v1.0

Organic carbon stocks and potential vulnerability in marine sediments around Aotearoa New Zealand

Prepared for Parliamentary Commissioner for the Environment

June 2023

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NIWA CLIENT REPORT No: 2023162WN
Report date: June 2023
NIWA Project: PCE23301

Revision	Description	Date
Version 0.1	Draft in preparation/in review	9 June 2023
Version 1.0	Final version sent to client	30 June 2023

Quality Assurance Statement		
	Reviewed by:	Alison MacDiarmid
	Formatting checked by:	Jess Moffat
	Approved for release by:	Alison MacDiarmid

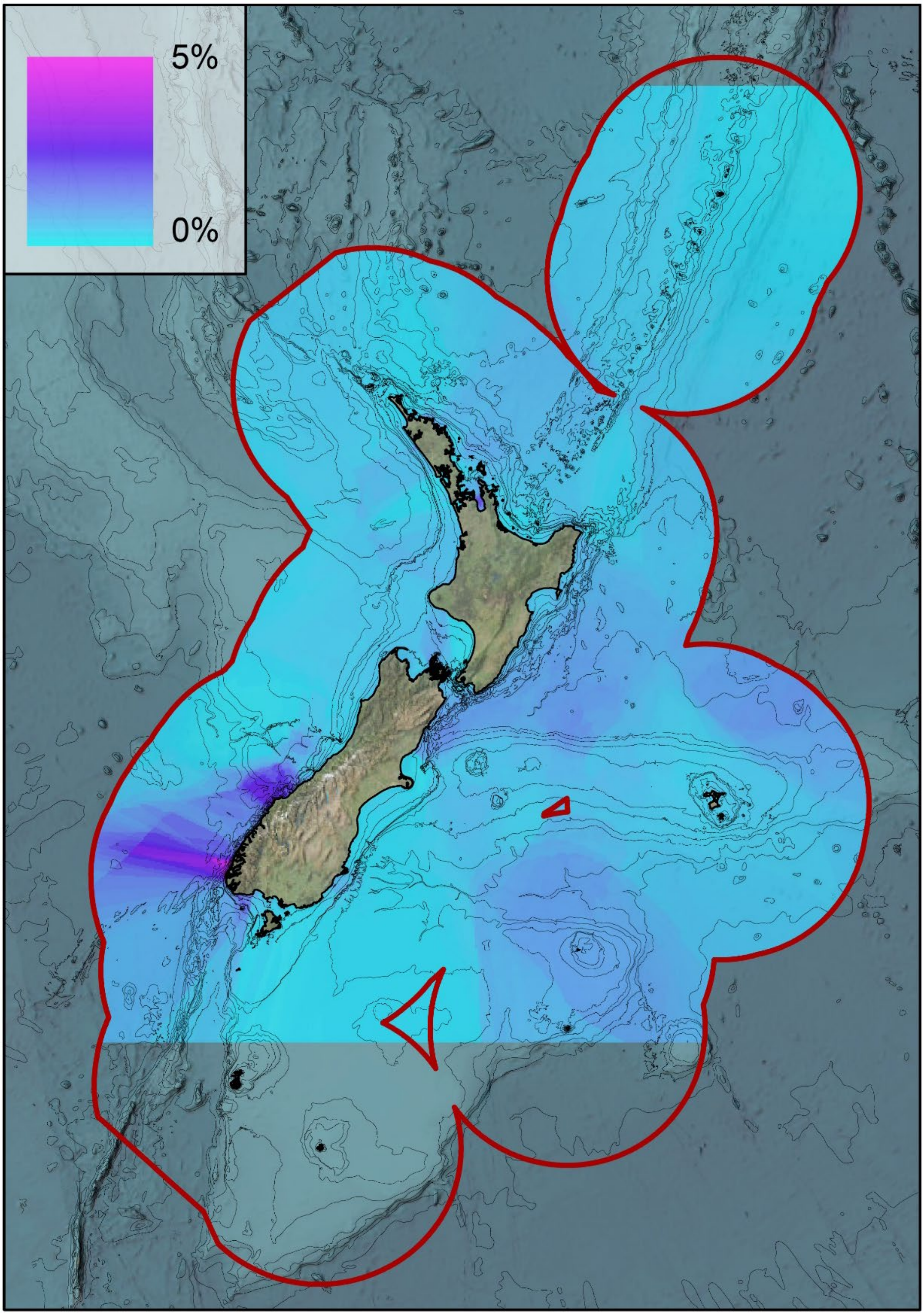

Image shows the modelled distribution of the percentage of Organic Carbon in surface marine sediments (0-10 cm) around Aotearoa New Zealand.

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Executive summary

Marine sediments are one of the largest repositories of organic carbon (OC) on Earth and play a vital role in regulating climate change by accumulating and burying carbon on timescales of thousands to millions of years if left undisturbed. While the efficacy of marine sediments to regulate climate on shorter timescales is less certain, historically persistent and ongoing physical seafloor disturbance by anthropogenic activities, such as bottom trawling, seabed mining, dredging and anchoring, have the potential to release sedimentary OC back into the overlying seawater. With this process, there is the opportunity for this carbon to be remineralised into CO_2, thereby offsetting the absorption efficiency of the oceans for taking up atmospheric CO_2.

Based on the methods developed and utilised initially for the United Kingdom Exclusive Economic Zone (EEZ), we have compiled a new database of OC measurements in marine sediments around Aotearoa New Zealand. For the first time, an EEZ-scale inventory of sedimentary OC is available, from shallow harbours and estuaries to deep-water abyssal plains and subduction trenches. The focus is on the top 10 cm of sediment, as used in previous studies, because the organic matter residing here is likely to be the most reactive and vulnerable to remineralisation, especially if affected by natural or anthropogenic seafloor disturbances. As a first-order approximation, the magnitude of the OC stocks in the top 10 cm of marine sediments throughout the Aotearoa New Zealand EEZ is at least 1890±250 Mt OC for the areas of the EEZ that our statistical methods were able to robustly extrapolate to, and as much as ~2240±290 Mt OC, making assumptions of the OC content in those areas that we were not able to model satisfactorily. This represents about 1% of the estimated global OC stocks in marine sediments. These carbon stocks are distributed unevenly across the EEZ with shallow coastal and continental shelf environments (0-200 m water depths) accounting for only ~7%, compared to ~12% globally. A substantial amount of carbon (~26%) resides in New Zealand's continental slope sediments (200-1500 m), about four-times more than global estimates for the same environments. Due to the large area of the EEZ deeper than 1500 m, a substantial amount of OC is captured in deep-water sediments (~66%, ~1250 Mt), a similar proportion as for the global sedimentary OC inventory for abyssal, basin and hadal environments (~79%). Average estimates of OC stocks and percentages indicate that these are consistent across water depths at 0.5-0.6 kg/m^2 and ~0.5%, respectively, with highest values (typically with OC contents greater than 5%) found in shallow embayments such as Tikapa Moana-o-Hauraki Firth of Thames and the Fiordland fjords in southwest Te Waipounamu South Island.

Given that the most pervasive activity physically disturbing marine sediments is bottom trawling at water depths less than 1500 m, the vulnerability of OC to this anthropogenic activity was evaluated combining information from the new OC database in relation to assumed sediment type lability, particle sinking speeds and OC degradation rates. This analysis has led to the development of a vulnerability index for OC to bottom trawling that emphasises the likely impact of trawling on OC stocks in continental shelf and slope environments, particularly off south Westland, with moderate levels suggested for western Te Awa-a-Kiwi Foveaux Strait, Bounty Plateau, central northern Chatham Rise and along the east coast from Kaikōura to Te Matau-a-Māui Hawkes Bay. The spatial extent of vulnerability models in this context are governed by the distribution of bottom trawling and high levels of OC. In Aotearoa, bottom trawling is not permitted in many harbours and fjords where numerous studies have revealed carbon densities are particularly high. As such, the logical extension for analysing OC disturbance and vulnerability in Aotearoa should focus on shallow marine embayments, harbours and fjords, which host a range of cumulative anthropogenic activities that

disturb the seabed and potentially OC stocks (e.g., seabed mining, dredging, anchoring). There is also a need to measure and monitor environments that have not as yet been impacted by human activities, particularly deep-water habitats that remain the greatest repository of OC on Earth.

1 Background

In December 2022 the Parliamentary Commissioner for the Environment (PCE) commissioned NIWA to undertake a study of the organic carbon (OC) stocks in marine sediments around Aotearoa New Zealand and their potential vulnerability to anthropogenic disturbance.

The PCE is interested in determining the possible scale of the impacts of human activities on marine benthic environments, focussing on OC. In the absence of human disturbance, marine sediments act as a significant repository for OC, particularly in deep-water environments. In shallower locations (coastal embayments, continental shelf and slope) anthropogenic impacts increase substantially and there is the potential for these sedimentary OC stocks to be released back into the water column and potentially remineralised to CO_2. The PCE is interested in setting direction for Government policy with regard to carbon sequestration by the oceans, and to identify the uncertainties and gaps in our knowledge that will assist in developing policy outcomes for the benefit of Aotearoa New Zealand.

2 Introduction

Marine sediments are the eventual repository for **organic carbon** (OC) that is produced in the surface ocean and sinks to the seabed, or are introduced laterally from terrestrial systems, such that seafloor sediments act as an ultimate sequestration pathway for capturing and ultimately storing atmospheric carbon dioxide (CO_2) in the deep-sea. In the sun-lit surface ocean, dissolved CO_2 (in the form of carbonate CO_3^{2-} and bicarbonate HCO_3^- ions) is taken up and converted into organic matter during photosynthesis by phytoplankton (microscopic marine algae). This organic matter is remineralised by bacterial degradation and metabolic processes (grazing, reproduction) by higher trophic level organisms, such as zooplankton, within the marine food web. Organic material in the form of dead phytoplankton and/or by-products of zooplankton grazing (faecal pellets, carcasses) sinks out of the surface ocean and is deposited on the seabed, where the OC is either utilised as a food source by benthic organisms or is buried in marine sediments. The process of transferring OC to the deep-sea is known as the marine **biological carbon pump** (Boyd et al., 2019; Volk & Hoffert, 1985). During the transition to the seabed, organic materials can be remineralised and repackaged multiple times by a variety of food web processes, resulting in a globally significant pool of dissolved inorganic carbon at water depths >200 m. This myriad of complex and interacting processes form the basis of the **global marine carbon cycle** (Archer, 2010; Schimel et al., 1995; Siegenthaler & Sarmiento, 1993).

The burial of OC (and inorganic carbonate materials) in marine sediments acts as an important buffering mechanism against increasing CO_2 concentrations in the atmosphere by removing carbon from further contact with the overlying seawater and ultimately the atmosphere on timescales greater than 1000 years (i.e., at the timescale of full ocean basin overturning) (Archer et al., 2000; Broecker & Denton, 1990). Many attempts have been made to estimate the magnitude of the ocean carbon reservoirs and the fluxes between them (Archer, 2010; Friedlingstein et al., 2022; Schimel et al., 1995; Siegenthaler & Sarmiento, 1993), with 10 000-45 000 MtC stored in coastal systems and 1 750 000 MtC in marine surface sediments, compared to 37 000 000 MtC in the form of dissolved inorganic carbon and 700 000 MtC in organic carbon (Friedlingstein et al., 2022) (Figure 2-1). There is also recognition that continental margin environments account for a disproportionate amount of the world's global primary production based on the relatively small areal extent of such habitats (i.e., ~20% of global ocean net primary production; (Chen, 2010; Chen & Borges, 2009; Muller-Karger et al., 2005). These environments also having the potential to sequester and store significant amounts of organic carbon (i.e., ~60 Mt C/y or 40% of the OC stored annually in global marine sediments: (Muller-Karger et al., 2005). In coastal systems, the concept of 'Blue Carbon' has been advocated as a mechanism for increasing carbon sequestration by plant growth and OC burial in marine sediments, especially in coastal wetlands (e.g., saltmarshes, mangroves) and seagrass habitats, as a means of offsetting CO_2 emissions (Geraldi et al., 2019; Jankowska et al., 2022; Lovelock & Duarte, 2019; Macreadie et al., 2021). Macroalgae and marine sediments are now also being proposed for inclusion in 'blue carbon' initiatives as these systems also sequester and store OC (Graves et al., 2022; Krause-Jensen et al., 2018) (Figure 2-1).

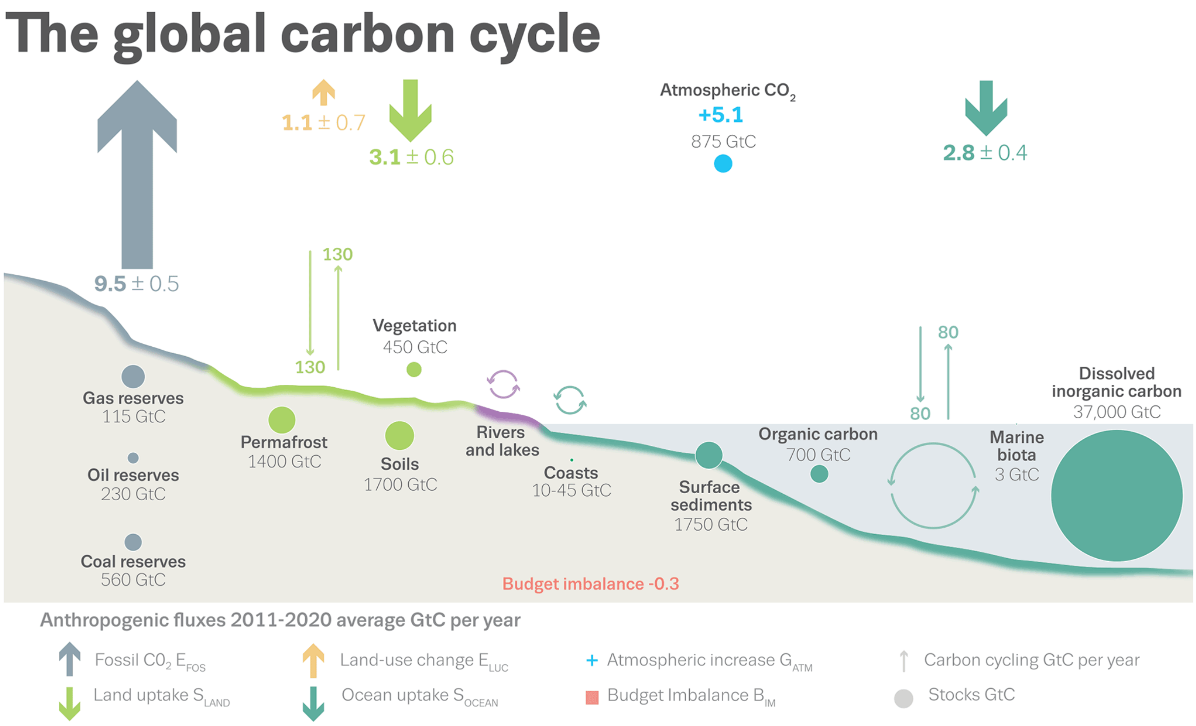

Figure 2-1: Schematic diagram showing the reservoirs and fluxes within the global carbon cycle and perturbations due to anthropogenic activities. The carbon stocks and fluxes (in GtC and GtC per year, respectively) are taken from anthropogenic perturbations are averaged globally for 2011-2020 (figure from Friedlingstein et al. (2022) based on Canadell et al. (2021) and Price & Warren (2016)).

While only a very small percentage of the OC produced in the upper ocean reaches the seafloor and is sequestered and buried in marine sediments (<0.5% of the surface carbon production (Burdige, 2007; Hedges & Keil, 1995; Middelburg, 2019)), it is estimated that OC in surficial marine sediments comprises a substantial reservoir in the global carbon cycle, estimated to be ~87,000 ± 43,000 Mt by Lee et al. (2019) and as high as 3,117,000 Mt OC within the top 1 m by Atwood et al. (2020) due to the large areal extent of the oceans on planet Earth. Furthermore, these global stores of OC are estimated to increase by 160 Mt annually through accumulation and burial (Hedges & Keil, 1995). It is likely that inorganic carbon (IC) in the form of carbonate (shelly) materials is also a large storage reservoir of carbon, compared to OC (i.e., ~5 times larger IC reservoir in UK marine sediments) (Smeaton et al., 2021)(although not considered by the present report – see Section 7 Recommendations).

Natural and anthropogenic disturbance of marine sediments, especially in shallow waters (<50 m water depth), can release sequestered OC into the water column, which can then re-equilibrate with the atmosphere (Duplisea et al., 2001), thereby reducing the sequestration and buffering potential of this carbon reservoir in the global carbon cycle (Sala et al., 2021). Sala et al. (2021)'s paper proved to be somewhat contentious in a number of areas (Epstein et al., 2022; Hiddink et al., 2023; Hilborn & Kaiser, 2022), as refuted by Sala et al. (2022) and co-authors (Atwood et al., 2023). One area of conflict concerned the potential scale of seabed disturbance by bottom trawling in releasing significant amounts of OC from marine sediments into the water column (i.e., estimated as 1.47 Pg of aqueous CO_2 emissions) (Sala et al., 2021) due to increased carbon metabolism in the sediment over the first year following trawling (cf. (Epstein et al., 2022; Hiddink et al., 2023).

Within the Aotearoa New Zealand context, there is a need to develop similar scientific approaches to quantify the total amount of OC stored in marine sediments on the Exclusive Economic Zone (EEZ)-scale, as has been undertaken by other researchers on the NW European shelf (Diesing et al., 2017, 2021; Legge et al., 2020) and around the United Kingdom (UK) (Black et al., 2022; Luisetti et al., 2019; Smeaton et al., 2021). The present study provides: (1) the first estimates for the total OC content of marine sediments around Aotearoa New Zealand at the EEZ-scale; (2) delineates regions that may be potentially vulnerable to OC release from marine sediments due to repetitive anthropogenic disturbances, in particular bottom trawling; and (3) considerations to the possible fate and impact of this released OC on marine ecosystems and climate implications. In this context, the present study should be viewed as a pilot from which more accurate measurements and quantitative approaches can be adopted in the future. By way of a template, we have largely adapted the methods as used by Black et al. (2022) for the UK EEZ, with the aim of developing a similar map showing the distribution of an OC vulnerability index that highlights the seafloor areas that are least and most vulnerable to potential disturbance by bottom trawling and other anthropogenic activities, as shown in Figure 2-2.

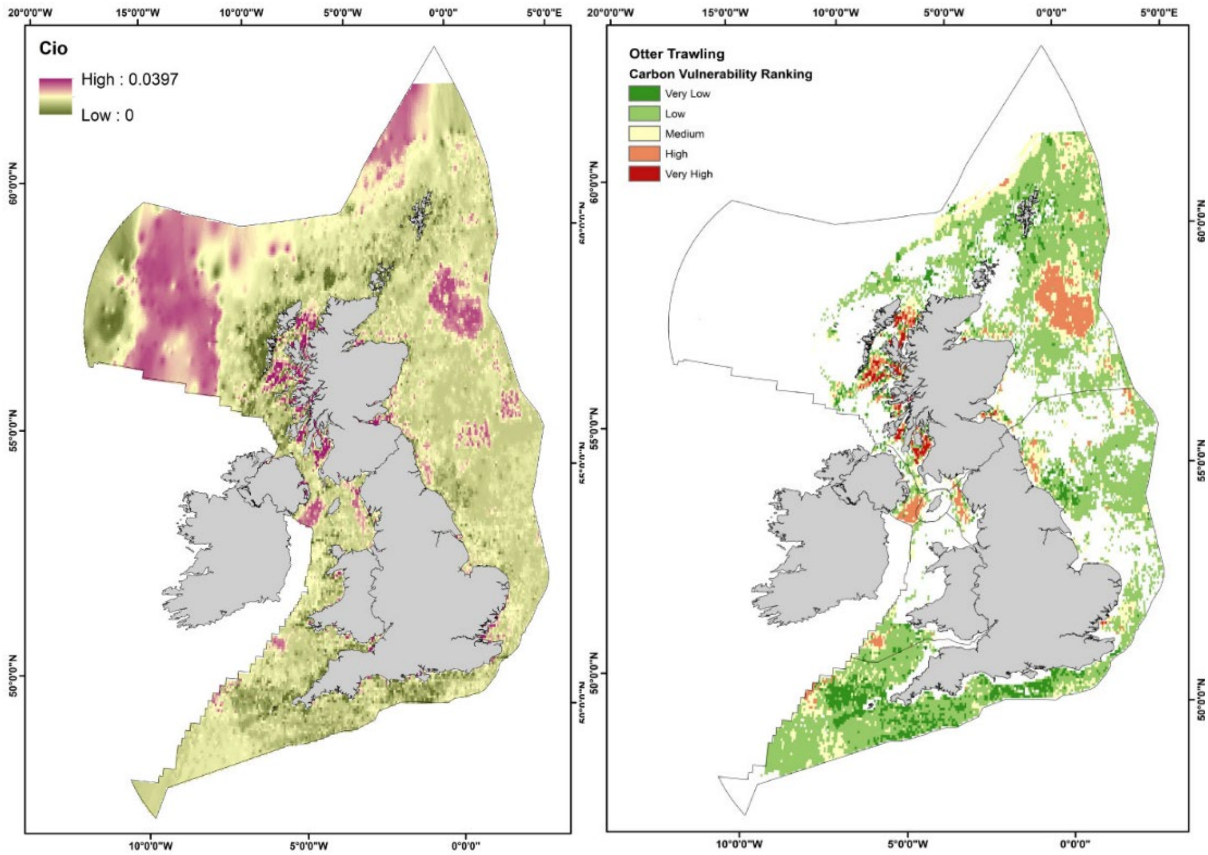

Figure 2-2: Examples of Organic Carbon content (C_{i0}) (left panel) and Carbon Vulnerability Index map for otter trawling (right panel) in the United Kingdom EEZ from Black et al. (2022) .

3 Methods

3.1 Study area

The study area encompasses the 200 nautical mile (NM) Aotearoa New Zealand Exclusive Economic Zone (EEZ) and the 12 NM Territorial Seas, extending from shallow bays, fjords, harbours and estuaries to the deep-sea (>5000 m). While the focus of the present study is on water depths shallower than 1500 m (i.e., bottom trawling depths), the study area extends into deeper waters, including subduction trenches (such as the Kermadec Trench to the NE) and the abyssal seafloor of Te Tai-o-Rēhua Tasman Sea to the west and SW Te Moana-nui-a-Kiwa Pacific Ocean to the east of Aotearoa New Zealand.

