Ecological Indicators 104 (2019) 686–694

Contents lists available at ScienceDirect

Ecological Indicators

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

Soil structure quality indicators and their limit values

Alice Johannes[a,*], Peter Weisskopf[a], Rainer Schulin[b], Pascal Boivin[c]

[a] Swiss Federal Research Station Agroscope, Soil Fertility and Soil Protection Group, Department of Natural Resources & Agriculture, Reckenholzstrasse 191, CH-8046 Zurich, Switzerland

[b] ETH Zurich, Institute of Terrestrial Ecosystems, Universitätstrasse 16, 8092 Zürich, Switzerland

[c] University of Applied Science of Western Switzerland Hepia, Soils and Substrates Group, Institute Land-Nature-Environment, route de Presinge 150, 1254 Jussy, Geneva, Switzerland

ARTICLE INFO

Keywords:
Soil health
Soil physical properties
Air content
Porosity
VESS
Visual examination

ABSTRACT

Most soil functions, such as food production, carbon and nutrient cycling or water regulation and filtration strongly depend on soil structure quality (SSQ). But SSQ is increasingly threatened by compaction, carbon loss and erosion. SSQ should be protected by environmental regulations, however, reliable and easy methods for SSQ assessment are still missing. The aim of this study was to define a classification scheme and its indicators for soil structure protection regulation. Therefore, the physical properties of soil samples were determined with shrinkage analysis and their structure quality was scored with CoreVESS to provide a classification scheme independent from the indicators. We collected 185 undisturbed samples from the A horizon of Cambi-Luvisols across western Switzerland. CoreVESS score (Sq) 2 was used to identify the target value corresponding to good structure quality. Sq 3 was used to identify the trigger value, i.e. the limit between good and poor SSQ. Sq 4 was used to identify the remediation value. We found that structural porosity and gravimetric air content at -100 hPa (A_{-100}) determined on undisturbed samples equilibrated free to swell in the laboratory were the best suited parameter to assess SSQ. They were correlated to SOC for soils with good SSQ, but not for soils with poor SSQ. As SOC was highly correlated to gravimetric water content at -100 hPa (W_{-100}), it was possible to approximate SOC by W_{-100} in order to simplify the method for application. A_{-100} and W_{-100} are easy and inexpensive to determine and are therefore proposed as indicators. The limit values of A_{-100} were identified as following: target is $0.023 + 0.288\,W_{-100}\,cm^3g^{-1}$, trigger is $0.068\,cm^3g^{-1}$ and remediation is $0.045\,cm^3g^{-1}$. These values were designed to be useful to the Swiss environmental law. They apply to the Cambi-luvisol A horizons, and their applicability to subsoil or other soil types should be further studied.

1. Introduction

Protecting soil structure quality (SSQ) is a key condition for the sustainable management of soil functions. Soil structure integrates many soil properties and determines soil fertility, soil biodiversity, nutrient cycling, carbon sequestration and the quantitative and qualitative regulations of water cycle (Bronick and Lal, 2005; Rabot et al., 2018). Due to soil organic carbon (SOC) loss and increasing mechanical stress under intensive agriculture, soil structure quality (SSQ) has dramatically degraded since the middle of 20th century (Hamza and Anderson, 2005; Toth et al., 2008; Lal, 2015), with adverse impacts on all major ecological soil functions from local to global scale.

Regulations are necessary for soil management and protection. Therefore, undisputable assessment of SSQ must be available. This requires appropriate indicators and availability of a classification scheme whose thresholds were determined independently from the indicator (Lebert et al., 2007). A considerable amount of literature has been dedicated to this question (Bünemann et al., 2018) and many physical approaches have been explored (e.g. (Hakansson and Lipiec, 2000; Horn and Fleige, 2003; Arvidsson and Keller, 2004; Alaoui et al., 2011; Nawaz et al., 2013)). However, so far, no consensus has been reached and, therefore, no environmental regulation with limit values is implemented. This can be related to two main difficulties concerning soil physical properties: lack of accuracy and high variability. Finally, to be suited for practical application, the methods should be inexpensive, easy and fast to perform. This is a difficulty with mechanical properties which are expensive to characterize and require technical expertise, while large and unexplained spatial variability were reported (Nielsen et al., 1973; Sisson and Wierenga, 1981; Vauclin, 1982; Gascuel-Odoux, 1987; Iversen et al., 2001; Moldrup et al., 2003).

* Corresponding author.
E-mail address: alice.johannes@agroscope.admin.ch (A. Johannes).

https://doi.org/10.1016/j.ecolind.2019.05.040
Received 21 August 2018; Received in revised form 1 May 2019; Accepted 14 May 2019
Available online 24 May 2019
1470-160X/

Since compaction preferentially impacts larger pores, some studies focused on air permeability close to water saturation (Lebert et al., 2007) or on coarse pore volume (Schäffer et al., 2007). Because of their relative simplicity and expected limited variability, bulk density or total porosity, were often used in soil compaction diagnosis (Hakansson and Lipiec, 2000). However, the spatial and temporal variability of bulk density or total porosity is driven by many factors additional to mechanical stress like soil swelling with water content (Goutal et al., 2012) and soil constituents (Schäffer et al., 2008; Goutal-Pousse et al., 2016), which jeopardize the possibility to diagnose stress induced changes. Because shrinkage analysis (ShA) is inexpensive and associated standard errors are small (Boivin, 2007), this technique has a good potential to characterize SSQ in general, as already proposed in much earlier work (Haines, 1923; McGarry and Daniells, 1987). It provided accurate assessment of compaction with accounting for the effects of field water content and soil constituents (Schäffer et al., 2008; Goutal-Pousse et al., 2016).

The shrinkage curve (ShC) is defined as the soil volume change with water content (Haines, 1923). Modelling the ShC with the XP model of Braudeau et al. (1999) results in the partitioning of soil porosity into structural and plasma pore volumes. The plasma is formed by the matrix of soil colloids (Glossary of Soil Science Terms, n.d.), namely clay minerals, organic matter and oxides, and its porosity is formed by the inter-colloidal particle voids. Structural porosity consists of biopores, cracks, vughs and packing voids (Brewer, 1964). Therefore, it integrates short term effects of soil biota (Young and Crawford, 2004; Kohler-Milleret et al., 2013), shrink-swell cycles and mechanical stresses. ShA characterizes plasma and structural porosities over the full soil water content range and, thus, does not depend on the soil water content at sampling. The volume of the structural pores, which are particularly sensitive to compaction, is linearly related to the plasma constituents, in particular to clay and SOC (Schäffer et al., 2008; Goutal-Pousse et al., 2016). The knowledge of these relationships allowed these authors to standardize the measured volumes with respect to the content of the sample for improved compaction diagnosis taking into account the spatial variability of the plasma constituents. Moreover, they observed a change in the constituent to volume relationship after compaction. According to these results, structure degradation should not only be considered based on observed changes of volumes, but also on the change in the constituent to pore volume relationship.

