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How biased is size fractionation derived mineral-associated organic carbon?

Christopher Poeplau [a,*], Maria Skovgaard Andersen [b], Cora Vos [a]

[a] Thünen Institute of Climate-Smart Agriculture, Bundesallee 68, 38116 Braunschweig, Germany
[b] Department of Plant and Environmental Sciences, University of Copenhagen, Denmark

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ABSTRACT

Mineral-associated organic carbon (MAOC) is regarded as the more persistent soil organic carbon (SOC) as opposed to the more fast-cycling particulate organic carbon (POC). Both fractions are typically isolated using physical fractionation based on size (wet sieving) or density (flotation in heavy solution). Size fractionation is faster and cheaper, and concepts about organo-mineral interactions are centered around the reactive silt + clay-sized soil fraction. However, with wet-sieving, there is a chance that fine (f)POC is also quantified as MAOC. A systematic quantification of such contamination and a comprehensive comparison of the two physical fractionation methods is missing. We selected 40 archived agricultural topsoils forming an SOC x texture gradient matrix to evaluate fPOC contents and characteristics by an additional density fractionation step. Subsequently, we quantitatively compared size and density-derived fractions from a total of 140 samples from the same archive. With on average 2.2 ± 4.2 % of total SOC, the contribution of fPOC to MAOC was very low. The isolated fPOC fraction also resembled MAOC in its physico-chemical properties with abundance of mineral particles, narrow C:N ratio and being relatively enriched in ^{13}C. Most OC-rich sandy soils had outlying high fPOC contents, leading to overestimations of MAOC by up to 212 %. Accordingly, size and density fractionation were very similar for a wide range of soils, while for 22 OC-rich sandy soils (> 800 g kg^{-1} sand, >20 g kg^{-1} SOC) size fractionation strongly overestimated MAOC. Simple physical fractionation cannot be conducted without certain (cross)-contaminations, while their magnitude appears to be minor given the multiple sources of error in organic matter fractionation. However, POC-rich sandy soils should not be fractionated by size (alone).

1. Introduction

The fractionation of soil organic carbon (SOC) has the goal of isolating SOC pools of different biogeochemical stability (Christensen, 1985; Guggenberger et al., 1994; Paul et al., 2001). It is well established that most biomass in heterotrophically active soils (e.g. non-permanently frozen, well aerated, sufficient moisture) is decomposed in the first years after incorporation and returned to the atmosphere as CO_2 (Janzen et al., 2022). Only a small part is stabilized in the soil and can be stored for decades to centuries, in certain exceptions even millennia (Trumbore et al., 1989). Based on state-of-the-art understanding of chemical and/or physical SOC stabilization mechanisms in the soil, scientists developed many different methods to fractionate soils (Lützow et al., 2006; Poeplau et al., 2018; Rocci et al., 2024). In recent years, the interactions of SOC with the mineral phase in their various forms are thought to be the most important stabilization processes (Kleber et al., 2021). Accordingly, it has been proposed to simplify and harmonize fractionation schemes and isolate no more than two fractions, which might be particularly helpful in high throughput applications: particulate organic carbon (POC) and mineral associated organic carbon (MAOC) (Cotrufo et al., 2019; Lavallee et al., 2020). This isolation is done either by size or density. Size fractionation is based on the notion that sand-sized particles have a low specific surface area which is not charged and are therefore OC free, once all larger aggregates are dispersed (Lavallee et al., 2020). When splitting the sample at a size cutoff of 20, 50, or 63 μm, the coarse fraction is assumed to contain only POC, i.e. non-stabilized plant debris, while the fine fraction contains all SOC that is associated to silt and clay-sized particles and micro-aggregates (Lavallee et al., 2020; Moni et al., 2012). When using density fractionation, i.e. letting light material float in a liquid with a density of typically 1.6 or 1.8 g cm^{-3}, it is assumed that MAOC is entirely recovered in the non-floating heavy fraction (Cerli et al., 2012). In such

* Corresponding author.
E-mail address: Christopher.poeplau@thuenen.de (C. Poeplau).

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a binary approach, the likelihood that the isolated OC pools are not homogenous in their biogeochemical properties, but may both contain labile and more stabilized OC at the same time is high. Any intermediate pool, e.g. organic matter occluded in aggregates, is not quantified as such, but allocated to either the stable or labile part (Six et al., 2001). Resulting functional overlaps of the two fractions can hamper the interpretation of SOC fraction distribution (Cécillon et al., 2021; Curtin et al., 2019).

Size fractionation is cheaper, faster and usually has higher OC as well as mass recoveries than density fractionation (Poeplau et al., 2018). Furthermore, it does not rely on a heavy metal-containing salt such as sodium polytungstate (Helbling et al., 2021), but can be done with only water after some kind of aggregate dispersion. Therefore, it has become more wide-spread in recent years and is used as a high-throughput method to derive a POC fraction and a, more stabilized, MAOC fraction (Cotrufo et al., 2019; Karunaratne et al., 2024; van Wesemael et al., 2019). However, when applying size fractionation alone, there is a risk of contaminating the MAOC fraction with clay or silt-sized POC, i.e. material that is small but not associated to minerals and thus potentially labile. After dispersion, such fine (f)POC will end up in the fine particle fraction and will then be interpreted as MAOC, which would not have happened with density separation. Even dispersion itself may lead to disintegration of POC and create small organic particles that are washed through the sieve (Amelung and Zech, 1999). Such contamination of MAOC with fPOC might depend on the chosen dispersion method, but also on a variety of soil properties, such as texture, total SOC content or total POC content, and thus aggravate the comparison across studies and soils. This can be particularly problematic when a diverse sample set is used to deduce some kind of generic, mechanistic understanding, e.g. related to the maximum storage capacity of MAOC. For example, several authors found that the OC loading of fine particles, here defined as the amount of carbon per silt and clay, in sandy soils can be much higher than in more fine-textured soils (Begill et al., 2023; Poeplau et al., 2024; Schweizer et al., 2021). This is an interesting finding per se and might carry important information about SOC stabilization pathways in general. However, the effect of fine POC on the calculated OC loading is negatively correlated with the amount of sit and clay particles, so that OC loading in coarse-textured soils is much more biased than in fine-textured soils. A higher OC loading in sandy soils might thus also be an artefact of size fractionation to some extent (Georgiou et al., 2025).

At the same time, it is also important to understand the quality and functional nature of fPOC. For example, in a fractionation method comparison, Poeplau et al. (2018) found that after C3-C4 vegetation changes, fine POC had similar proportions of new OC as MAOC, while coarse POC was much more dominated by new C. When occluded in aggregates, fine POC persists for a longer time than coarse POC (Golchin et al., 1994). Furthermore, minerals with MAOC may start floating in a dense solution, in turn leading to contamination of fPOC with actual MAOC (Six et al., 2024). Thus, although it might be semantically inaccurate to distribute such a heterogeneous fPOC fraction to MAOC, it might not be fundamentally wrong to do so from a functional point of view. In any case, the inclusion of such a potentially intermediate pool will blur the distinction between POC and MAOC, which is conceptually based on stabilization mechanisms. However, for fully understanding the fPOC bias in MAOC, it is important to not only quantify it, but also to evaluate its composition as compared to that of POC and MAOC.

Scattered studies exist, which quantified and characterized the amount of fine POC (Witzgall et al., 2021) or the difference between density and size fractionation protocols (Leuthold et al., 2024). However, a systematic investigation of the potential size fractionation bias regarding the overestimation of MAOC across a larger variety of soils is missing. For the interpretation of past and future studies based on size fractionation alone, it is however important to gain a general understanding of the most influential soil properties on relative and absolute contributions of fPOC to MAOC and potentially come up with methodological adjustments to account for such bias. We approached this in two stages. First, we used 40 temperate agricultural soils along gradients of SOC and texture to systematically assess the following questions: (i) how high is the average contamination of MAOC with fine POC and can SOC content or texture be used to explain or predict the fine POC content, (ii) is the high C loading of fine fractions in sandy soils an artefact of size fractionation, and (iii) is fine POC more similar to MAOC or coarse POC? Second, we used two independent, pre-existing datasets originating from the German Agricultural Soil Inventory (Vos et al., 2018) to quantitatively compare the MAOC fraction derived from size and density fractionation. This was done to investigate, (iv) if size fractionation generally overestimates MAOC contents, or (v) if soils with certain properties are particularly prone to such methodological biases.

