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SOC: clay ratio: A mechanistically-sound, universal soil health indicator across ecological zones and land use categories?

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A R T I C L E I N F O

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A B S T R A C T

The European Union has recently launched a proposal for a soil monitoring and resilience directive ("soil monitoring law", SML), defining the SOC: clay ratio as descriptor of the soil organic carbon (SOC) status, with a ratio of 1/13 separating "healthy" from "unhealthy" soils. Using data of the Lower Austrian soil database, this article explores the mechanistic foundation and applicability of the SOC: clay ratio in the ecologically diverse study region. We observe considerable variation of the SOC: clay ratio among agroecological regions because clay content and SOC are driven by different ecological variables, with clay content related to the texture of parent materials. After stratification by land use (cropland versus grassland), we built multiple regression models starting with an initial set of predictor variables including mean annual precipitation (MAP) and temperature (MAT), clay content, $CaCO_3$ equivalent, amorphous oxyhydroxides of Al (Al_o) and Fe (Fe_o), and pH to identify the main drivers of SOC and their relative importance. The final models explain between 23 and 77 % of the overall SOC variation, and reveal that SOC is primarily controlled by Al_o and the $CaCO_3$ equivalent across the entire study region and within most agroecological and soil units, with smaller contributions of clay content and MAP. The set of relevant SOC drivers and their relative importance vary with spatial scale (entire study region versus agroecological and soil units), the aridity index (defined as MAT: MAP) and the state of soil development, as reflected by soil pH. With some notable exceptions, Al_o is most important in more humid regions and acidic soils, whereas the relevance of $CaCO_3$ equivalent and clay content increases with pH and aridity.

The limited importance of clay content indicates that the SOC: clay ratio is a poor descriptor of soil health in the study region. Moreover, we could not confirm a meaningful functional relation between the SOC: clay ratio and the quality of soil structure derived from visual assessment. These findings challenge the universal use of the SOC: clay ratio as descriptor of soil health, and its threshold of 1/13 to distinguish the soil health status across different ecological zones. If SOC is not primarily driven by clay content, also the use of correction factors to the SOC: clay threshold as suggested by the SML is not appropriate.

To derive meaningful regional benchmarks of SOC, we suggest to employ multiple regression analysis with the main SOC drivers as input variables. The regression equation can be used to predict the SOC levels expected for the average management regime of the region at any given values of the relevant main soil and climate drivers. This approach can be further refined by scaling down to the soil unit level, and by developing relations for different, clearly defined categories of soil management, and their calibration to soil functional properties (e.g., air capacity, structure quality scores) in order to link the benchmarks to soil management, soil health and related ecosystem services.

1. Introduction

Soil health has been defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans", and is closely connected to the functional ability of soils to support not only food production and human health, but also multiple ecosystem services (Lehmann et al., 2020). Linking soil health to monitoring and soil management requires its quantification by meaningful indicators (descriptors) (Lehmann et al., 2020).

Because of its fundamental role in determining soil functions, soil

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organic carbon (SOC) is the most frequently used descriptor of soil health (Bünemann et al., 2018). Clay content has long been recognized as one of the main potential drivers of SOC accumulation in soil (Wiesmeier et al., 2019), an observation that is linked to SOC stabilization through complexation to clay-sized mineral surfaces (Dexter et al., 2008; Hassink, 1997; Feng et al., 2013). For selected French and Polish cropland and grassland soils, Dexter et al. (2008) showed that clay-complexed carbon (COC) is proportional to SOC in soils with small SOC levels (e.g., many cropland soils) because the clay fraction is not saturated. In contrast, COC is proportional to the clay content in soils with high SOC levels (e.g., many grassland soils) as the clay fraction is saturated. As a consequence, the specific volume (i.e., the reciprocal of bulk density) was found to be correlated with SOC in cropland soils (low SOC) but to clay content in soils beneath grassland (high SOC). Using regression analysis, Dexter et al. (2008) estimated that clay saturation by COC is obtained at a SOC: clay ratio of ~1/10. Their conclusion that soil structural properties are controlled by COC rather than SOC was challenged by Johannes et al. (2017a), using a dataset of Cambisols and Luvisols from a region in Western Switzerland. In contrast to Dexter et al. (2008), Johannes et al. (2017a) could not establish an optimum in the correlation between structural properties and a COC fraction of SOC proportional to the clay content. Note that apart from restricting the investigation to two similar soil groups they covered a wider range of SOC and clay content, and followed a standardised sampling and volume measurement protocol. The results of Johannes et al. (2017a) indicate that for soils without evidence of physical stress or structure degradation, an increase of SOC is related to a proportional increase of soil porosity independent of the proportion of SOC complexed by clay (i.e., COC). However, Johannes et al. (2017a) found a relation between the SOC: clay ratio and visually assessed soil structure quality scores (CoreVESS method) when considering the full range of soil structure quality. Using the slopes of linear regression lines between clay content and SOC for the predefined structure quality classes, the authors derived SOC: clay ratio thresholds to distinguish between the structure quality classes that are considered as "very good" (>1:8), "good" (1:8 to 1:10), "moderate" (1:10 to 1:13) and "degraded" (<1:13). Note that the regression lines represent the average SOC: clay ratio of each structure quality class, which implies that the thresholds should be interpreted in terms of likeliness rather than exact boundaries. The applicability of this approach was confirmed for soils from the same region with clay contents up to 515 g kg^{-1} by Johannes et al. (2023), and applied to various soil groups of England and Wales by Prout et al. (2021). Based on their results, Johannes et al. (2023) conclude that even in soils with high clay content, desired SOC: clay ratios of 1:10 can be reached by appropriate soil management.

The paper of Johannes et al. (2017a) and the subsequent application of the SOC: clay ratio to soils across England and Wales by Prout et al. (2021) have prompted the European Commission to define the SOC: clay ratio as key descriptor of soil health in the recently launched proposal for a European Soil Monitoring and Resilience Directive (or briefly, Soil Monitoring Law, SML; revision of the Council of the European Union, 2024). Moreover, even though it has been widely acknowledged by soil scientists that the inherent variability of soil characteristics in response to environmental factors (Drexler et al., 2022; Wiesmeier et al., 2019) makes it difficult to establish universal soil health benchmarks (Bünemann et al., 2018), the Council of the European Union (2024) has laid down a general threshold for the SOC: clay ratio of 1/13 to distinguish "healthy" and "unhealthy" soils across Europe. The SML proposal defines grassland soils as reference systems to establish "corrective factors to the ratio where specific soil types or climatic conditions justify it, taking into account the link to structural stability". However, this still implies that the variation of the SOC: clay ratio throughout Europe is primarily controlled by clay content and only modified by other factors, which requires investigation.

In response to the SML proposal, the applicability of the SOC: clay ratio and related threshold values across Europe have been questioned by Poeplau and Don (2023) and Rabot et al. (2024) using the German and French soil databases, respectively. Using the German soil inventory database, Poeplau and Don (2023) argue that the SOC: clay ratio is strongly biased as the proportion of soils classified as degraded by the SOC: clay threshold <1/13 increases unproportionally with clay content. However, in contrast to Johannes et al. (2017a), they did not exclude sandy soils, which explains a large proportion of the bias due to a strong increase of SOC: clay ratios at clay contents <100 g kg^{-1}. Similarly, Rabot et al. (2024) and Prout et al. (2021) report high SOC: clay ratios for sandy Podzols in France and England and Wales, respectively. Moreover, it has been shown that a large share of cropland soils in France and almost all Chernozems in Germany fall below the threshold of 1/13, which is likely reflecting other factors such as climate rather than the impact of management (Poeplau and Don, 2023; Rabot et al., 2024).

The studies showing that the SOC: clay ratio is linked to soil structural quality are based on the observation that clay content captures a major part of the variation of SOC, i.e., clay content can be considered as main driver (Dexter et al., 2008; Johannes et al., 2017a; Johannes et al., 2023; Prout et al., 2021). However, evidence accumulates that in various environmental settings clay content as a driver of SOC may be outperformed by other soil variables that are important for sorption and stabilization of organic matter. In particular, amorphous oxyhydroxides of aluminium (Al_o) and the Ca status of soils (exchangeable Ca, $CaCO_3$) have been shown to be superior to clay content as predictors of SOC at continental (Rasmussen et al., 2018) to regional (Bösch et al., 2023; Wenzel et al., 2023) and local (Fukumasu et al., 2021) scale. Based on their findings for European soils, Rasmussen et al., 2018 derived a conceptual model relating the relative importance of SOC drivers to pedogenesis. By scaling the drivers to pH as indicator of the general state of the soil system, they propose Ca, and to a lesser extent clay content as major controls of SOC in water-limited alkaline soils, and Fe and Al complexes and oxyhydroxides in acidic soils with better water availability (Rasmussen et al., 2018). These findings challenge the general applicability of the SOC: clay ratio as descriptor of SOC status and soil health.

Here we aim at testing the applicability of the SOC: clay ratio concept and related thresholds by using different datasets from an ecologically diverse region in Central Europe, Lower Austria. In particular, we address the following research questions:

- Is clay content a relevant denominator of SOC levels in the soils of the study region, or are SOC levels better related to other environmental variables? How do the (combinations of) main drivers vary among ecological and soil units of the study region?
- Can the relation of the SOC: clay ratio and structure quality indicators be extended to our study region, including soils formed in less humid conditions?
- To what extent does the SOC: clay ratio vary across ecological conditions, and how is this variation related to the variability of the input variables clay content, SOC and their drivers?
- Which alternative approaches could be established to assess soil health in relation to the SOC status?

We hypothesize that.

(1) clay content and SOC in the study region are driven by different environmental variables, thus introducing artifacts when assessing the SOC status of soil across highly variable ecological conditions;
(2) other soil and climate variables may be more important drivers of SOC in the study region, and if this applies, a functional relation between the SOC: clay ratio and soil structural properties cannot be established;
(3) the relation between SOC and its main drivers can be much improved if investigated within ecologically uniform regions

and/or soil groups thus supporting the development of meaningful baselines and criteria for soil health and related monitoring.

2. Materials and methods

2.1. Ecological characterisation of the study region

The study region, Lower Austria, is located in Central Europe and represents one of the NUTS 2 units of the European Union. The region covers an area of 19,180 km^2, of which 6,768 km^2 is cultivated for crop production, and 1,752 km^2 for permanent grassland including pastures (Statistik Austria, 2020; Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft, 2023).

Climatic conditions in the study area show large variation. Mean annual precipitation (MAP) ranges between ~470 and ~2100 mm, mean annual temperatures (MAT) between ~0.7 and ~10 °C (Strauss et al., 2013).

Lower Austria comprises five main agroecological regions (MAR), which are further divided in 22 small agroecological regions (SAR) with relatively uniform environmental conditions in terms of climate, geology and soil cover for agricultural production (Figure S1). The distribution of soil groups according to IUSS Working Group WRB (2022) among MARs and land use categories is shown in Table S2, the share of soil groups within each MAR in Table 1, indicating substantial variation of the soil cover among the agroecological regions, and preferential association of certain soil groups with either cropland or grassland. Overall, the study region is dominated by Cambisols, Phaeozems and Chernozems, with smaller shares of Regosols, Stagnosols, Gleysols, Fluvisols and Luvisols. Cambisols and Cambic Phaeozems are more important in less aridic regions (compare aridity index in Table 2), especially beneath grassland, whereas Chernozems and closely related Calcaric Chernic Phaeozems dominate the dryer lowland regions in the eastern part of Lower Austria (Tables 1 and 2).