Soil structure refers to the size, shape and arrangement of solids and voids, and associated functions (Lal, 1991). Visual assessment of SSQ addresses most of these properties and receives, therefore, growing interest, in particular the VESS method (Ball et al., 2007). VESS is inexpensive, rapid and easy to perform. As it provides semi-quantitative assessment of SSQ at best and suffers from being subjective and depending on expert opinion, it isn't suitable for structure degradation assessment in the frame of regulation. It was found, however, to be well correlated to physical properties (Guimarães et al., 2013; Pulido Moncada et al., 2014; Johannes et al., 2017a). Moreover, Johannes et al. (2017a) proposed an adaptation of the VESS scoring to the clod scale, called CoreVESS, and reported good relationships between the visual score of the cores and their physical properties determined with ShA. VESS can, therefore, serve as an independent classification scheme of good and poor SSQ to identify the corresponding limit values of soil physical properties, which was the aim of this study.

The study was performed in Switzerland on the A horizon of the main arable soil type, which was sampled at Swiss scale. After determining the SSQ CoreVESS scores and ShA properties on a large series of undisturbed samples, we determined the physical properties that discriminated the best the SSQ categories, and we determined their relationships with colloid contents (clay and SOC), according to SSQ classes, which provided a first indicator of the SSQ. We then examined the possibility to replace the corresponding properties by equivalent and inexpensive measurement and quantified the correctness of the resulting indicator.

2. Material and methods

2.1. Sampling and dataset description

We used two data sets obtained at large geographical scale and one dataset from a compaction experiment. The two first datasets were obtained from the same general type of soil, classified as brown soils or "Braunerde/sol brun" according to the Swiss soil map, which roughly corresponds to Cambi-Luvisols according to WRB (Food and Agriculture Organization, 2014). It is the most widely distributed soil type under arable land use in Switzerland and in Europe. The first set used by Johannes et al. (2017b) contained 161 samples randomly collected in 161 different fields across the Swiss cantons of Vaud, Bern and Fribourg, over an area of approximately 120 km^2. The sampling locations covered almost all the "Braunerde/sol brun" area, thus broadly representing this soil type at Swiss scale. The sampled soils all developed on mixed moraine – molasses bedrock. To be representative of soil uses we selected in equal proportions conventionally tilled fields, permanent pastures and no-till fields, meaning in this case fields claimed to not have been tilled for more than 10 years. We sampled different SSQ as scored with VESS spade test. The second dataset is from the same geographical area and soil type and consisted of 20 samples at 20 locations where the soil structure was obviously degraded. They corresponded either to tilled soils or trampled pastures. The 181 locations from the two datasets are represented by dots on the map (Fig. 1). Additionally, 12 non-compacted and 12 compacted samples were collected from a field compaction experiment in 2013 from the Soil Structure Observatory (SSO; (Keller et al., 2017)) located at Agroscope Zurich, Switzerland. The location of the compaction experiment is represented by a cross in Fig. 1. This soil is classified as a pseudogleyed Cambisol with a loamy texture according to WRB (Food and Agriculture Organization, 2014).

All samples were collected in spring, summer and autumn from 2012 to 2014. For tilled soils the time lag between tillage and sampling was variable, but we never sampled immediately after tillage. The sampling depth was chosen to extend from 5 to 10 cm below the soil surface, as we wanted to exclude the root-enmeshed uppermost soil on pastures and meadows. Undisturbed samples were collected with a custom-made sampler, which yielded soil cores encased in PVC cylinders cut on their length. This allowed the soil cores to be retrieved with minimal disturbance on the structure for analysis and visual evaluation. The samples covered two textural classes, i.e. soils with loam and sandy loam texture according to FAO classification (Food and Agriculture Organization, 2014). The samples were stored at 4 °C in their plastic bag and PVC cylinder before analysis.

2.2. Soil characterization

To minimize the impact of local variability the following measurements and evaluations were performed consecutively on the same undisturbed sample.

2.2.1. Physical properties: Shrinkage curve analysis

Each sample was equilibrated at a matric potential of −10 hPa in a sand box after removal from the PVC cylinder to allow free swelling. After equilibration, the sample was placed in a plastic bag to prevent evaporation, weighed, and its volume determined with the plastic bag

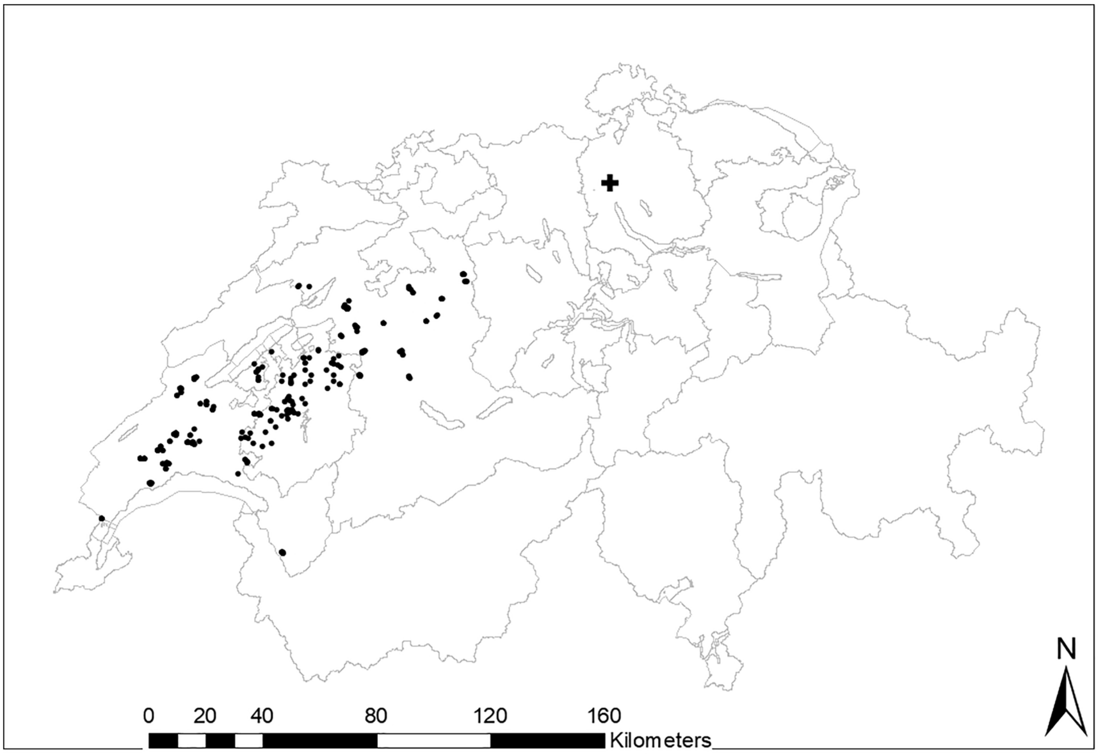

Fig. 1. Map of the 181 soil sampling locations. The location of the SSO compaction experiment is represented by a cross.

method (Boivin et al., 1990). The samples were then placed in the shrinkage apparatus described in (Boivin et al., 2004). Continuous changes in soil height (linear displacement transducer), mass (weighing scale) and matric potential (2 mm-large tensiometer) were recorded every 5 min until height and weight remained constant. The changes in gravimetric water content were calculated using the recorded weight during analysis and the 105 °C oven-dried sample weight, after removing the dry mass of the coarse fraction (> 2 mm). The sample volumes were measured a second time with the plastic bag method at air-dried state and the changes in height were converted to changes in volume after removing the coarse fraction volume as described by Schäffer et al. (2008). This allowed calculating the shrinkage curves of the < 2 mm fabric of the soil.

