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Sediment heterogeneity affects variability of resuspension-induced CO_2 production

Ines Bartl[1], Simon Thrush[1]

[1]Institute of Marine Science, The University of Auckland, Auckland 1142, New Zealand

Correspondence to: Ines Bartl (ines.bartl@auckland.ac.nz)

Abstract. Demersal fishing is a major anthropogenic disturbance to marine sediments, with global implications for benthic carbon cycling and greenhouse gas emissions. Resuspension of sediment organic carbon during bottom trawling enhances oxic mineralisation, converting stored organic matter into aqueous CO_2 and reducing the long-term carbon storage potential of the seafloor. Sediment heterogeneity likely plays a role in the vulnerability of sedimentary organic carbon to resuspension, but spatial estimates of trawling-induced CO_2 release from resuspended sediment rarely account for this heterogeneity. In this study, we conducted a large-scale survey in the Hauraki Gulf, New Zealand, to assess how sediment characteristics affect resuspension-induced CO_2 production (RCO2P). Using a resuspension assay at 57 sites, we quantified RCO2P and it with measurements of sediment grain size, organic matter content and quality, and phytopigments. Boosted regression tree modelling revealed that organic matter content has the strongest influence, with a non-linear relationship to RCO2P and interaction effects with water depth and medium sand content. Vulnerability to CO_2 release was highest in sediments with > 3 % organic matter and < 27 % medium sand, particularly at depths between 55 – 95 m. Our results demonstrate that sediment heterogeneity must be accounted for in regional assessments of seafloor carbon storage and disturbance impacts. For this, the resuspension assay offers a practical tool to empirically assess carbon storage vulnerability and can complement model-based approaches to inform spatial management of demersal fisheries.

1 Introduction

Marine anthropogenic activities are a major disruption for the seafloor and its ecological functioning. The most prominent disturbance is demersal fishing; a method whereby weighted gear is dragged over the marine sediment to catch bottom-dwelling fish and benthic shellfish. Approximately 21.9 Gt of sediment are resuspended with this fishing technique globally each year (Oberle et al., 2016), which destroys benthic habitats (Thrush and Dayton, 2003), and alters benthic carbon (C) cycling processes (Bradshaw et al., 2021; Polymenakou et al., 2005; Pusceddu et al., 2005). Globally, bottom trawling is estimated to cause a loss of stored organic C to aqueous CO_2 of 0.58 Gt per year (Sala et al., 2021), with 55-60% released back to the atmosphere, highlighting the considerable contribution of demersal fishing to greenhouse gas production (Atwood et al., 2024). However, little regulatory action has been taken to account for the vulnerability of marine sediment C storage to

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Preprint. Discussion started: 8 July 2025

disturbance (Porz et al., 2024). Spatial fisheries management that incorporates seafloor C storage could sustain natural C sinks which would not only support the mitigation of anthropogenic CO_2 emissions but also help stabilize the Earth's climate and sustain marine biodiversity (Hiddink et al., 2023; Matthews et al., 2022; Thrush and Dayton, 2003).

Large organic C stocks are found in the sediments of coastal and shelf seas (Bianchi et al., 2018; Najjar et al., 2018), which at the same time are highly impacted by demersal fishing (Oberle et al., 2016). These productive marine systems span a wide range of environmental settings covering water depths of up to 200 m, different hydrodynamic regimes, light availabilities, temperatures, productivity and proximity to land – all influencing sediment characteristics and biophysico-chemical conditions in the sediment thus creating sediment heterogeneity. Sediment heterogeneity plays an important role for the reactivity of organic C and thus how much of it is mineralised or buried (Arndt et al., 2013; Burdige, 2007; Middelburg, 2018; Snelgrove et al., 2018). When sediment organic C is resuspended, it becomes exposed to oxygen which can change its reactivity and stimulate heterotrophic processes that convert organic C to aqueous CO_2 (Bianchi et al., 2016; Ståhlberg et al., 2006). Not only fresh labile organic matter, but also older refractory components were found to be remineralised to aqueous CO_2 when re-introduced to oxygen (Hulthe et al., 1998). This causes organic C mineralisation rates often being higher in resuspended sediments compared to undisturbed sediments (Almroth-Rosell et al., 2012; Bartl et al., 2025; Polymenakou et al., 2005; Ståhlberg et al., 2006) affecting the proportion of organic carbon that can be buried long-term.

