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Soil structure degradation evaluation for environmental legislation (STRUDEL)

Reference values and methodology for soil structure quality and compaction diagnosis

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Summary

Soil structure degradation is one of the major environmental threats. In Switzerland, the ordinance of impact on soils OIS (OIS, 2016) is the legislative basis for soil protection. Limit values (guide, trigger and clean-up values) for chemical pollution are currently available. But soil physical protection is scarce and no limit values exist for diagnosing soil structure quality, in the frame of compaction threats for example. The limit values of the OIS originally constructed for chemical pollution would need a slight adaptation to soil physical protection where no direct toxicity is involved. Providing these limit values for soil physical protection and the associated methodology was the main aim objective of the project "Soil structure degradation evaluation for environmental legislation" (STRUDEL).

The shrinkage curve is the continuous measurement of the soil volume over the whole water content range, i.e. how the soil shrinks and swells with varying moisture content. Many soil physical properties are generated by this method, including simple porosity parameters and bulk densities at various matric potentials. Shrinkage curve was found to be promising to diagnose soil compaction at field scale. In the STRUDEL project, we applied the method at large scale. A considerable amount of undisturbed soil samples was taken mainly from topsoils, but also from subsoils, in typical soil types (Cambisols, Luvisols) across the whole Swiss plateau. These undisturbed soil samples represented a wide range of differing site conditions (with differing soil composition regarding texture and soil organic carbon content (SOC)), and management conditions (permanent pasture, arable farming with or without soil tillage).

In order to have sufficiently reliable physical parameters to build reference values, needed to overcome several challenges. First challenge: the high variability of soil physical properties, the temporal and spatial variability and the influence of soil components (such as clay or soil organic carbon content) have on soil physical properties. In the report, we describe the mechanisms used to “solve” these problems. The second challenge was to answer the question “what is a good soil structure and what is not and where to draw the limit”. To cope with this question, STRUDEL used the method "Visual Evaluation of Soil Structure quality" (VESS) which is a semi-quantitative method yielding score from Sq1 ("good structure") to Sq5 ("poor structure"). This field method was improved during the project and translated into national languages and an adaptation of the method to laboratory-controlled conditions, named Core-VESS, was developed. The link between analytical structural soil parameters and visual assessment of soil structure, both from the same undisturbed soil sample, provided the possibility to develop reference values for the protection of soil structure. Based on the datasets in the STRUDEL database, procedures to build quantitative limit values for structural soil parameters and to test their discriminative power were developed. Applying these procedures to the STRUDEL database resulted in the proposition of limit values for several structural soil parameters with good discriminating power. Gravimetric air content at -100 hPa (A_{-100}) was the best suited parameter to assess soil structure quality and therefore a simple methodology is described here to measure and interpret this parameter called the "Soil Structure Degradation Index" (SSDI).

To make these findings applicable for soil specialists implementing physical soil protection in the cantons, STRUDEL described a simple two-step methodology how to proceed in the case of suspected impacts on soil structure. In the first step the course of action to make visual assessments in the field is described; in the second step the procedure to take soil samples for the analysis of structural soil parameters is outlined. To facilitate the use of structural soil parameters of this second step for the implementation of physical soil protection, STRUDEL proposed simplified analytical methods that could easily and cost-effectively be applied in an ordinary lab, but are nevertheless meaningful and reliable.

Last, but not least, a very important outcome of the project is the proposition of the SOC:clay-ratio as a tool for SOC management. A SOM:clay-ratio of about 17% (SOC:clay-ratio of 10%) is proposed as target value for Soil Organic Matter (SOM) management. This ratio can also be seen as a "Soil Structure Vulnerability Index" (SSVI). These SOC target values are functionally justified (in terms of soil structure quality) instead of statistically based on mean values of soils which are not necessarily in good shape. This study was motivated by the extreme importance SOC has for soil structure quality and soil quality in general. SOC is very highly correlated to soil physical properties and having enough SOC in a soil is a crucial aspect for soil structure. Such a reference value for the SOM:clay-ratio would set a goal for farmers to check their SOM management regularly and improve the quality of their soils; this would also help to reach targets of climate protection by presumably increased carbon sequestration in arable soils.

The main STRUDEL findings are documented as data sheets and videos, and are publicly available on the STRUDEL website www.strudel.agroscope.ch.

All the data analyzed and assessed on undisturbed soil samples are stored in the STRUDEL database, which is currently managed by Agroscope and available for FOEN.

Die Beeinträchtigung der Bodenstruktur ist eine der wichtigsten Bedrohungen für die Bodenqualität. In der Schweiz ist die Verordnung über Belastungen des Bodens VBBo (OIS, 2016) die gesetzliche Grundlage für den Bodenschutz. Grenzwerte für die Beurteilung chemischer Bodenbelastungen (Richt-, Prüf- und Sanierungswerte) sind verfügbar. Physikalischer Bodenschutz im Bereich der Verdichtungsgefährdung wird nur in eingeschränktem Ausmass vollzogen, u.a. weil keine Grenzwerte für die Beurteilung der Bodenstrukturqualität vorliegen. Das Konzept der VBBo Grenzwerte ist momentan auf die Beurteilung chemischer Bodenbelastungen ausgerichtet und müsste für den Einsatz im physikalischen Bodenschutz leicht angepasst werden, weil beispielsweise keine direkte Humantoxizität zu erwarten ist. Grenzwerte für den physikalischen Bodenschutz und die notwendigen Methoden für deren Erarbeitung zur Verfügung zu stellen war das Hauptziel des Projektes "Soil structure degradation evaluation for environmental legislation" (STRUDEL).

Die Schrumpfungskurve zeigt den Zusammenhang zwischen dem Volumen und dem Wassergehalt einer Bodenprobe durch kontinuierliche Messungen während des Austrocknungsprozesses vom wassergesättigten bis zum absolut trockenen Zustand, d.h. sie zeigt, wie stark eine Bodenstruktur mit abnehmender Bodenfeuchtigkeit schrumpft. Mit der Schrumpfungsmethode können viele Bodeneigenschaften bestimmt werden, beispielsweise einfache Porositätsparameter und Lagerungsdichten bei verschiedenen Matrixpotenzialen. Die Schrumpfungsmethode wurde als vielversprechend beurteilt, um Bodenstrukturschäden im Feldmassstab beurteilen zu können. Im STRUDEL-Projekt wurde die Methode auf einer noch grösseren Skala eingesetzt. Eine beträchtliche Anzahl an ungestörten Bodenproben wurde überwiegend aus den Oberböden, aber auch aus den Unterböden typischer landwirtschaftlich genutzter Böden (Braunerden und Parabraunerden) des gesamten Schweizer Mittellandes entnommen. Diese ungestörten Bodenproben repräsentierten einen grossen Ausschnitt unterschiedlicher Standortbedingungen (insbesondere auch bezüglich Textur und Gehalt an organischer Bodensubstanz (OBS)) und Bewirtschaftungsverhältnissen (Dauergrasland, Ackerland mit und ohne Bodenbearbeitung).

Um genügend verlässliche physikalische Bodenparameter für die Grenzwerte zur Verfügung zu haben, mussten verschiedene Probleme gelöst werden. Zunächst musste eine Lösung für die üblicherweise hohe Variabilität physikalischer Bodenparameter und ihre Beeinflussung durch die Bodenzusammensetzung (wie den Gehalt an Ton oder organischer Bodensubstanz) gefunden werden. Im Schlussbericht beschreiben wir, welche Lösungsansätze dafür verwendet worden sind. Danach musste eine Antwort gefunden werden auf die Frage "welche Bodenstruktur ist gut und welche schlecht, und wo liegt die Grenze zwischen diesen beiden Beurteilungen?". Zur Lösung dieses Problems wurde im STRUDEL-Projekt die Methode "Visual Evaluation of Soil Structure quality" (VESS) zur visuellen Beurteilung der Bodenstrukturqualität eingesetzt, eine semi-quantitative Methode, die Beurteilungen der Strukturqualität von Klasse Sq1 ("gut") bis zu Klasse Sq5 ("schlecht") ermöglicht. Diese Feldmethode wurde im Projektverlauf verbessert und in die Landessprachen übersetzt; ausserdem wurde eine an die Beurteilung von Bodenproben unter kontrollierten Laborbedingungen angepasste Version CoreVESS entwickelt. Die Verbindung zwischen analytisch bestimmten Strukturparametern und der visuellen Strukturbeurteilung an derselben ungestörten Bodenprobe ermöglichte das Ableiten von Grenzwerten für den physikalischen Bodenschutz. Basierend auf den Datensätzen in der STRUDEL-Datenbank wurden Vorgehensweisen entwickelt, um quantitative Grenzwerte für Bodenstrukturparameter zu bestimmen und deren Unterscheidungs- bzw. Klassifikationsvermögen zu testen. Aus der Anwendung dieser Vorgehensweisen auf die Datensätze der STRUDEL-Datenbank ergaben sich Grenzwert-Vorschläge für mehrere Strukturparameter mit gutem Unterscheidungsvermögen. Der Parameter "Luftgehalt bei -100 hPa" (gravimetrisch) bzw. "Makroporenvolumen bei -100 hPa" (volumetrisch) war der am besten geeignete Parameter zum Beurteilen der Strukturqualität. Im Schlussbericht wird eine einfache Methode beschrieben, wie dieser Parameter (auch als "Soil Structure Degradation Index" (SSDI) bezeichnet) gemessen, berechnet und interpretiert werden kann.

Um diese Ergebnisse für Fachleute im kantonalen Bodenschutz-Vollzug anwendbar zu machen, wurde im STRUDEL-Projekt eine einfache, zweistufige Methode zum Vorgehen bei Verdachtsfällen von Bodenstruktur-Beeinträchtigungen ausgearbeitet. Zunächst wird der Strukturzustand im Feld visuell erfasst und beurteilt, danach werden bei Bedarf ungestörte Bodenproben entnommen und Strukturparameter im Labor analysiert. Um die Nutzung analytischer Strukturparameter beim Vollzug des physikalischen Bodenschutzes zu erleichtern, finden sich im STRUDEL Schlussbericht vereinfachte Analysemethoden, die sich einfach und kostengünstig in normalen Laborumgebungen einsetzen lassen und trotzdem sinnvolle und verlässliche Ergebnisse liefern.

Nicht zuletzt ist der Vorschlag des OBS:Ton-Verhältnisses als Hilfsmittel für die Beurteilung des Gehaltes an organischer Bodensubstanz ein weiteres Ergebnis aus dem STRUDEL-Projekt. Ein gravimetrisches OBS:Ton-Verhältnis von etwa 17% (entsprechend einem Corg:Ton-Verhältnis von etwa 10%) wird als Zielwert für die Bewirtschaftung der organischen Bodensubstanz betrachtet (und kann als "Soil Structure Vulnerability Index" (SSVI) bezeichnet werden). Diese Zielwertfunktion für die Beurteilung des organischer Bodensubstanzgehaltes ist funktionell begründet und stützt sich ab auf den in STRUDEL festgestellten Zusammenhang zwischen Strukturqualität und Gehalt an organischer Bodensubstanz; damit unterscheidet sie sich von häufig verwendeten statistischen Kennwerten für Gehaltswerte an organischer Bodensubstanz. Diese STRUDEL-Arbeiten wurden wegen der grossen Bedeutung der organischen Bodensubstanz für die Strukturqualität und die Bodenqualität insgesamt durchgeführt. Der Gehalt an organischer Bodensubstanz ist stark korreliert mit verschiedenen (nicht nur physikalischen) Bodenparametern. Ein ausreichender Gehalt an organischer Bodensubstanz ist eine notwendige (allerdings nicht hinreichende) Voraussetzung für eine hohe Strukturqualität und eine günstige Strukturentwicklung von Böden. Grenz- bzw. Zielwerte für das OBS:Ton-Verhältnis von Böden würde den LandwirtInnen klare Ziele für ihre Bewirtschaftungssteuerung und damit auch für die Entwicklung der Qualität ihrer Böden setzen. Dies könnte in einem ersten Schritt auch dazu führen, dass durch Verbesserungen des Gehaltes an organischer Bodensubstanz in ackerbaulich intensiv genutzten Böden (und damit eine verstärkte C-Sequestrierung in diesen Böden) auch Klimaschutzziele erreicht werden könnten.

Die wichtigsten Ergebnisse des STRUDEL-Projektes sind in Merkblättern und Kurzfilmen dokumentiert worden und sind auf der STRUDEL Website http://www.strudel.agroscope.ch öffentlich zugänglich.

Alle im Rahmen des STRUDEL-Projektes an den ungestörten Bodenproben gemessenen und bestimmten Werte sind in der STRUDEL Datenbank gespeichert; diese wird momentan durch Agroscope betrieben und ist beim BAFU erhältlich.

La dégradation de la structure du sol est l'une des principales menaces environnementales. En Suisse, l'ordonnance sur les atteintes portées aux sols Osol (OIS, 2016) constitue la base législative de la protection des sols. Des valeurs limites (valeur indicative, seuil d'investigation et seuil d'assainissement) pour la pollution chimique sont actuellement disponibles. Mais la protection physique des sols est rare et il n'existe pas de valeurs limites pour diagnostiquer la qualité de la structure des sols, dans le cadre de la compaction par exemple. Les valeurs limites de l'OIS initialement construites pour la pollution chimique nécessiteraient une légère adaptation à la protection physique des sols puisqu'aucune toxicité directe n'est impliquée. Fournir ces valeurs limites pour la protection physique des sols et la méthodologie associée était l'objectif principal du projet "Soil structure degradation evaluation for environmental legislation" (STRUDEL).

La courbe de retrait est la mesure continue du volume du sol sur toute la gamme de teneur en eau. Cela traduit la façon dont le sol se rétrécit et se gonfle en fonction de la teneur en eau. De nombreuses propriétés physiques du sol sont générées par cette méthode, y compris des paramètres de porosité simples et des densités apparentes à divers potentiels matriciels. La courbe de retrait s'est avérée prometteuse pour diagnostiquer la compaction du sol à l'échelle d'une parcelle. Dans le cadre du projet STRUDEL, nous avons appliqué la méthode à grande échelle. Une quantité considérable d'échantillons de sol non remaniés a été prélevée principalement dans les couches supérieures, mais aussi dans les sous-sols, dans des sols communs de la région (Cambisols, Luvisols) sur l'ensemble du plateau suisse. Ces échantillons de sol non-remaniés représentaient un large éventail de conditions de site différentes (avec une composition de sol différente en ce qui concerne la texture et la teneur en carbone organique du sol (SOC)), et de conditions de gestion (prairies permanente, terres assolées avec ou sans travail du sol).

Afin de disposer de paramètres physiques suffisamment fiables pour établir des valeurs de référence, il a fallu surmonter plusieurs difficultés. En premier lieu, la grande variabilité des propriétés physiques du sol, c'est-à-dire la variabilité temporelle, la variabilité spatiale et l'influence que les composants du sol (tels que l'argile ou la teneur en carbone organique du sol) ont sur les propriétés physiques. Dans le rapport, nous décrivons les mécanismes utilisés pour "résoudre" ces problèmes. La deuxième difficulté était de répondre à la question "qu'est-ce qu'une bonne structure de sol et qu'est-ce qui ne l'est pas et où tirer la limite". Pour répondre à cette question, STRUDEL a utilisé la méthode "Visual Evaluation of Soil Structure quality" (VESS) qui est une méthode semi-quantitative donnant des scores allant de Sq1 (bonne structure) à Sq5 (mauvaise structure). Cette méthode de terrain a été améliorée au cours du projet et traduite dans les langues nationales, et une adaptation de la méthode aux conditions contrôlées en laboratoire, appelée CoreVESS, a été développée. Le lien entre les paramètres structurels analytiques du sol et l'évaluation visuelle de la structure du sol, tous deux à partir du même échantillon de sol non-remanié, a permis de développer des valeurs de référence pour la protection de la structure du sol. L'application de ces procédures à la base de données STRUDEL a permis de proposer des valeurs limites pour plusieurs paramètres structurels du sol ayant un bon pouvoir discriminant. La teneur en air gravimétrique à -100 hPa (A_{-100}) était le paramètre le mieux adapté pour évaluer la qualité de la structure du sol, c'est pourquoi une méthodologie simple pour mesurer et interpréter cet indice de dégradation de la structure du sol ("Soil Structure Degradation Index" SSDI) est décrite dans le rapport.

Pour l'application par les spécialistes cantonaux de la protection des sols, la méthode de diagnostic de la compaction ou de la dégradation de la structure des sols est proposée en deux étapes. La première étape consiste à procéder à des évaluations visuelles sur le terrain ; si la première étape est insuffisante, la deuxième étape consiste à prélever des échantillons de sol non-remaniés pour l'analyse de la structure du sol. Afin de faciliter l'utilisation de ces paramètres de structure du sol, STRUDEL propose une méthodologie simplifiée à moindre coût accessibles par des laboratoires ordinaires, mais qui est néanmoins significative et fiable.

Enfin, un résultat très important du projet est la proposition du ratio carbone:argile comme outil de gestion de la matière organique. Un ratio matière organique:argile d'environ 17% (rapport carbone:argile de 10%) est proposé comme valeur cible pour la gestion de la matière organique. Ce ratio peut également être considéré comme un indice de vulnérabilité de la structure des sols ("Soil Structure Vulnerability Index" SSVI). Ces valeurs cibles pour le carbone sont justifiées fonctionnellement (en termes de qualité de la structure du sol) plutôt que statistiquement avec des moyennes ne représentant pas nécessairement la qualité du sol. Cette étude a été motivée par l'importance du carbone pour la qualité de la structure des sols et la qualité des sols en général. Le carbone est en effet fortement corrélé aux propriétés physiques du sol et avoir suffisamment de carbone dans un sol est un aspect crucial pour la structure du sol. Cette valeur cible permettrait aux agriculteurs de vérifier régulièrement leur gestion de la matière organique et d'améliorer la qualité de leurs sols. Une meilleure gestion de la matière organique dans le sol grâce à des valeurs cibles contribuerait également à atteindre les objectifs de protection du climat en augmentant la séquestration du carbone dans les sols arables.

