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Shrinkage analysis of repacked soil samples enables quantifying the soil's potential physical quality

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Abstract

This paper investigates the physical properties of soil samples repacked from aggregate beds and the potential for retrieving representative soil pore properties at the field scale based on shrinkage analysis of a repacked composite sample. This approach was tested on 60 arable fields in Switzerland presenting a large range of soil organic carbon (SOC) and texture. Soil cores constituted from composite samples were repacked at the observed field bulk density. Their pore properties were compared to undisturbed soil samples from the same fields. The soil pore properties were characterized using shrinkage analysis and correlated to soil texture and SOC. The repacking protocol successfully recreated structured samples. The <40-µm equivalent diameter pore and structural pore size distributions were comparable to those of the undisturbed soils. For pores >40 µm, a larger porosity was measured for repacked samples compared to undisturbed ones, limiting the approach to assess the structure and dynamics of larger soil pores. Furthermore, soil clay content as well as SOC were strong predictors for the samples' physical properties including pore space. The increase in structural porosity in the repacked sample was inversely proportional to the structural porosity already present in the undisturbed samples. Steeper regression slopes of the pore volume to SOC or clay relationship were observed for the repacked samples. These slope changes were comparable to those observed in soil structure restoration experiments and opposite to those observed in soil compaction trials. We conclude that repacking soil from a composite sample allows us to characterize the potential soil structure condition with respect to its SOC and clay content. The method can be used to assess soil structure quality in response to changes in soil management.

1 | INTRODUCTION

Arable soils are particularly under threat of erosion, organic carbon loss, and structure degradation (Montanarella et al., 2016). Owing to the critical role of soil services in achieving the United Nations Sustainable Development Goals (Bouma, 2020), protecting and increasing soil quality, defined as "the capacity of the soil to function" (Karlen et al., 2008), has become, therefore, a top priority in an increasing number of countries. Evaluating and monitoring soil quality requires the collection of appropriate indicators (Bünemann et al., 2018). To this end, monitoring networks are currently operated,

Abbreviation: SOC, soil organic carbon; SOM, soil organic matter; V_P, total porosity; V_{Pl}, plasma porosity; V_{Str}, structural porosity; W, gravimetric water content.

such as LUCAS in the EU (https://esdac.jrc.ec.europa.eu/projects/lucas), RMQS in France (https://www.gissol.fr/le-gis/programmes/rmqs-34), or NABO in Switzerland (Gubler et al., 2015). Most networks are based on a grid of sampling locations providing information on the soil properties and their changes with time on a large scale. Among many biogeochemical soil quality indicators, soil structure quality and related physical properties are key components of soil quality and fertility and should be accounted for in-field monitoring. Sampling strategies of most soil quality monitoring networks are based on composites of multiple samples collected on some meter square. Since in cropland the soil management unit is the field, it is, therefore, necessary to provide relevant information at field scale (Cook et al., 2013). Composite sampling from multiple aliquots allows accurate and inexpensive determination of average chemical soil properties at field scale (Deluz et al., 2020). Determining the soil physical properties, however, requires working on undisturbed samples (Rabot et al., 2018; Vogel et al., 2022), which cannot be mixed to retrieve an average sample, thus not allowing to work with composites. Unfortunately, physical properties are known to exhibit significant and, in parts, unpredictable spatial variability (e.g., Nielsen et al., 1973; Sisson & Wierenga, 1981; Vauclin et al., 1982). As a result, assessing soil physical quality at field scale may require the collection and characterization of multiple undisturbed samples, a process that is time-consuming, expensive, and, therefore, practically not applicable in routine. Semiquantitative methods such as Visual Evaluation of Soil Structure (VESS) have been introduced to overcome this difficulty (Ball et al., 2007). They allow fast and inexpensive characterization at field scale (Leopizzi et al., 2018) but do not provide physical values sensu stricto. Working on repacked soil samples, that is, aggregate beds, would allow characterizing composite samples, thus providing both chemical and physical properties at field scale with limited cost. However, the extent to which some physical properties of repacked samples may represent the undisturbed physical properties of a soil sample is not documented. Moreover, the physical condition of the soil is determined both by its components such as texture, organic carbon, oxides, and biological activity (Goutal-Pousse et al., 2016) and by external stresses such as trafficking (e.g., Alaoui et al., 2011; Ampoorter et al., 2010; Schäffer et al., 2008). The physical changes resulting from stresses can occur on very short time scales, while the changes in soil components occur on much larger time scales. Therefore, the soil's physical quality should be evaluated relative to its content and compared to the potential quality it should have.

Among approaches to studying soil physical properties (Rabot et al., 2018), shrinkage analysis receives growing attention as a tool to characterize key physical soil features such as soil pore systems and hydro-structural properties (Boivin, 2023). Soil shrinkage was defined as the soil volume change with a change in water content (Haines, 1923), which can be represented in the form of the soil shrinkage curve (ShC), with gravimetric water content in abscissa and specific volume in ordinates. Soil shrinkage analysis (ShA) was widely used to characterize the soil hydro-structural stability, the pore systems, and their volume change with water contents, with applications in soil physical characterization and management (Boivin, 2023). ShA consists of fitting a model to the ShC, whose parameters allow quantifying the hydro-structural properties of the soil. Most applications were performed using the so-called "exponential" (XP) model (Braudeau et al., 1999). This mechanistic model combines the shrinkage of the two soil pore systems, namely, the plasma and structural pore systems (Brewer, 1964; Verrecchia & Trombino, 2021). Plasma pores refer to the intercolloidal spaces resulting from the association of clay minerals and their oxide and organic matter coatings (Soil Science Society of America, 2008), while structural pores refer to the biopores, cracks, and lacunar voids (Brewer, 1964). Plasma pores are too small for most living organisms and instead provide a buffer for water and nutrients. The walls of the pores, which are made up of colloids, are charged and therefore highly reactive. By contrast, structural pores are of larger size than the plasma pores; they are responsible for major soil functions such as biota habitat and air and water distribution in the soil. The two pore systems are highly complementary; they have distinct roles and behavior in soil, and a good soil structure corresponds to small volumes of plasma pores connected by structural pores, as highlighted by Johannes, Weisskopf et al. (2017). Fitting an XP model on experimental ShC allows to calculate the volumes of the two pore systems and calculate their air and water content, as well as their volume change with water content (Boivin, 2023). ShA allowed to quantify the role of soil colloids in determining the pore systems volume and behavior, and their response to stresses or restoration (e.g., Boivin et al., 2004, 2009; Fell et al., 2018; Goutal-Pousse et al., 2016; Schäffer et al., 2008). Repacked soil samples from <2-mm

