual type of aggregates index	1-2, good and moderately good soil structural quality	This dissertation Chapter 7
	3, moderate soil structural quality	
	4-5, moderately poor and poor soil structural quality	
S index	≥ 0.050 and 0.050 > S ≥ 0.035, very good and good soil physical quality < 0.035, poor soil physical quality < 0.020, very poor soil physical quality	Dexter and Czyz (2007)

Table 10-2 Mean values of the S index together with the van Genuchten parameters used in its calculation. The values of the parameters θ_s, α and *n* of van Genuchten equation were calculated using the constraint m = 1-1/n, the residual water content was fitted to zero.

	V2	V3	V4	V5	V6	B1	B2	B3	B4
θ_s	0.4113	0.2547	0.3577	0.2401	0.3206	0.3909	0.3175	0.2968	0.2788
α	0.2316	0.0271	0.0124	0.0138	0.0305	0.0324	0.0158	0.0266	0.0088
n	1.1606	1.1892	1.2057	1.1483	1.1057	1.2999	1.2065	1.2128	1.2643
S	0.0454	0.0302	0.0445	0.0235	0.0243	0.0648	0.0405	0.0385	0.0421

θ_s is the water content at saturation (kg kg^{-1}); α and *n* (cm^{-1}) are parameters respectively related to the matric potential and the curve's slope at its inflection point. S is the slope of the water release curve at its inflection point.

10.3.2. Soil physical quality based on different indicators: comparison of S' soil physical quality designation

The physical quality of the soils under study was evaluated by comparing the indicators values and their given classes (Table 10-3). Based on the research conducted by Reynolds et al. (2009), soils were grouped in function of SPQ classes. Soils were organized into three groups based on the SPQ classes given by the different indicators. 'Good-SPQ', 'Moderate-SPQ', and 'Poor-SPQ'. A general 'moderate' class was allocated to each site based on the predominant designation among the indicators. For instance, some of the studied soils indicate moderate – good condition, or moderate – poor condition, or just moderate. In any case, those soils were classified as 'moderate-group' because they do not belong to the 'Good' or the 'Poor' group.

Group 1 'Good-SPQ' included only soil V2. BD, AC, PAWC, SOC, StI, K_s, WSA, VESS, VSA, SS_VSA and Tyagg classified the physical quality of the soil as 'good' for crop production. This suggests no limitation for root growth as well as water storage and movement. Although the majority of the other SPQ indicators fell within their respective optimal ranges, RWC was out of the optimal range, being above the higher critical value ('limited aeration'). In this group, the 'good' SPQ designation provided by S index was thus consistent with the designations provided by most of the other indicators.

The soils in Group 2 (V4, V5, B1, B2, B3 and B4) were considered as having a 'Moderate-SPQ' for agricultural purposes. Here, different ranges between 'good' and 'poor' were given among the SPQ indicators. For instance, V5 had high SOC content and WSA, but evidence of loss of structural quality was manifested by a high BD, limited aeration (AC and RWC), limited water storage (PAWC) and poor macrostructure arrangement (VESS). The other soils of this group have evidence of quality loss in either aggregate stability (WSA) or macro structural quality (VESS, VSA, SS_VSA and Tyagg). The SPQ designation provided by the S index for these soils was not consistent with those of the majority of the other indicators (Table 10-3).

Group 3 'Poor-SPQ' included V3 and V6 soils. A degraded or compacted condition was designated by a high BD, poor aeration (AC and RWC), low to medium SOC content, 'moderate' to 'poor' WSA, 'poor' structural and soil quality (VESS, VSA, SS_VSA and Tyagg) and low values of StI. The SPQ designations of the S index were consistent with those of the other indicators.

Comparison of the SPQ classes shown in Table 10-3 confirms that complexity of soil structure must be assessed by the integration of several indicators instead of using a sole indicator. Additionally, the optimal ranges and critical limits of the physical properties used, including visual evaluation of macro structure, seemed consistent and applicable to a wide range of agricultural soils, differing in crop and land management, soil texture and climate. This has been demonstrated by other authors such as Reynolds et al. (2009), Newell-Price et al. (2013) and this dissertation in Chapters 6, 7 and 8.

For the suited set of soils, the critical limit of S = 0.035 is capable of classifying the physical quality of the soils in the same way as other SPQ indicators, only when the condition of the soils is 'optimal' or 'degraded', but not when it is intermediate. A 'moderate' class provides evidence of structure dynamics during degradation or amelioration processes. Therefore, the appropriate evaluation of this particular condition is meaningful. Although the study conducted was limited, with only one soil classified as 'Good-SPQ' and two soils classified as 'Poor-SPQ', the SPQ groups were considered reliable/good enough to be used to conduct the comparative analysis among the SPQ indicators.

A higher value of S was obtained for the 'Good-SPQ' group as compared to 'Poor-SPQ' group. However, it must be emphasized that intermediate values of S were not present within the 'Moderate-SPQ' group. The values of S within the 'Moderate-SPQ' group surpassed or followed those from the other SPQ groups. Results suggest no clear tendency for high values of S to relate to 'good' soil condition for crop production, or low values of S to correspond to limiting conditions (Table 10-3).

The value of S = 0.035 has been questioned by Van Lier (2014) and Reynolds et al. (2009) because of its inconsistent designations of SPQ with a lack of uniformity with other physical indicators. Consequently, the critical limit proposed by Dexter (2004a) as a discriminating threshold of soil degradation problems does not appear to be applicable for any type of soil or under any condition of management and should be used judiciously and in relation to other indicators for assessing SPQ.

10.3.3. Soil physical quality estimation based on S' critical value

In order to further evaluate the use of the critical limit S = 0.035, simple regressions of S on other individual SPQ variables from the studied data set (Tables 10-4) were used to predict S at the optimal range or critical limit of each SPQ variable. This prediction was used as a tool to discover differences in optimal ranges or critical limits of the S index as compared to proposed by Dexter (2004a).

Table 10-3 Global comparison of indicators and indices of soil physical quality (SPQ)**.** See Table 10-1 for critical limits of indicators.

Soil	BD	AC	PAWC	RWC	SOC*	StI	K_s	WSA	VESS	VSA	SS_VSA	Tyagg	S
						‘Good-SPQ’							
V2- clay loam-NT	1.37	0.08	0.15	0.74	24.4	7.3	25.97	82.2	2.0	43.0	1.6	2.0	0.045
	Good	Limited	Good	Aeration limited	High	Low risk	Rapid	Good	Intact	Good	Good	Mod*-good	Good
						‘Moderate-SPQ’							
V4-Loam-NT-Tp	1.34	0.08	0.19	0.75	20.3	4.9	0.76	43.1	3.3	30.7	0.7	3.8	0.044
	Good	Limited	Good	Aeration limited	Medium	Degraded	Medium	Bad	Firm	Mod	Poor	Mod-poor	Good
V5-Silt loam-CT	1.65	0.02	0.13	0.88	29.1	5.9	0.75	93.4	3.5	28.2	1.0	3.5	0.023
	Compacted	Limited	Limited	Aeration limited	High	high risk	Medium	Good	Firm/Compact	Mod	Mod	Mod	Poor
B1-Sandy loam-CT	1.33	0.13	0.19	0.46	11.1	7.7	1.9	44.9	2.9	31.3	1.5	2.8	0.064
	Good	Limited	Good	Water limited	Mod-low	low risk	Medium	Bad	Intact/Firm	Mod	Good	Mod	Very good
B2-Silt loam-CT	1.44	0.07	0.16	0.68	13.4	2.9	0.06	37.9	3.7	23.6	0.9	3.4	0.040
	Mod	Limited	Good	Good	Ideal	Degraded	Very low	Bad	Firm/Compact	Mod	Mod	Mod	Good
B3-Silt loam-CT	1.53	0.09	0.15	0.64	9.40	2.0	18.9	34.5	3.1	34.8	1.4	2.4	0.038
	Compacted	Limited	Good	Good	Low	Degraded	Rapid	Bad	Firm	Mod	Good	Mod-good	Good
B4-Loam-RT	1.46	0.09	0.18	0.66	9.60	2.6	0.36	39.6	2.6	40.1	1.4	2.7	0.042
	Mod	Limited	Good	Good	Low	Degraded	Medium	Bad	Intact/Firm	Good	Good	Mod	Good
						‘Poor-SPQ’							
V3-Loam-CT	1.55	0.10	0.15	0.68	7.5	2.5	0.88	37.1	4.2	14.9	0.0	4.3	0.030
	Compacted	Limited	Good	Ideal	Low	Degraded	Medium	Bad	Compact	Poor	Poor	Mod-poor	Poor
V6-Silty clay-NT-Tp	1.53	0.05	0.12	0.92	16.1	2.9	1.81	57.3	4.4	11.0	0.3	4.0	0.024
	Compacted	Limited	Limited	Aeration limited	Medium	Degraded	Medium	Mod	Compact	Poor	Poor	Mod-poor	Poor

* Moderate; V2-V6 are ‘tropical’ soils from Venezuela; B1-B4 are ‘temperate’ soils from Belgium; NT = no-till; CT = conventional tillage; Tp = trampling by cows; RT = reduced tillage; BD = bulk density (Mg m^{-3}); AC = air capacity (cm^3 cm^{-3}); PAWC = plant available water capacity (cm^3 cm^{-3}); RWC = relative water capacity; SOC = soil organic carbon (g kg^{-1}); StI = structural stability index (%); K_s = saturated hydraulic conductivity (cm h^{-1}); WSA = water stable aggregates (%); VESS = visual evaluation of soil structure; VSA = visual soil assessment; SS_VSA = soil structure indicator of the VSA protocol; Tyagg = visual type of aggregates index; S = slope of the water release curve at its inflection point.

Statistical relationships between S and other SWRC-related indicators must be seen within the limitations of inter-dependency between the variables. Therefore, in contrast to Dexter (2004a) and Dexter and Czyz (2007), the regression equations were calculated just to find any tendency of relationship between variables but not for developing estimation equations. Results showed significant relationships with low coefficient of determination (R^2) (Table 10-4). This can be attributed to the large and wide range of the data set and to the existence of non-linear relations between the variables.

The critical limits of S obtained by the equations shown in Table 10-4 differ with the type of predictor variable. It varies within a range of 0.047-0.038 for 'Good-SPQ' class, and 0.040-0.029 for 'Poor-SPQ' class. In any case the criterion of a boundary value of S = 0.035 is not generally valid and does not apply for the soils in this study.

Andrade and Stone (2009) found that for their Brazilian 'Cerrado' soils a critical value of S = 0.045 was adequate to separate soils of good structure from soils with a tendency for degradation, while values of S < 0.025 corresponded to physically degraded soils. Using the critical values suggested by Andrade and Stone (2009), Cunha et al. (2011) found that S was well correlated to other soil physical properties and enabled evaluation of the SPQ of 'tropical' soils under different soil tillage systems and cover crops.

Aparicio and Costa (2007) found that, for Argentinean Pampas' soils, values of S ranged between 0.60-0.82, which surpassed the threshold value of S = 0.035. Although S was only correlated with BD, total porosity and penetration resistance, it was included as a predictor variable for estimating the number of years of continuous cropping of Argentinean Pampas soils (a measure related to soil quality). Aparicio and Costa (2007) supported the use of S as a good indicator of soil quality based on the selection made by the statistical model. However, the very high values of S (which could imply values of parameters such as n out of normal range), and the lack of correlation between S and other indicators within different soil layers, are aspects that were overlooked when selecting S as a predictor variable (e.g., indicators) to be included in their model.

In low-lying agricultural peat soils in England, where S values range between 0.22-1.03, lower values of S corresponded to loss of structural pores and degradation in soil structure (Kechavarzi et al., 2010). On the contrary, according to Van Lier (2012) high values of S have been found in degraded soils and low values of S without apparent association with soil productivity. This author stated that S index does not have a generally applicable critical value for a wider range of soils, and that its use should be limited for comparison of different tillage and management practices in a soil. Additionally, relationships found between S index and porosity are explained by the fact that in agricultural soils, macropores are destroyed (Van Lier, 2014). This author also emphasized that variation in θ_s affects proportionally the value of S. Therefore, the correlations found between S and porosity are 'may be considered as a mere reflection of this mathematical fact'.

Table 10-4 The relationships between S index and other soil physical quality indicators and the estimation of critical values of S index using other SPQ indicators' critical values (n = 54).

Linear model[a]	R^2	P value	Critical limits of the predictor variables	Estimated critical values of S[b]
S = - 0.893(BD) – 0.132	0.54	0.00	1.33 Mg m^{-3} (lower limit)	0.047
			1.48 Mg m^{-3} (upper limit)	0.035
S = 1.678 (AC) – 1.678	0.60	0.00	> 0.10 m^3 m^{-3} (optimal value)	> 0.030
S = - 0.764 (RWC) – 0.898	0.60	0.00	0.6 - 0.7 m^3 m^{-3} (optimal value)	0.044- 0.036
S = 0.001 (K_s) – 1.465	0.25	0.01	18 - 1.8 cm h^{-1} (optimal range)	0.035-0.034
S = - 0.054 (VESS) – 1.266	0.14	0.01	1-2 (acceptable condition of soil structure)	0.047-0.042
			3 (moderate condition of soil structure)	0.037
			4-5 (limiting condition of soil structure)	0.032-0.029
S = 0.005 (VSA) – 1.595	0.15	0.01	< 20 (poor soil quality)	0.032
			> 37 (good soil quality)	0.039

[a] Predictor variables are bulk density (BD), air capacity (AC), relative water capacity (RWC), saturated hydraulic conductivity (K_s), visual evaluation of soil structure (VESS), visual soil assessment (VSA). S = slope of the water release curve at its inflection point; $\log_{10}$ values of S.
R^2 = coefficient of determination, P value at a level of significance equal to 0.05.
[b] S values estimated using the models given in the first column and the critical limits of the predictor variables given in the fourth column. According to Dexter and Czyz (2007), S ≥ 0.050 and 0.050 – 0.035 indicate very good and good SPQ, < 0.035 indicates poor SPQ, and < 0.020 indicates very poor SPQ.