The Aotearoa New Zealand EEZ is one of the largest maritime dependencies globally, encompassing an area of 4,120,363 km^2. Extending between ~26°S and ~56°S latitude and 160°E and 170°W longitude, the Aotearoa New Zealand EEZ contains a complex variety of submarine features such as continental shelves, slopes, undersea ridges, volcanoes, seamounts, canyons, channels, troughs and trenches (Mitchell et al., 2008, 2012) (Figure 3-1). This seascape constitutes the submerged component of arguably Earth's seventh continental landmass (Mortimer et al., 2017), now sitting astride the Pacific-Australia plate boundary (King, 2000; Lamarche et al., 1997; Strogen et al., 2022; Wallace et al., 2009). This complex geological setting leads to diverse oceanographic and benthic environments (Chiswell et al., 2015; Leathwick et al., 2012; MacDiarmid et al., 2012; Snelder et al., 2007; Stevens et al., 2021). The average water depth of the Aotearoa New Zealand EEZ is ~2400 m; however, water depths can exceed 10,000 m, such as along the Kermadec Trench (Figure 3-1).

In consultation with the PCE, four water depth zones were defined to use in estimating OC inventories and vulnerability throughout the EEZ: 0-50 m, >50-200 m, >200-1500 m, and >1500 m. These water depths correspond, respectively, to coastal embayments and the inner shelf, mid- to outer shelf, upper continental slope, and mid-slope to hadal environments (>6000 m). It is noted that while we have incorporated data from shallow intertidal environments (Berthelsen et al., 2020; Clark et al., 2018); R. Bulmer, MBIE Smart Idea Blue Carbon project; see Section 3.3), we have not attempted to determine the blue carbon stocks in coastal habitats, such as seagrasses, saltmarshes and mangrove forests.

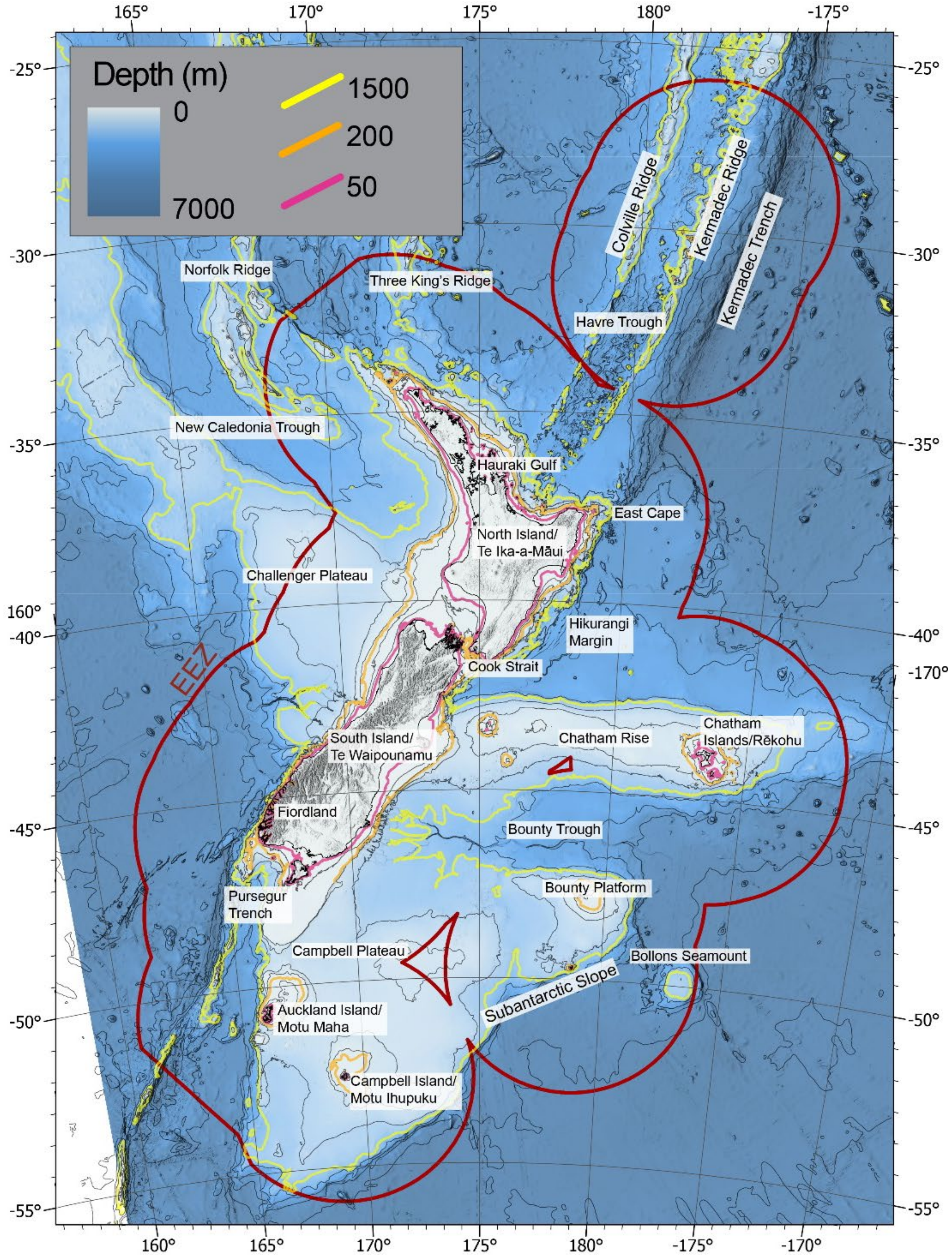

Figure 3-1: Map showing Aotearoa New Zealand, the outer boundary of the Exclusive Economic Zone (200 NM, thick red line) and placenames used in the text of the present report. Thin yellow, orange and pink lines show the 1500 m, 200 m and 50 m bathymetric contours, respectively. Bathymetric data from (Mitchell et al., 2012)

3.2 Methodology

The initial focus of the project was to determine the OC content in surficial marine sediments throughout the Aotearoa New Zealand EEZ, while acknowledging that this parameter is likely to include sedimentary organic material that encompasses a range of timescales, reactivities and sources (Arndt et al., 2013; Burdige, 2007; Hedges & Keil, 1995). The OC and sediment data compilations for the present project concentrated on measurements in the top 10 cm of sediment, as used in previous studies, specifically Black et al. (2022), because the organic matter residing here is likely to be the most reactive and vulnerable to remineralisation (Bianchi et al., 2018; Burdige, 2007; Hedges & Keil, 1995), especially if affected by natural or anthropogenic seafloor disturbances. We largely followed the methods used by Black et al. (2022), who assessed the impact of bottom trawling on the OC content of marine sediments around the United Kingdom (UK). These methods were used as an initial guide and modified according to the datasets that we were able to generate. Key parameters used by Black et al. (2022) in their analysis were:

- Sediment type (%OC, grain-size, Folk classification, grain density, settling velocity);
- Reactivity of organic matter and annual OC degradation constants; and
- Spatial distribution of fishing effort and depth of disturbance based on bottom gear type (otter trawls, beam trawls, dredges and seine trawls).

From these parameters, the intensity of fishing activity, the proportion of resettled sediment after trawl disturbance, organic matter lability and a time factor (1 year) were calculated from which the potential amount of material "lost" due to trawling could be calculated, informed by estimates of the amount of OC in the top 10 cm of marine sediments. Black et al. (2022) used Fuzzy Set Theory, which determines the possibility of membership between different types of spatial information (typically by assigning values between 0 and 1) to model the potential vulnerability of OC in marine sediments. This method assigns a numerical ranking of 1 to areas where sediment OC is most vulnerable, while a value of 0 identifies the least vulnerable locations. Fuzzy Set Theory estimates the possibility of something being true or occurring, not the probability, which estimates the likelihood of these events.

The approach adopted in the present study was modified from Black et al. (2022) in the following major ways, as also summarised in Figure 3-2:

- Use of 2.65 g/cm^3 as a bulk density estimate for marine sediments (Diesing et al., 2017) since this value is commonly used in sediment studies, as it is the density of quartz, a common component in marine sediments (e.g., Best & Gunn, 1999). We elected not to use the derived mean value of 2.60 ± 0.12 g/cm^3 from Smeaton et al. (2021), since this value was determined from UK data and may not be entirely representative of the more heterogenous Aotearoa New Zealand seascape and associated sediments;
- We did not distinguish between fishing gear type, assuming all bottom trawling in the MPI-FNZ trawl footprint database were essentially otter trawls as distinguished by Black et al. (2022) in the UK study. The bottom trawl footprint data are based on door-spread as are the data presented in Black et al. (2022) for otter trawls (e.g., (Eigaard et al., 2016; Hiddink et al., 2017);

- General Linearised Models were used to partition out the key parameters driving OC variability in marine sediments to enable proxies for OC to be determined and extrapolated across the large and spatially heterogenous EEZ domain (see Section 3.5.3).

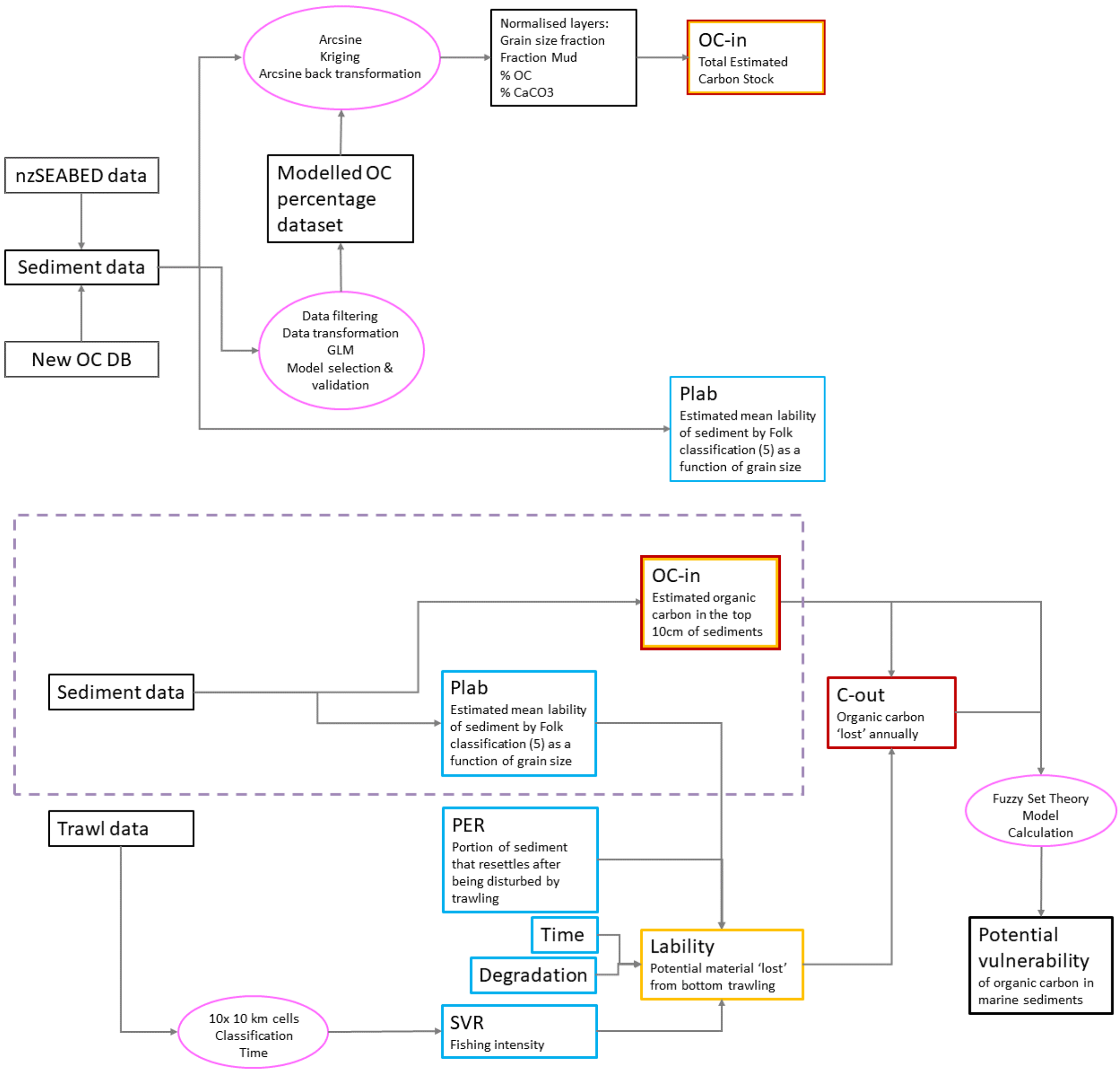

Figure 3-2: Top: Detailed flowchart of the processing steps for deriving sediment OC data (as encompassed in the dashed box in the flowchart in the bottom panel). Bottom: Flowchart of data compilation, QA/QC, statistical and ArcGIS processing used to assess the vulnerability of OC in marine sediments in the present study. Acronyms are defined in the text: OC-in = Organic Carbon content in top 10 cm surface sediment; Plab = sediment lability; C-out = OC remaining in the sediment after trawling disturbance; PER = ratio of particle settling velocities; SVR = swept volume ratio; nzSEABED = sediment database from Bostock et al. (2019a) and Bostock et al. (2019b).

3.3 Datasets

Several existing and new datasets were utilised in the present study based on the data parameters and the workflow employed by Black et al. (2022) for the UK EEZ. Each of these datasets are described in detail below.

All seabed descriptions, geochemical data and grain-size information represent a significant compilation of available offshore data across the Aotearoa New Zealand EEZ, reflecting more than 60 years of offshore data collection (i.e., from late 1950s to present-day) (see Bostock et al., 2019a, 2019b). We acknowledge that there may be some data aliasing due to the different collection dates, especially in relation to the MPI-FNZ bottom trawl footprint data, which are available only for the period 1989 to 2022 (see Section 3.3.3). To maximise the input data for our first-order assessment, however, we compiled all OC and sediment data, regardless of the collection date.

Primary datasets considered for this study include:

- Organic Carbon data (Percentage OC and Percentage Total Organic Matter (TOM))
- Carbonate (Percentage $CaCO_3$)
- Grain-size fraction (Percentage Gravel, Sand, Silt, Clay, and Mud [Silt + Clay])

A summary of the statistics from the data compilation and analysis is presented in Appendix A. Since no central data repository for samples collected across the EEZ presently exists, it remains uncertain how much data may be missing from this compilation dataset.

Due to the variability of source datasets, the compilation of all data into a singular input database was undertaken through the initial development of two separate compilation datasets. These datasets can be summarised by:

1. nzSEABED Database (Bostock et al., 2019a, 2019b) 9970 entries
2. New sediment OC Database (this study) 13,988 entries

These databases were first compiled separately since the nzSEABED database presents an overview of NIWA's legacy grain-size, TOM, and accessory mineralogy data only. Additional data curating was required for the new OC database (see Section 3.4). These data required statistical modelling to derive OC values based on identified statistical relationships (See Section 3.5).

3.3.1 Organic carbon and total organic matter (TOM)

OC in marine sediments represents the measured carbon content of organic materials, while Total Organic Matter (TOM) comprises organic compounds derived directly or indirectly from biological processes and organisms. In soils, a relationship to convert %OC to %TOM is in the order of 1.7 to 1.9 (e.g., Sleutel et al., 2007) but it has been difficult to find a similar relationship explicitly stated for marine sediments in the literature. It is likely, however, that phytoplankton-related biomass in marine systems will contain higher amounts of other highly reactive organic compounds and elements than more refractory terrestrial organic matter (Burdige, 2005; Hedges et al., 1997) therefore the $\%OC_{marine}$:$\%TOM_{marine}$ is likely to be higher than these soil values.

A new compilation of data was initiated to encompass as many OC and TOM data points available for the present study, given the time-constraints of the contract period. With the recognition of a large amount of uncompiled data held by researchers in the Marine Geology group based in NIWA

Wellington, personal contact was also made with other researchers in NIWA, GNS Science, independent research organisations (Tidal Research, Cawthron Institute), universities (specifically, Auckland, Waikato, Victoria, Canterbury and Otago) and government departments (Ministry for Primary Industries – Fisheries NZ (MPI-FNZ), Department of Conservation) to request data for input into the new compilation. We also obtained permission from several regional authorities to use their data via contacts made by study contributors. Contact was also made with selected members of the aquaculture and offshore oil and gas industries.

Key data that contributed substantially to the new OC compilation for the present study, include:

- Various NIWA Wellington Marine Geology and Biology published and unpublished datasets (Dr Scott Nodder, Dr Katie Maier, Dr Alan Orpin, Dr Daniel Leduc, Dr Sarah Seabrook), collected under numerous historic and current government research grants and voyages, including Ocean Survey 2020 Chatham Rise-Challenger Plateau (2004-05) and Bay of Islands (2008-09), Mountains-to-Sea (2000-10), "*Gas Hydrates: Economic Opportunities and Environmental Impact*" (HYDEE 2017-22, MBIE Endeavour contract: C05X1708) and "*Resilience of Benthic Communities to the Effects of Sedimentation*" (ROBES, 2016-2021, CO1X1614);

- Data provided from the historic Fisheries Resource Impact Assessments (FRIA) project in Te Tauihu Marlborough Sounds (Dr Sean Handley, data compiled by the late Russell Cole, NIWA Nelson);

- Data from MPI-FNZ scallop surveys (Dr Rachel Hale (NIWA Nelson), Dr James Williams (NIWA Auckland));

- Data from Tikapa Moana-o-Hauraki Firth of Thames and Ihutai Avon-Heathcote rivers estuary system provided by Dr John Zeldis (NIWA Christchurch);

- Data from the OMV Ltd environmental survey of the Great South Basin and from the StatOil survey of the Reinga Basin (Dr Alan Orpin);

- Estuarine and harbour data compiled by Dr Richard Bulmer (Tidal Research Ltd), Dr Carolyn Lundquist (NIWA Hamilton), and a variety of other New Zealand collaborators under the New Zealand Ministry of Business, Innovation and Employment (MBIE) Smart Idea Blue Carbon 2021-23 study (*"Carbon sequestration via New Zealand's estuarine sediments: Implications for GHG budgets"*);

- Tikapa Moana-o-Hauraki Firth of Thames, Kaipara Harbour and Te Hoiere Pelorus Sound data from commercial contracts with regional councils from Dr Andrew Swales (NIWA Hamilton); and

- The National Estuary Dataset (Berthelsen et al., 2020) and Tauranga subtidal data (D. Clark et al., 2018) provided by Dr Dana Clark (Cawthron Institute), compiled under the Oranga Taiao Oranga Tangata (OTOT) research programme, funded by MBIE contract MAUX1502, led by Murray Patterson (Massey University).

Additional data were compiled from other key environments, such as Fiordland, from published literature (e.g., Cui et al., 2016; Hinojosa et al., 2014; Knudson et al., 2011; Ramirez et al., 2016; Smith et al., 2010, 2015) unpublished university theses and commercial reports, where these were noted during the data compilation process.

The compiled data includes a variety of "OC" or "TOM" measurements, regardless of the analytical method used to determine these parameters. Arguably the most accurate estimates of organic carbon content are from samples run through a CHN-analyser after acidification to remove carbonates (e.g., (Kennedy et al., 2005; Verardo et al., 1990). Such analyses are typically costly, however, and cheaper options are often employed in studies to derive estimates of total organic matter (TOM) content, such as by loss-on-ignition. This method is a standardised laboratory technique involving the combustion of sediment at high temperature (~400-500°C) and measuring the weight of sediment lost after combustion (e.g., Sutherland, 1998). The more costly CHN or mass spectrometry approaches are beneficial in that in addition to estimates of OC content, more information on the chemical composition of the organic matter can be garnered from measuring simultaneously the N content and hence C:N ratios of the substrates (as a measure of OM lability and/or source), perhaps along with stable isotope ratios of C and N ($\delta^{13}C$ and $\delta^{15}N$, respectively).

OC data were checked and filtered to standardise input parameters (such as geographic location - latitudes, longitudes, sampling gear type, sampling date) and to remove duplicates. Data were expressed as averages representing the top 10 cm of seafloor sediment, similar to the approach adopted by Smeaton et al. (2021) and Black et al. (2022). Additional OC results from the modelled proxy dataset (Section 3.5) were integrated with the measured OC dataset, with an arcsine transformation applied prior to the generation of the following krig output layers using ArcPro:

A. Grain size fractions (class-based);

B. Fraction Mud (Fmud, percentage);

C. Percentage OC; and

D. Percentage $CaCO_3$ (class-based).

The arcsine transformed data was then back-transformed and the datasets for each krig layer were normalised to a 0-100% scale. Using equations from Smeaton et al. (2021, pp. 7–8), and additional references from Diesing et al. (2017) and Jenkins (2005), *raster calculator* in ArcPro was then used to derive an estimate of the total OC stocks in the Aotearoa New Zealand EEZ using the following procedures:

A. Volume (V = Area [Raster area – 62 500 m^2) x Depth [0.1 m]);

B. Porosity ($\Phi = 0.3805 \times F_{mud} + 0.42071$);

C. Dry Bulk Density (Dry Bulk Density (kg m^{-3}) = $(1 - \Phi)$ × Grain Density (constant 2650 kg m^{-3});

D. Mass (kg) = Volume (m^3) × Dry Bulk Density (kg m^{-3});

E. Carbon Stock (kg) = Mass (kg) × Organic Carbon Content (%); and

F. Carbon Storage (kg m^{-2}) = Carbon Stock (kg)/Area (m^2).

The final output was stored as a raster layer as "Total Estimated Carbon Stock".

The Aotearoa New Zealand-wide OC data compilation presented here is not considered to be exhaustive, especially as it is recognised that there are other data sources that need to be further investigated, such as unpublished university theses and other sediment datasets held by MBIE (e.g., for petroleum and mineral licence areas) and collected by other fisheries projects at MPI-FNZ (e.g., scampi assessments). International data repositories, such as Pangaea (https://www.pangaea.de/) or global compilations (e.g., Atwood et al., 2020; Hayes et al., 2021; Hohmann, 2022; Lee et al., 2019; MOSAIC http://mosaic.ethz.ch/) were not interrogated as part of the data compilation since it was anticipated that the NIWA archives (Bostock et al., 2019a, 2019b) and targeted data requests would generate most of the accessible data for the Aotearoa New Zealand region. In support of this approach, it is noted that in the global sediment OC compilation undertaken by Seiter et al. (2004) and in the most up-to-date compilation in the MOSAIC database there are only two data points in the entire SW Pacific region. Accordingly, the data compilation conducted as a key aspect of the present project is the first comprehensive representation of OC marine sediment data from throughout the Aotearoa New Zealand EEZ. The initial data compilation provided a total of 17,000 individual OC (or TOM) data points that was later reduced to 11,000 (Figure 4-1; Appendix A) upon data quality checks (see Section 3.4), including the removal of duplicate samples and those lacking critical information, such as geographic location. The overall statistics of the dataset are summarised in Appendix A.

