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Visual Evaluation of Soil Structure (VESS) in temperate forest soils: pH mediates the effects of texture and organic carbon on soil structure and hydraulic functioning

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Abstract. Soil structure is an important determinant of ecosystem functioning in forest soils, because it influences water flow, aeration, root growth, and biological activity. The Visual Evaluation of Soil Structure (VESS) is a rapid field method to assess soil structural quality in agricultural systems, but its applicability to temperate forest soils remains largely unknown. We evaluated the applicability and interpretation of VESS across 27 temperate forest sites in Switzerland that span a wide range of soil textures, pH values, and soil organic carbon (SOC) contents. At each site, VESS assessments were combined with measurements of saturated hydraulic conductivity (K_{sat}), bulk density, soil texture, SOC content, pH and the SOC:clay ratio. A single property alone was not sufficient to explain the variation in VESS scores. However, strong relationships emerged when soils were grouped into three aggregation regimes defined by pH, clay and sand content ($R^2 = 0.65$). In acidic coarse-textured soils, VESS scores improved with increasing pH and silt content, controlled by aggregate stabilization by Fe/Al-oxyhydroxides. In acidic soils with more clay (19-43%), better VESS scores were associated with increasing SOC content but decreasing SOC:clay ratios, indicating the limiting effect of clay surfaces saturated with organic matter. In contrast, in near-neutral soils VESS scores improved as SOC:clay ratios increased. This trend is in agreement with findings from non-forested lands where the pH is typically in the neutral range as well. The relationship between VESS and K_{sat} was likewise dependent on aggregation regimes defined by pH and texture. Since saturated conductivity is very sensitive to the formation of large pore networks and not only aggregate formation, cluster-specific analyses identified four hydraulic regimes. In three of the four identified clusters, better VESS scores were associated with higher K_{sat}. Only under strongly acidic conditions did this relationship reverse. This indicates a decoupling between aggregate-scale structural quality and the preferential flow pathways governing saturated water flow. The classification of four regimes allowed to express K_{sat} as function of VESS score and one basic soil property with coefficient of determination $R^2 = 0.89$. We conclude that VESS is a useful tool for assessing soil structural quality in temperate forest soils across a broad range of textural conditions. However, its interpretation depends strongly on the aggregation regimes that are controlled by pH, governing both the visual expression of soil structure and its relationship to hydraulic functioning.

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1 Introduction

In forest ecosystems, soil structure, defined as the spatial organization of soil particles and pores (Rabot et al., 2018), is important for sustaining multiple essential soil functions and ecosystem services. It governs hydraulic processes such as water storage and transport as well as gas exchange, which together are crucial for plant growth and microbial activity (Adhikari and Hartemink, 2016; Bünemann et al., 2018; Wang et al., 2019). A well-developed soil structure facilitates root penetration, as it controls both rooting depth and accessibility to water and nutrients (Osman, 2013). Because soil pores control the movement of water (and gases), hydraulic properties such as saturated hydraulic conductivity are often interpreted as functional expressions of soil structure, reflecting the presence and connectivity of macropores that enable rapid water flow under saturated conditions (Buczko et al., 2006; Zhang et al., 2021; Basset et al., 2023).

Soil structure formation in temperate forests results from the interaction of biological, chemical, and physical processes. Roots, microorganisms, and soil fauna contribute to aggregation through pore formation, organic binding agents, and bioturbation (Dexter, 1988; Carminati et al., 2009; Helliwell et al., 2014; Sharma et al., 2017). Chemical stabilization further occurs through interactions among soil organic matter, clay minerals, and polyvalent cations. Depending on soil pH, aggregation may be dominated by mineral-associated stabilization mechanisms, organic matter-mediated binding processes or calcium-associated stabilization pathways (Lützow et al., 2006; Rowley et al., 2018). At the same time, climatic drivers such as wetting-drying and freeze-thaw cycles continuously reorganize soil structure over time (Leuther and Schlüter, 2021; Edwards, 2013). Consequently, pH may play a central role in determining the dominant aggregation mechanisms that shape soil structure in forest soils.

Assessing soil structure holistically remains challenging due to its multidimensional character and the occurrence of structural features across scales, which makes its comprehensive assessments both time and resource-intensive (Schmücker et al., 2026). One method to assess soil structure that has gained increasing attention in recent years is the semi-quantitative visual evaluation of soil structure (VESS; Moncada et al., 2014; Cornelis et al., 2019; Johannes et al., 2023; Wang et al., 2026). VESS is used to evaluate soil aggregation and porosity in the field and integrates multiple diagnostics such as size, shape, strength, and visible porosity of aggregates, along with root characteristics into a single numeric score (Ball et al., 2007; Guimarães et al., 2011). Beyond operational advantages, VESS scores have been shown to be related to established indicators of soil structural quality. Previous studies reported correlations with soil bulk density (BD), penetration resistance, total porosity, macroporosity, air-filled porosity, earthworm bioturbation, and soil organic carbon content (Pulido Moncada et al., 2014; Cherubin et al., 2017; Cornelis et al., 2019; Aji et al., 2021; Yakovenko et al., 2024). Moncada et al. (2014) reported a strong correlation between VESS scores and saturated hydraulic conductivity (K_{sat}) in tropical soils from Venezuela.

Evidence also suggests that VESS relates to indicators of soil structural stability that are linked to soil organic matter dynamics. In a study across 161 cropland sites, Johannes et al. (2017a) reported strong correlations between CoreVESS (a modified version of VESS that is conducted in the lab) scores and SOC:clay ratio benchmarks. In agricultural soils, the ratio of SOC to clay content has been suggested as a practical metric for evaluating soil structural status, with a SOC:clay ratio greater than 1:10 often interpreted as indicative of favorable structural conditions (Johannes et al., 2023) and has further been proposed

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as a soil health indicator of the EU's Soil Monitoring Law (European Commission, 2023). These findings indicate that VESS can capture soil health attributes beyond purely physical properties. However, the mechanisms through which SOC contributes to aggregation are known to vary with soil properties such as pH and mineralogy (Rowley et al., 2018). Consequently, the transferability of SOC:clay benchmarks across different soil environments remains under debate (Prout et al., 2021; Rabot et al., 2024; Wenzel et al., 2024).

To date, the application of VESS has primarily focused on managed agricultural systems, specifically cropland, grassland and pasture. In forest environments, the use of VESS has been largely limited to studies that examine the effects of land-use change on soil physical quality in the tropics and subtropics. In these studies, long-term grassland or forest plots have been utilized merely as reference soils against which agricultural degradation is evaluated (Pulido Moncada et al., 2014; Guimarães et al., 2017; Tuchtenhagen et al., 2018; Aji et al., 2021). Consequently, little is known about how VESS relates to soil physical quality in temperate forest soils themselves. Soil structure in forest ecosystems develops under conditions that differ substantially from those in agricultural soils. In the latter, structural attributes and aggregation are strongly influenced by tillage, machinery traffic, and the growth and turnover of annual crop roots. These processes frequently disrupt aggregates and pore continuity and can compress the soil matrix (Rabot et al., 2018; Keller et al., 2019; Or et al., 2021; Panagos et al., 2024). In contrast, forest soil structure generally develops over longer timescales under the influence of perennial root systems, continuous inputs of soil organic matter (SOM), and intense biological activity, including extensive fungal networks. Although forest soils may also be compacted depending on management practices, these processes differ fundamentally from the repeated tillage and regular machinery traffic that characterize agricultural systems. Furthermore, forest soils tend to be more acidic than many agricultural soils because they are typically not limed. This acidity arises from the continuous production of organic acids and CO_2 during litter decomposition and from plant uptake of base cations such as calcium and magnesium that are subsequently stored in woody biomass. Soil acidity influences mineral weathering and organo–mineral interactions, both of which affect aggregate formation and stabilization (Lützow et al., 2006; Osman, 2013). Because pH influences both the stabilization of SOM and the dominant mechanisms of aggregation, it may also affect how visual indicators of soil structure should be interpreted in forest soils. Accordingly, although VESS has proven useful in agricultural systems, understanding whether it can reliably capture structural characteristics in temperate forest soils is therefore important for evaluating its broader applicability as a soil structural assessment tool across ecosystems.

