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# Underestimation of carbon dioxide emissions from organic-rich agricultural soils



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Organic-rich agricultural soils, including drained peatlands, are hotspots for biogenic $CO_2$ emissions. Due to microbial mineralisation, the organic carbon (OC) content of these soils transitions to that of mineral soils, but it remains unclear how the residual OC content controls the rate of $CO_2$ emission. Here we show that area-scaled $CO_2$ emissions from topsoils with >6% OC are not controlled by OC content and OC density in a comprehensive laboratory incubation experiment. National greenhouse gas inventories assign area-scaled $CO_2$ emission factors to soils with >12% OC, while soils with 6-12% OC are mostly disregarded or treated with lower emission factors. In this respect, our results suggest that $CO_2$ emissions from organic soils could be underestimated by up to 40% in the Danish national inventory submission to the United Nations Framework Convention on Climate Change (UNFCCC). We conclude that global underestimation of area-scaled $CO_2$ emissions from 6-12% OC soils occurs in countries with large proportions of organic soils in transition from organic to organo-mineral soils due to agricultural management. Refining $CO_2$ emission estimates for 6-12% OC soils is critical for the accuracy of national inventories, but also for recognising the climate benefits of initiatives to rewet drained organic soils.

Organic-rich soils, such as peatlands, have developed over centuries to millennia under water-logged conditions, where aerobic microbial mineralisation of decaying plant material is inhibited by low oxygen ($O_2$) diffusion[1–3]. The OC content of peat soils can exceed 45% (wt/wt) and represents a terrestrial carbon (C) pool of approximately 600 Gt C, compared to 875 Gt of $CO_2$-C in the contemporary atmosphere[4,5]. Therefore, the dynamics of $CO_2$ uptake and release from organic-rich soils are critical to past and future atmospheric $CO_2$ levels and climate change trajectories[6–8].

Millions of hectares of organic-rich soils are managed for agricultural purposes, mainly as productive cropland or grasslands[4,9]. This involves artificial drainage and other practices (liming, fertilisation, tillage) that alter the physical and biochemical properties of the soils[10,11]. In particular, drainage increases the supply of $O_2$ to the soil microorganisms, leading to high $CO_2$ emissions from the mineralisation of the accumulated organic matter[11,12]. Globally, drained peat soils alone emit 2 Gt $CO_2$ equivalents per year[4], resulting in large proportions of soils being in transition from true peat to organo-mineral soils with lower OC content[13–16].

As part of large-scale efforts to mitigate climate change, rewetting of drained organic soils is an emerging strategy to reduce $CO_2$ emissions from the agricultural sector[17,18]. Rewetting involves restoring natural hydrological regimes by disconnecting drainage pipes and ditches, thereby creating wet anaerobic soils that minimise aerobic mineralisation and $CO_2$ emissions[3,17]. Comprehensive data syntheses show that rewetting contributes to net climate benefits[17,19] although the anaerobic conditions can increase methane ($CH_4$) emissions due to acetoclastic and hydrogenotrophic $CH_4$ production combined with restricted microbial $CH_4$ oxidation (methanotrophy) near the soil surface[20,21].

National reporting of $CO_2$ emissions from drained and rewetted organic soils is made to the UNFCCC as part of the land use, land-use change and forestry (LULUCF) sector, following the guidelines of the Intergovernmental Panel on Climate Change (IPCC)[22,23]. For Denmark, the national inventory report for 2022 includes direct emissions of 1.9 and 2.6 Mt $CO_2$ from drained soils with 6–12% and >12% OC, respectively, under the land use categories of cropland and grassland[24]. This is calculated from national emission factors (i.e., area-scaled net $CO_2$ emissions) for soils with >12% OC[12,24], and assuming that the emission factors for soils with 6–12% OC are half of those for soils with >12% OC[24]. It is highly uncertain, however, whether and how soil OC content controls area-scaled $CO_2$ emissions