Some physical properties are directly measured on the ShC, namely soil specific volume and gravimetric water content, which can be referred to a matric potential using the tensiometer reading, or to air dry state. The gravimetric air content of the soil can be calculated from these values by subtracting the gravimetric water content and the specific solid phase volume to the specific soil volume, with taking into account the particle density, averaged at $1/2.65\ cm^3\ g^{-1}$ in this work. The corresponding properties were denoted V, W and A for specific volume, gravimetric water content and gravimetric air content, respectively, with the matric potential or “dry” (for air-dry) in subscript.

Additional properties were determined by modelling the ShC with XP model (Braudeau et al., 1999), which allowed quantifying separately the specific volumes of the structural and plasma porosities and their air and water contents at any W (Schäffer et al., 2008). Briefly, this modelling procedure is based on the fitting of the transition points between the linear and curvilinear domains of the S-shape ShC. We used the procedures described in e.g. (Schäffer et al., 2008) for the fitting.

In the following we use physical properties provided by ShA at a given matric potential (e.g. −10 hPa) or transition points of the ShC, along the full water content range. The corresponding results are, therefore, independent from field water content at sampling and account for the shrink-swell properties of the soil. We mainly focused on the plasma and structural pore volumes at maximum plasma swelling (MS) which is close to field capacity.

2.2.2. Scoring SSQ with CoreVESS

We used CoreVESS as independent criteria to determine the SSQ classification scheme. Briefly, after ShC measurement, the undisturbed soil samples were equilibrated at −100 hPa (field capacity) in a sand box, prior to visual examination. The following criteria were evaluated: breaking difficulty, aggregate shape, and visible porosity. The visual evaluation was performed in blind test by two people in order to have as objective evaluations as possible. A CoreVESS score (Sq) from 1 to 5 was given to each sample and when there was a hesitation between two scores, half points were attributed, which yielded 9 different classes of scores. According to the authors of VESS (Ball et al., 2017), scores Sq 1–2.9 do not require changes in management, Sq values ≤ 2 indicate a soil with good structural quality in relation to productivity. Sq values between 2 and 3 indicate fair structural quality, Sq values 3–4 indicate poor soil structural quality requiring long term improvement, and Sq > 4 indicate that short term improvements are needed for sustained agricultural productivity.

Accordingly, we used the CoreVESS scores to determine the SSQ thresholds for the physical parameters. Three threshold levels of quality were considered, as it is done in the Swiss regulation for soil protection (Federal Office for the Environment, 2013). Below the remediation limit, remediation measures must be taken. Below the trigger limit, investigations must determine the causes of the problem and whether a

Table 1
Main soil characteristics per soil structure quality score. SOC: soil organic carbon, CEC: cation exchange capacity, SD: standard deviation.

	CoreVESS	1	1.5	2	2.5	3	3.5	4	4.5	5	< 3	> 3
	N	10	13	36	28	36	21	26	11	4	87	62
SOC (%)	mean	2.8	2.4	2.0	1.8	1.7	1.6	1.7	1.8	1.6	2.1	1.7
	SD	0.6	0.8	0.6	0.5	0.6	0.4	0.4	0.7	0.5	0.7	0.5
	min	1.8	1.5	1.1	1.1	0.8	1.0	1.2	0.8	0.9	1.1	0.8
	max	3.9	3.6	3.4	2.8	3.4	2.4	2.7	2.8	2.1	3.9	2.8
pH	mean	7.0	6.5	6.4	6.6	6.4	6.6	6.8	6.5	6.9	6.6	6.7
	SD	0.5	0.8	0.7	0.7	0.7	0.6	0.6	0.8	0.4	0.7	0.6
	min	6.1	5.0	5.1	5.4	5.0	5.4	5.4	5.5	6.4	5.0	5.4
	max	7.9	7.5	8.0	7.5	7.6	7.7	7.6	7.6	7.2	8.0	7.7
CEC ($cmol_+ kg^{-1}$)	mean	19.4	17.1	13.4	12.4	11.7	12.4	15.0	14.5	14.3	14.3	14.0
	SD	3.0	5.6	4.6	4.3	4.9	4.5	4.2	5.5	4.4	5.0	4.6
	min	15.7	6.6	5.8	6.3	5.3	6.4	7.6	7.9	8.1	5.8	6.4
	max	23.7	25.3	21.7	20.3	21.8	18.8	20.3	26.3	17.4	25.3	26.3
clay (%)	mean	24.6	23.0	19.9	19.5	18.6	18.8	21.8	22.8	23.9	20.8	21.1
	SD	3.4	4.2	5.8	5.2	4.5	4.3	5.0	3.7	6.3	5.4	4.9
	min	18.7	16.8	10.0	10.9	11.0	11.8	9.9	15.6	16.4	10.0	9.9
	max	28.2	32.1	34.3	30.8	27.2	27.4	27.9	26.9	29.2	34.3	29.2
silt (%)	mean	39.9	41.7	34.8	36.7	36.6	38.9	43.5	41.0	38.6	37.0	41.2
	SD	6.3	8.3	6.4	8.1	8.6	8.9	10.4	4.6	5.2	7.6	8.9
	min	32.4	26.9	20.3	23.6	22.6	28.3	23.4	34.9	30.9	20.3	23.4
	max	49.4	55.7	48.6	54.0	56.0	56.4	57.7	49.1	42.1	55.7	57.7
sand (%)	mean	34.4	34.9	44.2	43.0	44.5	42.1	34.5	36.3	37.5	41.3	37.6
	SD	7.4	10.4	9.8	11.8	11.7	12.2	14.6	6.1	9.6	10.9	12.6
	min	22.5	19.6	26.8	20.3	20.1	18.6	14.4	26.1	29.0	19.6	14.4
	max	44.2	54.8	65.7	61.3	62.4	59.9	66.7	46.6	48.2	65.7	66.7

modification in soil management is necessary. Above the target limit, the quality is considered guaranteed in the long term. Sq = 3 was used to determine the trigger limit. Sq = 2 was used to identify the target value and Sq = 4 was used to identify the remediation value.

The distribution of VESS scores among our samples is presented in Table 1. According to the classification of Ball et al. (2007), 87 samples had a good structure quality (Sq < 3), 36 samples a medium structure quality (Sq = 3) and 62 samples a poor structure quality (Sq > 3). For the samples collected in the SSO compaction experiment the cause for structural damage is known. For most of the other samples the cause for structure degradation was not known, since most samples with poor structure were obtained from locations without visible signs of compaction at the soil surface.

2.2.3. Chemical analyses

After CoreVESS analysis, the samples were oven-dried at 105 °C, weighted and sieved to 2 mm to determine weight and volume of the coarse fraction (> 2 mm). SOC was analysed on the fine earth of the sample (< 2 mm fraction) using the method of Walkley and Black (1934). Prior to this, we measured SOC on a subseries of samples dried at 40 °C and 105 °C, respectively, to make sure that no volatile SOC was lost after drying at 105 °C, and the two SOC content series were highly correlated following a 1:1 line ($R^2 > 0.99$). Texture was determined with the traditional pipette method. pH was determined in 1:2.5 soil:-water suspensions. Cation exchange capacity was determined using the cobalt hexamine chloride method (Ciesielski and Sterckeman, 1997). The main soil characteristics are presented in Table 1.