To our knowledge, no study has examined the application of VESS in temperate forest soils. Therefore, the objective of this study is to test whether VESS is indicative of soil structure in temperate forest soils, where soil aggregation processes and pore formation mechanisms differ substantially from those in agricultural and grassland ecosystems. In addition, we examine whether relationships between VESS-scores and important soil health metrics, such as K_{sat} and the SOC:clay ratio, that have previously been reported for agricultural soils, also hold in temperate forest soils. Therefore, we selected 27 forest sites across a wide range of soil textures and pH across Swiss forests. At each site, VESS was performed in situ, and undisturbed soil samples (250 mL) were collected for measurements of K_{sat}, and basic soil properties such as texture, SOC, pH, and bulk density. We thereby want to address the following questions:

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1. Does VESS exhibit similar relationships with soil structural properties in temperate forest soils as previously reported for agricultural systems?
2. Does the relationship between structural and basic soil properties change with differences in aggregate and soil formation?
3. Do relationships between VESS and important soil health indicators, such as K_{sat} and the SOC:clay ratio, also occur in temperate forest soils, or do they change with different aggregate stabilization mechanisms in the more acidic forest soils?

2 Material and Methods

2.1 Site descriptions

The study was conducted at 27 forest sites across Switzerland (Fig. 1). Most sites were located in the Swiss *Mittelland* plateau, within the cantons of Bern and Solothurn. The elevations of the site ranged from 431 to 1502 m above sea level. According to the world reference base classification system (Schad, 2023), the soils included *Cambisol*, *Dystric Cambisol*, *Luvisol*, *Stagnosol*, *Regosol* and *Rendzic Leptosol*. Mean annual precipitation ranged from 785 to 1549 mm and mean annual temperatures ranged from 4.2 to 9.6 °C (Frehner et al., 2011). A detailed description of the sites is provided in Tab. S1 in the supplementary material.

2.2 Experimental design

The sites were chosen based on their texture and SOC content. Candidate locations were selected from the *Swiss Soil Dataset* (Service Centre NABODAT, 2024), which is an assembled database from projects since the 1960s that contains a large number of soil samples across Switzerland.

The targeted selection of sampling locations covered nine textural soil classes. Within each class, at least one site with a SOC:clay ratio $<$ 1:10 and at least one with a SOC:clay ratio $>$ 1:10, as this threshold has been proposed as a benchmark distinguishing moderate from good structural quality (Johannes et al., 2023).

To ensure that differences in structural quality primarily reflected natural soil-forming processes rather than mechanical disturbance, only unmanaged forest sites without visible signs of compaction were selected. Soil samples were collected in late spring and early summer of 2024. At each site, the forest litter was removed and four undisturbed volumetric soil samples were collected from the topsoil (5–10 cm depth) using 250 mL cylindrical cores (8 cm diameter, 5 cm height). The cores were arranged in a square pattern with 1 m spacing. The samples were extracted vertically and stored at 4 °C until laboratory analysis. Additionally, in the center of the square, the topsoil structure was assessed in situ using the VESS method (see section 2.3). Soil moisture conditions at the time of sampling were estimated using recorded suction values from nearby monitoring stations for the topsoil (0-20 cm depth; Bodenmessnetz Schweiz, 2023). Additional information on soil moisture conditions and distance to the respective monitoring stations is provided in Tab. S2 in the supplementary material.

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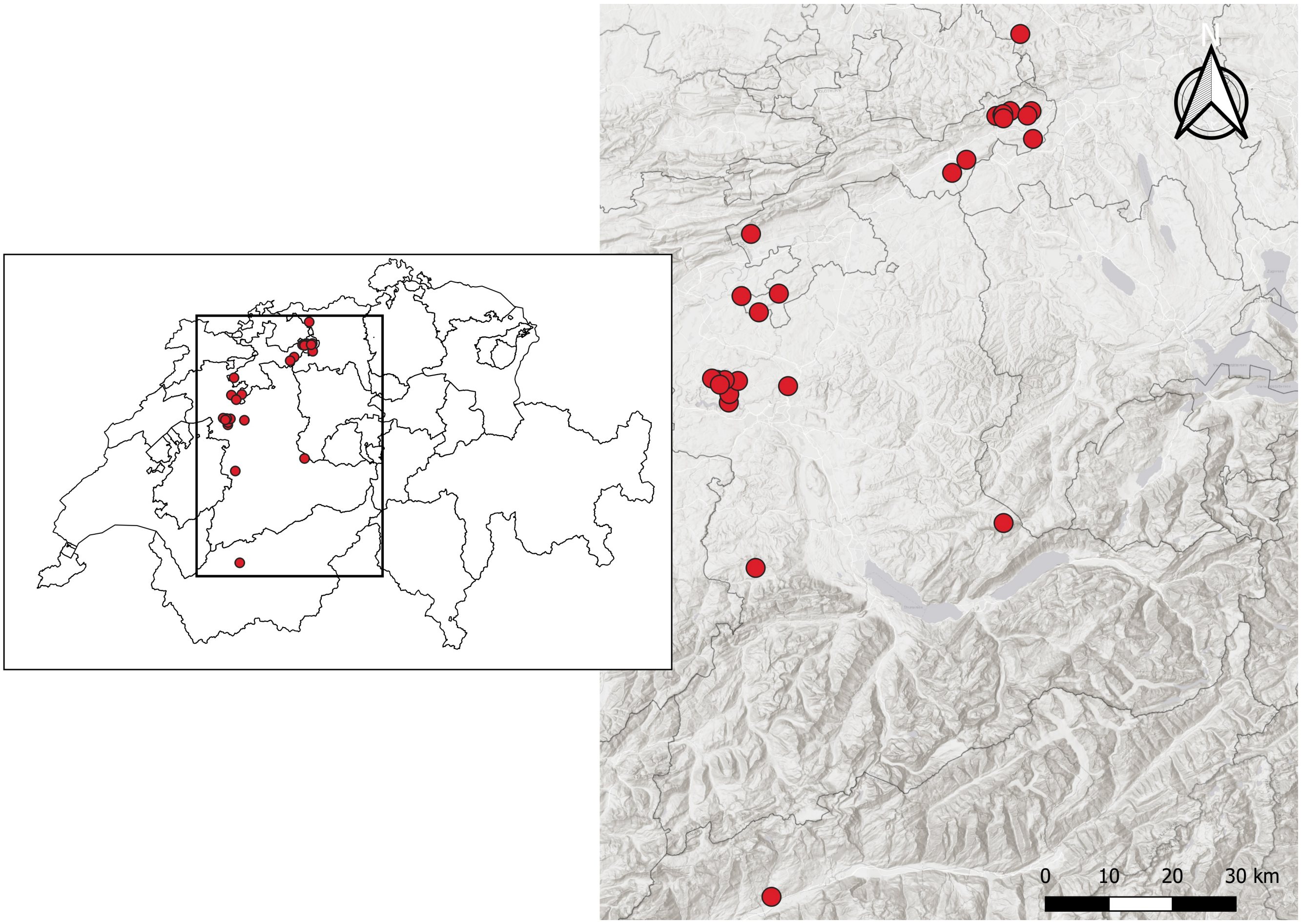

Figure 1. The 27 sampling sites are shown as red dots on the map. Sites were mainly located in the cantons of Bern and Solothurn (Cantonal boundaries: swissBOUNDARIES3D, swisstopo, 2025; elevation hillshade combined from Esri World Hillshade and CARTO Positron basemaps).