2. Materials and methods

2.1. Selection of soils to quantify the fine particulate organic carbon content

To assess the importance and nature of POC in the fine size fraction (fPOC), we made a systematic selection of 40 soils from the archive of the German Agricultural Soil Inventory. This archive holds more than 20,000 individual oven dried (40 °C) and sieved (2 mm) samples from cropland and grassland soils that have been sampled and analysed in the course of the first (2011–2018) and second (ongoing since 2023) national soil inventory. Detailed descriptions of sampling design and physical and chemical analyses can be found in (Poeplau et al., 2021). In this case, only samples from 0-10 cm depth were considered. Four different levels of SOC contents (10, 30, 50 and 80 g kg^{-1}) in each of 10 different texture classes (silt and clay content classes in steps of 100 g kg^{-1}) were selected. In the German soil classification, the cut-off between silt and sand is at 63 μm. As shown in Fig. S1, it was possible to select soils with approximately 10 (9.7–11.9), 30 (29.9–31.1) and 50 (50.0–53.5) g kg^{-1} SOC in each texture class, while it was more difficult to find soils with 80 (68.7–87.8) g kg^{-1} SOC. The δ^{13}C isotopic signature was measured as a qualitative indicator, hence only carbonate free soils as well as cropland soils without maize (C4 plant) in the rotation were considered. Crop rotations were available for 10 years prior to sampling from a farmer's questionnaire (Jacobs et al., 2020). This might not be enough to completely diminish any potential C4 signal from the past, but decreased the likelihood of a major source of noise in the δ^{13}C signature. Beyond SOC, texture and the absence of carbonates and maize in the rotation, no further selection criteria were applied. In cases where several candidate samples were available, we chose the one closest to the desired SOC content.

2.2. Fractionation

Size fractionation was conducted with a size cut-off of 50 μm (Fig. 1), to comply with a majority of studies around the globe on POC and MAOC derived from size fractionation (Begill et al., 2023; Delahaie et al., 2024; Karunaratne et al., 2024). In brief, 30 g of 2 mm sieved soil was suspended in deionized water to a total volume of 150 ml in a 250 ml glass beaker. In the case of the sandiest soils (0–100 g kg^{-1} silt + clay), 40 g of 2 mm sieved soil was used to ensure sufficient MAOC and fPOC material to be isolated for further analyses. The suspension was subjected to 100 J ml^{-1} of ultrasonic, which has been found to be non-significantly different from the previously more common 450 J ml^{-1} regarding its dispersion efficiency, as measured by the range of the fraction of new carbon in POC and MAOC (Just et al., 2021). The latter also has the disadvantage that the sample starts boiling, if not cooled, which would certainly alter organic matter composition. Finally, 100 J ml^{-1} was also chosen as an intermediate energy setting to achieve both high dispersion and relatively low chance of POC disintegration.

For sonication, the tip of the 13 mm diameter sonotrode was immersed into the suspension by 1.5 cm. After dispersion, the sample was directly poured over a 50 μm sieve and sieved through using a pump

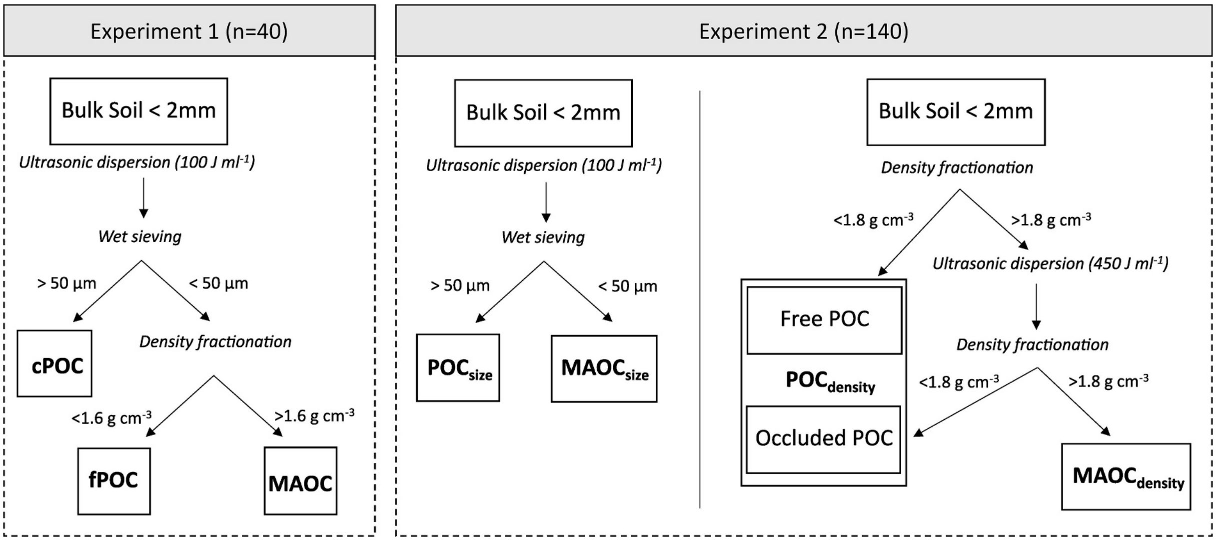

Fig. 1. Schematic overview of the fractionation methods used in the two different experiments (cPOC = coarse Particulare Organic Carbon, fPOC = fine Particulate Organic Carbon, MAOC = Mineral-Associated Organic Carbon, $MAOC_{size}$ = size fractionation derived MAOC and $MAOC_{density}$ = density fractionation derived MAOC).

spray. A gentle circulation of the suspension and particles on the sieve was ensured using the index finger, without rubbing the soil on the sieve. Sieving was considered complete, when the rinsing water was clear, which was checked using a fresh beaker underneath the sieve. The maximum rinsing water accepted was 2 l, which was sufficient in all cases. After sieving, the coarse fraction on the sieve was transferred into a glass bowl using the pump spray. The suspended fine fraction was centrifuged at 2000 g for 15 min, after which the supernatant was carefully decanted. It was attempted to decant as much water as possible without losing soil. In the next step, sodium polytungstate (SPT) solution with a density of 1.6 g cm^{-3} was added to the fine fraction to transfer it from the centrifuge vessels into 50 ml centrifuge tubes (Golchin et al., 1994). At least two tubes were needed for each soil, and the SPT soil suspension was filled up to at least 45 ml to allow for a clear separation between light and heavy particles. For fine textured soil, three tubes were needed. After filling in SPT, the falcon tubes were vortexed to enable the floating of fPOC and centrifuged at 2000 g for 10 min. Subsequently, the floating material and clear SPT was carefully decanted onto a 0.45 µm glass fibre filter. The decanted tubes containing the remaining fine fraction were filled again with SPT for a second time, vortexed and centrifuged again to ensure a complete removal of fPOC from the sample. Any floating material was collected on the same filter as before and finally washed with 0.25 l of deionized water using underpressure. The SPT solution was collected, filtered through 0.45 µm and recycled without further cleaning. Dilution of the SPT solution with the residual water in the soil samples was considered negligible and after 40 samples, the recycled SPT solution had a density of 1.5 g cm^{-3}. The soil remaining in the centrifuge tubes was washed to remove the SPT. To do so, the tubes were filled with deionized water, vortexed, centrifuged and decanted three times (10 min, 2000 g). All samples were dried at 60 °C and milled prior to further analysis. Only the fPOC was not milled, since its quantity was not sufficient. For homogenization, we gently crushed and stirred the dried fPOC with a spatula. Some of the samples had so little material, that it was completely used up for one analysis and for four samples, we did not observe any fPOC at all. Average mass recovery was 96.6 ± 1.8 % and average carbon recovery was 98.8 ± 14.0 %. Mass recovery was negatively correlated with clay content (R^2 = 0.23, data not shown), which can be explained by the fact that clay particles are most easily lost during the fractionation process (to a minor extent during decanting, and due to stickiness off the soil and vessels and tools).