Table 2 compiles the mean values of important characteristics of the main and small agroecological regions, derived from the point data available in the Lower Austrian soil database (for details see Section 2.2). Among the subregions, elevation varies between 152 and 774 m, mean annual precipitation (MAP) between 485 and 1153 L m^{-2}, and mean annual temperature (MAT) between 6.07 and 9.77 °C. The aridity index, defined as the ratio of MAT: MAP, ranges from 0.007 to 0.019, indicating considerable variation of the climatic water balance. The clay content of the topsoils (0–20 cm) ranges from 108 to 312 g kg^{-1}, the carbonate equivalent from <2 to 296 g kg^{-1}. The concentration of amorphous oxyhydroxides of Al (Al$_o$) and Fe (Fe$_o$) range from 629 to 2230, and 828 to 4270 mg kg^{-1}, respectively, soil pH from 4.9 to 7.5. Soil organic carbon (SOC) concentrations vary between 13.7 and 37.9 g kg^{-1}, the ratio of resistant oxidizable carbon (ROC) to SOC between 0.053 and 0.238, the ratio of SOC: clay between 0.064 and 0.338. Overall, this reflects a considerable variation of climatic and soil characteristics among the MARs of Lower Austria. Note that the SOC: clay ratios are particularly small in SARs characterised by high aridity (Table 2). These lowland regions are dominated by Chernozems and Chernic Phaeozems characterized by deep reaching accumulation of soil organic matter (SOM).

Fig. 1 shows the share of land use in the SARs and MARs. MAR 2 is dominated by grasslands (~80 %); relevant shares of grasslands on the total agricultural land are also observed in the main agroecological regions 3 (~40 %), 4 and 6 (~30 %) whereas MAR 8 is almost completely covered by cropland. The cropland areas are generally dominated by cereals (~40 % in MARs 2, 3 and 6; ~60 % in MARs 4 and 8). The share of maize does not exceed 10 % of the cropland area, except in MAR 6 (~30 %). The proportion of root crops varies between >1 and ~10 %, with the largest share observed in MAR 8a. Nitrogen fixing crops cover between ~5 and ~15 % of the cropland, with the largest share observed in the MAR 3, followed by MAR 2 and MAR 4. The remaining cropland (~15 to 20 %) is primarily made up by fodder grass (MARs 2 and 3) or other crops (MARs 8a and 8b), or a similar share of both (MARs 4 and 6). The variation of land use category shares among SARs within each MAR is relatively small (Fig. 1), except MAR 2, where the share of grassland varies considerably between ~60 (SAR 209) and almost 100 % (SAR 206). Within MAR 8, a notable variation of the coverage of the total agricultural area by permanent crops (mainly viticulture) is observed, with the largest shares in SAR 801 (~55 %), SAR 802 and SAR 810 (~10 %).

2.2. Description of datasets

2.2.1. The Lower Austrian soil monitoring system

The soil monitoring programme of Lower Austria was initiated in 1990 (Amt der Niederösterreichischen Landesregierung, 1994). The initial sampling was conducted between May 1991 and May 1992 at the nodes of a regular, 3.9 x 3.9 km grid system, with additional sampling sites located in the centres of the grid cells. At the regular grid nodes, 576 cropland and 149 grassland soils were described in the field, and soil was sampled from the layers 0–20, 20–40, 40–50, and 50–70 cm. Given the more pronounced pedogenetic differentiation of grassland topsoils, 0–5, 5–10, and 10–20 cm increments were sampled and analysed separately. Additional topsoil samples (0–20 cm) were collected from centres of each grid cell, resulting in 575 cropland and 149 grassland sites. For these sites, profile descriptions are not available. More details about sampling procedures can be obtained from Wenzel

Table 1
Share of soil groups (IUSS Working Group WRB, 2022) in Lower Austria and within each main agroecological region and their land use categories. Data is retrieved from the Lower Austrian database. Shares >10 % are printed in blue.

Main agroecological region	Land use category	Total number of soils	Share of soil groups (WRB, 2022) on agroecological main regions beneath cropland (%)																	
			Cambisol / Cambic Phaeozem				Chernozem & Calcaric Phaeozem	(Calcaric) Fluvisol	Gleysol		(Eutric) Luvisol	Phaeozem (Calcaric)		Regosol				Eutric Regosol & Phaeozem	Eutric Stagnosol	Other soils
			Calcaric		Eutric				Calcaric	Eutric		Relictigleyic	Solimovic	Calcaric		Eutric				
				Leptic		Leptic									"eroded"	(incl. "eroded")	Relictistagnic			
Lower Austria	All	855	7.4	2.3	7.3	21.1	23.4	1.6	1.3	2.3	1.2	7.1	6.1	2.3	5.8	0.7	2.5	1.6	5.3	0.7
	Cropland	749	8.0	1.2	7.2	18.3	26.4	1.6	1.3	1.5	1.3	8.1	6.9	2.3	6.7	0.4	2.8	1.9	3.6	0.4
	Grassland	106	2.8	10.4	7.5	40.6	1.9	1.9	0.9	8.5				2.8		2.8			17.0	2.8
2 Voralpen	All	75	12.0	16.0	8.0	30.7	1.3	5.3		2.7				6.7		2.7			13.3	1.3
	Cropland	30	23.3	10.0	13.3	23.3	3.3	6.7						13.3					6.7	
	Grassland	45	4.4	20.0	4.4	35.6		4.4		4.4				2.2		4.4			17.8	2.2
3 Alpenostrand	All	53	1.9		17.0	77.4		1.9						1.9						
	Cropland	41	2.4		17.1	75.6		2.4						2.4						
	Grassland	12			16.7	83.3		0.0												
4 Waldviertel	All	165	3.6	0.6	4.8	63.6		0.6		7.9	1.8			0.6		1.8	10.3		3.6	0.6
	Cropland	145	4.1	0.7	5.5	64.8		0.7		4.1	2.1			0.7		1.4	11.7		3.4	0.7
	Grassland	20				55.0				35.0						5.0			5.0	
6 Alpenvorland	All	98	13.3	3.1	27.6	6.1	4.1		2.0	5.1	4.1	2.0		2.0					28.6	2.0
	Cropland	75	17.3	2.7	30.7	1.3	4.0		2.7	6.7	5.3	2.7		1.3					25.3	
	Grassland	23	0.0	4.3	17.4	21.7	4.3							4.3					39.1	8.7
8a Nordöstliches Flach- und Hügelland (north)	All	337	8.0		3.3	1.5	40.4	2.1	1.2		0.9	6.8	15.1	0.6	14.8	0.3	1.2	3.3	0.3	0.3
	Cropland	335	7.8		3.3	1.2	40.6	2.1	1.2		0.9	6.9	15.2	0.6	14.9	0.3	1.2	3.3	0.3	0.3
	Grassland	2	50.0			50.0														
8b Nordöstliches Flach- und Hügelland (south)	All	127	5.5	3.1	0.8		46.5	0.8	3.9			28.3	0.8	7.1				2.4		0.8
	Cropland	123	5.7	2.4	0.8		47.2	0.8	3.3			29.3	0.8	6.5				2.4		0.8
	Grassland	4		25.0			25.0		25.0					25.0						

Table 2
Geographic, climatic and soil characteristics of the main (MAR) and small (SAR) agroecological regions of Lower Austria. Data is retrieved from the Lower Austrian database (dataset 1) as mean values of observations at the cropland and grassland sites within each region. For variability measures (standard deviations) see Table S3.

Main region (MAR)	SAR	Obser-vations	Elevation	MAP [a]	MAT [b]	Aridity	Sand	Silt	Clay	$CaCO_3$ equivalent	Al_o	Fe_o	pH	SOC	C:N	ROC:	SOC:
			m	$L\ m^{-2}$	°C	index [c]			$g\ kg^{-1}$		$mg\ kg^{-1}$			$g\ kg^{-1}$		SOC [d]	clay
2 Voralpen	All	74	497	972	7.65	0.009	234	549	217	96	1052	2783	6.28	33.7	10.7	0.099	0.181
	206	32	585	1153	7.18	0.007	177	578	245	102	1269	3240	6.20	37.9	11.0	0.089	0.174
	207	19	480	928	7.66	0.009	323	493	185	39	893	2670	5.88	30.6	10.3	0.078	0.177
	208	10	353	746	8.46	0.012	156	596	248	42	1147	3120	6.33	32.1	10.9	0.107	0.128
	209	13	419	766	8.16	0.011	306	522	172	206	675	1564	7.04	29.0	10.6	0.146	0.244
3 Alpenostrand	307	53	620	827	7.59	0.009	420	468	112	8	1310	2974	5.50	25.1	10.1	0.066	0.257
4 Waldviertel	All	165	596	678	6.85	0.010	478	397	127	7	1438	3496	5.37	23.3	12.0	0.062	0.220
	403	44	774	759	6.07	0.008	538	353	108	6	2225	4267	5.22	30.5	13.5	0.053	0.338
	404	39	579	665	6.73	0.010	563	328	119	2	1592	3546	4.90	26.2	13.8	0.056	0.225
	405	51	532	603	7.09	0.012	392	462	146	5	880	3359	5.56	17.7	10.7	0.064	0.146
	406	31	472	705	7.74	0.011	429	441	130	17	1045	2562	5.87	18.8	9.9	0.080	0.166
6 Alpenvorland	All	98	323	828	8.60	0.011	200	587	213	29	816	2864	6.23	19.9	9.6	0.090	0.104
	610	45	346	931	8.47	0.009	212	599	190	16	862	3141	6.00	20.2	9.3	0.076	0.121
	611	53	304	741	8.72	0.012	191	577	232	41	776	2629	6.43	19.6	9.9	0.101	0.091
8 Nordöstliches Flach- und Hügelland	All	465	237	549	9.21	0.017	245	524	231	124	839	1021	7.28	18.6	10.7	0.192	0.095
	801	3	418	567	8.11	0.014	473	323	203	34	629	1430	6.30	16.3	15.7	0.117	0.104
	802	44	276	513	8.91	0.017	217	542	241	82	803	867	7.37	14.7	11.8	0.197	0.068
	803	34	419	533	7.96	0.015	216	559	225	13	757	1801	6.62	13.7	9.5	0.102	0.071
	804	31	213	598	9.21	0.015	225	526	248	96	849	1346	7.25	16.3	9.9	0.179	0.069
	805	90	250	537	9.10	0.017	179	583	238	122	760	903	7.39	14.5	11.0	0.218	0.064
	806	25	202	485	9.31	0.019	387	363	250	35	698	1102	7.18	15.9	9.5	0.167	0.066
	807	84	207	519	9.29	0.018	210	564	227	80	783	832	7.24	15.1	10.4	0.198	0.069
	808	27	152	560	9.77	0.017	337	468	194	145	914	828	7.28	16.7	11.4	0.238	0.091
	809	81	183	571	9.73	0.017	253	509	237	182	1024	1080	7.41	26.5	10.9	0.196	0.119
	810	14	244	613	9.34	0.015	257	431	312	267	866	913	7.37	26.0	10.9	0.193	0.094
	811	32	274	628	9.23	0.015	367	462	171	296	926	882	7.50	32.8	10.2	0.183	0.299

[a] Mean annual precipitation (mean of all observations).
[b] Mean annual temperature (mean of all observations).
[c] Aridity index defined as ratio between MAT: MAP.
[d] Ratio between resistant oxidizable carbon (ROC) and soil organic carbon (SOC).