Modelling estimates of organic C mineralisation to CO_2 in trawled sediments quantify rates using first-order degradation rate constants and assumptions on organic C reactivity as empirical measurements on resuspension induced CO_2 production are limited (Atwood et al., 2024; Muñoz et al., 2023; Porz et al., 2024; Sala et al., 2021). Different rate constants are used for different oceanic regions (Muñoz et al., 2023; Sala et al., 2021), or different organic C labilities (Porz et al., 2024; Zhang et al., 2019) alongside assumptions that either all organic C (Luisetti et al., 2019) or only the labile fraction of organic C (Sala et al., 2021) is mineralised once resuspended. This results in estimations differing by up to two orders of magnitude (Luisetti et al., 2019; Muñoz et al., 2023; Porz et al., 2024; Sala et al., 2021) with limited integration of sediment heterogeneity. This generates uncertainty in these quantifications, particularly at regional scales (Atwood et al., 2024; Epstein et al., 2022). Recent trawling impact assessments have therefore used alternative qualitative and semi-quantitative approaches to evaluate the vulnerability of the seafloor C storage to demersal fishing and the risk of CO_2 production in resuspended sediments (Black et al., 2022; Epstein et al., 2025). However, rates of resuspension-induced organic C mineralisation to CO_2 are crucial quantifications to assess the CO_2 footprint of demersal trawling and the loss of C storage function along with its climatological consequences. Simple and efficient empirical measurements of sediment heterogeneity and resuspension-induced CO_2 production can provide a practical solution to enable assessments of the vulnerability of C storage to resuspension (Bartl et al., 2025). This will not only complement geospatial modelling approaches but also open opportunities to find solutions to sustainably manage the seafloor's carbon storage function.

To address the key question of how sediment heterogeneity affects resuspension-induced CO_2 production (RCO2P), we conducted a survey in the Hauraki Gulf (New Zealand), a heterogeneous marine coastal system that experiences anthropogenic impacts including dredging and bottom trawling. Working in heterogeneous systems requires a large sample size of empirical measurements and we therefore applied a resuspension assay at 57 sampling sites arrayed across a range of sediment types. We used surface sediment grain size fractions, organic matter content and quality, and phytopigments as measures of sediment heterogeneity and analysed their influence on RCO2P using boosted regression tree modeling. With our results we aim to contribute to discussions on the spatial management of demersal fisheries in coastal and shelf seas such as the Hauraki Gulf.

2 Methods

2.1 Study site and sampling

The Hauraki Gulf is a semi-enclosed, oligotrophic shelf sea of up to 150 m water depth in the northeast of the North Island, New Zealand. The seafloor consists of a large variety of volcanic and alluvial sediments ranging from coarse, calcareous sand and gravel to fine sands and silts with high clay content (Manighetti and Carter, 1999). The south-eastward flowing East Auckland Current and tidal currents dominate the water circulation and sediment transport in the Gulf (Manighetti and Carter, 1999; Sharples, 1997; Zeldis, 2004). Terrestrial organic C input is low and confined to the Firth of Thames, while in the inner Gulf sediment organic matter is a mixture of terrestrial sources and marine primary production and at the outer gulf marine primary production dominates (Sikes et al., 2009).

In February and March 2024, 57 sites were visited in the Hauraki Gulf and outer shelf with the *R/V Te Kaihōpara* (Fig. 1). Sites were chosen to encompass the widest range of seafloor characteristics. Sediments were sampled using a HAPS corer *(*KC Denmark*,* 14 cm diameter) and three HAPS cores were taken at each site. Subsamples for surface sediment (0 – 3 cm) characterisation were taken using acid-cleaned (10 % HCl) plastic syringes (Polypropylene) with cut-off tips, and subsamples for the resuspension assay were taken in pairs of small sediment cores in acid-cleaned acrylic core-liners (inner diameter = 3.4 cm, core-liner height = 14 cm). Subsampled cores that contained large macrofauna were discarded from use for the re-suspension assay. The sediment characteristics samples were immediately transferred to acid-cleaned polypropylene containers, stored in ice and frozen at -20 °C at the end of a sampling day. The small cores for the assay were stored with open tops in dark seawater tanks at ambient bottom-water temperature (± 2 °C) and assays were conducted within 2 hours of sampling.

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Preprint. Discussion started: 8 July 2025

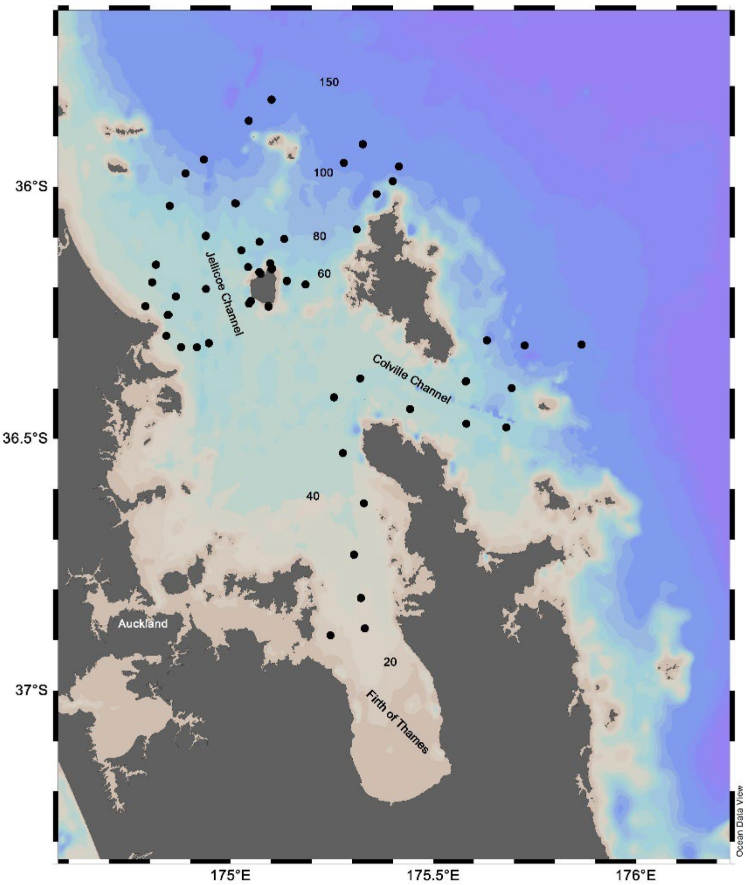

Figure 1: Study sites in the Hauraki Gulf (black dots). Brown to blue shading represents bathymetry with depths (m) shown by numbers.