By visual inspection, the fPOC fraction strongly glittered, which hinted towards a certain proportion of minerals that floated in the SPT solution. To take a closer look, several samples were inspected under a binocular with an 200-times amplification, which confirmed the high abundance of mineral-phase components. Generally, it might be easier and more common to perform a density fractionation step first, and then a size fractionation of both heavy and light fraction to derive coarse and fine POC and MAOC (Leuthold et al., 2024). However, here it was decided to perform a usual size fractionation, i.e. first potentially "contaminate" the fine fraction with fPOC and then try to quantify this contamination afterwards. It is unlikely that a changed order would have avoided the floating of minerals.

2.3. Comparing size and density fractionation

In the second part of this study (Experiment 2), two pre-existing datasets were compared to test if size and density fractionation would yield significantly different MAOC contents (Fig. 1). The first dataset was a density fractionation dataset (MAOC, occluded POC and free lighPOC) that was produced during the first German Agricultural Soil Inventory (Vos et al., 2018). The fractionation was based on the method described by Golchin et al. (1994) using a density of 1.8 g cm^{-3}. In that approach, two POC fractions are isolated, free and occluded POC, which were merged to $POC_{density}$ for the present study. In total, 145 topsoil samples were fractionated, selected to be representative for German agricultural mineral soils. The majority of these samples were fractionated in another context by size (50 µm cut-off), as described in 2.2 (unpublished), yet without a quantification of the fPOC fraction. We identified an overlap of 140 samples, which were available for a quantitative method comparison. Soil properties of this dataset covered wide ranges (e.g. clay contents between 9–600 g kg^{-1}, SOC contents between 8–79 g kg^{-1}, and pH($CaCl_2$) values between 3.5–7.5). It should be noted that the two methods varied in more methodological aspects than just the type of fractionation. For example, the density fractionation used an ultrasonic energy of 450 J ml^{-1}, which was applied in SPT, while the size fractionation set used an ultrasonic energy of 100 J ml^{-1} applied in deionized water.

2.4. Chemical analysis

The 120 samples of Experiment 1, i.e. coarse POC (cPOC), fPOC and

MAOC of 40 samples (Fig. 1), were analyzed for total C and nitrogen (N) contents as well as $\delta^{13}C$ using an isotope ratio mass spectrometer (DeltaPlus, Thermo Fisher Scientific, Waltham, MA, USA) coupled to an elemental analyzer (CE Instrument FLASH EA 1122NA 1500, Wigan UK). Both, $\delta^{13}C$ and C:N ratio were used as indicators for the degree of microbial transformation in the soil, with MAOC being expected to have a more positive $\delta^{13}C$ value and a narrower C:N ratio as POC (Krüger et al., 2024; Lavallee et al., 2020). The samples of the second part of the study (Experiment 2) were analyzed for C and N contents via dry combustion in an elemental analyzer (LECO, TruMac and RC612). Both machines are regularly compared with internal soil standards.

2.5. Statistical analysis

We used an additive forward stepwise regression approach to identify the most important explanatory variables for MAOC, cPOC and fPOC contents in the 40 fractionated soils. As candidates, we used bulk SOC, C:N ratio, clay, silt and sand content. C:N ratio was considered as indicator of organic matter quality and/or origin indicator (Vos et al., 2018). We checked collinearity of the explanatory variables in a correlation matrix and excluded those combinations with a Pearson correlation coefficient > 0.8. This was the case for silt and sand. Variables were added to the model, until no improvement was achieved, as checked by the Akaike Information Criterion (AIC). Approximate normal distribution of the model residuals was visually assessed using histograms and QQ-plots. In case of non-normality, the data was log-transformed. This was the case for fPOC content (additive regression model). The Breusch-Pagan test for homoscedasticity was used for the additive regression models using the package *lmtest* (Hothorn et al., 2015), and in case of heteroscedasticity, weighted least squares regressions were computed to build more robust model fits. This was done for all three dependent variables (Tab. 1). Furthermore, a Kruskal-Wallis-Test with Dunn-Test as *post-Hoc* test was conducted using the R package *rstatix* (Kassambara, 2021) to evaluate if the three fractions would significantly differ in C:N ratio and the natural abundance of ^{13}C ($\delta^{13}C$). A non-parametric test was needed, since variance homogeneity was not given, as revealed by a Levene-Test. Significance was generally assessed at a level of $p < 0.05$. Finally, we used a logarithmic model to describe the relationship between silt + clay content and the C loading of the fine fraction (including fPOC), which was better suited than a linear model, as evaluated using the AIC. All statistical analyses and plots were made in R, version 4.4.0 (Team, 2022).

3. Results

3.1. Distribution of organic carbon in different fractions

On average, 63.0 ± 23.5 % of the total SOC was stored as MAOC, 34.7 ± 20.9 % in cPOC and only 2.2 ± 4.2 % was recovered as fPOC (Fig. 2). A total of six soils (15 %) contained high to outlying high proportions of fPOC, reaching up to 18.2 % of total SOC. All were sandy soils with more than 50 % of total SOC being stored as POC (fPOC + cPOC). When excluding those six soils, the average value for the proportion of fPOC was 0.6 ± 3.3 %.

MAOC was strongly and positively correlated with initial SOC and clay content, explaining 62 % of the total variation (Tab. 1). The amount of cPOC was best explained by the model including SOC, clay content and C:N ratio ($R^2 = 0.77$). In both cases, clay content was a better predictor than silt + clay combined, or silt and sand alone. As expected, clay had a positive influence on MAOC, but a negative influence on cPOC (Tab. 1, Fig. S2). A log-transformation was necessary for fPOC, which was positively correlated with SOC and also negatively with clay content ($R^2 = 0.38$).

Table 1
Summary of the linear regression models built to explain mineral associated organic carbon (MAOC) content as well as coarse and fine particulate organic carbon (cPOC, fPOC) contents in g kg^{-1} with coefficients, their estimates and p values, and adjusted R^2 and p values.

Dependent Variable	Coefficient	Estimate	$p_{Coefficient}$	Adj. R^2_{Model}	p_{Model}
MAOC	Intercept	0.98	0.765	0.62	<0.001
	SOC	2.94	<0.001		
	Clay	0.61	<0.001		
cPOC	Intercept	11.02	0.118	0.77	<0.001
	SOC	7.19	<0.001		
	Clay	−0.66	<0.001		
	C:N ratio	−1.03	0.051		
log(fPOC + 1)	Intercept	0.41	0.029	0.38	<0.001
	SOC	0.14	<0.001		
	Clay	−0.03	<0.001		

3.2. Biogeochemical characteristics of the isolated fPOC fraction

The fPOC fraction had an average SOC content of 241.1 ± 126.6 g kg^{-1}. A pure, density derived POC fraction is expected to mainly consist of organic particles with SOC contents around 400 g kg^{-1} (typical C content of plant material). There was a bimodal distribution of the measured SOC contents with as many observations between 100–200 g kg^{-1} SOC as between 300–400 g kg^{-1} SOC (Fig. 3a). This is well in line with the visual inspections, which revealed significant contents of minerals in the isolated fPOC fraction. Indeed, the OC content of the fPOC fraction was negatively correlated with clay content, indicating the floating of clay minerals during density fractionation (Fig. 3b). Furthermore, C:N ratios and $\delta^{13}C$ values of fPOC were generally closer to MAOC than to cPOC (Figs. 4a and 4b), i.e. less negative and less wide, respectively. The average differences between MAOC and cPOC as well as between fPOC and cPOC were highly significant for both parameters, while no significant difference was found for MAOC and fPOC (Tab. 2).