2.3. Statistical analyses

All statistical analyses were computed with the R software (version 3.1.0). Multiple and simple linear regression analyses were performed with the "lm" function of the R software. To find which variables allowed the best distinction between structure quality scores, we used a linear discriminant analysis with a stepwise variable selection for classification. For the stepwise variable selection, we used the "stepclass" function of the package "klaR" (Roever et al., 2018).

3. Results

CoreVESS scores and corresponding analytical properties of the soil samples are reported in Table 1.

3.1. Selection of variables for soil structure quality classification

More than 70 variables were initially included in the stepwise variable selection, including all measured and modelled physical properties from ShA and all chemical and textural properties. The variable that classified the best the scores 1–5 (with half point distinction) was structural porosity at MS. The correctness rate of this classification was 32.94%. An additional variable (in this case gravimetric air content at −10 hPa) only improved the correctness rate by 1.21%. When classifying only three structure quality categories (Sq < 3, Sq = 3 and Sq > 3), gravimetric air content at −100 hPa (A_{-100}) provided the highest correctness rate and the result with structural porosity at MS was very close. A supplementary variable only improved the correctness rate by 2.90%. The mean A_{-100} and structural porosity at MS values for score-class 3 distinguished good structures (Sq < 3) from poor structures (Sq > 3) with 91.0% and 89.9% correctness, respectively.

3.2. Relationships between SOC and physical properties according to structure quality

The physical properties determined with ShA are linearly correlated to the colloidal content of the soil and a structure degradation results in a change in the slope of these relationships (Schäffer et al., 2008; Goutal-Pousse et al., 2016). Therefore, we considered the effect of soil

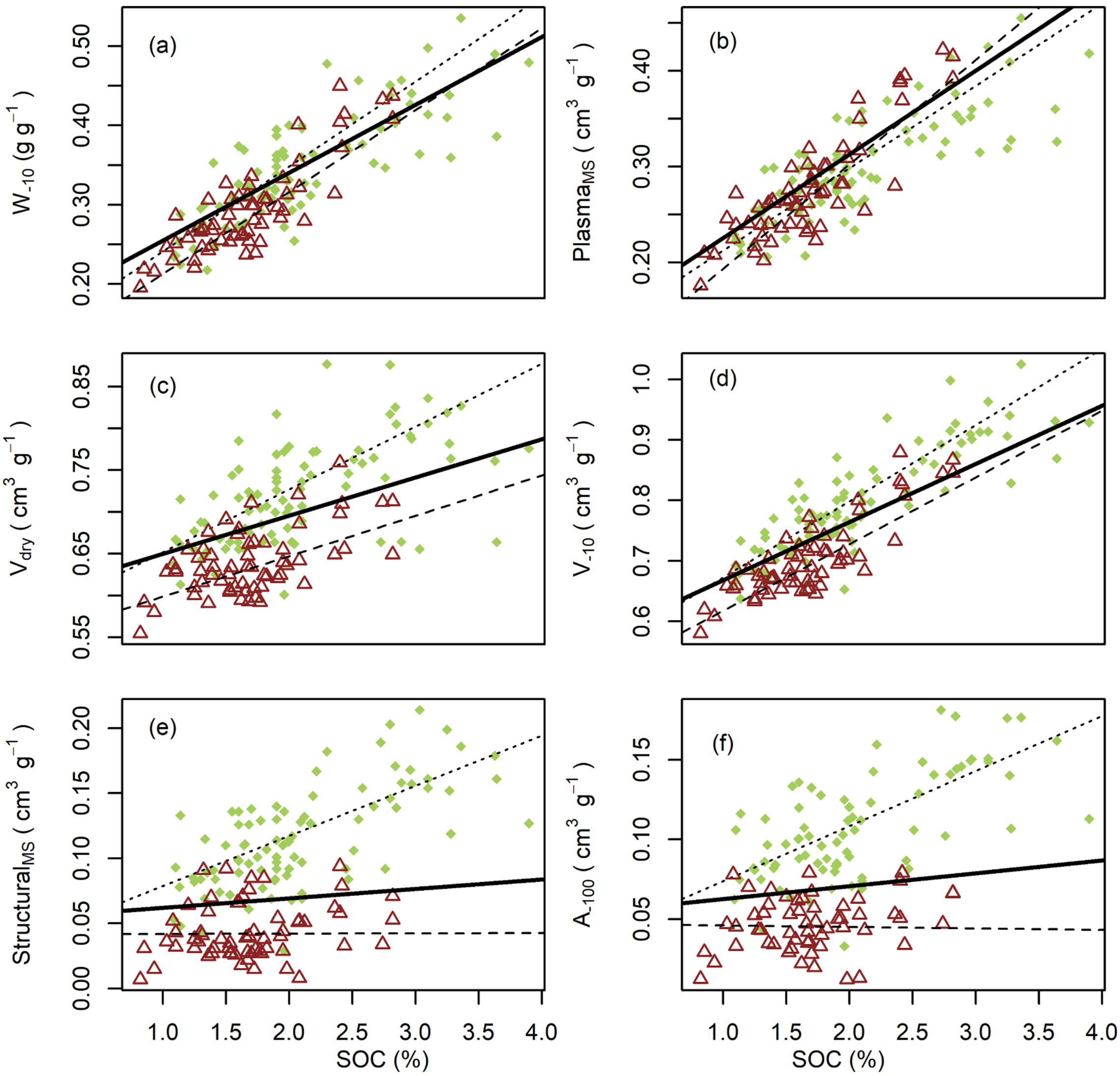

Fig. 2. Regression lines for structural quality scores Sq = 2 (dotted line), Sq = 3 (solid line) and Sq = 4 (dashed line) of (a) water content at −10 hPa (W_{-10}), (b) plasma porosity at maximum swelling point ($Plasma_{MS}$), (c) dry specific volume (V_{dry}), (d) specific volume at −10 hPa (V_{-10}), (e) structural porosity at maximum swelling point ($Structural_{MS}$) and (f) gravimetric air content at −100 hPa (A_{-100}) as a function of soil organic carbon content (SOC) with observations of good structural quality (Sq < 3, represented by full dots) and poor structural quality (Sq > 3, represented by open triangles).

colloid content on the physical properties in the structure degradation classification.

Multiple linear regression analysis revealed close relationships between SOC content and the physical parameters determined in this study (Fig. 2, Table 2), while the relationship with clay content was not significant when SOC was present in the regression. Therefore, we focused on SOC only in the following. Fig. 2 reports the regressions of Sq = 2, Sq = 3 and Sq = 4 for some of the physical properties as a function of SOC with corresponding equations given in Table 2. Soils with good SSQ (Sq < 3) and soils with poor SSQ Sq > 3 are also reported to illustrate the power of discrimination of the corresponding indicators. Water content (see Fig. 2a for W-10) or plasma porosity at MS (Fig. 2b) showed particularly close relationships with SOC in all SSQ scores. The relationship between SOC and specific volume was better determined at −10 hPa (Fig. 2d) than at air-dry state (Fig. 2c, Table 2), and the slope of the relationship decreased two-fold with drying. On the other hand, the dry specific volume seemed to discriminate different SSQ better than the specific volume at −10 hPa. The SOC relationships to structural porosity at MS (Fig. 2e) and A_{-100} (in Fig. 2f) were less clearly determined and significant only for Sq = 2 (Table 2). The difference in slope between regressions for the different scores in Fig. 2, and the separation between < 3 and > 3 scores, however, seem larger when considering structural porosity at MS and A_{-100} as a function of SOC (Fig. 2), while there seemed to be no or poor difference between SSQ classes with plasma, water contents and wet soil volume properties.