2.2 Resuspension assay

To quantify the production of aqueous CO_2 through enhanced organic C mineralisation in resuspended sediments, we conducted the resuspension assay according to Bartl et al. (2025). The assay incubates undisturbed sediments in cores and resuspended sediments in glass bottles and measures the change in oxygen concentration through time to determine the sediment oxygen demand (SOD). SOD (mmol m^{-2} h^{-1}) was calculated from oxygen concentration measurements (OXROB10 probe and FireSting GO2 oxygen meter, Pyroscience, Germany) at the start and end of the incubation period and normalised to incubation time and area of the sediment core. At each site three pairs of control cores and resuspension treatments were incubated in the dark for 4-6 h at ambient bottom water temperatures. From SOD, organic carbon mineralisation to CO_2 was estimated using a respiratory quotient of 0.9 for inner shelf sediments (Jørgensen et al., 2022). Resuspension-induced CO_2 production (RCO2P) was then calculated as the difference of CO_2 production in the resuspension treatment and the undisturbed

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sediment of each sample pair. The factor increase in CO_2 production in the resuspension treatment was calculated by dividing it with the CO_2 production from the undisturbed core. RCO2P will be used as a proxy for the vulnerability of sediment organic C to resuspension with higher RCO2P rates indicating higher sediment OC vulnerability.

2.3 Sediment characteristics

Sediment characterisation involved analysis of organic matter content, grain size and phytopigment concentration in the top 3-cm surface sediments. Sediment samples were homogenised, and subsamples (5 mL) were dried at 60 °C for seven days. Subsequently, sediment organic matter content was determined through weight loss on ignition by burning the dried sediment samples at 450 °C for 4 hours. For sediment grain size distribution, sediments were digested with 10 % H_2O_2 for six weeks to remove organic matter, washed using DI-water and dispersed using 5 % sodium hexametaphosphate before laser diffraction analysis using a Malvern Mastersizer-3000 (Malvern, UK). The following grain size classes were used in data analysis: coarse sands (500 – 2000 µm, covering size classes of coarse and very coarse sand), medium sand (250 – 500 µm), fine sands (63 – 250 µm, covering size classes of fine and very fine sand), and mud (< 63 µm). Shell hash/ gravel was quantified via wet sieving and weighing of two dried size classes, > 2 mm (shell hash and gravel) and < 2mm (remaining sediment). Only one site contained actual gravel, all other sites had only shell hash in the > 2mm size class. The phytopigments chlorophyll *a* and Phaeophytin were extracted from homogenized, freeze-dried sediment samples (1 g) over 24 hours using 3 mL 90% aqueous acetone (Buffan-Dubau and Carman, 2000; Sun et al., 1991). Pigment absorbances were measured before and after acidification using a spectrophotometer (ThermoFisher Scientific, Type 1530, Finland) and concentrations were calculated according to Lorenzen et al. (1967). The chlorophyll *a* (Chl.a) concentration serves as an indicator of algal biomass whereas the total phytopigment concentration (Chl.a + Phaeophytin) was used to characterise the freshness of organic matter in the sediment, by calculating the mass ratios of organic matter content to phytopigment concentration (Pusceddu et al., 2010). Lower ratios indicate fresh, less degraded organic matter while higher reflect older, more degraded organic matter.

2.4 Data analysis

A total of 171 samples were collected and analysed for each sediment characteristic alongside 171 resuspension assays. 34 data points of the resuspension assay were removed from data analysis after thorough data quality assessment (lost samples, > 30 % oxygen decline, or large macrofauna in samples, see Bartl et al., 2025). Two Chlorophyll *a* datapoints were interpolated as average of the other two site replicates to yield a complete data set with 137 samples spread capturing the ranges of water depth and sediment characteristics of our sampling sites. To understand how the sediment heterogeneity affects RCO2P, and which sediments are most vulnerable to releasing CO_2 when resuspended, we conducted supervised gradient boosting machine learning using boosted regression trees (Friedman, 2001). Boosted regression tree models (BRT) build ensembles of decision trees sequentially where each new tree attempts to correct the errors made by the previous ensemble. BRT captures both, non-linear relationships of environmental factors with the response variable and factor interactions, making it suitable to understand ecological processes from heterogeneous environmental data while maintaining strong predictive power (Lucas, 2020;

https://doi.org/10.5194/egusphere-2025-3045
Preprint. Discussion started: 8 July 2025