From the relations between S and the other indicators found in the studied soils, it is suggested that a range of S values could be established per soil type (textural class) instead of a unique value. This is supported by Garg et al. (2009) who stated that the value of S decreases as the texture coarsens. These authors found that for Indian soils (6-81% of clay) S decreases with an increase in average clay content up to 20-30%, thereafter S started increasing steadily and then decreased drastically, when the average clay content exceeds 45%. In fact, in the previous Chapter it was found that 33% was the optimal level of clay content beyond which soil structural quality decreases.

10.3.4. The S index as a boundary between textural and structural porosity

Figure 10-2 shows the mean of the pore volume distributions and SWRC of the soils grouped as 'Good-SPQ', 'Moderate-SPQ' and 'Poor-SPQ'.

The curve of the 'Good-SPQ' group was used as the 'optimal' pore volume distribution. The mean curve of the 'Moderate-SPQ' group had a normalised pore-volume distribution with greater densities of smaller pores and smaller densities of larger pores compared to the 'Good-SPQ' group. Its SWRC showed greater degrees of saturation than the 'Good-SPQ' group. This relates with a poorer SPQ as compared to the 'Good-SPQ' group.

The 'Poor-SPQ' group had a lower density of smaller pores compared to the 'Moderate-SPQ', whereas the opposite was true compared to the 'Good-SPQ'. The lowest density of large pores was present in this group of soils. The SWRC showed higher degrees of saturation for the 'Poor-SPQ' group than for the other groups. This water storage excess corresponds with a very low proportion of large pores relative to soils with 'Good-SPQ'.

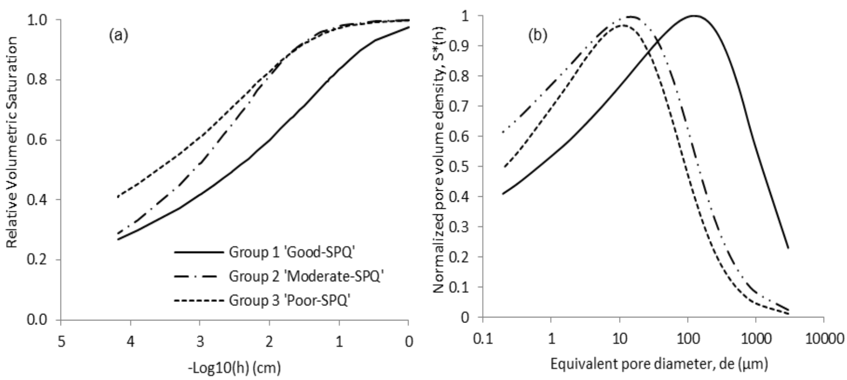


Figure 10-2 The soil water release curve (a) and the normalized pore volume distribution (b) of the group of soils with 'good', 'moderate' and 'poor' soil physical quality (SPQ).

The skewness and kurtosis values of the ‘Moderate-SPQ’ and ‘Poor-SPQ’ groups are similar to that of the ‘Good-SPQ’ group (Table 10-5). This corresponds with results from Reynolds et al. (2009) who mentioned that evidently, loss of aeration capacity and structural quality affect the location parameters of the pore volume distribution much more than the shape parameters. The d_{mode}, d_{mean}, and d_{median} for ‘Good-SPQ’ group are greater than the mean values of the other groups. d_{mode} value (125.6 µm) was consistent with the optimal d_{mode} range of 60-140 µm proposed by Reynolds et al. (2009) for soils grouped as ‘Good-SPQ’. These location parameters of the SWRC are therefore more consistent indicators of the SPQ present in the soils under study than shape parameters such as skewness and kurtosis.

The description of pore volume distribution and the relative location of the SWRCs confirm the grouping of the soils, for assessing SPQ, based on the water release-related indicators, physical properties and visual examinations (Table 10-5). Porosity parameters are therefore more consistent indicators of SPQ than S for the ‘tropical’ and ‘temperate’ studied soils. In any case, if the SPQ is evaluated through porosity status of the soil, S has no additional value over total porosity, which is easier to determine than S (Van Lier, 2014).

Table 10-5 Location and shape parameters for the pore volume distributions of the soils studied.

	Location parameters			Shape parameters	
	d_{mean}	d_{median} --- (µm) ---	d_{mode}	Skewness	Kurtosis
		‘Good-SPQ’			
V2- clay loam-NT	2.80	9.27	125.60	-0.41	1.14
		‘Moderate-SPQ’			
V4-Loam-NT-Tp	0.53	1.30	8.59	-0.38	1.15
V5-Silt loam-CT	0.11	0.39	6.97	-0.42	1.14
B1-Sandy loam-CT	5.73	9.96	31.26	-0.34	1.16
B2-Silt loam-CT	0.69	1.67	10.93	-0.38	1.15
B3-Silt loam-CT	1.32	3.11	18.93	-0.38	1.15
B4-Loam-RT	1.02	1.96	7.62	-0.35	1.15
		‘Poor-SPQ’			
V3-Loam-CT	0.78	2.10	17.24	-0.39	1.15
V6-Silty clay-NT-Tp	0.02	0.13	10.90	-0.44	1.12

V2-V6 are ‘tropical’ soils from Venezuela, B1-B4 are ‘temperate’ soils from Belgium, NT = no-till, CT = conventional tillage, Tp = trampling by cows, RT = reduced tillage,

Distribution of the small (textural) and large (structural) pores was evident from the pore volume distribution curve. According to the S theory the boundary between these pore sizes can be established at the inflection point. As an illustration, Table 10-6 summarises water content and matric potential at the inflection point and their respective equivalent pore diameter.

The inflection point of the SWRC for the 'Good-SPQ' group occurs at 0.31 kg kg^{-1} of water content with h = -24 cm. For those soils with evidence of loss of structural quality ('Moderate-SPQ' and 'Poor-SPQ' groups), the inflection point is in a range of 0.18-0.27 kg kg^{-1} with h between -95 to -346 cm, with most values closer to FC, except for the sandy loam soil (B1).

The equivalent pore diameter at the inflection point of the SWRC was considerably higher for 'Good-SPQ' soils (126.44 µm) than for the 'Moderate-SPQ' (7-32 µm) and 'Poor-SPQ' soils (10-18 µm). Those soils showing deterioration of their physical quality had a very low range of 7-31 µm equivalent pore diameter at the inflection point.

In the literature, the diameter boundary between textural (or matrix) and structural porosity has been proposed as 50 µm (Lal and Shukla, 2004; Pagliai and Vignozzi, 2002). Results showed that at the inflection point an overlapping of the textural and structural pores exists. For instance, for the clay loam soil ('Good-SPQ') and the silty clay and loam soils ('Poor-SPQ'), the d_i was equal to 126.44 and 10.97-17.35 µm, respectively. Hence, according to Dexter (2004a) pores larger than these values correspond to structural porosity, whereas lower values are textural pores.

Table 10-6 Water content, matric potential and equivalent pore diameter at the inflection point of the water release curve

	Θ_i (kg kg^{-1})	h_i (cm)	d_i (µm)	θ_{-33kPa} (kg kg^{-1})
		'Good-SPQ'		
V2	0.31	23.73	126.44	0.26
		'Moderate- SPQ'		
V4	0.26	346.73	8.65	0.28
V5	0.18	427.66	7.01	0.20
B1	0.27	95.32	31.47	0.17
B2	0.23	272.64	11.00	0.22
B3	0.21	157.40	19.06	0.19
B4	0.19	391.29	7.67	0.20
		'Poor- SPQ'		
V3	0.19	172.88	17.35	0.18
V6	0.25	273.47	10.97	0.25

θ_i is the water content at the inflection point, h_i is the modulus of the water potential at the inflection point, d_i is the pore diameter at the inflection point, θ_{-33kPa} the water content at -33kPa ('field capacity').

The boundary of textural and structural porosity is therefore difficult to delineate by parameters at the inflection point of the SWRC. Reynolds et al. (2009) argue that 'if the two distributions do indeed overlap, then $h=h_i$ in S-index does not demark an actual or literal boundary between structure pores and matrix pores but only a notional boundary'. In fact, a boundary between textural and structural porosity is an 'arbitrary concept', because there is no specific value of matric potential or diameter distinguishing between these two types of pores.

10.3.5. Visual examination and S index resolution

The question remains whether visual examination of soil quality is a subjective assessment or whether it is more objective to estimate the quality of a soil based on a single value or index derived from the SWRC of a small volume?

In order to assess the objectivity of the SPQ indicators evaluated in this dissertation (in terms of their resolution) a comparison of their coefficients of variation was conducted. Values of coefficients of variation (Table 10-7) for SWRC-related indicators, soil physical properties and scores from visual examinations were similar ($P > 0.05$), except for K_s. This suggests that SPQ can be evaluated by both quantitative and semi-quantitative indicators with similar proportion of variation accounted for. Although soil physical indicators, including the S index and visual examination methods differ in scale of study (size of the samples), the visual examination methods were able to detect the differences in physical condition among soils similar to other physical indicators.

In this study, a wide range of size scales was involved from a few micrometres to several centimetres. For instance, from < 2 mm sieved and disturbed samples (SOC and StI), 1-2 mm aggregates (WSA), 10-20 mm aggregates (Tyagg), 100 cm^3 soil cores (K_s, PAWC, AC, RWC and BD) to 20x10x20 cm soil blocks (VESS and VSA). The S index was determined from 100 cm^3 soil sample data and related to the volume, continuity and size of a pore space ranging from 7 to 126 µm (at the inflection point of the SWRC).

The influence of scale in soil structure assessment is very well known (Besson et al., 2013; Dexter, 1988). Therefore, with the purpose of evaluating soil quality, in terms of soil structure status, an integration of S with other indicators at different scales can be established. For instance, soil quality assessed by comparison of both SWRC-related indicators and visual examination on the same soil.

Van Lier (2014) emphasized that soil quality is an expression of the complexity of the system (here the soil) and that the use of a simple single indicator such as S index should be viewed with great caution and scepticism. Mainly, because 'as an absolute indicator, the value of S alone has proven to be incapable of predicting SPQ'.

Table 10-7 Statistics of the soil physical quality indicators evaluated

	n	Minimum	Maximum	Statistic	Std. Error	Std. Deviation	Levene's test for coefficient of variation*
BD	54	1.26	1.70	1.46	0.016	0.11	0.07 a
AC	54	0.002	0.191	0.08	0.006	0.04	0.42 a
RWC	54	0.42	1.03	0.71	0.019	0.14	0.15 a
StI	54	1.85	9.15	4.34	0.310	2.28	0.42 a
K_s	54	0.02	220.77	20.93	6.557	48.19	1.21 b
VESS	54	2.00	5.00	3.25	0.113	0.83	0.22 a
VSA	54	6.50	45.50	28.61	1.412	10.38	0.27 a
SS_VSA	54	0.00	2.00	1.09	0.104	0.76	0.47 a
Tyagg	54	2.00	5.00	3.21	0.123	0.90	0.26 a
S	54	0.017	0.104	0.039	0.002	0.015	0.28 a

BD = bulk density (Mg m^{-3}); AC = air capacity (cm^3 cm^{-3}); RWC = relative water capacity; StI = structural stability index (%); K_s = saturated hydraulic conductivity (cm h^{-1}); VESS = visual evaluation of soil structure; VSA = visual soil assessment; SS_VSA = soil structure indicator of the VSA protocol; Tyagg = type of aggregate score; S = slope of the water release curve at its inflection point.
* Data followed by the same letter indicate homogenous subsets of Levene's test of the coefficient of variation among soil physical quality indicators at α = 0.05.

Conclusions about the sensitivity of the indicators of SPQ compared in this dissertation cannot be drawn from the studied data set because of the differences in factors such as soil type, climate, vegetation that affect soil structural quality, as well as their possible interactions. Ideally, a comparison of the sensitivity of the indicators should be conducted by monitoring changes in SPQ with land use or soil management. Nevertheless, one of the limitations of the visual examination methods is that the scoring factor, which covers a wide range, might limit sensitivity to changes in soil quality, whereas other more continuous parameters such as SWRC-related indicators (soil porosity, BD, PAWC) may it be more sensitive temporally or spatially.

Finally, visual examinations of SPQ are methods that summarise in a single score the evaluation of several visible and tactile features (such as macroporosity, size, shape and rupture resistance of aggregates, root limitations, proportion of clods and soil colour) involved in characterizing one of the most complex properties of the soil, the soil structure. These methods have been proved capable for evaluating changes in structure dynamics and therefore related to soil physical properties and provide straightforward and reliable measurements of the SPQ (Boizard et al., 2013; Mueller et al., 2013; this dissertation Chapters 6, 7 and 8).

10.4. Conclusions

The lack of similarity between S index and the other indicators used in classifying the physical quality of the studied soils demonstrates that the proposed critical limits for S are not generally valid and do not apply for any soil condition. Although this research was conducted in a minimum data set of medium-textured soils, the results can be generalized to other soils. It was also demonstrated that the visual examinations have at least similar resolution to the other indicators of SPQ evaluated in the studied group of soils. Additionally, the use of S as an indicator to be considered as part of a minimum data set of indicators of SPQ assessment is less viable when other indicators such as BD, porosity, VSA, Tyagg are much more easily determined and consistent than S. Finally, it is important to highlight that rather than using a simple approach such S for assessing SPQ, integrated assessments, based on the complexity of the system and its interrelated processes, are preferred.

Chapter 11

General discussion and conclusion

The development and selection of methodologies and parameters to measure and assess how the soil functions are affected by anthropogenic means, has been identified as one of the most important goals for soil science in the 21st century (Lima et al., 2013; Adewopo et al., 2014). In this scope, efforts for establishing adequate protocols or methodologies to characterize soil quality are needed. A universal set of indicators for soil quality assessment is not possible because of the various environments present across agricultural areas worldwide. Additionally, the selection of indicators depends on the soil function of interest (Andrews et al., 2002).