3.3. C loading of the fine fraction with and without the contribution of fPOC

The OC loading of the total fine fraction followed an exponential decline with increasing silt + clay contents (Fig. 5a, AIC of 436 for the logarithmic fit, AIC of 441 for the alternative linear fit). As expected, the OC-rich soils had a generally higher OC loading than C-poorer soils. However, with increasing silt + clay content, the difference in OC loading between soils of contrasting SOC levels decreased. When substracting the fPOC fraction from MAOC, the pattern remained similar yet with a less drastic decrease in the low silt + clay content range (Fig. 5b). Also, as informed by the AIC, there was no justification for a logarithmic fit in those corrected MAOC values (AIC of 411 for logarithmic fit, AIC of 409 for linear fit). Soils with a silt + clay content of less than 300 g kg^{-1} had an average OC loading of 107.5 ± 48.6 g kg^{-1}, those with the fPOC included had an average OC loading of 152.5 ± 91.6 g kg^{-1}.

3.4. Comparing density and size fractionation of inventory samples

The proportions and absolute contents of MAOC derived from density and size fractionation as compared for 140 agricultural soils were very similar for soils below a sand content of 800 g kg^{-1} and a SOC content of 20 g kg^{-1} (Fig. 6a). However, for OC-rich sandy soils, the $MAOC_{density}$ content was much lower than the $MAOC_{size}$ content. At the other end, very fine-textured soils (sand content < 200 g kg^{-1}) tended to have slightly less MAOC when isolated by size fractionation than by density. Accordingly, the effect of SOC on the difference between the two methods was texture-dependent (Fig. 6b). In sandy soils, increasing SOC content led to an increasing difference between $MAOC_{size}$ and $MAOC_{density}$ towards higher $MAOC_{size}$ contents. However, for the most fine-textured soils, a slight opposing trend was observed, i.e., a tendency of more $MAOC_{density}$ than $MAOC_{size}$ with increasing SOC content.

When OC-rich sandy soils (n = 22) were separated from the dataset,

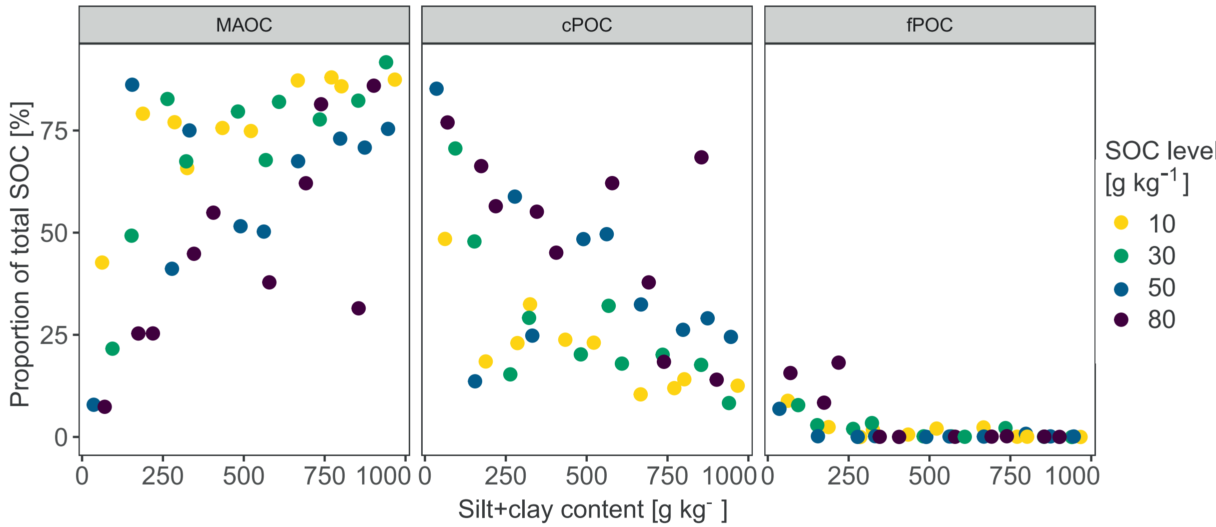

Fig. 2. Proportions of total soil organic carbon (SOC) for mineral-associated organic carbon (MAOC), coarse particulate organic carbon (cPOC) and fine particulate organic carbon (fPOC) in all fractionated soils of Experiment 1 as a function of silt and clay content, n = 40.

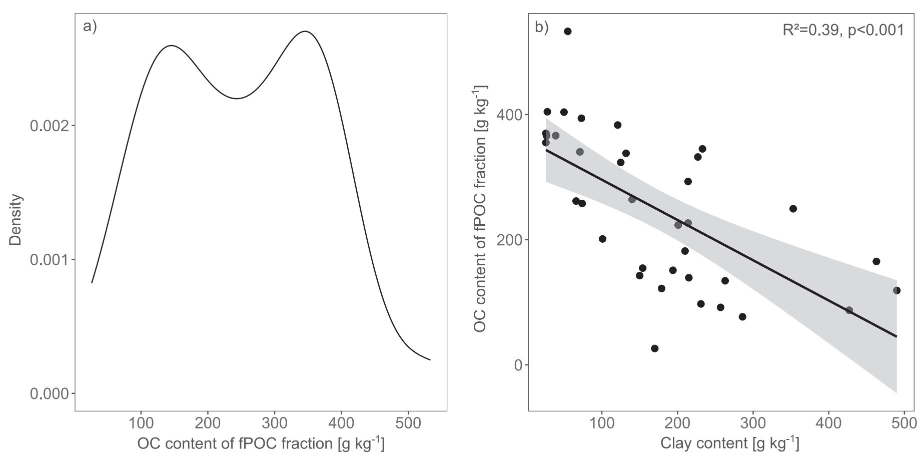

Fig. 3. A) density distribution of the organic carbon contents measured in the fine particulate organic carbon (fpoc) fraction, b) organic carbon contents of the fPOC fraction as a function of clay content with linear regression, its 95 % confidence interval as well as coefficient of determination (R^2) and p value, n = 36.

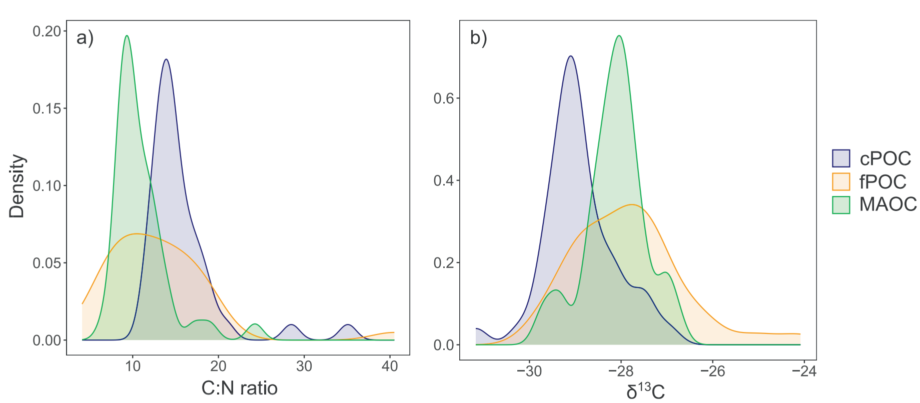

Fig. 4. Density distributions of measured a) carbon to nitrogen ratios and b) $\delta^{13}C$ values in the fine particulate organic carbon (fPOC) fraction as compared to coarse particulate organic carbon (cPOC) and mineral-associated organic carbon (MAOC), n = 40 for MAOC and cPOC, n = 36 for fPOC.

both methods yielded almost identical average MAOC and POC contents (Fig. 7a). For POC, size and density fractionation yielded average contents of 4.8 ± 4.7 and 4.6 ± 3.8 g kg^{-1}, respectively; average MAOC contents were 20.5 ± 12.9 and 20.7 ± 14.5 g kg^{-1} for size and density. In contrast, the proportions of POC and MAOC did not match for the separated sandy soils (Fig. 7b).

Table 2
Summary of the analysis of variance conducted to test for differences in the $\delta^{13}C$ value and the C:N ratio between the three fractions mineral associated organic carbon (MAOC), as well as coarse and fine particulate organic carbon (cPOC, fPOC).