Core Ideas

- The structural porosity of repacked samples was optimized compared to undisturbed soil.
- Repacking soil samples can preserve soil fine porosity but not coarse porosity.
- Physical properties of repacked samples show high correlation with SOC and clay.
- Repacked soil samples can indicate potential physical properties of undisturbed soil.

size aggregate beds were characterized with ShA for different purposes, such as their hydro-structural characterization (Braudeau & Mohtar, 2006; Braudeau et al., 1999), experimental studies of the effect of clay type, and clay content on the soil properties (Boivin et al., 2004), or compaction effect on the pore systems (Schäffer et al., 2013). However, the comparability of the physical properties of the pore space of repacked soil samples with respect to undisturbed soil was not discussed, which is the aim of this study.

To answer how far repacked samples can represent physical properties of undisturbed samples, we collected soil samples in 60 arable fields in western Switzerland, selected to represent a wide range of soil texture and soil organic carbon (SOC) contents, and compared the pore volumes of repacked and undisturbed soil samples as quantified by shrinkage analysis. We hypothesized (i) that the larger structural pores (e.g., such as earthworm galleries) cannot be represented in repacked samples, but that (ii) the small-size structural pores and the plasma pore volumes of repacked samples will be similar to those of undisturbed soil samples, and (iii) that the relationships of pore volumes with clay and SOC contents are key characteristics of soil structure (Fell et al., 2018) that should be considered to reveal differences or similarities in pore properties between repacked and undisturbed samples.

2 | MATERIALS AND METHODS

2.1 | Study area and sampled fields

In spring 2021 we collected undisturbed and composite soil samples from the topsoil (5- to 10-cm soil depth) of 60 cropland fields ranging from 0.3 to 6 ha of surface area, with a 2.6-ha average surface area, located in the Swiss plateau and Swiss Jura regions (Figure 1). The soils from the Swiss plateau formed after the last glaciation on mixed quaternary carbonated moraines with some tertiary molasses, and the soils from the Jura region formed on Jurassic limestone containing some loess deposits. The average annual rainfall ranged between 900 and 1100 mm, and the average annual temperature between 10.1 and 14.0°C. All fields were classified as Cambisols with some calcaric Cambisols according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). The sampled fields (Table 1) were selected to represent a wide range of SOC, clay, pH, and low carbonate content. Fields presenting heterogeneous distribution patterns of those variables within field boundaries were not considered. Characterized in previous studies, SOC and clay were the major constituents determining their shrinkage properties in the fields (Dupla et al., 2022; Johannes et al., 2023; Johannes, Matter, et al., 2017). The SOC content ranged from 1% to 7%, the clay content ranged from 9.3% to 60.3%, the pH (1/2.5 H_2O extract) ranged from 5.2 to 7.8, and the carbonate content ranged between 0% and 17.6% with a highly right-dissymmetrical distribution, with two-thirds of the soil samples free of carbonates.

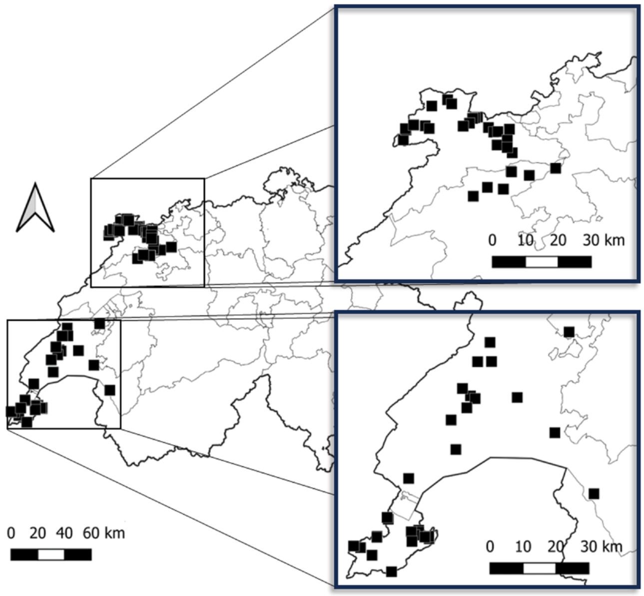

FIGURE 1 Location of the 60 sampled fields in Switzerland. The two squares zoom the 30 sampled fields in the northwest (Jura and Bern) and the 30 sampled fields in the southwest (Leman region).

2.2 | Soil sampling approach

Undisturbed and composite samples were collected in each field at the 5- to 10-cm depth before any soil tillage. The undisturbed soil cores of approximately 100 cm^3 (60-mm diameter and 50 mm height) were collected at the center of each field after visual evaluation of the surface and avoiding wheel tracks or any visible soil disturbance. The composite samples were made of 20 aliquots collected along the field diagonals with a 2.5-cm inside diameter gouge following the protocol determined in Deluz et al. (2020). All samples were placed in sealed plastic bags, stored in a cool box during transportation to the lab, and stored at 4°C for 2 weeks prior to analyses.

With the aim to limit costs and time, the repacked samples made from a composite of 20 auger samples were compared to a single undisturbed sample in each field. Though the short-scale variability of shrinkage properties is small (Boivin, 2007), and the selected fields were visually homogeneous, collecting a single undisturbed soil sample per field does not allow for the capture of the spatial variability of the soil properties. Collecting multiple samples in each field, however, would have been very expensive and time-consuming. Our objective was not to represent the field's physical properties but to collect an undisturbed sample with a SOC content and

TABLE 1 Mean, median, standard deviation (SD), minimum, and maximum values of the main characteristics of the sampled fields on the two types of samples, composite and undisturbed: soil organic carbon (SOC) content, texture (clay, silt, and sand content), carbonate content ($CaCO_3$), and pH.