Because of the need to establish capable tools for assessing the dynamic changes of the soil under agricultural systems, this dissertation provided an evaluation of direct and indirect methods to assess soil structural quality. Soil structure regulates the majority of the chemical, physical and biological properties and processes of soil. Hence, in a strict sense, soil quality is essentially soil structure-related. The overall aim of this dissertation was to test and develop soil structural quality indicators for medium-textured soils in tropical and temperate environments, to improve frameworks for assessing soil quality (from an agricultural perspective) and thus contribute to soil conservation and sustainable agriculture approaches.

Because the diagnosis of soil structural quality should consider soil structural stability, soil structural form and soil structural resilience as part of a measurement package, this dissertation was structured in three parts: (i) the assessment of soil structural stability, (ii) the evaluation of the soil structural form, and (iii) the integration and comparison of these parameters in combination with indirect methods for assessing soil structure. The most important points of this dissertation are briefly restated as follows.

11.1. Soil physical quality assessment based on aggregate stability

As mentioned in Chapter 1, several studies have pointed out the effect of the procedure applied (mechanisms and pre-treatment involved) on structural stability assessment. In Chapter 3, in order to select appropriate aggregate stability methods that enable evaluation of the structural stability quality of both ‘tropical’ and ‘temperate’ soils, a comparative study was conducted among the most frequently used wet sieving methods. Results showed that all methods involving fast wetting led to comparable findings when assessing structural stability quality of medium-textured soils under both tropical and temperate environments. The similarities obtained illustrate that there is no effect of the immersion of aggregates into different liquids for shaking and different aggregate sizes, when fast wetting is involved. The comparable wet sieving methods simulate identical aggressive forces (slaking and shaking), which promote the same mechanics of the breakdown of the unstable aggregates. Differences obtained with those methods involving drop impacts and slow wetting 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.

So far a unique methodology to evaluate aggregate stability is lacking, Chapter 3 showed the possibility of using aggregate stability data from two different methods involving fast wetting. This could allow enhancing databases for selection of minimum data set of indicators. Concluding about which method of aggregate stability determination is the ‘most suitable and applicable’ for a broad range of land uses and soil managements in agricultural soils remains difficult.

Because of the method dependence of the aggregate stability measurements, the aggregate stability estimation from parameters such as SOM content and mineral particles has been preferred by some researchers. In Chapter 4 the main goal was to evaluate whether the SOM fractions could be more sensitive indicators of aggregate stability instead of SOM *per se.* Results showed similarities in the relationships between SOM content and SOM fractions with aggregate stability among soils. Differentiation in SOM fractions, SOM content and aggregate stability was clearly affected by soil management and land use.

It was notable that soil management and land use influenced the concentration of specific SOM fractions. However, these SOM fractions did not show to be more sensitive indicators of changes in aggregate stability than SOM content. In fact, a general separation of stable and unstable soils, between samples of high and low SOM was observed, respectively. What is remarkable was the differences in aggregate stability/SOM quality among the different soil types and between the studied geographical areas. This indicates that the assessments of SOM fractions are important to obtain information about the SOM dynamic and its selective contribution to the build-up of different aggregate sizes.

For more insights in the selection of aggregate stability methods, in Chapter 5, the hypothesis proposed by Fernández-Ugalde et al. (2013) was tested. They stated that ‘clay mineral distribution among aggregate-size classes may be influenced by the physical dispersion protocol, which can involve different dispersion mechanisms'. It was also aimed to assess clay-mineral-based evidence for the aggregate hierarchy. Although this research (Chapter 5) was conducted on limited data, it has demonstrated that there is similar mineralogical composition in each aggregate size class. The absence of selective clay mineral distribution was also observed when two different fractionation methods (dLdB and LB1) for aggregate size distribution were applied.

In Chapter 5, the perspective of working with the proper method to achieve the objective of the study is again highlighted. The use of the peak intensity of the XRD patterns, as indicators of mineralogical composition differences, appears not to be the most accurate method for seeking clay-mineral-based evidence for the aggregate hierarchy. Therefore, the need to use more advanced quantitative techniques in combination with chemical analysis was emphasized. This will allow obtaining more insights in the assessment of clay mineralogy as binding agent responsible for building aggregates.

In Part I was demonstrated that although aggregate stability is a key factor in the assessment of soil structural quality, the method's sensitivity in detecting changes in soil structure on agricultural soils is very dependable upon the procedure applied. This is well-known by researchers but in the majority of the cases the choice of methods is based on reasons such as equipment availability or traditional used methods. This is why the general interpretation of the aggregate stability must be in concert with the method applied and in combination with other soil physical properties for a wider and more accurate assessment of the structural quality of the soil.

11.2. The use of visual examination methods for assessing soil structural quality

In the past decade the Working Group F 'Visual Soil Examination and Evaluation' of the International Soil & Tillage Research Organisation (ISTRO) has been stimulating interest in field methods of visual-tactile soil assessment, to encourage their wider use (Ball et al., 2013). This working group has published several articles mainly focused on:

(i) The development of new or modification of old procedures for field assessment of soil structure,

(ii) The use of topsoil examination for revealing differences in quality between land use types,

(iii) The use of profile description for detecting topsoil and subsoil structure degradation such as compaction by tillage, and

(iv) The application of visual soil examination and evaluation methods in overall assessment of soil quality and its association with drainage status and crop performance.

In Part II of this dissertation, was examined the use of visual examination method for assessing soil structural quality. Visual soil examination and evaluation has been mainly applied to soil from 'temperate' and 'subtropical' regions. Those pertaining to subtropics were mainly conducted on Oxisols in Brazil (Guimarães et al, 2013; Giarola et al., 2013), which show a particular physical behaviour. In tropical countries such as Venezuela, Oxisols are not common in the agricultural region. Instead, Mollisols, Ultisols and Alfisols are of greatest importance on those regions.

Chapter 6 aimed to assess the applicability of three of such visual examination methods in assessing soil structural quality on 'tropical' soils. The acceptable performance of the visual examinations methods, in medium-textured 'tropical' Venezuelan soils supports the idea of applying them as complementary methods for assessing structural quality not only in temperate regions (for which they were developed), and subtropical ones (as demonstrated by other researchers), but tropical environments as well. However, results showed that adjustment and improvements are needed. For instance, (i) the rating of indicators such as number of earthworms in the VSA method, which must be in relation to the 'local' faunal population and activity, and (ii) the inclusion of potential rooting depth as a parameter of the root system condition in the SQSP method, mainly in those cases where the soil is not continuously used and fallow periods are considered. Although the research conducted in the 'tropical' soils from Venezuela was small, rather limited, with only six different soils being considered, the results can be generalized to the central-northern part of Venezuela. Results may also hold true for other agricultural areas with similar conditions.

In order to understand the relationship between visual morphological descriptions of soil structure and measured soil physical properties, a comprehensive study of the interrelations between these variables was conducted under different soil type and land use and under temperate conditions (for which the methods were developed).

In Chapter 7, the feasibility and reliability of visual examinations for detecting changes in soil structure quality due to land use was clearly displayed. Two morphological properties, viz. visual aggregate stability and type of aggregate, proved to be important parameters for an integrated structural form evaluation when topsoil examination methods are applied. Site-specific relationships between morphological descriptions and soil physical properties were evident. Results showed also that visual quality was associated with soil physical and hydraulic properties in silt loam and sandy loam soils differently. On top of that, it was also found that the well-established visual examination methods showed potential for quantifying soil structural information to be included into models for predicting hydraulic properties.

In order to validate visual examination methods, in Chapter 8, it was evaluated whether visual examination methods are sensitive enough to detect significant changes in soil structural quality related to soil management. Results showed that the visual examinations were also capable to capture soil structure dynamics due to soil management within an agricultural cycle. In the silt loam, all methods were responsive to land use effects on soil quality and sensitive in detecting changes in soil structural quality between evaluation periods. Compaction on the soil surface after harvesting was also detected by visual examination, mainly in a silt loam soil. Therefore, this study demonstrated that the visual examination methods are responsive in evaluating the effect of land use on soil structural quality, and are capable of representing structural dynamics (related to soil management) in an agricultural cycle.

Site-specific relationships between tested physical and hydraulic properties and visual examination were evident in both Chapters 7 and 8. This suggests that texture is a key factor in the susceptibility of a soil to deformation of its structure by compaction by machinery or trampling. Because not all these relationships were significantly related, the results reflect the complexity of the soil structure and support that an overall evaluation of soil structural quality must be preferred instead of an isolated analysis of a specific indicator. It is suggested to judge the structural quality of soil in terms of its overall quality and its suitability for the soil function of interest (e.g as a growth medium).

Part II of the dissertation contributes to the assessment of the performance and suitability of the visual examination methods. This allows agreement with McKenzie (2013), who stated that these methods could be considered as crucial components of future schemes for soil assessment in conjunction with modern soil databases. This author also mentioned that ‘much remains to be learnt about soil amelioration requirements of land with various degrees of soil physical, chemical and biological constraints under a broad range of rural land uses and for contrasting climate conditions’, additionally, much remains to be achieved about the assessment of soil structural quality in terms of the selection of indicators for a wide range of conditions present in agricultural soils.

11.3. Integrated and simple approaches for assessing soil structural quality

To date soil structural quality assessment is mainly based on a selection of soil physical properties from soil analysis data or on the use of soil quality kits (structural form evaluation). However, these evaluations are mainly conducted separately and little effort has been made to integrate structural form and soil physical analysis into soil quality frameworks. In part III of this dissertation, a way to integrate information from soil structural quality indicators using statistical techniques that enable to work with classificatory and quantitative variables was evaluated.

In Chapter 9, decision trees were tested as a tool to integrate direct and indirect measurements of soil structure. This approach tried to help in the difficult process of selecting appropriate indicators of soil quality based on an integrated assessment. Because of the complexity of the soil structure, soil structural data need a good and accurate analysis, for which decision trees appeared to be suitable. From the results, it is recommended to select the models using both statistical indices and cross-checking knowledge. The implementation of soil quality frameworks and models, in dynamic environments such as agricultural soils, should always be joined with interpretation based on soil available knowledge to check whether model results are reliable.

Decision trees are flexible in adding factors that are important to the objective of the assessment or to the management systems, or to remove those that cannot be quantified with the data available (Yemefack et al., 2006). This dissertation gave new insights in the integration of direct (e.g. structural form and aggregate stability) and indirect (e.g. BD, SOC, porosity, water movement and storage properties) methods for assessing soil structure.

On the other hand, Chapter 10 examined the use of an absolute indicator of soil physical quality derived from the SWRC. This was contemplated because of the tendency of researchers to seek for a unique indicator that allows an isolated evaluation of soil quality. From the result presented in Chapter 10, it becomes clear that unique indices such as S are not applicable for any condition. The main limitation of the soil physical quality index S is that its values do not show a clear tendency in relation to soil condition for crop production. Such an index S has to be merely considered as a comparative indicator of soil porosity alteration for comparison of soil quality within the same soil.

Although this research was conducted using a limited data set of medium-textured soils only, the results can be generalized to other soil types, as inconsistency on the efficiency of S as indicator of soil physical quality have been reported by other researchers. From the comparative analysis conducted, it was concluded that S has no additional value over other soil physical indicators at classifying soil physical quality. The findings in Chapter 10 support that of Van Lier (2012; 2014), who stated that understanding the processes occurring in the soil starts in the recognition of the complexity of the medium, followed by the description of the mechanisms and interactions linked to those processes. Therefore, it is too ambitious to consider that a unique indicator such as S index could be used to evaluate soil physical quality as such. Research efforts should be focussed on evaluation of soil quality, as a key factor of land degradation assessment, from a more complex point of view or integrated approach.

The general implications of the findings of this dissertation pertaining to the assessment and choice of soil structural quality indicators can be stated as follow.

In agroecosystems, soil is a key component to the interactions of several processes that control the energy and nutrients flows. From this point of view, Liebig's 'Law of the Minimum' reminds soil scientists to assess those soil structural quality related limitations that are of importance in constrained agricultural environments. This dissertation contributes to the selection of appropriate indicators that allow assessing and monitoring changes in soil structural quality. Its findings can be considered as a basis for wider scopes such as soil conservation and sustainable agriculture approaches.

The applicability of the results, method' performances and models built, is limited to the studied fields. Notwithstanding this, the importance of testing methods for soil quality assessment was demonstrated focusing on the criteria of suitability, applicability and adaptability. A larger data set including different land use and soil managements should be considered to make conclusions for a larger scale.

The integrated and comprehensive assessment of soil structure for both tropical and temperate environments, confirms the need of considering aggregate stability, structural form and soil physical properties for an accurate and judiciously evaluation of soil structural quality. Additionally, this dissertation opens an interest to require researchers-farmers collaboration, with emphasis on collecting data needed for detecting structural dynamics in agricultural soils. Farmers can play an important role in generating the data related to structural form by using the visual examinations.

11.4. Recommendation for further research

When measuring soil structural quality, a 'prior selection' of the method to apply, is an important step for selecting a minimum data set of indicators. This selection should be based on the objective of the study and the capacity of the method to distinguish structural status among soils or treatments.

Several aspects still need further investigation:

(i) Although much is known about structural stability, several aspects are still under study. Standardization of methods used for aggregate stability determination represents a gap in this area of research. This dissertation only focused on wet sieving methods, whereas it might be important to include turbidimetric techniques, raindrop impact test, and fractionation involving centrifugation and sonication as well. The inclusion of these methods for a general comparison should enable to classify the aggregate stability methods in function of their applicability. For instance, methods suitable for getting more insights in aggregation mechanism and processes, and those for detecting changes in structural stability as a result of agricultural practices.

(ii) Another point concerns the further study of the relationships between the SOM fractions and their capacity to act differently as a binding agent in different aggregate sizes. This is based on the hypothesis that the disruptive action of the different mechanisms involved in the methods for aggregate stability assessment, might affect the organic-mineral links at each aggregate size level differently. This knowledge can be useful to the selection of the most appropriate aggregate stability method in accordance to the scope and objective of the study.