Dependent Variable	p_{Model}	Dunn test pair	p_{Tukey}
$\delta^{13}C$	<0.001	fPOC-cPOC	<0.001
		MAOC-cPOC	<0.001
		MAOC-fPOC	0.56
C:N ratio	<0.001	fPOC-cPOC	0.001
		MAOC-cPOC	<0.001
		MAOC-fPOC	0.059

4. Discussion

4.1. Contamination of MAOC with fine POC

In Experiment 1, we investigated the potential contamination of size-fractionation derived MAOC fractions in an SOC-texture matrix. It has been suggested, that depending on soil properties, such operational bias can be significant (Cotrufo et al., 2023; Lavallee et al., 2020), while a comprehensive assessment was missing. For temperate agricultural soils, the contamination of MAOC with fPOC was negligible in the vast majority of soils. On average, it did not account for more than 2.2 ± 4.2 % of total SOC, with only 6 out of 40 soils having more than 3 % of fPOC (Fig. 2). Those six soils had an average sand content of 86 %, and average C:N ratio of 15 and the proportion of SOC stored as MAOC was very low (on average 28 %), which is in line with the suggestion of Six et al. (2024), that fPOC contamination of MAOC might particularly be problematic in soils rich in POC. It has been observed before, that OC-rich sandy soils with wide C:N ratios (previously named 'black sands') can have extraordinarily high (potentially refractory) POC contents with unique organic matter chemistry, most likely due to their land cover history as peatland or heathlands (Springob and Kirchmann, 2002; Vos et al., 2018). The experiment thus identified a group of soils, in which fPOC contamination is highly relevant. For the 34 other soils, the proportion of fPOC was on average 0.5 % of total SOC, or 0.8 % of total MAOC. This is smaller than the cumulative random error that fractionation comes along with, involving subsampling inaccuracies, losses or redistribution of carbon during different fractionation steps, as well as analytical errors of elemental analysis. For example, in a method comparison by Poeplau et al. (2018), the most similar method to the size fractionation performed in this study (Sanderman et al., 2013) had an average coefficient of variation of 3 % for the MAOC fraction. Also, a carbon recovery between 90 and 110 % is typically expected (Poeplau et al., 2018), no matter how accurate and thoroughly the actual fractionation is conducted. For lack of an alternative, any deviation from 100 % (of the bulk SOC value) is corrected through all fractions equally (Jaconi et al., 2019). This is likely to cause higher biases than adding fPOC to MAOC, since e.g. the loss of carbon is likely to be unequally distributed during fractionation and a recovery of more than 100 % might be mainly driven by individual POC particles than by MAOC. Finally, the order of magnitude of observed fPOC contents was comparable to that previously observed for dissolved, i.e. cold water extractable organic carbon (Zimmermann et al., 2007). Depending on the actual protocol, this rather labile fraction is either added to MAOC

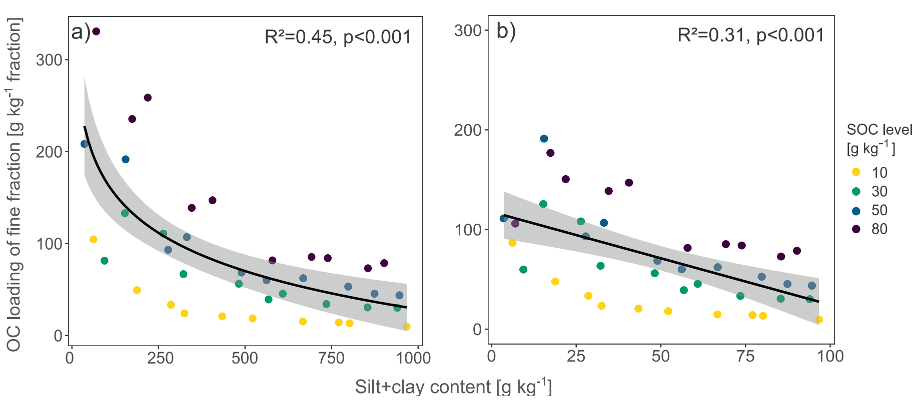

Fig. 5. Organic carbon loading of the fine fraction as a function of silt + clay content in the fractionated soils of Experiment 1. In a) the contaminating fine particulate organic carbon fraction was included in the calculation of loading, in b) it was excluded. Black lines are loess regression fits with 95 % confidence interval in gray, n = 40.

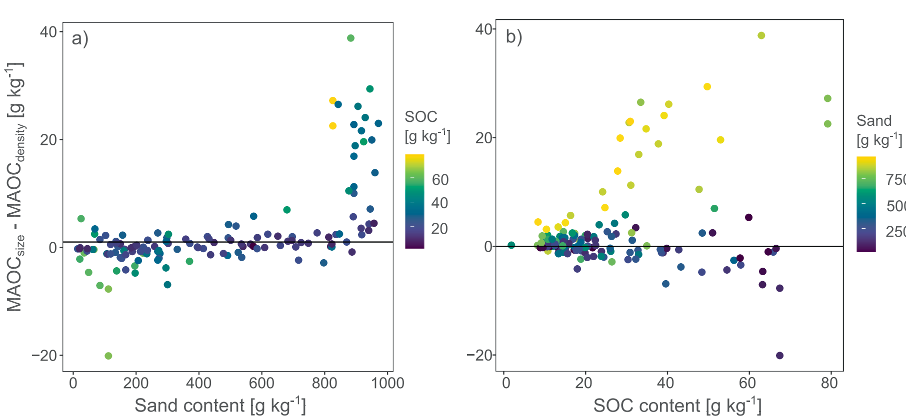

Fig. 6. Difference between size and density-derived mineral associated organic carbon (MAOC) contents as a function of a) sand content and b) soil organic carbon (SOC) content of 140 soils of the German Agricultural Soil inventory.

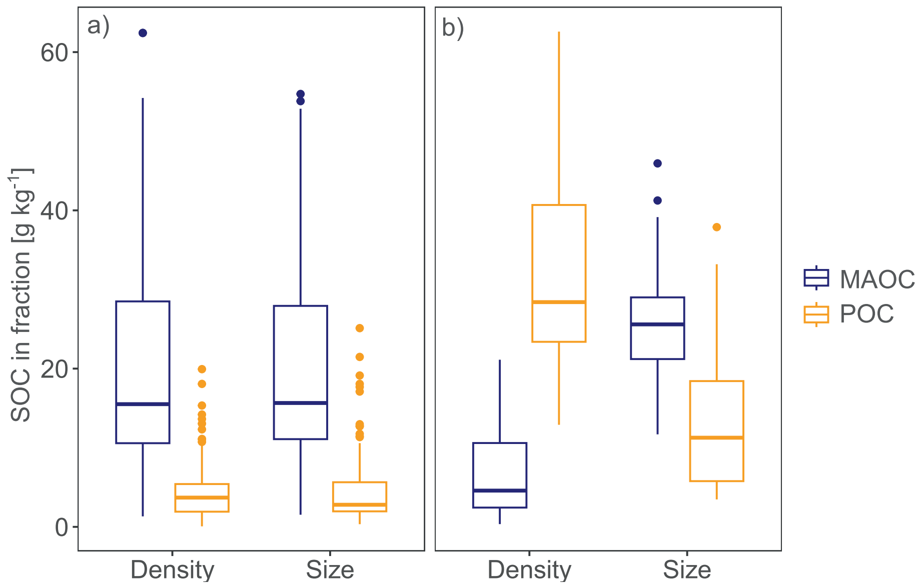

Fig. 7. Density and size-derived mineral-associated organic carbon (MAOC) contents and particulate organic carbon (POC) contents for two different clusters of soils a) all soils excluding 22 OC-rich sandy soils (n = 118) and b) the 22 OC-rich sandy soils only.

(when suspension is fully dried), or discarded (after centrifugation), then observed as a loss of carbon and finally redistributed to MAOC and POC to equal shares – in essence, it is ignored.