These observations are in line with the result of the stepwise classification and in accord with the framework of soil structure degradation and restoration proposed in (Schäffer et al., 2008; Goutal-Pousse et al., 2016). In these studies, and in the present, structural porosity increases with SOC content, and the slope of this relationship is decreased when the structure is degraded. The former studies, however, were dealing with compaction experiment. According to our results, the same patterns (decrease of the effect of SOC on volumes with compaction) apply to structure degradation, thus featuring a general framework of soil structure behaviour.

Based on these results, structural porosity at MS and/or A_{-100} as a function of SOC could be the indicators of SSQ, and the corresponding

Table 2
Linear regression parameters of some physical properties as a function of SOC for soil structure quality scores Sq = 2, Sq = 3 and Sq = 4. W_{-10}: water content at −10 hPa ($g\,g^{-1}$), $Plasma_{MS}$: plasma porosity at maximum swelling point, V_{dry}: dry specific volume ($cm^3\,g^{-1}$), V_{-10}: specific volume at −10 hPa ($cm^3\,g^{-1}$), $Structural_{MS}$: structural porosity at maximum swelling point, A_{-100}: gravimetric air content at −100 hPa ($cm^3\,g^{-1}$).

Physical property	CoreVESS	Intercept	Slope	R^2
W_{-10}	Sq = 2	0.134***	0.107***	0.75
	Sq = 3	0.169***	0.086***	0.76
	Sq = 4	0.109***	0.103***	0.74
$Plasma_{MS}$	Sq = 2	0.127***	0.086***	0.73
	Sq = 3	0.138***	0.087***	0.79
	Sq = 4	0.085**	0.109***	0.68
V_{dry}	Sq = 2	0.577***	0.075***	0.60
	Sq = 3	0.604***	0.046***	0.42
	Sq = 4	0.551***	0.048**	0.33
V_{-10}	Sq = 2	0.546***	0.126***	0.82
	Sq = 3	0.572***	0.096***	0.77
	Sq = 4	0.507***	0.110***	0.67
$Structural_{MS}$	Sq = 2	0.040**	0.039***	0.48
	Sq = 3	0.055**	0.007 (n.s.)	0.02
	Sq = 4	0.042(n.s.)	0.000(n.s.)	0.00
A_{-100}	Sq = 2	0.039**	0.035***	0.54
	Sq = 3	0.055***	0.008 (n.s.)	0.04
	Sq = 4	0.047*	− 0.001 (n.s.)	0.00

*** significant at level 0.001.
n.s.: non significant.

regressions for Sq = 2, 3 and 4 could be proposed as a classification scheme. Indeed, in these soils structural porosity at MS and A_{-100} are strongly correlated, with a slope of the linear regression of 1 and R2 = 0.95 (not shown). This is not surprising since air content represents a major part of the structural porosity at MS, which is observed at an average matric potential of −70 hPa. At −100 hPa the air content has increased upon drainage of the structural porosity compared to MS, thus leading to nearly equal values. Since A_{-100} is easier to determine, we focus on this parameter in the following.

3.3. Simplified SSQ indicators

Determining the SOC of soil samples is technically demanding and generates analytical costs. Soil structure degradation diagnosis should require as few, inexpensive and easy-to-perform analyses as possible. SOC was closely correlated to soil water content close to water saturation in all soil structure quality classes (Table 3), as already found by Goutal et al. (2012). Among the correlations between W and SOC at −10, −60, −100, −330 and −500 (not shown), water contents at −100 hPa and −60 hPa showed the closest correlation with SOC. The full data set (all SSQ scores included) yielded a linear regression with $R^2 = 0.72$ between W_{-100} and SOC (Fig. 3). Therefore, we investigated the possibility to replace SOC value by W_{-100} for the target value in particular, because only samples in good structural state, Sq = 2, were shown to be positively influenced by SOC with significant slope (Table 2).

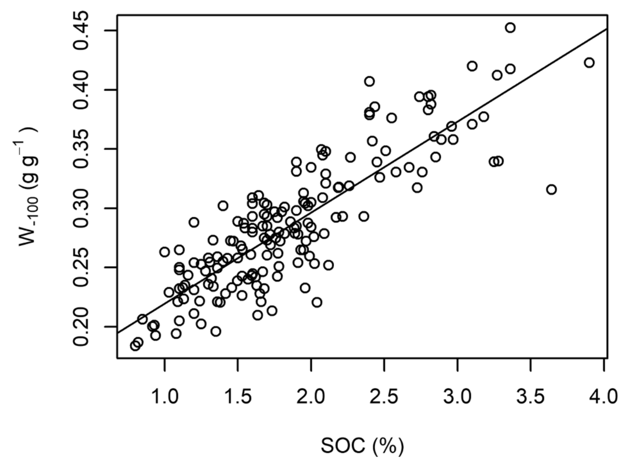

Fig. 3. Gravimetric water content at −100 hPa (W_{-100}) as a function of soil organic carbon (SOC).

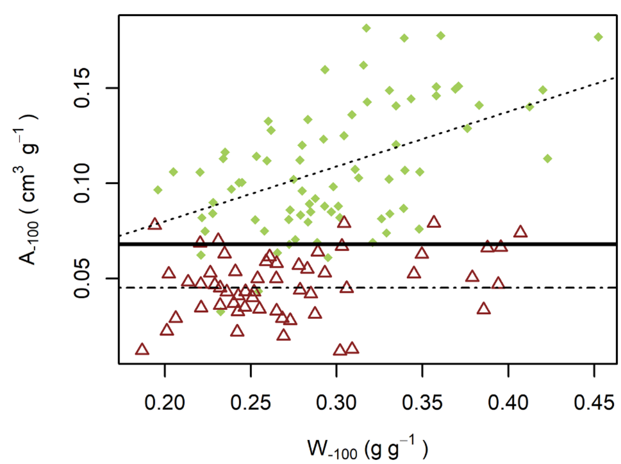

Fig. 4. Gravimetric air content at −100 hPa (A_{-100}) as a function of gravimetric water content at −100 hPa (W_{-100}) with target values (dotted line), trigger limit (full line) and remediation threshold (dashed line) and with observations of good structural quality (Sq < 3, represented by full dots) and poor structural quality (Sq > 3, represented by open triangles).

Fig. 4 presents A_{-100} as a function of W_{-100}. The regression describing the *target* value (Sq = 2) was

$$A_{-100} = 0.023 + 0.288 \times W_{-100} (R^2 = 0.34) \quad (1)$$

with significant intercept and slope. For Sq = 3 and Sq = 4, the slopes of the regression lines were not significant. Therefore, the *trigger* and *remediation* values were the mean values of Sq = 3 and Sq = 4, namely 0.068 $cm^3 g^{-1}$ and 0.045 $cm^3 g^{-1}$, respectively (Table 3). In Fig. 4, 89.3% of the poor structures (Sq > 3) and 92.2% of the acceptable structures (Sq < 3) according to CoreVESS are located in the right categories.

Table 3
Topsoil limit values of gravimetric air content at −100 hPa and their interpretation.