2.3 VESS

To evaluate the topsoil structure using VESS, a small soil pit measuring approximately 20 × 20 cm width and 30 cm depth was excavated to expose the soil profile. Then, a block of soil was extracted from the pit walls with minimal disturbance to preserve its natural structure, and is then placed on a flat surface. For examination of the soil block, horizons (if present) were first identified. The block was then gently broken apart by hand into natural aggregates, and the following criteria were assessed: aggregate size and shape, porosity and internal structure, root penetration, and soil colour, following the criteria described in Tab. S3 in the supplementary material. Based on these observations, each horizon was assigned a structural quality score ranging from 1 (very good) to 5 (very poor). If multiple horizons occurred within the upper 30 cm, an overall score was

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calculated as the weighted mean of the individual horizon scores. The procedure is described in detail by Guimarães et al. (2011). However, for subsequent statistical analyses, only VESS scores corresponding to the depth from which the soil cores were taken (5 - 10 cm) have been used. If a block in this depth range contained two horizons, the weighted mean of their respective scores was calculated and used in the analysis. To limit damage of destructive sampling, the evaluation was based on a single soil block per site.

2.4 Assessment of saturated hydraulic conductivity

In the laboratory, soil samples were saturated for three days under a gradually rising water table in preparation for the measurement of saturated hydraulic conductivity using the falling head method with the KSAT device (Meter Group GmbH, Munich, Germany). K_{sat} was expressed in cm d^{-1} and corrected to viscosity at 10°C in the SoilView Software (METER Group GmbH, Munich, Germany). For each sample, a minimum of three measurements were performed and the median value of those was used for further calculation.

2.5 Soil physicochemical characterization

Following the analysis of K_{sat}, the samples were oven-dried at 105 °C for 24 hours to determine the dry mass and bulk density. In this study, the bulk density calculation also included coarse fragments larger than 2 mm. Afterwards, soil texture was determined using the pipette method according to ISO 11277:2020. Oven-dried samples were sieved to < 2 mm, pretreated with H_2O_2 to remove organic matter and dispersed with sodium hexametaphosphate before gravimetric determination of clay, silt, and sand fractions. Soil pH was measured following ISO 10390:2005 in a 1:2.5 (w/v) soil–water suspension after 12 hours of equilibration. SOC content was determined using the temperature gradient method in accordance with DIN 19539:2016b and the Agroscope reference method for total organic carbon (TOC; Agroscope, 2021), in which organic carbon is oxidized under an oxygen atmosphere at temperatures ≤ 400°C.

2.6 Statistical analysis

The statistical analysis aimed to identify soil conditions under which VESS and structure-related soil properties showed relevant relationships. For each topsoil, the median value of the typically four soil samples was calculated and was used to explore the relationships between (1) basic soil properties (not related to soil structure), (2) VESS score (one value per topsoil), (3) and the saturated hydraulic conductivity as a structure-related property. Based on the different aggregate formation mechanisms in forest soils listed in the introduction, we expect that no universal rules between structural and basic soil properties exist. Instead, we applied a rule-based regression approach that first partitions the dataset into groups of similar soils and subsequently fits simple linear models within each group. Accordingly, we were looking for relationships in various subdomains representing different aggregation regimes. In a first step, a cluster-analysis including the basic soil properties clay content [%], silt content [%], sand content [%], SOC content [%], and pH [-] was conducted. For that purpose, we explored the 10 possible three-dimensional subdomains combining three basic soil properties and built clusters using a hierarchical agglomerative grouping

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algorithm (Ward, 1963). The 27 topsoils within the 3D phase-space were subdivided into a small number of clusters (fulfilling the constraints specified below). For clustering, the original values of the basic soil properties were scaled between 0 and 1 (by subtracting the mean value and dividing by standard deviation, followed by scaling with corresponding extreme values) to identify groups with similarity regarding the three soil properties. For each subdomain formed by three soil properties, an ordinary least squares linear model was built and fitted as follows:

$$VESS = \beta_0^v + \beta_{x_1}^v \cdot x_1 + \beta_{x_2}^v \cdot x_2 \tag{1}$$

$$SSP = \beta_0^s + \beta_x^s \cdot x + \beta_{\text{vess}}^s \cdot VESS \tag{2}$$

with VESS being the VESS score [-], soil structure related soil property SSP (i.e., $\log_{10}$ K_{sat}), basic soil properties x_1 and x_2 with their corresponding coefficients β^v (for a model explaining VESS) and x (model for structural property), respectively. Note that for the model predicting VESS score (Eq. (1)) two basic soil properties are used as covariates but only one for the model predicting the structural soil property (Eq. (2)) where the VESS score serves as 2nd covariate. In addition, considering the dominant role of the ratio of soil organic carbon [%] to clay [%] for the VESS score of non-forested soils (Johannes et al., 2017a), it was tested as basic soil property in Eq. (1) as well, together with texture, organic carbon content and pH. The coefficients $\beta^{v/s}$ including the intercept β_0 were fitted to the experimental data. A cluster is classified as 'explanatory', if the coefficient of determination of such model with two explanatory variables R_2^2 is above a threshold value of 0.5. In the case of the model predicting SSP, we added as second constraint as follows: for the simpler model predicted with the basic soil property alone ($SSP = \beta_0^s + \beta_x^s \cdot x$) the following condition must be fulfilled for the coefficient of determination R_1^2 for the model without VESS score

$$\frac{R_2^2 - R_1^2}{R_2^2} \geq 0.25 \tag{3}$$

to ensure that the VESS score contributes substantially to R_2^2.

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3 Results

3.1 Range of soil properties

The scores of the visual evaluation of soil structures are defined ranging from very good (score 1) to very poor (score 5). For field sampling of forest soils, scores ranged from 1.0 to 3.0 with an average value of 2.0. The median values of various basic and structure related topsoil properties cover a wide range of soil textural classes, soil organic carbon, and pH (see Tab. 1 and Fig. 2). Unlike typical crop- and grasslands, these soils exhibit lower pH (minimum 3.4) and higher organic carbon contents (maximum 15.4%).

Table 1. Minimum and maximum values of forest soil properties measured at 27 locations across Switzerland. Note that the reported values refer to the median of several cylindrical soil cores. (*In case of soil organic carbon (SOC), the minimum value was below the detection limit of 0.2% and was set to 0.1%.)

Clay [%]		Silt [%]		Sand [%]		C_{org} [%]		pH [-]		$\log_{10} K_{sat}$ [cm day^{-1}]		ρ_{bulk} [g cm^{-3}]	
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
8.1	77.3	12.7	68.7	6.4	78	0.1*	15.4	3.4	7.2	1.89	4.0	0.46	1.36

Due to the high organic content, also the SOC:clay ratio can be much higher than the threshold of 0.125 found for non-forested land in Johannes et al. (2017a) to separate between good and poor structure. While there is only one ratio value (0.10) below the threshold (1:8) for the samples with good VESS score equal or smaller than 1.4 (Fig. 2b), there were several topsoils with VESS scores > 2.0 (indicating poorer VESS) with very high SOC:clay ratios (up to 1:1.2).

3.2 Factors and mechanisms controlling the visual score of soil structure quality

First, an ordinary least squares regression was fit to all 27 topsoil samples with a model for each basic soil properties as univariate covariate. As shown in Fig. 3, no significant relationship was observed between the VESS score and a single basic soil property. All coefficients of determination were below $R_1^2 = 0.1$, and all F-tests yielded p values greater than 0.05. In contrast, combining two soil properties substantially improved the relationships with VESS score ($R_2^2 > 0.65$) for specific combinations. As explained in the Material and Methods section, cluster analysis was performed across all possible 3D subdomains, here resulting in a separation of the 27 topsoils into three clusters containing at least six soils each. The constraint ($R_2^2 > 0.5$) could not be achieved when only two clusters were used.