Apart from the fact that the fPOC fraction was of minor quantitative importance, its qualitative assessment revealed that its presence in the MAOC fraction might not even be considered a contamination. First of all, the average C content of the fPOC fraction was 241 g kg^{-1}, although approximately 400 g kg^{-1} is expected for pure plant material. This reveals that it contained a considerable amount of mineral particles, and thus also contaminated with MAOC to some extent. It is well known that a certain fraction of mineral particles start floating during density fractionation (Six et al., 2024), may it be due to their high surface area or because they are attached to lighter organic particles. This highlights that also density fractionation cannot lead to a completely 'clean' separation of MAOC and POC, especially in fine-textured soils (Fig. 3b). The isotopic signature of the fPOC fraction as well as the C:N ratio, both indicators of the degree of organic matter transformation, rather resembled MAOC than POC (Fig. 4). This is well in line with the observation of Poeplau et al. (2018), who found that the fine light fraction of three different soils was closer to the fine heavy fraction than the coarse light fraction regarding its enrichment of new, C4-derived carbon. It mainly highlights the imperfection of both these two-pool fractionation approaches.

While the amount of cPOC and MAOC could be well explained by SOC and clay content (Begill et al., 2023; Matus, 2021), and for cPOC also C:N ratio, there was no strong general pattern to explain fPOC. While SOC and clay content were significantly correlated with fPOC content, those correlations were strongly driven by the few sandy soils with very high fPOC contents (Fig. 2). It was thus not possible to derive some kind of transfer function from the current study to potentially correct MAOC for fPOC.

4.2. Size or density fractionation?

The larger dataset including 140 soils (Experiment 2) confirmed the findings of the first experiment, i.e. that fPOC contamination in size-derived MAOC is negligible for a wide range of soils. Despite the large differences between the two compared protocols, including a different ultrasonic dispersion energy, average POC and MAOC contents were almost identical for a relatively large and diverse sample set of agricultural soils excluding OC-rich sandy soils (Figs. 6, 7). At least for the majority of temperate agricultural soils, it can thus be assumed that quantitative results of studies based on size-derived fractions are not strongly biased by the methodological choice (Begill et al., 2023). Leuthold et al. (2024) also found no quantitative difference between size and density-derived MAOC across a similarly wide range of agricultural soils from farms in the United States.

For OC-rich sandy soils (>800 g kg^{-1} sand, >20 g kg^{-1} SOC), size and density fractionation were not comparable at all. The most obvious reason for this is that they store a large proportion of their total SOC as fPOC, which is erroneously accounted for as MAOC during size fractionation. The average C:N ratio of 17.1 ± 3.7 confirms the distinct composition, origin and most likely also stability of SOC in these soils (Sleutel et al., 2008). It is likely that the general concept of size or density fractionation to derive relatively stable and labile fractions might not be applicable to this specific group of soils, since mineral association may not be the most important stabilization mechanism and since POC might be relatively stable. This is suggested by the fact that the organic matter of those soils is likely to originate from the historic land cover (peatland or heathland), which can be centuries ago (Vos et al., 2018). An ultimate proof of exceptional biogeochemical stability of the organic matter in such OC-rich sandy soils is however missing, which warrants further investigations.

Interestingly, for very fine-textured soils, an opposite tendency was observed, i.e. $MAOC_{size}$ was smaller than $MAOC_{density}$. In this case, it could indeed be related to a somewhat incomplete dispersion of aggregates, which was then isolated in the POC fraction after size fractionation. As described above, we used an ultrasonic dispersion energy of 100 J ml^{-1} for the size fractionation, while 450 J ml^{-1} was used for the density fractionation. Just et al. (2021) found no average difference between the two, apart from clay-rich soils, indicating a somewhat incomplete dispersion of aggregates in this case. It is thus possible that the observed difference between $MAOC_{size}$ and $MAOC_{density}$ in fine-textured soils of this study was rather related to the ultrasonic pretreatment than the fractionation method itself. With a density of 1.8 g cm^{-3}, even more fine particles might have been floating during density fractionation of Experiment 2. However, obviously this did not counterbalance the potential ultrasonic bias in this case.

This study was not designed to ultimately define which fractionation method should be used in future studies to isolate POC and MAOC. Nevertheless, the results help to further classify both approaches and their advantages and disadvantages to some extent. Both have been carried out for many decades (Cambardella and Elliott, 1993), which has led to a huge datasets that can be mined and used for comprehensive investigations (Georgiou et al., 2022; Matus, 2021). It is never straightforward to compare and merge fractionation results from different studies, since protocols never fully align. The two experiments in this study revealed, that methodological biases (due to dispersion and fractionation method) depend on soil properties, such as texture. The combination of size and density fractionated POC and MAOC contents in larger syntheses across wide texture gradients, should thus be avoided or treated with great care. Nevertheless, the present study, as well as earlier investigations (Leuthold et al., 2024), also suggest that the quantitative difference between size and density derived POC and MAOC is small for a wide range of soils. Size fractionation is far cheaper and faster than density fractionation and thus better suited for high-throughput applications or to get a general rough idea about the proportion of SOC in both fractions. It usually has a higher recovery and reproducibility than density fractionation, which makes it a more robust method against random and systematic laboratory errors (Poeplau et al., 2018). Also, to study the interaction of organic matter and reactive minerals, i.e. clay or short range order minerals, it is more advantageous to isolate a fine fraction directly, instead of isolating a bulk mineral fraction (Eusterhues et al., 2005). Concepts of mineralogical storage capacity are generally based on fine fraction OC (Georgiou et al., 2022; Karunaratne et al., 2024). Furthermore, according to the present study, the fine POC fraction is often more similar to MAOC than to coarse POC, which has also been found in a comprehensive method comparison using soils that had a C3-C4 vegetation change (Poeplau et al., 2018). For a maximum split in kinetic properties between the two fractions, size fractionation might thus still be preferable (Poeplau et al., 2018). The similarity of fPOC and MAOC also highlights that density fractionation cannot be free of contamination, since clay particles with associated MAOC floats at a relatively low density (here 1.6 g cm^{-3}). Nevertheless, pure size fractionation will always have a double contamination issue, i.e. coarse MAOC in the so-called POC fraction (Leuthold et al., 2024), and fine POC in the so-called MAOC fraction. Even though both these contaminations might be negligible in size for many soils and potentially even level each other out approximately, they can lead to huge biases and potentially wrong interpretations in certain soils (Six et al., 2024). This is a serious short-coming of size fractionation that should certainly not be ignored: OC-rich sandy soils, and potentially also other soils rich in POC, such as forest soils, should not be fractionated by size alone.

One potential way forward can be a combined size-density fractionation (Leuthold et al., 2024; Wasner et al., 2024), which would increase the number of isolated fractions. Depending on the research question, the isolation of multiple fractions should indeed be (re-) considered. It has been shown that this large fraction, which can account for more than 80 % of bulk SOC in agricultural soils, is in fact rather active (Poeplau et al., 2023; Ridgeway et al., 2022). Most likely, this is only true for a part of it (Torn et al., 2013), so an additional fractionation step, or an additional measurement, could split MAOC into two more homogeneous fractions. Chemical oxidation is one example, which was shown to isolate a somewhat meaningful fraction that is positively correlated to Fe and Al (hydr)oxides in soils (Mikutta and Kaiser, 2011). At the same time, the authors also found a negative correlation of the chemically oxidized OC and the amount of OC that was mineralized in a 90 days incubation, concluding that these pools did not align well with each other. Another option could be the isolation of an intermediately stable pool, which could comprise fPOC, aggregate-occluded POC, as well as the rather loosely bound MAOC (e.g. organo-organo interactions) (Wasner et al., 2024). Finally, also the combination of simple size or density fractionation with additional measurements such as RockEval or infrared spectroscopy, to get an idea of the proportion of stable OC in MAOC might be a way to better characterize this large and heterogenous MAOC pool (Baldock et al., 2013; Schiedung et al., 2025). It should however be kept in mind, that the phyisco-chemical alterations of soils during fractionation may also affect the thermal and spectral properties of the isolated fractions to some extent.