Main soil parameter	Sample type	Average	Median	SD	Minimum	Maximum
SOC (%)	Composite	2.8	2.7	1.2	1.0	6.8
	Undisturbed	2.9	2.6	1.4	1.0	7.0
Clay (%)	Composite	31.0	28.9	9.8	12.0	55.2
	Undisturbed	31.3	29.5	11.2	9.3	60.3
Silt (%)	Composite	44.3	41.8	10.6	25.9	68.9
	Undisturbed	43.7	41.7	10.8	19.3	66.5
Sand (%)	Composite	24.3	27.3	15.7	1.7	54.4
	Undisturbed	23.9	23.1	16.9	1.0	58.2
$CaCO_3$ (%)	Composite	1.9	1.2	2.5	0.0	9.4
	Undisturbed	2.2	0.0	4.2	0.0	17.6
pH	Composite	6.9	6.9	0.4	5.5	7.6
	Undisturbed	6.6	6.8	0.6	5.2	7.6

texture close to the field average. We assumed that visual evaluation of the soil structure, whose variability is small at field scale (Leopizzi et al., 2018), enabled us to take a sample free of particular stresses such as wheel tracks and to avoid areas with higher heterogeneity of soil properties.

2.3 | Preparation of repacked samples

The composite samples were air-dried, homogenized, and sieved to 2 mm to remove the coarse fraction. Repacked samples were then prepared using the procedure described in Schäffer et al. (2013) and Boivin et al. (2004). Briefly, the sieved soil was placed in plastic cylinders (60-mm diameter and 50 mm height) by pouring and gently compressing successive layers of aggregate mass, allowing it to reach the same bulk density as for the undisturbed sample. The samples were then rewetted at −10 hPa in a sandbox and air-dried five times to allow reconstituting a structure. The number of wetting and drying cycles was determined in a preliminary experiment showing no ShC difference between the fourth and fifth cycles.

2.4 | Shrinkage curve measurement and analysis

The repacked and undisturbed soil cores were equilibrated at a matric potential of −10 hPa in the sandbox, and their bulk volume was measured using a 3D structured light scanner (EinScanSP scanner from SHINING 3D) prior to being introduced in the shrinkage apparatus to measure their ShC upon slow drying. Changes in sample weight and height (shrinking) were recorded quasi-continuously (one observation every 5 min) as described in Boivin et al. (2004). The ShC measurement device includes a micro tensiometer (2-mm diameter) inserted at the center of the sample to record simultaneously the water retention curve, as described in Boivin et al. (2004). When steady weight and volume were observed, the air-dried sample volume was measured. The undisturbed samples were sieved to 2 mm to determine the coarse (>2 mm) fraction volume and weight, which were subtracted from the sample volume and weight. The sample ShC was, therefore, represented as the specific (i.e., per unit of mass) volume V (cm^3 g^{-1}) of the fine soil as a function of its gravimetric water content W (g g^{-1}).

The XP model was then fitted to the experimental ShC for shrinkage analysis (ShA) as described in Schäffer et al. (2013). Briefly, the XP model assumes a dual pore system in the soil, corresponding to the structural and plasma pores, respectively (Boivin et al., 2004). Based on the assumed properties of these pore systems, the XP model allows to describe the ShC as a succession of linear shrinkage domains overlapping in curvilinear sections (Figure 2). Fitting the coordinates of the transition points between the linear and curvilinear sections allows then to calculate the structural and plasma pore volume, water content, and air content at any soil water content. Moreover, the slopes of the linear domains, namely, structural and basic shrinkage domains (Figure 2), quantify the capacity of the pore structure to withstand drying forces (Schäffer et al., 2013), which can, therefore, be interpreted as the hydro-structural stability of soil.

In the following, we focused on the specific total pore volume, denoted V_P (cm^3 g^{-1}), the gravimetric soil water content, W (g g^{-1}), the specific air content, Air (cm^3 g^{-1}), the structural pore volume, V_{Str} (cm^3 g^{-1}), and the plasma pore volume, V_{Pl} (cm^3 g^{-1}). Each of these values can be taken at a selected matric potential from −10 hPa to tensiometer

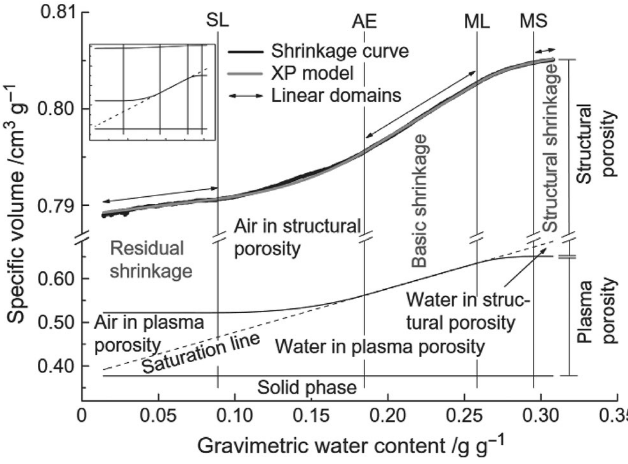

FIGURE 2 Example of an experimental shrinkage curve and fitted exponential (XP) model, with the transition points (SL: shrinkage limit; AE: air entry; ML: macroporosity limit; MS: maximum swelling), linear domains (residual shrinkage, basic shrinkage, and structural shrinkage), and calculated specific volume of the pore systems (from bottom to top: solid phase, water in plasma porosity, air in plasma porosity, water in structural porosity, air in structural porosity, and bulk soil volume that is shrinkage curve) with saturation 1:1 line. Figure and legend taken from Schäffer et al. (2013).

cavitation (∼−1000 hPa). The corresponding matric potential is used as subscript in the following. For example, the specific air volume at −100 hPa is denoted Air_{-100}. In the results and discussion (Section 3), for the sake of brevity, we focused on the values observed at −100 hPa, which are often used to determine available water at field capacity (Nemes et al., 2011) and critical values of soil structure quality (Johannes et al., 2019).

2.5 | Calculation of equivalent pore size distribution

The Jurin–Laplace law (Panter et al., 2023) was used to determine the equivalent diameter of the draining pores at the air-water interface meniscus. We used the following simplified equation, which assumes a 0 contact angle and pure water surface tension and density:

$$d\ (\mathrm{cm}) = 0.3/h \quad (1)$$

where d is the equivalent diameter of the soil pores in cm and h is the measured matric potential expressed in -hPa.