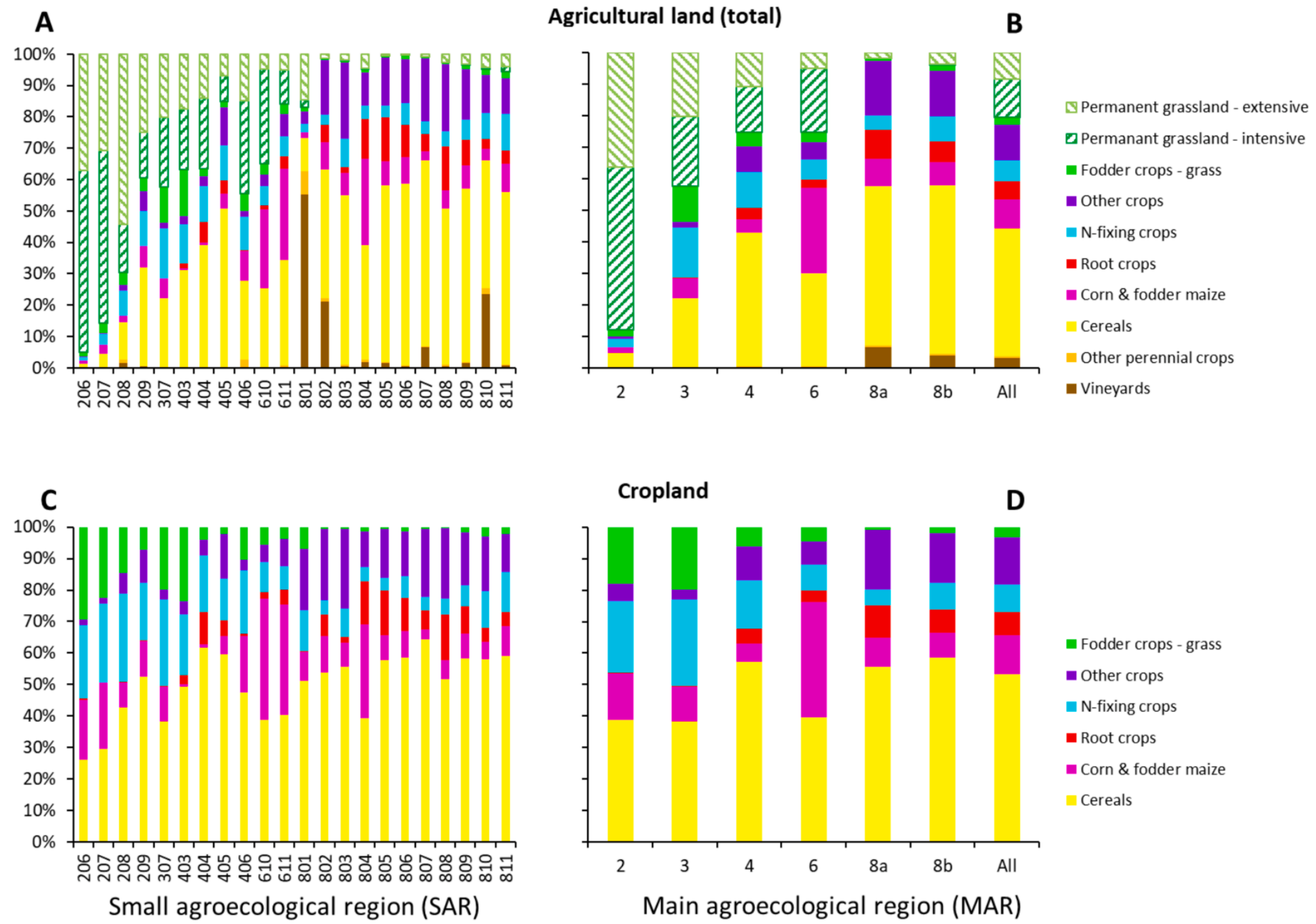

Fig. 1. Share of land use categories within small (panels A, C) and main (panels B, D) agroecological regions on total agricultural land (panels A, B) and cropland (C, D) in Lower Austria in 2010. The label "All" refers to the entire study region. MAR 8a comprises the SARs 801 to 808, MAR 8b the SARS 909 to 811. Data). Source: Statistics Austria (https://www.statistik.at/en/databases/statcube-statistical-database)

et al. (2022).

2.2.2. Dataset 1

Dataset 1 includes data of 750 cropland and 105 grassland topsoils (0 – 20 cm) covering all agroecological regions. It includes sampling sites from the regular nodes and the centres of the grid system. Soil analytical data relevant for this article include soil texture (sand, silt and clay content), total nitrogen, and soil pH. For the purpose of this article, only topsoil data (0–20 cm) were retrieved from the database. In addition, we measured archived samples for soil organic carbon (SOC), resistant oxidizable carbon (ROC) and total inorganic carbon (TIC) by dry combustion, and amorphous oxyhydroxides of Al (Al_o) and Fe (Fe_o). However, description of soil structure is not available for part of these soils.

2.2.3. Dataset 2

Dataset 2 is a subset of dataset 1 from regular grid nodes for which detailed soil profile descriptions, including soil structure assessments according to Blum et al. (1996) are available. It includes 485 cropland topsoils (0–20 cm) from all agroecological regions.

2.3. Soil analysis

Prior to analysis, soils of all four datasets were air-dried and passed through a 2-mm screen.

Sand (2000–63 μm), silt (63–2 μm) and clay (<2 μm) contents were measured using a combined sieving and sedimentation method after dispersion with sodium pyrophosphate and, for samples with SOM > 50 g kg^{-1}, pretreatment with H_2O_2 (ÖNORM L 1061, 1988). Total nitrogen was measured using the Kjeldahl method (ÖNORM L 1082, 1989). Soil pH was measured in a 0.01 M $CaCl_2$ suspension after equilibrating for 2 h at a solution-soil ratio of 2.5 mL^{-1} g (ÖNORM L 1083, 1989).

Using archived samples, we measured SOC, ROC and TIC concentrations by sequential determination of the carbon concentrations at 400, 600 and 900 °C using a soli TOC cube® carbon analyser (Elementar, Langenselbold, Germany; Wenzel et al., 2023). The sum of the fractions up to 600 °C represents SOC, the fraction released between 400 and 600 °C ROC, and the one between 600 and 900 °C TIC. Using the stochiometric ratio between C and $CaCO_3$, TIC was converted to the $CaCO_3$ equivalent.

The amorphous oxyhydroxides of Al and Fe (Al_o and Fe_o) were measured by a modified Loeppert and Inskeep (1996) procedure (Wenzel et al., 2023).

2.4. Soil structure quality assessment

We assessed structural quality indices using the Visual Evaluation of Soil Structure (VESS) score method (Ball et al., 2007; Johannes et al., 2017b). The method requires information on structure shape, size, visual porosity and root abundance and distribution. We adapted the method to the data available in the Lower Austrian database (dataset 2) by first assigning individual scores for structure size and shape, visual porosity, and root abundance according to the requirements shown in

Table S1. Finally, the VESS score was calculated as the arithmetic mean of the individual scores and rounded to integers, yielding the VESS scores 1 to 5. According to Johannes et al. (2017a), we rated the quality of soil structure as very good (VESS < 2), good (2 ≤ VESS < 3), moderate (3 ≤ VESS < 4), and degraded (≥4).

2.5. Calculations and statistical analysis

The SOC: clay ratio was calculated by entering both variables in g kg^{-1}. Similarly, we calculated SOC: Al_o ratios, with the input variables SOC (g kg^{-1}) and Al_o (mg kg^{-1}). An aridity index was calculated as the ratio between MAT (°C) and MAP (L m^{-2}).

The percentage of fine-textured parent materials within each agro-ecological subregion was obtained by allocating the information available for each monitoring site (dataset 1) to the two classes "fine textured" or "coarse textured". Fine-textured parent materials include solimovic materials, fluviatile sediments, pre-weathered (relictic) materials, loess and other fine quaternary and tertiary sediments, molasse, slope sediments of the Flysch zone, and the weathering residuals on carbonate rocks. Coarse-textured parent materials include silicious igneous and metamorphic rocks (e.g., granite, gneiss, granodiorite) and sandstones.

Using the regression function of EXCEL Version 16.0, we performed single and multiple regression and correlation analysis to explore linear relationships between variables after checking the prerequisites (Gauss–Markov assumptions) using variable scatter plots, standardised residual plots and Q-Q plots.

To identify drivers of SOC concentrations, using dataset 1, we built multiple regression models by starting with a set of independent climatic (MAP, MAT) and soil variables (clay content, $CaCO_3$ equivalent, Al_o, Fe_o, pH) expected to explain a considerable part of the variation of SOC concentrations in Lower Austrian topsoils (0–20 cm). For obtaining the final model, variables were sequentially removed if they did not contribute explanatory value. The models were run for the entire study

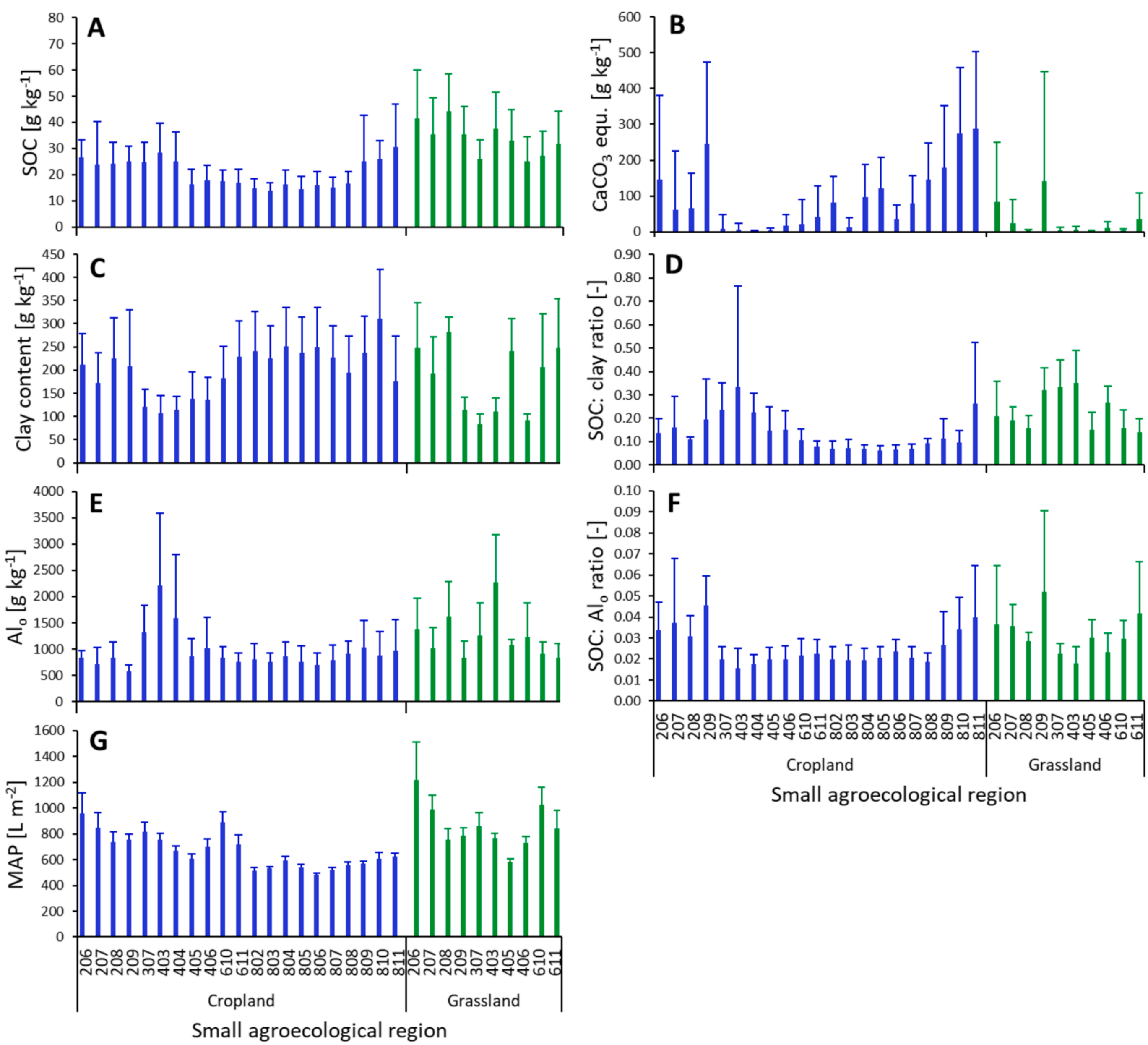

Fig. 2. Variation of SOC concentrations (panel A), selected potential drivers (panels B, C, E and G), and the ratios of SOC: clay (panel D) and SOC: Al_o (panel F) across the SARs in topsoils (0–20 cm, dataset 1) beneath cropland and grassland of Lower Austria (arithmetic means ± standard deviations). For grassland soils, data is only shown for SARs with relevant share of grassland sites.