3.3.2 Sediment parameters

Grain-size data were also requested with any OC or TOM data from the various agencies and individuals as outlined above in Section 3.3.1. These data were combined with the more extensive grain-size dataset, compiled and presented by Bostock et al. (2019a) for the continental slope and deep-sea and by Bostock et al. (2019b) for the continental shelf around Aotearoa New Zealand (Figure 4-1). The parameters of interest reflect the physical composition of marine sediments, subdivided according to %gravel (>2 mm or 2000 µm-diameter), %sand (2000-63 µm), %mud (<63 µm) and their composition based on %$CaCO_3$ content (calcium carbonate, which includes shell materials). The grain-size classification thresholds are formulated from Udden (1898) and Wentworth (1922) (the Udden-Wentworth scale), amended by Folk (1965). The Folk classifications are used to determine the distribution of broad sediment types and to estimate OC lability across the study area, as part of the Black et al. (2022) methodology.

As for OC, these data also represent a wide range of analytical techniques used to calculate sediment grain-size distributions and carbonate content, ranging from sieve and fall-tube estimates (Van der Linden, 1968) and modern light diffraction-based techniques for grain-size (Blott & Pye, 2012) to loss-on-acidification and vacuum gasometric methods for carbonate content (Jones & Kaiteris, 1983).

3.3.3 Anthropogenic disturbances

The spatial and temporal extent of bottom trawling fishing effort across the Aotearoa New Zealand-EEZ was made using existing data provided by MPI-FNZ (e.g., Baird & Mules, 2021; Black & Tilney, 2015) (Figure 4-7). The most up-to-date analysis of bottom trawl footprint data (covering the period from October 1989 to September 2021) was used in the present study, released by MPI-FNZ prior to their own official report release, which updates the previous compilation by Baird and Mules (2021). Data was moderated based on the '3x3' rule to ensure fishing effort confidentiality within grid-cells with less than three fishing tows over the 1989-2021 period, following the approach of Black et al. (2022) who also used integrated the UK fishing data collected between 2009-2017 (~8 years). Furthermore, the sediment and OC datasets that we compiled are derived from collections made over a sustained time period (i.e., ~60 years, e.g., see Bostock et al. (2019a, 2019b)), thereby justifying the use of all the data from the entire ~32-year trawl footprint time-series rather than focussing on shorter time periods. We derived our analyses from the bottom trawl footprint dataset using the cumulative swept area, based on door spread, for each 5 km x 5 km grid cell area in which there were more than three tows to estimate the extent of anthropogenic disturbance due to bottom trawling in the Aotearoa New Zealand EEZ. Analysis of the variable impact of different fishing gear types was not undertaken in the present study, as was analysed by Black et al. (2022) with the UK fishing data.

In the present study, the impact of other anthropogenic seafloor disturbances, especially in shallow water environments, was not fully addressed, although we have compiled many of the geospatial data required for undertaking further analyses using the new sediment OC dataset and the methods adopted in the present study (Figure 3-3). We have also included discussion on important aspects of these other anthropogenic impacts on marine sediment OC stocks (see Section 5.4). Accordingly, future research could adopt similar disturbance metrics to enable impacts such as nearshore anchoring, seabed mining, deep-water dredging and spoil disposal zones, port infrastructure, seafloor-trenching and laying of telecommunication and power cables, and protected areas for conservation (e.g., marine reserves as established under the Marine Reserves Act 1971), or restricted to certain activities, such as areas set aside for aquaculture, dredging and spoil dumping or Benthic Protection Areas as mandated under the Fisheries (Benthic Protection Areas) Regulations 2007 (Figure 3-3) (also see Section 7 Recommendations). The establishment or protection of marine protected areas to act as carbon storage repositories for mitigating or offsetting greenhouse gas emissions (e.g., Luisetti et al., 2020), especially for those areas with restricted or no bottom trawling activity (Epstein & Roberts, 2022, 2023; Hilborn & Kaiser, 2022; Sala et al., 2022; Sala et al., 2021), could be assessed more fully. In the case of the present project, anthropogenic activities, such as the installation of submarine telecommunication and power cables, pipelines, and port and offshore infrastructure (e.g., oil platforms), essentially represent one-off seafloor disturbances, compared to bottom trawling, which generally has high spatial and temporal density (Baird & Mules, 2021; Black et al., 2022; Black & Tilney, 2015). The more pervasive though localised seafloor disturbance caused by anchoring (Watson et al., 2022) or other shipping-related activities (e.g., propellor wash, channel entrance dredging) in harbours, ports and fjords needs to be more fully evaluated, especially in Aotearoa New Zealand where most of these environments are largely protected from bottom trawling yet also host significant sediment repositories of OC as observed elsewhere (e.g., Diesing et al., 2017, 2021; Luisetti et al., 2019; Smeaton et al., 2021; Smeaton & Austin, 2022).

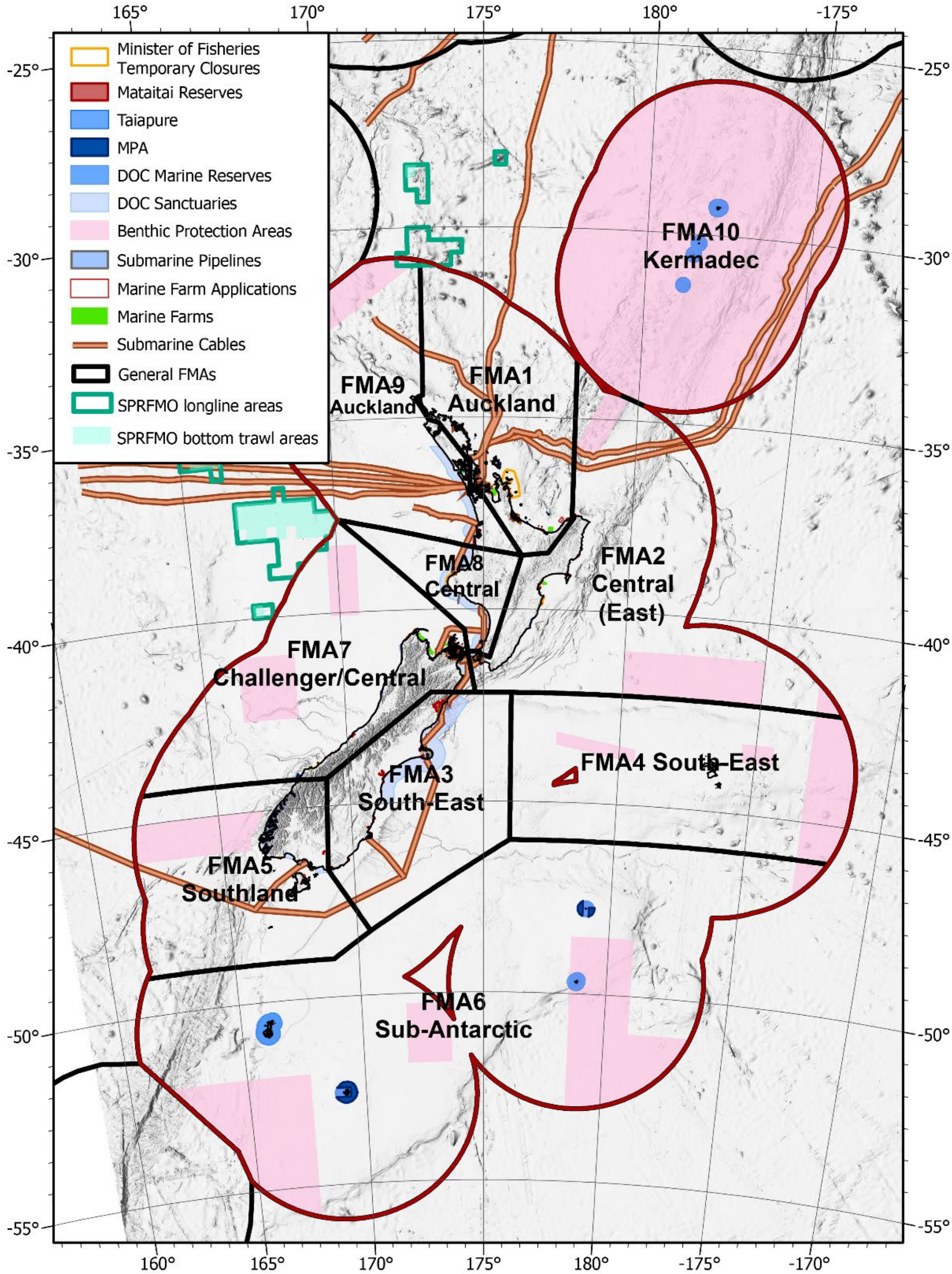

Figure 3-3: Anthropogenic activities and various protected areas within the Aotearoa New Zealand EEZ (200 NM, thick red line). Reference is also made to the assessments in MacDiarmid, A. et al. (2012). "Ministry of Fisheries Temporary Closures" refers to areas temporarily closed to fishing under Sections 186A and B of the Fisheries Act 1996, especially for Māori customary purposes; MPA = Marine Protected Areas; DOC = Department of Conservation; FMAs = Fisheries Management Areas; SPRFRO = South Pacific Regional Fisheries Management Organisation.

3.4 QA and QC – final database compilation

3.4.1 Data Cleaning

Although the new OC database represents data from a variety of sources, including published databases, these data were integrated into a bespoke data structure to ensure consistency between datasets for subsequent analysis (Appendix A). Unique sampling identifications were based on the Survey or Source data, the Site or Station number or identifier, and the Sample Depth Interval. Where an analytical detection limit was identified, the maximum credible value was used (e.g., <0.1% was altered to 0.1 in the database). Although likely resulting in an overestimation, the additional error this introduces was viewed as minimal with respect to the wider dataset. Due to the project-specific approach to sediment sampling in many offshore surveys across the Aotearoa New Zealand EEZ, many of the input datasets are inconsistent with regards to captured data types (e.g., OC vs TOM) and sediment sampling intervals. To ensure consistency between input values for analysis, a weighted average was undertaken on all samples to average values to reflect the upper 10 cm of each sample location. Data normalisation factored in instances where either the sample interval was inconsistent with depth (e.g., sample intervals increasing with depth, i.e., 0-0.5 cm, 0.5-1 cm, 1-2 cm, 2-3 cm, etc), or instances where the entire recorded sample for a particular site exceeded 10 cm depth (e.g., ODP/IODP drilling or NIWA core sites). These normalised values were calculated using the SUMPROD Function in MS Excel to generate weighted averages for the required 0-10 cm interval in instances where multiple samples at varying depths were collected at a single site. Instances where repeat samples were collected at the same site, an average of all samples were taken for final output values.

Once all data were normalised to 10 cm depth, the entire OC database comprised 12,281 data entries (including the nzSEABED database; Bostock et al., 2019a, 2019b). From these OC data, an additional 271 entries were excluded from analysis due to either missing or incorrect positioning. Of all entries incorporated into the new OC database, less than 10% of all data contained OC values (1063 entries in total).

3.5 Proxy development – statistical relationships between sediment parameters

Due to the recognition that there was likely to be inadequate spatial coverage of OC or TOM data across the vast Aotearoa New Zealand EEZ, it was identified early on in the process that proxy estimates for OC from more spatially extensive analyses, such as grain-size, specifically %Mud, %Carbonate, and %TOM would need to be employed to provide more accurate extrapolations of the OC distribution in surface sediments. In this process, it was also recognised that several proxy models may need to be built and tested to predict OC in sediments where no OC data are present.

A multivariate approach to deriving suitable OC proxies was required since no single predictor variable had a strong enough relationship with %OC to build an effective proxy model using bivariate statistics based on two variables alone (see Appendix B, Figure 3-4 and Figure 3-5). Multiple linear regression was trialled, but the datasets invalidated too many assumptions for strict linear regression. Therefore, a generalised linear model (GLM) was chosen as it provides more flexibility for data that invalidates assumptions of linear regression. The GLM acts as a "least absolute shrinkage and selection operator" (LASSO) model and removes predictor variables via a penalty function as they are deemed not to have adequate statistical power in driving the relationships (James et al., 2013).

The relationship between OC and TOM was found to be non-linear (Figure 3-4 and Figure 3-7), perhaps driven by the diverse and heterogenous nature of the seascapes and depositional environments within the Aotearoa New Zealand EEZ. A log transform was subsequently applied to the TOM data to force a linear relationship. Mud and Sand fraction data were constrained to a sum of 100%, due to a paucity of Gravel data from the same sites, but also contained abundant true zero values. Log transformations have limited use, and the log +1 transformation demonstrated did not sufficiently open up the data structure needed for the GLM analysis. An alternative data transformation that is also routinely used for compositional data is the arcsine transformation (as in Smeaton et al. (2021) and references therein). This approach provides a satisfactory statistically robust result and improves the use of the data for use in predictive models, as employed in the present study.

3.5.1 Data preparation for statistical analyses

A subset of the data was extracted for training and evaluating the OC proxy models under the following conditions:

- Data for Organic Carbon Percentage (%OC), Total Organic Matter (TOM), Grainsize (Mud, Sand, Gravel), and Carbonate percentage are comprehensive and complete for each site.
- Dataset contains no NA entries.

TOM was filtered for values below <0.2% as these inputs were below the detection limit and as such were assigned the detection limit as the value (i.e., 0.2%). This caused substantial bias in the dataset. It is important to note that it was originally hypothesised that water depth would be a significant predictor of OC content in surficial marine sediments. After modelling with the GLM-LASSO regression method, and investigating bivariate plots, it was concluded that water depth does not have a relationship with %OC around Aotearoa New Zealand. Therefore, water depth was omitted from the predictive models.

Interrogation of TOM vs OC values (Figure 3-4) revealed a group of outliers that had C:N ratio values greater than 27. According to Lamb et al. (2006), C:N molar ratios above 27 represent terrestrial organic matter (their Figure 2). After filtering the data for values with a C:N molar ratio greater than 27, the majority of outliers were from:

- Samples with acidification treatment from NIWA survey CR3040 (41%); and
- Samples from the Tikapa Moana-o-Hauraki Firth of Thames (25%).

The remaining excluded data with high C:N molar ratios were from individual samples from miscellaneous areas and studies. In the case of the samples from CR3040, it is likely there is an analytical issue that affected the nitrogen and carbon contents if these samples, resulted from the acidification sample treatment step prior to CHN analysis, resulting in the high C:N molar ratio results. The anomalous Tikapa Moana-o-Hauraki Firth of Thames and several associated Hauraki Gulf samples are likely related to the overwhelmingly terrestrial plant signature affecting the carbon contained in these sediments (e.g., Sikes et al., 2009).

In the present study, since the focus is on prediction of OC in marine sediments, samples displaying anomalous or highly terrestrial carbon signatures (i.e., molar C:N >27) were removed from the model training and validation datasets (*n* = 12). Note that these samples were only removed from the model training and validation datasets, not from the data that were subsequently used in deriving %OC distributions. The final dataset used in the proxy estimations comprise 263 sites where all of the above criteria were satisfied, with 75% used for training and 25% used for testing the GLM-LASSO regression models.

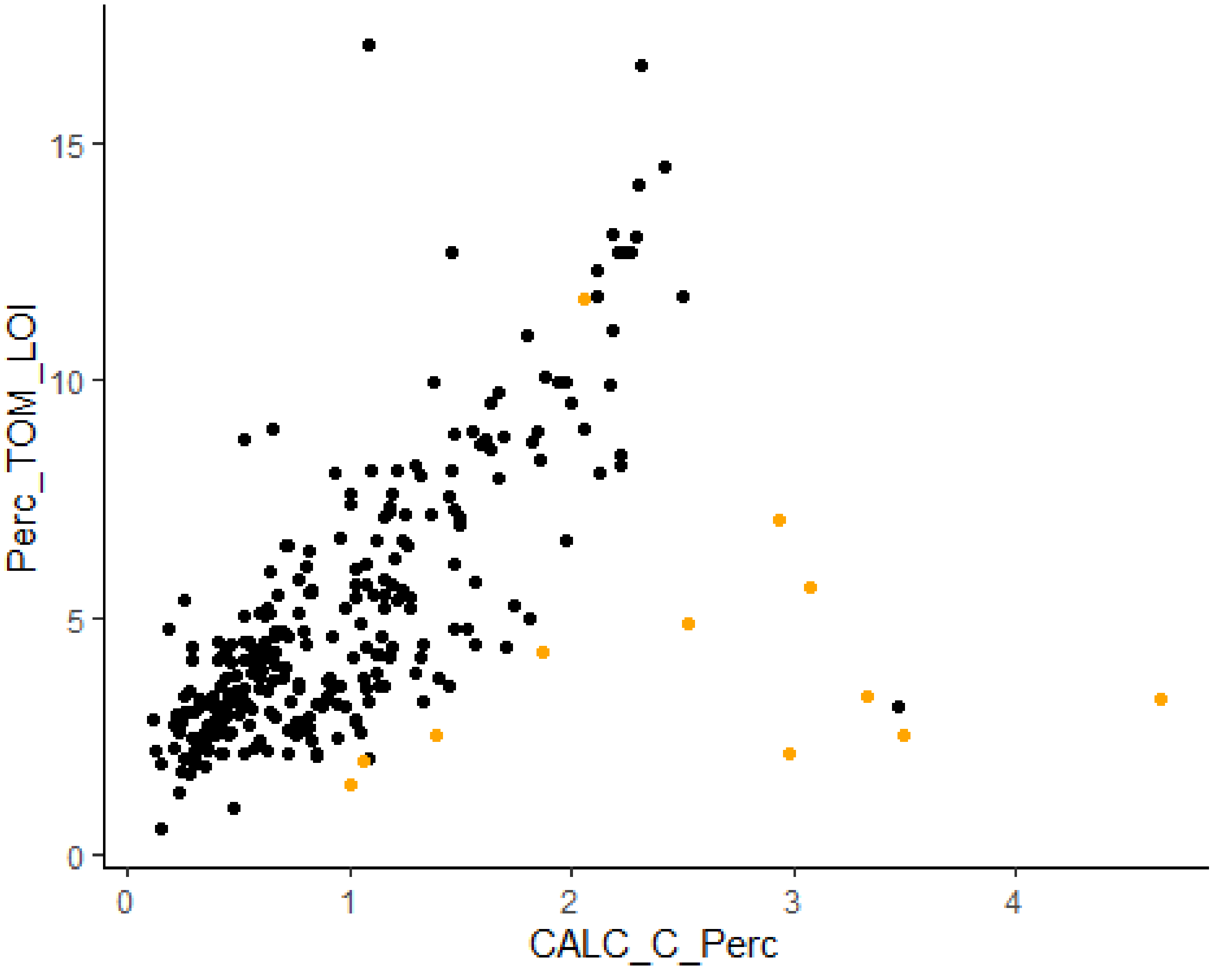

Figure 3-4: %Organic Carbon (CALC_C_Perc) vs %Total Organic Matter (Perc_TOM_LOI) relationship (*n* = 275). Orange dots indicate samples that were excluded from the final model training and validation dataset due to having C:N molar ratios >27 (as in Lamb et al. (2006) (*n* = 12). LOI = Loss-on-Ignition.

3.5.2 Data Treatments

Bivariate plots of each potential predictor variable versus dependent variable were assessed visually for linearity (Figure 3-5). Ordinary least squares regression (OLS) was also applied pairwise with each predictor variable. Residuals were visually interrogated for their variance (homoskedasticity), and Quartile-Quartile plots used to determine if the residuals of the regression are normally distributed or not (see Appendix B).

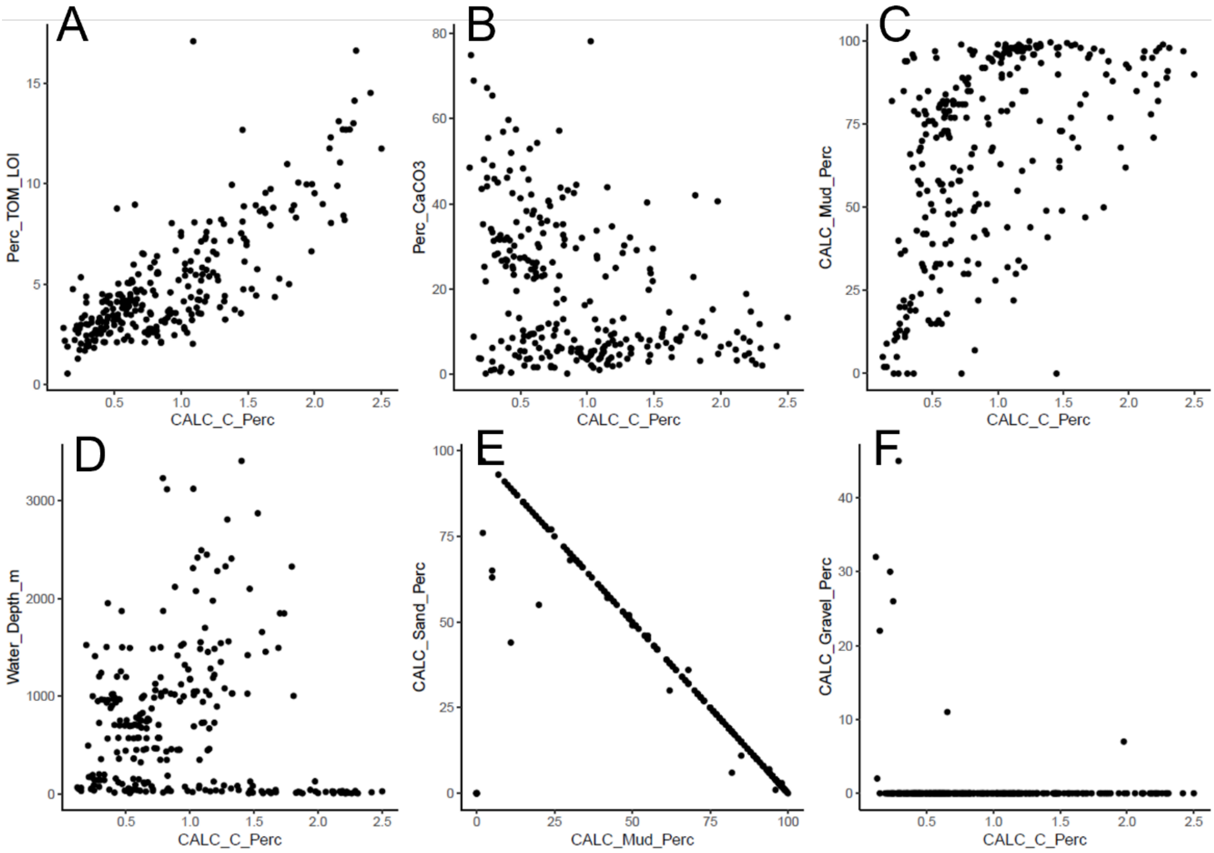

Figure 3-5: Bivariate plots of %Organic Carbon, OC (CALC_C_Perc) plotted against other potential predictor variables. A. %Total organic matter, TOM (Perc_TOM_LOI), B. %Calcium Carbonate (CaCO3), C. %Mud, D. Water Depth (m), E. %Sand and F. %Gravel.