Rubbens et al., 2023). In our BRT, we included the following environmental factors as features: water depth (Depth), shell hash content (Shell hash), coarse sand content (C-Sand), medium sand content (M-Sand), fine sand content (F-Sand), mud content (Mud), organic matter content (OM), and the mass ratio of organic matter to total chlorophyll (OM:Phyto). The response variable is resuspension-induced CO_2 production (RCO2P). To perform BRT the data set was split into a training set (75 % of the samples) and a testing set (25 % of the samples). The following hyperparameters, i.e. the settings for BRT, were tuned using the gridsearch-function and a 4-fold cross-validation: number of trees = 500, maximum tree depth = 3, minimum number of samples in final leaf = 4, learning rate = 0.05, and subsampling = 0.8. To create a robust model for interpretation we ran 50 BRT iterations with 50 different splits of training and testing data and will report mean diagnostic metrics. To identify the importance of single features, the impact of feature interactions and the relationship between features and RCO2P, we used the SHAP values which assigns a contribution score to each feature through which the feature's impact on the modelled RCO2P can be quantified (Li, 2022; Lundberg et al., 2018; Lundberg and Lee, 2017). Feature importance and feature interaction importance will be represented by mean absolute SHAP values to provide an insight into which environmental variable is most influential for modelled RCO2P. To account for collinearity in our features, we used the tree-based SHAP algorithm and performed SHAP cluster analysis to identify correlating features. All analyses were performed using Python (Jupyter Notebook, v 7.2.2) and the packages scikit.learn and SHAP (Lundberg et al., 2017, 2020; Pedregosa et al., 2011).

3 Results

3.1 Sediment characteristics affecting resuspension-induced CO_2 production

The sampled sites covered a large variety of sediment grain sizes as well as organic matter quantities and qualities (Table 1, Fig. S1 and S2) confirming that the selection of our sampling sites is a solid representation of sediment heterogeneity in the Hauraki Gulf. CO_2 production rates determined via the resuspension assay were 1.4 – 19.4 times higher in the resuspended sediments compared to undisturbed sediments and RCO2P strongly varied from 0.1 to 3.7 mmol CO_2 m^{-2} h^{-1} (Table 1).

Table 1: Sediment characteristics and CO_2 production rates determined through the resuspension assay. Values shown are average ± standard deviation and ranges from minimum to maximum values. Undisturbed CO_2 production was measured from incubation of undisturbed sediment cores while resuspension-induced CO_2 production (RCO2P) was determined from incubation of a resuspension treatment. OM:Phyto is the mass ratio of organic matter content and Phytopigments and Phaeo:Chla is the mass ratio of Phaeopigments and Chlorophyll. Both represent measures of organic matter freshness with lower ratio reflecting higher freshness.

Sediment characteristic	Average ± Std	Range
Shell hash (%)	3.7 ± 5.7	0 – 39.8
Coarse sand (%)	10.8 ± 12.9	0 – 62.0
Medium sand (%)	22.7 ± 14.1	1.4 – 53.9
Fine sand (%)	30.0 ± 13.7	1.7 – 67.7
Mud (%)	36.4 ± 24.8	0.6 – 84.0

https://doi.org/10.5194/egusphere-2025-3045
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Organic matter (%dw)	4.0 ± 2.1	0.9 – 9.6
Chl.a (µg g^{-1} dw)	1.8 ± 1.5	0.3 – 8.0
OM:Phyto (mass)	5.2 ± 2.7	1.2 – 16.1
Resuspension assay		
Undisturbed CO2P (mmol m^{-2} h^{-1})	0.3 ± 0.1	0.1 – 1.0
RCO2P (mmol m^{-2} h^{-1})	1.6 ± 0.9	0.1 – 3.7
Factor increase of RCO2P	6.9 ± 3.9	1.4 – 19.4

The 50 iterations of the BRT model performed well in predicting RCO2P with an R^2 of 0.57 ± 0.1 and a root mean squared error was 0.56 ± 0.1 mmol CO_2 m^{-2} h^{-1}, a strong result for highly variable environmental data. SHAP values from the BRT model show how much each feature (sediment characteristics and water depth) contributes to an increase (positive SHAP values) or decrease (negative SHAP values) of modelled RCO2P which is used to evaluate feature importance and relationships. Organic matter content was by far the most influential factor on modelled RCO2P, followed by water depth and the sand fractions (Fig. 3A). Interestingly, the freshness of organic matter measured via OM:Phyto had low feature importance for RCO2P (Fig. 2A). SHAP cluster analysis showed that there were strong correlations ($r > 0.7$, i.e. cluster distance < 0.3) among 8 out of the 9 features particularly between organic matter and mud content (Fig. 2A). This clustering suggests that correlating features carry similar information for the prediction of modelled RCO2P and that a reduction of features could be tested when using the model for prediction. SHAP interaction scores revealed two strong interactions (OM and MSAND: 0.049, OM and DEPTH: 0.021, Fig. 2B) suggesting that the most important features also have interaction effects on RCO2P. Partial dependence plots for the three most important features revealed a predominance of non-linear relationships between modelled RCO2P and features (Fig. 2C-E). Along the concentration range of organic matter, there is a strong shift from negative to positive SHAP values at 3 % OM, indicating that RCO2P are highest in sediments with an OM of > 3 % (Fig. 2C). Similarly, sediments with lower fractions of medium sand (< 27 %) and from water depths of > 55 m are linked to high RCO2P (Fig. 2D, E). Interestingly, SHAP values peaked at water depths between 55 – 95 m before levelling off at greater depths (Fig. 2D). Overall, the BRT results revealed that organic matter contributes most to the variability of RCO2P, and their non-linear relationship suggests context dependent influences of OM through interactions with water depth and medium sand.