region (Lower Austria), within the main agroecological regions (MARs) and their major soil units (WRB soil groups). The relative importance of each predictor in the linear regression models was calculated according to the Lindeman, Merenda and Gold (LMG) method implemented in the R-package "relaimpo" (Groemping, 2006; R Core Team, 2023). The sum of all individual R^2s equals to the model's R^2.

As clay content in topsoils was expected to be primarily controlled by the type of parent material and, due to weathering, by climatic factors, multiple regression models were run with arithmetic means of clay content in the agroecological subregions as dependent variable; the percentage of fine-textured parent materials, and the arithmetic means of MAP and MAT of each region were used as independent variables for the initial model runs. For obtaining the final model, variables were sequentially removed if they did not contribute to explanatory value. Similarly, we employed multiple regression analysis to explore relations between potential SOC drivers and the mean values of SOC of the major WRB soil groups in the study region.

To obtain the confidence intervals (95 % probability) of single regression lines, we used own computations in EXCEL Version 16.0.

All figures and tables were prepared in EXCEL Version 16.0.

3. Results

3.1. SOC and potential drivers in the agroecological regions of the study area

3.1.1. Variation among agroecological regions

The variation of the arithmetic means of SOC, its potential drivers and the ratios of SOC to clay content and to Al_o among the SARs of Lower Austria (Figure S1) are shown separately for cropland and grassland topsoils (0 – 20 cm) in Fig. 2.

The SOC concentrations (Fig. 2, panel A) are particularly small beneath croplands of the SARs of MAR 8 that are located north of the river Danube (MAR 8a, comprising the SARs 802 to 808), whereas the clay contents (Fig. 2, panel C) are in the upper range observed for the entire study region, resulting in particularly small SOC: clay ratios (Fig. 2, panel D). Similar conditions are observed for the cropland soils in SAR 611, a lowland region directly neighbouring MAR 8 (Figure S1). Cropland soils in the SARs of MAR 8 located south of the Danube (MAR 8b, SARS 809 – 811) show generally larger SOC: clay ratios, owing to higher SOC concentrations, and in the case of subregion 811, also related to a rather low clay content. Relatively large SOC concentrations are also observed in the cropland soils across the pre-alpine (mean elevation 353–585 m; Table 2) MAR 2. Along with high clay contents varying around 200 g kg^{-1}, this translates to mean SOC: clay ratios ranging between ~0.1 to ~0.2 (Fig. 2). The largest SOC: clay ratios (~0.25–0.35) are observed in the MARs 3 and 4 that are characterised by particularly low clay contents. The variation of the SOC: clay ratio within MAR 4 is mainly driven by differential clay contents (Fig. 2). The majority of the SARs (802 to 807) within MAR 8 displays mean values of the SOC: clay ratio close to the threshold 1/13 deemed to separate "moderate" from "degraded" soil structure quality according to Johannes et al. (2017a).

SOC levels and related SOC: clay ratios in grassland topsoils (0–20 cm) are only available for SARs with relevant share of grassland sites. As expected, the mean SOC concentrations are generally larger than in the cropland soils of the same region, also resulting in higher SOC: clay ratios (Fig. 2), with mean values generally exceeding the SOC: clay threshold 1/8 deemed to indicate very good structural quality according to Johannes et al. (2017a).

The variation of other potential drivers of SOC among SARs is shown in the panels B ($CaCO_3$ equivalent), E (Al_o) and F (MAP) of Fig. 2. The mean values of the $CaCO_3$ equivalents in cropland topsoils vary considerably between almost zero and ~300 g kg^{-1}, those beneath grassland are generally smaller than in the corresponding SAR beneath cropland (Fig. 2). In most SARs, the mean values of Al_o beneath croplands vary between ~600 and 1000 mg kg^{-1}, except in regions with coincidence of particularly low carbonate equivalent and clay content (i. e., in SARs 307, 403, and 404) where Al_o ranges between ~1250 and ~2000 mg kg^{-1}. Beneath grassland, we observe a tendency of larger Al_o concentrations as compared to the corresponding cropland soils (Fig. 2). The mean Al_o: SOC ratios beneath croplands range from ~0.06 to ~0.33, the variation seems to be related to that of the $CaCO_3$ equivalent. Beneath grasslands, the SOC: Al_o ratios are in most SARs larger than in cropland soils, however, the difference is less pronounced than in the case of the SOC: clay ratio (Fig. 2). In the lowlands of MAR 8, MAP received by cropland soils varies between ~500 and ~600 L m^{-2}, in all other regions between ~600 and 1000 L m^{-2}; we observe a tendency towards higher MAP associated with the grassland soils (Fig. 2).

3.1.2. Drivers of SOC and clay content in the study area and within agroecological regions

The clay content of the topsoils (0–20 cm) varies among the SARs by a factor of 2.7 between 108 and 312 g kg^{-1} (Table 2, Fig. 2). Panel A of Fig. 3 depicts the relation between the percentage of sites with fine-textured parent materials within each SAR and the corresponding arithmetic means of the clay content in topsoils. The type of parent material explains ~63 % (adjusted r^2) of the clay content variation, indicating its dominant role in determining the textural composition of Lower Austrian topsoils. Including potential climatic drivers of soil clay formation (MAP and MAT and MAT: MAP ratio, respectively) in a multiple linear regression model did not add explanatory value to the regression model.

In contrast to clay content, the arithmetic means of the SOC concentrations in topsoils of the SARs are not related to the share of fine-textured parent material (Fig. 3, panel B). Moreover, there is no relation between mean SOC concentrations and mean clay contents of the SARs (Fig. 3, panel C).

The results of multiple regression models explaining SOC levels in topsoils by climatic and soil drivers are compiled in Table 3 (cropland soils) and Table 4 (grassland soils). Fig. 4 shows the relative importance of the relevant predictors for each of the models. The relative importance refers to the individual contribution of each predictor to the overall R^2 of the models.

The model explains ~55 % of the total variation of SOC concentrations in cropland topsoils of the entire study region (Table 3). Accordingly, SOC concentrations are primarily predicted by Al_o (~37 % of the overall variation) followed by $CaCO_3$ equivalent (~11 %), with smaller contributions of MAP (~6 %) and clay content (<1 %). The regression models for the individual MARs reveal that Al_o is consistently among the main drivers of SOC, explaining between ~6 and 66 % of the total SOC variation in cropland topsoils (Table 3, Fig. 4). However, the MARs 2 and 6 notably deviate from the overall observation that Al_o is the main driver as in MAR 2 SOC is primarily explained by the $CaCO_3$ equivalent (~28 %), and in MAR 6 by the clay content (~14 %). Moreover, the importance of other drivers varies among the MARs (Fig. 4), with relevant contribution of clay content only in MAR 8a. Interestingly, the explanatory value (adjusted R^2) of the regression models for individual MARs exceeds that of the entire region model where Al_o is the main SOC driver, whereas is clearly smaller in MAR 2 and MAR 6 (Table 3).

Table 3 also shows regression models for the most abundant WRB soil groups (compare Table 1) beneath cropland. Compared to the respective geographical units, the explanatory value is moderately improved for Eutric Leptic Cambisols in the entire study region, and for Chernozems/Calcaric (Chernic) Phaeozems in the MARs 8a and 8b. For the other soil groups, either marginal change or a lower explanatory value of the model is observed (Table 3). The soil group models also deviate partly from the full geographic models in terms of the composition of the SOC driver set, and the relative importance of the drivers. Moreover, climatic drivers (MAP) are only important at the scale of the entire study region, except MAR 6, which is characterized by relatively large variation of MAP (compare Table 2).

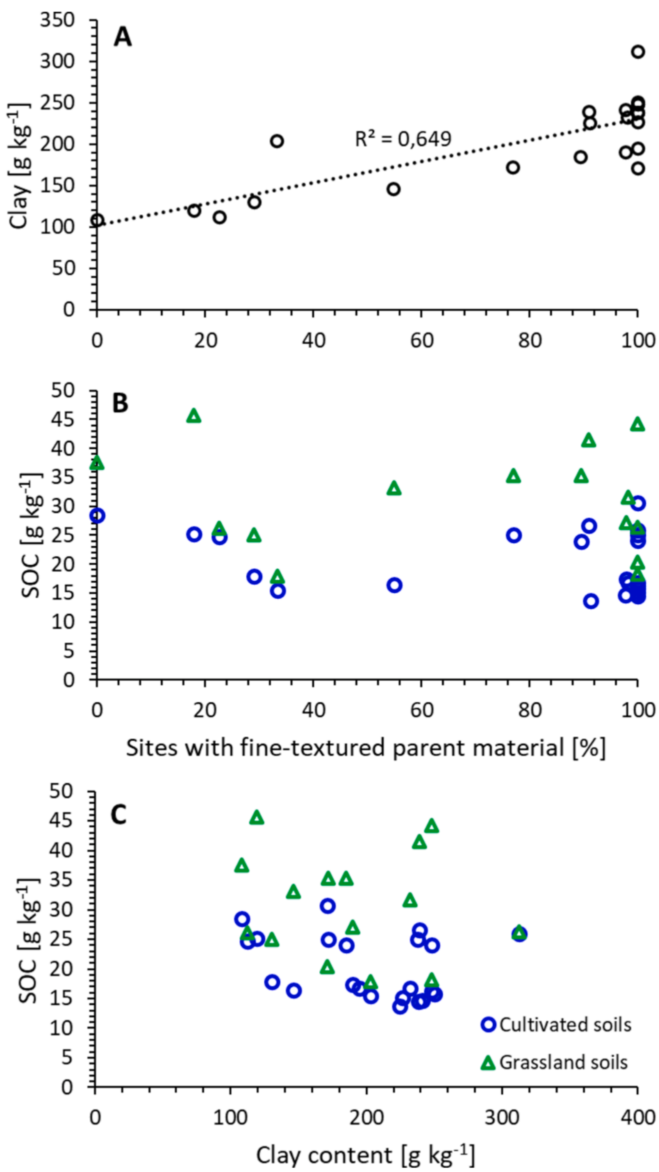

Fig. 3. Relations between the arithmetic means of clay contents (panel A) or SOC concentrations (panel B) in topsoils (0–20 cm), and the share of sites with fine-textured parent materials in the SARs of Lower Austria (Dataset 1). As the regression model for the effect of the percentage of fine-textured parent materials on clay content is significant (critical F value of ANOVA 6.07 10^{-6}; adjusted $r^2 = 0.6315$, standard error 32.6, n = 22), the regression line is shown. Panel C shows the relation between clay and SOC.