TOM

Percentage TOM showed a non-linear positive relationship with %OC (Figure 3-6, Figure 3-7). Since we are building linear models, it is appropriate to apply a data transformation to the TOM data to encourage a linear relationship (James et al., 2013). In this instance a log transformation was applied. Whilst the R^2 value is slightly less than that obtained for the non-transformed data, the overall fit of the data and distribution of the residuals was improved (Appendix B).

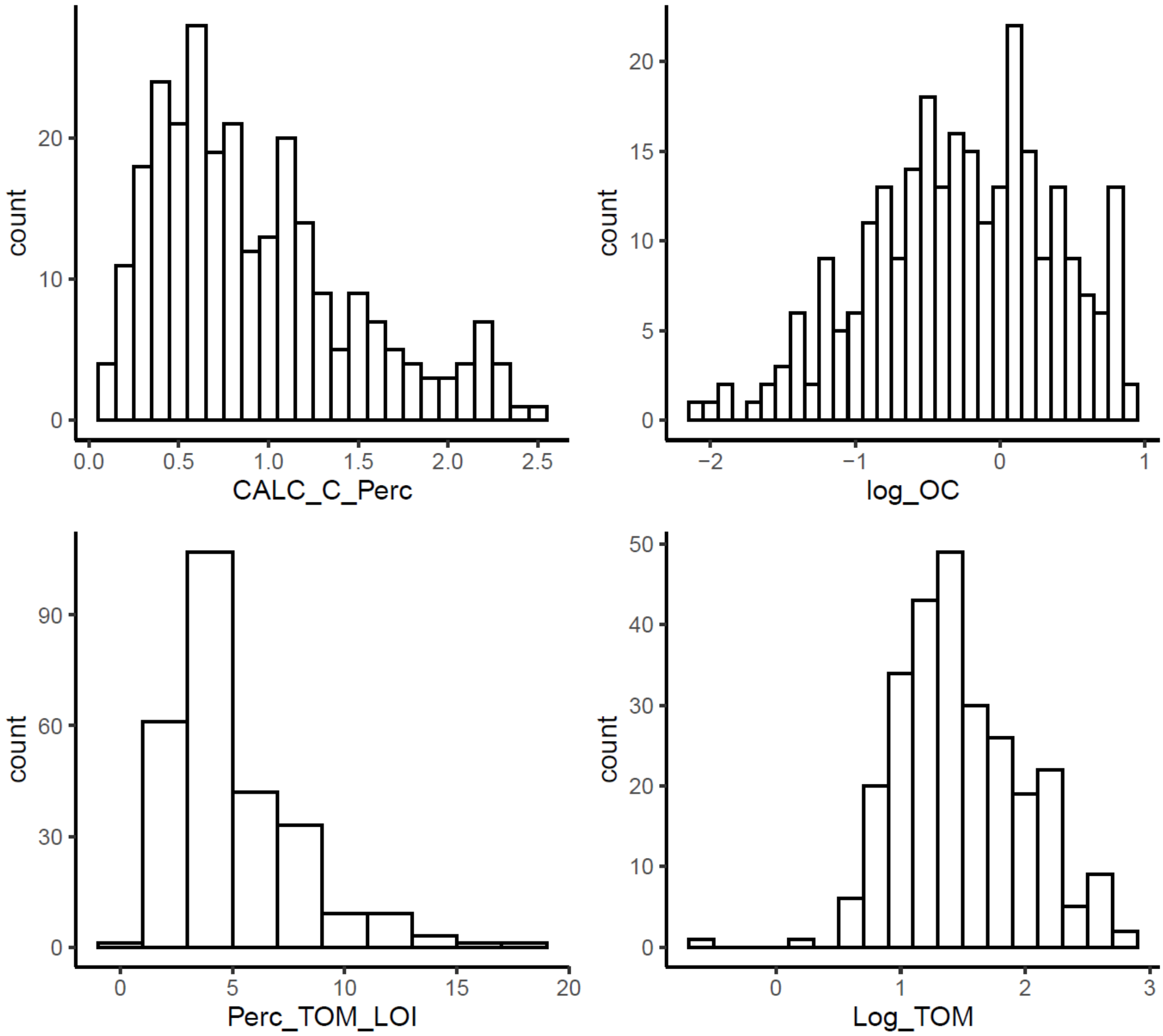

Figure 3-6: Distribution plots showing data counts for %OC (CALC_C_Perc) and %TOM (Perc_TOM_LOI) data used in the new data compilation and analysis. Top left, top right – %OC before and after logarithmic transformation. Bottom left, bottom right – %TOM before and after logarithmic transformation.

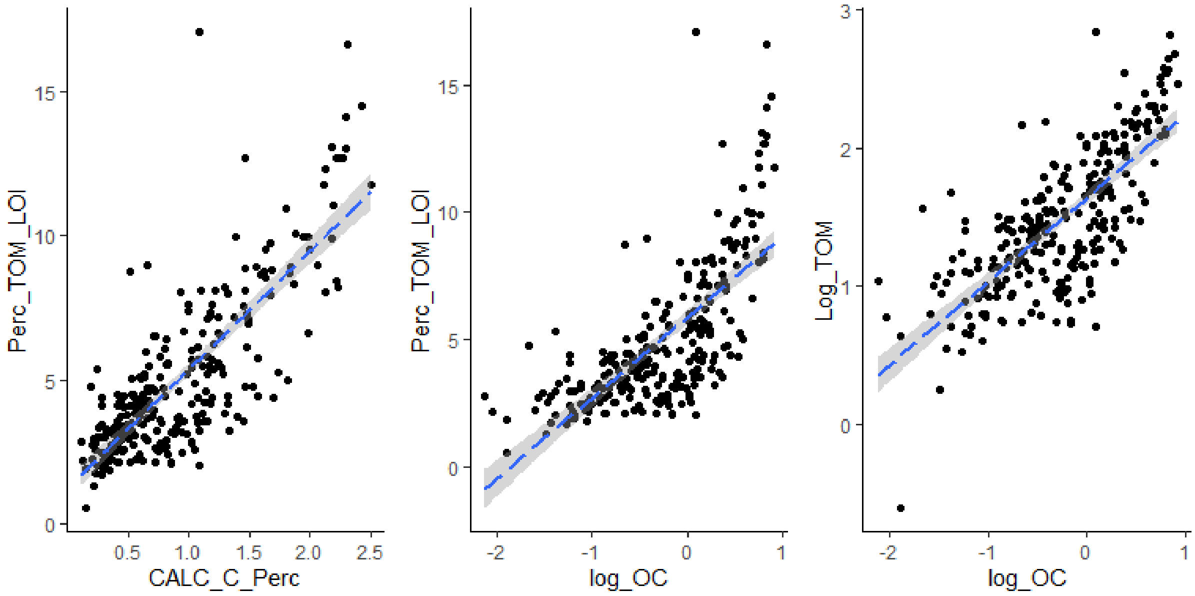

Figure 3-7: %OC vs %TOM linear regression model relationships. Left panel: %OC vs %TOM (adjusted R^2 0.63), Middle panel: log (%OC) vs %TOM (adjusted R^2 0.55), Right panel: log (%OC) vs log (%TOM) (adjusted R^2 0.53). Note how the log transforms of the data (right panel) improves the data coverage relative to the light blue dashed regression line, in contrast to the raw data (left panel) or if only OC was log transformed (middle panel). The grey shaded area along the regression line shows the 95% confidence interval of the regression model. LOI = Loss-on-Ignition.

Grain-size

Grain-size data were binned into Mud, Sand and Gravel percentages for all samples. Each grain-size bin was interrogated in bivariate plots against %OC to explore possible linear relationships. Since grain-size percentage is a proportional data type, the data are constrained between 0 and 100. This can cause issues with further statistical analysis (Aitchison, 1982). To open up the dataset, a data transformation was applied to the data. Usually, compositional data is best treated with a log or log ratio transformation (Aitchison, 1982); however, this dataset contains substantial true zero values. Following methodology applied by Sokal & Rohlf (1981), cited by Smeaton et al. (2021), an arcsine data transformation was applied, which preserves critical true zero data. As this data transformation can only be applied to values between 0 and 1, the data were then scaled by dividing *X* by 100, where *X* is the Percentage Mud, Sand or Gravel.

$$Y = arcsin\sqrt{(X/100)}$$

The bivariate plots below demonstrate the effect of data transformation for proportional data types. These simple transformations open up the data and allow for improv ed linear model fitting across the entire dataset.

Mud grain-size data are heavily biased at the extremes of 0 and 100%; however, a general trend is observed where mud is positively correlated with OC content (Figure 3-8), consistent with the findings of Smeaton et al. (2021) and Black et al. (2022), although as noted by Smeaton and Austin (2019) such relationships are stronger further offshore since the the long transport times allows the sedimentary OC to degrade to the same extent, compared to the coastal ocean where transport pathways are short. The adjusted R^2 values, however, are low (~0-30 to 0.35) for all of the plots of %OC vs %Mud (Figure 3-8), suggesting that the linear regression models are only explaining ~30-35% of the variance between these two parameters.

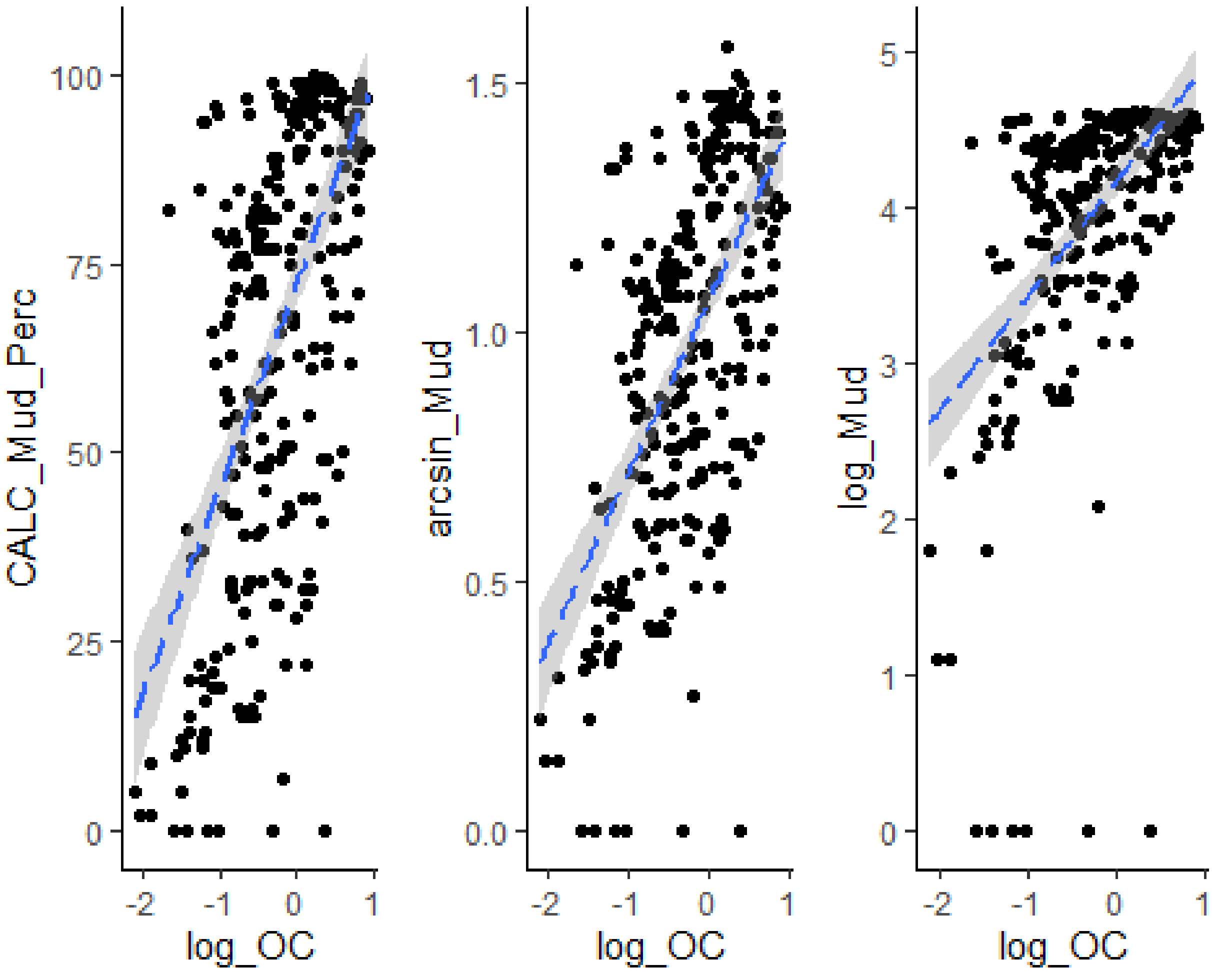

Figure 3-8: %OC vs %Mud linear regression model relationships. Left panel: log(%OC) vs %Mud (adjusted R^2 = 0.345), Middle panel: log(%OC) vs arcsin (%Mud) (adjusted R^2 = 0.351), Right panel: log (%OC) vs log (%Mud) (adjusted R^2 = 0.280). The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

Weak linear regression relationships were found between %OC with %Sand (adjusted R^2 ~0.20-0.26) or %Gravel (adjusted R^2 ~0.03), especially as %Sand co-varies with %Mud as typically most samples comprise relative proportions of sand and mud only (see Figure 3-5 and Appendix B).

Carbonate

Similarly, there were only weak statistical linear relationships between %OC and %$CaCO_3$, (adjusted R^2 ~0.09-0.21) even with logarithmic and arcsine data transformations applied (Figure 3-9 and Appendix B), indicating the poor predictive power of this compositional variable in terms of sedimentary OC content.

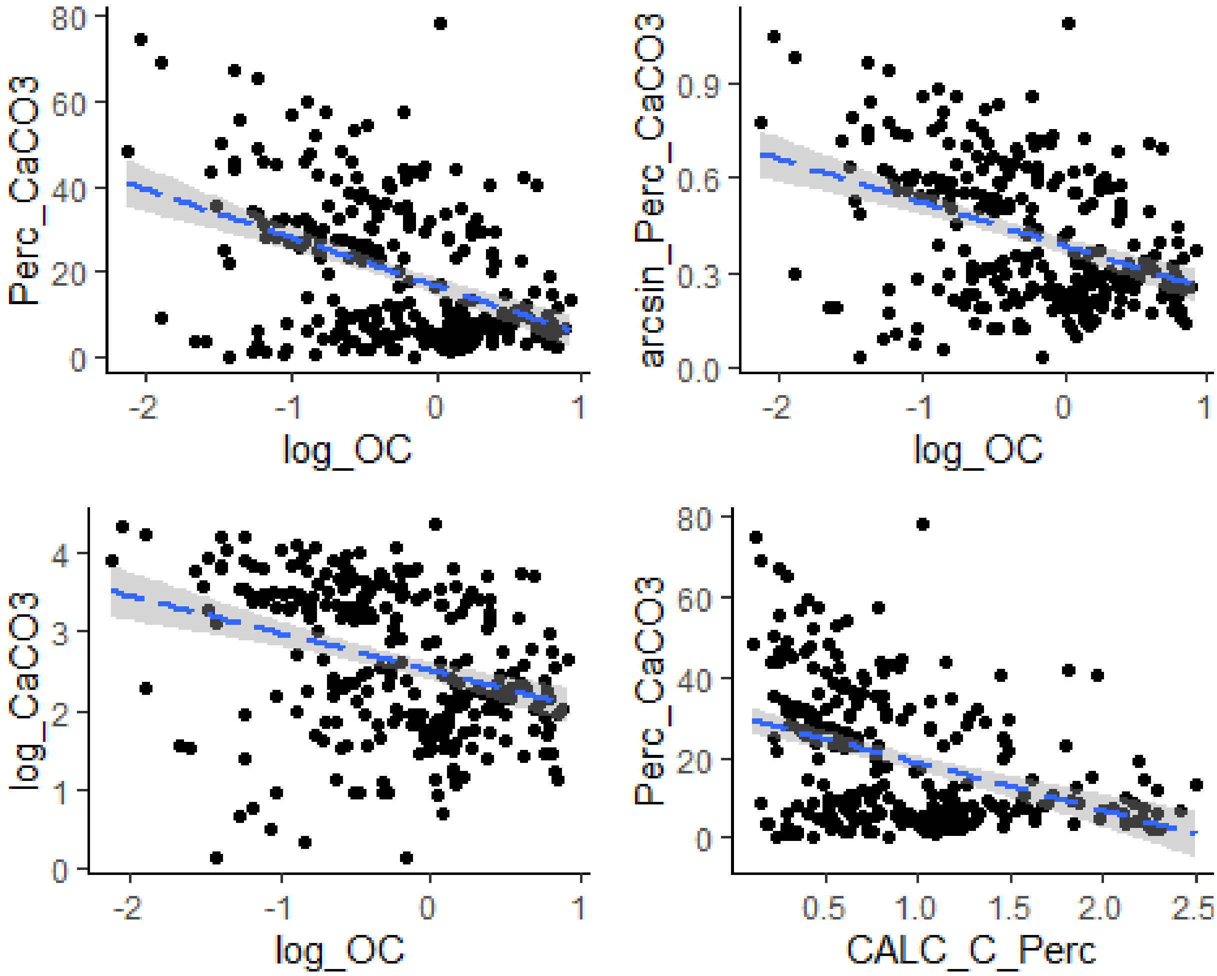

Figure 3-9: %OC vs %CaCO₃ linear regression model relationships. Top left panel: log(%OC) vs %$CaCO_3$ (adjusted R^2 0.174, Top right panel: log(%OC) vs arcsin(%$CaCO_3$) (adjusted R^2 0.094), Bottom left panel: log(%OC) vs log(%$CaCO_3$) (adjusted R^2 0.205), Bottom right panel: %OC vs %$CaCO_3$ (adjusted R^2 0.160). The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

3.5.3 Generalised Linear Models

It is acknowledged that the predictor variables Mud, Sand and Gravel will, in many cases, display a colinear relationship. This is due to the data being compositional and therefore must contain relative proportions of each grain-size bin and sum to 100% for each sample. This makes these three variables not truly independent, which does violate one of the fundamental assumptions of linear regression.

Despite this observation, colinear variables can still be incorporated into regression models for the purpose of prediction since:

> *"The fact that some or all predictor variables are correlated among themselves does not, in general, inhibit our ability to obtain a good fit nor does it tend to affect inferences about mean responses or predictions of new observations" (Kutner, 2005, p. 283).*

Therefore, all variables were included in our prediction models. A generalised linear model (GLM) was chosen for application to our data as the assumptions are not as rigid as other models. A GLM with a LASSO regression function was selected as most appropriate since this regression analysis method enhances the prediction accuracy and interpretability of the resulting statistical model. This means that a penalty function is applied to the predictor variables, and they can be minimised to zero (Friedman et al., 2010; Tay et al., 2021). The *glmnet* function also standardises the input data as a default. As the predictor variable is log normal, regressing with a log transformed response variable induces potential under approximation of the back-transformed variable as the error term is not easily back-transformed (Duan 1983). Using a log-link in the GLM accounts for the non-linear behavior of the response variable with the output on the same scale as the original input data. Therefore, we have chosen GLM over Multiple Linear Regression (MLR) as an appropriate method for deriving our OC proxies.

Data were further split into training (75%) and testing datasets (25%), using pseudo-random methods whereby a seed or "key" is written into the algorithm code so that in subsequent analyses the same datasets will be selected while the initial selection for these datasets remains random. Four different statistical models were then tested for their applicability to our datasets (Figure 3-10, Figure 3-11, Figure 3-12 andFigure 3-13):

1. LASSO with Gaussian family (default), which is essentially MLR with LASSO.
2. LASSO GLM Gaussian family with log-link.
3. LASSO GLM Inverse Gaussian Family with log-link (non-negative positive skew distribution).
4. LASSO GLM Gamma Family with log-link (right skewed distribution).

The Model Set 1 for the GLM analyses utilises a combination of the variables %TOM, Grain-size, and %$CaCO_3$ for predicting %OC, while Model Set 2 uses %TOM and Grain-size only. It is important to note that the Model Set 1 does not have a log-link and therefore does not respect zero as a limit. As shown in Figure 3-13, this leads to unrealistic negative predicted values. The combination of a log link and distribution family that is non-negative and right skewed results in realistic predictions within the limits of the actual data.