(iii) In soils with aggregate hierarchy, the composition of the SOM is the main factor most likely to be responsible for the build-up and stabilization of aggregates (Six et al., 2000). Further research would be needed to support that 'soil structure development would be different in soils in which the proportion of the various 2:1 clay mineral types is different' (Fernández-Ugalde et al., 2013).

(iv) Because of the differences in the relationships between morphological and physical-hydraulic properties demonstrated in this study for soils under contrasting texture and land use, further studies in correlating morphological evaluations and quantitative soil physical properties could be conducted in other soil textures and management systems.

(v) Evaluation of the performance of the visual examination methods could also be conducted for soil types such as Vertisols and paddy soils, with characteristics inherent to these soil types included as indicators of soil quality in order to reduce erroneous interpretation.

(vi) As mentioned by authors such as McKenzie (2013), 'optimal depths and intensities of sampling for visual-tactile procedures, and associated soil chemical test, need to be refined for application under different land uses and contrasting landscapes'. Additionally, the effect of moisture content on the score and the frequency of evaluation should be assessed.

(vii) Assessment of soil structural quality can be considered as part of the greenhouse gas emission studies, because of the importance of the structural status in limiting gaseous exchange.

(viii) The sensitivity of methods to assess soil structure should be evaluated; particularly the minimum number of sample necessary and uncertainties related to spatial variability need further attention.

(ix) When evaluating soil structural quality for crop production, features and soil requirements of the crop should be considered.

(x) Research on the applicability of visual examination in tropical regions is still quite limited and needs further research.

(xi) Using soil structural quality could guide research collaboration between policy makers, farmers and soil scientists, with emphasis on addressing key research needs.

Appendix 1. Score card used for evaluating the quality of soils under cropping by Visual Soil Assessment method (Source: Shepherd, 2009).

SCORE CARD

VISUAL INDICATORS TO ASSESS SOIL QUALITY UNDER CROPPING

SOIL INDICATORS

Land owner:
Land use:
Site location:
GPS ref:
Sample depth:
Topsoil depth:
Soil type:
Soil classification:
Drainage class (p. 73):
Date:

Textural group: (upper 1m) ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey

Moisture condition: ☐ Dry ☐ Slightly moist ☐ Moist ☐ Very moist ☐ Wet

Seasonal weather: ☐ Dry ☐ Wet ☐ Cold ☐ Warm ☐ Average

Visual Indicators of Soil Quality	Visual Score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS Ranking
Soil texture (p. 70)		× 3	
Soil structure (p. 71)		× 3	
Soil porosity (p. 72)		× 3	
Number and colour of soil mottles (p. 73)		× 2	
Soil colour (p. 74)		× 2	
Earthworms (Number =) (p. 76) (Average size =)		× 3	
Soil smell (p.78)		× 2	
Potential rooting depth (mm) (p. 80)		× 3	
Surface ponding (p. 82)		× 3	
Surface cover and surface crusting (p. 84)		× 2	
Soil erosion (wind/water) (p. 85)		× 1	
SOIL QUALITY INDEX (Sum of VS rankings)			

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20 – 37
Good	> 37

Appendix 2. Score card used for evaluating the quality of soils under pastoral grazing by Visual Soil Assessment method (Source: Shepherd, 2009).

SCORE CARD

VISUAL INDICATORS TO ASSESS SOIL QUALITY UNDER PASTORAL GRAZING ON FLAT TO ROLLING COUNTRY

SOIL INDICATORS

Land owner:	Land use:
Site location:	GPS ref:
Sample depth:	Top-soil depth:
Soil type:	Soil classification:
Drainage class (p. 19):	Date:

Textural group: (upper 1m) ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey

Moisture condition: ☐ Dry ☐ Slightly moist ☐ Moist ☐ Very moist ☐ Wet

Seasonal weather conditions: ☐ Dry ☐ Wet ☐ Cold ☐ Warm ☐ Average

Visual Indicators of Soil Quality	Visual Score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS Ranking
Soil texture (p. 16)		× 3	
Soil structure (p. 17)		× 3	
Soil porosity (p. 18)		× 3	
Number and colour of soil mottles (p. 19)		× 2	
Soil colour (p. 20)		× 2	
Earthworms (Number =) (p.22) (Average size =)		× 3	
Soil smell (p.24)		× 2	
Potential rooting depth (mm) (p. 26)		× 3	
Surface ponding (p. 28)		× 3	
Surface relief (p. 30)		× 1	
SOIL QUALITY INDEX (Sum of VS rankings)			

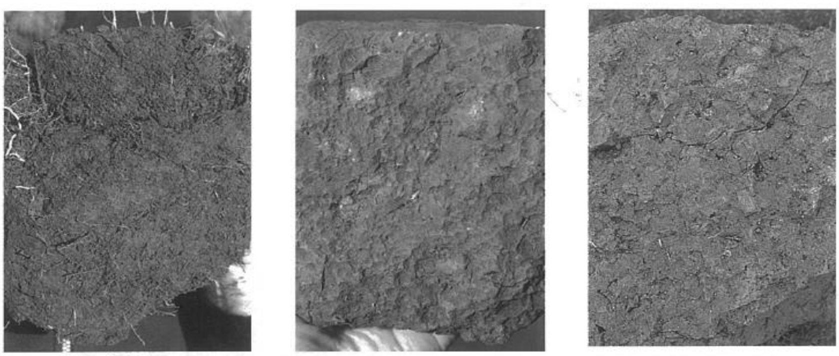
Soil Quality Assessment	Soil Quality index
Poor	< 20
Moderate	20–35
Good	> 35

Appendix 3. Criteria used for assessing the soil quality indicators involve in the visual soil assessment (VSA) method by Shepherd (2009).

3.1. How to score soil texture (Source: Shepherd, 2009).

Visual score	Textural class	Description
2 (Good)	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
1.5 (Moderately good)	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 (Moderate)	Loamy silt Sandy loam	Smooth feel, non-sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 (Moderately poor)	Silty clay & clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 (Poor)	Loamy sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger.
	Sand	Gritty and rasping sound. Cannot be moulded into a ball.

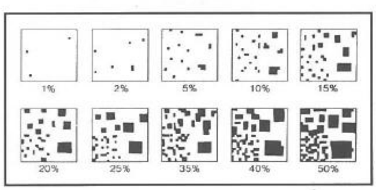
3.2. Visual scoring of the number and colour of soil mottles (Source: Shepherd, 2009).



GOOD CONDITION VS = 2
Mottles are generally absent

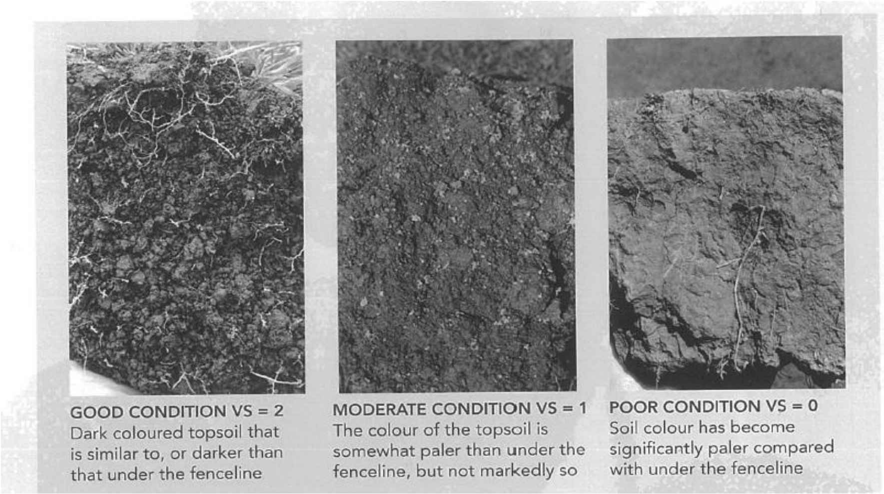
MODERATE CONDITION VS = 1
Soil has many (10–20%) fine and medium orange and grey mottles

POOR CONDITION VS = 0
Soil has profuse (> 50%) medium and coarse orange and particularly grey mottles



Percentage chart

3.3. Visual scoring of soil colour (Source: Shepherd, 2009).



3.4. Visual score for earthworms (Source: Shepherd, 2009).

Visual score	Earthworm numbers (per 200 mm cube of soil)
2 (Good)	≥ 45 (with preferably 3 or more species)
1.5 (Moderately good)	35-44
1 (Moderate)	25-34 (with preferably 2 or more species)
0.5 (Moderately poor)	15-24
0 (Poor)	<15 (with predominantly 1 species)

3.5. Criteria of how to assess soil smell (Source: Shepherd, 2009).

Remove a spade slice of soil and break it into two. Put the fresh faces of the soil close to your nose and sniff three times and compare the odour with the criteria given in the table below.

Visual score	Soil smell
2 (Good)	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell
1 (Moderate)	Soil has a slight earthy, sweet odour or a 'mineral' smell
0 (Poor)	Soil has a putrid, sour, chemical or unpleasant smell

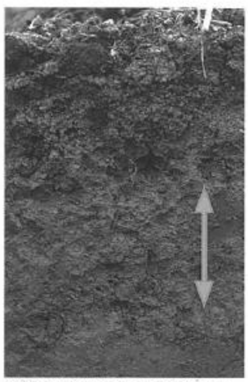
3.6. Potential rooting depth (Source: Shepherd, 2009).

Examine for the presence of a limiting or restricting layer by rapidly jabbing the side of the soil profile with a knife, starting at the top and progressing systematically to the bottom of the hole. Note the presence of horizontal grow of the roots.

Visual score	Potential rooting depth (mm)
2 (Good)	> 800
1.5 (Moderately good)	600-800
1 (Moderate)	400-600
0.5 (Moderately poor)	200-400
0 (Poor)	<200

3.7. Identifying the presence of a strongly developed hard pan (Source: Shepherd, 2009).

NO HARD PAN
The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5.



MODERATELY DEVELOPED HARD PAN
The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed)

STRONGLY DEVELOPED HARD PAN
The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed)

3.8. Visual scoring of surface ponding (Source: Shepherd, 2009).

GOOD CONDITION VS = 2
No ponding of water evident after 1 day* following heavy rain on soils that were at or near saturation

MODERATE CONDITION VS = 1
Moderate surface ponding occurs for 3–5 day* after heavy rain on soils that were at or near saturation

POOR CONDITION VS = 0
Significant surface ponding occurs for longer than 7 days* after heavy rainfall on soils that were at or close to saturation

3.9. Visual scoring of surface relief (Source: Shepherd, 2009).

GOOD CONDITION VS = 2
Surface is relatively smooth and unbroken

MODERATE CONDITION VS = 1
Surface terrain is somewhat broken up and incised by occasional heavy treading events but it is not difficult to walk over

POOR CONDITION VS = 0
Surface is very broken and deeply incised by severe repeated treading. The terrain is difficult to walk across and care must be taken to avoid twisting ankles

References

A

Abid, M., Lal, R., 2008. Tillage and drainage impact on soil quality - I. Aggregate stability, carbon and nitrogen pools. Soil & Tillage Research 100, 89-98.

Adewopo, J.B., VanZomeren, C., Bhomia, R.K., Almaraz, M., Bacon, A.R., Eggleston, E., Judy, J.D., Lewis, R.W., Lusk, M., Miller, B., 2014. Top-Ranked Priority Research Questions for Soil Science in the 21 Century. Soil Sci. Soc. Am. J. 78, 337-347.

Alvarez, M.F., Osterrieth, M.L., del Rio, J.L., 2012. Changes on aggregates morphology and roughness induced by different uses of Typical Argiudolls, Buenos Aires province, Argentina. Soil & Tillage Research 119, 38-49.

Alvarez, R., Steinbach, H. S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil & Tillage Research 104, 1-15.

Amezketa, E., 1999. Soil aggregate stability: A review. Journal of Sustainable Agriculture 14, 83-151.

An, S., Mentler A., Mayer, H., Blum, W.E.H., 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.

Anderson, J., Ingram, J., 1993. Tropical Soil Biology and Fertility: A Handbook of Methods, 1993. CAB International, Wallingford.

Andrade, R.D.S., Stone, L.F., 2009. Índice S como indicador da qualidade física de solos do cerrado brasileiro. Revista Brasileira de Engenharia Agrícola e Ambiental 13, 382-388.

Andressen, R., 2007. Circulación atmosférica y tipos de clima. Fundación Empresas Polar. Geo Venezuela 2, pp 238-328.

Andrews, S.S., Flora, C.B., Mitchell, J.P., Karlen, D.L., 2003. Growers' perceptions and acceptance of soil quality indices. Geoderma 114, 187-213.

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945-1962.

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agriculture Ecosystems & Environment 90, 25-45.

Aparicio, V., Costa, J. L., 2007. Soil quality indicators under continous cropping systems in the Argentinean Pampas. Soil & Tillage Research 96, 155-165.

Araujo, Y., López-Hernández, D., 1999. Caracterización de las poblaciones de lombrices de tierra en un sistema de agricultura orgánica ubicado en una sabana en el Amazonas venezolano. Ecotropicos 12(1), 49-55.

Armenise, E., Redmile-Gordon, M.A., Stellacci, A.M., Ciccarese, A., Rubino, P., 2013. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. Soil & Tillage Research 130, 91-98.

Arshad, M.A., Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7: 25-32.

Arshad, M.A., Martin, S., 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems & Environment 88, 153-160.

Askari, M. S., Cui, J., Holden, N. M., 2013. The visual evaluation of soil structure under arable management. Soil & Tillage Research 134, 1-10.

B

Ball, B.C., 2013. Soil structure and greenhouse gas emissions: a synthesis of 20 years of experimentation. European Journal of Soil Science 64, 357-373.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use and Management 23, 329-337.

Ball, B.C., Douglas, J.T., 2003. A simple procedure for assessing soil structural, rooting and surface conditions. Soil Use and Management 19, 50-56.