For grassland soils across the entire study region, the model explains ~37 % of the overall SOC variation (Table 4), with $CaCO_3$ as main driver contributing ~22 %, followed by Al_o (~10 %) and clay content (~7 %) (Fig. 4). Multiple regression models were also run for MARs with sufficient number of observations. Al_o is identified as main SOC driver in the MARs 2 (~26 %), 3 (~77 %) and 4 (~23 %), whereas in MAR 6 SOC is best predicted by clay content (~42 %), with the $CaCO_3$ equivalent adding explanatory value in MAR 2 (~15 %) (Table 4, Fig. 4). SOC in Cambisols (including Calcaric and Eutric qualifiers) beneath grasslands across the study region is primarily controlled by the $CaCO_3$ equivalent (26 %), followed by Al_o (~22 %) and clay content (~9 %). Similarly, SOC in the Cambisols of MAR 2 is primarily controlled by the $CaCO_3$ equivalent (36 %), followed by Al_o (24 %). The explanatory value of the grassland soil models is clearly improved by downscaling from the level of the entire study region or MARs to the soil group level (Table 4; Fig. 4).

Fig. 5 displays linear regressions of SOC on Al_o in cropland topsoils for two selected regions (MARs 3 and 4), where Al_o is the only relevant driver of SOC according to the multiple regression models summarized in Table 3. The figure exemplifies the pronounced differences in the range of Al_o and SOC among and within regions. The 95 % confidence intervals provide evidence for relatively accurate prediction of the position of the true regression line based on the available sample data.

3.2. SOC and potential drivers according to WRB soil groups

3.2.1. Variation among WRB soil groups

The variation of SOC, its drivers and of the ratios of SOC to clay content and Al_o among relevant soil groups in the study region (compare Tables 1 and 2) are depicted in Fig. 6.

The concentration of SOC varies among soil groups by a factor of 2.9 beneath cropland, and a factor of 1.9 beneath grassland, the corresponding factors for clay content are 2.6 and 2.1. The resulting SOC: clay ratios vary by a factor of 4.3 beneath cropland and 1.7 in grassland soils (Fig. 6). Al_o varies among soil groups by a factor of 2.8 (cropland) and 1.2 (grassland), the corresponding factors for the SOC: Al_o ratio are 2.2 and 1.7, respectively. The $CaCO_3$ equivalents range up to ~250 g kg^{-1}, and as observed for the SARs, soil groups with high $CaCO_3$ equivalents (Calcaric Cambisols, Calcaric Regosols) show larger SOC: Al_o ratios than their non-calcareous equivalents with Eutric sub-qualifier. The mean values of MAP for each of the soil groups reflect their association with certain climatic conditions. Low MAP (<600 L m^{-2}) is observed for soil groups known to develop in rather dry conditions, including Chernozems/Calcaric Phaeozems and their associated eroded ("eroded" Calcaric Phaeozems) and solimovic (Calcaric Phaeozems (solimovic)) derivates. In contrast, Cambisols and Stagnosols are related to MAP > 640 L m^{-2} (Fig. 6).

Beneath grasslands, the number of observations only allows for reporting the data of three soil groups (Fig. 6). SOC concentrations in Cambisols are larger in those with Calcaric as compared to Eutric qualifiers. Whereas the variation of Al_o among the soil groups is small, clay content differs considerably between Calcaric and Eutric Cambisols. This results in SOC: clay ratios that are inversely related to SOC, whereas SOC: Al_o ratios appear to reflect the SOC status of the soils (Fig. 6).

3.2.2. Drivers of SOC in relation to WRB soil groups

To explain the variability of the SOC status among the soil groups, we built multiple regression models using an initial set of climatic (MAT, MAP) and soil characteristics (clay content, $CaCO_3$ equivalent, Al_o, pH) as explanatory variables. Variables with no relevant contribution to the models overall explanatory value (adjusted r^2) were removed from the final model reported in Table S3. Accordingly, Al_o is identified as the main driver explaining the variation of SOC among WRB soil groups, with relevant contribution of the $CaCO_3$ equivalent. Both variables show a positive relation to SOC (Table S3). In contrast, the regression coefficients of the climatic variables and clay content are not significant ($p < 0.05$), and do not contribute to explain the variation of the SOC status among WRB soil groups. The single regressions depicted in Fig. 7 further illustrate the contributions of Al_o (panel A) and the $CaCO_3$ equivalent (panel B) to explain the SOC status of the WRB soil groups in the study region. Moreover, Al_o and the $CaCO_3$ equivalent vary independently (Fig. 7, panel C), which allows to investigate the effect of the $CaCO_3$ equivalent on the variation of the SOC: Al_o ratio (Fig. 7, panel D). This shows that ~80 % of the differences of the SOC: Al_o ratio among soil groups is explained by the $CaCO_3$ equivalent (Table S3, Fig. 6), indicating an additive effect of Al_o and Ca as drivers of SOC.

3.3. Relations between the SOC: clay ratio and structure quality

Panel A of Fig. 8 depicts the relation between SOC and clay content in all cropland topsoils across Lower Austria (dataset 2) for four different soil structure quality classes (Johannes et al., 2017a) assessed by the

Table 3
Multiple regression models explaining soil organic carbon concentrations (SOC) in cropland topsoils (0 – 20 cm) of Lower Austria, its main agroecological regions (MARs), and selected WRB soil groups by soil and climatic drivers (dataset 1). For further details (regression coefficients, their standard errors and p values) see Table S4.

Model parameter	Entire study region (Lower Austria)	Main agroecological region					
		MAR 2	MAR 3	MAR 4	MAR 6	MAR 8a	MAR 8b
	All soil groups	**All soil groups**	**All soil groups**	**All soil groups**	**All soil groups**	**All soil groups**	**All soil groups**
Number of observations	750	30	41	145	75	336	123
Adjusted r^2	0.544	0.305	0.611	0.656	0.299	0.575	0.628
Standard error	6.885	8.180	4.745	5.925	4.062	2.886	10.174
Critical F value (ANOVA)	$2.12\ 10^{-26}$	0.00280	$9.93\ 10^{-10}$	$4.02\ 10^{-35}$	0.00001	$2.41\ 10^{-61}$	$6.01\ 10^{-27}$
F value for test statistic	224.59705	7.36695	63.75113	275.01872	8.90958	149.63719	104.12175
	Eutric Leptic Cambisols[1)]		**Eutric Leptic Cambisols[1)]**	**Eutric Leptic Cambisols[1)]**	**Eutric Cambisols[1)]**	**Chernozeoms/ Phaeozems[2)]**	**Chernozeoms/ Phaeozems[2)]**
Number of observations	135		31	94	24	136	58
Adjusted r^2	0.637		0.541	0.644	0.193	0.647	0.719
Standard error	6.043		4.924	6.396	3.728	2.324	3.550
Critical F value (ANOVA)	$3.57\ 10^{-30}$		$1.47\ 10^{-6}$	$1.48\ 10^{-22}$	0.01834	$9.86\ 10^{-30}$	$2.53\ 10^{-16}$
F value for test statistic	118.37976		36.36252	169.10449	6.49207	80.78062	74.01018
	Chernozeoms/ Phaeozems[2)]					**Solimovic Phaeozems[3)]**	**Relictigleyic Phaeozems[4)]**
Number of observations	198					52	37
Adjusted r^2	0.568					0.574	0.489
Standard error	3.444					2.270	8.725
Critical F value (ANOVA)	$5.68\ 10^{-35}$					$3.19\ 10^{-7}$	$4.18\ 10^{-6}$
F value for test statistic	65.65405					35.31139	18.22473
	Relictigleyic Phaeozems[4)]					**Calcaric Regosols ("eroded")**	
Number of observations	58					49	
Adjusted r^2	0.546					0.528	
Standard error	7.794					1.968	
Critical F value (ANOVA)	$1.43\ 10^{-10}$					$2.07\ 10^{-9}$	
F value for test statistic	35.21398					54.68224	

1) including Cambic Phaeozems with the same principal qualifiers.
2) Chernozems and associated Calcaric (Chernic) Phaeozems.
3) Calcaric Solimovic Phaeozems.
4) Calcaric Relictigleyic Phaeozems, mainly dervied from previously hydromorphic soils.

Table 4
Multiple regression models explaining soil organic carbon concentrations (SOC) in grassland topsoils (0 – 20 cm) of Lower Austria, its main agroecological regions (MARs), and selected WRB soil groups by soil and climatic drivers (dataset 1). For further details (regression coefficients, their standard errors and p values) see Table S5.

Model parameter	Entire study region (Lower Austria)		Main agroecological region				
			MAR 2		MAR 3	MAR 4	MAR 6
	All soil groups	**Cambisols[1)]**	**All soil groups**	**Cambisols[1)]**	**All soil groups**	**All soil groups**	**All soil groups**
Number of observations	105	64	44	28	12	20	23
Adjusted r^2	0.373	0.546	0.387	0.564	0.750	0.183	0.171
Standard error	14.713	10.617	12.874	12.312	3.529	11.764	9.934
Critical F value (ANOVA)	$6.59\ 10^{-11}$	$5.58\ 10^{-11}$	$1.68\ 10^{-5}$	$1.19\ 10^{-5}$	$1.66\ 10^{-4}$	0.03395	0.02862
F value for test statistic	21.65168	26.28529	14.55293	18.47261	33.99129	5.26844	5.52320

1) Calcaric and Eutric Cambisols and Cambic Phaeozems, with and without Leptic qualifier.

VESS method according to Ball et al. (2007). Whereas the regressions models are significant ($p < 0.05$), for the slopes this applies only for the regression line representing “good” structure quality. All correlation coefficients are very small, resulting in $r^2 < 0.03$. The regression lines representing “good” and “moderate” structure qualities are virtually identical, whereas the one for “very good” quality classes has a negative slope.