Les principales conclusions de STRUDEL ont été documentées sous forme de fiches techniques et de vidéos, et sont accessibles au public sur le site web de STRUDEL www.strudel.agroscope.ch.

Toutes les données analysées et évaluées sur des échantillons de sol non-remanié sont stockées dans la base de données STRUDEL, qui est actuellement soutenue par Agroscope et à la disposition de l'OFEV.

1 Initial situation and aim

1.1 Soils and soil structure: functions and threats

Although soils are as important for human beings as air or water, the soils underneath our feet are forgotten by most. For the year of the soil, 2015, the FAO produced an infographic reminding us of the many functions soils deliver (FAO, 2015a). A majority of these soil functions depend directly on soil structure (Figure 1), e.g. food provision, water purification, contaminant reduction, carbon sequestration, nutrient cycling, habitat for organisms, flood regulation.

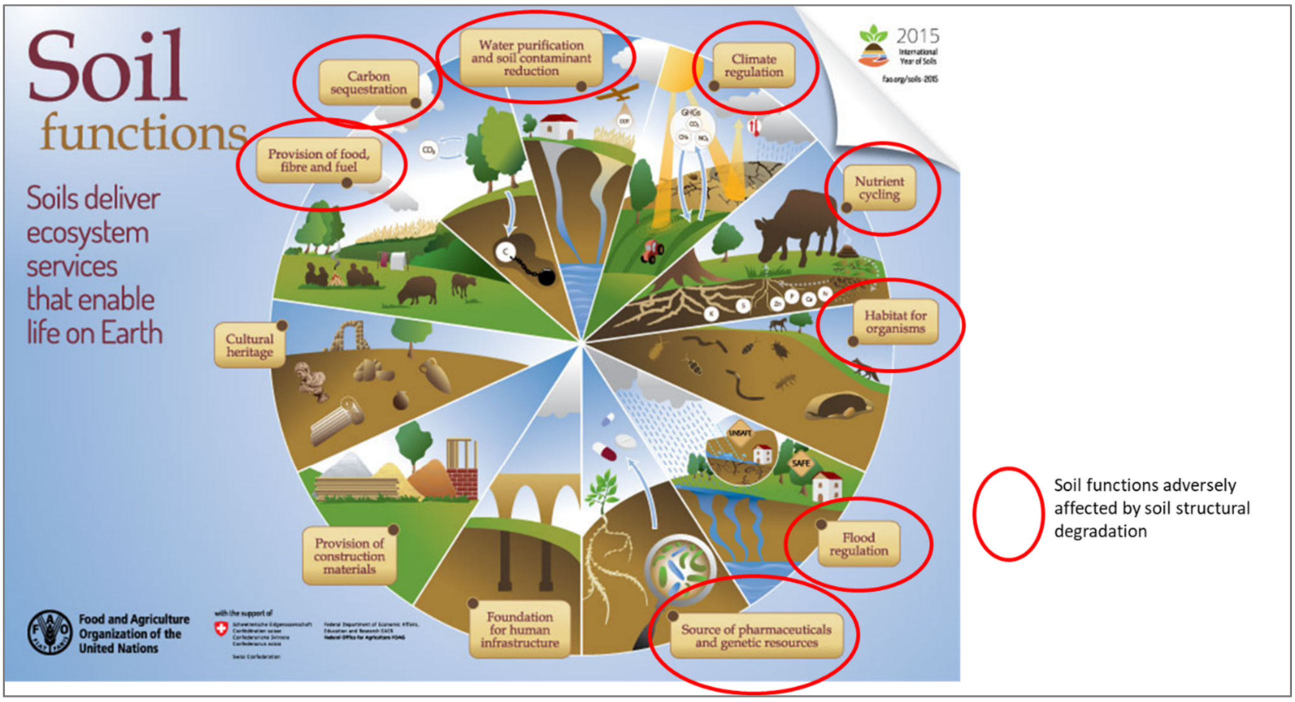


Figure 1: Modified illustration of the soil function schema from FAO (2015a). The soil functions depending on soil structure quality are encircled in red.

But soils are quantitatively and qualitatively threatened in many ways, preventing them from fulfilling all of their functions. In Switzerland, in average every second 1 m^2 of agricultural soil is lost to urbanization for traffic and building areas or other infrastructure (Office fédéral de la statistique, 2013). What is left for agriculture is qualitatively threatened by pollution and structural degradation. Structural degradation includes compaction by mechanical impacts (Hamza and Anderson, 2005; Soane and van Ouwerkerk, 1995), disaggregation by carbon depletion (Kay and Munkholm, 2004) and soil loss by erosion (Lal, 2001). Urbanization is often associated with construction of infrastructure that leads to temporary use of adjacent agricultural land by heavy construction machinery and thereby also to soil compaction. Modern industrialized agriculture involves the use of heavy agricultural machinery causing soil compaction by high mechanical impacts. Intensified agricultural management of our soils may lead to carbon depletion, which is weakening soil structure by reducing aggregate stability, thereby increasing the risks for puddling and erosion. The expected costs resulting from the loss of soil functions, e.g. increased frequencies and severities of flooding events, heavier water pollution or reduced crop yields, are just starting to make us realize how threatened our soils and their ecosystem functions are, and how dearly we should value them and preserve their structure.

1.2 Soil compaction in topsoil and subsoil

Compaction threatens structure quality of both topsoils and subsoils, but through different ways, with slightly different consequences and different regeneration times. This section is not meant to give an exhaustive description of all possible cases, causes and processes, but rather to depict typical cases in order to clarify the different problematics with compaction at different soil depths (Table 1).

Topsoil compaction mainly occurs in agricultural fields through inappropriate use of agricultural machinery (e.g. field traffic or soil tillage with too heavy or inappropriately equipped or adjusted vehicles in wet conditions). These structural degradations are visible at the soil surface. Subsoil compaction is mainly caused by the use of heavy machinery in agriculture (harvesters, slurry tankers, compost spreaders), forestry (forwarder) and construction work (excavators, dumpers) or when heavy piles of material are stored on the soil during construction work.

Both topsoil and subsoil compaction may have dramatic consequences on soil functions, water and nutrient cycles, and biological activity by soil organisms and plant roots. Topsoil compaction specifically impacts seedling development which is a crucial moment in the plant growth cycle, and the damaged structure of the surface soil may enhance the risk of surface-runoff and erosion. In the case of subsoil compaction, the immediate damage may be invisible, but the effects are, however, long-lasting, e.g. regarding root penetration in subsoils, use of subsoil resources by crops, the resistance of crops to extreme weather conditions (too dry or too wet), or the water regime.

In both cases, severe compaction effects occur in seconds, but recovery of the impacts will last years or decades: topsoils will need years of good agricultural practices to regenerate, and subsoils may need the use of rural engineering techniques and may never recover their full functions at a human time scale.

Table 1: Topsoil and subsoil compaction problematics

	Topsoil	Subsoil
Compaction speed	Seconds	Seconds
Regeneration speed	Months or years depending on compaction severity (with good agricultural practices)	Years or decades depending on compaction severity (with rural engineering techniques and good agricultural practices)
Frequency	Frequent	Rare
Particular difficulty		Invisible. Beyond the typical working depth of agricultural machinery
Typical compaction situation	During agricultural, forestry or construction operations on soils, e.g. field traffic or soil tillage, using inappropriately equipped vehicles in wet conditions	During agricultural, forestry or construction operations on soils, using heavy machinery in wet conditions; exceptionally in construction operations: huge piles for material storage
Typical consequences	Loss of soil functions, e.g. impaired plant development (seedlings, roots), impaired activity of soil organisms, impaired water regime (surface runoff) and nutrient cycles, increased risk for puddling and erosion	Loss of soil functions, e.g. water logging (roots are asphyxiated), roots cannot penetrate subsoils (reduced resistance against dry spells), impaired water regime (reduced replenishment of groundwater) and nutrient cycles. → plants become more sensitive to extreme weather conditions.

1.3 Physical soil protection in Switzerland

In Switzerland, the protection of soils is based on the Ordinance relating to Impacts on the Soil (OIS 2016) within the framework of the environmental protection legislation. In the OIS, it is stipulated that the purpose of qualitative soil protection is to ensure the long-term preservation of soil fertility (meaning "soil functions").

In the Commentary on the ordinance of July 1st 1998 relating to impacts on soil (SAEFL, 2001) the paragraph on terminology specifies the relationship between soil fertility and physical soil protection. *“The definition of the term 'soil fertility' is very broad and goes well beyond productivity and yield in the agronomic sense:*
Physical impacts are detrimental changes in soil structure, constitution and thickness caused directly or indirectly by human activity. They may be manifested as erosion (soil denudation and transport of loose soil by water and wind), compaction (mechanical structure of soil cavities and destruction of soil aggregates), mixing of soil strata (changes in the natural structure of the soil, e.g. in building excavation) and soil mineralisation (loss of soil through mineralisation of organic soils following drainage).“

The OIS contains limit values for chemical soil protection against several organic and inorganic chemical pollutants (guide, trigger and clean-up value) (SAEFL, 2001), as well as guide values for physical soil protection against soil erosion. In its current version, OIS does not include any limit values for physical soil protection against structural degradation by **compaction or by disaggregation**.

Figure 2 explains how these limit values have to be interpreted for chemical soil protection:

- When the guide value is exceeded, long-term fertility is no longer guaranteed.
- When the trigger value is exceeded, restrictions on soil use take place, depending on the mode of exploitation.
- When the clean-up value is exceeded, certain soil uses are forbidden and the soil may has to be decontaminated.

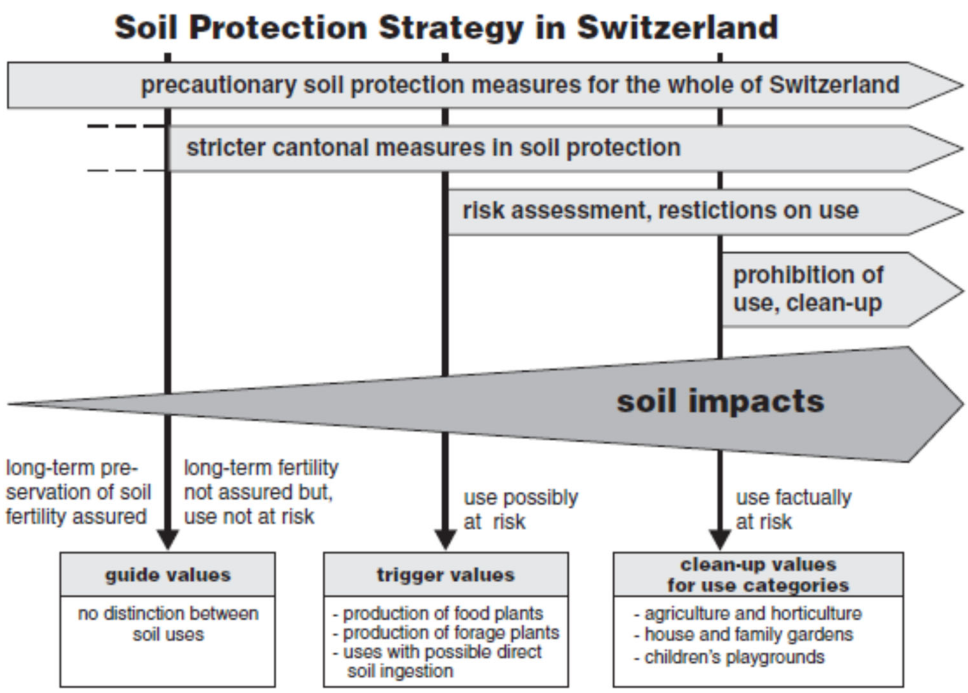


Figure 2: Soil protection strategy in Switzerland (source: commentary on the ordinance of 1 July 1998 relating to impact on the soils (SAEFL, 2001))

This scheme (Figure 2) applies to soil protection against chemical pollution. In the case of physical soil protection, some terms make no sense, e.g. the "clean-up value". In a future release of the OIS addressing physical soil protection against structural degradations the limit values should therefore be accordingly adapted and eventually renamed.

1.4 Adaptation proposition of the OIS' current three-step limit value-system for chemical soil protection to physical soil protection

The three-step limit value-system is relevant for chemical soil protection, where organisms can be intoxicated and where chemical impacts usually develop rather slowly and continuously. This system needs adaptation to physical soil protection, because there is no notion of direct intoxication in soil physics. Another adaptation is necessary because - depending on soil depth - the temporal dynamics of structural changes in topsoil may be extremely high.

The following propositions for terminology and an interpretation scheme are meant as a reflection basis for the revision of the OIS:

- Contrarily to chemical pollutants, where zero is most of the time the best value for contaminant concentration (= no contaminant detectable), soil physical parameters have certain values to characterize a functional soil. This is why we suggest the existence of a “**target value**" (Zielwert/valeur cible), proposed as a desirable value for soil structure quality. This value should be seen as a tool for soil management.
- In view of soil structure dynamics the difference of interpretation between “guide” and “trigger” value is difficult to make for soil physical protection. The "**guide value**" can retain its interpretation as indicator for the transition between “preserving soil function in the long term” and “non-assuring soil functions in the long term”. But from the measures interpretation, it could be merged with the “**trigger value**” indicating a restriction in use. In Figure 3 and Figure 4, we called it **“guide/trigger value”** because of this dual interpretation.
- Contrarily to chemical pollutants, the term “clean-up value” does not make sense for soil physical quality. However, a structurally impaired soil can theoretically be remediated, but appropriate action has to be put into effect; therefore we propose for this situation the term "**remediation value**" (Massnahmenwert/valeur de remediation).

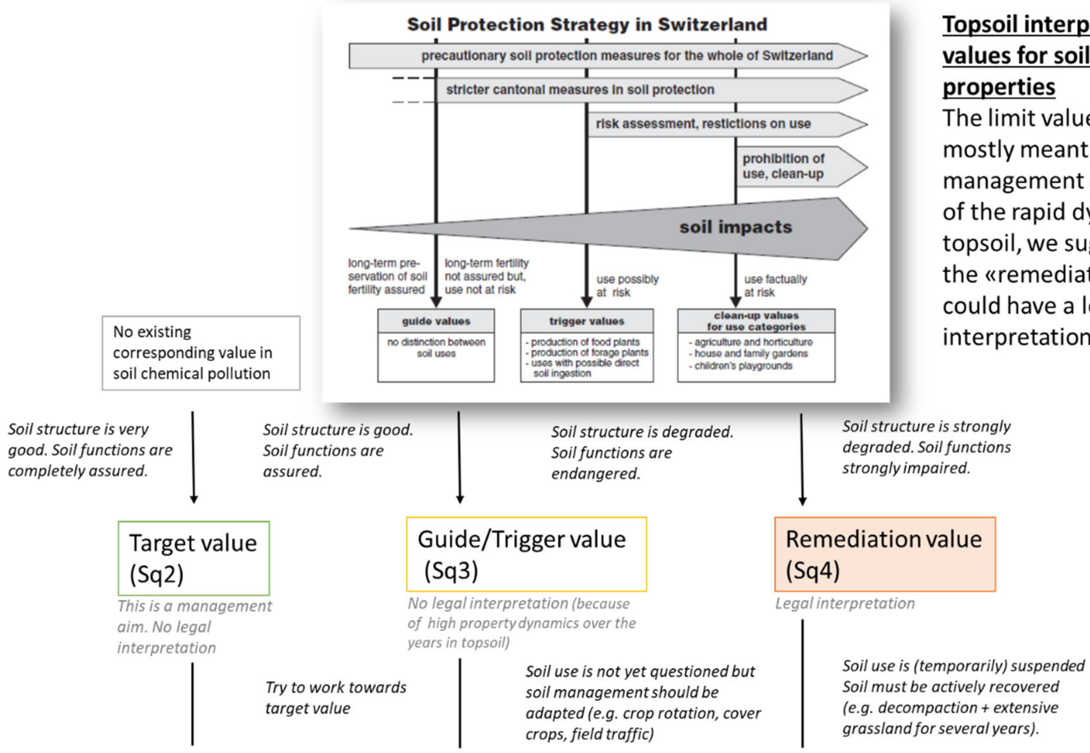
In Figure 3 and Figure 4 we illustrate the above-mentioned adaptations and provide a possible interpretation of these limit values for soil physical protection, whose application might differ in the topsoil or in the subsoil, depending on the type of soil degradation that occurred.

1.4.1 Prevention against soil compaction in practice

In Switzerland, the cantons are responsible for implementing soil protection. Currently, physical soil protection against structural degradation is mostly based on prevention against soil compaction, particularly on construction sites. For soil protection in agriculture there exists an implementation guide "Bodenschutz in der Landwirtschaft" (FOEN and FOAG, 2013), which explains the implementation of the topics "compaction" and "erosion" according to the environmental protection legislation.

Preventive action during construction projects is systematically enforced. Authorization for large construction projects is usually given when “good practice guidelines for construction works” (detailed in “Construire en préservant les sols”, FOEN, 2001) are respected accordingly: planning, realization and restoration measures are accompanied by specialized advisors ("soil specialist on construction sites” SSCS), and soil quality checks are executed by representatives of Cantonal Soil Protection Offices.