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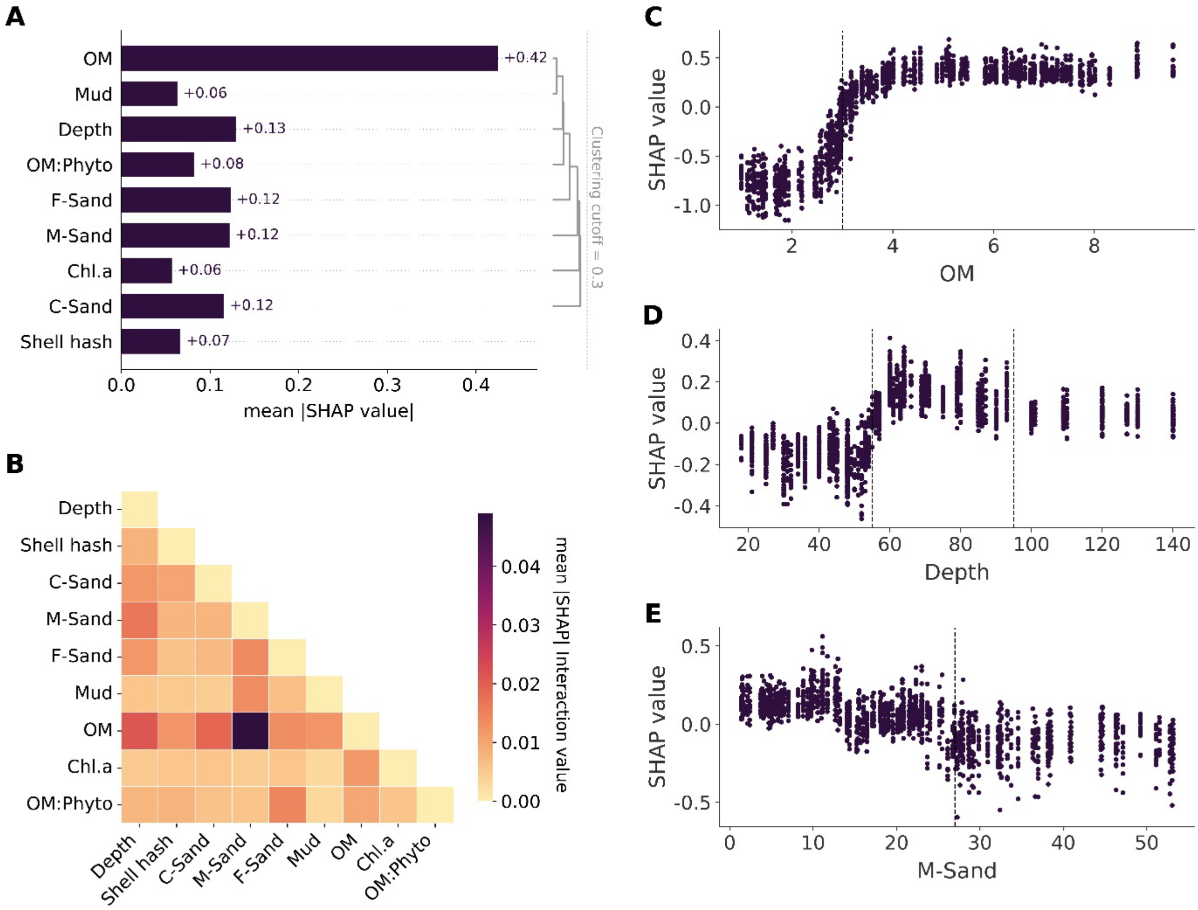

Figure 2: Results from the BRT model: (A) Feature importance and (B) Feature Interaction Importance based on mean absolute SHAP values. Higher values indicate higher influence of feature on modelled RCO2P. (C – E) Partial-dependence-plots showing the relationship between SHAP values and predictors organic matter content (OM), water depth (Depth), and medium sand content (M-Sand). Positive SHAP values represent a positive impact and thus higher RCO2P than average, vice versa for negative SHAP values. The shape of the scatter shows non-linear relationships between SHAP value, i.e. modelled RCO2P, and features, with strong shifts along the concentration gradient of OM and M-Sand at 3 % and 27 %, respectively, and at 55 m and 95 m water depth (vertical dashed lines).