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from drained organic soils[16,25–29]. Indeed, there is a global lack of data documenting the $CO_2$ emissions from soils with 6–12% OC, and Denmark is the only country to have tentatively assigned an emission factor to these soils[24]. This is partly related to the inconsistent and complex definitions of OC-rich soils, which vary between countries and organisations[15,30]. The Danish classification defines soils with >6% OC as organic soils[31], while other countries and the IPCC use thresholds of >12% OC or even higher[15,16,23,27,30]. According to IPCC, soils with 6–12% OC can be excluded from reporting of greenhouse gas (GHG) emissions, and their GHG balance can be estimated like that of mineral soils[27,28]. However, evidence from a few exisisting field studies suggests that soils with around 10% OC[16,28] and as low as 5% OC[13] can emit $CO_2$ at similar rates to soils with >12% OC. This highlights the need for benchmarking of $CO_2$ emission factors for soils with different OC contents, including the 6–12% OC range, to avoid systematic underestimation of national GHG emissions reported under LULUCF.

To address this knowledge gap, we compared the area-scaled $CO_2$ emissions (mg $CO_2$-C $h^{-1}$ $m^{-2}$) from organic soils with a wide range of OC contents (6.2–52.1%, $n = 103$), which was facilitated by a comprehensive study under controlled aerobic conditions with undisturbed soil cores sampled across Denmark (Supplementary Fig. 1).

## Results and discussion

### Area-scaled $CO_2$ emissions

Area-scaled $CO_2$ emissions at standardised water potentials (pF 2) were not significantly different for classes with different OC content, defined by intervals of 6% OC (Fig. 1a and Supplementary Table 1; medians, $P = 0.14$, $\chi^2 = 8.36$, d$f = 5$; means, $P = 0.17$, $F = 1.60$, d$f = 5$). This was also concluded when comparing emissions from soils with 6–12% OC and >12% OC (Fig. 1b; medians, $P = 0.21$, $\chi^2 = 1.55$, df = 1; means, $P = 0.31$, $F = 1.02$, d$f = 1$). These emission data complement German field studies on drained organic soils, where (i) similar $CO_2$ emissions were reported for soils with 9.2–10.9% and 15.6–17.2% OC under grassland and arable management[16], (ii) grasslands with OC contents of around 10% were found to emit as much $CO_2$ as soils with >30% OC[28] and (iii) even drained grasslands with 5% OC could emit as much $CO_2$ as true peat soils[13]. The larger data set presented here confirms that OC content in the soil (wt/wt) is a poor predictor of area-specific $CO_2$ emissions, and therefore, it is questionable to assign an emission factor to 6–12% OC soils that is half of the emission factor for soils with >12% OC[24]. In fact, the mean $CO_2$ emission from 6-12% OC soils was only 8.9% lower than that from >12% OC soils (Fig. 1b), and the 95% confidence interval for the group means overlapped strongly (9.4–14.1 and 11.8–14.3 mg $CO_2$-C $h^{-1}$ $m^{-2}$ for the 6–12% and >12% OC groups, respectively), making it uncertain to assign different emission factors. On the other hand, the present data also suggest that disaggregation of emission factors for soils with even higher OC contents may not be justified (Fig. 1a).

Linear regression analyses (Fig. 2a) confirmed the weak and non-significant association between OC content and area-scaled $CO_2$ emission rates ($r^2 = 0.008$, $F(1, 101) = 0.779$, $P = 0.38$). However, the role of OC as an explanatory variable for area-scaled $CO_2$ emissions could be stronger for soil OC density in the soil (wt/vol) than for OC content, as OC density integrates the amount of OC available for microbial mineralisation, i.e., taking into account the soil bulk density[15]. Nevertheless, OC density (Fig. 2b) also had a weak and non-significant effect on area-scaled $CO_2$ emissions ($r^2 = 0.014$, $F(1, 101) = 1.469$, $P = 0.23$). This is consistent with field studies, where OC stock was a non-significant predictor of $CO_2$ emissions, even when specifically considering the amount of OC that was exposed to aerobic mineralisation, referred to as effective[16,28] or aerated[13] OC stock, i.e., depending on the drainage depth.