For three out of 10 subdomains a linear model according to (Eq. 1a) could be built combining two basic soil properties and obtaining $R_2^2 > 0.5$. The strongest correlations were obtained for three clusters in a subdomain defined by pH, clay and sand

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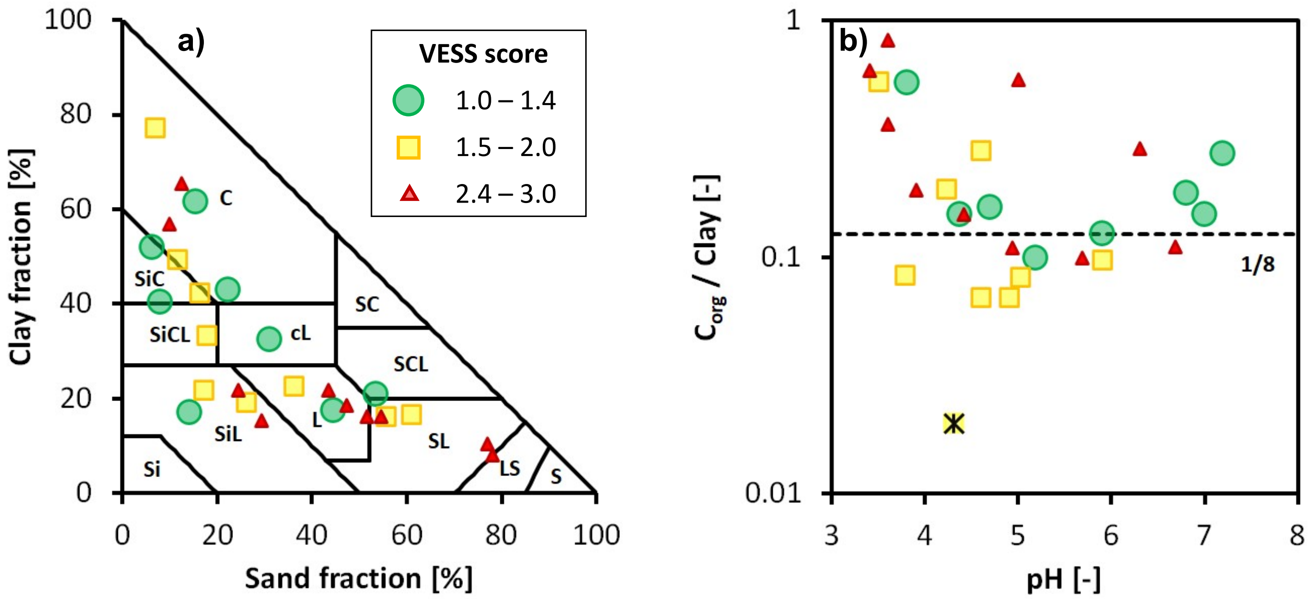

Figure 2. Basic soil properties of the 27 forest topsoils. The size and color of the symbols denote the score of the visual evaluation of soil structure (VESS; the larger the symbols, the better the visual score). (a) The VESS scores are distributed across the soil textural classes. (b) The ratio between soil organic carbon and clay content covers a wider range than documented for crop- and grassland. Several sites show a low structural quality (red triangles) despite the value of a ratio that is much higher than the threshold proposed for healthy soils for non-forested soil (dashed horizontal line). The value marked with a cross was set to 0.02 because the true value of 0.005 would limit the visibility of the details for larger values.

content. The three clusters and the subdomains are shown in Fig. 4 and represented: acidic soils with low clay and high sand contents (cluster a, eq. 4), acidic soils with moderate clay and lower sand contents (cluster b, eq. 5), and near-neutral soils with moderate to high clay and low sand contents (cluster c, eq. 6).

The conditions defining the three clusters and the corresponding coefficients between VESS scores and basic soil properties are listed below.

Cluster (a): acidic (pH 3.4-5.0), low clay (8-21%), and high sand content (45-78%)

$$VESS = 11.66 - 0.10 \cdot silt - 1.66 \cdot pH \tag{4}$$

Cluster (b): acidic (pH 3.5-5.2), moderate clay (19-43%) and low sand content (16-44%)

$$VESS = 2.344 - 0.436 \cdot SOC + 9.07 \cdot ratio_{SOC:clay} \tag{5}$$

Cluster (c): near-neutral (pH 5.0-7.2), high clay (15-77%) and low sand content (6-29%)

$$VESS = 2.08 + 0.115 \cdot sand - 10.89 \cdot ratio_{SOC:clay} \tag{6}$$

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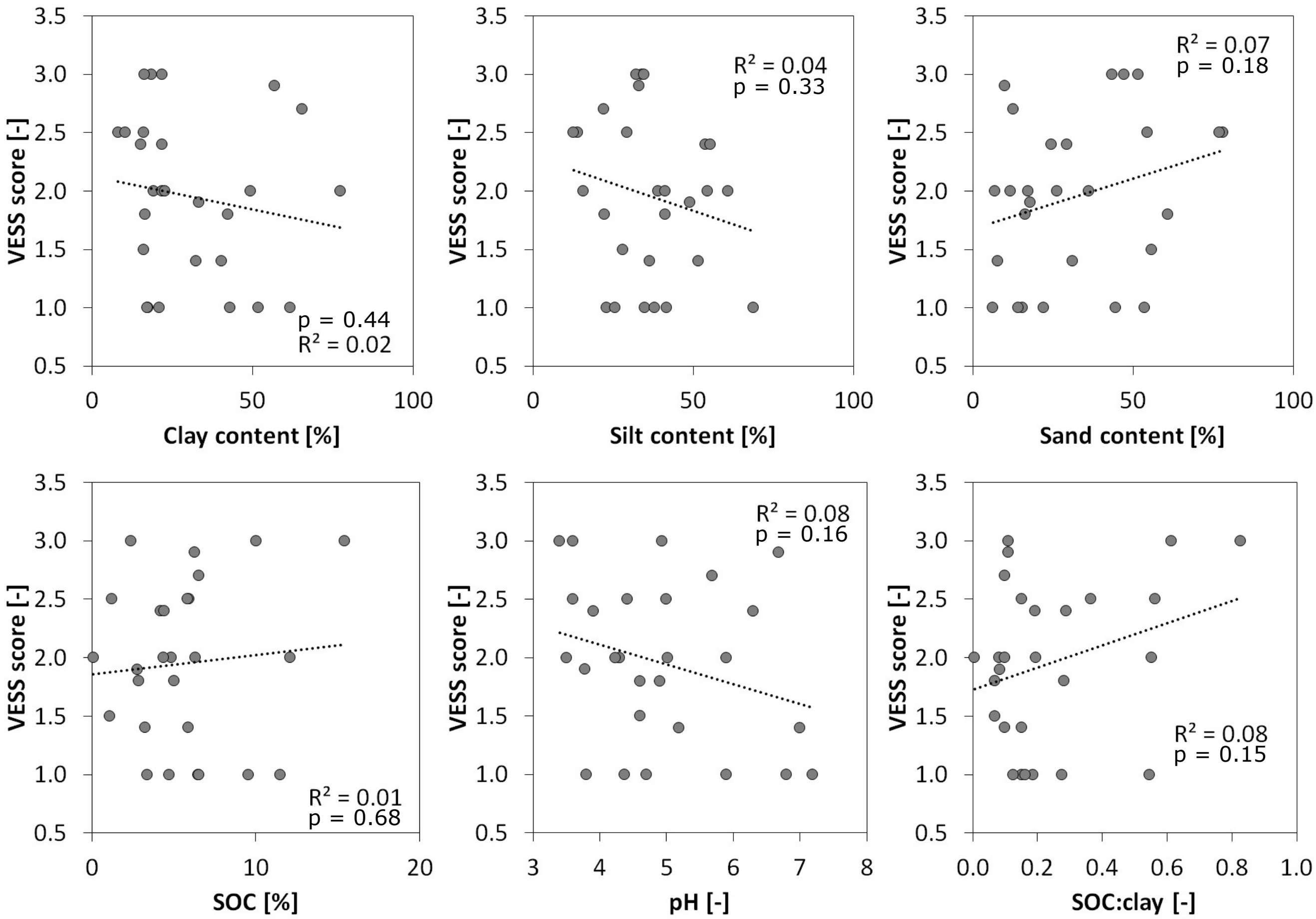

Figure 3. Univariate linear relationships between visual score of soil structural quality (VESS score) and basic soil properties including the ratio between soil organic carbon (SOC) and clay. Note that good soil structure quality is manifested by small VESS values (typically between 1.0 and 2.5). No single basic soil property clearly explains the variations of the VESS score, with all of the relationships yielding non-significant F-tests ($p > 0.05$). The weak but positive relationship between VESS score and carbon-clay ratio would indicate a counter-intuitive decrease of structure quality with increasing SOC:clay. This spurious trend is just a result of superposition of different aggregation regimes.