To account for a possible bias by coarse-textured soils, panel B of

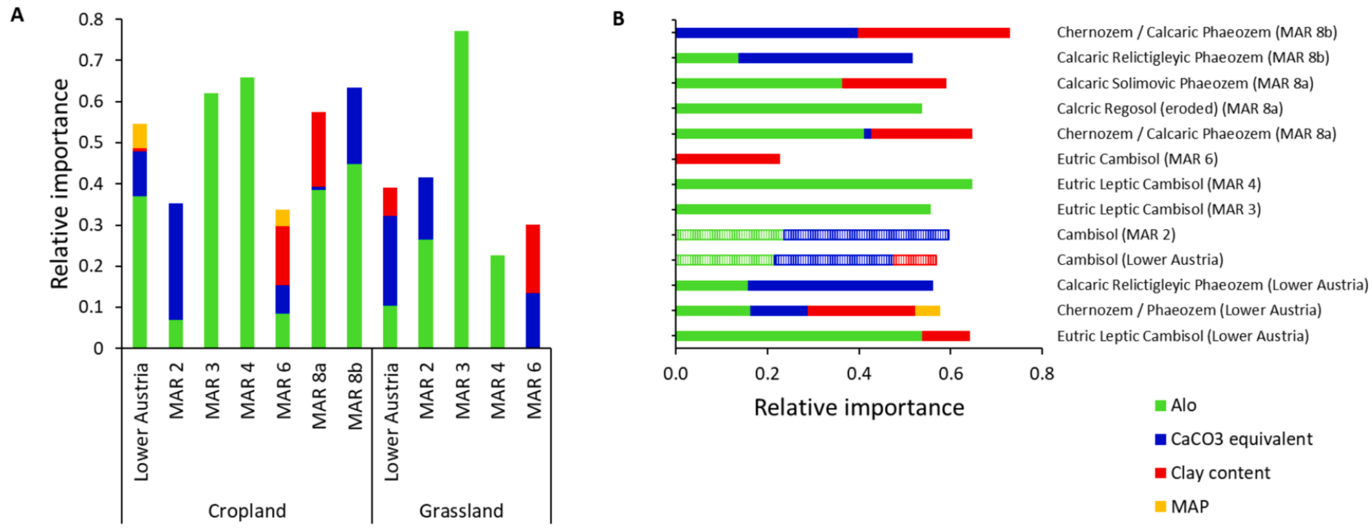

Fig. 4. Relative importance (individual R^2 calculated by the LMG method) of the SOC predictors in the linear regression models presented in Tables 3 (cropland) and 4 (grassland). The sum of individual R^2 yields the squared correlation coefficients of the regression models. Panel A shows the results for the regional models, panel B those for WRB soil groups within the indicated regions. The hatched columns in panel B refer to grassland soils, all other columns to cropland soils.

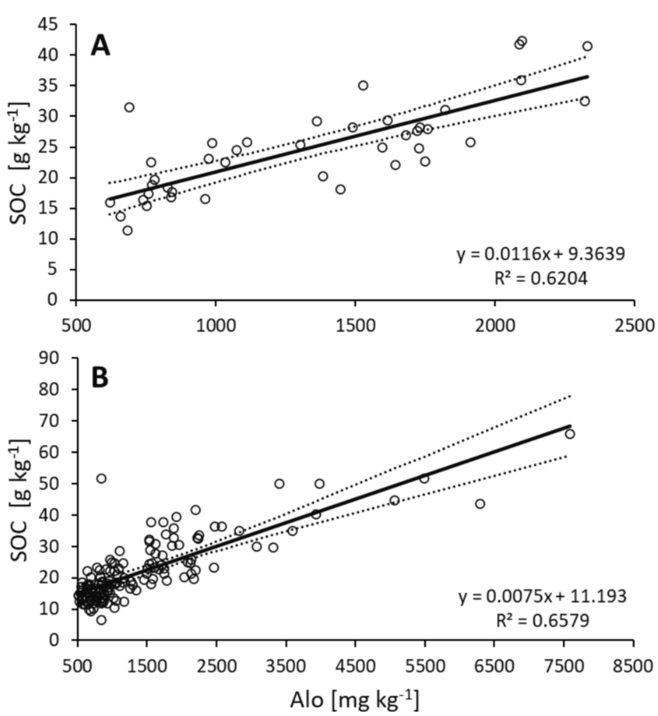

Fig. 5. Linear regressions of SOC on Al_o in cropland topsoils (0–20 cm) of MAR 3 (panel A) and MAR 4 (panel B). The dashed lines show the confidence intervals (95 % probability) of the regression line.

Fig. 8 shows the relations after removal of soil with clay contents <200 g kg^{-1}. This shifts the regression line of the "very good" structure class towards a positive relation and improves the correlation coefficient to ~0.5, however, the slope remains insignificant ($p < 0.05$). Therefore, even after removal of the coarse-textured soils, we find no significant, meaningful separation of the structure quality classes.

A rather poor differentiation of structure quality classes by SOC – clay relationships is also indicated by the large number (panel C) and percentage (panel D) of soils with "very good" and "good" soil structure according to the VESS method below the 1/13 threshold of the SOC: clay ratio (Fig. 8). According to Johannes et al. (2017a), this threshold should separate "moderate" from "degraded" soil structure qualities. Even though we observe a trend of decreasing share of soils with "very good" soil structure with decreasing SOC: clay ratio, and an opposite trend for "moderate" structure qualities, the separation is weak (Fig. 8, panels C and D).

4. Discussion

4.1. Al_o and $CaCO_3$ equivalent are the primary controls of SOC in the study region

Multiple regression models identify Al_o and the $CaCO_3$ equivalent as main drivers of SOC in topsoils (0 – 20 cm) beneath cropland (Table 3) and grassland (Table 4) at the scale of the study region and within the majority of the MARs (Fig. 4), and explain a considerable share of the variation of SOC among WRB soil groups (Table S3, Fig. 7).

The importance of amorphous oxyhydroxides of Al as predictor of SOC has been demonstrated before for European soils (Rasmussen et al., 2018), and for forest and hedgerow soils in the study region (Bösch et al., 2023; Wenzel et al., 2023). Atomic –scale modelling has shown that a large variety of common constituents of SOM, including small organic molecules (e.g., carboxylic acids) and biopolymers (e.g., cellulose) can adsorb via multiple hydrogen bonds and possibly covalent bonds to oxyhydroxides of Al (Ahmad and Martsinovich, 2023). The large specific surface area and, as compared to clay minerals, the higher affinity for sorption of SOM compounds (Wiesmeier et al., 2019), may provide a mechanistic explanation for our findings. Oxyhydroxides of Al form coatings on clay mineral surfaces, especially in the lower pH range, where they exhibit positive net surface charge (Goldberg, 1989), thus enhancing the accessibility for interactions with SOM. In addition, SOC can be protected by Al oxyhydroxides through stabilization of aggregates (Goldberg, 1989; Rasmussen et al., 2018; Wiesmeier et al., 2019).

The observed role of the $CaCO_3$ equivalent as predictor of SOC in the study region is related to the formation of electrostatic Ca bridges between SOM and mineral surfaces (Wiesmeier et al., 2019). Carbonate-rich soils are characterized by high Ca^{2+} concentrations in soil solution and dominance of Ca^{2+} on the exchange complex. The $CaCO_3$ equivalent explains ~80 % of the variation of the SOC: Al_o ratio among soil groups, with a 2-fold increase of the latter over the observed range of the $CaCO_3$ equivalent in the study region (Fig. 7), indicating that the effects of Al_o and the $CaCO_3$ equivalent are additive.

Overall, clay content explains only <1 % (cropland) and ~7 % (grassland) of the overall SOC variation in the entire study region. At the

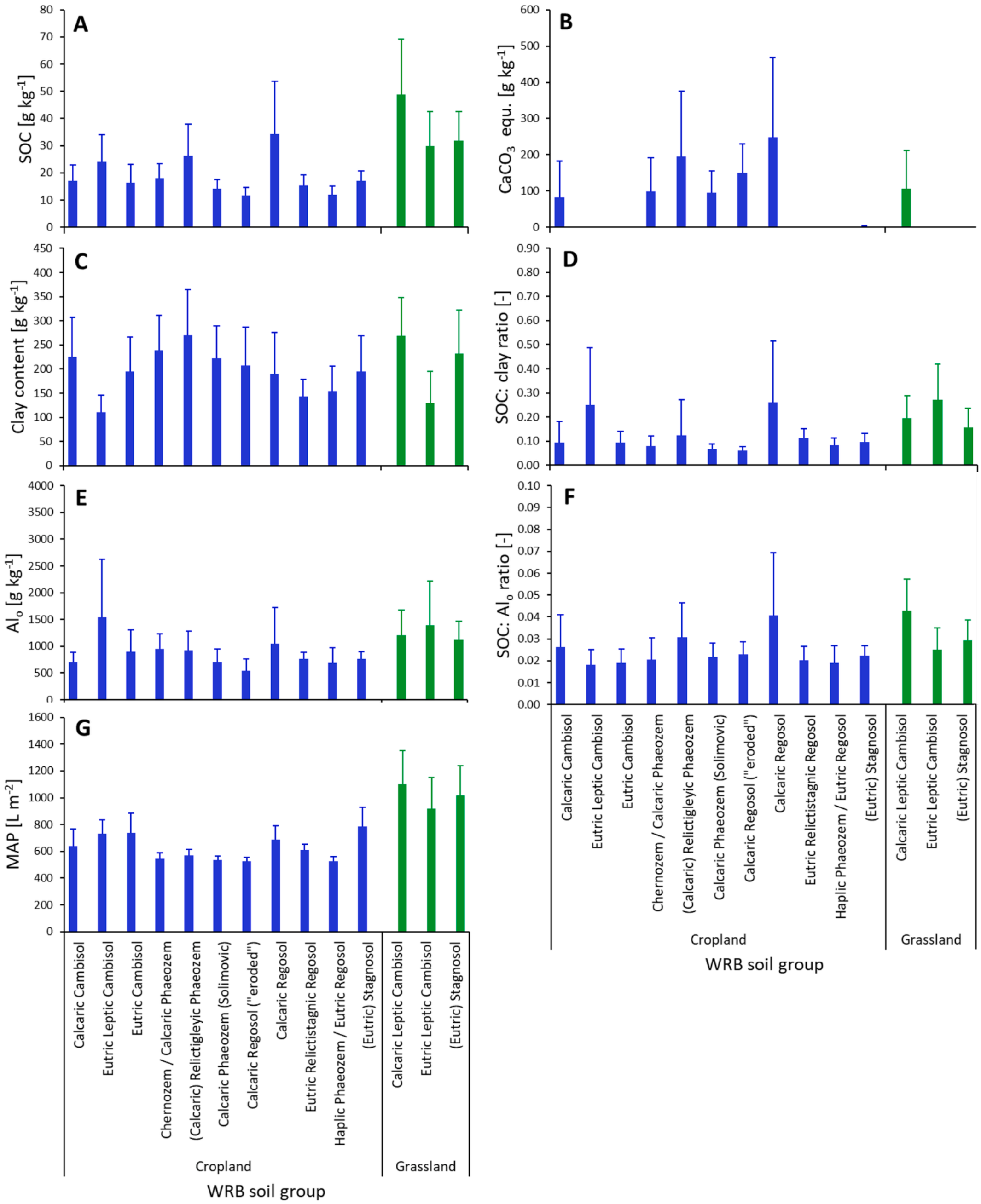

Fig. 6. Variation of SOC concentrations (panel A), selected potential drivers (panels B, C E and G), and the ratios of SOC: clay (panel D) and SOC: Al_o (panel F) among soil groups according to IUSS Working Group WRB (2022) in topsoils (0–20 cm, dataset 1) beneath cropland and grassland of Lower Austria (arithmetic means ± standard deviations). Data is shown only for soil groups with >10 observations.

scale of agroecological regions, clay content is identified as main driver only in MAR 6, however, the proportion of SOC variation explained is rather small (~14 % beneath cropland, 17 % beneath grassland). In MAR 8a, clay content explains ~18 % to the overall SOC variation, however, the main predictor in this region is Al_o (Fig. 4).

Apart from the general dominance of Al_o and $CaCO_3$ equivalent, the relevant set of SOC drivers varies with scale and among MARs (Table 3; Table 4). In accordance with scale-dependent hierarchy of SOC drivers (Wiesmeier et al., 2019), we find decreasing importance of the climate variable MAP when downscaling from the entire study region (NUTS 2 level) to the main agroecological regions (Fig. 4). Along this line, the variability of climate factors decreases (Table 2), resulting in a shift from climatic to soil drivers. Note that even at regional scale (Lower Austria, ~10^{11} m^2) climate seems to be less important than expected from the conceptualization by Wiesmeier et al. (2019), whereas soil chemical characteristics (in particular Al_o, $CaCO_3$ equivalent), deemed to become important only below landscape/farm level (~104 to 105 m^2; Wiesmeier et al., 2019), are the main predictors of SOC across the entire study region (Fig. 4).