The difference in water content between two pore sizes was used to estimate the volume of the pores drained between the corresponding equivalent pore diameters. The volume was attributed to the mean diameter between these two values, and this calculation was repeated on the whole water retention curve to estimate the equivalent pore size distribution of a sample. The same procedure was applied to determine the equivalent pore size distribution of the structural porosity.

2.6 | Texture and soil organic carbon analyses

All samples were analyzed for texture and SOC content. SOC was determined using the modified Walkley and Black (1934) (ISO 14235) method, corrected using the equation of Brogan (1966), to yield similar results to dry combustion. The resulting SOC analysis was validated by independent (ISO 17043) interlaboratory ring tests. Soil texture was determined by sedimentation (ISO 11277).

2.7 | Data analysis

All statistical data processing was carried out using the R software (version 3.6.1; R Core Team, 2024). The significance level considered for all the statistical tests was $p < 0.05$. Linear regression analysis was used to assess the relationships between physical parameters and SOC and clay content. The significance of differences between pore size distributions was tested with Student t-tests and Kruskal–Wallis tests when the equality of variance between the distributions was not respected according to the Bartlett R test (Bartlett, 1937) and when the distribution did not follow normality according to the Shapiro test (Royston, 1995). The significance of differences between distributions was determined using the Kolmogorov–Smirnov test. The significance of differences in the regression slopes or with the 1:1 line was assessed with Student t-tests, and the significance of differences between two linear models was assessed with analysis of variance (ANOVA). Finally, the significance of differences between two correlation coefficients was assessed with the Fischer's z-tests of the "diffcor" R package (Blötner, 2024).

3 | RESULTS AND DISCUSSION

3.1 | Soil organic carbon and clay content in repacked and undisturbed samples

We observed linear relationships between SOC content and clay content of the repacked and undisturbed sample series, respectively, with slopes of 0.93 and 0.98 and coefficients of determination (R^2) of 0.98 and 0.99, respectively, when the regressions were forced through the origin (Figure 3).

Note that the SOC content and texture of the field composite and undisturbed samples are very close, which is unsurprising considering the limited variability of SOC at this scale (Deluz et al., 2020) and because fields with

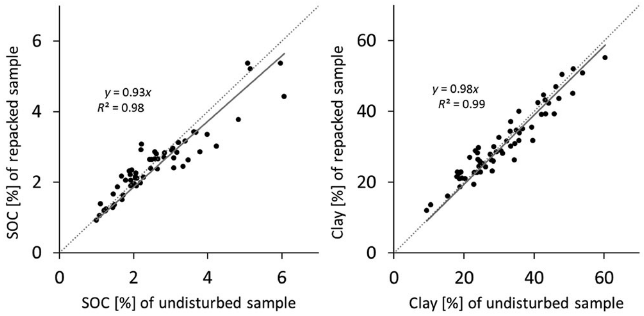

FIGURE 3 Linear regressions between soil organic carbon (SOC, left) and clay (right) contents of repacked (ordinates) and undisturbed (abscissa) samples, and linear regression properties. Solid dots: observations. Solid line: regression. Dotted line: 1:1 line.

heterogeneous texture were discarded (Figure 3). Statistical tests assessing differences in mean and distribution between the two sample types confirmed these observations. The *p*-values of the *t*-test were 0.45 and 0.90, respectively, for SOC and clay, indicating highly nonsignificant differences between the two sample types. Similarly, the *p*-values of the Kolmogorov–Smirov test were 0.49 for SOC and 0.93 for clay, respectively. This allows us to compare the series of undisturbed and repacked soil samples physical properties as a function of texture and SOC content.

3.2 | Shrinkage curves

The shrinkage curves of the repacked and undisturbed soil samples are presented in Figure 4A, while Figure 4B,C displays two examples with contrasting soil properties, namely, 30% clay and 2.6% SOC (Figure 4B) and 15% clay and 1.2% SOC (Figure 4C). Both repacked and undisturbed samples of ShCs showed the typical "S-shape" (Figure 2). The S-shape shrinkage curves are typical for structured soils (Figure 4A) in accordance with previous observations for repacked samples (e.g., Boivin et al., 2004; Braudeau et al., 1999). The specific soil volume of repacked samples was shifted to larger values, and the volume change with water content appeared larger as well, compared to undisturbed samples. In contrast, the range of water content seemed similar between repacked and undisturbed samples. Moreover, the structural shrinkage domain (Figure 2) appeared more developed in the case of repacked samples (Figure 4).

The slopes of the different shrinkage domains are summarized in Table 2. On average, the slope of the structural shrinkage domain of the repacked samples (0.14 cm^3 g^{-1}) was significantly smaller (p-value < 0.001) than the slope of the structural shrinkage domain of the undisturbed samples (0.48 cm^3 g^{-1}), thus denoting a larger hydro-structural stability upon drainage of the structural pores for repacked samples. In contrast, the basic shrinkage slope of the repacked samples (0.65 cm^3 g^{-1}) was significantly larger (p-value < 0.001) than for the undisturbed samples (0.51), although this difference was less marked. The residual shrinkage slope showed no significant difference between the two sample series.

3.3 | Pore volumes at −100 hPa

Figure 5 shows the relationships between the repacked (y-axis) and undisturbed (x-axis) sample properties V_{P-100} (5A, specific total pore volume at −100 hPa), W_{-100} (5B, water content at −100 hPa), Air_{-100} (5C, specific air content at −100 hPa), V_{Pl-100} (5D, specific plasma volume at −100 hPa), and $V_{Str-100}$ (5E, specific structural pore volume at −100 hPa), and their linear regressions. Figure 5F presents the relationship between the volume of the structural porosity in percentage of the sample volume (*X*-axis) and the relative increase in structural porosity after repacking (*Y*-axis). The linear relationship between V_{P-100} of the two sample series was strongly determined ($R^2 = 0.89$), with a slope of 1.1 and an intercept of 0.083, denoting a larger total specific pore volume in the repacked samples compared to the undisturbed ones (Figure 5A). A linear relationship ($R^2 = 0.79$) between repacked and undisturbed sample series W_{-100} was observed, with a slope of 0.72 and an intercept of 0.081. For most of the repacked soil samples, W_{-100} was, therefore, slightly smaller than in the undisturbed samples (Figure 5B). A linear relationship ($R^2 = 0.71$) with a slope of 0.67 and an intercept of 0.12 was observed for V_{Pl-100} (Figure 5D). The relationships for Air_{-100} and $V_{Str-100}$ were not linear according to the nonnormal distribution of the residuals based on the Shapiro test (p-value < 0.05). The Air_{-100} contents of repacked samples were scattered above the 1:1 line, thus corresponding to a larger air content at _100 hPa than in the undisturbed samples (Figure 5C). Most of the structural porosity volumes of the repacked samples were largely located above the 1:1 line, indicating a larger structural porosity volume compared with undisturbed samples, except for the undisturbed samples showing the largest structural pore volumes (Figure 5E). The relative increase in V_{Str} in repacked samples compared to undisturbed ones was inversely proportional to the relative volume of V_{Str} in the undisturbed sample (Figure 5F). The relationship was linear and highly determined ($R^2 = 0.78$), which means that the smaller the structural porosity volume in a sample, the larger its increase upon repacking. The larger V_{Str} percentages, namely, $V_{Str} > 40\%$ of the sample volume (seven observations in Figure 5F), even showed smaller structural porosity after repacking than under field conditions. The variations along the X-axis correspond both to variations in the sample components and biological activity, and variations in stresses experienced by the structure. The scattering of the values along the *y*-axis (relative increase of V_{Str}) may