4.3. How to interpret high organic carbon loadings of the fine fraction in sandy soils?

Sandy soils have been found to have higher OC loadings of the fine fraction than more fine-textured soils (Poeplau et al., 2024; Schweizer et al., 2021). This has been used as an argument, that the mineralogical capacity to store MAOC i) cannot be directly derived from a linear regression between content of fine fraction and MAOC across all texture classes and that ii) maximum observed MAOC contents in fine-textured soils are rather limited by available C inputs than by the reactive surface area of minerals (Poeplau et al., 2024). In other words: if the fine fraction of sandy soils can become very enriched in OC (with OC loadings of 150 g kg^{-1} silt and clay), there is no obvious reason other than too little C inputs why this should not be possible in more fine-texture soils. In that way, this finding challenged the postulated maximum OC loading of ~ 80–86 g OC per kg fine fraction (Georgiou et al., 2022; Six et al., 2024). However, it is possible that high OC loadings in sandy soils are an artefact of size fractionation via the contamination of fPOC to some degree (Georgiou et al., 2025). In the present study, it became very clear that this is true for OC-rich sandy soils. Therefore, it can indeed be problematic to calculate OC loadings for those. The same absolute amount of fPOC will affect OC loading in a very different way across the whole texture range. However, the first experiment of this study (Fig. 5) revealed that even after an additional step of density fractionation, the exponential negative relationship between OC loading of the fine fraction and fine fraction content remained highly significant. Soils with up to 30 % silt and clay had average fine fraction OC loadings of > 100 g kg^{-1}, which is well in line with the range observed by (Poeplau et al., 2024). It can thus be concluded that high OC loadings in sandy soils are sensitive to bias, yet most likely not exclusively explicable by such. Absolute values of OC loading should however not be directly derived from published size fractionation data.

5. Conclusions

This study is the first to systematically quantify potential bias of size fractionation to derive mineral-associated organic carbon in diverse temperate agricultural soils (Experiment 1). Not all carbon recovered in the fraction < 50 μm was mineral-associated, yet the average contribution of fine particle organic carbon to the so-called MAOC fraction was negligible for a wide range of soils. Furthermore, the isolated fine POC fraction was contaminated by minerals and therefore also MAOC. It is thus clear that also density fractionation does not lead to pure, uncontaminated POC and MAOC fractions. Size and density fractionation were well comparable for a wide range of soils (Experiment 2), despite differences in dispersion energies. However, in both experiments, MAOC of OC-rich sandy was strongly overestimated by size fractionation, which should be avoided for those soils. At the same time, density fractionation also has other disadvantages, such as lower recovery and reproducibility, which suggest that size fractionation might remain a good option for most soils. A method that combines the principles of size and density might be advisable, when high POC contents are expected. By doing so (Experiment 1), we revealed that the high OC-loadings in the fine fraction of sandy soils, as reported before, are not entirely artefacts but could have mechanistic reasons. Physical fractionation of soils to derive SOC pools of different functions and biogeochemical stability is currently more popular and at the same time more simplified than ever before. It should however be kept in mind, that it will always be rather imprecise compared to other analytical methods such as elemental analysis. Furthermore, especially the two-fractions approach remains superficial regarding its information content, since any intermediately stable carbon is inevitably submerged into either the labile or stable carbon fraction.

CRediT authorship contribution statement

Christopher Poeplau: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria Skovgaard Andersen:** Writing – review & editing, Methodology, Investigation. **Cora Vos:** Writing – review & editing, Methodology, Investigation.