Ball, B.C., Munkholm, L.J., Batey, T., 2013. Applications of visual soil evaluation. Soil & Tillage Research 127, 1-2.

Barthès, B.G., Kouakoua, E., Larre-Larrouy, M. C., Razafimbelo, T.M., de Luca, E. F., Azontonde, A., Neves, C. S. V. J., 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.

Batey, T., 2000. Soil profile description and evaluation. In: Soil and environmental analysis: physical methods , 2nd edn (Eds K.A. Smith & C.E. Mullins), pp. 595–628. Marcel Dekker, Inc., New York.

Batey, T., 2009. Soil compaction and soil management - a review. Soil Use and Management 25, 335-345.

Batey, T., McKenzie, D.C., 2006. Soil compaction: identification directly in the field. Soil Use and Management 22, 414-414.

Baveye, P., 2006. Comment on "Soil structure and management: A review" by CJ Bronick and R. Lal. Geoderma 134, 231-232.

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.

Besson, A., Séger, M., Giot, G., Cousin, I., 2013. Identifying the characteristic scales of soil structural recovery after compaction from three in-field methods of monitoring. Geoderma 204–205, 130–139.

Beste, A., 1999. An applicable field method for the evaluation of some ecologically significant soil-function-parameters in science and agricultural consulting practice. In: International Soil Conservation Organisation Conference 1999, West Lafayette, Indiana, USA.

Blott, S.J., Pye, K., 2001. Gradistat: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landforms 26, 1237–1248.

Böhm, W., 1979. Methods of Studying Root Systems. Ecological Studies 33. Springer, Berlin, Heidelberg, New York.

Boix-Fayos, C., Calvo-Cases, A., Imeson, A., Soriano-Soto, M., 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena 44, 47-67.

Boizard, H., Batey, T., McKenzie, D., Richard, G., Roger-Estrade, J., Ball, B. C., Bradley, I., Cattle, S., Hasinger, G., Munkholm, L., Murphy, B., Nievergelt, J., Shepherd, G., 2005. Field meeting ''Visual Soil Structure Assessment'' Held at the INRA Research Station, Estre´es-Mons, France, May 25–27, NRA-ISTRO report report, 24 pp. available at: http://iworx5.webxtra.net

Boizard, H., Yoon, S.W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J., Richard, G., 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil & Tillage Research 127, 34-44.

Botula, M.Y-D., Nemes, A., Mafuka, P., Van Ranst, E., Cornelis, W., 2013. Prediction of water retention of soils from the humid tropics by the nonparametric k-nearest neighbor approach. Vadose zone journal 12(2).

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

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

C

Calonego, J.C., Rosolem, C.A., 2011. Soil water retention and s index after crop rotation and chiseling. Revista Brasileira De Ciencia Do Solo 35, 1927-1937.

Camarsa, G., Sliva, J., Toland, J., Hudson, T., Nottingham, S., Rosskopf, N., Thévignot, C., 2014. LIFE and soil protection. In: LIFE Environment (Eds. H. Martin). European Commission. Luxembourg. Available at: http://ec.europa.eu/environment/life/publications/lifepublications/lifefocus/documents/soil_protection.pdf (acceded July 2014).

Carter, M., 2004. Researching structural complexity in agricultural soils. Soil & Tillage Research 79, 1-6.

Carter, M.R., Gregorich, E., Anderson, D., Doran, J., Janzen, H., Pierce, F., 1997. Concepts of soil quality and their significance. Developments in Soil Science 25, 1-19.

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

Chenu, C., Plante, A.F., 2006. Clay-sized organo-mineral complexes in a cultivation chronosequence: revisiting the concept of the 'primary organo-mineral complex'. European journal of soil science 57, 596-607.

Chisci, G., Bazzoffi, P., Mbagwu, J.S.C., 1989. Comparison of aggregate stability indices for soil classification and assessment of soil management practices. Soil Technol. 2:113-133.

Ciavatta, C., Govi, M., 1993. Use of insoluble polyvinylpyrrolidone and isoelectric focusing in the study of humic substances in soils and organic wastes. Journal of Chromatography A 643, 261-270.

Ciavatta, C., Govi, M., Antisari, L.V., Sequi, P., 1990. Characterization of humified compounds by extraction and fractionation on solid polyvinylpyrrolidone. Journal of Chromatography A 509, 141-146.

Clark, L. A., Pregibon, D., 1992. Tree-based models. In: Statistical Models in S (ed. J. M. Chambers and T. J. Hastie), pp. 317-419. Wadsworth, Pacific Grove, C.A.

Comerma, J., Paredes, R., 1978. Principales limitaciones y potencial agrícola de las tierras en Venezuela. Agronomía Tropical 28(2), 71-85.

Comerma, J.A., 1971. La 7ma aproximación y los suelos venezolanos. Agronomía Tropical 21(5):365-377. Available at : http://sian.inia.gob.ve/repositorio/revistas_ci/Agronomia%20Tropical/at2105/arti/comerma_j.htm

Cornelis, W.M., Khlosi, M., Hartmann, R., Van Meirvenne, M., De Vos, B., 2005. Comparison of unimodal analytical expressions for the soil–water retention curve. Soil Sci. Soc. Am. J. 69, 1902-1911.

Craul, P.J., 1999. Urban soils: applications and practices. John wiley & sons.

Cribb, J., 2010. The coming famine: the global food crisis and what we can do to avoid it. Univ of California Press.

Cunha, E.d.Q., Stone, L.F., Alves Moreira, J.A., de Brito Ferreira, E.P., Didonet, A.D., Leandro, W.M., 2011. Soil tillage systems and cover crops in organic production of common bean and corn. I - soil physical properties. Revista Brasileira De Ciencia Do Solo 35, 589-602.

D

D'Haene, K., Vermang, J., Cornelis, W.M., Leroy, B.L.M., Schiettecatte, W., De Neve, S., Gabriels, D., Hofman, G., 2008. Reduced tillage effects on physical properties of silt loam soils growing root crops. Soil & Tillage Research 99, 279-290.

Daniells, I., Larsen, D. (Eds.), 1991. SOILpakb: A Soil Management Package for Cotton Production on Cracking Clays. second ed. NSW Agriculture, Dubbo.

Daraghmeh, O. A., Jensen, J. R., Petersen, C. T., 2009. Soil structure stability under conventional and reduced tillage in a sandy loam. Geoderma 150, 64-71.

Dawidowski, J. B., Koolen, A. J., 1987. Changes of soil-water suction, conductivity and dry strength during deformation of wet undisturbed samples. Soil & Tillage Research 9, 169-180.

Day, J. H., 1983. Manual for describing soils in the field, Land Resource Research Institute Contribution No. 82-52, Research Branch, Agriculture Canada, Ottawa, Ontario.

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.

Debeljak, M., Cortet, J., Demsar, D., Krogh, P.H., Dzeroski, S., 2007. Hierarchical classification of environmental factors and agricultural practices affecting soil fauna under cropping systems using Bt maize. Pedobiologia 51, 229-238.

Debeljak, M., Dzeroski, S., 2011. Decision Trees in Ecological Modelling. In: Jopp, F., Reuter, H., Breckling, B. (eds.), Modelling Complex Ecological Dynamics, Springer-Verlag Berlin Heidelberg. DOI 10.1007/978-3-642-05029-9_14.

Denef, K., Six, J., 2005. Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. European journal of soil science 56, 469-479.

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

Dexter, A. R., 1988. Advances in Characterization of Soil Structure. Soil & Tillage Research 11, 199-238.

Dexter, A. R., 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, A. R., 2004b. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. Geoderma 120, 215-225.

Dexter, A. R., 2004c. Soil physical quality: Part III. Unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma 120, 227-239.

Dexter, A. R., Czyz, E.A., 2007. Applications of S-theory in the study of soil physical degradation and its consequences. Land Degradation & Development 18, 369-381.

Dexter, A. R., Czyz, E.A., Richard, G., Reszkowska, A., 2008. A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma 143, 243-253.

Dexter, A. R., Horn, R., 1988. Effects of land use and clay content on soil structure as measured by Fracture Surface Analysis. Zeitschrift für Pflanzenernährung und Bodenkunde 151, 325-330.

Dexter, A. R., Richard, G., 2009. Tillage of soils in relation to their bi-modal pore size distributions. Soil & Tillage Research 103, 113-118.

Dexter, A.R., Birkas, M., 2004. Prediction of the soil structures produced by tillage. Soil & Tillage Research 79, 233-238.

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

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. p. 3-21. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (eds.), Defining Soil Quality for a Sustainable Environment. SSSA Spec. Pub. No. 35, Soil Sci. Soc. Am., Am. Soc. Argon., Madison, WI.

Doran, J.W., Parkin, T.B., 1996. Quantitative indicators of soil quality: a minimum data set. SSSA Special Publication 49, 25-38.

Doran, J.W., Sarrantonio, M., Liebig, M.A., 1996. Soil health and sustainability. In: Sparks, D.L. (Ed.), Advances in Agronomy,56, 1-54.

Dumon, M., Tolossa, A.R., Capon, B., Detavernier, C., Van Ranst, E., 2014. Quantitative clay mineralogy of a Vertic Planosol in southwestern Ethiopia: Impact on soil formation hypotheses. Geoderma 214, 184-196.

Duval, M.E., Galantini, J.A., Iglesias, J.O., Canelo, S., Martinez, J.M., Wall, L., 2013. Analysis of organic fractions as indicators of soil quality under natural and cultivated systems. Soil & Tillage Research 131, 11-19.

E

Elizalde, G., Viloria, J., Rosales, A., 2007. Geografía de Suelos de Venezuela. Fundación Empresas Polar. Geo Venezuela 2, pp. 402-537.

Elliott, E. T., Cambardella, C.A., 1991. Physical separation of soil organic matter. Agri. Eco. Environ. 34: 407-419.

Emerson, W.W., 1967. A classification of soil aggregates based on their coherence in water. Aust. J. Soil Res. 5, 47-57.

Eswaran, H., Lal, R., Reich, P., 2001. Land degradation: an overview. In: Bridges, E.M., I.D. Hannam, L.R. Oldeman, F.W.T. Pening de Vries, S.J. Scherr, and S. Sompatpanit (Ed.), Responses to Land degradation. Proc. 2nd. International Conference on Land Degradation and Desertification, Khon Kaen, Thailand Oxford Press, New Delhi, India, pp. 20-35.

Evans, J., Fernandez, I.J., Rustad, L.E., Norton, S.A., 2001. Methods for Evaluating Carbon Fractions in Forest Soils: A Review. The University of Maine. Maine Agricultural and Forest Experiment Station Technical Bulletin 178. 42 p.

Everaert, G., Pauwels, I.S., Boets, P., Buysschaert, F., Goethals, P.L.M., 2013. Development and assessment of ecological models in the context of the European Water Framework Directive: Key issues for trainers in data-driven modelling approaches. Ecological Informatics 17, 111-116.

F

Fagroud, M., Van Meirvenne, M., 2002. Accounting for soil spatial autocorrelation in the design of experimental trials. Soil Sci. Soc. Am. J. 66, 1134-1142.

FAO, 1980. Metodología provisional para la evaluación de la degradación de los suelos. Roma, Italy. 86 pp.

FAO, 2006. Guidelines for soil description. Available at: ftp://ftp.fao.org/agl/agll/docs/guidel_soil_descr.pdf (accessed 12.2012).

Fernández-Ugalde, O., Barré, P., Hubert, F., Virto, I., Girardin, C., Ferrage, E., Caner, L., Chenu, C., 2013. Clay mineralogy differs qualitatively in aggregate-size classes: clay-mineral-based evidence for aggregate hierarchy in temperate soils. European journal of soil science 64, 410-422.

Field, D.J., McKenzie, D.C., Koppi, A.J., 1997. Development of an improved Vertisol stability test for SOILpak. Australian Journal of Soil Research 35, 843-852.

Fortun, C., Fortun, A., 1989. Diversos aspectos sobre el papel de la materia orgánica humificada en la formación y estabilización de los agregados del suelo. Edafol. Agrobiol. 48: 185-204.

G

Gabriels, W., Goethals, P.L.M., Dedecker, A.P., Lek, S., De Pauw, N., 2007. Analysis of macrobenthic communities in Flanders, Belgium, using a stepwise input variable selection procedure with artificial neural networks. Aquatic Ecology 41, 427-441.

Garbout, A., Munkholm, L.J., Hansen, S.B., 2013. Tillage effects on topsoil structural quality assessed using X-ray CT, soil cores and visual soil evaluation. Soil & Tillage Research 128, 104-109.

Garg, R.N., Mazumdar, S.P., Chattaraj, S., Chakraborty, D., Singh, R., Kumari, M., Saha, B., Trivedi, S.M., Kaur, R., K.H. Kamble, Singh, R. K., 2009. Assessment of soil physical conditions: evaluation of a single value index. Journal of Agricultural physics 9, 9-19.

Gautronneau, Y., Manichon, H., 1987. Guide méthodique du profil cultural. CEREF/ISARA, Lyon, France.

Gee, G.W., Or, D., 2002. Particle-size analysis. In: Methods of Soil Analysis. 3rd ed. Part. 4: Physical Methods (ed. Dane, J.H. & Topp, G.C.), pp. 255-293, Soil Sci. Soc. Am., Madison.

Giarola, B.N.F., da Silva, A.P., Tormena, C.A., Guimarães, L. R.M., Ball, B.C., 2013. On the Visual Evaluation of Soil Structure: The Brazilian experience in Oxisols under no-tillage. Soil & Tillage Research 127, 60-64.

Gijsman, A.J., 1996. Soil aggregate stability and soil organic matter fractions under agropastoral systems established in native savanna. Aust. J. Soil Res. 34, 891-907.

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. Versión preliminar. Maracay. CENIAP. 164 p.

Goethals, P.L.M., Dedecker, A.P., Gabriels, W., Lek, S., De Pauw, N., 2007. Applications of artificial neural networks predicting macroinvertebrates in freshwaters. Aquatic Ecology 41, 491-508.