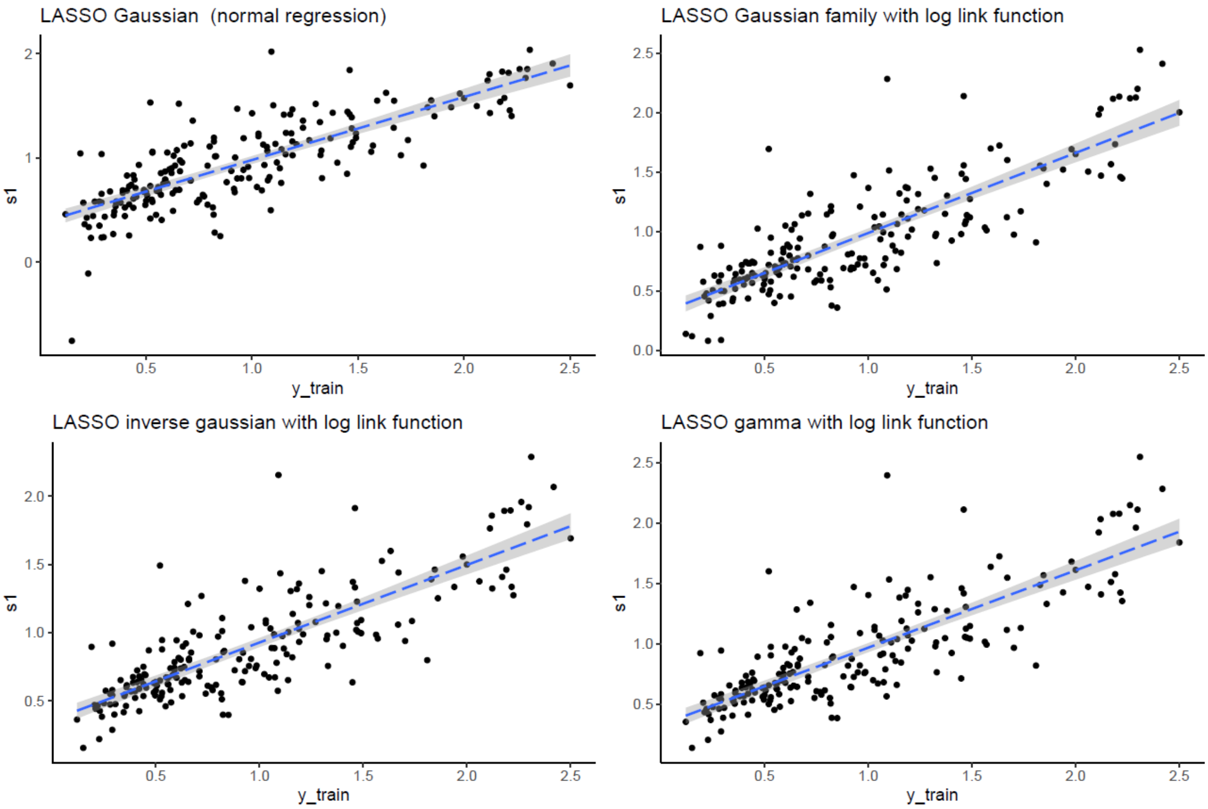

Figure 3-10: Model Set 1 Training Output. x–axis (y-train) = measured %OC, y–axis (s1) = predicted %OC. The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

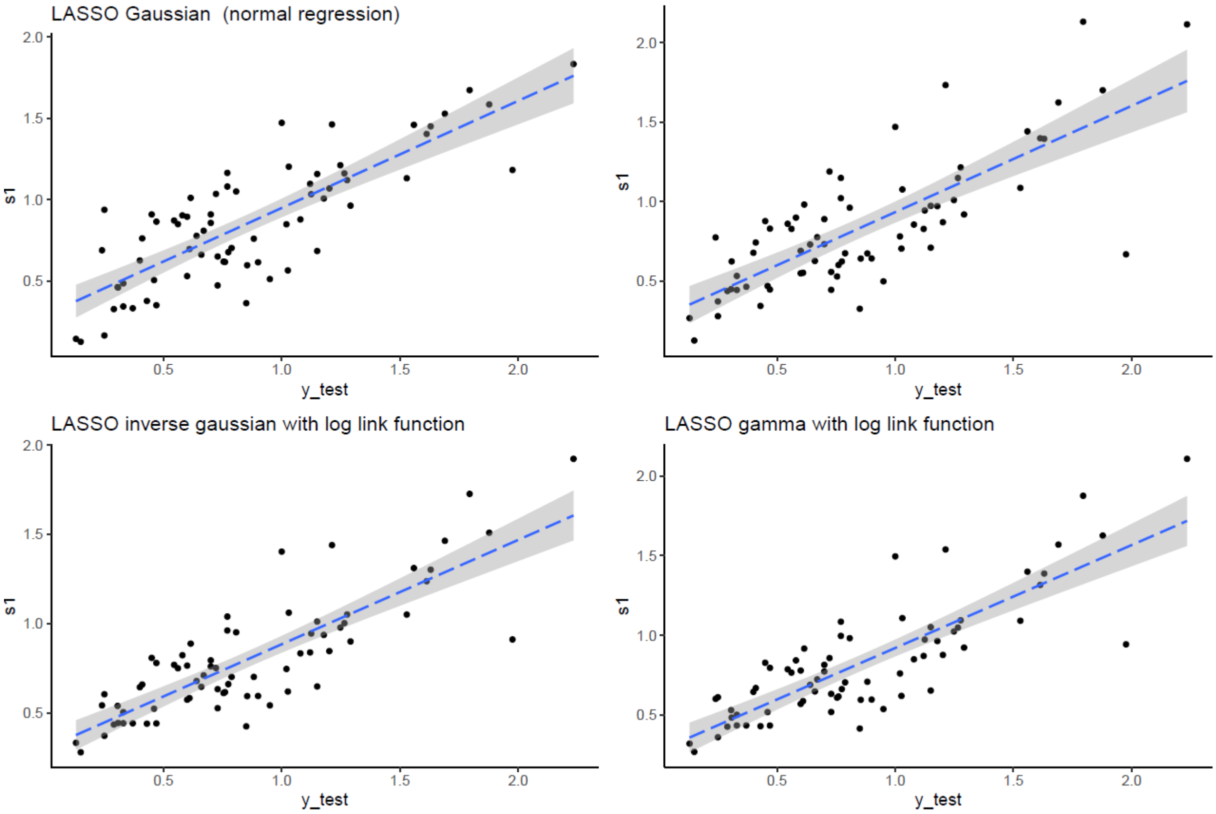

Figure 3-11: Model Set 1 Test Output. x–axis (y-test) = measured %OC, y–axis (s1) = predicted %OC. The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

Table 3-1: Regression coefficients for the gamma family log-link GLM Model Set 1.

	s0
(Intercept)	−1.228
arcsin_Mud	0.159
Log_TOM	0.704
log_CaCO3	.
arcsin_Sand	−0.293
arcsin_Gravel	−0.507

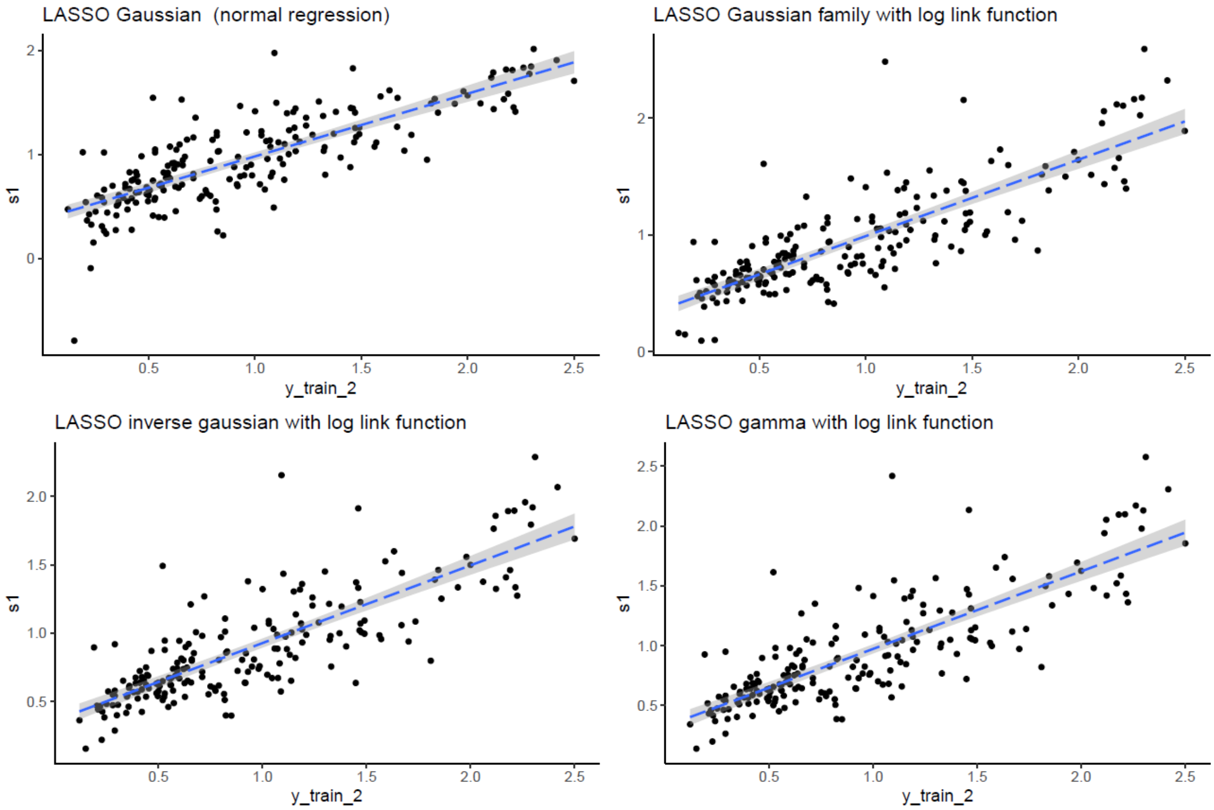

Figure 3-12: Model Set 2 Training Output. x−axis (y_train_2) = measured %OC, y−axis (s1) = predicted %OC. The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

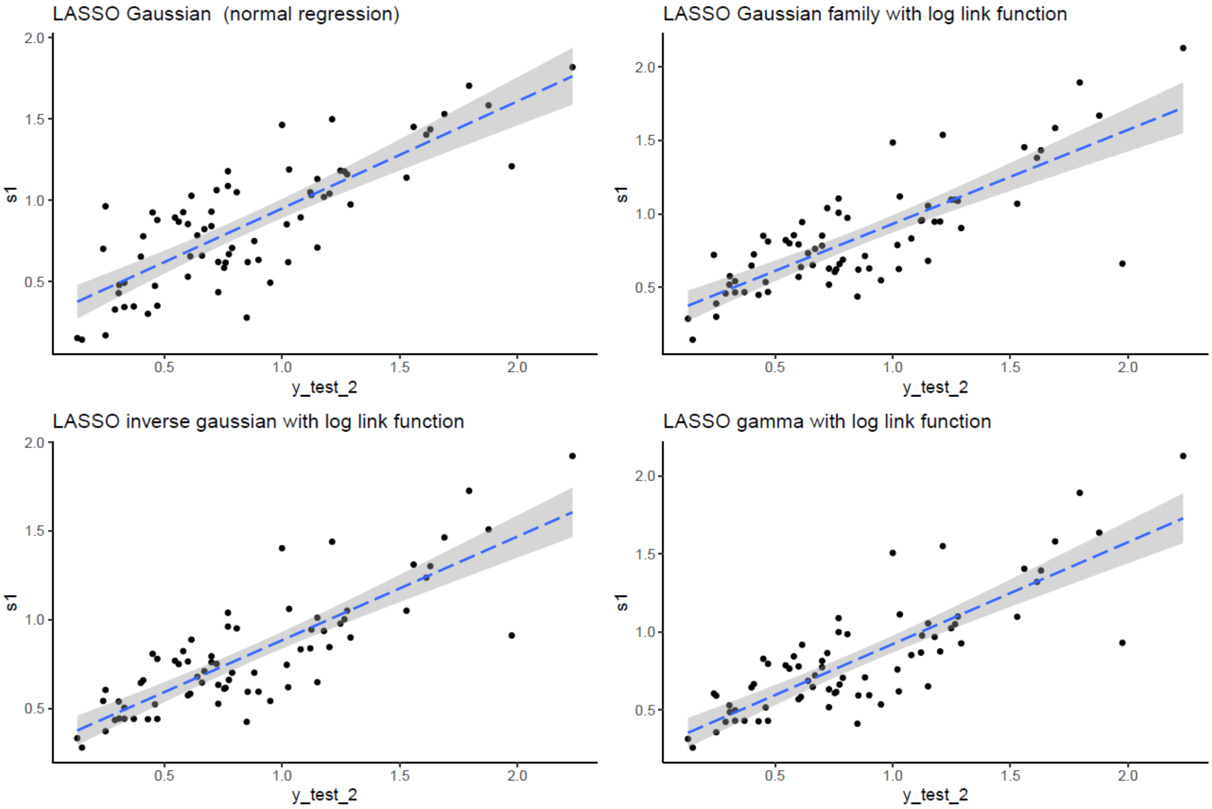

Figure 3-13: Model Set 2 Test Output. x–axis (y_test_2) = measured %OC, y–axis (s1) = predicted %OC. The light blue dashed line represents the linear regression between the variables, while the grey shaded area along the line shows the 95% confidence interval of the regression model.

Table 3-2: Regression coefficients for the gamma family log-link GLM Model Set 2.

	s0
(Intercept)	−1.227
arcsin_Mud	0.158
Log_TOM	0.709
arcsin_Sand	−0.305
arcsin_Gravel	−0.567

3.5.4 Model Summaries

Predicting OC from variables TOM, Grain-size, and $CaCO_3$ (Model Set 1)

The default multiple linear regression had a somewhat good performance compared to the Gaussian family log-link family (Table 3-3 and Table 3-4); however, the model predictions did not respect zero as a limit. Mean Squared Error (MSE) and R^2 were used as measures of model performance and to inform model selection. The ideal model has the lowest relative MSE, and highest R^2 for both training and test models. Additionally, over or underfitting of the model can be assessed by the relative differences in MSE and R^2 between training and testing model outputs.

The inverse Gaussian and gamma models with log-link performed the best, which is expected as they do model a right skewed distribution (see Figure 3-6). The inverse Gaussian model did have instabilities and would not converge effectively, therefore, the GLM model of the gamma family with a log-link function was chosen as the final model for this set of data.

Regarding the predictions made with the fitted GLM models, there is an assumption that the population without OC values that we are imputing is from the same population with the same distribution as the data used to create the models. We also have a limitation created by the data we used to train the model in that 2.5% OC content is the entire % spread of the model, after which point the model is extrapolating.

Table 3-3: Relative performance of the GLM proxy models used to predict OC values from other sediment variables, such as Total Organic Matter, Grain-size and $CaCO_3$.

	MSE_Train	MSE_Test	rsq_Train	rsq_Test
MLR	0.12	0.0754	0.636	0.649
Gauss_loglink	0.106	0.0916	0.679	0.585
invGauss_loglink	0.118	0.0745	0.663	0.683
Gamma_loglink	0.112	0.0709	0.662	0.675

Predicting OC from variables TOM and Grain-size (Model Set 2)

As above, predicting OC content from TOM and grain-size using inverse Gaussian and gamma models produced similar results (Table 3-4). Similarly, since the inverse Gaussian model had difficulties converging, the gamma GLM family with log-link was selected as the preferred model for estimating OC content.

Table 3-4: Relative performance of the GLM proxy models used to predict OC values from other sediment variables, such as Total Organic Matter and Grain-size.

	MSE_Train	MSE_Test	rsq_Train	rsq_Test
MLR	0.121	0.0781	0.633	0.637
Gauss_loglink	0.109	0.0805	0.671	0.627
invGauss_loglink	0.118	0.0745	0.663	0.683
Gamma_loglink	0.111	0.0711	0.662	0.673

3.6 Folk Classification: derived using Gradistat

The existing Bostock et al. (2019a, 2019b) surface sediment dataset and the new dataset generated as part of the present study needed the grain-size information derived from a 3 class % system (i.e., %Mud, %Sand, %Gravel) converted to a 15-16 class Folk textural group in order to assign a modified 5 Folk scale as used in Black et al. (2022) (their Supplementary material 1).

The Gradistat v9.1 programme provided an efficient and simple way to assign a textural descriptor to the data (Blott & Pye, 2012). In this conversion, %Mud, %Sand and %Gravel were converted into a modified fractional data input based on Mud being <63 µm in particle diameter, Sand 63-2000 µm and Gravel >2000-6400 µm.

A logic-based algorithm (*Vlookup*) was then used to further reduce the 15-16 Folk classification system to the modified 5 Folk system, comprising the grain-size textural classes Mud to Muddy Sand, Sand, Mixed Sediment, Coarse Sediment and Gravel (Black et al., 2022). This used a format where: if[cellx]="gravelly sandy mud", then [celly] ="mixed sediment", etc.

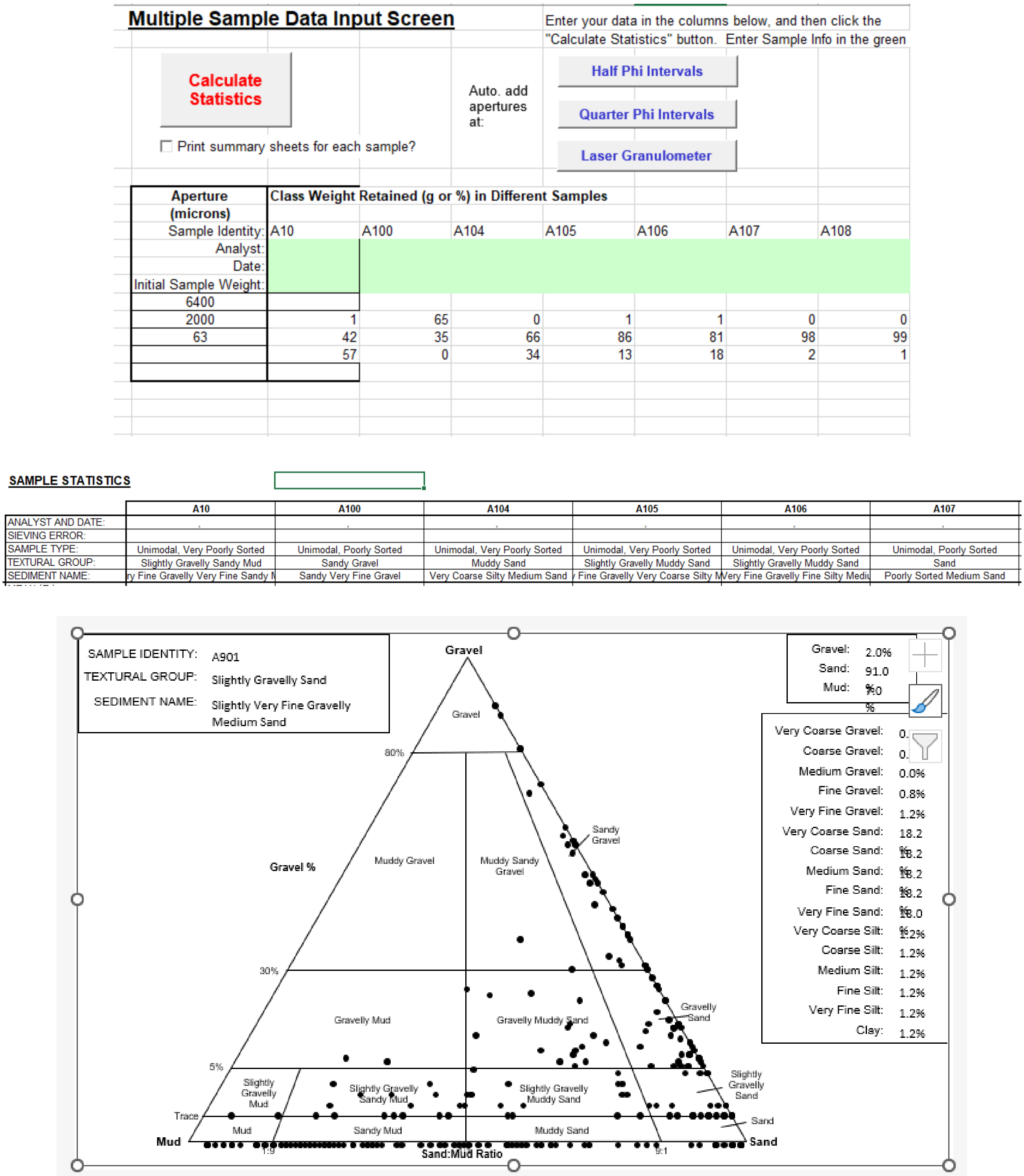

Figure 3-14: Examples of the output from the initial Gradistat analysis used to generate the Folk grain-size textural classification. Top panel: Multiple Sample Input, Middle panel: Sample statistics for samples A10 to A107, Bottom panel: Folk classification ternary diagram %Gravel vs %Sand vs %Mud.

3.7 Extrapolation methods – kriging, ArcGIS

All data with available geographic coordinate data (12 010 entries) were imported into the ESRI® ArcGIS Pro (version 2.9.5) geospatial software suite for analysis. Geospatial analysis included the use of surfacing tools to generate modelled sediment/composition distribution maps and the *raster calculator* to derive estimated OC quantities.

All raster surfaces for the various parameters were generated using simple kriging with an applied Gaussian distribution. Output rasters were sampled at a 250 m resolution due to high-resolution sample density in nearshore environments (e.g., Te Whanganui-a-Tara Wellington Harbour, Tikapa Moana-o-Hauraki Firth of Thames, fjords, various estuaries and harbours). The variance of gridded surfaces in low-sample density regions was consistent across wider EEZ, indicating a relatively consistent margin of error (i.e., a moderate relative error).

Table 3-5: ArcGIS exported data statistics.

Dataset parameter	Number of entries
Normalised dataset to top 10 cm	12,281
Entries removed from dataset (no geographic coordinates)	271
Entire dataset unnormalised	17,682 (includes location duplicates)
Total entries for krig surfacing	**12,010**
Entries within NZ 250m bathymetry grid	**11,335**
Entries within EEZ	**11,030**

3.8 Vulnerability Index

The vulnerability of OC in marine sediments to bottom trawling was estimated based on the methods outlined in Black et al. (2022), and as summarised in the flow-charts (Figure 3-2). In this method, the important derived parameters are *OC-in*, corresponding to the OC stocks in a defined grid cell and *C-out*, is the fractional amount of OC assumed to remain in the sediments (i.e., enabling a calculation to be made of the OC potentially "lost" or resuspended into the water column) due to bottom trawling.

The C_{out} parametrisation is derived from C_{in} multiplied by the term *(1 – La)* from Equation 4 below from Black et al. (2022) (see below), where *La* represents the combination of the Swept Volume Ratio (SVR), Potential Exposure Ratio (PER), the estimated sediment lability as a function of sediment type (*Plab*, see values in Table 3-6) and a sediment OC degradation term ($1\text{-}e^{-k,t}$) , where t = 1 year and the first-order degradation term (k) is assumed to be 23.34 based on an average value calculated from Supplementary Table 2 in Black et al. (2022). We have not evaluated the applicability of the k term to Aotearoa New Zealand since to the best of our knowledge such estimates have not been made for offshore marine sediments in the region. Accordingly, as a first-order estimate it was deemed suitable to use the value of k used in Black et al. (2022), especially as the value 23.34 was derived from the published literature, with values ranging from ~13 to 30.

SVR is represented in the model by Equation 5 below, which is the Swept Area Ratio (SAR), multiplied by the ratio of the estimated penetration depth of the trawling gear (P_{depth}, assumed to be 2.44 cm as used by Black et al. (2022) for otter trawls) relative to the depth of sediment used for estimating the

OC stocks (i.e., P_{layer} = 10 cm). SAR is taken from the bottom trawl footprint dataset as the aggregated area of seabed swept by bottom trawling in each fishing grid cell (5 km x 5 km) over the time-period 1989-2021 (i.e., 32 years), divided by the grid cell area (25 km^2) (Equation 1 below) and converted to an annual average by dividing by 32. Most bottom trawls in the Aotearoa New Zealand fishing fleet are essentially otter trawls, as described in Hiddink et al. (2017).

The term PER captures information on the settling behaviour of sediment in each sediment grain-size class based on mean particle-size and particle settling velocities (Equations 6 and 7 in Black et al. (2022)), which are constant across the five Folk sediment classification classes (Table 3-6).

The equations from Black et al. (2022) are provided below.