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

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References

Amelung, W., Zech, W., 1999. Minimisation of organic matter disruption during particle-size fractionation of grassland epipedons. Geoderma 92 (1–2), 73–85.
Baldock, J.A., Sanderman, J., Macdonald, L.M., Puccini, A., Hawke, B., Szarvas, S., McGowan, J., 2013. Quantifying the allocation of soil organic carbon to biologically significant fractions. Soil Res. 51 (8), 561–576.
Begill, N., Don, A., Poeplau, C., 2023. No detectable upper limit of mineral-associated organic carbon in temperate agricultural soils. Global Change Biology N/a(n/a).
Cambardella, C.A., Elliott, E.T., 1993. Methods for physical separation and characterization of soil organic matter fractions. Geoderma 56 (1–4), 449–457.
Cécillon, L., Baudin, F., Chenu, C., Christensen, B.T., Franko, U., Houot, S., Kanari, E., Kätterer, T., Merbach, I., van Oort, F., Poeplau, C., Quezada, J.C., Savignac, F., Soucémarianadin, L.N., Barré, P., 2021. Partitioning soil organic carbon into its centennially stable and active fractions with machine-learning models based on Rock-Eval® thermal analysis (PARTYSOCv2.0 and PARTYSOCv2.0EU). Geosci. Model Dev. 14 (6), 3879–3898.
Cerli, C., Celi, L., Kalbitz, K., Guggenberger, G., Kaiser, K., 2012. Separation of light and heavy organic matter fractions in soil — Testing for proper density cut-off and dispersion level. Geoderma 170, 403–416.
Christensen, B.T., 1985. Carbon and Nitrogen in Particle size Fractions Isolated from danish Arable Soils by Ultrasonic Dispersion and Gravity-Sedimentation. Acta Agric. Scand. 35 (2), 175–187.
Cotrufo, M.F., Lavallee, J.M., Six, J., Lugato, E., 2023. The robust concept of mineral-associated organic matter saturation: a letter to Begill et al., 2023. Glob. Chang. Biol. 29 (21).
Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. Nat. Geosci. 12 (12), 989–994.
Curtin, D., Beare, M.H., Qiu, W., Sharp, J., 2019. Does Particulate Organic Matter Fraction Meet the Criteria for a Model Soil Organic Matter Pool? Pedosphere 29 (2), 195–203.
Delahaie, A.A., Cécillon, L., Stojanova, M., Abiven, S., Arbelet, P., Arrouays, D., Baudin, F., Bispo, A., Boulonne, L., Chenu, C., Heinonsalo, J., Jolivet, C., Karhu, K., Martin, M., Pacini, L., Poeplau, C., Ratié, C., Roudier, P., Saby, N.P.A., Savignac, F., Barré, P., 2024. Investigating the complementarity of thermal and physical soil organic carbon fractions. Soil 10 (2), 795–812.
Eusterhues, K., Rumpel, C., Kögel-Knabner, I., 2005. Organo-mineral associations in sandy acid forest soils: importance of specific surface area, iron oxides and micropores. Eur. J. Soil Sci. 56 (6), 753–763.
Georgiou, K., Angers, D., Champiny, R.E., Cotrufo, M.F., Craig, M.E., Doetterl, S., Grandy, A.S., Lavallee, J.M., Lin, Y., Lugato, E., Poeplau, C., Rocci, K.S., Schweizer, S.A., Six, J., Wieder, W.R., 2025. Soil Carbon Saturation: what do we really know? Glob. Chang. Biol. 31 (5), e70197.
Georgiou, K., Jackson, R.B., Vindušková, O., Abramoff, R.Z., Ahlström, A., Feng, W., Harden, J.W., Pellegrini, A.F.A., Polley, H.W., Soong, J.L., Riley, W.J., Torn, M.S., 2022. Global stocks and capacity of mineral-associated soil organic carbon. Nat. Commun. 13 (1), 3797.
Golchin, A., Oades, J., Skjemstad, J., Clarke, P., 1994. Study of free and occluded particulate organic matter in soils by solid state ^{13}C Cp/MAS NMR spectroscopy and scanning electron microscopy. Soil Res. 32 (2), 285–309.
Guggenberger, G., Christensen, B.T., Zech, W., 1994. Land-use effects on the composition of organic-matter in particle-size separates of soil. 1. Lignin and carbohydrate signature. Eur. J. Soil Sci. 45 (4), 449–458.
Helbling, E., Pierson, D., Lajtha, K., 2021. Sources of soil carbon loss during soil density fractionation: Laboratory loss or seasonally variable soluble pools? Geoderma 382, 114776.
Hothorn, T., Zeileis, A., Farebrother, R.W., Cummins, C., Millo, G., Mitchell, D., Zeileis, M.A., 2015. Package 'lmtest'. Testing linear regression models 6.
Jacobs, A., Poeplau, C., Weiser, C., Fahrion-Nitschke, A., Don, A., 2020. Exports and inputs of organic carbon on agricultural soils in Germany. Nutrient Cycling in. Agroecosystems.
Jaconi, A., Poeplau, C., Ramirez-Lopez, L., Van Wesemael, B., Don, A., 2019. Log-ratio transformation is the key to determining soil organic carbon fractions with near-infrared spectroscopy. Eur. J. Soil Sci.
Janzen, H.H., van Groenigen, K.J., Powlson, D.S., Schwinghamer, T., van Groenigen, J. W., 2022. Photosynthetic limits on carbon sequestration in croplands. Geoderma 416, 115810.
Just, C., Poeplau, C., Don, A., van Wesemael, B., Kögel-Knabner, I., Wiesmeier, M., 2021. A simple Approach to Isolate Slow and Fast Cycling Organic Carbon Fractions in central European Soils—Importance of Dispersion Method. Front. Soil Sci. 1 (13).
Karunaratne, S., Asanopoulos, C., Jin, H., Baldock, J., Searle, R., Macdonald, B., Macdonald, L.M., 2024. Estimating the attainable soil organic carbon deficit in the soil fine fraction to inform feasible storage targets and de-risk carbon farming decisions. Soil Res. 62 (2), -.
Kassambara, A., 2021. rstatix: Pipe-friendly framework for basic statistical tests. R Package Version (7).
Kleber, M., Bourg, I.C., Coward, E.K., Hansel, C.M., Myneni, S.C.B., Nunan, N., 2021. Dynamic interactions at the mineral–organic matter interface. Nature Reviews Earth & Environment 2 (6), 402–421.
Krüger, N., Finn, D.R., Don, A., 2024. Soil depth gradients of organic carbon-13–A review on drivers and processes. Plant and Soil 495 (1), 113–136.
Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob. Chang. Biol. 26 (1), 261–273.
Leuthold, S., Lavallee, J.M., Haddix, M.L., Cotrufo, M.F., 2024. Contrasting properties of soil organic matter fractions isolated by different physical separation methodologies. Geoderma 445, 116870.
Lützow, M.v., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. European Journal of Soil Science 57(4), 426-445.
Matus, F.J., 2021. Fine silt and clay content is the main factor defining maximal C and N accumulations in soils: a meta-analysis. Sci. Rep. 11 (1), 6438.
Mikutta, R., Kaiser, K., 2011. Organic matter bound to mineral surfaces: Resistance to chemical and biological oxidation. Soil Biol. Biochem. 43 (8), 1738–1741.
Moni, C., Derrien, D., Hatton, P.J., Zeller, B., Kleber, M., 2012. Density fractions versus size separates: does physical fractionation isolate functional soil compartments? Biogeosciences 9 (12), 5181–5197.
Paul, E., Morris, S., Bohm, S., 2001. The determination of soil C pool sizes and turnover rates: biophysical fractionation and tracers. Assessment Methods for Soil Carbon 14, 193–206.
Poeplau, C., Begill, N., Liang, Z., Schiedung, M., 2023. Root litter quality drives the dynamic of native mineral-associated organic carbon in a temperate agricultural soil. Plant and Soil 491 (1), 439–456.
Poeplau, C., Dechow, R., Begill, N., Don, A., 2024. Towards an ecosystem capacity to stabilise organic carbon in soils. Glob. Chang. Biol. 30 (8), e17453.
Poeplau, C., Don, A., Six, J., Kaiser, M., Benbi, D., Chenu, C., Cotrufo, M.F., Derrien, D., Gioacchini, P., Grand, S., 2018. Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils–a comprehensive method comparison. Soil Biol. Biochem. 125, 10–26.
Poeplau, C., Jacobs, A., Don, A., Vos, C., Schneider, F., Wittnebel, M., Tiemeyer, B., Heidkamp, A., Prietz, R., Flessa, H., 2021. Stocks of organic carbon in German agricultural soils—Key results of the first comprehensive inventory. n/a(n/a).
Ridgeway, J.R., Morrissey, E.M., Brzostek, E.R., 2022. Plant litter traits control microbial decomposition and drive soil carbon stabilization. Soil Biol. Biochem. 175, 108857.
Rocci, K.S., Cotrufo, M.F., Ernakovich, J., Foster, E., Frey, S., Georgiou, K., Grandy, A.S., Malhotra, A., Reich, P.B., Schlerman, E.P., 2024. Bridging 20 years of soil organic matter frameworks: empirical support, model representation, and next steps. J. Geophys. Res. Biogeo. 129 (6), e2023JG007964.
Sanderman, J., Fillery, I.R.P., Jongepier, R., Massalsky, A., Roper, M.M., Macdonald, L. M., Maddern, T., Murphy, D.V., Baldock, J.A., 2013. Carbon sequestration under subtropical perennial pastures II: Carbon dynamics. Soil Res. 51 (8), 771–780.
Schiedung, M., Barré, P., Peoplau, C., 2025. Separating fast from slow cycling soil organic carbon – a multi-method comparison on land use change sites. Geoderma 453, 117154.
Schweizer, S.A., Mueller, C.W., Höschen, C., Ivanov, P., Kögel-Knabner, I., 2021. The role of clay content and mineral surface area for soil organic carbon storage in an arable toposequence. Biogeochemistry 156 (3), 401–420.

Six, J., Doetterl, S., Laub, M., Müller, C.R., Van de Broek, M., 2024. The six rights of how and when to test for soil C saturation. Soil 10 (1), 275–279.

Six, J., Guggenberger, G., Paustian, K., Haumaier, L., Elliott, E.T., Zech, W., 2001. Sources and composition of soil organic matter fractions between and within soil aggregates. Eur. J. Soil Sci. 52 (4), 607–618.

Sleutel, S., Leinweber, P., Begum, S.A., Kader, M.A., Van Oostveldt, P., De Neve, S.J.B., 2008. Composition of Organic Matter in Sandy Relict and Cultivated Heathlands as Examined by Pyrolysis-Field Ionization MS. 89 (2), 253–271.

Springob, G., Kirchmann, H., 2002. C-rich sandy Ap horizons of specific historical land-use contain large fractions of refractory organic matter. Soil Biol. Biochem. 34 (11), 1571–1581.

Team, R.C., 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. R version 4.4. 0.

Torn, M.S., Kleber, M., Zavaleta, E.S., Zhu, B., Field, C.B., Trumbore, S.E., 2013. A dual isotope approach to isolate soil carbon pools of different turnover times. Biogeosciences 10 (12), 8067–8081.

Trumbore, S.E., Vogel, J.S., Southon, J.R., 1989. AMS C-14 Measurements of fractionated soil organic matter- an approach to deciphering the soil carbon cycle. Radiocarbon 31 (3), 644–654.

van Wesemael, B., Chartin, C., Wiesmeier, M., von Lützow, M., Hobley, E., Carnol, M., Krüger, I., Campion, M., Roisin, C., Hennart, S., Kögel-Knabner, I., 2019. An indicator for organic matter dynamics in temperate agricultural soils. Agr Ecosyst Environ 274, 62–75.

Vos, C., Jaconi, A., Jacobs, A., Don, A., 2018. Hot regions of labile and stable soil organic carbon in Germany–Spatial variability and driving factors. Soil 4 (2), 153–167.

Wasner, D., Abramoff, R., Griepentrog, M., Venegas, E.Z., Boeckx, P., Doetterl, S., 2024. The Role of climate, Mineralogy and Stable Aggregates for Soil Organic Carbon Dynamics along a Geoclimatic Gradient. Global Biogeochem. Cycles 38 (7), e2023GB007934.

Witzgall, K., Vidal, A., Schubert, D.I., Höschen, C., Schweizer, S.A., Buegger, F., Pouteau, V., Chenu, C., Mueller, C.W., 2021. Particulate organic matter as a functional soil component for persistent soil organic carbon. Nat. Commun. 12 (1), 4115.

Zimmermann, M., Leifeld, J., Schmidt, M.W.I., Smith, P., Fuhrer, J., 2007. Measured soil organic matter fractions can be related to pools in the RothC model. Eur. J. Soil Sci. 58 (3), 658–667.