Rasmussen et al. (2018) proposed a conceptual model linking the SOC drivers to the chemical and hydrological status of soil systems. Accordingly, amorphous oxyhydroxides and complexes of Al and Fe (here represented by Al_o and Fe_o) are expected to be the primary controls of SOC in acidic soils at humid conditions, favouring the formation of amorphous oxyhydroxides. In contrast, Ca^{2+} (here represented by the $CaCO_3$ equivalent), and to a lesser extent clay content, are deemed to control SOC in calcareous soils of more aridic climates. Our results (Table 3) are partly consistent with this conceptualization. In particular,

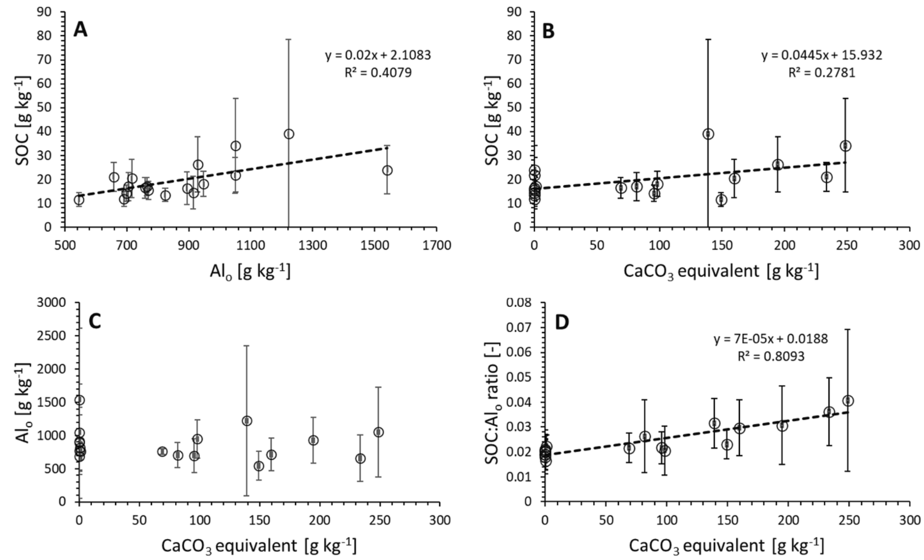

Fig. 7. Relations between Al_o and SOC (panel A), and the $CaCO_3$ equivalent and SOC (panel B), Al_o (panel C), and the SOC: Al_o ratio (panel D), respectively. Open circles show arithmetic means for the soil groups beneath cropland (compare Table 1), error bars the standard deviation. Linear regressions are depicted by dashed lines.

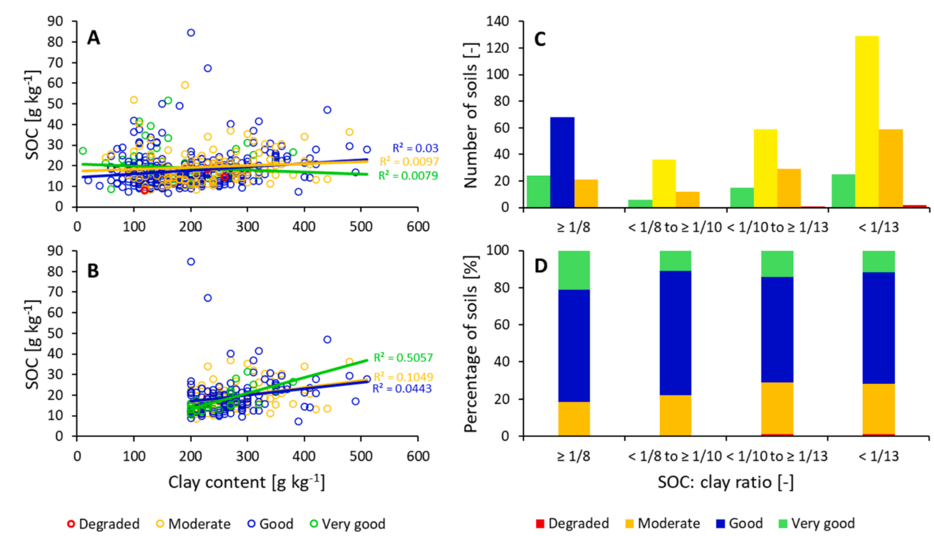

Fig. 8. Relations between SOC and clay content for three different soil structure quality classes (moderate, good, very good) according to the VESS method (Ball et al., 2007) for all cropland topsoils (0 – 20 cm) of dataset 2 (panel A; n = 485), and for soils with clay content ≥200 g clay kg^{-1} (panel B; n = 243). Panel C shows the corresponding numbers, panel D the percentages (panel D) of soils with different VESS scores within the four SOC: clay ratio categories defined by Johannes et al. (2017a): Very good (<Sq2), good (Sq2−<Sq3), moderate (Sq3−<Sq4), degraded (≥Sq4). All linear regressions (panels A and B) are significant at $p < 0.05$, the slopes are significant only for the regression lines representing "good" structure quality.

we observe that Al_o is the only relevant SOC driver in more humid regions (mean aridity index ≤ 0.010; Table 2) dominated by moderately acidic (mean pH ≤ 5.5; Table 2) soils (MARs 3 and 4), and, except in MAR 6, in Eutric Cambisols. This equally applies for cropland and grassland soils (Fig. 4, panel A). However, at the scale of MARs, Al_o is also the main driver of SOC in the dry (mean aridity index 0.017; Table 2) lowlands (MARs 8a and 8b) that are dominated by Chernozems and Calcaric (Chernic) Phaeozems with mean pH ~ 7.3 (Table 2). Within MAR 8a, this also applies at the soil group scale, with SOC being controlled primarily by Al_o in Chernozems/Calcaric (Chernic) Phaeozems, and their solimovic (Calcaric Solimovic Phaeozems) and eroded (Calcaric Regosols) derivates (Fig. 4, panel B). As there is no obvious explanation for the dominant role of Al_o in MAR 8a, this requires further investigation, however, it is in line with independent data for hedgerow and cropland soils reported for the same region (Wenzel et al., 2023).

More in accordance with expectations, the $CaCO_3$ equivalent is identified as the main driver of SOC at soil group level in MAR 8b (Fig. 4, panel B), which might be related to higher and more variable $CaCO_3$ levels (Fig. 2) in this region. Compared to the scale of the entire study region and the MARs, the relative importance of clay content increases at soil group level (Fig. 4). This may be related to less pronounced effects of the textural composition of the parent material at this scale.

The observed scale-dependent, regional variation of SOC drivers reinforces the critique for the definition of universal SOC indices such as the SOC: clay ratio, and universal thresholds or trigger values (1/13) as laid down in the SML proposal (Council of the European Union, 2024). Moreover, the limited importance of climatic drivers at regional (Fig. 4; Poeplau and Don, 2023; Rabot et al., 2024) to European scale (Rasmussen et al., 2018) does not support the correction of indices like the SOC: clay ratio by climate variables as suggested in the SML proposal.

4.2. Lack of mechanistic foundation and applicability of SOC: clay ratios as soil health descriptor in the study region

The recent proposal of the European Commission for a Soil Monitoring and Resilience Law (SML; Council of the European Union, 2024) defines the soil: clay ratio as descriptor of soil health in terms of the SOC status. The SML proposal is referring to the work of Prout et al. (2021), who, using the soil database for England and Wales, tested this concept which was initially introduced by Johannes et al. (2017a). The database for the latter was limited to Luvisols in the western part of Switzerland (Johannes et al., 2017a). Both articles present evidence for relatively strong relations between soil structural quality and the SOC: clay ratio, and agree on SOC: clay ratio thresholds (1/8, 1/10, 1/13) for distinguishing soils of differential structure quality.

In contrast to these previous studies, multiple regression models run with different datasets for cropland (Table 3) and grassland soils (Table 4) reveal that clay content has limited explanatory value for the variation of SOC levels in Lower Austrian soils, whereas, with the exception of MAR 6 and the Chernozems/Calcaric (Chernic) Phaeozems in the Lower Austria lowlands, Al_o and $CaCO_3$ equivalent are consistently identified as main drivers (for details see section 4.1). Accordingly, clay content has only limited importance for explaining SOC variation within spatial units at the scales of the entire study region, MARs and soil groups (Table 3, Table 4, Fig. 4), and among major soil groups (Table S3).

The clay content, one out of two input variables of the SOC: clay ratio, varies considerably among agroecological regions (Table 2, Fig. 2), and is largely (by ~63 %) controlled by the type of parent material (Fig. 3). Fine-textured parent materials, including quaternary (loess, fluviatile sediments) and tertiary sediments (molasse, marl) in lowland areas (MARs 6 and 8), partly pre-weathered residual clays derived from the weathering of limestone and dolomite rocks and slope sediments on clay-rich sedimentary rocks (Alpine MAR 2) are associated with mean clay contents >150 g kg^{-1} as observed in the MARs 2, 6 and 8. Mean clay contents <150 g kg^{-1} in topsoils are associated mainly with soil formation on igneous and metamorphic silicious rocks (mainly gneiss, granite, schists, granulite, granodiorite) as observed in the MARs 3 and 4. These observations show that clay content and SOC concentrations in Lower Austrian topsoils are controlled by different factors, poorly related, and are therefore at least partly decoupled. As a result, the SOC: clay ratio varies considerably among the MARs (Table 2) and SARs (Table 2; Fig. 2), with particularly small values associated with fine-textured parent materials dominating the lowlands of the MARs 6 and 8.

In contrast to the findings of Johannes et al. (2017a), the SOC: clay ratio does not allow for meaningful differentiation between structure quality classes (Fig. 8, panel A). Upon removal of soils with clay contents <200 g kg^{-1} (Fig. 8, pane B) to account for a possible bias by sandy soils (Poeplau and Don, 2023; Rabot et al., 2024), the regression line representing "very good" structure quality shifts from a negative to a positive relation, however, the slope is not significant ($p < 0.05$). Forcing the regression lines through zero as done by Johannes et al. (2017a) is not appropriate for our data as all intercepts are highly significant ($p < 10^{-11}$), and does result in better differentiation.

Our results contrast previous work conducted in other European regions (Johannes et al., 2017a; Johannes et al., 2023; Prout et al., 2021). These studies found reasonable differentiation of soil structure quality classes as, in contrast to our data, they were based on rather strong relations between clay content and SOC.