### Soil weight-specific and OC-specific emissions

Incubation studies with organic soils have previously investigated $CO_2$ emission rates as a function of OC content[25–27]. These studies were carried out with physically mixed or sieved samples and consequently reported soil weight-specific and/or OC-specific $CO_2$ emission rates (i.e., rates scaled by soil weight or OC quantity rather than soil area). We also calculated such rates from the present data, and in agreement with previous studies, soil weight-specific $CO_2$ emission rates increased systematically with increasing OC content (Fig. 2e and Supplementary Fig. 2a)[26,27]. Indeed, soils with 6–12% OC had median and mean weight-specific emissions that were almost half of those (47–51%) for soils with >12% OC (Supplementary Fig. 2b). The contrasting relationship between OC content and area-scaled or soil weight-specific $CO_2$ emissions is mainly explained by the fundamental negative relationship between OC content and soil bulk density[15,32] (Supplementary Fig. 3), which means soils with lower OC content have higher mass. Thus, for the same $CO_2$ emissions per unit area, soil cores or sites of similar (but arbitrary) depth will have lower soil weight-specific emissions for soils with, e.g., 6–12% OC than for soils with >12% OC. Therefore, in terms of practical $CO_2$ emission factors, comparisons of weight-specific $CO_2$ emissions are misleading because the role of bulk density is ignored. Nevertheless, soil weight-specific emissions may be relevant for analyses in other studies aiming at a detailed understanding of the soil physical and biochemical drivers of $CO_2$ emissions.

Carbon dioxide emissions scaled by the amount of OC (OC-specific $CO_2$ emissions) were negatively correlated with OC content and OC density (Fig. 2c, d), meaning that the OC in more degraded soils (i.e., with lower OC content) appeared to be more susceptible to mineralisation. Such negative relationships between measures of OC and OC-specific $CO_2$ emissions corroborate results from studies on disturbed soils. Incubation studies with sieved, air-dried samples (7.6–52.6% OC) indicated that the susceptibility of OC to mineralisation increased with decreasing OC content in German organic soils[26] and similar results were reported for Finnish soils (3.1–49.4% OC) incubated under anoxic and physically disturbed conditions[27]. The present results, obtained with structurally intact organic soils, support the possibility of positive feedback whereby organic soils in advanced stages of decomposition (i.e., with low OC content) may show an increased mineralisation rate[26,33,34]. However, other studies have emphasised the importance of OC quality and intrinsic decomposability for rates of $CO_2$ emission with the assumption that lower rates would be maintained by soils in advanced stages of decomposition, where the more easily decomposed fractions would already be depleted[35–37]. Yet, recalcitrant compounds, such as aromatics and

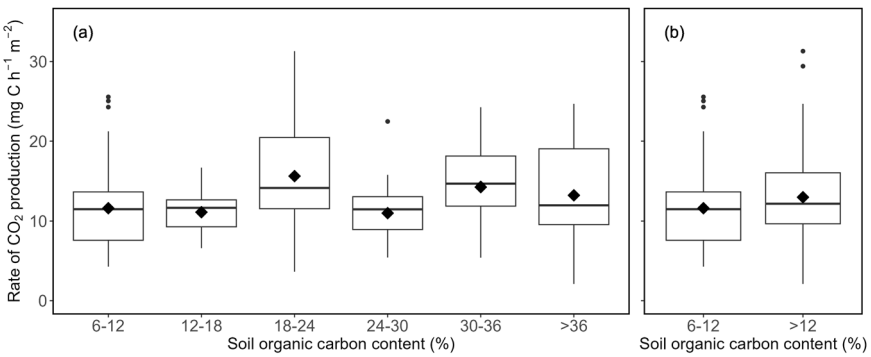


**Fig. 1 | Area-scaled $CO_2$ emission from soils in classes of different organic carbon content.** Area-scaled emission rates of $CO_2$ from soil cores in classes of increasing organic carbon (OC) content (wt/wt). $CO_2$ emissions were measured at standardised water potential (pF 2) and were not significantly different ($P > 0.05$) between individual OC classes (**a**) or between soils with 6-12% OC and >12% OC (**b**). Boxes show the interquartile range (IQR) with mean (diamond) and median (line). Whiskers extend to the lowest and highest values within the 1.5× IQR range; outliers are shown as dots.