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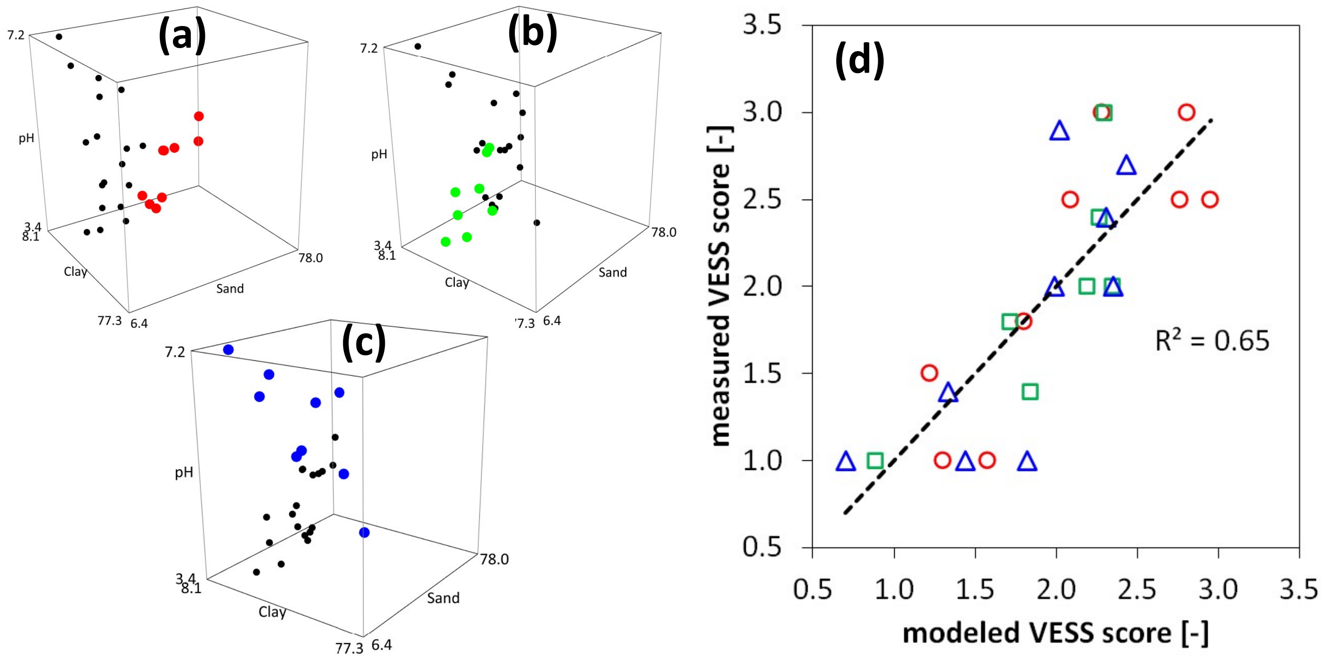

Figure 4. Cluster analysis to define different regimes of aggregate formation and predicting VESS score. Three clusters were separated in a subdomain defined by pH, clay and sand content. In panels (a) to (c), colored symbols represent the sites belonging to the respective cluster, whereas black symbols indicate the remaining sites that are not assigned to that cluster. (a) For the red cluster with acidic conditions and low clay content, structure quality increases with increasing pH. (b) For the green cluster with acidic conditions and higher clay content, there is a transition between stable mineral-associated to increasingly organic matter-mediated aggregation. (c) The blue cluster in neutral soils behaves similar to non-forested soils with better structure for increasing carbon-clay ratio. (d) Model performance to predict VESS score by combining the linear correlations found for the three clusters.

3.3 Relationship between saturated hydraulic conductivity and VESS score

Median K_{sat} values varied by more than two orders of magnitude across the 27 forest sites, ranging from 0.8 to 100 m day^{-1}. As shown in Fig. 5, the logarithm of K_{sat} exhibited weak to moderate relationships with several individual soil properties. The strongest relationship among the investigated variables was observed for pH ($R_1^2 = 0.55$, $p < 0.01$), whereas the relationship between K_{sat} and VESS score remained comparatively weak ($R_1^2 = 0.13$, $p = 0.07$). Nevertheless, lower VESS scores (better visual structure) generally corresponded to higher K_{sat} values.

Compared to the weak relationships observed between VESS score and individual soil properties (Fig. 3), K_{sat} showed stronger relationships with clay content, sand content and especially pH (Fig. 5). Coefficients of determination reached approximately $R_1^2 = 0.4$ for clay and sand content (both $p < 0.001$) and $R_1^2 = 0.55$ ($p < 0.001$) for pH, identifying pH as the strongest single predictor of K_{sat}. Interestingly, K_{sat} increased with increasing clay content and decreased with increasing sand content.

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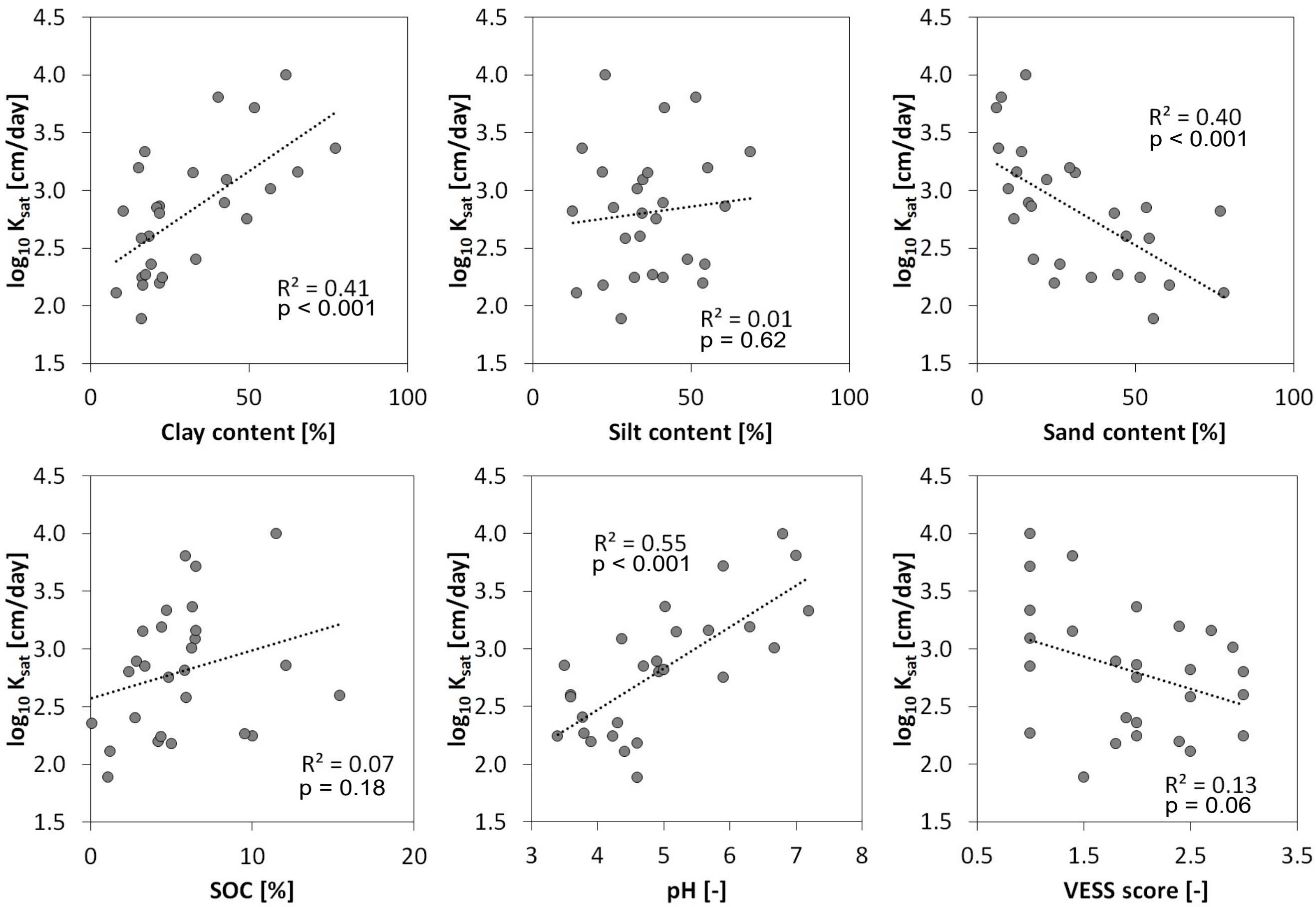