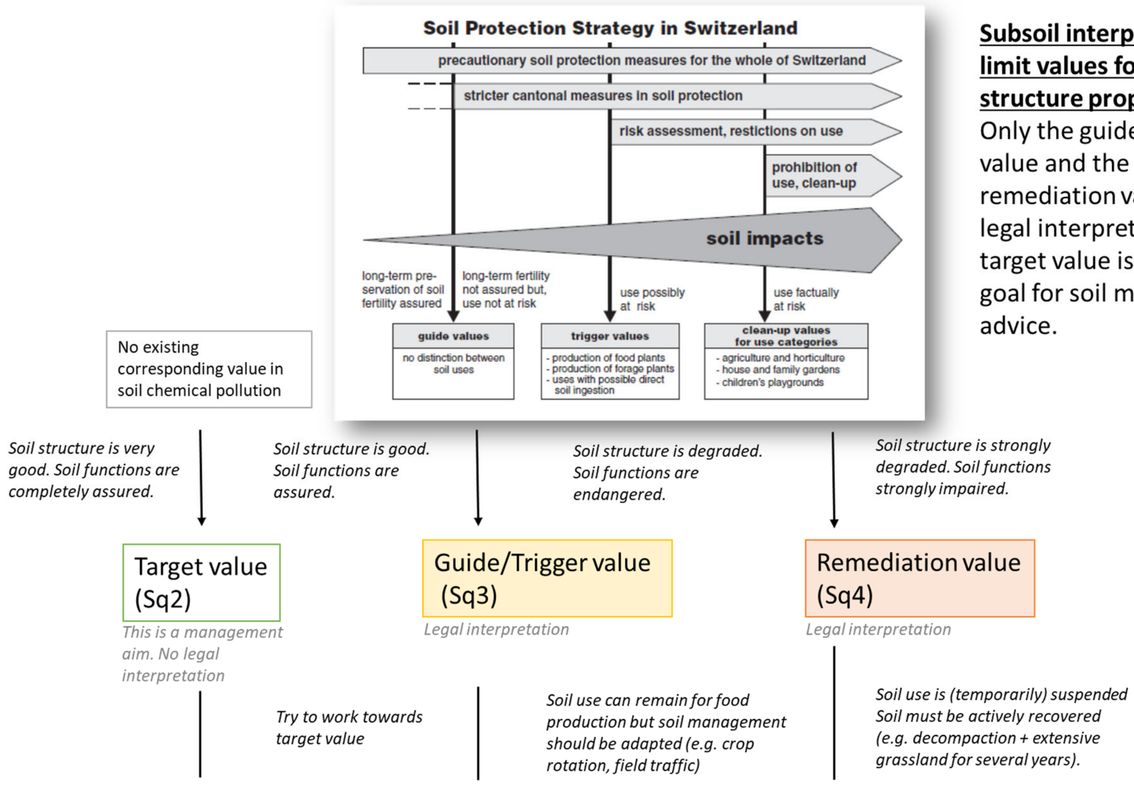
However, the lack of widely accepted and standardized methods and parameters to assess soil structure quality (including the availability of corresponding reference values) makes soil physical protection difficult to implement for cantonal soil protection specialists. For physical soil protection against soil structure degradation in agriculture, forestry and construction projects, methods, parameters and reference values to assess soil structure quality are needed.



Topsoil interpretation of limit values for soil structure properties

The limit values are here mostly meant as tools for soil management advice. Because of the rapid dynamics in topsoil, we suggest that only the «remediation value», could have a legal interpretation.

Figure 3: Adaptation of the OIS current three-step limit value system to the protection of topsoil structure quality



Subsoil interpretation of limit values for soil structure properties

Only the guide/trigger value and the remediation value have a legal interpretation. The target value is meant as a goal for soil management advice.

Figure 4: Adaptation of the OIS current three-step limit value system to the protection of subsoil structure quality

1.5 Aim of the STRUDEL project

As stated above, currently there is a gap in soil physical protection. In particular, there are no limit values available in the OIS to make the distinction between structurally damaged soils with poor structure quality and intact soils with good structure quality. The lack of reliable reference values can be explained by the difficulty of assessing structural soil properties and the difficulty of finding a reliable way to distinguish good structures from poor structures, which is necessary to develop reference values.

The aim of the STRUDEL project was to provide objective (meaning scientifically based, verifiable and extendable) ***reference values for soil structure quality,*** which are useful for both legislation and practical implementation. To be applicable, the methods to determine these parameters describing soil structure quality and to derive their corresponding reference values need to be accessible and easy to determine.

The STRUDEL project has also the objective to provide the ***methodological*** description ("protocol") for soil protection specialists and soil technicians how to use the reference values. Additionally, the project provides a platform (website) to facilitate the access to these documents.[1]

Given the importance of documenting the method for building reference values, the present report explains the concept how the reference values for different structural soil properties were developed, and how visual evaluation of soil structure quality contributed to this. The method to evaluate how well the limit values distinguish between "poor" and "good" soil structure quality is also explained.

The importance of soil organic carbon SOC (or SOM) for soil quality in general and soil structure quality in particular is crucial, and has also been the object of study in this project. Based on the results of this study, developing ***reference values for soil organic carbon content*** based on SOC effects on soil structure quality became in retrospect a very important outcome of this project. This is what led us to propose the SOC:clay-ratio as a good practice recommendation for SOM management.

[1] www.agroscope.admin.ch:
Startseite > Themen > Umwelt und Ressourcen > Boden, Gewässer, Nährstoffe > Bodenqualität und Bodennutzung > Physikalischer Bodenschutz (Projekt STRUDEL)
Page d'accueil > Thèmes Environnement et Ressources > Sol, Eaux, Éléments nutritifs > Qualité et utilisation du sol > Protection physique des sols (projet STRUDEL)

2 Difficulties related to determining structural soil properties

2.1 Variability in soil physical properties in general

Soil physical properties can traditionally be split into “dynamic or intensive” and “non-dynamic or extensive” soil parameters, respectively, and into parameters related to the solid substance or to the pore space of soils.

Fluid mechanics involves measurements of conductivity and permeability, which are related to pore network characteristics such as connectivity, pore diameter, pore length etc. Solid mechanics considers the stress – strain relationships. Both of these properties are called “intensive”.

Easier to determine are the properties related to weights and volumes: bulk density and porosities (e.g. total porosity, air-filled porosity, water content at a given matric potential). Because these properties are “extensive”, they are referred to units of mass or volume of soil.

“Intensive” soil properties are very often subject to extremely high variability (Sisson & Wierenga 1981), in particular the flow parameters, which are also very much dependent on sample size. This high variability was also observed when measuring e.g. precompression stress and air permeability (Ferber, 2014). These parameters are known to be highly sensitive for structural change, but yielded on the other hand high coefficients of variation (CV), ranging from 31% to 73%. On the other hand, “extensive” properties derived from the shrinkage curve and desorption measurements had CVs ranging from 8% to 20%. The shrinkage curve related properties’ CVs could be further decreased when taking SOC as co-variable into account, thus lowering them to a range of 6% to 13%.

For these reasons, the project STRUDEL concentrated on “extensive” physical properties derived from shrinkage curve and desorption curve measurements.

The potentially high variability in soil structural properties is doubtlessly one of the main difficulties that prevented the transfer of research methods used in soil science into practical application in implementing soil protection. Building limit values for soil structural properties is dependent on precisely measured parameters.

Soil scientists and soil protection specialists are well aware that even for “extensive” physical properties temporal and spatial variability are important obstacles in obtaining consistent information on soil structure quality. Figure 5 summarizes the main reasons inducing high temporal and spatial variability in the characterization of soil physical quality, and what was attempted in the project STRUDEL to work around these obstacles.

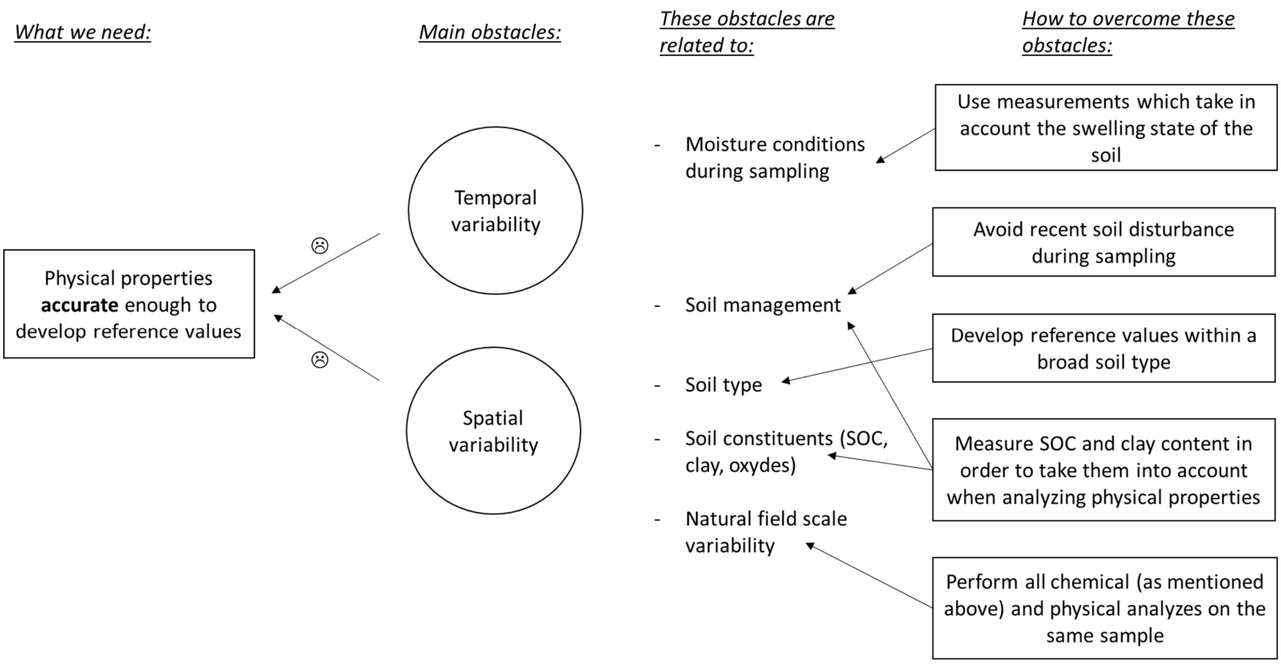


Figure 5: Temporal and spatial variability as main obstacles in providing accurate measurements of soil physical properties for limit values

2.2 Temporal variability

2.2.1 Problem description: varying moisture conditions induce variability

The problem of temporal variability comes from the fact that in soil physics, the volume of soil is often considered as rigid, and therefore constant. But in fact, as explained below, even the "non-dynamic/extensive" soil physical properties are dynamic.

Temporal variability is a major issue in physical characterization of soils, making comparisons over time difficult. There is of course an intrinsic natural evolution of soil structure in time, sometimes related to human impact, but this is not the problem depicted here. Short-term temporal variability is mostly related to varying moisture conditions. Moisture conditions can vary daily, hourly or even more rapidly. This is one of the reasons why it is stressed that "similar moisture conditions" at sampling time should be respected, and soil sampling should preferably be done at "field capacity". In practice, this requirement to take soil samples during similar moisture conditions is difficult to meet, especially in repeated samplings for time-series, when comparing a "before and after" compaction situation. The problem of varying moisture conditions is that it induces different soil swelling states, because clay minerals have the potential to change their volume depending on soil moisture ("shrinkage-swelling behavior"). A clay content of 10% is enough to induce a response in volume change due to varying moisture conditions. In practice, this means that sampling the same soil with a standard volume at different moisture conditions can result in different bulk densities.

2.2.2 Overcoming this problem by taking in account the shrink/swell state of the soil and standardizing the soil volume at an imposed matric potential

In order to avoid this problem, the STRUDEL project takes into account the swelling state of the soil. This was first done by measuring the whole shrinkage curve of every soil sample. In this particular case, the swelling state at which the sample has been taken is not important, because (i) the sample is free to swell or shrink and is standardized by bringing it to full water saturation and giving it time to swell to its maximum volume, and then (ii) by a controlled desorption to specific moisture conditions ("matric potentials"). With the shrinkage curve technique sample volume is monitored over the whole moisture content range from near saturation to air dry conditions.

Because in practice it is realistically not possible to perform a complete shrinkage curve analysis to assess soil structure quality for every soil sample, a few simple but meaningful physical properties were identified as indicators for soil compaction diagnosis; these were linked to reference values for the diagnosis of soil structure quality. The associated simplified methodology takes into account the swelling state of the sample and requires that the soil sample has to be standardized at a specific matric potential while being able to swell or shrink freely without constraint. The physical properties (porosities expressed either as air or water content of a soil sample at specific matric potentials) can be expressed either related to sample mass in a gravimetric relationship (cm^3/g of dry soil) or to sample volume in a volumetric relationship (cm^3/cm^3 of fully swollen soil).

- In a gravimetric relationship, the porosity is expressed per gram of dry soil, which is a constant figure, contrarily to the soil volume which fluctuates with moisture or compaction state (for the same dry soil mass). In the case of a comparison in compaction state, for example, a gravimetric relationship allows a direct comparison to observe a change in “how much air or water can this soil contain after compaction?”.
  In a volumetric relationship, only a proportion of water or air content per total volume is known. But if the total volume has decreased, this information will be amiss and one would have to take into account the bulk density in order to make a meaningful comparison of porosity. Else there might be a risk to only observe a shift in the proportion of coarse pores to fine pores for example, and completely miss out the total loss of porosity after a compaction. For this reason, it is usually preferred to work in gravimetric relationships throughout this report.
- The volumetric relationship is more intuitive for representing porosity because it is easy to imagine a proportion of air or water content for a certain soil volume. The advantage of this representation is that it is more representative for the physiological function of a soil: “which volume of air filled porosity is available for a plant root?”

2.2.3 Influence of soil management on soil structure properties

2.2.3.1 Ploughing

Soil management by humans has a major influence on soil structure. In ploughed fields for example, the soil is inverted and the soil structure disrupted.

During the STRUDEL project, samples were taken in all seasons except winter. Only fields that were recently ploughed were avoided. This precaution is necessary, but it is however reassuring to observe that this was the only “temporal constraint” in this study, and that it is possible to take soil samples in any season.

2.2.3.2 Soil organic carbon SOC

In a review about “soil structure and management” (Bronick et Lal, 2005), the predominant role of SOC is pointed out. By cultivating soil, the SOC balance of a soil is affected. And different agricultural systems will have different impacts on the SOC balance.

To take this into account, three different soil management practices were included in this study: permanent grass, no-tillage and conventional tillage in about equal proportions. Our results show that the effect of the different soil tillage practices on soil structure quality can mostly summed up to the SOC content. This particular aspect is detailed in section 2.4.2.

2.3 Field-scale variability

2.3.1 Problem description: specific influence of site properties and management activities on structural soil properties

The problem of field scale variability is very well known within the soil science community. For chemical measurements, this is partially solved by taking a mixed representative sample, i.e. soil from a large number of sampling points which are typical for a given field, and which therefore represent a typical average of the soil properties of this field. This is quite easy and inexpensive to achieve, because only one (mixed) sample is representative for the whole field, and one analysis of this sample is sufficient.

For the structural characterization of a soil, this procedure is not meaningful, because analyses can only be performed on undisturbed soil samples. If 15 sampling points are needed, then 15 separate analyses are needed as well. The necessary investment of time and money for representative soil sampling and analysis is a major hindrance in soil structure analysis at field level.

2.3.2 Overcoming field-scale variability by using an efficient assessment and sampling strategy and performing multiple measurements on one individual soil sample

For the purpose of developing reference values for soil structure quality, a "conventional" scientific approach to field characterization would have been too time consuming, too costly and not accurate enough. In the STRUDEL project information from more than 200 fields all across the Swiss plateau was used, because our aim was to collect a large number of samples from the soil types Cambisol and Luvisol (according to FAO, 2015b) or Braunerde and Parabraunerde (according to BGS, 2010), respectively, but spanning a large range of soil composition (clay and SOC content), soil subtypes, soil management conditions and geographical distribution.

The chosen methodological approach was to fully characterize (physically, chemically and visually) a soil sample typical of the field we collected it from. This procedure enabled us to collect a large number of samples, because only one sample per field was needed. Obtaining all the physical, chemical and visual characterizations from the same sample improved the assessment of causal relationships between variables, because they were related to the same identical soil structure unit. This helped to drastically reduce problems due to spatial variability.