3.2 Sediment types and areas with highest vulnerability to resuspension-induced CO_2 release

Based on the most important features (Fig. 2A, B) and the shifts in SHAP values along the concentration range of these features (Figs. 2C-D), we created scatter heatmaps using our full dataset to visualize which sediment types are most vulnerable to CO_2 release when resuspended (Fig. 3). Lowest RCO2P rates of 0.54 ± 0.4 mmol m^{-2} h^{-1} occur in coarser grained (> 27 % medium sand) sediments with low organic matter content (< 3 %) from shallow depths (< 55 m) creating a distinctive cluster (Fig 3A, B). This indicates a low to moderate vulnerability of these sediment types and corresponds to sampled areas in the Colville

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Preprint. Discussion started: 8 July 2025

and Jellicoe Channel (Fig. 4). Sediments containing > 3 % OM and < 27 % medium sand span RCO2P rates from 0.6-3.7 mmol m^{-2} h^{-1} corresponding to 2.3-19.5 times more CO_2 released compared to undisturbed sediments. This means that in the Hauraki Gulf, a considerable range of sediment types and a considerable portion of the sampled sites (73 %) in the Hauraki Gulf are moderately to highly vulnerable to releasing CO_2 when disturbed (Fig. 3A, Fig. 4).

Within the cluster of highly vulnerable sediments, two interesting patterns emerge from organic matter – depth interactions. Firstly, at sites deeper than 95m, both organic matter content of 6.9 ± 0.7% and RCO2P rates of 2 ± 0.33 mmol m^{-2} $h^{-1}$are relatively constant, with RCO2P around 4 times as high as in the shallower, low-OM cluster (Fig 3B). Secondly, the highest 10 % of RCO2P (> 2.7 mmol m^{-2} h^{-1}) can be found along a linear interaction between depth (44 – 95 m) and OM (3 – 9 %, linear regression: Depth = -5.54 x OM + 92.15, R^2 = 0.47, p = 0.007, Fig. 3B). This means that highest RCO2P rates can be found, both, at deeper sites with lower OM and at shallower sites with higher OM with those hotspots being located landward and seaward to the low-RCO2P areas in Colville and Jellicoe Channel (Fig. 4). These two patterns suggest that the deep muddy sediments of the Hauraki Gulf display a consistently high vulnerability to releasing CO_2 when disturbed while highest vulnerability is linked to an interaction of water depth and organic matter content.

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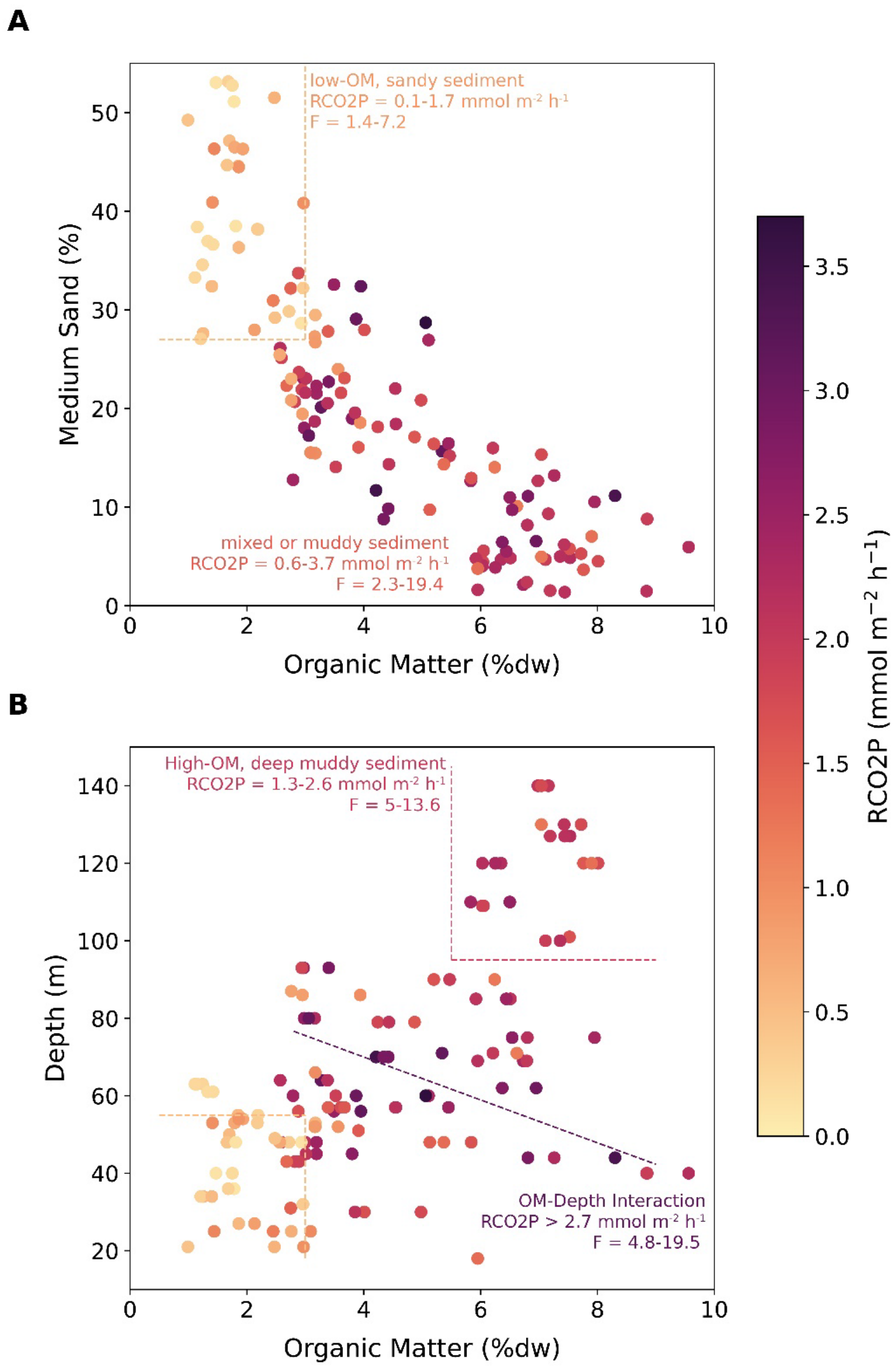