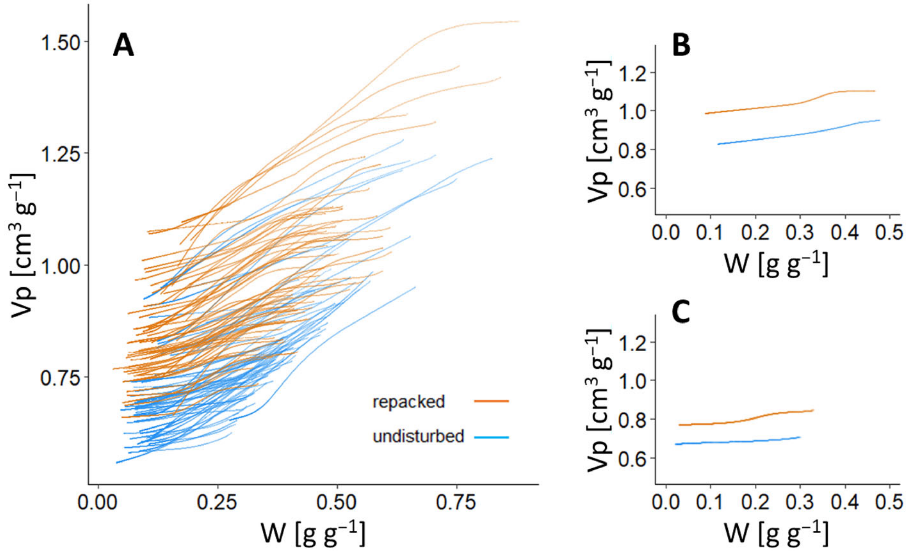

FIGURE 4 Experimental shrinkage curves (ShC) of repacked and undisturbed soil samples. (A) All 60 fields. (B) ShCs from field No. 52 (Jura) with ∼30% clay and 2.6% SOC. (C) ShCs from field No. 7 (Swiss Plateau) with ∼15% clay and 1.2% SOC. Orange: repacked samples, blue: undisturbed samples.

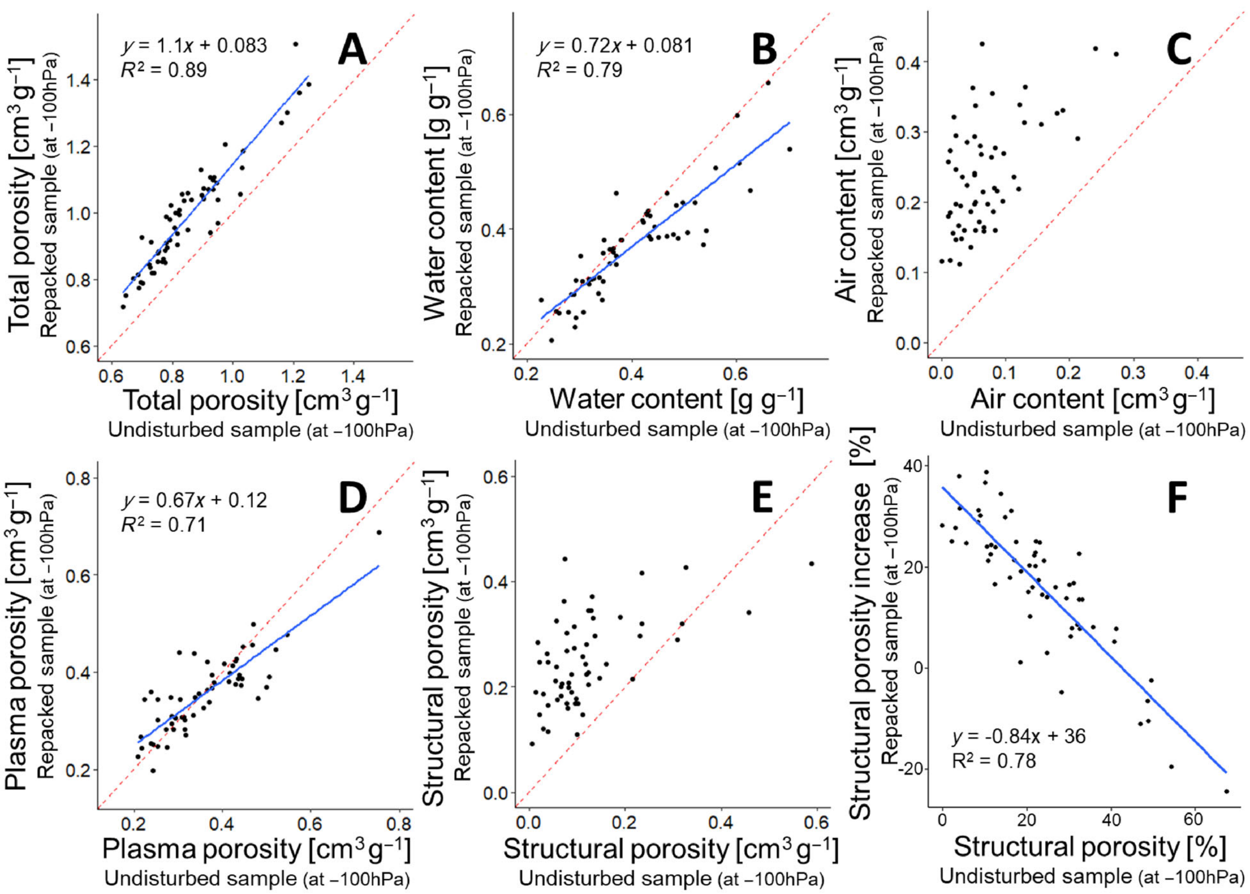

FIGURE 5 Relationships between repacked (ordinate axis) and undisturbed (abscissa axis) pore volumes or water contents at −100 hPa for (A) sample pore volume, (B) sample water content, (C) air content, (D) plasma pore volume, (E) structural pore volume, and (F) relative increase in structural porosity volume as a function of structural porosity relative volume in the sample. Solid blue lines: linear regressions, red dashed lines: 1:1 line (slope = 1, intercept = 0).