The observed poor relation between SOC: clay ratios and structure quality in Lower Austrian topsoils might be also related to different climatic conditions and soil formation processes. In contrast to western Switzerland and large parts of England and Wales, soils in the Lower Austrian lowlands (main agroecological region 8) formed under dryer conditions (Pannonian climate). The soil cover of this region is dominated by Chernozems and Calcaric (Chernic) Phaeozems with deep-reaching accumulation of SOC (chernic and mollic horizons), resulting in the largest SOC stocks to a depth of 50 cm observed for major soil groups in Lower Austria (Wenzel et al, 2022). Due to the large share of fine-textured parent materials (Fig. 3), the SOC: clay ratios in most SARs (801 to 808) are <0.07 (Table 2, Fig. 3) even though the soil structure scores indicate very good to good quality for the majority of soils (Fig. 8). The MAT at the soil sampling sites of MAR 8 is 9.21 ± 0.50 °C (arithmetic mean ± SD), the MAP is 549 ± 44 L m^{-2}, resulting in an aridity index of 0.017 ± 0.01 (Table 2). The soils of this region are also characterised by a large share (~19 % of total SOC) of resistant oxidizable carbon (ROC) as compared to other Lower Austrian soils (~10 %; Table 2), indicating specific chemical composition of SOM. ROC is thermically more stable (released between 400 to 600 °C) and likely to contain more aromatic compounds and chars than other SOC fractions, and may therefore contribute to stabilizing soil aggregates (Brodowski et al., 2006). Moreover, empirical evidence for good structure quality of Chernozems is available for southern Slovakia (MAT 9.0 to 10.4 °C, MAP 564 to 580 L m^{-2}) located in the immediate neighbourhood to our study region (Šimansky & Jonczak, 2016). These authors report a high average share of 74.6 % water-stable aggregates in topsoils (0–30 cm) at mean SOC concentrations of 13.5 ± 3.78 g kg^{-1}, i. e., even at SOC levels below those observed in the Lower Austrian Chernozem region (MAR 8, Table 2).

The large share of soils with "very good" and "good" structure but SOC: clay ratios < 1/13 (Fig. 8, panels C and D) provides further evidence that this criterium fails to separate soils of differential health status in the study region. Overall, our findings indicate that the use of the SOC: clay ratio as soil health criteria for the SOC status lacks mechanistic foundation in the study region, calling for alternative approaches (see Section 4.3).

4.3. Alternative approaches to assess soil health in relation to the SOC status in the study region

As shown in the previous sections, clay content is not among the main drivers of SOC concentrations in the study region and the majority of its agroecological units (Table 3, Table 4), and the set of drivers varies among the MARs, with varying contributions of Al_o, $CaCO_3$ equivalent, clay content, and MAP (Fig. 4). In contrast to some other regions (Johannes et al., 2017a; Johannes et al., 2023; Prout et al., 2021), the use of the SOC: clay ratio is therefore not a useful criteria of soil health assessment in the study region. The SML allows to apply "corrective factors to the ratio where specific soil types or climatic conditions justify it, taking into account the link to structural stability" (Council of the European Union, 2024). However, correcting the SOC: clay threshold by climatic drivers is misleading if, as in the case of our study region, both clay content and climate have no or only minor importance as drivers of SOC. Therefore, in regions where SOC is poorly related to clay content, alternative approaches to assess soil health are required.

Recently, Poeplau and Don (2023) suggested an alternative to the SOC: clay ratio that considers the clay content, albeit in a way deemed to make it a less strong denominator of SOC. The newly introduced SOC: SOC_{exp} ratio relates the SOC concentration of a given soil to an expected SOC concentration. The latter is derived from a linear regression of SOC concentrations on clay contents obtained from the dataset of the first German soil inventory, allowing for the calculation of SOC_{exp} by using known clay contents as input variable. However, to be meaningful, this approach still requires that clay content is the main driver of SOC, and the predictive power of the regression between SOC and clay content for German soils presented by Poeplau and Don (2023) is weak. Moreover, it is not considering functional relations to soil physical properties or the quality of soil structure.

We therefore propose to identify the main drivers of SOC by multiple regression models such as those presented in Table 3, and to derive regional benchmarks of the expected SOC concentrations. The models capture both soil and climatic drivers, according to their relative importance (Fig. 4) in the entire study region or in agroecological units (MARs). They explain ~54 % of the total SOC variation in the entire study region, and between ~23 and 77 % within the MARs. The variation that cannot be explained by the models varies between 23 and 77 %, and is expected to cover differences in soil management and a residual that likely comprises site factors such as topography (Vos et al., 2019) which were not included in the models, and errors, e.g. related to soil sampling and analysis.

For soil health assessment, measured data of SOC and the regionally relevant drivers can be benchmarked against the expected SOC concentration predicted by the regression model. For a given set of soil and climatic drivers, the predicted SOC values can be interpreted as benchmark for the typical (average) current management regime in the region. If SOC is primarily controlled by only one driver, the benchmark (typical SOC levels) is represented by the regression line. This is illustrated for two selected MARs in Fig. 5. The rather narrow bands of the confidence interval indicate that the regression models predict the true line of the population in the two regions (MAR 3 and 4) quite accurately. Soils with SOC levels above the upper boundary of the confidence interval in a region can be considered to be in relatively good condition, soils with SOC below the lower boundary are likely to benefit from improved management. Note that, at present, this approach is not based on the quantification of functional relations between SOC and soil physical properties with relevance for ecosystem services. However, in contrast to previous work (Poeplau and Don, 2023), it accounts for the inherent variation of SOC within a given region based on the relevant set of soil and climatic drivers, providing an estimate of the expected SOC level for the average regional management regime. In contrast to a uniform threshold across ecological zones as proposed in the SML (Council of the European Union, 2024), or for a given soil type/group (Poeplau and Don, 2023; Rabot et al., 2024), this approach allows for site-specific differentiation. For instance, in MAR 4 (Fig. 5, panel B) a soil with 30 g SOC kg^{-1} is clearly above average if the soil contains <2000 mg Al_o kg^{-1}, but likely to be deficient of SOC above this threshold. Regional calibration of SOC levels to soil functional properties such as air capacity, water retention, or quality of soil structure offers opportunities for refining the interpretation, and to establish better links to the soil health concept. However, at present such data are not available for the study region. Apart from calibration to physical properties, also chemical and biological functionalities could be considered. It may be also worthwhile to explore relations between regional SOC drivers (e.g., Al_o and $CaCO_3$), and functional properties such as soil structure quality.

The suggested approach can be further refined if site-specific management data become available. In this case, grouping (stratification) of SOC data according to predefined management regime categories allows to distinguish SOC benchmarks for poor, average, best-practice and pioneer management by taking the soil and climatic driver effects into consideration as described before. By relating the benchmarks to functional soil properties, soil management could be linked to soil health and ecosystem services. The SML proposal (Council of the European Union, 2024) requires member states to establish soil districts, with authorities responsible for improving monitoring the soil health status together with the relevant stakeholders (e.g., land owners). The proposed benchmarks for differential management regimes could be established for agroecological and soil units within each soil district, and used as criteria for soil health assessment and stakeholder advice.

Note that the suggested approach may have some limitations. The quality of interpretation depends on the explanatory value of the regression models, i.e. in particular, if the model captures the effects of the main drivers to a sufficiently large extent, allowing for interpretation of the residual variation as mainly driven by management. Using machine learning, Vos et al. (2019) found that soil management explains on average ~18 % of the total SOC stock variation in German topsoils (0 – 10 cm). For the northeastern part of the study region (parts of the MARs 8a and 4), Rosinger et al. (2023) report a mean difference between standard systems and after on average 26 years pioneer farming of ~20 % of the SOC stocks observed at 0–35 cm depth for standard systems. Some of the models presented in Table 3 and Table 4 have adjusted $r^2 <$ 0.5, indicating that not all relevant drivers are covered. Therefore, it is desirable to further improve the quality of the models by including additional soil and site characteristics, in particular topography (position in the landscape, slope; Vos et al., 2019), or to stratify data accordingly. Another source of poor model performance may arise from heterogenous soil cover within a given region, adding unexplained variation. This seems to apply for the MARs 2 and 6 as indicated by the large number of different soil groups (Table 2). There is scope for improving the models by more detailed stratification according to main soil units within the regions once a sufficient number of observations becomes available. We tested this approach for MARs with sufficient number of observations. Separate regression models for the most abundant soil groups (compare Table 1) within the entire study region and the individual MARs reveal that the stratification by soil group improves the explanatory value for cropland and grassland soils in the entire study region, and for grassland soils in MAR 2 (Fig. 4). Equally important, scaling the models to the soil group level within agroecological regions may change the set of relevant SOC drivers and their relative importance (Fig. 4).

Among other reasonings, the use of the SOC: clay ratio or other clay-related indices of SOC has been advocated because clay content is available in many databases. In contrast, the determination of pedogenic oxyhydroxides such as Al_o is less common, at present limiting their use in the context of soil health assessments. As shown here and advocated by Rasmussen et al. (2018), such alternate soil mineralogical proxies to clay content should be more widely included in models predicting SOC. One reason for the limited availability of data for pedogenic oxyhydroxides relates to the relatively high workload and costs (Wiesmeier et al, 2019). Standard methods for ammonium oxalate extraction as used in our work typically include the time-consuming removal of carbonates (Loeppert and Inskeep, 1996), thus increasing the workload substantially. However, at least for the carbonate content range observed in our study, this step can be neglected, because the extraction pH and yield were not affected. If the carbonate removal step is dismissed, the ammonium oxalate method becomes a rather simple soil extraction which should facilitate its integration in soil health assessment and monitoring frameworks.

5. Conclusions

We show that clay content is a weak predictor of SOC in topsoils (0 – 20 cm) of Lower Austria. Using multiple regression analysis, we identified amorphous oxyhydroxides of Al (Al_o) and $CaCO_3$ equivalent as main drivers, with varying but generally less important contributions of MAP and clay content, depending on the spatial scale and region considered. Regression models for soil units (major WRB soil groups) within the MARs improved the explanatory value in regions with high variability of the soil cover (e.g., the entire study region, MAR 2). We also show that the input variables of the SOC: clay ratio are at least partly driven by different environmental and soil variables, resulting in its considerable variation among agroecological regions. As a consequence, soils in regions with clay-rich parent materials but low SOC levels, e.g., due to climatic conditions, have inherently smaller SOC: clay ratios than others.

Given the weak relation between clay content and SOC, it is conclusive that we could not establish meaningful relations between the SOC: clay ratio and indices of structure quality for cropland topsoils of Lower Austria. Accordingly, the thresholds for SOC: clay ratios deemed to separate soils with differential structure quality as proposed by Johannes et al. (2017a) are not meaningful in Lower Austria, and probably also not in other regions where clay content is not among the main drivers of SOC, such as in France (Rabot et al, 2024) or Germany (Poeplau and Don, 2023).

These findings challenge the universal use of the SOC: clay ratio as descriptor of soil health, and the application of a threshold of 1/13 to distinguish the soil health status across different agroecological units at regional or even continental scale, as recently introduced by the SML proposal (Council of the European Union, 2024). Similarly, Rabot et al. (2024) have recently questioned the universal use of the SOC clay ratio and advocated to employ correction factors to the 1/13 threshold. However, given that SOC is not primarily controlled by clay content, and climate factors are not among the main SOC drivers in our study region, also the use of correction factors to the SOC: clay threshold (Council of the European Union, 2024) lacks mechanistic foundation and applicability. Further work should explore the possibility of alternative soil health descriptors by replacing clay content by the relevant regional SOC drivers.

Based on our results we propose to develop soil health benchmarks for SOC based on the identification of its main drivers within a given region or its soil units. Using multiple regression analysis, we suggest to determine regional SOC benchmarks representative for the average management regime as a function of the main soil drivers. This allows to separate the inherent variation by soil and climatic drivers from the effect of management. This approach could be further refined by developing relations for different, clearly defined categories of soil management (e.g., Rosinger et al., 2023), and by their calibration to soil functional properties (e.g., air capacity, structure quality scores) in order to link the benchmarks to soil management, soil health and related ecosystem services.

CRediT authorship contribution statement

Walter W. Wenzel: Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Alireza Golestanifard:** Writing – review & editing, Project administration, Investigation, Data curation. **Olivier Duboc:** Writing – review & editing, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2024.117080.

Data availability

Data will be made available on request.

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