Figure 5. Linear relationship between the logarithm of saturated hydraulic conductivity K_{sat} with basic soil properties and the score of the visual evaluation of soil structures (VESS). Note that the relationships between K_{sat} and clay and sand content are in contradiction to the expected increase of K_{sat} with increasing particle size (effect of structural pores). The pH shows the largest coefficient of determination, revealing its dominant role in structure formation. The trend for the VESS score is reasonable with K_{sat} decreasing with increasing VESS score (poor structure quality for high VESS scores). The p-value for clay, sand, and pH was very small, revealing the significant relationship with $\log_{10} K_{\mathrm{sat}}$

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To identify soil conditions under which stronger relationships emerged between $\log_{10}$ of K_{sat}, VESS score and selected soil properties, cluster analyses were performed across multiple three-dimensional subdomains. The strongest relationships were obtained within a subdomain defined by pH, sand content and soil organic carbon content (Fig. 6a-d). Within this framework, the 27 topsoil samples were grouped into four clusters containing at least five samples each (no combinations fulfilling the constraints with three clusters). Combining the cluster-specific linear relationships resulted in a strong agreement between modeled and measured K_{sat} values ($R_2^2 = 0.89$; Fig. 6e).

The resulting clusters represented: moderately acidic soils with high sand contents (cluster a, Eq. 7), moderately acidic soils with low sand contents (cluster b, Eq. 8), near-neutral soils with low sand contents (cluster c, Eq. 9), and very acidic soils with intermediate sand contents (cluster d, Eq. 10). Within these clusters, strong relationships emerged between K_{sat}, VESS score, and combinations of selected soil properties. The range of basic soil properties within each cluster is summarized in Tab. S4 of the Supplementary Material.

Cluster (a): moderate acidic (pH 4.4-5.0), high sand fraction (54-78%):

$$\log_{10} K_{\text{sat}} = 7.87 - 0.139 \cdot silt - 1.42 \cdot VESS \quad (7)$$

Cluster (b): moderate acidic (pH 3.8-5.2), low sand fraction (18-44%):

$$\log_{10} K_{\text{sat}} = 0.61 + 0.58 \cdot pH - 0.29 \cdot VESS \quad (8)$$

Cluster (c): near-neutral(pH 4.9-7.2), low sand fraction (6-30%):

$$\log_{10} K_{\text{sat}} = 3.24 + 0.10 \cdot pH - 0.29 \cdot VESS \quad (9)$$

Cluster (d): very acidic (pH 3.4-3.8), intermediate sand fraction (17-55%):

$$\log_{10} K_{\text{sat}} = 0.63 + 0.09 \cdot clay + 0.09 \cdot VESS \quad (10)$$

As shown in Fig. 6e, the saturated hydraulic conductivity was highest for the near-neutral soil. In three of the four clusters, K_{sat} increased with decreasing VESS score, indicating higher conductivity in soils with better visual structural quality. In contrast, the opposite relationship was observed in the very acidic cluster (d), where K_{sat} increased with increasing VESS score.

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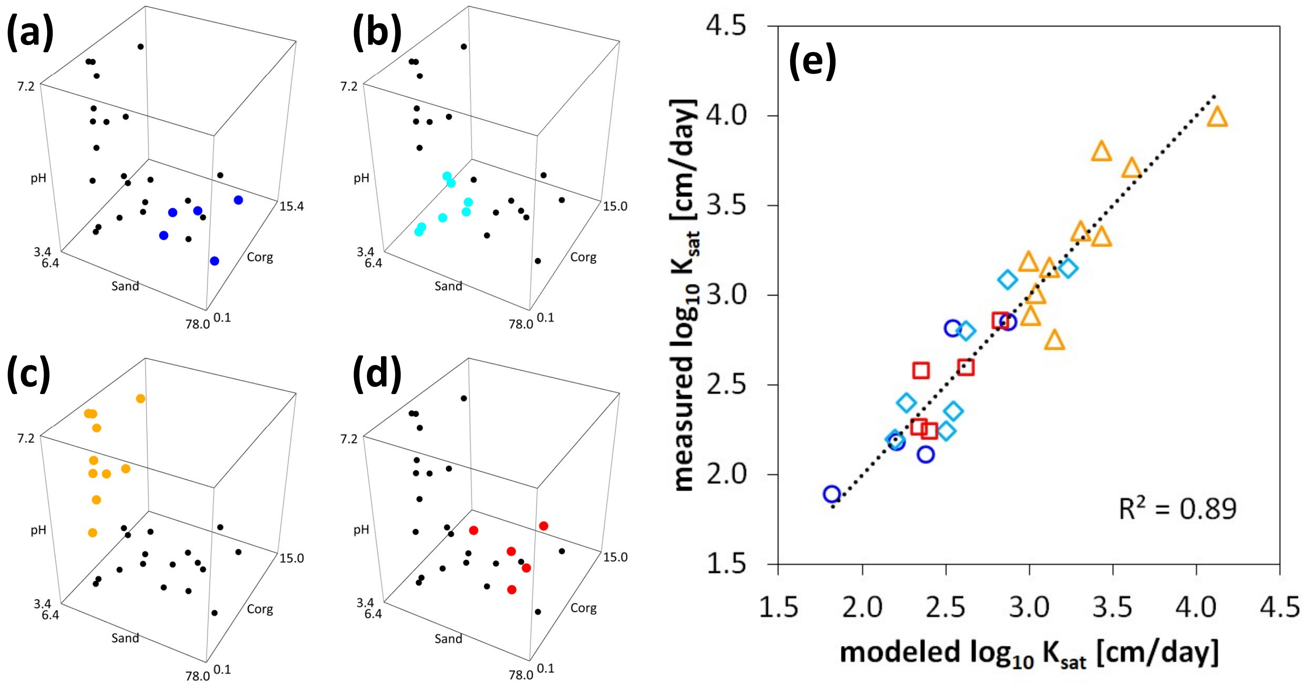

Figure 6. Cluster analysis to define different regimes controlling saturated hydraulic conductivity. In panels (a) to (d), colored symbols represent the sites belonging to the respective cluster, whereas black symbols indicate the remaining sites that are not assigned to that cluster. Clusters (a) and (b) are moderate acidic (pH 4-5) but differ in sand content. Cluster (c) has neutral pH and cluster (d) is very acidic (pH $<$ 4). (e) Model performance to predict $\log_{10}$ of K_{sat} by combining the linear correlations found for the four clusters.