TABLE 2 Mean, median, standard deviation (SD), minimum, and maximum values of the slopes of the structural, basic, and residual shrinkage domains for the repacked and undisturbed samples, respectively, with the *p*-value of their *t*-tests.

	Slope of structural shrinkage					Slope of basic shrinkage					Slope of residual shrinkage				
Sample type	Mean	Median	SD	Min.	Max.	Mean	Median	SD	Min.	Max.	Mean	SD	Median	Min.	Max.
Undisturbed	0.48	0.46	0.20	0.05	0.97	0.51	0.47	0.22	0.04	0.93	0.26	0.17	0.24	0.06	1.18
Repacked	0.14	0.12	0.10	−0.05	0.56	0.65	0.66	0.17	0.27	0.95	0.23	0.18	0.24	0.00	1.53
t-test *p*-value	<0.001					<0.001					0.49				

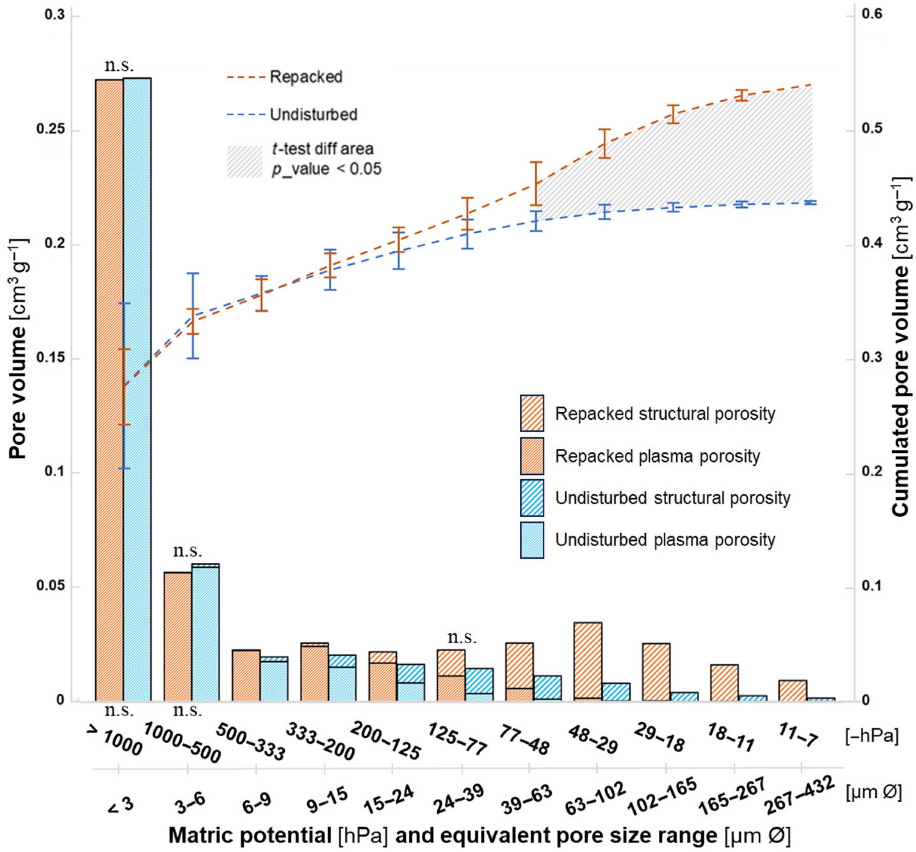

FIGURE 6 Volume of water released from the two pore systems (structural and plasma) at different ranges of matric potential and equivalent pore diameter as estimated from Jurin–Laplace's law, for repacked (orange) and undisturbed (blue) samples (bar plot, left *y*-axis, and *x*-axis) and corresponding cumulated pore volume (curve and dot plot, right *y*-axis and *x*-axis). No significant differences between pore systems (n.s. = *t*-test *p*-value > 0.05) are shown at the bottom and top of the bar plots for plasma and structural porosity, respectively. When not specified, differences are significant. Cumulative porosity plot points represent the mean, and error bars indicate standard error. Significant differences (*t*-test, *p*-value < 0.05) in cumulative total porosity are represented by the hatched area between the values of repacked and undisturbed samples.

correspond, for example, to variations in the presence of coarse biological pores or larger coarse fraction content.

3.4 | Pore size distributions

The plasma and structural pore volumes of the repacked and undisturbed samples are presented in Figure 6, with the cumulated total pore volume as a function of matric potential or equivalent pore diameter. However, the use of Jurin–Laplace's law for plasma pores is questionable since they are assumed to remain water saturated in this matric potential range (Boivin et al., 2004), thus not showing air-water menisci. Regardless of this reservation, there was no significant difference in cumulated volume between the two sample series at matric potentials smaller than −77 hPa, corresponding to equivalent pore diameters smaller than 39 µm. Therefore, the increase of sample porosity in the repacked samples compared to the undisturbed ones was mostly accounted for by pores with equivalent diameters larger than 39 µm. Additionally, the

TABLE 3 Description (regression equation, R^2, and p-value) of the linear models presented in Figure 7.