Swept area ratio (*SAR*):

$$SAR = \frac{Gear\ \ Width\ \ \times Vessel\ \ Speed\ \ \times Time\ \ Spent\ \ Fishing}{Cell\ \ Area} \qquad \text{Eq. 1}$$

Total fraction of OC present within each pixel *i* (*C-in$_i$*), derived from $C_{i,o}$ = OC content in marine sediments:

$$C_i^{in} = C_{i_0} \qquad \text{Eq. 2}$$

Fraction of total OC assumed to remain if the sediment in pixel *i* is exposed to fishing-based disturbance using gear *g* is denoted as C-out$_{i,g}$:

$$C_{i,g}^{out} = Ci_o\left(1 - La_{i,g}\right) \qquad \text{Eq. 3}$$

Estimated fraction of labile organic matter that would be "lost" from the sediment annually in the presence of fishing activity by gear type *g* in pixel *i*, as denoted by *La$_i$*:

$$La_i = SVR_{i,g} \times PER_i \times Plab_i \times \left(1 - e^{-k_i t}\right) \qquad \text{Eq. 4}$$

Swept Volume Ratio (*SVR*) is represented by Equation 5 below, where $SAR_{i,g}$ (Equation 1.) is the swept area ratio in pixel *i* by vessels using gear type *g*, $P_{depth,g}$ is the estimated average penetration depth of gear type *g* (2.44 cm for otter trawls, as in Black et al. (2022) from Hiddink et al. (2017), based on literature and data from Eigaard et al. (2016)), and P_{layer} is the depth of sediment (10 cm used in the present study and in Black et al. (2022):

$$SVR_{i,g} = SAR_{i,g} \times \frac{P_{depth_g}}{P_{layer}} \qquad \text{Eq. 5}$$

Potential Exposure ration (*PER*) where w_{max} is the maximum settling speed of the largest sediment size-class to the settling speeds (w_i) for each of the five Folk sediment classes (Table 3-6):

$$PER_i = \frac{w_i}{w_{max}} \qquad \text{Eq. 6}$$

Settling speed of sediment particles (*w*) where *R* is the submerged specific gravity (0.658 g/cm^3) for marine sediments, based on the densities of marine sediment from Tenzer and Gladkikh (2014),and where the density of seawater at 12°C is 1027 kg/m^3, *g* is the acceleration due to gravity (9.81 m/s^2), *D* is the mean diameter of the grain size within each of the Folk sediment classes (Table 3-6), C_1 is constant with a value of 18, and C_2 is constant with a value of 1.0, and *v* is the kinematic viscosity of seawater at 12°C (1.2346 mm^2/s):

$$w = \frac{RgD^2}{C_1 v + \left(0.75 C_2 R_g D^3\right)^{0.5}} \qquad \text{Eq. 7}$$

Values for *w* were not recalculated but were taken from the Supplementary Table 3 in Black et al. (2022) for each of the five Folk grain-size classes used in the present study. Salinity variations due to the influence of freshwater, especially in coastal and harbour or fjord settings, were not accounted for but could be investigated more fully in future studies. Similarly, variations in dry bulk density could also be parameterised more accurately and specifically for the Aotearoa New Zealand region, especially where biogenic carbonate sediments dominate, rather than inorganic minerals (as approximated in this case by using the density of quartz in the Organic Carbon Stock calculations in 3.3.1); for example, the high carbonate sediments found on the Campbell, Bounty and Challenger plateaux (Bostock et al., 2019b) (Figure 4-5D).

Table 3-6: Parameters used in the derivation of sediment OC parameters (from Black et al. (2022)).

Folk sediment type (grain-size diameter range)	Sediment lability (P_{lab})[a]	Mean grain-size (D, mm)[b]	Particle settling velocity (m/s)[c]	Potential Exposure Ratio (PER)[c]
Mud to Sandy Mud (0.001-0.125 mm)	0.0223	0.063	0.74	0.18
Sand (0.126-0.250 mm)	0.0065	0.187	1.27	0.31
Mixed Sediment (0.251-0.500 mm)	0.011	0.375	1.80	0.43
Coarse Sediment (0.501 mm – 2 cm)	0.0095	1.25	3.28	0.79
Gravel (2-2.56 cm)	0.0104	2	4.15	1

a from Smeaton and Austin (2022) and in Table in Black et al. (2022).
b from Table 1 in Black et al. (2022).
c from Supplementary Table 3 in Black et al. (2022).

4 Results

4.1 Data coverage

The areal coverages of the input datasets are estimated within the Aotearoa New Zealand EEZ based on a 10 km-diameter buffer around each sample point. A 10 km buffer was applied as this distance is equivalent to the resolution of available commercial fishing data once these have been aggregated (i.e., within 5 km x 5 km grid cells) for the purpose of the present study. This analysis indicates that the areal EEZ coverage of samples with %Mud values is 537,285 km^2 (13% of the total EEZ area), compared to 324,863 km^2 (8%) and 124,384 km^2 (3%) for $CaCO_3$ and OC, respectively.

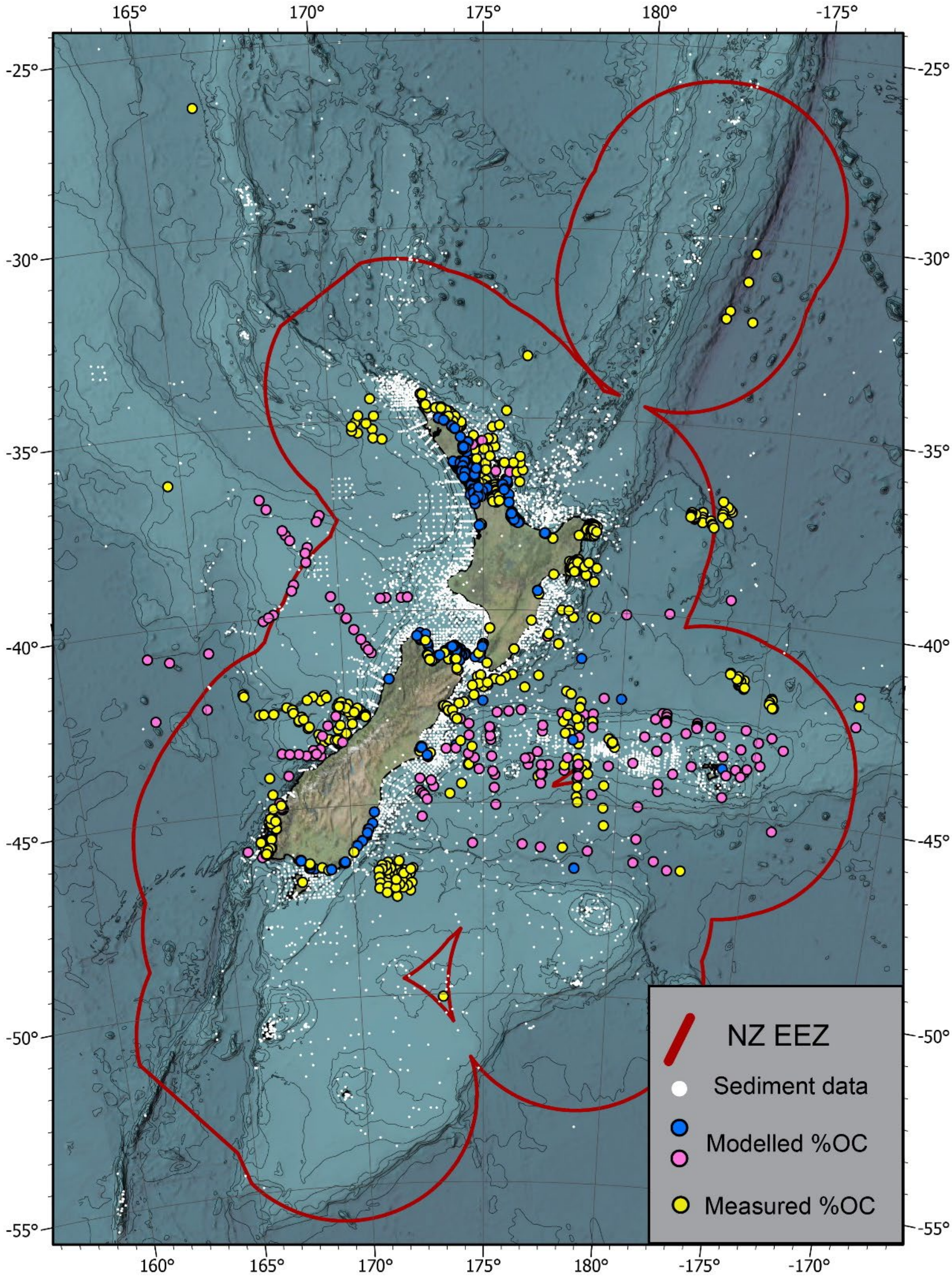

Figure 4-1: Sample data coverage across the Aotearoa New Zealand EEZ (200 NM, thick red line). White dots indicate mainly grain-size and $CaCO_3$ data from (Bostock et al., 2019a, 2019b); yellow dots are measured %OC data, and the pink and blue dots are, respectively, modelled sediment data based on proxy estimates from TOM, grainsize, and carbonate (Model Set 1, Gamma GLM) and TOM and Grainsize only (Model Set 2, Gamma GLM).

4.2 Organic carbon - % and stocks

The data range for the collated and modelled %OC ranged from 0% to ~11%, with the highest value observed in Doubtful Sound Fiordland (Hinojosa et al., 2014; Smith et al., 2010). The average %OC from the collated dataset is 0.80% (±0.86%, 1 standard deviation), with 0.58±0.34% estimated from the modelled data across the entire EEZ (Table 5-2). Figure 4-2 shows the modelled distribution of %OC across the Aotearoa New Zealand EEZ, with the high %OC values recorded in the Fiordland fjords included in the extrapolation, while Figure 4-3 excludes these measurements. These figures also depict the variances associated with the kriging process. Deeper water and carbonate-rich habitats, such as plateaux (Campbell and Challenger), have the lowest %OC content, with moderate values (<1-2%) close to the coast and out onto the continental shelf and upper slope, and a predominance of moderately high OC content in deep-water environments (Hikurangi margin and plateau) along the eastern margin of Te Ika-a-Māui North Island.

Kriging artefacts are apparent off southwestern Te Waipounamu South Island/Fiordland, where the high values around the south Westland canyons appear to drive the kriging extrapolation into data-poor areas offshore since when the high OC fjords in Fiordland are excluded, these patterns persist (Figure 4-2 cf. Figure 4-3). There may also be an issue with the kriging across the Bounty Plateau in the southeast quadrant of the EEZ, south of 45°S as this area is characterised by a low density of actual data upon which the kriging algorithm is based. The variances of the kriged surfaces in these areas, however, are deemed low, reflecting the reliance of the kriging algorithm on nearby robust data in south Westland and the Bounty Trough, respectively (Figure 4-2, right panel). High variances south of Te Waipounamu South Island occur in an area where there is very low data density, while localised high variances around Te Ika a Māui North Island seem to be related to robust data from large harbours (Kaipara, Manukau, Tauranga), being forced to extrapolate into data-sparse offshore regions (Figure 4-2, right panel). There are areas with no modelled data in the very south and north of the EEZ across the southern Campbell Plateau to Puysegur Trench (i.e., below 50°S latitude) and northern Kermadec regions, respectively. This is due to a lack of appropriate samples that are compatible with the OC proxy modelling, the absence of a correlation between water depth and OC content, which restricts extrapolation to under-sampled areas, and limitations with the kriging algorithm, which requires at least 12 neighbourhood samples to derive values. When the latter criterion is not realised the kriging algorithm stops and defines absolute sample limits as sample density drops.

The total OC stock in marine sediments within the Aotearoa New Zealand EEZ (including the Territorial Seas), based on the kriged %OC distribution shown in Figure 4-2, is ~1889 Mt OC. Obviously due to the kriging artefacts outlined above, where areas with both anomalously high OC values (southwest Fiordland, Bounty Plateau) and no data (southern Campbell Plateau, Puysegur Trench, northern Kermadec), this estimate should be regarded as first-order only and treated with some caution. The total area where data is absent because the kriging algorithm has not been able to model the OC content, represents 15% of the EEZ. Assuming the same distribution of OC content is extended for these areas, this would add an additional 354 Mt OC to the total OC stocks in the EEZ for a total of 2243 Mt OC. Based on the available data and the kriging methods used to derive the EEZ-scale OC distribution, it is difficult to derive absolute errors for these OC stocks. Given these are first-order estimates, we have taken the errors associated with the UK study by Smeaton et al. (2021) as an approximation, while acknowledging that our study could expect higher absolute errors given the data sparsity and geomorphic complexity of the Aotearoa NZ EEZ. Therefore, based on a minimum 13% estimated error (Smeaton et al., 2021), for the area we were able to model satisfactorily the **EEZ-wide OC stocks** are estimated to be **1889±246 Mt OC**, including the Fiordland fjords. For the entire EEZ, including the areas where the kriging algorithm was not able to model, the estimate is **2243±292 Mt OC**, including fjords. The exclusion of the fjords had minimal impact on the modelled %OC distributions, except for an apparent increase in %OC off southern Fiordland-Southland, west of Rakiura Stewart Island (Figure 4-3).

These estimates also allow us to highlight the importance of the Fiordland fjords as OC repositories, based on the difference between the OC estimates "with fjords" and "excluding fjords" (Figure 4-2 cf. Figure 4-3). If we exclude the fjords the EEZ estimate of surficial sediment OC stocks based on the kriged OC extent is 1734 Mt OC, compared to 2056 Mt OC for the entire EEZ. These values suggest that estimated %OC stocks in surficial sediments in the **fjords** of **157-187 Mt OC**, accounting for ~8% of the total sediment OC stocks in the Aotearoa NZ EEZ.

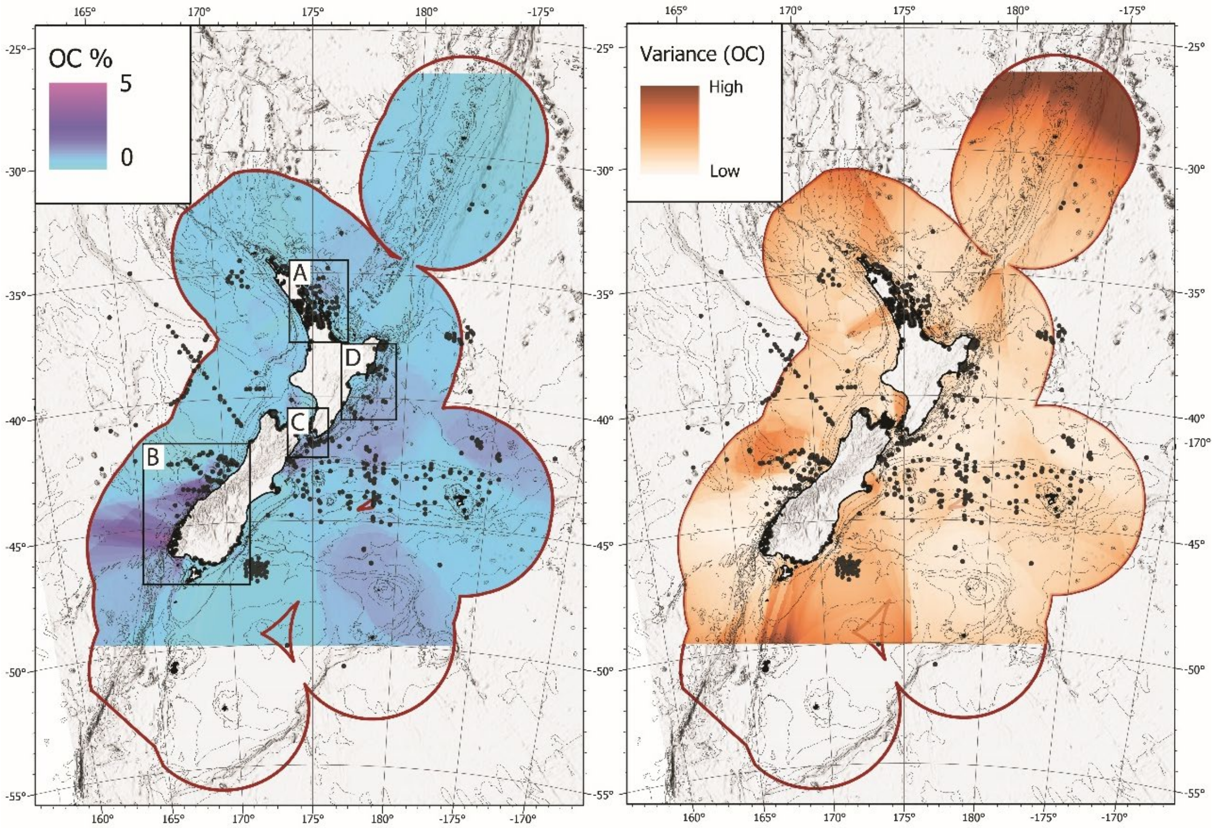

Figure 4-2: Modelled % Organic Carbon (%OC, left panel, and variance, right panel), including fjords, in surficial (0-10 cm) marine sediments from the continental shelf and deeper within the Aotearoa New Zealand EEZ and Territorial Seas (200 NM, thick red line). Black dots represent samples used in OC proxy model development. The labelled boxes (A-D) show the areas detailed in Figure 4-4. This variable is represented by the term "*C-in*" used by Black et al. (2022) and as shown in the flow chart of the method used in the present study based on this paper (Figure 3-2).

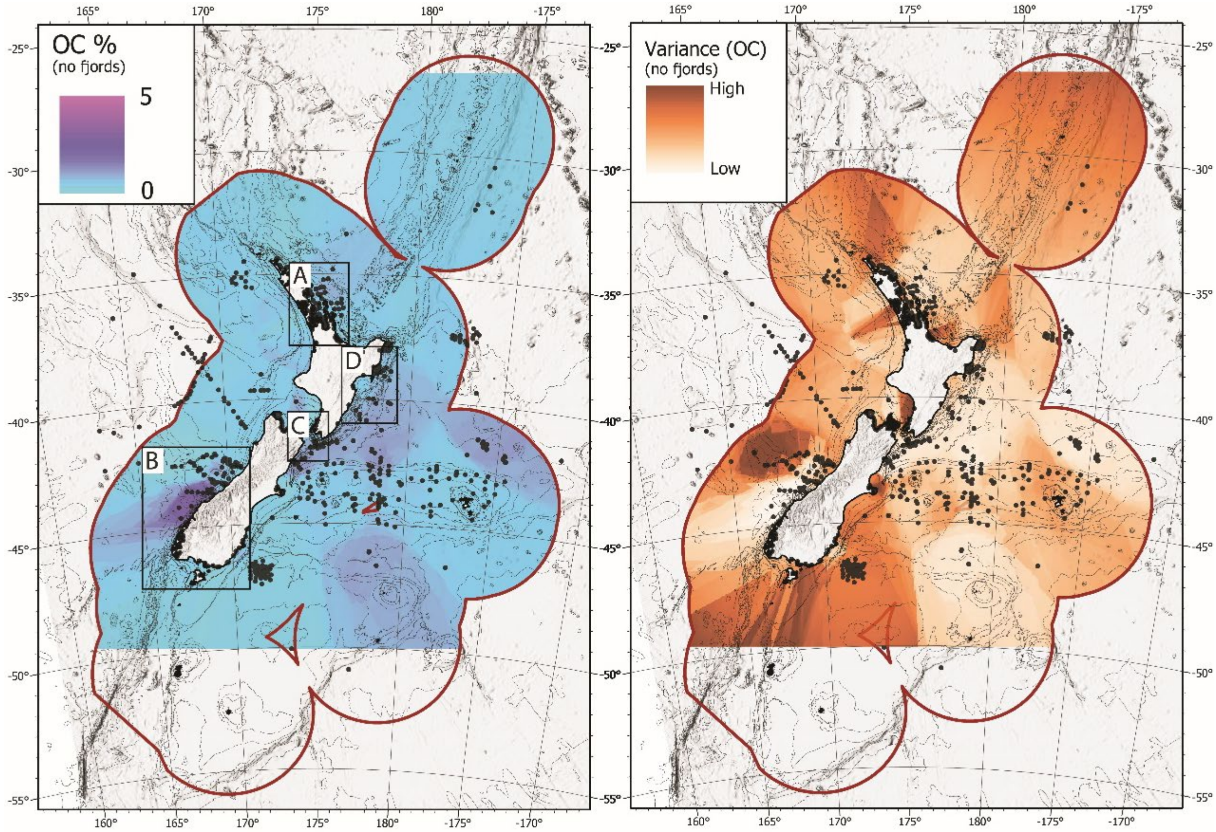

Figure 4-3: Modelled % Organic Carbon (%OC, left panel, and variance, right panel), excluding fjords, in surficial (0-10 cm) marine sediments from the continental shelf and deeper within the Aotearoa New Zealand EEZ and Territorial Seas (200 NM, thick red line). Black dots represent samples used in OC proxy model development. The labelled boxes (A-D) show the areas detailed in Figure 4-4. This variable is represented by the term "*C-in*" used by Black et al. (2022) and as shown in the flow chart of the method used in the present study based on this paper (Figure 3-2).

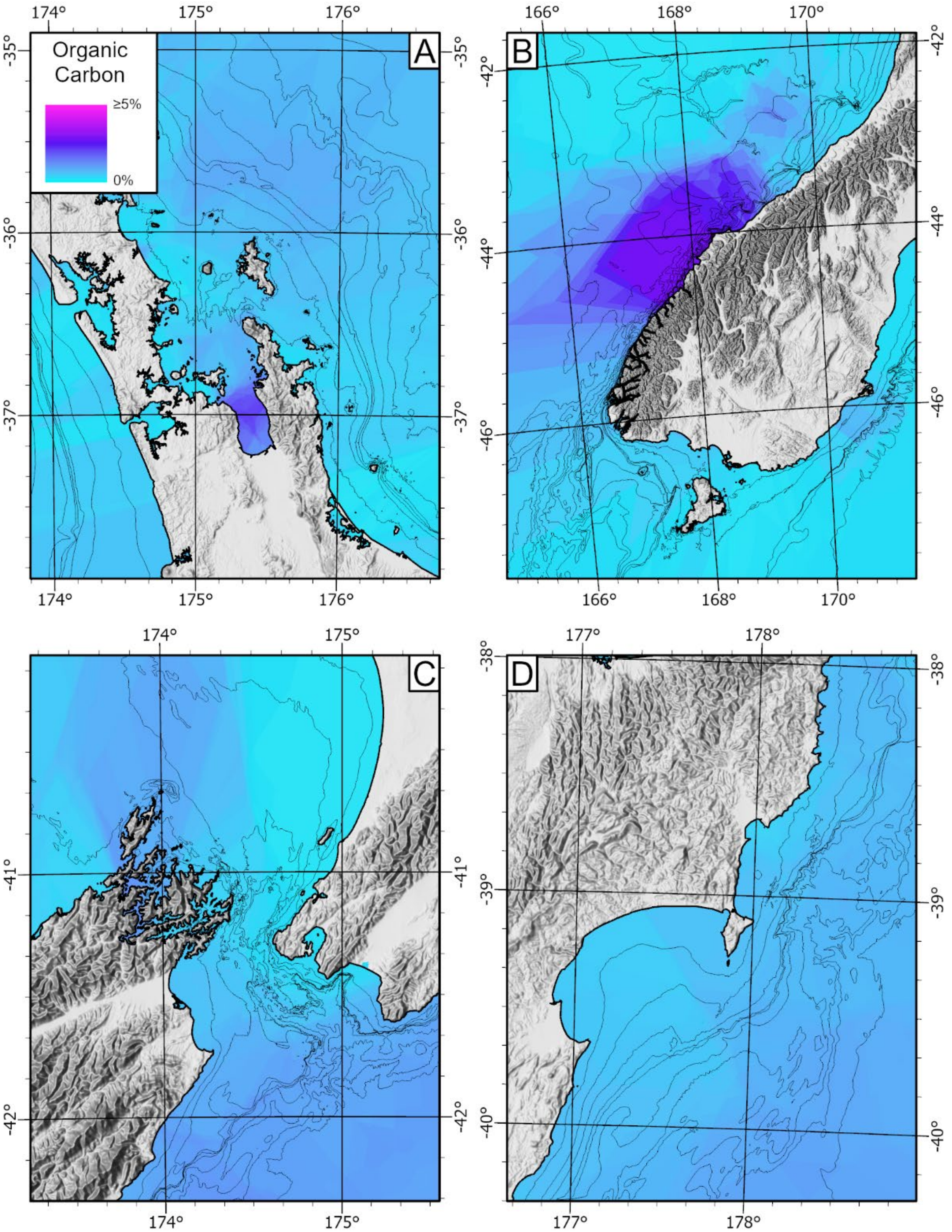

Figure 4-4: Detailed maps, excluding fjord data, of selected areas showing Organic Carbon content (%) in marine sediments. A. Tikapa Moana-o-Hauraki Firth of Thames and Hauraki Gulf, NE Te Ika-a-Māui North Island; B. Te Rua-o-te-moko Fiordland, SW Te Waipounamu South Island; C. Te Moana-o-Raukawakawa Cook Strait, central Aotearoa New Zealand; D. Te Matau-a-Māui Hawke's Bay and Tairāwhiti Gisborne, eastern Te Ika-a-Māui North Island. Locations of the detailed boxes are shown in Figure 4-2.