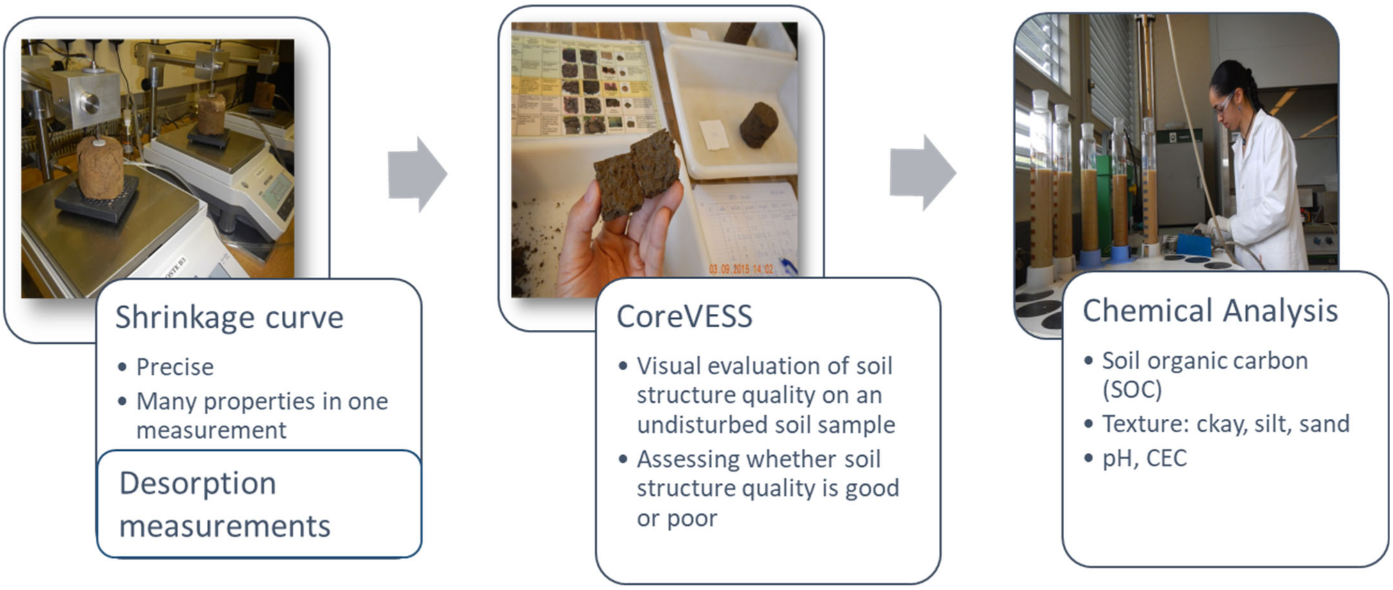
Each individual soil sample was characterized by the following information:

- agricultural practices and soil management as explanatory data;
- physical and chemical analyses of the individual sample;
- visual evaluation of soil structure quality of the individual sample.

Although this procedure bears fruit in terms of data analysis, the necessary organization needed for this procedure is much more complicated. There are difficulties in performing all the measurements consecutively on the same sample, partly because some measurements must be interrupted (e.g. the physical characterization cannot be completed before the result of visual evaluation is available, because the samples cannot be sieved and the stone fraction determined before the intact undisturbed sample is examined). Another risk associated with this procedure is that in case the sample identity is lost during one of the consecutive measurements, it is lost for all the properties and not only for the property where the mistake occurred. Finally, the time needed to gather all the sequentially measured data is considerable, because measurements cannot be done in parallel.

Practically, the sequence of analyses on one individual sample looked as follows (Figure 6): (1) First, shrinkage and desorption measurements were done, which yielded a large number of physical parameters (e.g. bulk densities, water contents, air contents at different matric potentials, equivalent to the determination of different pore size classes). (2) Secondly, the sample was visually evaluated with CoreVESS at a defined matric potential (assessment of soil structure quality, which is a destructive process). (3) Thirdly, the last physical parameters were measured (dry weight at 105°C and weight of the stone fraction after 2 mm sieving). (4) Finally, the separated fine earth was chemically analyzed (e.g. texture, SOC).

Figure 6: Illustration of the "all measurements on one sample" methodology: 1. Physical characterization through shrinkage and desorption curve, 2. Visual evaluation of soil structure quality with CoreVESS; 3. Chemical analyses and texture



2.4 Large scale variability

2.4.1 Influence of site properties (soil type, soil constituents) on soil physical properties

Different soil types and soils of different composition are known to have different physico-chemical properties. At the same time, it is known that soil physical properties strongly depend on colloidal soil constituents such as clay or organic carbon. These relationships should be observed by taking account the soil type (Manrique and Jones, 1991). It is therefore important for the diagnosis of soil structure quality to assess how far soil constituents influence physical properties. This was also highlighted by Schaeffer et al. (2008) and Goutal-Pousse et al. (2016), who found that the diagnosis of soil compaction at field scale was much improved by taking soil constituents into account.

In the STRUDEL project, we sampled soils from agricultural soils located on the Swiss plateau, i.e. from a large geographical area (samples from the datasets STRUDEL 1 and STRUDEL 2). This has a consequence on the range of soil compositions represented in the study. Clay content ranges from 10% to 44%, with a mean value at 21%. SOC content varies from 0.8% to 4.6%, with a mean value at 2.0% (detailed in section 4.3).

Most of these soils are Cambisols and Luvisols (according to WRB (FAO 2015b)) or Braunerde bzw. Parabraunerde (according to the Swiss soil classification system (BGS, 2010)), respectively, developed from moraine or molasses bedrock. They are considered in this study as one large broad soil type. In these Cambi-Luvisols SOC and clay are the most important soil structuring components. They play an important role in soil aggregation and soil structure formation (Kay, 2004). However, the predominant role of SOC over clay was highlighted in Chapter 2 of the doctoral thesis of A. Johannes (2016). In this study, we showed that although clay content is significantly correlated to physical properties, the correlation is poor. On the other hand, SOC is significantly and highly correlated to most physical properties. The effect of clay content was therefore interpreted as indirect, mainly through the protective effect of clay on SOC (Hassink and Whitmore, 1997). Therefore, the following chapter will concentrate on studying the effect of SOC on soil physical properties, together with the effect of soil management practices. The importance of clay content for SOC is illustrated by the SOC:clay-ratio concept, presented in section 5.2.

2.4.2 What is the influence of SOC and soil management on topsoil physical properties and which impact does it have on the building of limit values for soil structure quality?

The effect of soil management practices can first be described by comparing the mean values of SOC for each practice. At 5-10 cm depth, fields with permanent grass (PG) have higher SOC contents than no-tillage (NT) fields, which in turn have higher SOC contents than conventionally tilled (CT) fields. The tendency is the same for eastern and western Switzerland. The main regional difference resides in generally higher SOC contents for soils samples from Eastern Switzerland than from Western Switzerland. This can be explained by the different textures across regions. In our dataset, soils of Eastern Switzerland had a mean clay content of 26%, whereas soils of Western Switzerland had a mean clay content of 20%.

- Mean SOC values for Western Switzerland: PG: 2.24% > NT: 1.84% > CT 1.67%
- Mean SOC values for Eastern Switzerland: PG: 2.78% > NT: 2.26 > CT: 1.85%

Soil physical properties follow the same tendency as SOC for the different soil management practices. This can be observed in Figure 7, where different physical properties are expressed as a function of SOC. The green points representing PG are well represented at high SOC content, while CT are completely missing in this area. In general, the higher the SOC content, the better the physical properties.

This is particularly true for gravimetric water content at -100 hPa (W_{-100}), for which most of the variance is explained by SOC, no matter the practice. On the other hand, gravimetric air content at -100 hPa (A_{-100}) displays more variability, and the CT in Western Switzerland shows no relation to SOC at all. This could be explained by the effect of tillage.

Interestingly bulk density at -100 hPa shows a much better correlation to SOC than dry bulk density. This highlights again the importance of standardizing the matric potential of soil physical properties.

When observing how these relationships evolve with different soil structural qualities (Figure 8), a similar tendency can be observed. Poor structure qualities tend to be regrouped at the lower SOC end. Some properties such as W_{-100} still follow a strong linear relationship with SOC, no matter the soil structure quality. On the other hand, for some other physical properties, such as A_{-100}, the scatterplots of good and poor structure qualities are separated. This highlights the fact that some physical properties reflect the soil composition better (such as W_{-100}), while other reflect the soil structural state better (such as A_{-100}). This must be taken into account for the recommendation of limit values.

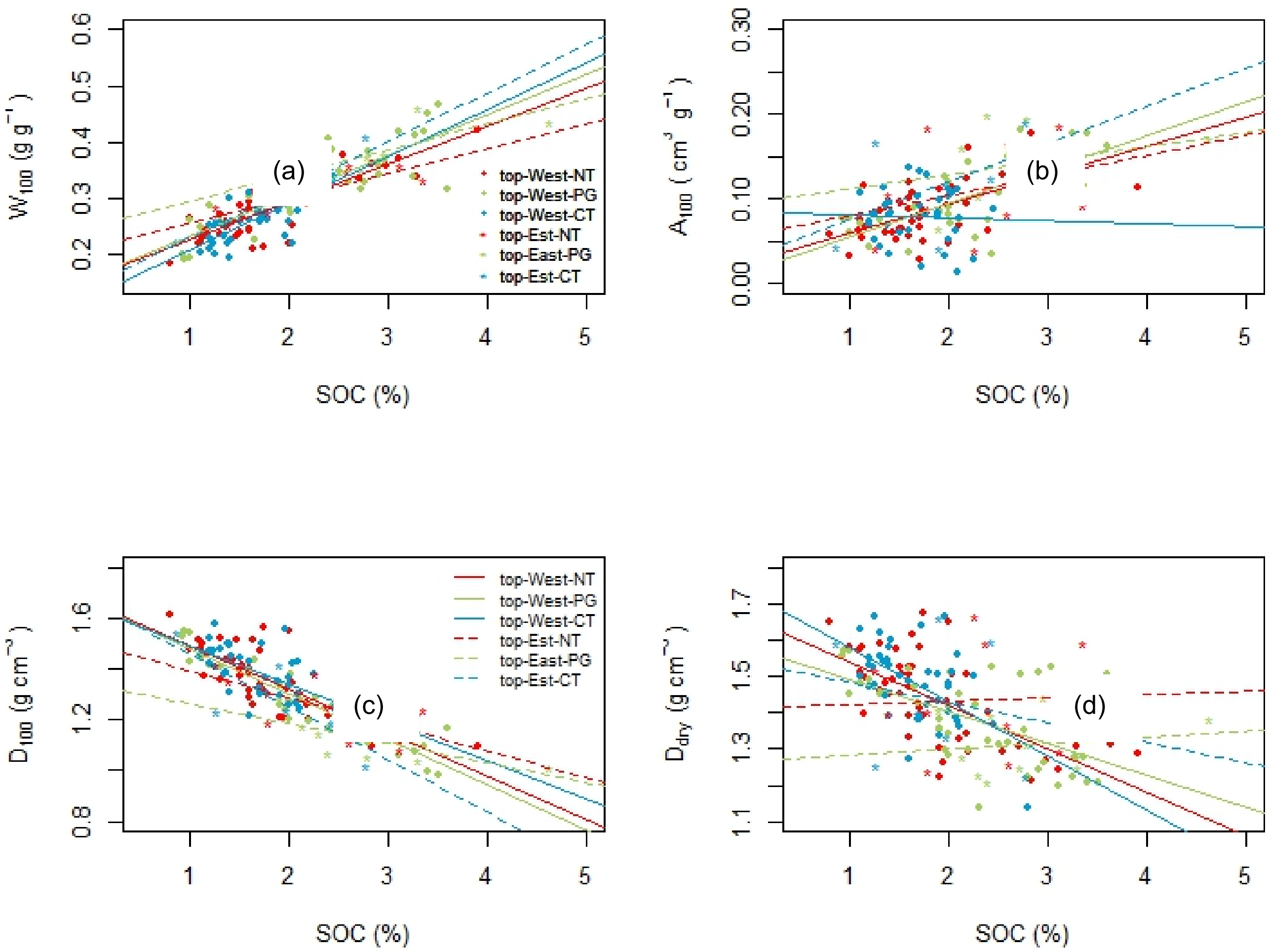


Figure 7: Soil physical properties of topsoils (gravimetric water content at -100 hPa (a), gravimetric air content at -100 hPa (b), bulk density at -100 hPa (c), dry bulk density (d)) as a function of soil organic carbon content (SOC) for Western Switzerland (BE,FR,VD) and Eastern Switzerland (East of BE) for different soil management practices (PG: permanent grass, NT: No tillage, CT: conventional tillage).

Another important aspect is that soils in a good structural state often show a stronger relation to SOC than soils in a poor structural state. This observation is in accordance with previous studies at field scale (Schaeffer et al., 2008; Goutal-Pousse et al., 2016). The fact that different soil structure qualities might or might not have a significant relationship to SOC must be taken into account for the recommendation of limit values. It may mean that this relationship will be taken into account for the calculation of the target value of a certain physical property, but not for the guide/trigger value of the same parameter for example.

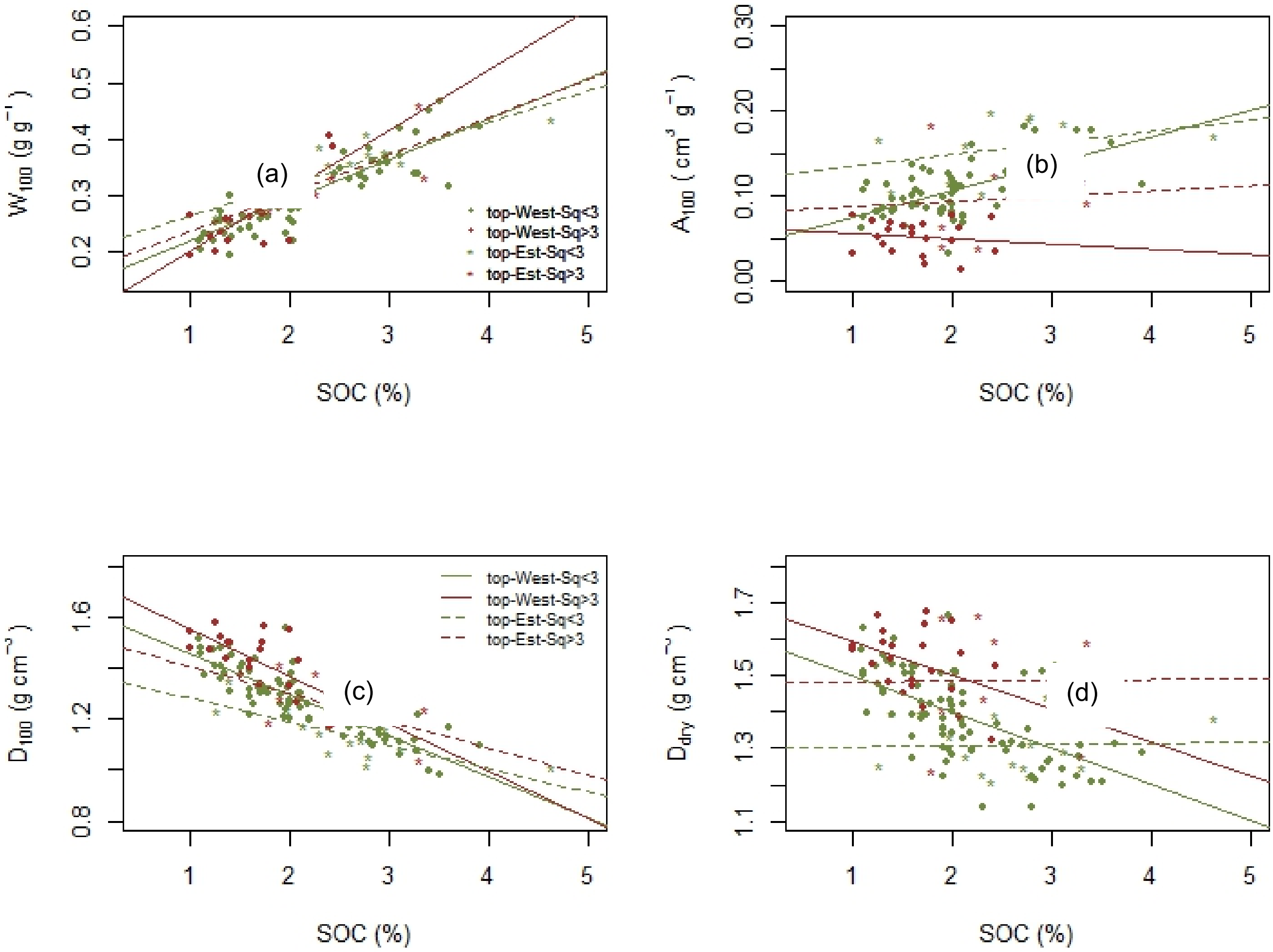


Figure 8: Soil physical properties of topsoils (gravimetric water content at -100 hPa (a), gravimetric air content at -100 hPa (b), bulk density at -100 hPa (c), dry bulk density (d)) as a function of soil organic carbon content (SOC) for Western Switzerland (BE,FR,VD) and Eastern Switzerland (East of BE) of poor structure qualities (Sq>3) and good structure qualities (Sq<3), visually assessed by CoreVESS.

Conclusions:

- At large scale, the information of soil management practices is mainly encompassed in SOC.
- The importance of SOC for physical properties is highlighted. The more SOC, the better the structural state. This naturally leads to the question: What is a “good” SOC content? (see section 5.2)
- Some structural parameters are better suited for a soil structure quality diagnosis and some structural parameters reflect the soil composition better. For example, air content reflects soil structure quality better than it reflects soil composition.
- On the other hand, water content (i.e. microporosity) is very well correlated to SOC, no matter the soil structure quality is. This relation is so strong, that W_{-100} can be used as a proxy for SOC. This is particularly interesting for practical reasons, because then a SOC analysis is not necessary and can be replaced by considering W_{-100}, which is a parameter that is analyzed for the calculation of A_{-100} anyway. The details leading to this conclusion are depicted in Johannes et al. (2019).
- Different soil structure qualities might or might not have a significant relationship to SOC. This must be taken into account for the recommendation of limit values. It can mean that the calculation of the target value for a certain structural parameter takes into account the relationship with SOC, whereas considering this correlation might not be needed for the calculation of the guide/trigger value for the same parameter.