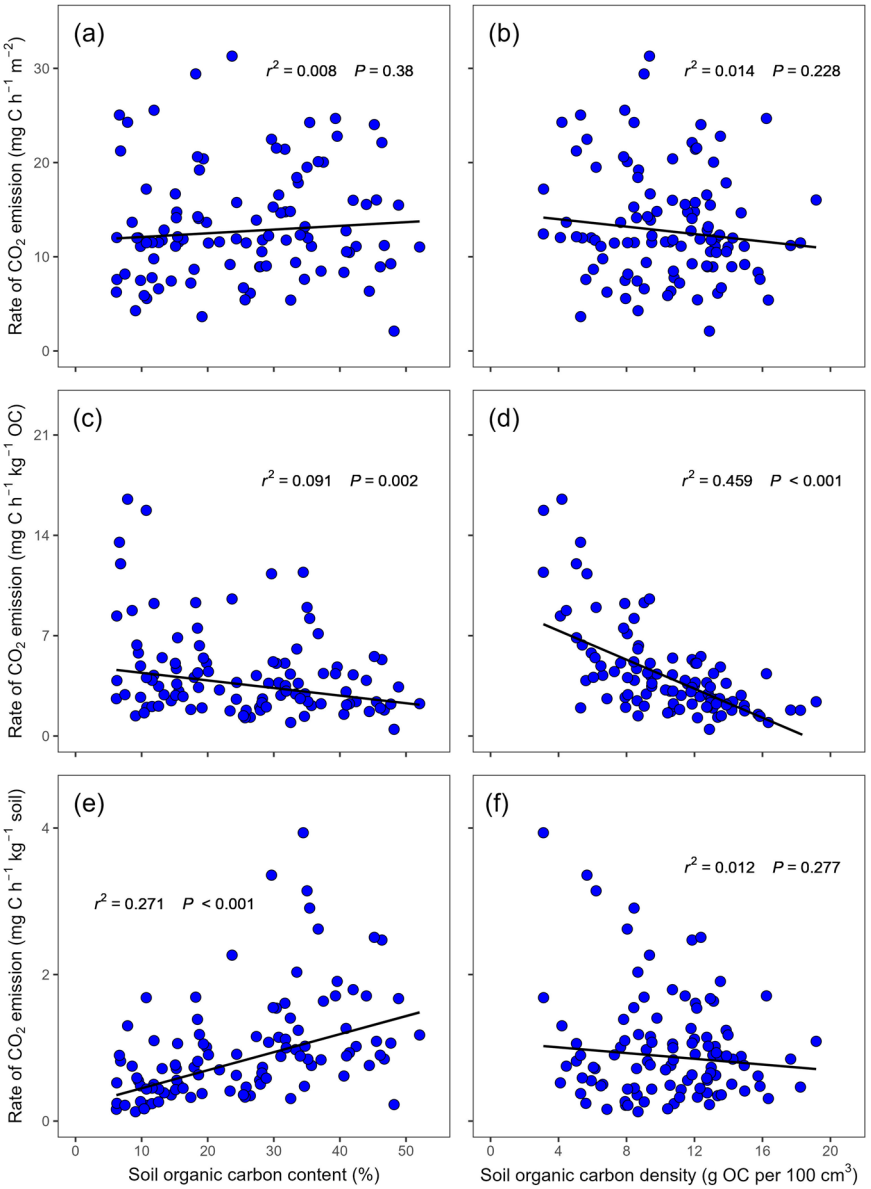


**Fig. 2 | $CO_2$ emission from soils at individual organic carbon (OC) content and OC density.** Area-scaled (**a**, **b**), OC-specific (**c**, **d**), and soil weight-specific (**e**, **f**) emission rates of $CO_2$ from individual soil cores ($n$ = 103). Emissions are plotted against soil OC content (**a**, **c**, **e**) and soil OC density (**b**, **d**, **f**) as explanatory variables. Coefficients of determination ($r^2$) and significance ($P$) of linear regressions are shown in each panel.

phenolics, were not found to be enriched in drained organic topsoils under agriculture in Germany[33], and simple chemical characteristics of OC as proxies for biochemical decomposability were unable to explain the variability in $CO_2$ emissions in a comprehensive study of drained organic soils in Switzerland[25]. In summary, the role of OC quality needs to be further clarified, but the present data do suggest that the remaining OC content as such is not a strong predictor of area-scaled $CO_2$ emission rates (Figs. 1 and 2a).