Figure 4-4 shows details of the modelled distribution of OC content in marine sediments around Aotearoa New Zealand. Locally there are high OC values in Tikapa Moana-o-Hauraki Firth of Thames, which is a large, mud-filled embayment at the southern end of the Hauraki Gulf, impacted heavily by anthropogenic nutrient and terrestrial sediment inputs (M. Green & Zeldis, 2015; Zeldis et al., 2022; Zeldis & Swaney, 2018) (Figure 4-4A). Conversely, while Te Rua-o-te-moko Fiordland represents a low impacted environment, especially in terms of its heavily forested hinterland and low erosion potential of its basement rocks and soils (Hicks et al., 2011), the modelled high OC values offshore (Figure 4-4B) seem to be an artefact of the kriging algorithm, mainly because of robust data just to the north off south Westland and the lack of suitable data for the OC proxy modelling in the deep-water offshore marine environment (Figure 4-4B). This circumstance arises independent of the very high OC content inside the fjords, up to 11 % (Cui et al., et al., 2016; Hinojosa et al., 2014; Ramirez et al., 2016), since when the kriging model is run excluding fjords this artefact remains (Figure 4-3). In the greater Cook Strait region, moderately high OC values extend through the main strait into deep water to the southeast and to the northwest north of Te Tai-o-Aorere Tasman Bay (Figure 4-4C), with relatively lower values corresponding to areas where the surface sediments are predominantly sandy (e.g., off the Manawatū coast; Lewis & Mitchell, 1981), where high kriging variance is also noted (Figure 4-2), or gravelly (e.g., in the Narrows, Te Moana-o-Raukawakawa Cook Strait; Lamarche et al., 2011). Off eastern Te Ika-a-Māui North Island, OC content in marine sediments is more homogenously distributed, with relatively lower values in Te Matau-a-Māui Hawke's Bay and Tūranganui-a-Kiwa Poverty Bay, increasing offshore into deeper water (Figure 4-4D), despite the wider Tairāwhiti region being recognised as a significant contributor to Aotearoa new Zealand's sediment and OC delivery to the coast (Carter et al., 2010; Hicks et al., 2011; Kuehl et al., 2016; Scott et al., 2006).

There is a potential for areas that are characterised by coarse or rocky substrates to have over-estimated interpolated OC contents in Figure 4-2 as such environments are expected to have low sediment cover and potentially low %OC. Figure 4-6 shows the distribution of coarse and gravel substrates, which are accounted for in the OC proxy modelling in the present study. To estimate the distribution of reef habitats and predominantly rocky substrates, these outputs could be integrated with spatial mapping products, such as the Department of Conservation's SeaSketch Estuaries Spatial Database (https://www.doc.govt.nz/nature/habitats/estuaries/estuaries-spatial-database/) or their New Zealand Seafloor Community Classification (https://www.doc.govt.nz/our-work/mpas-research-programme/seafloor-community-classification/) or Marine Data Portal (https://doc-marine-data-deptconservation.hub.arcgis.com/), or MPI-FNZ's Seamount Survey Database (https://marlin.niwa.co.nz/databases).

4.3 Sediment data

The broad patterns in sediment grain-size distribution and composition recognised by Bostock et al. (2019a) and Bostock et al. (2019b) from the nzSEABED database are apparent in the new compilation incorporating new available data (Figure 4-5). Mud dominates in the deep-water environments, especially in the New Caledonia and Bounty troughs on the western and eastern sides of the subaerial landmass, respectively, in the north across the South Fiji Basin and in the region of the Colville-Kermadec ridges and along the Hikurangi margin and on the Hikurangi Plateau, north of the Chatham Rise, on the eastern side of Aotearoa New Zealand (Figure 4-5A). Conversely, sand is predominant off southwest Fiordland, across the Campbell Plateau in the south of the EEZ and off the northern tip of Te Tai Tokerau Northland (Figure 4-5B). While gravel data are more sparse, and its distribution is correspondingly patchy, there are areas of high gravel content associated with the volcanic arc ridges and basins in the north (Colville-Havre-Kermadec) and south (Macquarie-Puysegur-Solander), off northern New Zealand, and along the Subantarctic Slope along the southeastern edge of the Campbell Plateau (Figure 4-5C). Calcium carbonate content of marine sediments highlights the carbonate-rich, foraminifera pelagic oozes found on the Campbell and Challenger plateaux and the bryozoan/molluscan-rich, coarse-grained surficial sediments of the Three Kings Ridge region (Figure 4-5D). Low %$CaCO_3$ is co-located with areas characterised by high mud and potentially terrigenous content, especially on the continental shelf, in the Hikurangi Trough and in association with the west coast South Island canyon systems (Figure 4-5D).

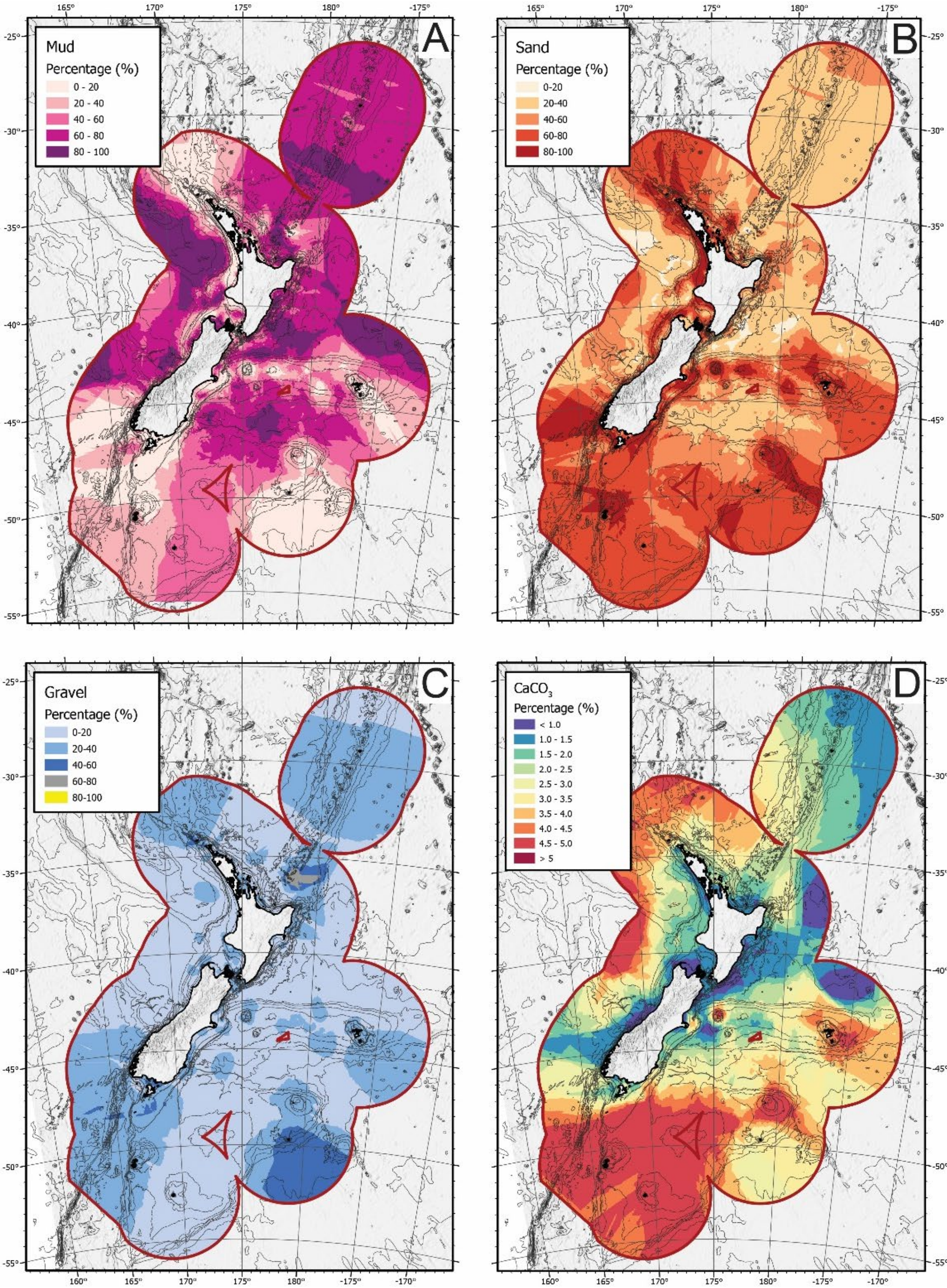

Figure 4-5: Updated maps of sediment grain-size and composition for the Aotearoa New Zealand EEZ (200 NM, red line). A. %Mud, B. %Sand, C. %Gravel, D. %$CaCO_3$. The maps are updates (Bostock et al., 2019a, 2019b), combining the nzSEABED data with the newly offshore data compiled for the present OC study.

The 5-class Folk classification used in the present study harmonises and integrates the textural data as presented above in Figure 4-5. Mud to Muddy Sand is predominant across the region, especially in deeper water environments, such as the northern part of the South Fiji Basin (outside the EEZ), in the New Caledonia Trough and eastern Tasman Sea around the Challenger Plateau, in the Havre Trough, north of the Te Moana a Toi-te-Huatahi Bay of Plenty, in the Hikurangi Trough and Hikurangi Plateau to the east and the Bounty Trough and central Campbell Plateau to the south (Figure 4-6). Sand-dominated substrates occur along much of the continental shelf and slope around Aotearoa New Zealand and out into deeper water along the Colville-Kermadec volcanic arc ridges to the north, the Chatham Rise to the east and over much of the Campbell Plateau to the south. Mixed and coarser sediments, including gravels, are prominent off southern Te Waipounamu South Island, off Te Tai Tokerau Northland, in the eastern Te Moana a Toi-te-Huatahi Bay of Plenty and along the Subantarctic Slope to the southeast of the EEZ (Figure 4-6).

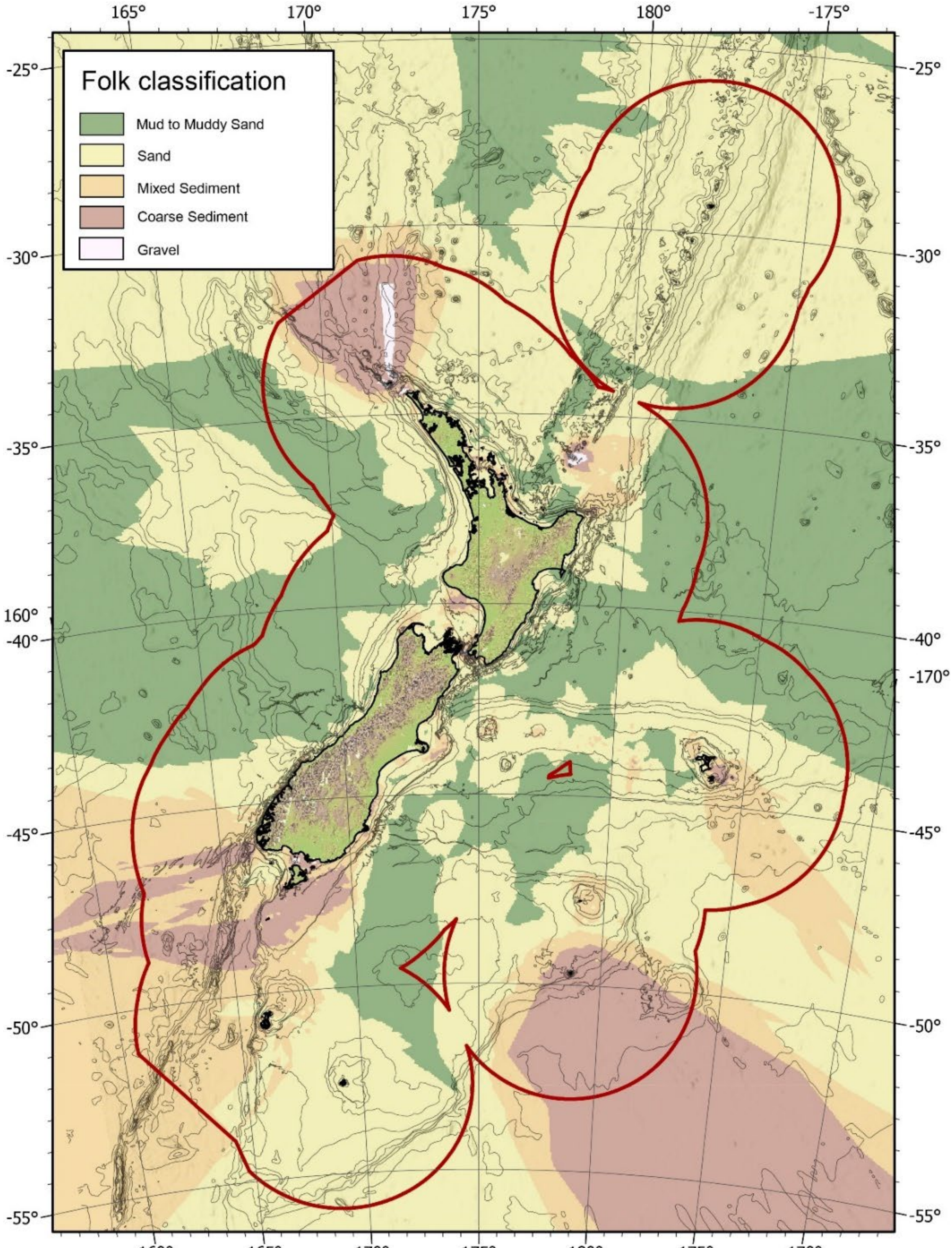

Figure 4-6: Five-class Folk textural classification of marine sediments in the Aotearoa New Zealand EEZ (200 NM, red line). For textural definitions of each class, as taken from Black et al. (2022), refer to the text.

4.4 Anthropogenic impacts on the seafloor – bottom trawling

The data provided by MPI-FNZ show the distribution of bottom trawling throughout the Aotearoa New Zealand EEZ over a period of about three decades (31 years and 11 months; 1989-2021). Most of the continental shelf and slope has been trawled multiple times as have deep-water environments of the Chatham Rise, Challenger Plateau and Campbell Plateau, targeting deep-water and middle-depth species, such as orange roughy, oreos, southern blue whiting and hoki (Figure 4-7).

It is estimated that ~462,643 km^2 of the seabed within the EEZ (11.3%) has been exposed to trawling over the past ~32 years, termed the trawl footprint. However, the total seabed area (including areas that are trawled repeatedly over the same location (termed the aggregated swept area) is ~4.9 million km^2, an area 20% larger than our EEZ. This demonstrates that some locations along the continental slope and inner continental shelf have experienced pervasive bottom trawling activity, with some areas exposed to more than twenty thousand trawls over the three decades, equivalent to 1.7 bottom tows per day for 32 years, in a given 5 km x 5 km grid cell. Approximately 40% of all 5 km x 5 km grid cells, have an aggregated swept areas larger than their total area of 25 km^2. Since there has only been very targeted, exploratory fishing activity in deep-water locations, most of the EEZ deeper than 1500 m water depth hasn't experienced any bottom trawling disturbance at all since 1989 (Baird & Mules, 2021; Black & Tilney, 2015) (Figure 4-7).

Harbours and fjords are excluded from industrial bottom trawling as are marine reserves and benthic and cable protection areas once they are gazetted formally; for example, the MPI-FNZ benthic protection areas on the crest and eastern end of the Chatham Rise can be seen clearly in the bottom trawling data in Figure 4-7.

Other human impacts that physically disturb the seabed include offshore infrastructure (e.g., emplacement of submarine cables and pipelines). Unlike benthic trawling, these impacts physically disturb the seabed once and were therefore not included in the current study to ensure a similar approach was adopted for all human impacts, such that locations with fewer than four bottom trawls were excluded from the present study.

The regions with highest OC (i.e., harbours, embayments and fjords) are not impacted by benthic trawling (Figure 4-7). However, these locations do host a range of other anthropogenic impacts analogous to trawling, such as ship anchoring (Broad et al., 2020; Davis et al., 2016) and dredging, which should be included in future assessments of OC disturbance (see Section 7 Recommendations).

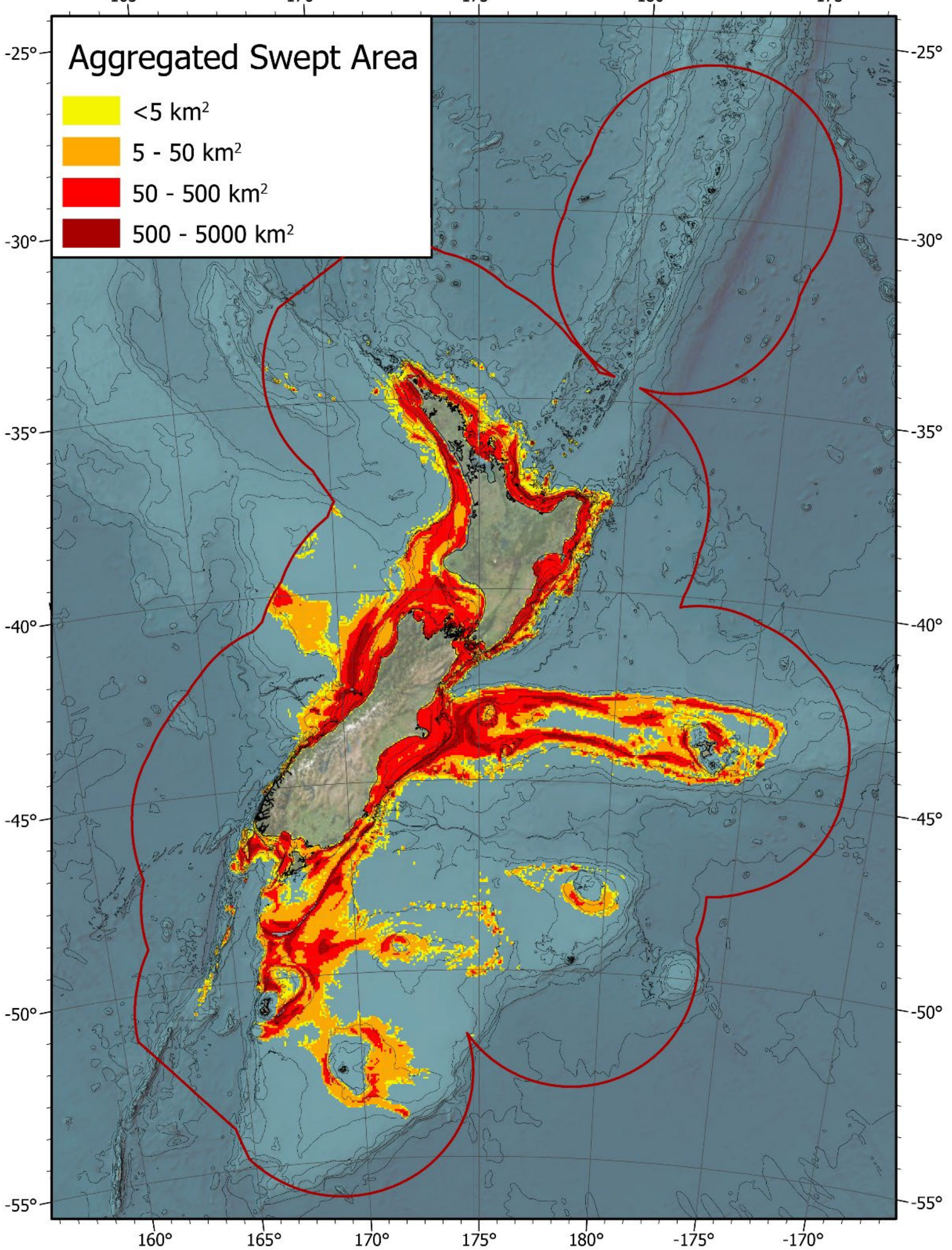

Figure 4-7: Bottom trawling activity within the Aotearoa New Zealand EEZ (200 NM, thick red line) for the period 1989-2021. The swept area data during the entire 32-year timeseries have been aggregated into 5 km x 5 km grid cells, with data with <4 tows in the cell excluded from the analysis for confidentiality purposes. Raw data courtesy of MPI-FNZ.