González de Juana, C., Iturralde, J. M., Picardi, X., 1980. Geología de Venezuela y de sus cuencas petrolíferas. Caracas, Venezuela. Ediciones FONINVES. 1.031 p.

Greenland, D.J., 1981. Soil management and soil degradation. Journal of Soil Science 32, 301-322.

Grover, B.L., 1955. Simplified air permeameters for soil in place. Soil Sci. Soc. Am. Proc. 19:414-418.

Guber, A.K., Rawls, W.J., Shein, E.V., Pachepsky, Y.A., 2003. Effect of soil aggregate size distribution on water retention. Soil Science 168, 223-233.

Guimarães, D.V., Gonzaga, M.I.S., da Silva, T.O., da Silva, T.L., da Silva Dias, N., Matias, M.I.S., 2013. Soil organic matter pools and carbon fractions in soil under different land uses. Soil & Tillage Research 126, 177-182.

Guimarães, L. R.M., Ball, B.C., Tormena, C.A., Balarezo Giarola, N.F., da Silva, A.P., 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil & Tillage Research 127, 92-99.

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use and Management 27, 395-403.

H

Hakansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil & Tillage Research 53, 71-85.

Hall, M., Frank, E., Holmes, G., Pfahringer, B., Reutemann, P., Witten, I.H., 2009. The WEKA Data Mining Software: An Update. SIGKDD Explorations, Volume 11 (1).

Haynes, R. J., Beare, M. H., 1997. Influence of six crop species on aggregate stability and some labile organic matter fractions. Soil Biology and Biochemistry 29(11), 1647-1653.

Haynes, R.J., 2000. Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. Soil Biology and Biochemistry 32, 211-219.

Heanes, D.L., 1984. Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. Communications in Soil Science and Plant Analysis 15, 1191–1213.

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

Hernández-Hernández, R.M., López-Hernández, D., 2002. El tipo de labranza como agente modificador de la materia orgánica: Un modelo para los suelos de sabana de los Llanos Centrales venezolanos. Interciencia 27:529-536.

Hillel, D., 1998. Environmental Soil Physics. Academic Press. San Diego. 771p.

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., Fleige, H., 2009. Risk assessment of subsoil compaction for arable soils in Northwest Germany at farm scale. Soil & Tillage Research 102, 201-208.

Horn, R., Smucker, A., 2005. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. Soil & Tillage Research 82, 5-14.

Horn, R., Taubner, H., Wuttke, M., Baumgartl, T., 1994. Soil physical properties related to soil structure. Soil & Tillage Research 30, 187-216.

Hu, W., Shao, M., Wang, Q., Fan, J., Horton, R., 2009. Temporal changes of soil hydraulic properties under different land uses. Geoderma 149, 355-366.

Hubert, F., Caner, L., Meunier, A., Ferrage, E., 2012. Unraveling complex< 2 µm clay mineralogy from soils using X-ray diffraction profile modeling on particle-size sub-fractions: Implications for soil pedogenesis and reactivity. American Mineralogist 97, 384-398.

I

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

Ingelmo, F., Jose Molina, M., Miguel de Paz, J., Visconti, F., 2011. Soil saturated hydraulic conductivity assessment from expert evaluation of field characteristics using an ordered logistic regression model. Soil & Tillage Research 115, 27-38.

IUSS Working Group WRB, 2006. World reference base for soil resources 2006.World Soil Resources Reports No. 103. FAO, Rome.

J

Jindaluang, W., Kheoruenromne, I., Suddhiprakarn, A., Singh, B.P., Singh, B., 2013. Influence of soil texture and mineralogy on organic matter content and composition in physically separated fractions soils of Thailand. Geoderma 195–196, 207-219.

K

Kahle, M., Kleber, M., Jahn, R., 2002. Review of XRD-based quantitative analyses of clay minerals in soils: the suitability of mineral intensity factors. Geoderma 109, 191-205.

Karlen, D.L., Ditzler, C.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma 114, 145-156.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61, 4-10.

Karlen, D.L., Stott, D.E., 1994. A framework for evaluating physical and chemical indicators of soil quality In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment, pp. 53-72.

Kay, B.D., Angers, D.A., Groenevelt, P.H., Baldock, J.A., 1988. Quantifying the influence of cropping history on soil structure. Canadian Journal of Soil Science 68, 359–368.

Kechavarzi, C., Dawson, Q., Leeds-Harrison, P.B., 2010. Physical properties of low-lying agricultural peat soils in England. Geoderma 154, 196-202.

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

Kerebel, A., Holden, N. M., 2013. Allocation of grass fields to Hybrid Soil Moisture Deficit model drainage classes using visual indicators. Soil & Tillage Research 127, 45-59.

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Methods of soil analysis Part 1. (ed. A. Klute), pp. 687–734. 2nd. ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Kodesova, R., Jirku, V., Kodes, V., Muehlhanselova, M., Nikodem, A., Zigova, A., 2011. Soil structure and soil hydraulic properties of Haplic Luvisol used as arable land and grassland. Soil & Tillage Research 111, 154-161.

Kutilek, M., 2004. Soil hydraulic properties as related to soil structure. Soil & Tillage Research 79, 175-184.

L

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.

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

Lal, R., 1991. Soil structure and sustainability. Journal of Sustainable Agriculture 1, 67-92.

Lal, R., Shukla, M.K., 2004. Principles of Soil Physics. Marcel Dekker, New York. CRC Press. ISBN 0-8247-5324-0.

Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. In: J. Dumanski, E. Pushparajah, M. Latham, and R. Myers (Eds.) International Workshop on Evaluation for Sustainable Land Management in the Developing World. Vol. 2: Technical Papers. Proc. Int. Workshop., Chiang Rai, Thailand. 15-21 Sept. 1991. Int. Board for Soil Res. and Management, Bangkok, Thailand.

Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodability: I. Theory and methodology. European Journal of Soil Science 47, 425-437.

Lee, S.B., Lee, C.H., Jung, K.Y., Park, K.D., Lee, D., Kim, P.J., 2009. Changes of soil organic carbon and its fractions in relation to soil physical properties in a long-term fertilized paddy. Soil & Tillage Research 104, 227-232.

Leroy, B.L.M., Herath, H.M.S.K., 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 Sci. Util. 16, 43-51.

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(5), 1603-1609.

Lilburne, L., Sparling, G., Schipper, L., 2004. Soil quality monitoring in New Zealand: development of an interpretative framework. Agriculture, Ecosystems & Environment 104, 535-544.

Lilly, A., Nemes, A., Rawls, W.J., Pachepsky, Y.A., 2008. Probabilistic approach to the identification of input variables to estimate hydraulic conductivity. Soil Sci. Soc. Am. J. 72, 16-24.

Lima, A.C.R., Brussaard, L., Totola, M.R., Hoogmoed, W.B., de Goede, R.G.M., 2013. A functional evaluation of three indicator sets for assessing soil quality. Applied Soil Ecology 64, 194-200.

Lin, H.S., McInnes, K.J., Wilding, L.P., Hallmark, C.T., 1999a. Effects of soil morphology on hydraulic properties: I. Quantification of soil morphology. Soil Sci. Soc. Am. J. 63, 948-954.

Lin, H.S., McInnes, K.J., Wilding, L.P., Hallmark, C.T., 1999b. Effects of soil morphology on hydraulic properties: II. Hydraulic pedotransfer functions. Soil Sci. Soc. Am. J. 63, 955-961.

Logsdon, S.D., Jaynes, D.B., 1993. Methodology for determining hydraulic conductivity with tension infiltrometers Soil Sci. Soc. Am. J. 57, 1426-1431.

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil & Tillage Research 70, 1-18.

Lozano, Z., Rivero, C., Bravo, C., Hernández, R. M., 2011. Fracciones de la materia orgánica del suelo bajo sistemas de siembra directa y cultivos de cobertura. Rev. Fac. Agron. LUZ. 28, 35-56.

Lützow, M.V., Kögel-Knabner, I., Kschmitt, K.E., Matzner, E., Guggenberger, G., Marschner, B., Flessa. H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions: a review. European Journal of Soil Science 57: 426–445.

M

Maia, C.E., 2011. Use of the s-index to evaluate soil physical quality. Revista Brasileira De Ciencia Do Solo 35, 1959-1965.

Manel, S., Williams, H.C., Ormerod, S.J., 2001. Evaluating presence-absence models in ecology: the need to account for prevalence. Journal of Applied Ecology 38, 921-931.

Márquez, C.O., Garcia, V. J., Cambardella, C. A., Schultz, R. C., Isenhart, T. M., 2004. Aggregate-size stability distribution and soil stability. Soil Sci. Soc. Am. J. 68, 725 - 735.

McGarry, D., 2006. A methodology of a visual soil field assessment tool to support, enhances, and contributes to the LADA program. FAO, Roma. 50 p. ftp://ftp.fao.org/agl/agll/lada/vsfast_methodology.pdf. [Last accessed 19 May 2011].

McKeague, J.A., Wang, C., Coen, G.M., 1986. Describing and interpreting the macrostructure of mineral soils – a preliminary report. Technical Bulletin. 1986-2E. LRRI contribution 84-50. 47p.

McKenzie, D.C. (Ed.), 1998. SOILpak for Cotton Growers. third ed. NSW Agriculture, Orange.

McKenzie, D.C., 2001. Rapid assessment of soil compaction damage - I. The SOILpak score, a semi-quantitative measure of soil structural form. Australian Journal of Soil Research 39, 117-125.

McKenzie, D.C., 2013. Visual soil examination techniques as part of a soil appraisal framework for farm evaluation in Australia. Soil & Tillage Research 127, 26-33.

McKenzie, N., Jacquier, D., 1997. Improving the field estimation of saturated hydraulic conductivity in soil survey. Australian Journal of Soil Research 35, 803-825.

McQueen, D. J., Shepherd, T. G., 2002. Physical changes and compaction sensitivity of a fine-textured, poorly drained soil (Typic Endoaquept) under varying durations of cropping, Manawatu Region, New Zealand. Soil & Tillage Research 63, 93-107.

Minasny, B., Hartemink, A.E., 2011. Predicting soil properties in the tropics. Earth-Science Reviews 106, 52-62.

Mooney, S.J., Tams, A.R., Berry, P.M., 2006. A reliable method for preserving soil structure in the field for subsequent morphological examinations. Geoderma 133, 338-344.

Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 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 & Tillage Research 103, 178-187.

Mueller, L., Shepherd, G., Schindler, U., Ball, B.C., Munkholm, L.J., 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 & Tillage Research 127, 74-84.

Munkholm, L.J., Heck, R.J., Deen, B., 2013. Long-term rotation and tillage effects on soil structure and crop yield. Soil & Tillage Research 127, 85-91.

Munkholm, LJ., 2000. The spade analysis - a modification of the qualitative spade diagnosis for scientific use. DIAS-report No. 28 Plant Production, Danish Institute of Agricultural Sciences 40 pp.

Murphy, B.W., Crawford, M.H., Duncan, D.A., McKenzie, D.C., Koen, T.B., 2013. The use of visual soil assessment schemes to evaluate surface structure in a soil monitoring program. Soil & Tillage Research 127, 3-12.

N

Nascente, A.S., Li, Y.C., Crusciol, C.A.C., 2013. Cover crops and no-till effects on physical fractions of soil organic matter. Soil & Tillage Research 130, 52-57.

Newell-Price, J.P., Whittingham, M.J., Chambers, B.J., Peel, S., 2013. Visual soil evaluation in relation to measured soil physical properties in a survey of grassland soil compaction in England and Wales. Soil & Tillage Research 127, 65-73.

Nguyen, M. P., Le Van, K., Cornelis, W., 2014. Using categorical soil structure information to improve soil water retention estimates of tropical delta soils. Soil Research 52 (5):443-452.

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

Nimmo, J.R., Perkins, K.S., 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.

Novotny, E., Blum, W., Gerzabek, M., Mangrich, A., 1999. Soil management system effects on size fractionated humic substances. Geoderma 92, 87-109.

NRCS (Natural resources conservation services), 2003. Saturated Hydraulic Conductivity: Water Movement Concepts and Class History. United States Department of Agriculture. Available at: http://soils.usda.gov/technical/technotes/note6.html (Verified August 8, 2013).

O

Osman, K.T., 2013. Soil degradation, conservation and remediation. Springer.

Ouhadi, V., Yong, R., 2003. Impact of clay microstructure and mass absorption coefficient on the quantitative mineral identification by XRD analysis. Applied clay science 23, 141-148.

P

Pachepsky, Y.A., Rawls, W.J., 2003. Soil structure and pedotransfer functions. European Journal of Soil Science 54, 443-451.

Pagliai, M., Vignozzi, N., 2002. The soil pore system as an indicator of soil quality. Advances in GeoEcology, 35, 69-80.

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

Peerlkamp, P.K., 1959. A visual method of soil structure evaluation. Meded. v.d. Landbouwhogeschool en Opzoekingsstations van de Staat te Gent. XXIV, 24, 216-221.

Pierce, F.J., Larson, W.E., Dowdy, R.H., Graham, W.A.P., 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, C. J. M. G., 1992. Fertility of soils : A future for farming in the West African Savannah. Springer-Verlag, Berlin, Germany.

Pla, I., 1990. La degradación y el desarrollo agrícola de Venezuela. Agronomía Tropical 40 (1-3), 2-27.

Pojasok, T., Kav, B. D, 1990. Assessment of a combination of wet sieving and turbidimetry to characterize the structural stability of moist aggregates. Can. J. Soil Sci.70, 33-42.

Puget, P., Chenu, C., Balesdent, J., 1995. Total and young organic matter distributions in aggregates of silty cultivated soils, European Journal of Soil Science 46, 449-459.

Pulido Moncada, M., Flores, B., Rondón, T., Hernández-Hernández, R. M., Lozano, Z., 2010. Cambios en fracciones dinámicas de la materia orgánica de dos suelos, Inceptisol y Ultisol, por el uso con cultivo de citricas. Bioagro 22, 201-210.