3 Difficulties in building reference values: where is the limit between "good" and "poor" soil structure quality?

3.1 Problem description: The need to classify quantitative analytical results of structural soil parameters according to qualitative information on soil structure quality

There are some propositions for limit values for soil structure quality available in the literature. In particular, Document 13 of the BGS/SSP (BGS, 2004) listed several physical methods and the associated limit values. In Switzerland, the most used properties are macropore volume at pF1.8 and effective density (bulk density considering clay content). These properties are discussed in section 5.1.1. Unfortunately, there is little documentation on how these limit values were developed and which criteria were used. As stated by Lebert et al. (2007), one of the criteria to determine the suitability of a parameter as an indicator of harmful soil compaction is the “availability of a classification scheme for the parameter discriminating good and poor soil structure quality”. In future (e.g. in the context of an OIS revision) it will be relevant to provide clear indications on the methodology and the data used to determine limit values for structural soil parameters.

Soil structure degradation greatly impacts vital soil functions, but the consequences for human beings are only indirect ones. So how to define what is a "good" or a "poor" soil structure when no toxicity is involved like in the case of chemical soil pollution?

Currently, this problem is solved pragmatically by “expert’s judgement” on the field. This judgement is mostly based on the visual evaluation of soil structure quality.

3.2 Chosen Solution: Visual evaluation of soil structure quality

For our purpose, we chose to use a semi-quantitative method, called VESS, that we adapted to our purpose of identifying reference values: the adapted method to visually assess the soil structure quality of soil cores in the laboratory is called CoreVESS. CoreVESS is a more objective visual evaluation method performed on an undisturbed soil sample standardized for soil moisture in the laboratory.

This expert solution is totally empiric, based on visual assessment, and inexpensive.

Visual evaluations and measured soil physical parameters are known to be correlated (Guimaraes et al., 2013, Moncada et al., 2015). The first scientific peer-reviewed article published in the STRUDEL project was “*To what extent do physical measurements match with visual evaluations of soil structure?”* (Johannes et al, 2017a). This paper describes the relationship between different physical properties (measured with the shrinkage methodology) and visual evaluations. We showed that the relationship could be drastically improved when visual evaluations and physical properties are determined at the same scale, in our case, on the same soil sample.

Similarly to VESS, CoreVESS yields soil structure quality scores from 1 ("good") to 5 ("poor"). The soil quality scores are usually denoted “Sq” and were used in STRUDEL to establish reference values as presented below. The scores are normally expressed as integral number, but may also be given as half number to describe structural quality more precisely.

3.3 The STRUDEL method to build limit values for soil structure quality

The STRUDEL project does not only propose limit values for the assessment of soil structure quality. It provides also a method to derive limit values for structural properties measured on undisturbed soil samples. The STRUDEL method to build limit values is based on combining the measurement of structural parameters with the visual evaluation of soil structure quality using CoreVESS on the same undisturbed soil sample.

N.B. To use this methodology it is necessary to extract the soil sample easily from the sampling cylinder without damaging it, so that a CoreVESS evaluation is possible. Therefore the use of split PVC cylinders in the simplified STRUDEL method or of soil samples (clods) directly cut out of soils (without using rigid sampling cylinders) were well adapted to this purpose.

Figure 9 shows which CoreVESS scores were used to generate the three limit values.

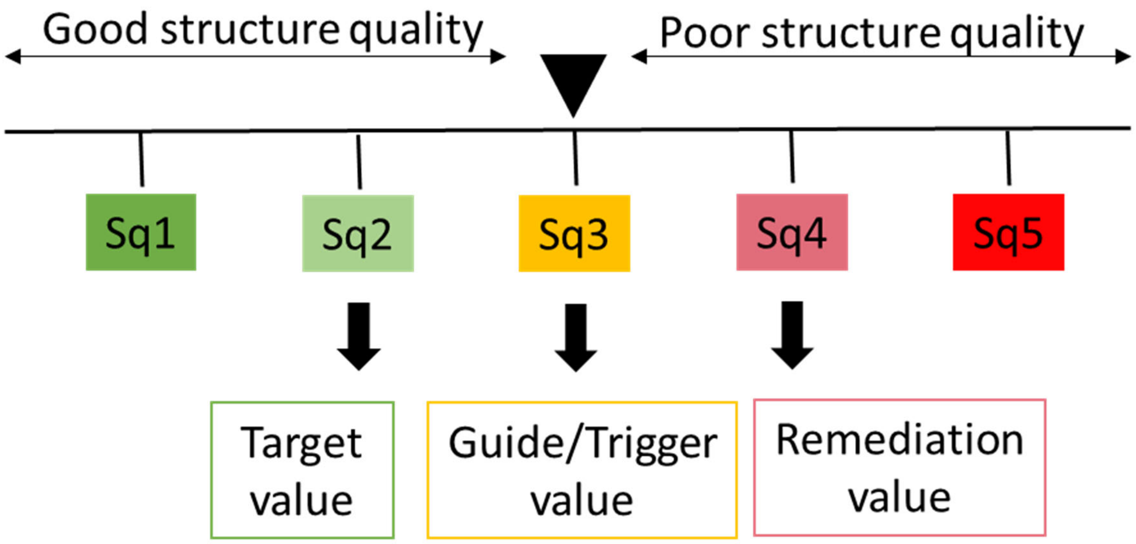


Figure 9: CoreVESS scores for soil structure quality used to establish the three limit values: target value, guide/trigger value and remediation value for a future release of the OIS.

The statistical procedure to build these limit values was the following:

A. <u>Test for a significant relationship with SOC or W_{-100}</u>

For a given structural soil parameter, all the samples of the dataset with either a score of…

- Sq2 to build the "target value"
- Sq3 to build the "guide/trigger value"
- Sq4 to build the "remediation value"

…were pooled and statistically **checked for any significant linear relationship with SOC or its proxy W_{-100}** (importance of which is explained in chapter 0).

B. <u>Depending on the result of the above correlation test, the limit value will either be a linear equation or a mean value</u>

- If the relationship (slope of the linear regression) was statistically significant, the limit value is built as an equation (of the linear regression) containing W_{-100} as variable.
- If the relationship (slope of the linear regression) is NOT statistically significant, the limit value is simply the mean value of all the samples from the dataset with that particular score.

N.B. As already highlighted in chapter 2.4.2, the relationship of the studied physical properties with SOC is always clearer for soils with a good structure quality, while soils with a poor structure quality didn't show any relationship to SOC. It is therefore not surprising that mainly target values have an equation as limit value and that remediation values usually have a simple number (mean value of all the Sq4 samples for the given structural soil property).

C. <u>Check the discriminating power (classification rate) of the given soil physical parameter</u>

Here, we will explain the verification procedure by which we determined the classification rate of the guide/trigger value built with STRUDEL samples. For a specific structural soil parameter:

- First the dataset is separated in two:
    - A dataset with samples which had better scores than Sq3, meaning we only use samples with scores from Sq1-Sq2.5 ("good structure")
    - Another dataset with samples which had poorer scores than Sq3, meaning we only use samples which scored Sq3.5-5 ("poor structure")
    - The samples which were used to build the limit value (i.e. the Sq3 samples) are removed
- Then the percentage of samples that were visually evaluated as having a “good structure” <u>and</u> that were classified by the limit value of the physical parameter as belonging to the “good structure” group is calculated ("good as good");
- Finally the percentage of samples that were visually evaluated as having a “poor structure” <u>and</u> that were classified by the limit value of the physical parameter as belonging to the “poor structure” group is calculated ("poor as poor").

This verification procedure (summarized in Table 2) yields two percentages (correct classification “poor as poor” and “good as good” depicted in the green fields of Table 2) to illustrate the correct classification rates. It is important that both percentages are satisfactory and that they are balanced. Otherwise it could mean that the classification of a structural soil parameter by a given limit value is either too strict (all samples are classified as poor, although many of them are actually in a good structural state) or too lenient (all samples are classified as good, even the samples that show clear signs of structural degradation).

Table 2: Schema of limit value verification procedure explaining how the classification rates are calculated

		Assessment of soil structure quality (by CoreVESS)	
		good	**poor**
Assignment of analyzed structural soil property to soil structure quality (by limit value)	**poor**	Wrong (error type 1, alpha)	Correct
	good	Correct	Wrong (error type 2, beta)

This verification procedure needs a sufficient number of values for both "good" and "poor" soil structure quality. Theoretically it is possible to check the discriminating power of any limit value (target and remediation values too), if a sufficient number of values is available.

In the STRUDEL project we applied this method to build limit values, using soil samples taken in agricultural fields all across Switzerland; these samples have the advantage to be representative of the given field situation and represent a structural state which is the result of the soil history. It is therefore a realistic picture of what can be found in Switzerland. There is however a disadvantage of taking soil samples in random fields: it is not possible to foresee the structural quality of this sample (contrarily to scientific field experiments where the degradation history should be known). Therefore, it is not possible to know whether there will be sufficient samples of a desired structure quality (CoreVESS score) to develop valid reference values.

Based on this methodology to build and verify limit values a database was set up containing the analyzed structural properties and the evaluated structure quality scores of all soil samples of the STRUDEL project; this database is presently managed by Agroscope. The statistical procedure to build the limit values and their classification rate is available as R code from Agroscope and the authors, respectively. This allows for improving and broadening the system of limit values by adding measurements and evaluations from new soil samples and new field situations. This means also that the quality of these limit values can continuously be improved thanks to an increasing database or be specified thanks to a more refined classification of site or management conditions.

This procedure to build reference values can be used for different structural properties as long as the soil structure quality of the sample can be visually evaluated, too.

4 Material and Methods

4.1 Study area – sampling – soil characteristics

Soil samples have been taken from autumn 2012 to autumn 2018 in different seasons. Sampling tooks place in different cantons (Figure 10) all over the Swiss plateau (Figure 11) with a target on soils classified as Braunerde and Parabraunerde in the Swiss soil classification system (BGS, 2010). This soil type is intermediate between Cambisol and Luvisol soil groups of the World Reference Base for soil resources (FAO, 2015b).

For datasets of STRUDEL 1 and 2, sampling took place in agricultural soils on approximatively one third conventionally tilled fields (CT), one third no-tillage fields (NT) claimed to be practiced since at least 10 years and one third permanent grass (PG), either pasture or not. No-till fields were first selected via the "Swiss-No-Till" association registry. Sites under CT and PG were generally easily found in the neighboring area of the NT fields. The sampling sites tend therefore to be clustered. In cantons where an extended soil monitoring network exist, such as the FRIBO for canton Fribourg, some monitoring sites could be included. Samples from the Soil Structure Observatory (SSO) long-term experiment in Reckenholz (Keller et al., 2017) were also included in the project.

Table 3: Number of samples taken in the STRUDEL sampling campaigns

Time of sampling	Number of samples* and fields	Sampled depth	Canton	Framework and main involved persons
Autumn 2012-Spring 2013	65* sampling points in 65 fields	5-10 cm, 15-20 cm	VD	STRUDEL 1 and Master thesis of Léonie Givord at UNINE (AJ)
Autumn 2013	64* sampling points in 64 fields	5-10 cm, 30-35 cm	FR	STRUDEL 1 and Master thesis of Tania Ferber at UNINE (AJ)
Spring 2014	66 sampling points in 66 fields	5-10 cm, 30-35 cm	BE	STRUDEL 1 and Bachelor thesis of Elisabeth Busset at HEPIA (AJ)
Spring 2015	58 sampling points in 58 fields	5-10 cm, 30-35 cm	VD,FR,BE	STRUDEL 1 and Master thesis of Adrien Matter at HES-SO (PB,QC)
April 2013	18 sampling points in 3 fields	5-10 cm, 30-35 cm	ZH	SSO project (AJ, PB, PM)
June-July 2017	32 sampling points in 32 fields	5-10 cm, 30-35 cm	ZH,TG,SH, AG,SO,LU	STRUDEL 2 (AJ, CS)
Nov. 2014	29 sampling points in 19 fields	5-10 cm	ZH	Bachelor thesis of Gregor Rieche at ZHAW (PB)
May 2017	30 sampling points in 10 fields	5-10 cm	LU, SZ, UR, NW,OW	Bachelor thesis of Hans Sturzenegger at ZHAW (AJ)
Spring 2018	54 sampling points in 5 fields	5-10 cm, 30-35 cm	ZH,BL,GE, BE	Implementation tests (BS)
October 2018	96 sampling points in 3 fields	5-10 cm	ZH	SSO project and Master thesis of Antoine Boudraa at UNINE (AJ)

In total 426 samples in 322 fields
*replicate samples had to be re-analysed to include CoreVESS scoring in the procedure. All physical analyses had to be done a second time in order to offer best concordance between physical measurement and CoreVESS score of the same sample.
AJ:A. Johannes, PB: P.Boivin, QC: Q. Chappuis, PM:P. Manalili, CS: C. Schlaiss, BS: B. Seitz

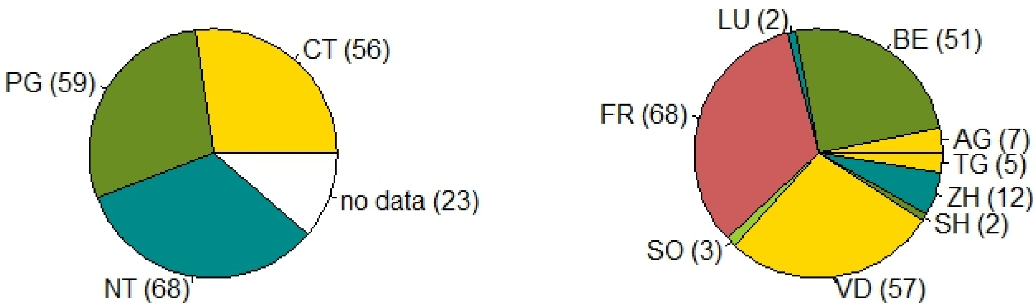


Figure 10: Pie charts of different soil management practices (PG: permanent grass, CT: conventional tillage, NT: no tillage) on the left and on the right of the different cantons represented in datasets STRUDEL 1 and 2.

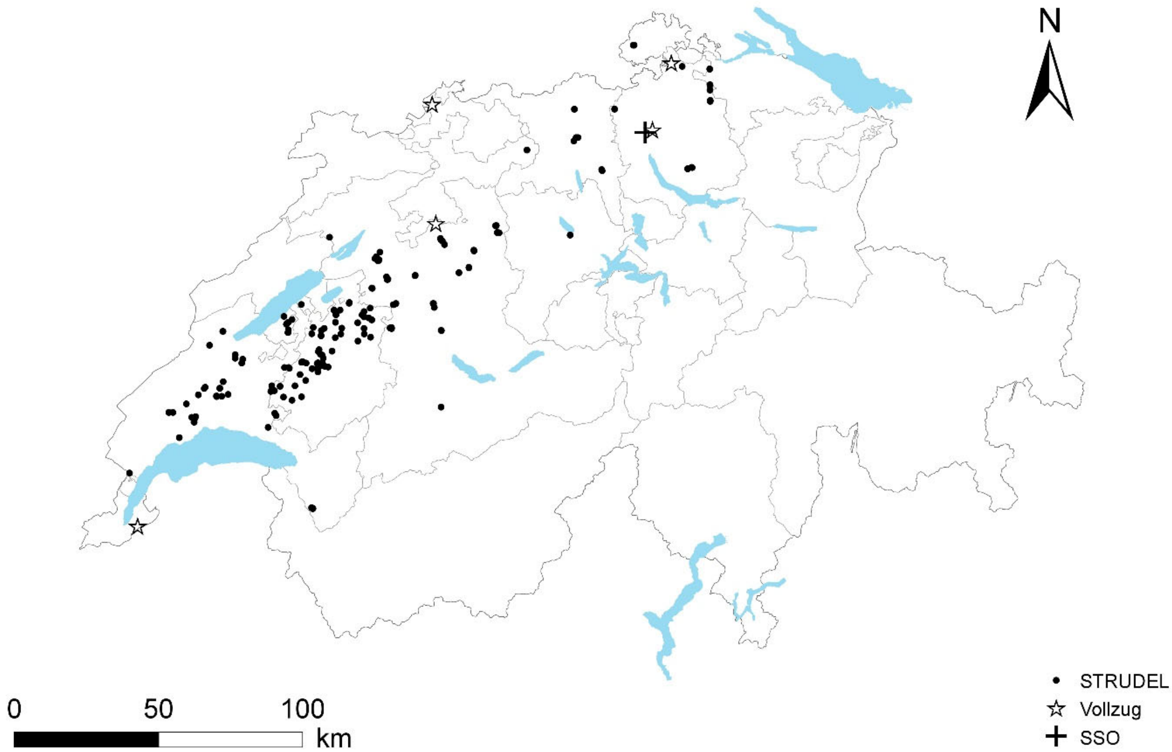


Figure 11: Map of the sampling points of the STRUDEL project including the SSO compaction experiment point and the implementation test points.

4.2 Texture and chemical analyses

5 texture fractions (clay, fine silt, coarse silt, fine sand, coarse sand) were determined according to the traditional pipette method.
Soil organic carbon was determined by oxidation using potassium dichromate and sulfuric acid (Walkley and Black, 1934).
pH was measured in a water extract with pH meter.
Effective cation exchange capacity (CEC) was determined by means of cobalt hexamine trichloride (Ciesielski et al., 1997).

4.3 Soil composition

SOC and clay can be considered as the main soil structure forming constituents in Cambisols and in Luvisols (Braunerden and Parabraunerden). Thanks to the large geographical coverage of the sampling during this study, a large range of SOC and of texture is represented in the STRUDEL data. Clay content ranges from 10% to 44% with a mean value at 21%. SOC content varies from 0.8% to 4.6% with a mean value at 2.0% (Figure 12).

Although the soil structure forming constituents are the same in most of the agriculturally used Swiss soils, their amount can vary across Swiss regions. For instance soils in eastern Switzerland have in average higher clay contents than in western Switzerland.