220 **Figure 3: Heatmaps showing the resuspension-induced CO_2 production (RCO2P, colour gradient) related to (A) organic matter content (x-axis) and medium sand content (y-axis), and (B) organic matter content (x-axis) and water depth (y-axis). Yellow dashed lines represent the thresholds determined from the partial dependence plots from the BRT model (see Fig. 3), red dashed lines represent the cut-off to deep-water sites (> 95 m) and the purple dashed line shows the linear regression between organic matter and water depth (y = -5.54x + 92.15, R^2=0.47, p=0.007) for the 90th quantile of RCO2P rates indicating an interaction effect of both features on RCO2P rates > 2.7 mmol m^{-2} h^{-1}.**

https://doi.org/10.5194/egusphere-2025-3045
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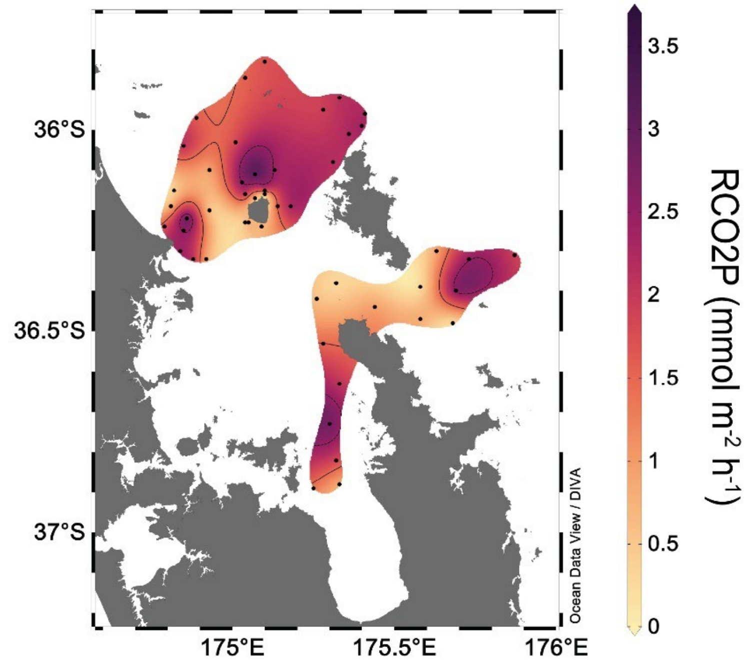

Figure 4: Surface map of resuspension-induced CO_2 production (RCO2P) rates. Contour lines are RCO2P at 1.7 mmol m^{-2} h^{-1} (solid) representing the low-RCO2P cluster and at 2.7 mmol m^{-2} h^{-1} (dashed) representing RCO2P hotspots. Values were spatially interpolated using DIVA-gridding in Ocean Data View (Schlitzer, 2025)**.**

4 Discussion

The broad range of water depths and sediment characteristics of Hauraki Gulf sediments allowed us to investigate the effects of sediment heterogeneity on resuspension-induced CO_2 production. Our results show that in these heterogeneous sediments, organic matter content, sand content and water depth played important and interactive roles explaining the variability of RCO2P. Both, non-linear relationships of RCO2P with organic matter content, water depth, and sand content and interaction effects of these three features allowed us to identify that any sediment with less than 27 % medium sand and more than 3 % organic matter had a moderate to high risk of releasing CO_2 when resuspended, making 73 % of our sampled sites at high risk to lose their C storage function when disturbed.