Limit value	A_{-100}	Corresponding CoreVESS score	Interpretation
Target	$0.023 + 0.288 \times W_{-100}$	Sq = 2	A guide value for soil management. Healthy soils should be above this value.
Trigger	0.068 $cm^3 g^{-1}$	Sq = 3	Value below which the reasons for the poor soil structure quality should be investigated and soil management must be adapted to improve structure quality.
Remediation	0.045 $cm^3 g^{-1}$	Sq = 4	Short term improvements of soil structure quality are needed.

A_{-100}: Gravimetric air content at −100 hPa ($cm^3\,g^{-1}$); W_{-100}: Gravimetric water content at −100 hPa ($g\,g^{-1}$).

4. Discussion

Gravimetric air content close to water saturation is often called coarse porosity and according to the law of Jurin-Laplace A_{-100} represents the volume of pores larger than 15 µm in equivalent radius. Similar indicators were already used in previous studies. Volumetric coarse porosity obtained by subtracting volumetric water content at −60 hPa (pF = 1.8) to saturated volumetric water content is recommended as criteria for compaction diagnosis (Häusler and Buchter, 2004; Lebert et al., 2007) with trigger and remediation values of 7% v/v and 5% v/v, respectively. Though it is a volumetric air content and the thresholds do not account for SOC, this indicator seems close to the one proposed in this study. Applied to our data set, however, this method classified 77% of the soils in poor structural state (Sq > 3) above the 5% v/v trigger value, i.e. acceptable.

This discrepancy can be related to several considerations. Firstly, these threshold values were not determined based on visual evaluation but based on previously reported oxygen diffusion data from different soil types (Fluehler, 1973; Dumbeck, 1986). Secondly, referring to a dry soil mass seems more suitable than referring to the soil volume for compaction diagnosis. Applying a constant v/v ratio of air to soils with different compaction intensities leads to use the same volume criteria for different dry mass of solids, probably resulting in quite different oxygen diffusion condition between structural porosity and plasma.

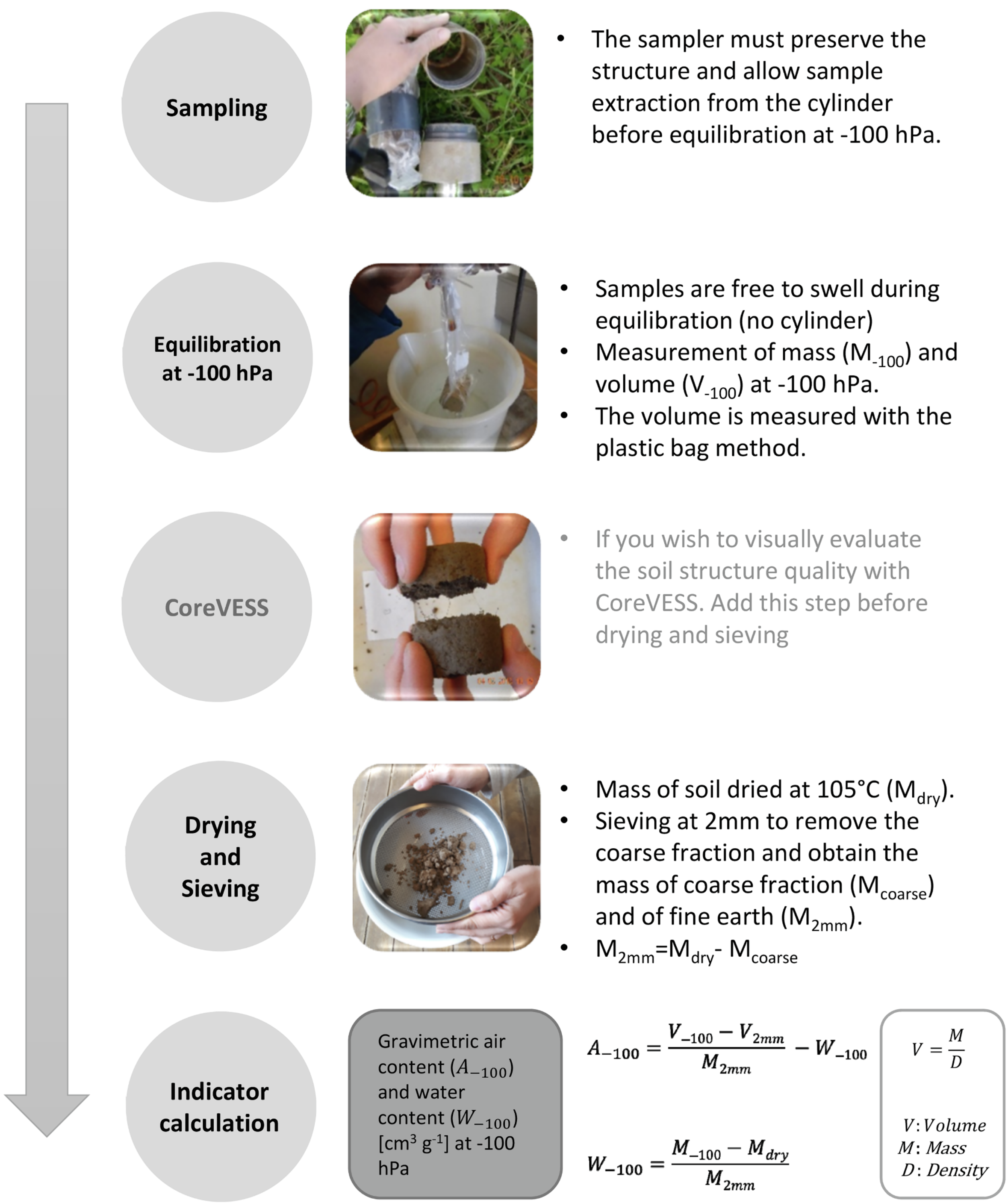

Fig. 5. Methodological procedure to sample, analyse and calculate the soil structure quality indicators: gravimetric air content at −100 hPa and gravimetric water content at −100 hPa.

Thirdly, the samples in the present study were not collected with the classical steel cylinder method. The soils were free to swell in the laboratory, and their properties were all determined either at standard matric potentials or swelling points. With the classical steel cylinder method, the swelling state of the soil depends on the water content at sampling, and the soil cannot swell if equilibrated at a matric potential closer to saturation. Moreover, the plastic bag method used to measure the volume in this study adapts to any shape of soil, even if it has shrunk or swelled after conditioning at −100 hPa or has a slightly irregular shape, which can occur in stony soils during sampling. It is therefore the opinion of the authors, that in order to use the identified limit values of A_{-100}, the precaution of using the same methodology as with the ShA is necessary (Fig. 5).

A problem is often encountered with the coarse porosity indicator of SSQ in tilled soils. Depending on the tillage method and sampling date, a large coarse porosity eventually not reflecting the SSQ may be present. Therefore, we expected that some samples originating from degraded conventionally tilled fields would present artificially high A_{-100} values, although having been visually scored as samples with poor or medium SSQ. Surprisingly there was no indication of that. Out of the 5 samples with poor scores (Sq > 3) but classified above the trigger threshold, there were 2 conventionally tilled fields, 1 permanent grassland and 2 with missing information. Out of the 15 samples with medium scores (Sq = 3) classified by the method as “above the trigger value”, there were 5 conventionally tilled fields, 5 permanent grassland sites, 4 no-till fields and 1 with missing information.