Model variables			Regression equation			
Dependent	**Independent figure**	**Sample type**	**Slope**	**Intercept**	R^2	p**-value**
SOC (%)	∼Total porosity (cm^3 g^{-1}) 7A	Repacked	$y = 0.15x$	+0.61	0.84	<0.01
		Undisturbed	$y = 0.11x$	+0.56	0.83	<0.01
	∼Water content (g g^{-1}) 7B	Repacked	$y = 0.097x$	+0.14	0.90	<0.01
		Undisturbed	$y = 0.091x$	+0.17	0.82	<0.01
	∼Air content (cm^3 g^{-1}) 7C	Repacked	* $y = 0.057x$	+0.095	0.44 *	<0.01
		Undisturbed	$y = 0.021x$	+0.017	0.18	<0.01
Clay (%)	∼Total porosity (cm^3 g^{-1}) 7D	Repacked	$y = 0.01x$	+0.67	0.39	<0.01
		Undisturbed	$y = 0.0068x$	+0.64	0.28	<0.01
	∼Water content (g g^{-1}) 7E	Repacked	$y = 0.0072x$	+0.15	0.52	<0.01
		Undisturbed	$y = 0.0067x$	+0.20	0.41	<0.01
	∼Air content (cm^3 g^{-1}) 7F	Repacked	$y = 0.003x$	+0.051	0.11	<0.01
		Undisturbed	$y = 0.00004x$	+0.14	0.02	0.93

Note: The * symbol in front of the equation indicates a significant difference between linear models (analysis of variance [ANOVA] p-value < 0.05). The * symbol behind the R^2 indicates a significant difference in the correlation coefficient (Fischer's z-test p-value < 0.05).

larger the equivalent pore diameter, the larger the difference between the pore volumes of repacked and undisturbed samples. According to ShA, the increase in cumulated pore volume above 39-µm equivalent diameter was due to the significant increase in structural porosity in the repacked samples compared to undisturbed ones. While the sample cumulated pore volume was not different between sample types below 39-µm equivalent pore diameter, the relative proportion of plasma and structural pore volumes was slightly changed. Significant differences in structural pore volume were found for all equivalent diameter classes except the <3 µm, 3–6 µm, and 24–39 µm ranges. Significant differences in plasma pore volume were found for the <3 µm, 3–6 µm, and >102 µm classes, respectively. The shift in plasma and structural pore volumes observed for <40-µm equivalent diameters was, however, negligible in volume (Figure 6). It can be due to more cracking in the plasma on undisturbed samples corresponding to a larger air entry water content on the shrinkage curve, which should be further discussed.

3.5 | Relationship of pore volume to soil organic carbon and clay content

The relationships of the physical parameters with SOC and clay content are presented in Figure 7 together with the corresponding linear regressions, whose properties are reported in Table 3. All linear regressions were significant (p-value < 0.05) except for Air_{-100} to clay in undisturbed samples (Figure 7F). All linear relationships were significantly different between repacked and undisturbed samples (ANOVA p-value < 0.05) except for the relationships between W_{-100} and SOC, and between W_{-100} and clay (Figure 7B,E). The R^2 values, slopes, and intercepts were always larger for repacked samples. Correlation coefficients were not significantly different, except it was higher according to the Fischer-Z test for Air_{-100} to SOC in repacked samples compared to undisturbed samples (Figure 7C).

3.6 | Changes observed between repacked and undisturbed samples

Compared to undisturbed samples, two main changes were observed after repacking regarding the soil pore volumes and the relationships of pore volumes with SOC and clay content.

First, although repacked at the field-observed bulk density, we observed a general increase in soil sample porosity (sample volume), thus a decrease in sample bulk density, after the five wetting and drying cycles of the repacking process. The increase in pore volume can be attributed to pores >40-µm equivalent diameter corresponding to fast-draining structural pores. The larger the equivalent diameter, the larger was the increase in pore volume. Moreover, the larger the structural porosity in the undisturbed soil, the lower was the increase after repacking (Figure 5E,F). When repacking samples, most of the biopores were destroyed; the structural pores in the repacked samples can, therefore, be attributed to packing voids between aggregates when repacking and micro-cracks that formed during the wetting-drying cycles. The large biopores, such as anecic worm galleries, increase the structural porosity of undisturbed samples, particularly when the soil is compacted (Sauzet et al., 2021), which may account for the heterogeneity in the relationship between sample and repacked sample structural porosity volume (Figure 5F).