We speculate that rate-limiting properties for $CO_2$ emissions may differ among our 103 organic soils, including a combination of inorganic geochemical properties[38], but also properties related to the microbiome and soil physical conditions at the study sites.

### Role of soil water content

While OC measures were poor predictors of area-scaled $CO_2$ emissions, soil volumetric water content (VWC) was the most significant single predictor ($r^2$ = 0.34, $F$ (1, 101) = 51.41, $P$ < 0.001) across in situ water contents (Supplementary Fig. 4) and even when standardised to pF 2, i.e., across a more narrow range of VWC (Supplementary Table 2 and 3). Single chemical attributes are generally poor or insufficient proxies for $CO_2$ emissions[25,38], but several studies have identified water table depth as an overarching driver of $CO_2$ emissions under field conditions, where higher water tables reduce $CO_2$ emissions by limiting $O_2$ availability[19,39–41]. Nevertheless, $CO_2$ emissions increased with higher VWC in the present range of 27–87% (Supplementary Fig. 4). Thus, while the diffusive $O_2$ supply may limit $CO_2$ emissions under fully water-logged conditions, increased intermediate water availability may stimulate aerobic microbial activity by increasing (i) soluble substrate diffusion, (ii) microbial mobility and (iii) intracellular water potential in drained organic soils[32,42,43]. Therefore, as found also for mineral soils[44], partial rewetting of organic topsoil does not necessarily result in reduced $CO_2$ emissions. This role of VWC was consistent with the absence of $CH_4$ emissions in our soil incubations, which could arise if the higher water contents inhibited aerobic mineralisation.

Given the importance of soil water availability for microbial metabolism, we studied $CO_2$ emissions at a standardised water potential of pF 2. However, measurements of $CO_2$ emissions at in situ water contents corroborated the rates measured at pF 2 (Supplementary Fig. 5) and confirmed the lack of association between OC content and area-scaled $CO_2$ emissions over separate intervals of VWC (Supplementary Fig. 6). Overall, these results support the conclusion that OC content and OC density are ineffective predictors of area-scaled $CO_2$ emissions and that $CO_2$ emission factors may not be different between soils with 6-12% and >12% OC.

### Implications for national GHG inventories

Adjustments to the national emission factors accepted under the UNFCCC are not trivial and require scientific documentation beyond the scope of this study. However, the technical implications of potentially similar $CO_2$ emission factors for soils with 6–12% and >12% OC are imperative. As an example, such parity suggests that the Danish National Inventory Report[24] may underestimate the direct $CO_2$ emissions from managed croplands and grasslands on organic soils by 40% (Supplementary Table 4). Based on the National Inventory Report[24] and analyses by the Danish Council on Climate Change[45], the Danish government has decided to support the rewetting of 100,000 ha of drained organic agricultural soils by 2030, including both soils with 6–12% OC and soils with >12% OC. Strategies and the climate effect of rewetting the soils with >12% OC have been analysed[19], but the most efficient strategy for the whole rewetting initiative will fundamentally depend on how the emissions from soils with 6–12% OC are conceived since these are likely to be currently underestimated[45].

We infer that a similar or even greater underestimation of area-scaled $CO_2$ emissions for 6–12% OC soils exists in many other countries with large proportions of organic soils in transition from true peat to organo-mineral soils due to extensive agricultural management. Global mapping of agricultural soils with 6–12% OC soils is underdeveloped, and national area estimates outside of Denmark are not readily available. However, agricultural cropland and grassland soils with 6–12% OC ($n = 477$) may be even more common than those with >12% OC ($n = 196$) as indicated by point data from the LUCAS (Land Use/Cover Area frame Survey) module of the European Soil Database, which contains observations from more than 20,000 sites stratified across the EU in a 2 by 2 km grid[46]. Improved soil mapping and development of emission factors for 6–12% OC soils is needed to improve national GHG accounting for organic soils under the UNFCCC, but also to allow for better estimates of the climate benefits of global initiatives to rewet drained organic soils. The present study, under controlled conditions, allowed for the relative comparison of $CO_2$ emissions from organic topsoils with a wide range of OC contents and showed that area-scaled emissions are not controlled by the OC content as such. While these results provide valuable insights, they also highlight the need for targeted field research to refine $CO_2$ emission factors for soils with 6–12% OC, which we recommend should be given high priority.