Although taken on a quite large geographical scale, we found close linear relationships between the investigated physical properties and SOC. The influence of SOC on physical soil properties has often been recognized. Manrique and Jones (1991) obtained similar results for bulk density on a large series of soils and the relationship to SOC was particularly close when they considered only Inceptisols, which are close to Cambi-Luvisols. Therefore, it might be necessary to define the thresholds of SSQ within soil groups at first, which should be investigated.

The impact of compaction on these relationships had been investigated at field scale in previous compaction experiments (Schäffer et al., 2008; Goutal-Pousse et al., 2016). These authors mostly reported a decrease in the slope of the structural porosity to SOC relationship in a cultivated Cambi-Luvisol and in an acid forest soil. In contrast, they found no change in plasma porosity with increasing mechanical stress, except for extreme compaction (Boivin et al., 2006; Schäffer et al., 2013). Our study shows that similar relationships of SOC to structural and plasma porosity also hold on a larger geographical scale. Moreover, the degradation of structure observed in many samples of this study cannot be directly attributed to compaction. Low SOC values and tillage probably play a dominant role in the loss of structure quality in that case (Kay and Munkholm, 2004), in good agreement with the conclusions of Johannes et al. (2017a,b). We observed, however, a decrease in structural porosity and in the slope of its relationship to SOC, and no change in the SOC-plasma porosity relationship with scores, similar to reported in compaction experiment. The decrease of the slope of the structural porosity to SOC relationship appears, therefore, as a general characteristic (or indicator) of soil structure degradation.

The simplified classification scheme uses gravimetric water and air content at −100 hPa as indicators. These parameters are determined easily in the same experiment (Fig. 5). Undisturbed soil samples can be equilibrated free to swell at −100 hPa on a sandbox. Then the sample weight can be measured with an electronic scale, and the sample volume can be measured with the plastic bag method, which only requires a water-jet pump. These inexpensive devices can be available to any soil technician, therefore, the method can be widely applied. Equilibrating soil samples to higher matric potentials is even easier. Therefore, we tried to classify the structure quality using the gravimetric air and water contents at −10, −30 and −60 hPa matric potentials, respectively. The corresponding classifications yielded 19%, 17% and 12% incorrectly classified samples (good and poor structures), compared to 9% with −100 hPa.

In this study, only topsoil samples were considered in identifying the limit values. But the structural degradation of the subsoil is a serious issue with compaction. SOC plays a very limited role on soil structure below the A horizons. The application of the same procedure to subsoil samples should, therefore, be investigated in future research, and would most likely take into account clay content.

Finally, if application of the method is considered for soil protection regulation, also the sampling strategy must be defined. Since there is a strong agreement between visual evaluation and measurement, the sampling area should probably be directed according to the visual expertise of the damaged area.

5. Conclusions

A classification scheme of soil structure quality is proposed with gravimetric air content and water content measured at −100 hPa as indicators. These indicators were derived as analogous and easier to determine than structural porosity at plasma maximum swelling and SOC, respectively. Target, trigger and remediation values for topsoil structure quality were defined for the Cambi-luvisol group based on the regressions between these indicators for samples that received CoreVESS scores of 2, 3 and 4, respectively. The trigger value successfully classified 89.3% of the poor structures (Sq > 3) and 92.2% of the acceptable structures (Sq < 3) according to CoreVESS in the right categories. These limit values apply at large geographical scale on the whole Cambi-Luvisol soil group, which is the most represented soil group in Switzerland and Europe.

The indicators fulfil the major requirements for the application in the frame of soil protection regulation, namely inexpensive and easy to determine properties, and unambiguous classification based on available classification scheme. The methods for indicator characterization require little expertise and inexpensive equipment. They can be performed, therefore, at any place by any soil expert. The limit values are however only available for topsoil and their validity should be investigated for other depths and soil types in future studies.

Acknowledgements

We gratefully acknowledge the support provided for the STRUDEL project by the Swiss Federal Office of the Environment (SFOEN Project 13.001.KP/M044-1527) and for the SSO project by the Swiss National Science Foundation (SNSF) as part of the National Research Program “Sustainable use of soil as a resource (NRP 68 Project 406840-143061).

Furthermore, we would like to express our gratitude to Léonie Givord, Tania Ferber, Elisabeth Busset, Adrien Matter, Quentin Chappuis and Mervin Manalili for their help with the sampling and the physical measurements, to Aline Chambettaz for the chemical analyses, and to Thomas Keller for giving us the opportunity to include the SSO site in this study.

References

Alaoui, A., Lipiec, J., Gerke, H.H., 2011. A review of the changes in the soil pore system due to soil deformation: a hydrodynamic perspective. Soil Tillage Res. 115–116, 1–15. https://doi.org/10.1016/j.still.2011.06.002.

Arvidsson, J., Keller, T., 2004. Soil precompression stress: I. A survey of Swedish arable soils. Soil Tillage Res. 77, 85–95. https://doi.org/10.1016/j.still.2004.01.003.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality – a development of the Peerlkamp test. Soil Use Manage. 23, 329–337.

Ball, B.C., Guimarães, R.M.L., Cloy, J.M., Hargreaves, P.R., Shepherd, T.G., McKenzie, B.M., 2017. Visual soil evaluation: a summary of some applications and potential developments for agriculture. Soil Tillage Res. 173, 114–124. https://doi.org/10.1016/j.still.2016.07.006.

Boivin, P., 2007. Anisotropy, cracking, and shrinkage of vertisol samples. Experimental study and shrinkage modeling. Geoderma 138, 25–38.

Boivin, P., Brunet, D., Gascuel-Odoux, C., 1990. Densité apparente d’échantillon de sol: méthode de la poche plastique (in French). Milieux Poreux Transfer. Hydr. Bull GFHN