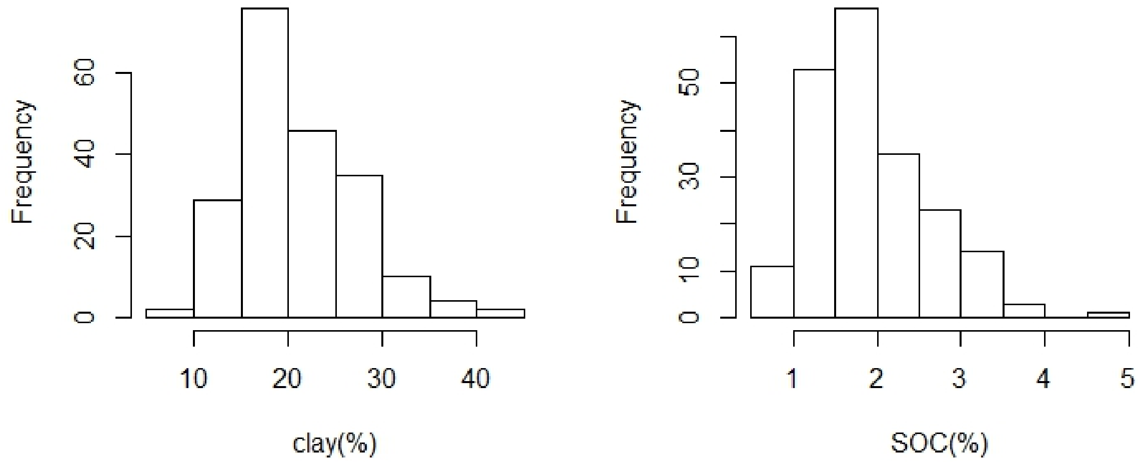


Figure 12 Histograms of clay content and soil organic carbon (SOC) content from topsoils of datasets STRUDEL 1 and 2.

4.4 Shrinkage curve analysis

Shrinkage measurements and shrinkage curve analysis by modeling (ShC) were the main methods used for physical analysis in this project.

The shrinkage measurement is a precise physical method to determine volume and weight of a soil sample during a dessication (and shrinkage) process from saturation to air dryness over the whole water content range:

1) The soil sample is placed without a restricting cylindrical ring ("unconfined") on a sandbox to be equilibrated to -10 hPa. During equilibration the sample can swell freely in all three dimensions; at equilibration the sample is swelled to its maximum volume.

2) After equilibration, the sample is left for drying on a scale until the weight is constant. (Figure 13). During drying, the weight (transformed into water content), height (transformed into volume) and matric potential (via a mini-tensiometer until -850 hPa env.) are recorded continuously (every five minutes). This drying process usually takes 4 to 10 days, depending on sample texture, sample structure and room climate (e.g. clayey soils take more time to dry). The sample volume at the beginning and at the end of the drying process is measured with the plastic bag method.

Many physical properties can be determined from these few measured parameters, ranging from porosity and desorption curve properties to modelled ShC properties differentiating plasma porosity from structural porosity. Figure 14 shows some of these modelled ShC properties with the XP model of Braudeau et al. (1999). The four transition points (from larger to smaller volume and water content: MS (maximum swelling point), ML (macroporosity limit), AE (Air entry point in the plasma), SL (shrinkage limit)) allow to characterize a shrinkage curve which usually has the shape of an S. On a typical shrinkage curve there are three linear and two curvy domains.

In this concept of plasma and structural porosity, the difference in porosity is not only related to the pore size, but also to the behavior of the pore regarding hydric stress:

- When loosing water, plasma pores shrink in a similar way as a clay paste would (i.e. with a 1:1 slope), until “air entry point” is reached. The plasma is formed by the matrix of soil colloids, namely clay minerals, organic matter and oxides, and its porosity is formed by the inter-colloidal particle voids. (Brewer et al. 1964)
- On the other hand, structural pores have a rigid behavior when loosing water, and tend to retain their shape. 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

Figure 13: Soil shrinkage measurement: unconfined soil samples are drying on a scale, which is continuously measuring sample weight; sample height is continuously determined by a transducer; a micro-tensiometer is measuring continuously matric potential.

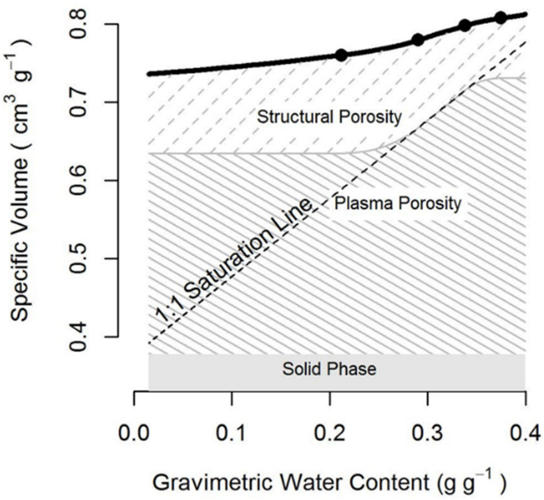


Figure 14: modeled shrinkage curve (ShC): Specific volume (soil volume per unit dry soil mass) as a function of gravimetric water content with the four transitions points of the Braudeau model, enabling to distinguish structural porosity from plasma porosity.

4.5 Visual evaluation of soil structure quality in the field by VESS

In the first samplings in VD and FR, only qualitative observations were recorded by a spade test. Because these observations were very difficult to process statistically (not systematic enough, difficult to compare among each other), in 2014 we opted for another method of visual assessment, which was faster and comparable because it provided numerical results thanks to a semi-quantitative scoring of soil structure quality: the VESS method (Ball et al., 2007, Guimaraes et al., 2011). VESS stands for Visual Evaluation of Soil Structure and is practiced with a chart containing pictures which illustrate the different soil structure qualities. These pictures are accompanied by descriptions and by a scoring system ranging from Sq1 ("good") to Sq5 ("poor"). The evaluation is based on observation of aggregate shape, breaking resistance, and visible porosity.

There are two different charts for the evaluation of topsoil and subsoil: VESS and SubVESS.

Additional information concerning the method and work in the STRUDEL project:

- **VESS**: During the STRUDEL project the VESS field chart (Ball et al., 2007, Guimaraes et al., 2011) was constantly improved and translated into French and German, resulting in the new release $VESS_{2020}$, available on www.strudel.agroscope.ch.
- **SubVESS**: During the STRUDEL project, SubVESS (Ball et al. 2015) was transferred from a profile method into a spade method and translated into French and German, resulting in the new release $subVESS_{2020}$, available on www.strudel.agroscope.ch.

4.6 Visual evaluation of the samples structure quality by CoreVESS

CoreVESS is described in the article "To what extent do physical measurements match with visual evaluations of soil structure?" (Johannes et al. 2017a). It is an adaptation of the above mentioned field method VESS (Visual Evaluation of Soil Structure; Ball et al., 2007; Guimarães et al., 2011) which was adapted to the needs of the STRUDEL project, namely the assessment of a soil sample. These adaptations improved the objectivity of the method by standardizing the evaluation conditions in the laboratory and by allowing the blind evaluation of "anonymous" samples. The main adaptations from VESS to CoreVESS are summarized here:

- Soil moisture of the sample is standardized on a suction plate (in STRUDEL: at -100 hPa matric potential) to homogenize the evaluation conditions.
- The soil samples are anonymized and then assessed under blind test conditions, thereby providing a higher objectivity of the assessment.
- Some assessment criteria of the VESS field method, such as the aggregate size, have to be adapted to the sample-based CoreVESS method, because large size-classes are superior to the size of the sample.

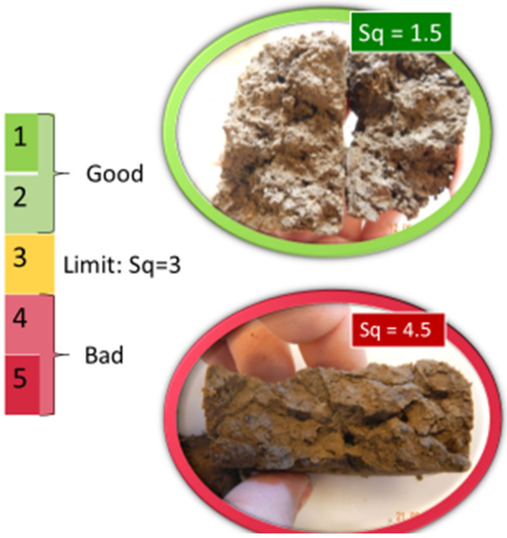


Figure 15: Illustration of good and poor structure qualities with the soil structure quality evaluation scale of CoreVESS

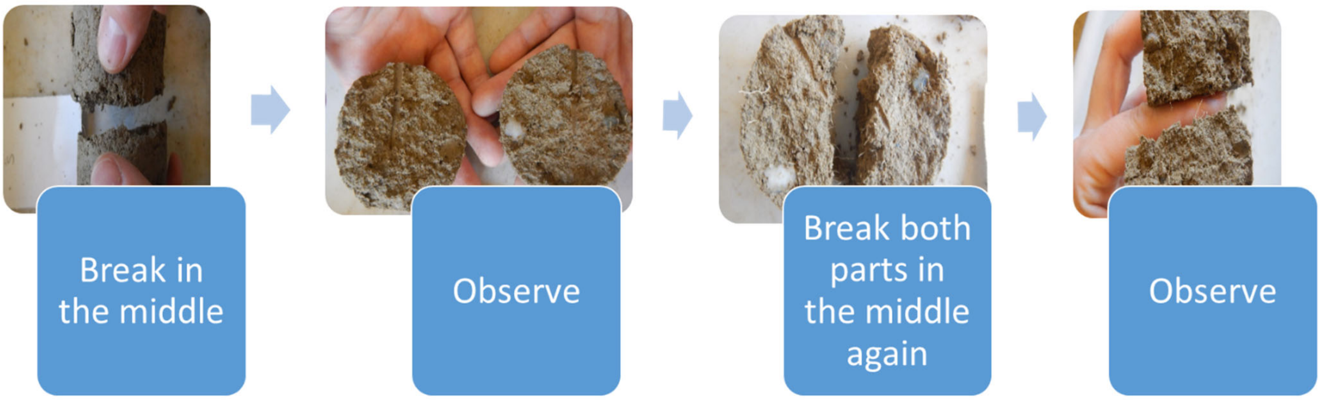


Figure 16: Evaluation and Observation procedure during CoreVESS assessment

CoreVESS follows the same evaluation scheme as VESS with scores ranging from Sq1 (good structure quality) to Sq5 (poor structure quality) as illustrated in Figure 15. The observation procedure is illustrated in Figure 16.

5 Main STRUDEL results

5.1 Reference values for parameters describing structural soil properties

5.1.1 Existing limit values for soil structural parameters

There are a few limit values existing in the literature. The structural soil parameters most frequently associated with limit values in Switzerland are effective density (bulk density taking into account the clay content of a soil), macropore volume at pF1.8 (= matric potential at -60 hPa), and saturated hydraulic conductivity. Suggestions for limit values for these three parameters are described in Document 13 of the BGS/SSP (BGS, 2004). The recent publication of STRUDEL describes the limit values for gravimetric air content at -100 hPa for topsoils (Johannes et al., 2019). The associated limit values of these parameters are available in Table 6.

In this chapter, we compare how three different properties classify soil structure quality as visually assessed. Table 4 presents the classification rates for the parameters

- "gravimetric air content at -100 hPa (pF2)", noted A_{-100}
- "macropore volume at -60 hPa (pF1.8)", noted MP60
- "effective bulk density"

These properties were determined on the STRUDEL soil samples. It must be noted that the parameters presented here were all determined based on shrinkage measurements. Because this methodology may lead to slightly different values than with the original protocol for the two parameters mentioned in Document 13: (i) macropore volume was calculated here as air content at -100 hPa, instead of difference of water content between full saturation and pF1.8 (i.e. between 0 and 60 hPa) as mentioned in Document 13. (ii) bulk density used here for calculating the effective density is based on the sample volume determined at -100 hPa, as no particular matric potential is mentioned in Document 13.

The classification rates shown in Table 4 were calculated following the statistical procedure described in chapter 3.3. It shows the proportion of soils with a good structure quality (Sq<3) that was classified by the guide/trigger value of the parameter as being a “good" structure, and the proportion of soils with a poor structure quality (Sq>3) that were classified by the guide/trigger value of the parameter as being a “poor" structure.

As shown in Table 4, the worst classification rates were found for effective density for "poor" structure quality: depending on the data set only 3.9 to 6.3% of the samples were correctly classified for any depth. In other words even the very compacted soils will be classified incorrectly as “good” with this method. This means that the guide/trigger value for effective density is clearly not effective in assessing the structure quality of soil samples and therefore will not help to diagnose a soil compaction case in over 90% of the cases. That is why it is not surprising that soil protection specialists of the cantons are generally not convinced of the guide/trigger values provided for effective density to assess soil structure quality. In contrast, macropore volume at pF1.8 (MP60) and gravimetric air content at -100 hPa (A_{-100}), which in principle are related to the same structural property (the size of the pore space of the biggest pores), display similar good classification rates, meaning similar discrimination power. It is slightly higher for A_{-100} in topsoils with 90% correct assignments to “good as good” and 80% correct assignments to “poor as poor”, while MP60 has 92% correct assignments to “good as good” and 63% correct assignments to “poor as poor”. The guide/trigger value for MP60 seems to be slightly too tolerant to identify a poor structure quality, as only 63% of soil samples with poor structure quality were correctly assigned. In contrast the guide/trigger value for A_{-100} showed lower discrimination power for subsoils, namely 58% for “good as good” and 94% for “poor as poor”, which shows that it is too severe with good subsoil structures. This is an indication that the existing guide/trigger value for A_{-100} developed on topsoils should be adapted to subsoils, as proposed in the following chapter.

Table 4: Classification rates ("discrimination power") of correct assignment for good structure quality ("good as good") and poor structure quality ("poor as poor") of existing guide/trigger values for three structural soil properties (gravimetric air content at -100 hPa, macropore volume at -60 hPa, effective density) from different STRUDEL datasets. All soil samples were visually evaluated with CoreVESS to assess soil structure quality.

		Gravimetric air content at -100 hPa guide/trigger value: 0.068 $cm^3\ g^{-1}$ (Johannes et al., 2019)			
		"good as good"[2)]		"poor as poor"[3)]	
Dataset	Depth	%	n (Sq <3)	%	n (Sq >3)
all	topsoil	**89.7**	136	**80.2**	106
	subsoil	**57.5**	113	**93.6**	47
STRUDEL	topsoil	95.1	81	77.1	48
	subsoil	64.3	84	90.0	10
STRUDEL West	topsoil	94.3	70	76.2	21
STRUDEL Ost	topsoil	100.0	10	20.0	5
Vollzug	topsoil	93.1	29	89.7	29
	subsoil	83.3	12	94.6	37

		Macropore volume at -60 hPa (pF 1.8) guide/trigger value: 7.0 vol% (BGS, 2004)			
		"good as good"[2)]		"poor as poor"[3)]	
Dataset	Depth	%	n (Sq <3)	%	n (Sq >3)
all	topsoil	**92.0**	112	**62.8**	77
	subsoil	**79.1**	86	100.0	2
STRUDEL	topsoil	94.2	86	66.7	48
	subsoil	92.8	69	100.0	2
STRUDEL West	topsoil	94.6	74	61.9	21
STRUDEL Ost	topsoil	90.9	11	20.0	5
Vollzug	topsoil				
	subsoil				

[1)] In grey: unreliable classification rates based on less than 10 samples

[2)] n (Sq < 3) = number of samples in the dataset that obtained a CoreVESS score of less than 3, corresponding to a "good" structure quality. Classification rate (in %) = proportion of samples with "good" structure quality that was correctly classified by the guide/trigger value.

[3)] n (Sq > 3) = number of samples in the dataset that obtained a CoreVESS score of more than 3, corresponding to a "poor" structure quality. Classification rate (in %) = proportion of samples with "poor" structure quality that was correctly classified by the guide/trigger value.

		Effective density (BD+0.009*clay) guide/trigger value: 1.8 g cm3 (BGS, 2004)			
		"good as good"[2)]		"poor as poor"[3)]	
Dataset	Depth	%	n (Sq <3)	%	n (Sq >3)
all	topsoil	**99.1**	114	**3.9**	77
	subsoil	**86.1**	86	0.0	1
STRUDEL	topsoil	98.9	88	6.3	48
	subsoil	91.3	69	0.0	1
STRUDEL West	topsoil	98.7	74	4.8	21
STRUDEL Ost	topsoil	100.0	13	0.0	5
Vollzug	topsoil				
	subsoil				

5.1.2 Soil structure parameters, their limit values and their classification rates for soil structure quality

Reliable classification of structural soil parameters to soil structure quality as visually evaluated by CoreVESS was first described in the STRUDEL project for topsoils with the parameter "gravimetric air content at -100 hPa" (A_{-100}) (Johannes et al 2019). This parameter was selected among over 70 other parameters as being the best suited to assess soil structure quality. Figure 17 shows graphically the different limit values.