Pulido Moncada, M., Gabriels, D., Lobo, D., De Beuf, K., Figueroa, R., Cornelis, W.M., 2014. A comparison of methods to assess susceptibility to soil sealing. Geoderma 226–227, 397-404.

Pulido Moncada, M., Lobo, L.D., Lozano, P.Z., 2009. Association between soil structure stability indicators and organic matter in Venezuelan agricultural soils. Agrociencia 43, 221-230.

R

Rawlins, B.G., Wragg, J., Lark, R.M., 2013. Application of a novel method for soil aggregate stability measurement by laser granulometry with sonication. European Journal of Soil Science 64, 92-103.

Raymond, F. I., 2002. The Australian Soil Classification (Revised ed.). Collingwood, Victoria: CSIRO Publishing. ISBN 0-643-06898-8.

RETC (RETention Curve), 2008. RETC model. USDA-ARS U.S. Salinity Laboratory, Riverside, CA, USA. http://ars.usda.gov/Services/docs.htm?docid=8952.

Reynolds, R.C., 1986. The Lorentz-polarisation factor and preferred orientation in oriented clay aggregates. Clays Clay Miner. 43, 359-367.

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., Lu, X., 2002. Indicators of good soil physical quality: density and storage parameters. Geoderma 110(1), 131-146.

Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S., 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64, 478-484.

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A., Yang, X.M., 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152, 252-263.

Reynolds, W.D., Drury, C.F., Yang, X.M., Fox, C.A., Tan, C.S., Zhang, T.Q., 2007. Land management effects on the near-surface physical quality of a clay loam soil. Soil & Tillage Research 96, 316-330.

Reynolds, W.D., Elrick, D.E., 1991. Determination of hydraulic conductivity using a tension infiltrometer. Soil Sci. Soc. Am. J. 55, 633-639.

Roger-Estrade, J., Richard, G., Caneill, J., Boizard, H., Coquet, Y., Defossez, P., Manichon, H., 2004. Morphological characterisation of soil structure in tilled fields: from a diagnosis method to the modelling of structural changes over time. Soil & Tillage Research 79, 33-49.

Roger-Estrade, J., Richard, G., Dexter, A. R., Boizard, H., Tourdonnet, S., Bertrand, M., Caneill, J., 2009. Integration of soil structure variations with time and space into models for crop management. A review. Agronomy for Sustainable Development, 29, 135-142.

Rohošková, M., Valla, M., 2004. Comparison of two methods for aggregate stability measurement – a review. Plant soil environ. 50 (8), 379-382.

S

Saey, T., Simpson, D., Vitharana, U.W.A., Vermeersch, H., Vermang, J., Meirvenne, M.V., 2008. Reconstructing the paleotopography beneath the loess cover with the aid of an electromagnetic induction sensor. Catena 74, 58‑64.

Schiettecatte, W., Gabriels, D., Verbist, K., Oltenfreiter, G., Vermang, J., Bogman, P., Pulido Moncada, M., 2012. Soil erosion processes and control. Excursion guide. Ghent University, Belgium.

Schnitzer, M., Schuppli, P., 1989. Method for the sequential extraction of organic-matter from soils and soil fractions. Soil Sci. Soc. Am. J. 53, 1418-1424.

Scholefield, D., Patto, P.M., Hall, D.M., 1985. Laboratory research on the compressibility of 4 topsoils from grassland. Soil & Tillage Research 6, 1-16.

Schultz, B.B., 1985. Levene's test for relative variation. Systematic Biology 34 (4) 449‑456.

Sequi, P., De Nobili, M., Leita, L., Cercigni, G., 1986. A new index of humification. Agrochimical 30:175.

Seybold, C.A., Herrick, J.E., 2001. Aggregate stability kit for soil quality assessments. Catena 44, 37-45.

Shepherd, T. G., Saggar, S., Newman, R. H., Ross, C. W., Dando, J. L., 2001. Tillage-induced changes to soil structure and organic carbon fraction in New Zealand soils. Aust. J. Soil Res. 39: 465-489.

Shepherd, T.G., 2000. Visual soil assessment. Volume 1. Field guide for cropping and pastoral grazing on flat to rolling country. Horizins.mw/Landcare Research, Palmerston North. 84p.

Shepherd, T.G., 2009. Visual Soil Assessment. Volume 1. Field Guide for Pastoral Grazing and Cropping on Flat to Rolling Country, 2nd ed. Horizons Regional Council, Palmerston North, 119 pp.

Shepherd, T.G., Park, S.C., 2003. Visual Soil Assessment: A management tool for dairy farmers. In: Brookes, I.M. ed. Proceedings of the 1st Dairy Conference. Continuing Massey University Dairyfarming Annual (Volume 55) Dexcel's Ruakura Dairyfarmers' Conference, April 7–9, 2003, Rotorua. pp 111–123.

Shukla, M.K., Lal, R., Ebinger, M., 2003. Tillage effects on physical and hydrological properties of a typic argiaquoll in Central Ohio. Soil Science 168, 802-811.

Shukla, M.K., Lal, R., Ebinger, M., 2006. Determining soil quality indicators by factor analysis. Soil & Tillage Research 87, 194-204.

Silva Guedes, E.M., Fernandes, A.R., de Lima, H.V., Serra, A.P., Costa, J.R., Guedes, R.d.S., 2012. Impacts of different management systems on the physical quality of an amazonian oxisol. Revista Brasileira De Ciencia Do Solo 36, 1269-1277.

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 Research 79, 7–31.

Six, J., Feller, C., Denef, K., Ogle, S., de Moraes Sa, J.C., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils-Effects of no-tillage. Agronomie 22, 755-775.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681-689.

Sleutel, S., Kader, M.A., Begum, S.A., De Neve, S., 2010. Soil-organic-matter stability in sandy cropland soils is related to land-use history. Journal of Plant Nutrition and Soil Science 173, 19-29.

Sleutel, S., Kader, M.A., Leinweber, P., D'Haene, K., De Neve, S., 2007. Tillage management alters surface soil organic matter composition: A pyrolysis mass Spectroscopy study. Soil Sci. Soc. Am. J. 71, 1620-1628.

Soil Science Society of America (Ed.), 2008. Glossary of Soil Science Terms 2008. ASA-CSSA-SSSA. available at https://www.soils.org/publications/soils-glossary/#.

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

SPSS 15.0 Command Syntax Reference 2006, SPSS Inc., Chicago,USA.

T

Tavares, J. F., Ralisch, R., Guimarães, M. F., Medina, C.C., Balbino, L.C., Neves, C.S.V.J., 1999. Método do perfil cultural para avaliação do estado físico de solos em condições tropicais. Revista Brasileira de Ciencia do Solo 23, 393-399.

Tennant, D., 1975. A test of a modified line intersect method of estimating root length. Journal of Ecology 63, 955-1001.

Topp, G., Reynolds, W., Cook, F., Kirby, J., Carter, M., 1997. Physical attributes of soil quality. Developments in Soil Science 25, 21-58.

Tormena, C.A., Silva, Á.P.d., Imhoff, S.D.C., Dexter, A.R., 2008. Quantification of the soil physical quality of a tropical oxisol using the S index. Scientia Agricola 65, 56-60.

V

Van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Van Lier, J., 2012. Indice S: um indicador da qualidade fisica do solo?. In: Boletim informativo da Sociedade Brasileira de Ciencia do Solo 37 (3):24-27.

Van Lier, J., 2014. Revisiting the S-index for soil physical quality and its use in Brazil. Revista Brasileira de Ciência do Solo 38, 1-10.

Van Ranst, E., Verloo, M., Demeyer, A., Pauwels, J.M., 1999. Manual for the soil chemistry ad fertility laboratory. Analytical methods for soils and plants; equipment and management of consumables. Ghent University, Ghent, Belgium.

Van Reeuwijk, L.P., 1993. Procedures for soil analyses. 4th ed. International Soil Reference and Information Centre, the Netherlands.

Vanongeval, L., Bries, J., Meykens, J., Boon, W., Vandendriessche, H., Geypens, M., 2000. The chemical soil fertility of the Belgian cropland- and pasture areas (1996ą1999) [in Dutch]. Bodemkundige Dienst van BelgieČ vzw.

Verbist, K.M.J., Cornelis, W.M., Torfs, S., Gabriels, D., 2013. Comparing methods to determine hydraulic conductivities on stony soils. Soil Sci. Soc. Am. J. 77, 25-42.

Vereecken, H., Weynants, M., Javaux, M., Pachepsky, Y., Schaap, M.G., van Genuchten, M.T., 2010. Using pedotransfer functions to estimate the van Genuchten-Mualem soil hydraulic properties: A Review. Vadose Zone Journal 9, 795-820.

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.

Vermang, J., 2012. Erosion Processes and Physical Quality of Loamy Soils as Affected by Reduced Tillage. Ghent University. Faculty of Bioscience Engineering, Ghent, Belgium.

Vizitiu, O.P., Calciu, I., Pănoiu, I., Simota, C., 2011. Soil physical quality as quantified by S index and hidrophysical indices of some soils from Argeş hydrographic basin. Research Journal of Agricultural Science 43, 249-256.

W

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.

Walkley, A., Black, I.A., 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 Sci. 63, 251-263.

Witten, I.H., Frank, E., 2005. Data mining: practical machine learning tools and techniques. Morgan Kaufmann, San Francisco, USA, 560 pp.

Wooding, R.A., 1968. Steady infiltration from a shallow circular pond. Water Resources Research 4, 1259.

Y

Yemefack, M., Jetten, V., G., Rossiter, D., G., 2006. Developing a minimum data set for characterizing soil dynamics in shifting cultivation systems. Soil & Tillage Research 86, 84–98.

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

Young, I., Crawford, J., Rappoldt, C., 2001. New methods and models for characterising structural heterogeneity of soil. Soil & Tillage Research 61, 33-45.

Z

Zevin, L., Viaene, W., 1990. Impact of clay particle orientation on quantitative clay diffractometry. Clay Minerals 25, 401-418.

Summary

Soil degradation is a very common phenomenon in many countries worldwide, implying that much of the productive agricultural area of the planet has a 'poor' soil quality. A key factor of a soil's quality is its structure, which is a complex soil property that affects physical, chemical and biological properties and processes. Many methods and indices have been developed for assessing soil structure, but selecting a suitable minimum data set of soil structural quality (SSQ) indicators remains difficult.

The aim of this dissertation was therefore to test and develop SSQ indicators, based on the comparison of different methods, for the improvement of framework for assessing soil quality (agricultural interest) to contribute to soil conservation and sustainable agriculture approaches. This was achieved by determining similarities between and within direct and indirect methods and indices for assessing soil structure in both 'tropical' and 'temperate' medium-textured soils. Additionally, the evaluation of aggregate stability and soil structure were combined with data of soil analysis in order to assess the SSQ more comprehensively and accurately.

This dissertation was divided into three parts. Part I was focused on the assessment of SSQ based on aggregate stability; Part II presented the evaluation of the use of visual examination methods for assessing SSQ, and Part III examined integrated and simple approaches for assessing SSQ.

In Part I, focusing on the influence of wet sieving methods on SSQ assessment, an evaluation of the performance of different aggregate stability methods for detecting the SSQ was conducted. Results showed that wet sieving using the well-known fast wetting methods of Kemper and Rosenau and of Le Bissonnais rendered similar results in both tropical and temperate environments. The mean weight diameter values of these methods can be considered as a dependable indicator of SSQ for comparing different soils. Due to aggregate stability results were in some cases inconsistent with other soil physical indicators, it should be used judiciously and in combination with other indicators for a more integrated assessment of the soil structure.

Because the selection of a proper method for assessing aggregate stability under different conditions is complex, aggregate stability assessment might be combined with two of the main factors controlling aggregate formation and stabilization, viz. soil organic matter (SOM) and clay mineralogy. Therefore, these two main factors were the main focus of two studies. First, in both 'tropical' and 'temperate' soils, it was discussed the use of chemical and physical fractions of SOM instead of SOM *per se*, as they are more sensitive indicators of aggregate stability. Results showed that SOM content, SOM fractions and aggregate stability were clearly affected by soil management or land use regardless of the origin of the soils. It was also demonstrated that SOM fractions did not correlate better to aggregate stability than SOM *per se*. However, the differences in SOM

fractions observed among the studied soils support that they can be used as indicators to obtain more insights in SOM changes as a consequence of agricultural practices.

The main objective of the second study was to assess the mineral composition of the clay fraction within different aggregate sizes in three ‘tropical’ soils with different degree of weathering. Results showed that the mineralogical composition of the clay fraction did not vary within aggregate sizes. The absence of variation in clay mineralogy does not support the hypothesis of a selective contribution of the clay mineralogy to the aggregate hierarchy. The results did not differ when different fractionation methods for aggregate size distribution determination were used. It can be concluded that, the effect of the fractionation method on aggregate stability is more likely to be related with SOM constituents than to a selective contribution of the clay mineralogy.

In Part II of this dissertation, the soil structural form was furthermore assessed by comparison of the performance of visual examination methods in both tropical and temperate environments. First, the applicability of three visual examination methods was tested in ‘tropical’ soils. The results showed that the soil quality scoring procedure (SQSP), the visual evaluation of soil structure (VESS), and the visual soil assessment (VSA), were able to detect an unfavourable SSQ on soils under conventional tillage or animal trampling with low SOM content. In the ‘tropical’ soils there were also significant relationships between the visual assessment and soil physical properties, as has been reported for ‘temperate’ soils. It was found that for those cases where the rooting system cannot be evaluated, VSA and VESS are the most appropriate methods for assessing the SSQ. It is also important to mention that, the rating of the indicator ‘number of earthworms’ should be adjusted for ‘tropical’ soils to improve the accuracy of the VSA method.