4 Discussion

4.1 VESS across different soil properties

VESS was applied on topsoils from 27 sites spanning a range of textural classes and yielded scores between 1 and 3 (see Fig. 2a), but no consistent relationship with soil texture was observed. This suggests that VESS assessments are not systematically biased by soil texture and can therefore be used to assess soil structural quality across a broad range of forest soil textures. Previous studies have reached contrasting conclusions regarding the influence of texture on VESS. For instance, Cornelis et al. (2019) reported in a global meta-analysis that clayey and silty soils tend to receive higher (poorer) VESS scores than sandy soils, regardless of climate zone. In contrast, Johannes et al. (2017b) observed in a study on Cambi-Luvisols that only soils with more than 20 % clay content achieved the best VESS scores, as sandy soils lacked sufficient clay to develop a well-structured, crumbly soil architecture. We did not observe a consistent relationship between VESS scores and textural class within the investigated forest soils. This may suggest that, under unmanaged forest conditions, VESS assessments are not primarily driven

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by texture alone and may be suitable for evaluating structural quality across a broad range of forest soil textures.

Because soil texture alone could not explain the observed variability in VESS scores, we further evaluated the data in the context of the SOC:clay ratio, which has been proposed as an indicator of structural quality and SOM-related aggregation processes for crop- and grassland. A positive effect of SOC:clay ratio on structural quality was found for forests in the neutral pH-range but not for more acidic soils. Most samples exceeded the proposed benchmark of 1:8 (Johannes et al., 2017a), which would indicate very good structural quality for most forest sites, but some of these sites exhibited the highest recorded topsoil VESS scores. This was particularly evident in acidic soils, where high SOC:clay ratios frequently coincided with poorer structural conditions (Fig. 2b). Comparable observations were reported by Rabot et al. (2024), who found that many forest soils exceeded the 1:8 threshold despite displaying comparatively poor structural conditions in the field.

These findings indicate that the relationship between SOC accumulation and visually assessed soil structure depends on the dominant stabilization environment. Rowley et al. (2018) proposed that soil pH acts as a "master variable" that controls the dominant mechanisms of SOM stabilization. Under acidic conditions, stabilization is dominated by Al- and Fe-mediated sorption processes, whereas Ca-mediated aggregation, cation bridging, and carbonate-related mechanisms become increasingly important toward neutral and alkaline conditions.

Under acidic conditions in forest, SOM may be stabilized through mineral-associated sorption processes without necessarily promoting the formation of the friable, porous, biologically structured aggregate architecture that is typically associated with favorable VESS scores. As a result, high SOC content does not directly translate into visually well-structured topsoil conditions in acidic soils. This interpretation is supported by Wenzel et al. (2024), who stated that Al-oxyhydroxides are the main predictors of SOC in acidic soils, whereas $CaCO_3$ and Ca-related mechanisms become increasingly important under neutral to alkaline conditions. The pH-dependent mechanisms through which SOM contributes to aggregate stabilization will be discussed in the following subsection.

4.2 Aggregation regimes controlling visual soil structure quality in temperate forest soils

Because all investigated topsoils were free of visible signs of compaction, the observed variation in VESS scores is likely to reflect natural differences in soil composition and aggregation processes rather than varying degrees of anthropogenic structural degradation. Against this background, we explored whether the variability in VESS could be explained by distinct aggregation regimes. When exploring the relationships between basic soil properties (including the SOC:clay ratio) and visual structural quality (VESS score), no single soil property explained the variation in the VESS scores (Fig. 3). However, strong correlations emerged when combinations of two soil properties were evaluated within three clusters defined in a 3D subdomain based on pH, clay content, and sand content (Fig. 4).

In a subregion defined by low pH, low clay content, and high sand content (cluster a, see Eq. 4), pH appeared to be the dominant factor controlling the VESS score. Under these acidic conditions, pH likely influences both biological activity and mineral-mediated stabilization processes, thereby strongly affecting aggregate formation and soil structure.

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From a biological perspective, acidic conditions may suppress microbial and faunal activity. Soil pH strongly influences microbial community composition because many microbial groups, particularly bacteria, exhibit relatively narrow pH optima for growth and activity (Wang and Kuzyakov, 2024). In addition, nutrient availability and ion toxicity are closely linked to pH, with microbial biomass and activity generally being highest between pH 5 and 7 (Aciego Pietri and Brookes, 2008). Under strongly acidic conditions, SOM decomposition may therefore be reduced due to low pH and potentially toxic Al^{3+} concentrations (Tonneijck et al., 2010; Lian et al., 2019). Acidification may also reduce soil faunal activity. For example, Geissen et al. (2007) reported lower feeding activity and reduced earthworm abundance with increasing acidification across forest sites in Germany. Consequently, extremely acidic conditions may limit the biological processes that contribute to the formation of porous and biologically structured aggregates.

At the same time, acidic conditions may enhance mineral-associated SOM stabilization. Under low pH, Fe- and Al-phases become increasingly protonated, thereby increasing their sorptive capacity for negatively charged organic compounds (Chen et al., 2014; Ye et al., 2022). In addition, polyvalent Fe^{3+} and Al^{3+} ions may promote flocculation and aggregation through metal-mediated bridging and cementation mechanisms (Lützow et al., 2006; Goldberg, 1989). Thus, although acidic conditions may suppress biological structuring processes, they may simultaneously enhance abiotic stabilization mechanisms. The observed improvement in VESS scores with increasing pH within this acidic regime may therefore reflect a gradual recovery of biological aggregation processes while mineral-mediated stabilization mechanisms remain active. Consequently, the visual soil structure in cluster a may be mainly controlled by Fe/Al-mediated stabilization under acidic conditions.

In acidic soils with higher (moderate) clay contents (cluster b), the structural quality improved with increasing SOC content (VESS score decreased), whereas the opposite trend was observed for the SOC:clay ratio (Eq. 5). At first sight, this relationship appear contradictory, because both parameters are commonly linked to increasing SOM-related stabilization. However, the contrasting trends may indicate that the dominant stabilization mechanisms shift as the amount of organic carbon increases relative to the available mineral surface area.

At moderate clay contents, Fe- and Al-phases together with clay minerals still provide sufficient reactive surface area for the sorption and stabilization of organic compounds, thereby promoting mineral-associated organic matter (MAOM) formation and mechanically stable aggregate structures (Spielvogel et al., 2008; Kleber et al., 2015; Schweizer et al., 2021). Under these conditions, increasing SOC contents may therefore support aggregate formation and improve the visual soil structure. However, as organic carbon accumulates relative to the available clay surface area, mineral surfaces may progressively approach carbon saturation, thereby reducing the capacity for further mineral-mediated stabilization (Dexter et al., 2008). Consequently, the SOC:clay ratio may not simply reflect carbon abundance, but rather the balance between organic matter inputs and the mineral surface capacity available for stabilization.

This shift may also indicate a transition from predominantly mineral-associated stabilization mechanisms at low pH toward an aggregation regime increasingly driven by organic matter–mediated processes. Mineral-associated stabilization is commonly linked to smaller and more persistent microaggregates, whereas organic matter-driven aggregation tends to promote larger organic-rich aggregates with shorter turnover times (Lützow et al., 2006; Lavallee et al., 2020). Consequently, the ob-

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served VESS patterns may reflect a transition from mechanically stable mineral-associated aggregation toward structurally less resistant organic-dominated aggregate architectures under field conditions.

As pH approached neutral conditions and clay contents remained moderate to high (cluster c), the aggregate structure improved with increasing SOC:clay ratio (Eq. 6), which is consistent with the findings of Johannes et al. (2017a) for non-forested soils. In contrast to the acidic regimes of clusters a and b, these conditions may favor aggregation processes that are increasingly supported by biological activity and Ca-mediated organo-mineral interactions. As soil pH increases toward neutral conditions, Fe- and Al-mediated stabilization mechanisms become less dominant, whereas Ca-associated stabilization processes gain importance (Rowley et al., 2018; Wen et al., 2025). At the same time, microbial activity and SOM turnover generally increase under near-neutral conditions (Aciego Pietri and Brookes, 2008). Clarholm and Skyllberg (2013) described this pH range as a "window of opportunity" for SOM decomposition and nitrogen delivery, because Al-bridging is minimal while Ca-bridging remains moderate. Under these conditions, enhanced microbial processing together with moderate organo-mineral interactions may promote the formation of stable and biologically structured aggregates. Consequently, increasing SOC:clay ratios within this near-neutral regime may reflect a greater contribution of biologically processed organic matter to aggregate formation and stabilization, which is consistent with the observed improvement in VESS scores.