## Methods

### Study sites, soil sampling, and analyses

Denmark (43,000 $km^2$), situated in the northern part of Europe, has a temperate to cold climate with warm summer and no dry season (Cfb, Dfb in Köppen-Geiger classification)[47]. The mean monthly temperatures (1991–2020) range from 1.5 °C in February to 16.9 °C in August, and the mean annual precipitation is 759 mm[48]. The flat landscape (mean, 31 m a.s.l) is divided into an eastern part with loamy Weichselian moraines and a western part with sandy glacial outwash plains and Saalian moraines[47,49]. The area of soils with 6–12% and >12% OC was previously (2021) reported at 162,000 and 129,000 ha, respectively, of which 55–60% was used for agriculture[50].

The sampling sites for the study ($n = 103$) were selected to represent organic soils with a wide range of OC contents (>6% OC) from all regions of Denmark (Supplementary Fig. 1). Sampling positions were georeferenced (using differential GPS), the peat depth was measured using a soil auger, and the depth to the groundwater table was measured using piezometers. The land use was registered, and the topsoil was characterised according to the degree of decomposition (Supplementary Table 5).

Soil cores and bulk samples were taken from the topsoil at a depth of between 10 and 15 cm. Two soil cores were sampled in 100-$cm^3$ stainless steel rings (height, 3.5 cm; diameter, 6.1 cm) and stored in undisturbed intact layering at 2 °C for biological incubation experiments. Bulk soils were air-dried and sieved (2 mm) for measurement of total C and nitrogen (N) by dry combustion (Vario Max Cube, Elementar Analysensysteme, GmbH). All soils were free of inorganic carbonates as tested by HCl effervescence[51], and total C was rated as OC. Soil pH was measured using a glass electrode in a 1:5 (vol/vol) soil/water suspension (Supplementary Table 3).

### Incubations and measurement of $CO_2$ emissions

Soil cores in the metal rings ($n = 206$) were trimmed to the volume of 100 $cm^3$. From each site, soil cores were prepared for incubation at a standardised matric potential ($\psi_m$) of −100 hPa (referred to as pF 2) and at the in situ water content. Adjustment to pF 2 by controlled wetting and drying on sandboxes[52] was achieved in 2 weeks and allowed the effects of OC on $CO_2$ emissions to be studied without the interaction of randomly different soil water status at the sampling times. However, $CO_2$ emissions were also measured at in situ water contents to substantiate the rate measurements with pF 2 adjustment and to assess the role of OC content in $CO_2$ emissions at discrete water content classes.

Weights were recorded for all soil cores before they were sealed at the bottom with a plastic lid and incubated in airtight 1-L glass jars fitted with a rubber septum for gas sampling. The soils were temperature equilibrated and incubated in the dark at 15 °C for one week. Then, at intervals of 5–7 days, 10-mL headspace gas samples were withdrawn using a syringe with a hypodermic needle and transferred to evacuated 6-mL Exetainer vials (Labco Ltd., Lampeter, UK) for analysis of $CO_2$ (and $CH_4$) using an Agilent 7890 gas chromatography GC system (Agilent, Nærum, Denmark) configured and calibrated as previously described[53]. After each gas sampling, the jars were opened for 10 min to equilibrate with atmospheric air, and after closing, a gas sample was taken from each jar to document the new baseline concentrations. Four empty glass jars were included as controls. After the final gas sampling (60 days), weights and dry weights of all soil cores were recorded to calculate soil bulk density. Relative water losses during the 60-day incubation period were approximately 4.7% (median, $n = 206$) and were not compensated for in the intact soil cores due to the risk of preferential rewetting of the surface layer. The headspace concentration of $O_2$ after 7 days of soil incubation was checked in control experiments using gas chromatography[54] and was 19.4 ± 0.4% $O_2$ (mean ± standard deviation, $n = 10$), i.e., close to the atmospheric concentration.