28, 59–71.
Boivin, P., Garnier, P., Tessier, D., 2004. Relationship between clay content, clay type and shrinkage properties of soil samples. Soil Sci. Soc. Am. J. 68, 1145–1153.
Boivin, P., Schaeffer, B., Temgoua, E., Gratier, M., Steinman, G., 2006. Assessment of soil compaction using shrinkage curve measurement and modeling. Experimental data and perspectives. Soil Tillage Res. 88, 65–79.
Braudeau, E., Costantini, J.M., Bellier, G., Colleuille, H., 1999. New device and method for soil shrinkage curve measurement and characterization. Soil Sci. Soc. Am. J. 63, 525–535.
Brewer, R., 1964. Fabric and Mineral Analysis of Soils. John Wiley and Sons, New York.
Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124, 3–22. https://doi.org/10.1016/j.geoderma.2004.03.005.
Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussard, L., 2018. Soil quality – a critical review. Soil Biol. Biochem. 120, 105–125.
Ciesielski, H., Sterckeman, T., 1997. Determination of cation exchange capacity and exchangeable cations in soils by means of cobalt hexamine trichloride. Effects of experimental conditions. Agronomie 17, 1–7.
Dumbeck, G., 1986. Bodenphysikalische und funktionelle Aspekte der Packungsdichte von Böden. Dissertation Institut für Bodenkunde und Bodenerhaltung Universität Gissen, Germany.
Federal Office for the Environment, 2013. Swiss Environmental Law, A brief guide. Federal Office for the Environment, Swiss confederation, Berne.
Fluehler, H., 1973. Sauerstoffdiffusion im Boden. Mitteilgn. schweiz. Anst. forstl. Versuchswesen 49, 125–250.
Food and Agriculture Organization, 2014. World Reference Base for Soil Resources 2014 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. FAO, Rome.
Gascuel-Odoux, C., 1987. Variabilité spatiale des propriétés hydriques du sol, cas d'une seule variable: revue bibliographique. Agronomy 7 (1), 61–71.
Glossary of Soil Science Terms | Soil Science Society of America [WWW Document], n.d. https://www.soils.org/publications/soils-glossary (accessed 9.29.17).
Goutal, N., Ranger, J., Boivin, P., 2012. Assessment of the natural recovery rate of soil specific volume following forest soil compaction. Soil Sci. Soc. Am. J. 76, 1426–1435.
Goutal-Pousse, N., Lamy, F., Ranger, J., Boivin, P., 2016. Structural damage and recovery determined by the colloidal constituents in two forest soils compacted by heavy traffic. Eur. J. Soil Sci. 67, 160–172. https://doi.org/10.1111/ejss.12323.
Guimarães, R.M.L., Ball, B.C., Tormena, C.A., Giarola, N.F.B., da Silva, Á.P., 2013. Relating visual evaluation of soil structure to other physical properties in soils of contrasting texture and management. Soil Tillage Res. 127, 92–99. https://doi.org/10.1016/j.still.2012.01.020.
Haines, W.B., 1923. The volume changes associated with variations of water content in soil. J. Agric. Sci. 13, 296–311.
Häusler, S., Buchter, B., 2004. Teil 2: Vorschläge für Richt- und Prüfwerte zur Definition von Bodenschadverdichtungen. In: Buchter, B., Häusler, S., Schulin, R., Weisskopf, P., Tobias, S., (Eds.), Definition und Erfassung von Bodenschadverdichtungen. Positionspapier der BGS-Plattform Bodenschutz. Dokument 13 der Bodenkundlichen Gesellschaft der Schweiz.
Hakansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res. 53, 71–85.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009.
Horn, R., Fleige, H., 2003. A method for assessing the impact of load on mechanical stability and on physical properties of soils. Soil Tillage Res. 73, 89–99.
Iversen, B.V., Schjonning, P., Poulsen, T.G., Moldrup, P., 2001. In situ, on-site and laboratory measurements of soil air permeability: Boundary conditions and measurement scale. Soil Sci. 166, 97–106. https://doi.org/10.1097/00010694-200102000-00003.
Johannes, A., Weisskopf, P., Schulin, R., Boivin, P., 2017a. To what extent do physical measurements match with visual evaluation of soil structure? Soil Tillage Res. 173, 24–32.
Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P.C., Boivin, P., 2017b. Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? Geoderma 302, 14–21. https://doi.org/10.1016/j.geoderma.2017.04.021. 10.1016/j.still.2016.06.001.
Kay, B.D., Munkholm, L.J., 2004. Management-induced soil structure degradation – organic matter depletion and tillage. In: Schjønning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing Soil Quality: Challenges in Modern Agriculture. CABI Pub, Wallingford, Oxon; Cambridge, MA, pp. 185–197.
Keller, T., Colombi, T., Ruiz, S., Manalili, M.P., Rek, J., Stadelmann, V., Wunderli, H., Breitenstein, D., Reiser, R., Oberholzer, H., Schymanski, S., Romero-Ruiz, A., Linde, N., Weisskopf, P., Walter, A., Or, D., 2017. Long-term soil structure observatory for monitoring post-compaction evolution of soil structure. Vadose Zone J. 16. https://doi.org/10.2136/vzj2016.11.0118.
Kohler-Milleret, R., Bayon, R.-C.L., Chenu, C., Gobat, J.-M., Boivin, P., 2013. Impact of two root systems, earthworms and mycorrhizae on the physical properties of an unstable silt loam Luvisol and plant production. Plant Soil 1–15. https://doi.org/10.1007/s11104-013-1621-4.
Lal, R., 1991. Soil structure and sustainability. J. Sustain. Agric. 1, 67–92. https://doi.org/10.1300/J064v01n04_06.
Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7, 5875–5895.
Lebert, M., Böken, H., Glante, F., 2007. Soil compaction—indicators for the assessment of harmful changes to the soil in the context of the German Federal Soil Protection Act. J. Environ. Manage. 82, 388–397. https://doi.org/10.1016/j.jenvman.2005.11.022.
Manrique, L.A., Jones, C.A., 1991. Bulk density of soils in relation to soil physical and chemical properties. Soil Sci. Soc. Am. J. 55, 476–481. https://doi.org/10.2136/sssaj1991.03615995005500020030x.
McGarry, D., Daniells, I.G., 1987. Shrinkage curve indices to quantify cultivation effects on soil structure of a vertisol. Soil Sci. Soc. Am. J. 511575–511580.
Moldrup, P., Yoshikawa, S., Olesen, T., Komatsu, T., Rolston, D.E., 2003. Air permeability in undisturbed volcanic ash soils. Soil Sci. Soc. Am. J. 67, 32–40.
Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron. Sustain. Dev. 33, 291–309. https://doi.org/10.1007/s13593-011-0071-8.
Nielsen, D.R., Biggar, J.W., Erb, K.T., 1973. Spatial variability of field-measured soil water properties. Hilgardia 42, 215–259.
Pulido Moncada, M., Gabriels, D., Lobo, D., Rey, J.C., Cornelis, W.M., 2014. Visual field assessment of soil structural quality in tropical soils. Soil Tillage Res. 139, 8–18. https://doi.org/10.1016/j.still.2014.01.002.
Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137.
Roever, C., Raabe, N., Luebke, K., Ligges, U., Szepannek, G., Zentgraf, M., 2018. klaR: Classification and Visualization. R package Version 0.6-14.
Schäffer, B., Schulin, R., Boivin, P., 2013. Shrinkage properties of repacked soil at different states of uniaxial compression. Soil Sci. Soc. Am. J. 77, 1930–1943. https://doi.org/10.2136/sssaj2013.01.0035.
Schäffer, B., Schulin, R., Boivin, P., 2008. Changes in shrinkage of restored soil caused by compaction beneath heavy agricultural machinery. Eur. J. Soil Sci. 59, 771–783.
Schäffer, B., Stauber, M., Müller, R., Schulin, R., 2007. Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. Eur. J. Soil Sci. 58, 1062–1073. https://doi.org/10.1111/j.1365-2389.2007.00886.x.
Sisson, J.B., Wierenga, P.J., 1981. Spatial variability of steady-state infiltration rates as a stochastic process. Soil Sci. Soc. Am. J. 45, 699–704.
Toth, G., Montanarella, L., Rusco, E., 2008. Threats to Soil Quality in europe, EUR – Scientific and Technical Research series – ISSN 1018-5593. EUR 23438 EN – Joint Research Centre – Institute for Environment and Sustainability.
Vauclin, M., 1982. Méthodes d'étude de la variabilité spatiale des propriétés d'un sol. Colloq. SHF-INRA Avignon Juin 1982, 9–45.
Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.
Young, I.M., Crawford, J.W., 2004. Interactions and self-organization in the soil-microbe complex. Science 304, 1634–1637. https://doi.org/10.1126/science.1097394.