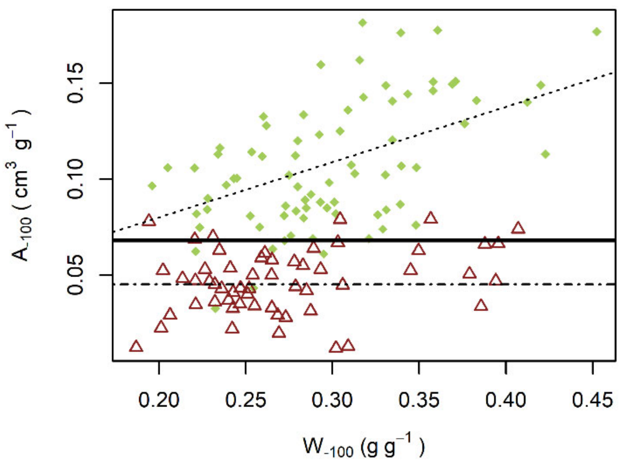


Figure 17: Gravimetric air content at -100 hPa (A_{-100}) as a function of gravimetric water content at -100 hPa (W_{-100}) with target values (dotted line), guide/trigger value (full line) and remediation value (dashed line) and with observations of good structural quality (Sq<3, represented by full dots) and poor structural quality (Sq>3, represented by open triangles). (Source: Johannes et al. 2019)

In this report we go a bit further and present limit values for more physical properties and depths and their classification rates (Table 5). We used the STRUDEL method for developing reference values to build limit values ("target", "guide/trigger" and "remediation" values) for several parameters easily determinable with the "simplified STRUDEL method" described in Chapter 6. We present the limit values for two different soil depths. The topsoil dataset had enough data points in each category to build limit values and determine classification rates. For the subsoils we show only the parameters with a sufficient number of data points. All physical parameters presented in Table 5 can be determined with the simplified STRUDEL method (chapter 6) and equilibration at matric potentials of either -60 hPa or -100 hPa, except the dry bulk density, which should be measured at dry state for which a different protocol than the “simplified STRUDEL method” is needed.

All parameters related to water and air contents, respectively, are displayed in both volumetric and gravimetric relationship:

- The gravimetric relationship answers the question "how much water or air can a given soil mass contain?"
- The volumetric relationship answers the question "what is the proportion of air or water in a given amount of soil volume?"

The pros and cons of using one relationship rather than the other are described in section 2.2.2. Our results show that in the topsoil, gravimetric relationships systematically displayed slightly better classification rates than volumetric relationships. In the subsoil, it is interesting to remark that of the two parameters "gravimetric air content at -100 Pa" and "volumetric air content at -100 Pa", the volumetric relationship showed slightly better classification rates.

Most of the time the limit values of the parameters were the mean value of all samples which obtained a certain score in visual structure evaluation. In some cases, when the correlation with W_{-100} was high and the classification rate was better, the limit value is expressed as the equation of the regression of the given property as a function of W_{-100}. (The procedure is detailed in section 3.3.)

With the classification rates, we can see that not all structural parameters delivered limit values which were well suited to assess soil structure quality. For instance water content at given matric potentials displayed quite poor classification rates. Air content or macropore volume, respectively, and dry bulk density were better suited because of their higher classification rates for both "good" and "poor" structure qualities. As discussed in section 2.4.2, we observe again that the parameters least correlated to SOC and clay content were generally the most efficient parameters to discriminate soil structure quality.

The subsoil section of Table 5 is incomplete. Only the samples from the “Vollzug" dataset taken from known compaction sites had a sufficient number of samples worse than Sq3 to provide reliable classification rates. This dataset had only undergone the “simplified STRUDEL method at -100 hPa” for physical characterization. But even in this dataset, the number of samples with exactly the score Sq4 was insufficient to propose a “remediation value”. Other subsoils that were taken randomly across the Swiss plateau in agricultural soils (and had undergone a complete shrinkage curve with the very large number of physical properties one can derive from it) had rather good scores, mostly better than Sq3. This is of course good news for Swiss subsoils in general, but frustrating for the STRUDEL project which cannot propose limit values for more physical soil properties. Therefore it is necessary to continuously supplement the STRUDEL database for structural soil parameters in order to improve the three types of limit values regarding discrimination power and reliability.

Table 5: Target, Guide/Trigger and Remediation values for some physical parameters in topsoils and subsoils. Classification rates are given for Guide/Trigger values

bulk density [g*cm^{3}]			classification				
all topsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	1.86-1.87*W_{-60}	1.87-1.73*W_{-60}	81.6	114	87.0	77	1.94-1.81*W_{-60}
at -100 hPa	1.84-1.83*W_{-100}	1.83-1.62*W_{-100}	**85.5**	138	**89.6**	106	1.95-1.84*W_{-100}
dry	1.78-1.30*W_{-100}	1.73-0.94*W_{-100}	70.6	109	89.6	77	1.87-1.14*W_{-100}
all subsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	1.91-1.76*W_{-60}						
at -100 hPa	1.96-2.05*W_{-100}	2.00-2.05*W_{-100}	78.8	113	74.5	47	
dry	1.85-1.29*W_{-100}						

gravimetric air content [cm^{3}*g^{-1}]			classification				
all topsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trig-ger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	0.012+0.27*W_{-60}	0.06	77.7	112	85.7	77	0.04
at -100 hPa	0.027+0.27*W_{-100}	0.07	**80.1**	136	**87.7**	106	0.05
all subsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	0.05						
at -100 hPa	0.07	0.05	77.0	113	70.2	47	

volumetric air content [vol%]			classification				
all topsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	12.62	8.06	77.7	112	81.8	77	6.56
at -100 hPa	13.60	9.63	**81.6**	136	**84.0**	106	7.34
all subsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at -60 hPa	16.8-33.3*W_{-60}						
at -100 hPa	10.0	7.3	78.8	113	74.5	47	

gravimetric water content [g*g]			classification				
all topsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at-10 hPa	0.34	0.30	66.9	121	71.1	83	0.28
at -60 hPa	0.31	0.28	62.3	114	66.2	77	0.26
at -100 hPa	0.30	0.28	50.0	138	70.8	106	0.24
-10 to -60 hPa	0.03	0.02	64.0	114	75.3	77	0.02
-10 to -100 hPa	0.05	0.04	67.9	109	74.0	77	0.03
all subsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at-10 hPa	0.26						
at -60 hPa	0.24						
at -100 hPa	0.22	0.22	29.2	113	29.8	47	
-10 to -60 hPa	0.02						
-10 to -100 hPa	0.03						

volumetric water content [vol%]			classification				
all topsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at-10 hPa	73.8	42.3	60.3	121	57.8	83	40.1
at -60 hPa	40.1	39.1	56.1	114	53.2	77	38.4
at -100 hPa	38.2	39.0	42.0	138	56.6	106	36.7
-10 to -60 hPa	4.0	3.1	60.5	114	74.0	77	2.6
-10 to -100 hPa	6.5	4.8	66.1	109	74.0	77	4.1
all subsoils			"good as good"		"poor as poor"		
moisture	Target value	Guide/Trigger value	%	n (Sq<3)	%	n (Sq>3)	Remediation value
at-10 hPa	37.1						
at -60 hPa	35.2						
at -100 hPa	33.9	34.3	21.2	113	25.5	47	
-10 to -60 hPa	2.6						
-10 to -100 hPa	4.7						

5.1.3 New propositions for limit values in BGS Document 13 and by the STRUDEL project

In the chapter above three limit values were proposed for A_{-100} and other physical properties that can be obtained with the same protocol. The procedure described in section 3.3 to build limit values can however be applied to other physical properties. In Table 6, the "new" limit values for the properties "effective density" and "macropore volume" are presented. A distinction is made between topsoils and subsoils. In the case of the effective density, a proposition was made for two different moisture states: dry state and moist state at -60 hPa. Because at dry state, the bulk density was insufficiently correlated to clay content, limit values are proposed for "simple" bulk density and not for effective density. For the -60hPa moisture state, the formula of effective density was modified according to the regression we observed in the STRUDEL dataset and a new guide/trigger value was proposed.

Table 6: Limit values for the structural parameters "bulk density" or "effective density", respectively, and "macropore volume" as proposed in the BGS document 13 (BGS, 2004) and proposition of new limit values by STRUDEL. Soil depth: topsoil limit value valid for ~0-20 cm, subsoil limit value valid for >= 30 cm

Parameter	Limit value proposed in **BGS document 13** (or in Johannes et al., 2019 for A_{-100})	Proposition of new limit value (STRUDEL building method for limit values (data set: STRUDEL study))	Remarks
Bulk density (with or without taking in account the effect of clay)	Effective density (= bulk density* [g/cm^3] + 0.009*clay content [% w/w]) guide/trigger value: 1.70 g/cm^3 action value: 1.80 g/cm^3 *no particular specification of swelling state/matric potential	**Dry** bulk density, guide/trigger value: - topsoils:1.48 g/cm^3 - subsoils: 1.69 g/cm^3 **New effective density at -60 hPa** (BD_{-60} [g/cm^3] +0.013*clay[% w/w])): Topsoil guide/trigger value: 1.63 g/cm^3 Effective density at -60 hPa: subsoil (tentative) guide/trigger value: 1.56 g/cm^3	The limit value for dry bulk density doesn't need to be adapted to clay content, because dry bulk density is not sufficiently correlated to clay content. The formula to calculate the effective density is modified. The limit value proposed for effective density at -60 hPa is tentative because of insufficient number of samples. This low number of samples also explained why no correlation with clay could be highlighted.
Macropore volume (MP60)	Macropore volume **at -60 hPa**, guide/trigger value: 7 vol.% remediation value: 5 vol.%	Macropore volume* **at -100 hPa**, guide/trigger value: - topsoils: 8.9 vol.% - subsoils: 7.7 vol.% *represented by volumetric air content at -100 or -60 hPa in Table 5	We propose here limit values for macropore volume at -100 hPa instead of -60 hPa, because we had an insufficient number of subsoils at -60 hPa to propose a reliable limit value for that depth.

5.2 The SOC:clay-ratio as indicator for the vulnerability of a soil structure

5.2.1 Introduction

As stated in Chapter 2.4, most soil structure properties are surprisingly closely related to SOC, even under different soil management conditions. The relation is always positive: the more SOC, the better the physical properties. SOC is also considered by many authors as the main indicator for soil structure quality (Kay 1998) and soil quality (or soil health, respectively) in general (Bünemann et al, 2018, Wander et al., 2019). Therefore, the question arises: **what is a good SOC content?** It seems evident to any soil scientist that no universal value can be used: One cannot expect the same optimal SOC content in a sandy soil and in a clayey soil. Soil texture, in particular clay content, is very important for the SOC binding potential.

SOC:clay-ratio was studied by many scientists (e.g. Dexter et al., 2005, Getahun et al, 2016, Schjonning et al., 2012). The STRUDEL project contributed to this knowledge by giving a soil structure quality interpretation to the SOC:clay-ratio. Results were published in the paper: "Optimal organic carbon content for soil structure quality: Does clay content matter?" (Johannes et al, 2017b), where we used visual evaluations with CoreVESS to provide reference values for SOC based on the SOC:clay-ratio.

5.2.2 SOC:clay-ratio, an indicator of soil structure vulnerability (SSVI)

For Johannes et al. (2017b) a large dataset of over 150 samples was used, which was taken in the cantons of Vaud, Fribourg and Bern. In this dataset, the origin of the poor soil structure quality of the Sq>3 samples is unknown and probably a result of several afflictions including carbon loss and mechanical impacts, which probably cannot completely be separated one from the other.

The loss of SOC leads to a more vulnerable soil structure. SOC and clay are major binding agents for soil aggregates, and therefore stability at aggregate level is decreased when SOC content decreases (Oades, 1984). This loss of soil structure stability leads to increased vulnerability against external forces (e.g. raindrops, mechanical impacts of vehicles) the result of which can be seen when soil structure quality is visually assessed. The gradual decline in soil structure quality with decreasing SOC:clay-ratio is illustrated in Figure 189.

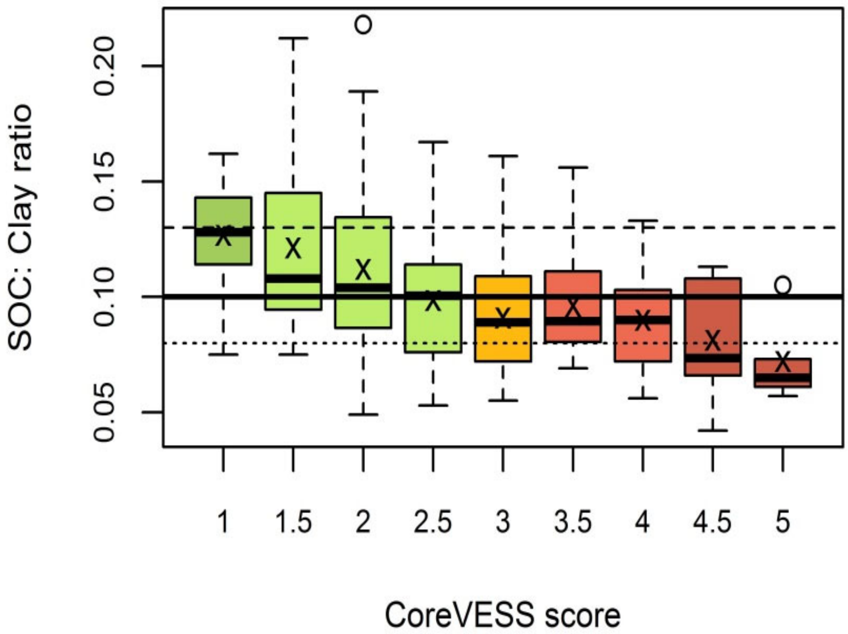


Figure 18: Boxplots of SOC:clay-ratio for different CoreVESS scores. Boxplots show mean values (cross), median values (solid horizontal line), 50th percentile values (box outline), minimum and maximum values (whiskers) and outliers (open circles). The dashed line indicates a SOC:clay-ratio of 1:8, the full line a SOC:clay-ratio of 1:10, and the dotted line a SOC:clay-ratio of 1:13. (Source: Johannes et al., 2017b)

5.2.3 SOC:clay-ratio of 10% as a soil management goal

Table 7 shows the interpretation of the SOC:clay-ratio via visual assessment of soil structure quality as published in Johannes et al., 2017b. In Table 8, we adapted the reference values to SOM, resulting in a SOM:clay-ratio, and added the soil management interpretation scheme as well as a few examples to illustrate these numbers.

Such a reference value for the SOM:clay-ratio would set a goal for farmers to check their SOM management regularly and to invest in their SOM management if necessary, in order to improve the quality of their soils. Another important side benefice would be to help to reach targets of climate protection by presumably increasing carbon sequestration in arable soils.

Table 7: Interpretation of soil structure quality with different SOC:clay-ratios. (Johannes et al., 2017b)

SOC:clay-ratio	Expected structural quality	CoreVESS
> 1:8	very good	< 2
1:8 - 1:10	good	2 - 3
1:10 – 1:13	medium[1)]	3 - 4
< 1:13	poor	≥ 4

[1)] improvement to SOC:clay-ratio of 1:10 suggested

Table 8: Soil organic matter management and soil structure quality interpretation depending on SOC:clay-ratio, illustrated with two examples for soils of different clay content

			SOM content[1)] for	
Soil management interpretation	SOC:clay-ratio reference values	Soil structure quality interpretation	clay content 10%	clay content 20%
Top value!	> 1:8	very good	> 2.2%	> 4.4%
Goal	**1:8 – 1:10**	**good**	1.7 – 2.2%	3.4 – 4.4%
Improvement	1:10 – 1:13	medium	1.4 – 1.7%	2.8 – 3.4%
Urgent improvement!	< 1:13	poor	< 1.4%	< 2.8%

[1)] SOM = 1.725*SOC

5.2.4 Reflection on currently available interpretation schemes for SOM content of soils

An available interpretation scheme for SOM contents of soils (PRIF/GRUD: Richner and Sinaj, 2017) is mainly based on statistical considerations and the choice of meaningful data sets and data structures related to both site and management conditions. Information about soil quality within these datasets is however not explicitly available. Given the period when the interpretation scheme was developed (~1970-1990), it is probable that the considered soils were already carbon depleted. This carbon depleted state of soils should not be surprising as there was a worldwide tendency to loose carbon from arable soils since 1950 (Aguilera et al. 2018, Sanderman et al, 2017).

It therefore would be worthwhile to rethink the interpretation of SOC or SOM content in regard to functional soil quality aspects rather than to statistical values, which may be based on soils already in a critical carbon depleted state as references.

The above mentioned SOC:clay- or SOM:clay-ratio could be used in a functionally justified interpretation scheme for SOC or SOM content related to soil structure quality.

6 The STRUDEL methodology for soil structure quality assessment (or: for compaction diagnosis)

The full methodology is presented on the website http://www.strudel.agroscope.ch to make it easier accessible. All methodological descriptions are available in three languages (ENG, DE, FR) and can be downloaded. Explaining videos for field work and lab measurements can also be streamed in three languages.

The general methodology suggests to first start with a field characterization, followed by measurements of physical properties, if more investigations are needed (Figure 1920).