### Calculations and statistics

Emissions of $CO_2$ during each of the 5–7 day incubation intervals were calculated as:

$$\mathrm{CO_2\ emission\ (\mu g\ CO_2{-}C)} = (\mathrm{C_t} - \mathrm{C_0}) \times \mathrm{V_h} \times \mathrm{M} \times \mathrm{V_m^{-1}} \quad (1)$$

where $C_0$ and $C_t$ are the $CO_2$ headspace concentrations (μL $L^{-1}$) at the start and end of the incubation interval, respectively, $V_h$ is the effective headspace volume (0.9 L), $M$ is the molar mass of carbon (12 g $mol^{-1}$), and $V_m$ is the molar gas volume at 15 °C (23.6 L $mol^{-1}$). Cumulative $CO_2$ emissions over the 60-day incubation period ($\Sigma CO_2$) were calculated by summing the individual 5–7 day $CO_2$ emissions. Area-scaled, soil-weight-specific, and OC-specific $CO_2$ emission rates were calculated as:

$$\mathrm{Area{-}scaled\ emission\ rate\ (mg\ CO_2{-}C\ h^{-1}\ m^{-2})} = \Sigma\mathrm{CO_2} \times \mathrm{time^{-1}} \times \mathrm{A^{-1}} \quad (2)$$

$$\mathrm{Soil\ weight{-}specific\ emission\ rate\ (mg\ CO_2{-}C\ h^{-1}\ kg^{-1}\ soil)} = \Sigma\mathrm{CO_2} \times \mathrm{time^{-1}} \times \mathrm{soil\ dw^{-1}} \quad (3)$$

$$\mathrm{OC{-}specific\ emission\ rate\ (mg\ CO_2{-}C\ h^{-1}\ kg^{-1}\ OC)} = \Sigma\mathrm{CO_2} \times \mathrm{time^{-1}} \times \mathrm{OC\ mass^{-1}} \quad (4)$$

where $\Sigma CO_2$ is the 60-day cumulative $CO_2$-C emission, time is the total incubation time (1440 h), $A$ is the surface area of the soil cores (29.2 $cm^2$), soil dw is the dry weight of the individual soil cores, and OC mass is the weight (kg) of OC for the individual 100 $cm^3$ soil core.

Statistical analyses were performed using R version 4.3.0[55]. Differences in mean $CO_2$ emission rates for different classes of OC content were tested

by one-way analysis of variance (ANOVA) using the *F*-statistic[56]. Assumptions of normal distribution and homogeneity of variance were tested by Shapiro–Wilk and Levene's tests, respectively, and by visual inspection of residuals against fitted values and histogram of residuals[56]. In the case of non-normal distribution and/or heteroscedasticity, data were log or square root transformed for ANOVA analysis. Reported means are results extracted from the statistical models after back-transforming from the log or square root scale, using the *emmeans* function (i.e., *emmeans* (model, ~OC content, type = "response")). Significant ANOVA tests ($P < 0.05$) were followed by post-hoc pairwise comparisons using the *emmeans* function with Tukey adjusted *P* values[56,57]. In addition to tests on means, differences in median $CO_2$ emission rates between OC classes were tested using the non-parametric Kruskal-Wallis test, which computes *P*-values that are based on the $\chi^2$ distribution[56].

Ordinary least squares regressions between $CO_2$ emissions and soil parameters, as explanatory variables were performed using the *lm* function in R. Coefficients of determination ($r^2$), were used as a measure of the explained variation in $CO_2$ emissions[56]. In case of non-normal distribution and/or heteroscedasticity, data were log or square root transformed for the analyses. The fitted lines in regression plots are a linear approximation of the analysis performed in log or square root scale.

Correlations between soil parameters were analysed using the *cor* function in the corrplot package in R. As the data transformations did not meet the assumptions of normal distribution, the non-parametric Spearman's rank correlation procedure was used[56].

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

The data and the results that support the findings of this study are available in Figshare with the identifier https://doi.org/10.6084/m9.figshare.25672755.

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## Author contributions

The study was conceived by L.E. and designed by L.E., M.H.G., and L.W.J. Data were collected by Z.L., C.H., and P.L.W. and analysis made by Z.L., C.P., M.M., and L.E. Funding was secured by L.E. and M.H.G. Z.L. and L.E. wrote the paper with contributions and comments from C.H., P.L.W, C.P., M.H.G., L.W.J., M.M., and J.L.

## Competing interests

The authors declare no competing interests.

## Additional information

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