Together, these three clusters suggest that the visual expression of soil structure in temperate forest soils is not controlled by a single soil property, but rather emerges from the interaction between pH-dependent SOM stabilization mechanisms, mineral surface availability, and biologically mediated aggregation processes.

4.3 Aggregation regimes linking visual soil structure to hydraulic functioning

Similarly to the analysis of the factors controlling VESS, cluster analysis substantially improved the prediction of K_{sat} by identifying which soil properties interact with visual soil structure under specific pedochemical conditions. Whereas correlations between $\log_{10} K_{sat}$ and individual soil properties, including VESS and the SOC:clay ratio, ranged from weak to moderate (Fig. 5), much stronger relationships emerged when soils were separated into clusters defined by pH and texture (Fig. 6). Overall, these relationships suggest that aggregate characteristics assessed by VESS are linked to water flow through the soil, even though the method does not directly evaluate macropore connectivity. However, the strength and direction of the relationship between VESS and K_{sat} differed strongly among the identified regimes.

The clearest decoupling between visual structure and hydraulic functioning was observed in strongly acidic soils with pH values below 3.8 (cluster d). In contrast to the moderately acidic and near-neutral regimes, higher K_{sat} values in these soils coincided with poorer VESS scores. This inversion suggests that saturated flow in strongly acidic soils may be dominated by a limited number of hydraulically effective preferential pathways rather than by the overall aggregate structure captured visually by VESS.

One possible explanation is that strongly acidic conditions promote chemically dominated aggregation processes while simultaneously suppressing biological structure formation. Under low pH, Fe- and Al-associated stabilization mechanisms may enhance organo-mineral associations and produce dense aggregate structures through cation bridging and sorption processes (Lützow et al., 2006; Chen et al., 2014; Ye et al., 2022; Li et al., 2025), whereas reduced faunal activity may limit the formation

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of biologically structured pore systems (Geissen et al., 2007). In addition, acidic forest soils may promote fungal-dominated communities that enmesh SOM and aggregates and potentially increase water repellency (Rousk et al., 2010; Almeida et al., 2022), thereby shifting preferential flow pathways along root channels, fissures, cracks or isolated macropores at the inter-aggregate scale.

Such structures may contribute to saturated conductivity without substantially improving the aggregate-scale structural characteristics assessed by VESS. Thus, the observed decoupling in cluster d suggests that K_{sat} is controlled primarily by a few connected flow pathways rather than by the overall visual structural quality of the soil matrix.

As soil pH increased toward a moderately acidic regime (clusters a and b), better VESS scores became associated with higher K_{sat} values. In contrast to the strongly acidic soils of cluster d, this relationship suggests that visually observable aggregate characteristics increasingly correspond to hydraulically effective pore structures. This regime may represent a transitional state between chemically dominated aggregation and biologically mediated structure formation. As pH increases, microbial activity and mesofaunal abundance generally increase (Geissen et al., 2007; Aciego Pietri and Brookes, 2008), promoting the formation of biopores, burrows, and connected intra-aggregate pore networks (Brown et al., 2000; Porre et al., 2016). At the same time, mineral-associated stabilization mechanisms may remain sufficiently active to maintain aggregate stability. Consequently, structure-controlled pathways may increasingly develop both between and within aggregates, which is more directly reflected by the visual criteria underlying VESS.

Despite these similarities, clusters a and b differed in the soil properties controlling K_{sat}. In the coarse-textured soils of cluster a, silt content exerted a strong positive influence on conductivity. This relationship may reflect the limited capacity of sandy soils to form stable structural units. Even modest increases in the proportion of finer particles can provide additional material for aggregate formation, thereby promoting the development of a more organized pore system that facilitates water flow (Six et al., 2004). In contrast, pH became the dominant additional predictor of K_{sat} in the finer-textured soils of cluster b. This suggests that once sufficient fine material is available for stable aggregate formation, soil chemical conditions increasingly regulate the biological and physicochemical processes controlling pore connectivity. Under these conditions, increasing pH may promote greater faunal activity and root development, thereby enhancing the formation and connectivity of macropores through earthworm burrows and root channels.

The highest K_{sat} values were observed in soils with near-neutral pH and low sand contents (cluster c). Under these conditions, visually observable structural quality and hydraulic functioning appeared to co-develop, resulting in the relationship where better VESS scores coincided with higher conductivity. Compared to the acidic regimes, near-neutral conditions likely favor biologically mediated structure formation. Earthworm activity, root proliferation, and microbial turnover generally increase with increasing pH (Aciego Pietri and Brookes, 2008; Geissen et al., 2007; Clarholm and Skyllberg, 2013), thereby promoting the development of stable aggregate arrangements and connected macropore systems (Sharma et al., 2017). At the same time, Fe- and Al-mediated stabilization mechanisms become less dominant, whereas Ca-associated organo-mineral interactions gain importance (Lützow et al., 2006; Rowley et al., 2018). Under these conditions, aggregate-scale structural characteristics assessed visually by VESS may therefore more closely correspond to the pore architectures governing saturated water flow. These observations suggest that, under near-neutral conditions, temperate forest soils behave similarly to crop-

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land and grassland soils, where VESS has been shown to provide a reliable indicator of soil structural quality and hydraulic functioning (Moncada et al., 2014; Cornelis et al., 2019; Aji et al., 2021).

Together, these findings suggest that the relationship between visual soil structure and hydraulic functioning depends strongly on the dominant aggregation regime and the structural scale controlling water flow. Whereas strongly acidic soils appear to be governed primarily by isolated preferential pathways that are not fully captured by VESS, moderately acidic and near-neutral soils increasingly exhibit biologically structured and hydraulically connected pore systems that are reflected in the visual assessment.

5 Conclusion and Outlook

We investigated VESS in temperate forest soils with regard to its applicability, interpretation, and potential to predict structure-related soil properties, particularly K_{sat}. Our results suggest that forest soils follow distinct aggregation regimes along a pH gradient, which strongly influence both the visual expression of soil structure and its relationship to hydraulic functioning. Because all observations and measurements were conducted at sites without visible signs of compaction, the observed variation in structural quality is likely to reflect differences in soil properties and aggregation regimes rather than mechanical disturbance.

When these regimes were considered separately, clear relationships emerged between VESS and multiple structure-related soil properties across a broad range of textural and pH conditions. In moderately acidic and near-neutral soils, better VESS scores were consistently associated with higher K_{sat}. In contrast, VESS and K_{sat} became largely decoupled under strongly acidic conditions, which suggests that saturated flow in these soils is governed primarily by isolated preferential pathways rather than by the aggregate-scale structural characteristics captured visually by VESS.

To further evaluate the relevance of the four-cluster classification, other structure-related properties like bulk density and water content at 100 cm suction were analyzed (see Fig. S1 and Text S1 in supplementary material). While strong correlations could be expected in case of bulk density due to its dependency on organic carbon, the results for water content at 100 cm supports the validity of the proposed classification: applying the very same clustering approach as for K_{sat}, almost identical four clusters were formed (only 2 topsoil were in other clusters than for K_{sat}). Accordingly, strong correlations with VESS and selected basic soil properties emerged within the same four clusters: very acidic soils, moderately acidic coarse-textured soils, moderately acidic fine-textured soils, and neutral soils, which supports the validity of the proposed classification.

Together, these findings indicate that the interpretation of VESS in temperate forest soils depends strongly on the dominant aggregation regime and pedochemical environment. We therefore conclude that VESS represents a useful tool for assessing soil structural quality and functioning in temperate forest soils when interpreted in the context of pH and texture.

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Competing interests. The authors declare that they have no conflict of interest.

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