Our resuspension assay offers a simple and practical measure of oxic organic C mineralisation in the top 3 cm of sediment, providing insight into the vulnerability of seafloor C storage. Porz et al. (2024) presented a similar approach in their modelling study, defining sediment organic C vulnerability in the top 10 cm of the sediment as the maximum potential oxic organic C remineralization rate, based on three different degradation constants (k) for labile, semi-labile and refractory organic C. The range of modelled remineralisation rates reported by the authors (0.1 - 100 mmol C m^{-2} d^{-1}) is similar to our measurements (2 – 88 mmol C m^{-2} d^{-1}), supporting the assay's applicability for resuspension assessments. First-order kinetics imply that reactive organic carbon decomposes at a rate (k) directly proportional to its concentration (Middelburg, 1989). However, the non-linear relationship between RCO2P and OM content in our data suggests that the conversion of organic C to CO_2 changes disproportionately along the OM gradient. The resuspension process likely alters the reactivity of the resuspended OM pool and how bacteria metabolize it (Arndt et al., 2013; LaRowe et al., 2020). Using different rate constants for different organic C labilities may partly account for that, but the minor influence of OM lability (OM:Phyto ratio) on RCO2P in our sediments suggests that other physical, chemical and biological properties of the surrounding environment influence reactivity of resuspended organic matter. In this context, the importance of median sand content and OM-depth interaction in explaining variability of RCO2P suggest that other environmental factors play a role for the reactivity of sediment OM and thus RCO2P. The spatial distribution of larger grain sizes and OM along depth gradient can be a result of physical forces such as the Gulf's circulation and tidal currents (Black et al., 2000; Manighetti and Carter, 1999; Zeldis et al., 2004). This may indicate that physical transport and deposition pathways of OM within the Hauraki Gulf are important factors for RCO2P, though this hypothesis warrants further exploration. Broad classifications of degradation rate constants in models may overlook non-linear and interactive dynamics like the ones we found for the Hauraki Gulf. Our approach captured the sediment heterogeneity without relying on predefined categories, thus embracing variability in sediment characteristics as information, not noise. While our findings are specific to the Hauraki Gulf, they highlight the value of integrating continuous sediment heterogeneity data into regional trawling assessments for a real-world understanding of spatial patterns.

Our BRT model explained ~ 57 % of RCO2P variability, a strong result given the variability of sediment characteristics in the dataset. However, a substantial portion of variability remains unexplained, suggesting that additional drivers may be at play. One possibility is the respiration of small macrofauna and meiofauna within the incubated surface sediment. While samples with visibly large macrofauna were excluded, the presence of smaller macrofauna and meiofauna was observed by small worm burrows. These benthic species may alter their respiration in response to resuspension stress, potentially influencing RCO2P depending on their abundance and biomass. Such animal effects would also influence CO_2 production when the animals are disturbed by trawls or dredges. Including faunal abundance or biomass data could help clarify these effects in a diverse system would add substantially to the analytical time and likely restrict replication across a sampling region. Another factor influencing RCO2P is the history of trawling disturbance, which can influence both the concentration and reactivity of OM as well as how it is mediated through benthic faunal communities (Hale et al., 2017; Pusceddu et al., 2014; Tiano et al., 2022; Zhang et al., 2024). Incorporating a measure of historical disturbance frequency could improve assessments of RCO2P vulnerability if the data on trawling activity is collected at the level of precision necessary to link it to our sampling sites. Overall, our results clearly demonstrate that integrating sediment heterogeneity in resuspension assessments advances our spatial understanding of potential trawling impacts.

Recent discussions around confining trawling pressures focused on reducing the impact on benthic habitats and reef-forming benthic species (Bennion et al., 2024; Smith et al., 2023). As our understanding of the vulnerability of sediment C storage to

https://doi.org/10.5194/egusphere-2025-3045
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demersal fishing grows, it underlines the need to integrate it into the spatial management of the demersal fishery. Porz et al. (2024) identified a model scenario of seafloor carbon protection to be the most efficient in sediment organic carbon preservation and maintaining benthic macrofauna biomass for the highly impacted North Sea. It highlights that integrating seafloor carbon protection into spatial planning benefits sediment organic C sequestration and storage as a key climate function, reducing the CO_2 footprint of demersal fishing practices and protecting benthic species and habitats. Considerations of sediment carbon vulnerability are lacking in recent suggestions for 'trawling corridors' in the Hauraki Gulf (Fisheries New Zealand, 2023). We hope our empirical assessment of C storage vulnerability using the resuspension assay will provide relevant information to be included in the spatial management of demersal fishing in the Hauraki Gulf.

5 Conclusion

The risk of CO_2 release from the sediment as a consequence of resuspension is not something we can ignore as we seek to limit emissions and meet climate obligations. Our findings underscore the importance of accounting for sediment heterogeneity when assessing the vulnerability of seafloor carbon storage to anthropogenic disturbance. The resuspension assay provided a robust empirical measure of oxic organic carbon mineralisation in resuspended sediments, revealing that organic matter content, water depth, and sediment grain size interact and drive variability in resuspension-induced CO_2 production. These interactions highlight that sediment characteristics cannot be considered in isolation, and that context-dependent relationships are key to understanding carbon loss from marine sediments. The identification of sediment types and areas in the Hauraki Gulf with high RCO2P rates offers localised insight into where carbon storage is most at risk, and where management efforts could be focused.

By embracing sediment heterogeneity, our approach complements model-based assessments and provides a pathway for refining regional-scale predictions of carbon disturbance. As global efforts to reduce the carbon footprint of demersal fishing intensify, integrating sediment carbon vulnerability into spatial fisheries management becomes increasingly critical. Our results support the inclusion of seafloor carbon protection in regional planning, particularly in areas like the Hauraki Gulf where sediment heterogeneity and fishing pressure intersect. Moving forward, combining empirical assessments with improved data on faunal activity, organic matter reactivity, and disturbance history will enhance our ability to sustain natural C sinks in sediments and contribute to climate mitigation strategies.

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Data and code availability

Data and software code will be published upon acceptance of the manuscript, but are made available to the reviewers of this manuscript.

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