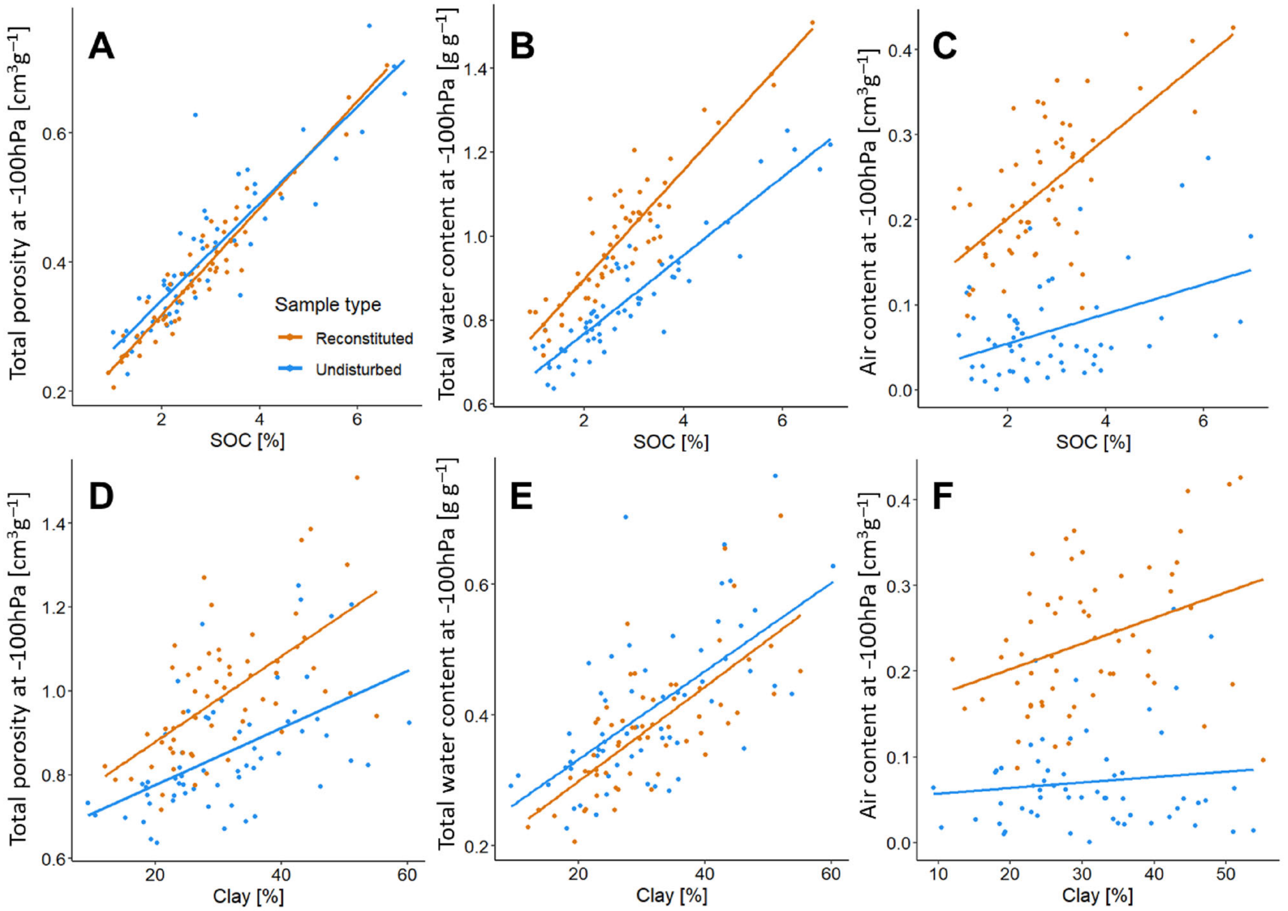

FIGURE 7 Linear regressions between physical parameters at −100 hPa (total porosity, water content, and air content) and main soil components (soil organic carbon [SOC] and clay) for the repacked (orange) and undisturbed (blue) sample. The solid lines represent linear regression models. The equations and other information related to these regressions are provided in Table 3.

Second, the increase in structural pore volume after repacking went with an increase in the slope of the relationships between SOC and clay, and the total pore volume, air content, and structural pore volume at −100 hPa. This was not observed for water content at −100 hPa, that is, saturated pores with a smaller diameter than 30 µm (Figure 7; Table 3), in accordance with the observation above that the main changes were observed in pores larger than 40-µm equivalent diameter. The increase or decrease in structural pore volumes and slopes of their relationships to SOC and clay were observed upon soil restructuration (Fell et al., 2018) and soil compaction (Goutal-Pousse et al., 2016; Schäffer et al., 2008), respectively. This suggests that both larger structural pore volumes and steeper slopes of their relationships with SOC or clay content observed with repacked samples indicate a better soil structural condition compared to undisturbed samples. This is also supported by the smaller structural shrinkage slope of the repacked samples (Table 2). From this point of view, we can conclude that repacking the soil allowed us to reach an optimum structural porosity volume with respect to the SOC and clay contents. The observation that the largest structural porosities in the undisturbed samples were not increased after repacking (Figure 5E,F) supports this conclusion.

Our findings have different implications for the characterization of soil structure. First, the smallest (<40-µm equivalent diameter) structural pores were not modified upon repacking (Figure 7). These pores are accounting for the air-water equilibrium and available water reserve in the soil (Nemes et al., 2011) and are the habitat for soil microbial communities (Kravchenko et al., 2019; Young & Crawford, 2004). Since these pore systems remain unchanged upon repacking, we may assume that they are more stable in the soil than the coarser ones, which is supported by their highly determined relationship with SOC content and also observed in previous studies (Fell et al., 2018; Goutal-Pousse et al., 2016; Johannes et al., 2019). Indeed, coarse pores can be generated and degraded quite fast, and from that perspective, they poorly inform on soil structure quality in the long term.

Second, working with repacked samples or aggregates bed was used and recommended previously by Braudeau et al. (1999) and Braudeau and Mohtar (2006) to characterize the soil hydro-structural soil behavior with shrinkage analysis. The results presented in this article confirms and illustrates the usefulness of the method but make us aware that the shrinkage curve of a repacked sample cannot be considered as representative of the undisturbed soil condition with respect to structural pore volume unless the soil structural porosity was already highly developed on the full range of equivalent pore diameter sizes. Moreover, the nature and shape of the structural pores were modified by repacking, particularly because biopores are largely destroyed.

4 | CONCLUSIONS

The repacked soil samples showed typical shrinkage properties of well-structured soils, with well-determined relationships to SOC and clay contents, in good agreement with previously reported results for undisturbed soil samples. The <40-µm equivalent diameter pores of undisturbed samples were not modified by repacking. The other hydro-structural properties were modified by repacking, namely, increased structural pore volume, increased slope of the SOC and clay to pore volume relationships, and decrease of the structural shrinkage slope (increase in hydro-structural stability). The increase in >40 µm equivalent diameter structural pores was attributed to the generation of packing voids and micro-cracks during the repacking process. The observed differences show that laboratory-repacked samples cannot be used to assess field undisturbed soil properties except for <40-µm equivalent diameter pores. These changes, however, were similar to those observed in soil structure restoration experiments and opposed to changes observed in soil compaction. Repacking allowed the development of the structural porosity volume, up to the maximum development of the structural porosity with respect to the soil components. We, therefore, conclude that repacking soil samples may allow quantifying the potential soil structure condition with respect to the sample SOC and clay content, which could be used as a reference in a perspective of soil regeneration.

Our findings introduce new perspectives on the application of repacked soil samples from aggregate beds. First, repacking allows to quantify the properties of composite samples, representing an average behavior at the field scale. The small size pores (<40 µm Ø) play a key role in water availability and as a habitat for life, making them valuable indicators of soil physical quality. Second, quantifying the potential soil structure condition with respect to its clay and SOC content in terms of shrinkage properties, structural pore volume, and size distribution after repacking could be used as a reference to which its actual physical condition could be compared for purposes such as structure quality monitoring and assessment.

AUTHOR CONTRIBUTIONS

Cédric Deluz: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing—original draft; writing—review and editing. **Alyssa Deluz**: Formal analysis; investigation; methodology; validation; writing—review and editing. **Thomas Keller**: Validation; writing—review and editing. **Sebastian Doetterl**: Supervision; validation; writing—review and editing. **Pascal Boivin**: Conceptualization; funding acquisition; project administration; resources; supervision; validation; writing—original draft; writing—review and editing.

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