A second study presented in Part II, focussed on a comprehensive study of the relationships between VESS, VSA, the visual assessment of aggregate stability and the visual type of aggregates index, with soil physical properties on soils with contrasting textures and under different land uses in a temperate environment. Results showed that the visual examination methods indicated differences in SSQ due to land use, which were confirmed by soil physical properties. Moreover, in the silt loam soil, the visual examinations were mostly related to properties such as SOM, plant available water capacity (PAWC), aggregate stability and porosity, whereas in the sandy loam soil they were mostly associated with water flow properties. From this, it was concluded that visual examinations are reliable semiquantitative methods to assess SSQ and could be considered as promising visual predictors of soil physical properties.

The validation of visual examination methods for assessing SSQ was conducted both before flowering and after harvesting in contrasting textured soil in the temperate environment. Results showed that soils under no-till resulted in the best SSQ compared to conventional tillage (CM) after harvesting, whereas SSQ of CM was better before cereal flowering than after harvesting. The visual examination methods were hence, responsive in evaluating the effect of land use on SSQ, and are capable of representing structural dynamics (related to soil management) in an agricultural cycle. The lack of interrelationships, between all the soil physical properties and the visual scores, however confirms the need to conduct an integrated assessment of the SSQ. To this end, a judiciously selection of a minimum data set of SSQ indicators should be conducted omitting redundant material.

In order to this, Part III of the dissertation presented a study where it was examined the use of integrated approaches and another where it was discussed the inconsistency of unique indicators of SSQ. Regarding the assessment of integrated approaches to evaluate SSQ, quantitative and qualitative data of soil structure, in both tropical and temperate environments, were used to grow classification trees and model trees. Results showed that the discriminating variables related to SSQ differ between geographic areas, highlighting the importance of the recognition of site-specific relationships. Furthermore, decision trees showed to be promising tools in demonstrating that the SSQ description required for merging morphological, physical and chemical properties for minimum data set of SSQ indicators. This statistical tool seems also promising for representing structural dynamics.

On the other hand, a more simplistic approach for assessing SSQ was tested, viz. S index. Comparisons of SSQ class and relationships between indicators were used to judge S' SSQ designation. For the studied medium-textured 'tropical' and 'temperate' soils, S was inconsistent at classifying SSQ compared to other indicators. Moreover, it was demonstrated that scores from visual examinations have at least similar resolution to the other indicators of SSQ evaluated, and that S did not correlate better to other soil physical indicators than visual examination. This demonstrates that the proposed S index is not generally valid and does not apply for any soil condition. Other indicators such as porosity parameters from the water release curve were more consistent indicators of SSQ than S.

The results of this dissertation allow drawing the conclusion that an appropriate minimum data set of indicators of SSQ should be based on an integrated assessment of aggregate stability, structural form and soil morphological related properties. Because of site-specific relationships factors such soil type, agricultural practices and climate should be considered as a part of the framework when assessing soil structural quality.

Curriculum vitae

Mansonia Alejandra Pulido Moncada
E-mail: mansoniapulido@gmail.com
Gender: Female
Nationality: Venezuelan
Languages: Spanish (native), English

Education

2004-2006	Magister Scientiarum in Soil Science. Universidad Central de Venezuela, Venezuela
1998-2003	Agronomist Engineer. Universidad Central de Venezuela, Venezuela

Work experience

2006 – Now	Lecturer – researcher (full time) at the Edaphology Department. Faculty of Agronomy, Universidad Central de Venezuela, Venezuela.
2004-2006	Lecturer (8 hours per week) on the regular courses: General Edaphology and Applied Edaphology I at the Edaphology Department. Faculty of Agronomy. Universidad Central de Venezuela, Venezuela.

Research Activity

Journal Articles:

International Journals

Pulido Moncada, M., Ball, B.C., Gabriels, D., Lobo, D., Cornelis, W.M., Evaluation of Soil Physical Quality Index S for Some "Tropical" and "Temperate" Medium Textured Soils. Soil Sci. Soc. Am. J., doi:10.2136/sssaj2014.06.0259.

Pulido Moncada, M., Gabriels, D., Cornelis, W. M., 2014. Data-driven analysis of soil quality indicators using limited data. Geoderma 235-236, 271–278.

Pulido Moncada, M., Gabriels, D., Lobo, D., De Beuf, K., Figueroa, R., Cornelis, W. M., 2014. A comparison of methods to assess susceptibility to soil sealing. Geoderma 226-227, 397-404.

Pulido Moncada, M., Helwig Penning, L., Timm, L. C., Gabriels, D., Cornelis, W. M., 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. Soil & Tillage Research 140, 20-28.

Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, B. J. C., Cornelis, W. M., 2014. Visual field assessment of soil structural quality in tropical soils. Soil & Tillage Research 139, 8-18.

Pulido Moncada, M., Gabriels, D., Cornelis, W., Lobo, D. 2013. Comparing aggregate stability tests for soil physical quality indicators. Land Degradation & Development. DOI: 10.1002/ldr.2225

Pulido Moncada, M., Lobo L. D., Lozano P. Z. 2009. Association between soil structure stability indicators and organic matter in Venezuelan agricultural soils. Agrociencia 43,221-230.

National Journals (In Spanish)

Hernández-Hernández, R. M., Pulido Moncada, M., Caballero, R. Cabriales, E., Castro, I., Ramírez, E., Rondón, T., Ferrer, J., Flores, B., Mendoza, B., 2013. Influencia del cambio de uso de la tierra sobre las sustancias húmicas y la estabilidad de los agregados en suelos de sabanas y bosques tropicales. Rev. Fac. Agron. (LUZ), 30:551-572.

Rivero, C., Cabrales, E., Santana, G., Rivas, M., Pulido Moncada, M., Rey, J.C., Lobo, D., Lozano, Z., Araque, H. 2013. Efecto del pastoreo de cerdos sobre las fracciones de nitrógeno, carbono y fósforo del suelo. Temas agrarios, 18 (1):23-33.

Rodríguez, M. A., Pulido Moncada, M., Rey, B. J.C., Lobo, L. D., Araque, H., Rivero, C. 2010. Efecto del pisoteo en sistemas de producción de cerdos a campo sobre propiedades del suelo. Agronomía Tropical. 60(2): 119-130.

Pulido Moncada, M., Flores, B., Rondón, T., Hernández- Hernández, R. M., Lozano, Z. 2010. Cambios en las fracciones dinámicas de la materia orgánica de dos suelos, Inceptisol y Ultisol, por el uso con cultivos de cítricas. Bioagro 22 (3): 201-210.

Lobo, D., Pulido Moncada, M. 2006. Métodos e índices para evaluar la estabilidad estructural de los suelos. Venesuelos 14: 22-37.

Gabriels, D., Lobo, D., Pulido Moncada, M. 2006. Métodos para determinar la conductividad hidráulica saturada y no saturada de los suelos. Venesuelos 14:7-22.

Pulido Moncada, M., Lobo, D., Lozano, Z., Hernández, R. 2002. Relación entre propiedades físicas de un suelo de los Llanos Centrales y el desarrollo de raíces de maíz (Zea mays L.) en sistemas mejorados maíz-ganado. Venesuelos 10 (1-2): 61-66.

Conference Contributions

International conference: oral presentation

Pulido Moncada, M., Cornelis, W., Gabriels, D., Timm, L.C., Lobo, D. 2014. Validation of morphological approaches for assessing soil structural quality of soils with contrasting characteristics. ISTRO VSEE-SC workshop, promoted by group F and B of ISTRO. Maringa, Brazil. 26 – 29 May.

Pulido Moncada, M., Rodríguez, A., Rey, J., Lobo, D., Araque, H. (In Spanish) Efecto del pisoteo en sistemas de producción de cerdos a campo sobre las propiedades físicas del suelo. XVIII Latin America Congress of Soil Science. San José, Costa Rica, 16 to 20 November 2009.

Pulido Moncada, M. (In Spanish) Indicadores de sellado y encostrados en suelos agrícolas de Venezuela bajos tres ambientes de evaluación. IX Latin America College on Soil Physics (ELAFIS). Cuenca, Ecuador. 01 to 10 October 2007.

Pulido Moncada, M. Sealing and crusting susceptibility in soils with different granulometry evaluated through indicators to three scales of study. College on Soil Physics, in the Abdus Salam International Centre for Theoretical Physics, Trieste - Italy, 12 to 30 September 2005.

International conference: poster

Pulido Moncada, M., Gabriels, D., Cornelis, W., Lobo, D., Rey, J.C. The use of visual field assessment of soil structural quality in tropical soils. College on Soil Physics 30th Anniversary. Trieste, Italy, 25 February-1 March 2013.

Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, J.C., Cornelis, W., Field assessment of soil structural quality in tropical conditions. The fourth Conference on Desertification and Land Degradation. Ghent, Belgium, June 19, 2012.

Pulido Moncada, M., Lobo, D., Gabriels, D., Rey, J.C., Sleutel, S., De Neve, S., Aggregate stability of Venezuelan soils sensitive to surface sealing and crusting. 6th International Congress of ESSC. Thessaloniki, Greece, May, 2011.

Pulido Moncada, M., Lobo, D., Figueroa, R., Gabriels, D., Soil sealing indicator for agricultural soils in Venezuela. 6th International Congress of ESSC. Thessaloniki, Greece, May, 2011.

Rivas, A. M. A., Arias, H., Rivero, C., Pulido Moncada, M., Rey, J. C., Lobo, D., Lozano, Z. (In Spanish) Evaluación del impacto del manejo de sistema de producción de cerdos a campo sobre la materia orgánica de un suelo. XVIII Latin America Congress of Soil Science. San José, Costa Rica, 16 to 20 November 2009.

Santana, G., Rivero C., Pulido Moncada, M., Rey, J. C., Lobo, D., Lozano, Z. (In Spanish) Evaluación del impacto del manejo de sistemas de producción de cerdos a campo sobre el N del suelo y otras variables. XVIII Latin America Congress of Soil Science. San José, Costa Rica, 16 to 20 November 2009.

Pulido Moncada, M., Lobo, D., Lozano, Z. (In Spanish) Asociación entre indicadores de estabilidad estructural y tipos de materia orgánica en suelos agrícolas. XVII Latin-America Congress of Soil Science. León- Guanajuato, México. 17 to 21 de September 2007.

National conference: poster (In Spanish)

Lobo, D., Pulido Moncada, M., Rey, J.C., Rodríguez, G., Martínez, G. Índice de productividad de Pierce y el vigor en plantaciones de bananos (*Musa* AAA). XIX Venezuelan congress of soil science. Calabozo, Venezuela 21 - 25 November 2011.

Pulido Moncada, M., Flores, B., Rondón, T., Hernández, R.M., Lozano, Z. Cambios en la calidad de dos suelos, inceptisol y ultisol, por el uso de cultivo de cítricas. XVIII Venezuelan Congress of Soil Science. Zulia, Venezuela 09 to 13 March 2009.

Pulido Moncada, M., Lobo, D., Lozano, Z., Hernández, R.M. Relación entre propiedades físicas de un suelo de los Llanos Centrales y el desarrollo de raíces de maíz (*Zea mays* L.) en sistemas mejorados maíz-ganado. XVII Venezuelan Congress of Soil Science. Maracay, Venezuela 17 to 20 May 2005.

International Mobility

20 January - 20 April, 2014	Research collaboration at the Scotland's Rural College (SRUC), Edinburgh, Scotland. Research activities involved the design and implementation of experiments in the field and laboratory to study soil physical properties in relation to greenhouse gas flux trends currently being measured at SRUC's farm grassland research sites.
01 July – 10 Augusts, 2008	Internship at the Department of Soil Management, Faculty of Bioscience Engineering, Ghent University, Belgium. Research topic: Determination of soil organic matter associated with different size fractions by the method of dispersion with ultrasound and sedimentation, as part of a project entitled 'Relationship between structural stability and selected intrinsic characteristics of soil surface sealing problems'.

Supervised dissertations

Letiane Helwig Penning (2013) Comparison of standard procedures and visual field assessment for assessing soil structure quality of soils with contrasting textures. Internship exchange dissertation. Ghent University, Belgium.

Adriana Rodriguez (2008) Efecto del pisoteo de cerdos a campo sobre las propiedades físicas del suelo (Effect of pig trampling on soil physical properties). Bachelor's dissertation. Universidad Central de Venezuela, Venezuela.

Research Projects

Belgium

2010-2014 Evaluating indicators for assessing soil structural quality under different environments**.** Consejo de Desarrollo Científico y Humanístico (CDCH-UCV) and Ghent University. Project leader and coordinator.

Venezuela

2007-2008 Relationship between structural stability and some chemical and physical soil characteristics in agricultural soils with surface sealing and crusting (In spanish: Asociación entre la estabilidad estructural y algunas características físicas y químicas en suelos agrícolas venezolanos con problemas de sellado y encostrado). Project leader and coordinator. CDCH-UCV PI 01-00-6886-2007

2008-2009 Effect of pig trampling on soil quality (In Spanish: Impacto del manejo de sistemas de producción de cerdos a campo sobre el suelo). Co-researcher. CDCH-UCV PG 01-00-71432008

Other Activities

- Reviewer of Soil Science Society of American Journal and Soil & Tillage Research Journal (2014).
- Member of the Commission of Soil Properties and Processes of the Soil Science Society of Venezuela. 2009-2011.
- Coordinator of the Soil Physics Commission of the Soil Science Society of Venezuela. 2005-2009.
- Member of Organizing Committee of XVII Venezuelan Congress of Soil Science.

Honours and awards

- Member of the Stimulus Programme to Research (PEI) Level A, which is given by the Observatorio Nacional de Ciencia, Tecnología e Innovación (ONCTI) of Venezuela, 2011.
- Doctoral scholarship from CDCH-Universidad Central de Venezuela, 2010-2014.
- Member of the Research Promotion Program (PPI) Level candidate, which is given by the Observatorio Nacional de Ciencia, Tecnología e Innovación (ONCTI) of Venezuela, 2007.
- Master fellowship from CDCH-Universidad Central de Venezuela, 2004-2006.

Memberships

- International Soil Tillage Research Organization (ISTRO). Certificate № 834
- College of Engineers of Venezuela, CVI №: 190693
- Soil Science Society of Venezuela