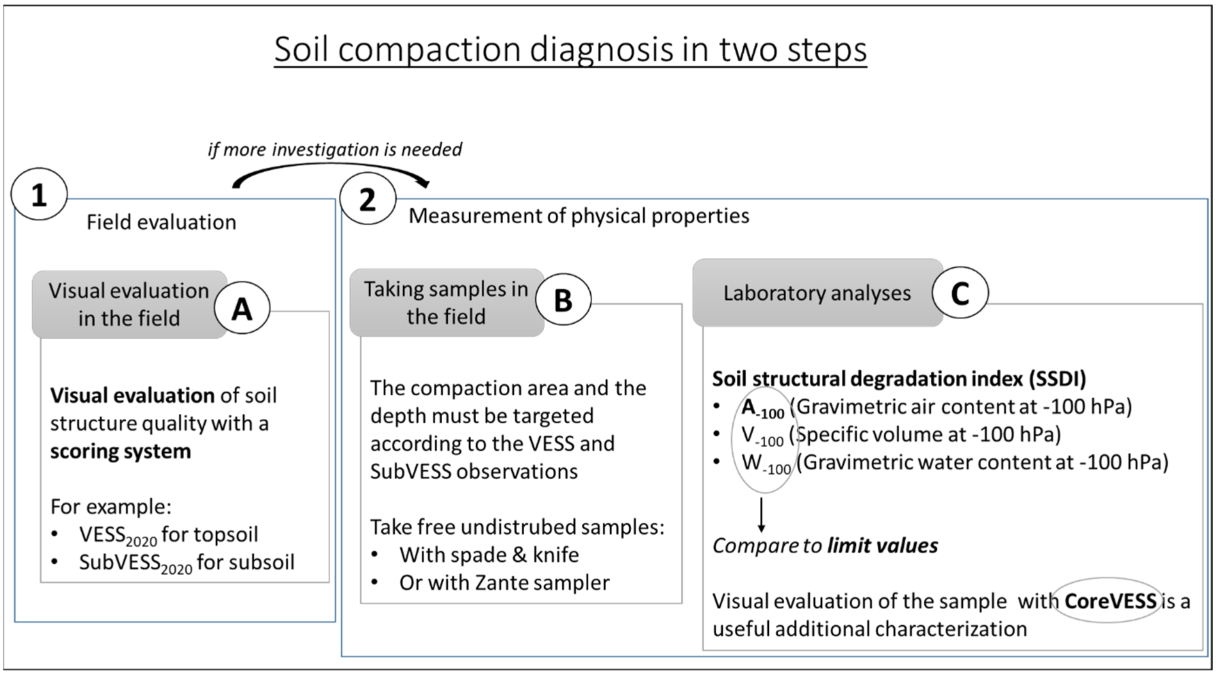


Figure 19: Schematic summary of the STRUDEL methodology: from field characterization with VESS and SubVESS to measurements of soil physical properties

6.1 Visual evaluation of soil structure quality in the field with VESS

The possible compaction damage has to be evaluated in the field by a soil specialist. We recommend that assessment of soil structure quality should be done first by using a validated visual scoring system in order to allow comparisons, e.g. with a future structural state after remediation or with results at other sites. The VESS method is suitable for this purpose. We assume that most assessment situations can be solved by a thorough and systematic visual evaluation of structure quality in the field.

In practice, make spade tests to 40 cm depth according to the evaluation design under suitable soil conditions and assess structure quality using the illustrated VESS scoring sheets for topsoil ($VESS_{2020}$) and subsoil ($SubVESS_{2020}$) evaluation (see http://www.strudel.agroscope.ch).

With these spade tests it is not only possible to do a visual evaluation of soil structure quality in the field, but also to identify, where soil samples need to be taken (geographical position in the field, soil depth), if soil structure characterization by physical measurements are needed.

6.2 Sampling undisturbed and unconfined soil samples for analysis

If a more precise or quantitative investigation is needed, an efficient sampling scheme has to be designed and sufficient undisturbed soil samples must be carefully taken from relevant soil depths and transported by experienced soil specialists.

The procedure for taking undisturbed soil samples is described in detail in the information sheets on the STRUDEL website; the STRUDEL method video shows the procedure in detail as well. In summary:

- 5 undisturbed and unconfined soil samples should be taken to describe a more or less homogenously compacted zone in a statistically sound way. Some spare replicates should be taken in case the original samples are damaged (living soil animals like earthworms or ants, large stones, poor sample quality, etc.).
- The samples have to be taken under adequate soil conditions (moisture around field capacity!).
- The undisturbed soil samples can be taken using different sampling equipment (e.g. Zante sampler, Humax sampler) or simply by taking a block of soil ("clod") with a spade or a shovel (e.g. in stone-rich soils or in soils that are extremely compact). If a sample block ("clod") is taken, it should be larger than necessary for the analysis, so it can be prepared properly in the lab.
- The undisturbed soil samples (especially block samples without a protective sampling cylinder) must be transported very carefully from the field to the lab.

6.3 Measuring the SSDI: Preparing undisturbed soil samples, analyzing soil physical properties, and visually evaluating soil structure quality in the lab

The procedure to measure the SSDI (Soil Structure Degradation Index) is described in detail in the information on lab analysis methods on the STRUDEL website.

- Preparation:
    - In order to secure a good contact between the soil sample and the desorption plate, a flat sample surface has to be carefully prepared prior to analysis.

- Equilibrate the soil samples to -60 or -100 hPa on a desorption plate, and determine gravimetric air content or macropore volume; evaluate structure quality visually:
    1) first place the carefully prepared soil samples on the desorption plate which is covered by a water layer of env. 2 mm (take care not to include air bubbles between sample and desorption plate); bring the samples in about 5 days close to saturation (about -10 hPa). The aim of first saturating the soil sample is to fill nearly all the pore space with water, so that desorption at -60 or -100 hPa can be done reliably and precisely.
    2) then start draining the soil samples on the desorption plate by increasing matric potential to -60 or -100 hPa for about a week (or as long as necessary to reach constant mass).
    3) visual evaluation of soil structure quality is done on the equilibrated soil sample according to the CoreVESS method.
    4) finally dry the soil sample at 105 °C for 24 hours to determine the dry weight. If stone content is above 5 vol%, do remove stones with a 2 mm sieve and determine weight and volume of the fine earth fraction (soil sample without stones).
    - weights (saturated weight, weight at -60 or -100 hPa, dry weight) are measured with a balance; volume is determined with the plastic bag method (for the saturated and the air dry sample; must be repeated at least twice).
    - calculation of parameters and comparison to limit values.

7 List of supplementary material

Document	Type	Where accessible	Short description
www.strudel.agroscope.ch	Website	www.strudel.agroscope.ch	The website gives a short presentation of the STRUDEL project and provides an online platform to download all the relevant documents
$VESS_{2020}$ sheet	Document/fact sheet	www.strudel.agroscope.ch	Illustrated VESS chart (visual evaluation of soil structure (Ball et al. 2007; Guimarães et al. 2011)) for field assessment of topsoil structure quality
$SubVESS_{2020}$ sheet	Document/fact sheet	www.strudel.agroscope.ch	Illustrated SubVESS chart (visual evaluation of subsoil structure (Ball et al. 2015)) for field assessment of subsoil structure quality
CoreVESS sheet	Document/fact sheet	www.strudel.agroscope.ch	Illustrated CoreVESS chart (visual evalution of soil structure on soil cores (Johannes et al, 2017a)) for assessment of the soil structure quality of undisturbed soil cores in the lab (controlled moisture conditions)
STRUDEL limit values	Document/fact sheet	www.strudel.agroscope.ch	Table of limit values for different physical soil properties
STRUDEL Lab method	Document/fact sheet	www.strudel.agroscope.ch	Description of the STRUDEL method for analyzing gravimetric air and water content at -100 hPa and specific volume and bulk density at -100 hPa
STRUDEL Sampling Method	Document/fact sheet	www.strudel.agroscope.ch	Description of the STRUDEL method for sampling undisturbed soil samples for the measurement of air and water content at -100 hPa, as well as of specific volume and bulk density at -100 hPa
Table with STRUDEL limit values	Document/fact sheet	www.strudel.agroscope.ch	A help for interpreting the soil physical measurements made with the “simplified STRUDEL method”.
Optimal organic carbon values	Document/fact sheet	www.strudel.agroscope.ch	Description of the SOC:clay (and SOM:clay) reference values

Document	Type	Where accessible	Short description
VESS Video	Video	DE: https://youtu.be/wIWD97duLDI FR : https://youtu.be/62Ur8lP3VDM EN: https://youtu.be/BWUeERE-wJw	Explaining the VESS method in three languages (German, French, English)
STRUDEL Method video	Video	DE: https://youtu.be/PV77qMfdbK4 FR: https://youtu.be/Y-CORRkH_xU EN: https://youtu.be/mbVFHd-JeLPI	Explaining the STRUDEL method: how to diagnose soil structure quality and compaction from sampling to the analysis of physical soilproperties and to the visual evaluation using Cor-eVESS; in three languages (German, French, English)
STRUDEL Data-base	Text file	Not accessible to public	All STRUDEL data as of 01.11.2020
Statistical ana-lysis tool	R code	Not accessible to public	The R code for all the statistical anal-ysis and all the statistical graphs in this report
To what extent do physical measurements match with vis-ual evaluation of soil struc-ture?	Scientific peer-reviewed paper	https://www.sciencedi-rect.com/science/ar-ticle/pii/S016719871630099X	Authors: A. Johannes, P. Weisskopf, R. Schulin, P. Boivin Publication Year: 2017 Journal: Soil and Tillage Research
Optimal or-ganic carbon values for soil structure qual-ity of arable soils. Does clay content matter?	Scientific peer-reviewed paper	https://www.sciencedi-rect.com/science/ar-ticle/pii/S0016706116305092	Authors: A. Johannes, A. Matter, P. Weisskopf, R. Schulin, P.C. Baveye, P. Boivin Publication Year: 2017 Journal: Geoderma
Soil structure quality indica-tors and their limit values	Scientific peer-reviewed paper	Open access: https://www.sci-encedirect.com/science/arti-cle/pii/S1470160X19303851	Authors: A. Johannes, P. Weisskopf, R. Schulin, P. Boivin Publication Year: 2019 Journal: Ecological Indicators

8 Perspectives

The STRUDEL project generated some major improvements in the fundamentals for the diagnosis of soil structure quality. It allowed filling an important gap in soil quality assessment for environmental protection purposes, namely the assessment of soil structure quality.

This goal can however be pursued by further completing the STRUDEL database.

The STRUDEL results can be helpful in the case of an OIS revision:

- The easily applicable and low-cost analytical and visual methods to determine and assess soil structure quality should – together with the simple two-step course of action - facilitate the use of quantitative methods in physical soil protection.
- The use of standardized methods allows for comparisons between different specialists, locations and cantons, and makes a systematic expansion of the STRUDEL database possible.
- The STRUDEL database can be the base for comparing data on soil structure, but also a tool to analyze and learn from existing and newly added data on soil structure quality.
- The methodological principles can be used to build limit values for structural soil parameters (and also for SOM).
- The current set of soil data in the STRUDEL database can be expanded with subsoils (of very poor structure quality) in order propose a "remediation value" in future, in addition to the "guide/trigger value" proposed here.
- Reference values for SOM (or for SOC, respectively) may provide functionally justified goals for SOM management in agriculture. They would take into account site specific properties regarding soil composition (clay content) and could be expressed as SOM:clay-ratio (or SOC:clay-ratio). According to the current state of knowledge, a SOM:clay-ratio of about 17% (SOC:clay-ratio of 10%) would be proposed as target value for SOM management. Such a reference value for the SOM:clay-ratio would set a goal for farmers to check their SOM management regularly and to invest in their SOM management if necessary, in order to improve the quality of their soils; this would also help to reach targets of climate protection by presumably increasing carbon sequestration in arable soils.

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10 Annexes

10.1 Annex 1: Organization and Management

The STRUDEL 1 project started in September 2013 and was initiated and led by Prof.Dr. Pascal Boivin (hepia), in collaboration with Dr. Peter Weisskopf (Agroscope) and Prof.Dr. Rainer Schulin (ETHZ). Alice Johannes (hepia) performed a large part of the investigations within the scope of her PhD work. This first part of the STRUDEL project ended in 2016 with the successful defense of Alice Johannes's PhD. The main results of STRUDEL 1 include proposals of reference values for topsoil structure quality of agricultural soils in the western part of Switzerland (BE, FR, VD), and of target values for optimal carbon content based on soil composition (clay content).

STRUDEL 1 was followed by a group of specialists from cantonal soil protection services, named the "STRUDEL Extension Committee". Their help was especially valuable in stressing the importance of choosing an explicit methodology for assessing soil structure quality in order to develop reference values.

STRUDEL 2 was started in 2017 by Agroscope, with Dr. Alice Johannes as project leader and post-doctoral researcher and Dr. Peter Weisskopf as project responsible, in collaboration with Prof.Dr. Pascal Boivin (hepia). The project ended in December 2019. The main outputs of STRUDEL 2 include the extension of reference values to subsoils and to agricultural site conditions of the central and eastern part of Switzerland (AG, LU, SH, SO, TG, ZH), as well as developing and testing methods to be applied by agriculture (farmers, advisers) and by cantonal soil protection services.

During STRUDEL 2, the working group VBphy followed the project. Their help was valuable to produce user-friendly methods.

Table 9: People involved in the projects STRUDEL 1 and STRUDEL 2

People	Institution	Function / period	Topic
Steering Committee STRUDEL 1 (2013-2016)			
Pascal Boivin	hepia	Project leader	
Peter Weisskopf	Agroscope	Accompanying expert	
Rainer Schulin	ETHZ	PhD supervisor	
Alice Johannes	hepia/ETHZ	PhD student	
Steering Committee STRUDEL 2 (2017-2019)			
Peter Weisskopf	Agroscope	Project responsible	
Alice Johannes	Agroscope	Project leader	
Pascal Boivin	hepia	Accompanying expert	
FOEN			
Jean-Pierre Clément	FOEN	Project representative 2013-2014	
Corsin Lang	FOEN	Project representative 2014-2019	

Students			
Léonie Givord	Master - Unine	2012-2013	Sampling VD
Tania Ferber	Master - Unine	2013-2014	Sampling FR
Elisabeth Busset	Bachelor - hepia	2014	Sampling BE
Gregor Rieche	Bachelor - ZHAW	2014-2015	Sampling ZH
Adrien Matter	Master - HES-SO	2015-2016	Sampling degraded soils
Hans Sturzenegger	Bachelor - ZHAW	2017	Est sampling
Antoine Boudraa	Master - Unine	2019-2020	Investigation SSO compaction experiment
Oher staff			
Aline Chambettaz	hepia	lab technician	Chemical analyses
Marlies Sommer	Agroscope	lab technician	Physical analyses
Quentin Chappuis	hepia	Civilist in 2015	CoreVESS
Caroline Schlaiss	Agroscope	Trainee in 2017	Sampling Eastern Switzerland
Benjamin Seitz	Agroscope	Assistant in 2018	Development implementation methods
Extension Committee of STRUDEL 1			
Andreas Chervet	Soil protection service canton Bern		Counselling
Etienne Diserens	Agroscope		Counselling
Achim Kayser	Soil protection service canton Thurgau		Counselling
Luzius Matlie	ZHAW		Counselling
Reto Meuli	Research group NABO, Agroscope		Counselling
Nicolas Rossier	Soil protection service canton Fribourg		Counselling
Adrian von Niederhäusern	Soil protection service canton Fribourg		Counselling
Peter Schwab	Research group NABO, Agroscope		Counselling
Matthias Stettler	HAFL		Counselling

10.2 Annex 2: other physical properties measured

Air permeability and precompression stress results are available in the master thesis of Tania Ferber (2014).

10.3 Annex 3: R file and Database description

The following datasets were used to test, develop or compare reference values:

- **“all_top”:** all the topsoil samples including “implementation”, the “degraded” samples from STRUDEL1 and the samples provided by the compaction experiment SSO
- **“all_sub”:** all the subsoil samples including “implementation” and the samples provided by the compaction experiment SSO
- **“STRUDEL_top”:** excludes “implementation” and “SSO experiment”
- **“STRUDEL__sub”:** excludes “implementation” and “SSO experiment”
- **“STWest_top”:** only topsoils from STRUDEL1 (western Switzerland) that were not sampled for their degraded features
- **“STOst_top”:** topsoils from STRUDEL 2 (eastern Switzerland)
- **“Vollzug_top”:** topsoil samples from the “implementation” sampling
- **“Vollzug_sub”:** subsoil samples from the “implementation” sampling

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A_{-100}: Gravimetric air content at -100 hPa
AE: air entry point (in a shrinkage curve)
AG: canton of Aargau
BBB: Bodenkundliche BauBegleiter
BD: Bulk Density
BE: canton of Bern
BGS: Bodenkundliche Gesellschaft der Schweiz
CEC: cation exchange capacity
CoreVESS: visual evaluation of soil structure on a core/clod
CT: conventional tillage
FAO: Food and Agriculture Organisation
FOEN: Federal Office of Environment
FR: canton of Fribourg
FRIBO: soil monitoring network of the canton of Fribourg
GE: canton of Genève
LU: canton of Luzern
MP60: macropore volume at pF1.8
MS: maximum swelling point (in a shrinkage curve)
ML: macroporosity limit (in a shrinkage curve)
NT: No Tillage
NW: canton of Nidwalden
OIS: Ordinance of Impact on Soils
OW: canton of Obwalden
PG: permanent grass
SH: canton of Schaffhausen
ShC: Shrinkage Curve
SL: shrinkage limit (in a shrinkage curve)
SO: canton of Solothurn
SOC: Soil Organic Carbon
SOM: Soil Organic Matter
SPSC: Spécialiste de la protection des sols sur chantiers
Sq: Soil Structure Quality (visually evaluated with VESS)
SSVI: Soil Structure Vulnerability Index
SSDI Soil Structure Degradation Index
SSO: Soil Structure Observatory (long-term compaction experiment)
SSP: Société Suisse de pédologie, Swiss Soil Science Society
SubVESS: visual evaluation of subsoil structure
SZ: canton of Schwyz
TG: canton of Thurgau
UR: canton of Uri
VESS: visual evaluation of soil structure
VD: canton of Vaud
W_{-100}: Gravimetric water content at -100 hPa
ZH: canton of Zürich