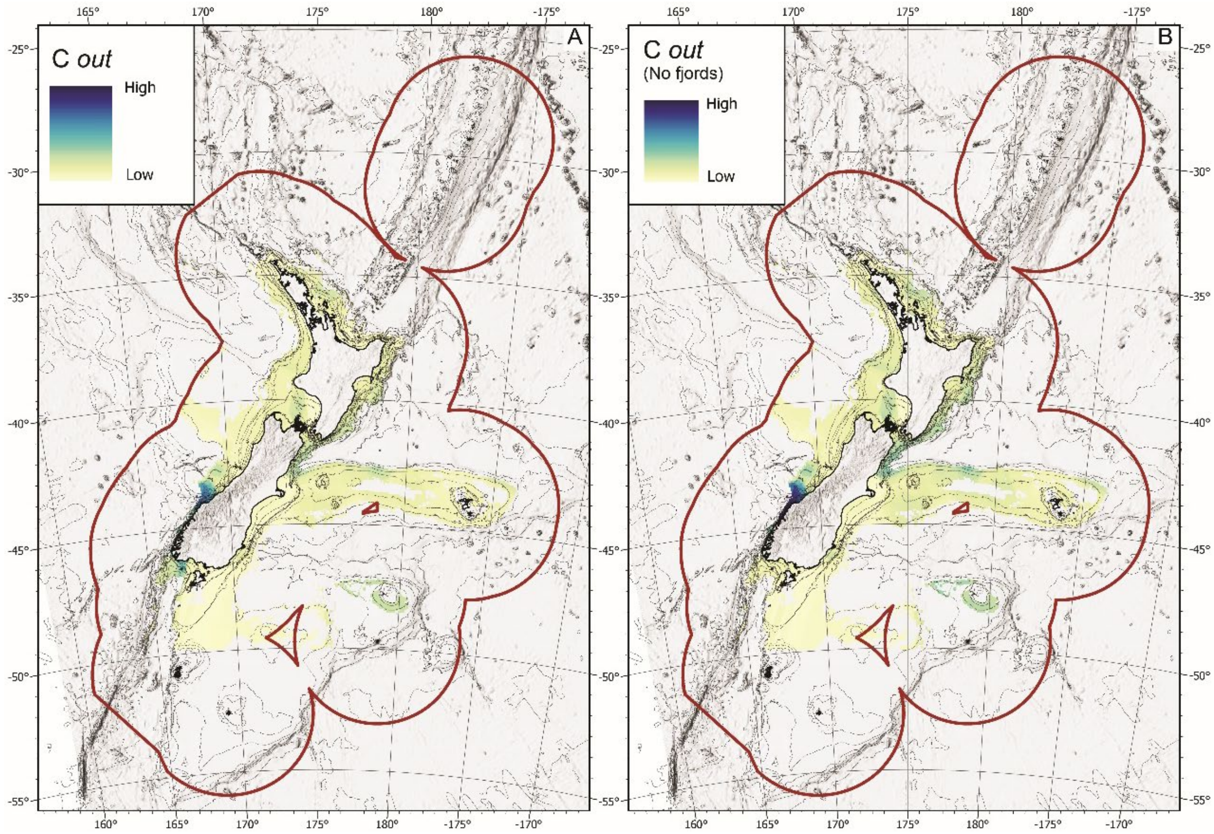

Figure 4-8: Modelled estimates of the parameter C_{out} based on the calculations in Black et al. (2022). C_{out} represents the fraction of total OC assumed to remain if the sediment in each 5 km x 5 km grid cell is exposed to fishing based disturbance, where $C_{out} = C_{in}(1 - La)$, C_{in} corresponds to the fraction of OC in the sediment (derived from %OC) and La is the estimated fraction of labile OM that would be "lost" from the sediment annually.

The parameter of C_{out} provides an indication of how much OC may be retained or lost (based on the parameterisation of *La* (see Section 3.8)) from surficial sediments due to bottom trawling activity. If the Fiordland fjords are included in the OC model, relatively high values occur off south Westland, with moderate sediment losses anticipated in central Westland canyons, in western Te Ara-a-Kiwa Foveaux Strait, on the edges of the Bounty Plateau, off northeastern Te Waipounamu South Island (including Kaikōura), east of Te Moana-o-Raukawakawa Cook Strait, along the Wairarapa coast (southeastern Te Ika-a-Māui) and on the central northern slope of the Chatham Rise (Figure 4-8).

4.5 OC vulnerability

The approach to determine sediment OC vulnerability to bottom trawling follows the methods of Black et al. (2022), taking into account parameters such as sediment texture and lability, particle settling velocity and OC degradation rates (Figure 4-9B). Many of the assumptions made by Black et al. (2022) are more pertinent to the UK study area but have been adopted in the present study due to a lack of suitable Aotearoa New Zealand data, while acknowledging the complex differences between these two regions. The methods followed in the present study are outlined in Section 3.3 and summarised in Figure 3-2.

The Black et al. (2022) model shows elevated sedimentary OC vulnerability particularly off south Westland, southern Fiordland, on the Bounty Plateau, Chatham Rise and along the eastern seaboard from northeastern Te Waipounamu (Kaikōura) across eastern Te Moana-o-Raukawakawa to Te Te

Matau-a-Māui Hawke's Bay (Figure 4-9, left panel, Figure 4-10). There is also moderate vulnerability identified across greater Cook Strait from western Te Tauihu to South Taranaki and along the west and northeast coasts of Te Ika-a-Māui North Island. When the fjord data were excluded, these patterns were maintained but the vulnerable area in western Te Ara-a-Kiwa Foveaux Strait disappeared (Figure 4-9, right panel, Figure 4-11B). It is also noted that the area of moderate vulnerability on Bounty Plateau are probably driven by kriging artefacts arising from a paucity of data in this region (see Section 4.2).

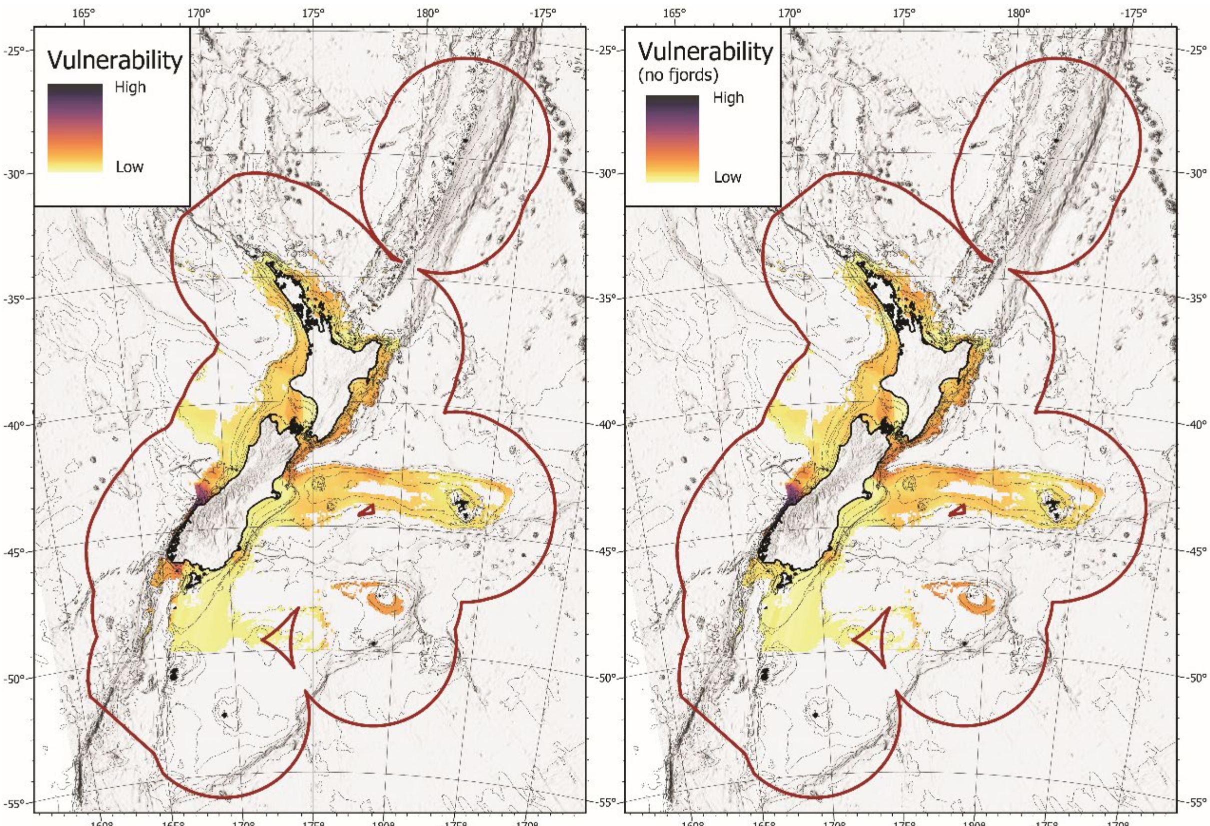

Figure 4-9: Vulnerability indices for sedimentary OC relative to bottom trawling activity within the Aotearoa New Zealand EEZ (200 NM, thick red line). Left panel: All data, including fjords; Right panel: All data, excluding fjords. These analyses used the approaches adopted by Black et al. (2022) to estimate vulnerability (see Section 3.8).

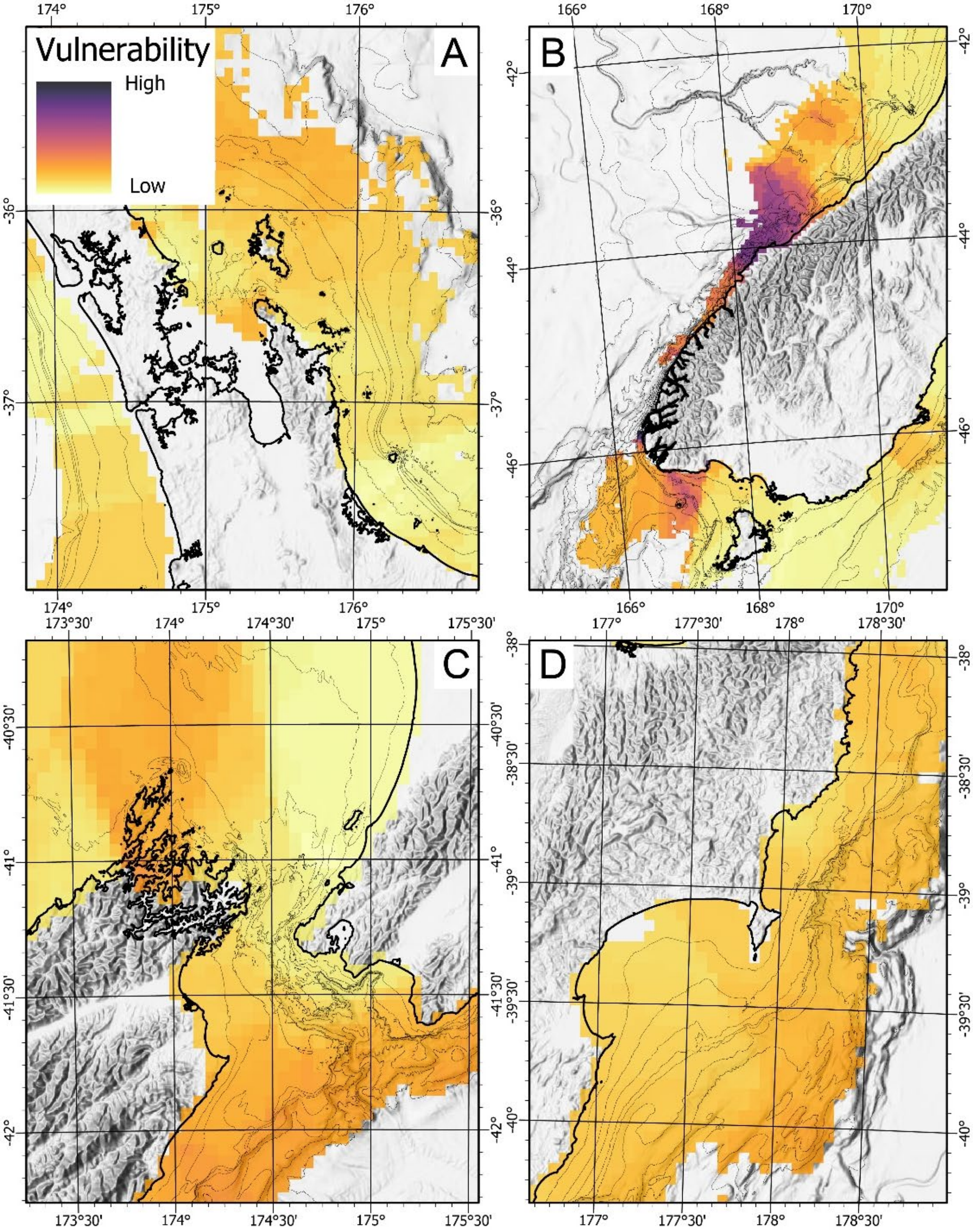

Figure 4-10: Detailed maps, including fjord data, of selected areas showing results from the Black et al. (2022) approach to evaluating sedimentary Organic Carbon vulnerability to bottom trawling. A. Tikapa Moana-o-Hauraki Firth of Thames and Hauraki Gulf, NE Te Ika-a-Māui North Island; B. Te Rua-o-te-moko Fiordland, SW Te Waipounamu South Island; C. Te Moana-o-Raukawakawa Cook Strait, central Aotearoa New Zealand; D. Te Matau-a-Māui Hawke's Bay and Tairāwhiti Gisborne, eastern Te Ika-a-Māui North Island. Locations of the detailed boxes are shown in Figure 4 2. Note that areas that are white indicate very low vulnerability; for example, in A., the Firth of Thames and inner Hauraki Gulf are shown as white, driven by the absence of bottom trawl data in this region (see Figure 4-7).

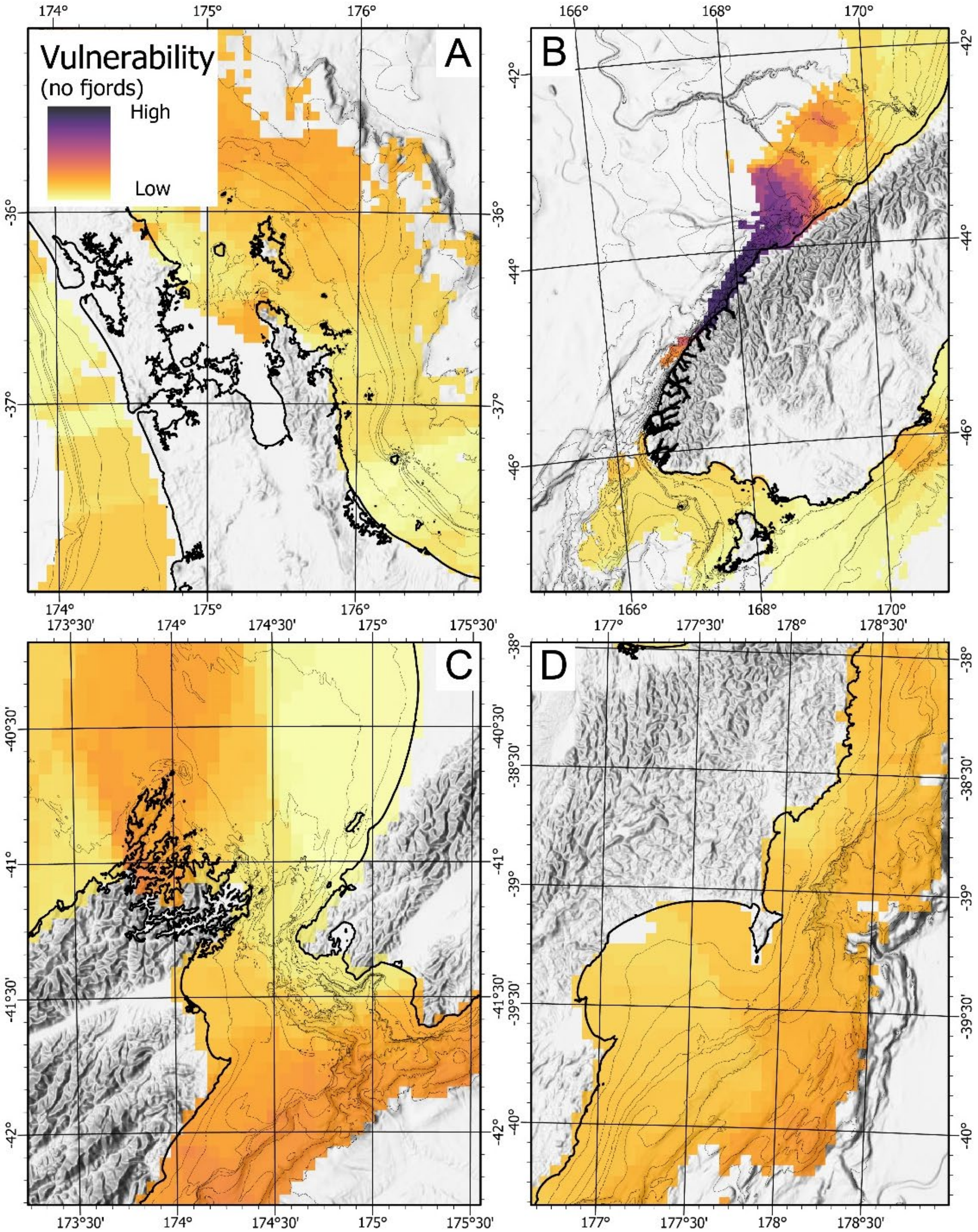

Figure 4-11: Detailed maps, excluding fjord data, of selected areas showing results from the Black et al. (2022) approach to evaluating sedimentary Organic Carbon vulnerability to bottom trawling. A. Tikapa Moana-o-Hauraki Firth of Thames and Hauraki Gulf, NE Te Ika-a-Māui North Island; B. Te Rua-o-te-moko Fiordland, SW Te Waipounamu South Island; C. Te Moana-o-Raukawakawa Cook Strait, central Aotearoa New Zealand; D. Te Matau-a-Māui Hawke's Bay and Tairāwhiti Gisborne, eastern Te Ika-a-Māui North Island. Locations of the detailed boxes are shown in Figure 4 2. Note that areas that are white indicate very low vulnerability; for example, in A., the Firth of Thames and inner Hauraki Gulf are shown as white, driven by the absence of bottom trawl data in this region (see Figure 4-7).

5 Discussion

5.1 Marine sediment OC stocks around Aotearoa New Zealand

Our first-order estimate of the OC stocks in surficial marine sediments, around Aotearoa New Zealand is ~**1890±250 Mt OC**, based on the area of the EEZ that we were able to model satisfactorily and assuming a 13% error estimate (Smeaton et al., 2021). This estimate does include some areas where the OC distribution is likely to be somewhat artefactual, driven by kriging errors due to a lack of data, but represent a first-order approximation of the EEZ-scale OC stocks (Figure 4-2). This estimate could be as much as ~**2240±290 Mt OC** if we extrapolate to include these areas that our proxy models were not able to generate OC distributions. In both cases, although these estimates should be viewed with caution, they nonetheless are the first attempt to quantify the amount of sedimentary OC across the entire ~4 million km^2 Aotearoa New Zealand EEZ. In comparison, the UK EEZ is substantially smaller (743,959 km^2, plus 10,057 km^2 for the Crown dependencies of Isle of Man and Channel Islands) than the Aotearoa New Zealand EEZ. Correspondingly, OC stocks in the marine surficial sediments of the UK EEZ are also much less at an estimated 524 ± 68 Mt OC (Smeaton et al., 2021).

On the NW European continental shelf, Diesing et al. (2017) have suggested sediment OC stock estimates in the top 10 cm in the range of 230-882 Mt OC, with a more likely estimate of 476 Mt, over an area of 1,111,812 km^2. More recent estimates over a much larger domain by Legge et al. (2020) suggest that these NW European shelf seas could potentially be storing between 6240-19,200 Mt C. While the highest OC values are typically associated with muddy sediments in these shelf seas (de Haas et al., 1997), much of the particulate OC is actually stored in coarse-grained sediments due to their greater spatial coverage and higher dry bulk density (Diesing et al., 2017). Smeaton et al. (2021) also included carbonate-rich sediments in their assessment, accounting for an estimated 2,582 ± 168 Mt of inorganic carbon (IC) stored in marine sediments, five-times larger than OC as a repository for seabed carbon.

Globally, our carbon stock values for the Aotearoa New Zealand EEZ of 1890 Mt OC represents ~1% of the global carbon stocks estimated to be stored in the top 10 cm of marine sediments(Atwood et al., 2020; Lee et al., 2019). This calculation is based on an estimate of 2,322,000,000 Mt C in the top 1 m of sediments from Atwood et al. (2020) and 87,000 Mt estimated in the top 5 cm from Lee et al. (2019), assuming an equal distribution of %carbon in the top 10 cm as throughout the top 1 m or 5 cm, respectively. The suggestion of uniformity in OC content over the top 5 or 10 cm is a reasonably robust assumption while OC variations with depth down to 1 m may be more difficult to justify, although in Atwood et al. (2020) the OC stock in the top 1 m was determined by taking the average OC stock per centimetre and multiplying it by 100, thereby assuming a constant OC content with sediment depth down to 1 m subsurface.

In light of such calculations, it is prudent to consider the data issues that varied between our study and those of these other worker's investigations. For example, the availability of robust, already compiled UK databases, with comprehensive parameter datasets, enabled Smeaton et al. (2021) to produce more rigorous carbon stock evaluations and to reduce their error estimates than were possible in our study. In Smeaton et al. (2021), they were able to utilise a total of 274,531 point-observations describing seabed type throughout the UK EEZ, which also encompassed 34,617 observations with concurrent %Mud, dry bulk density and OC values. In comparison, our study, which focussed on a significantly larger EEZ area and arguably a more complex and heterogenous seascape, was only able to utilise 11,000 point observations of seafloor sediment physical and compositional properties (mainly grain-size and %$CaCO_3$ from nzSEABED; (Bostock et al., 2019a, 2019b) and only ~1040 sites with %OC measurements, compared to 3770 data-points for %OC available to Smeaton et al. (2021) in their UK study. These factors limited the density of data coverage and hence a heavy reliance on proxy modelling to generate an OC dataset across the Aotearoa New Zealand EEZ. The proxy relationships proved to be not as robust as first anticipated, with no to weak correlations with %Mud, %$CaCO_3$ and water depth using simple linear regression (Figure 3-5). Our analysis, however, was strengthened by using GLMs with LASSO to derive multi-variate statistics with reasonably strong regression correlations (i.e., R^2 ~0.6-0.7) (see Table 3-1 Table 3-2Table 3-3Table 3-4).

Similarly, the lack of sufficient data density in specific parts of the EEZ meant that the kriging extrapolation algorithm was not able to operate at all, resulting in no extrapolated OC data returns, such as south of 50°S and in the very north of the Kermadec portion of the EEZ, or the kriging process produced anomalous, possible overestimates of OC content, such as off Fiordland and south of Bounty Platform (Figure 4-2). That said, where there appears to be sufficient data coverage, such as in central eastern Aotearoa New Zealand (i.e., Kaikōura-Cook Strait to offshore Wairarapa-Hawkes Bay-Tairāwhiti), the OC extrapolations are sensible and have probably led to reasonably robust estimates.

5.2 Distribution of offshore sediment OC stocks

As has been found in many previous studies (e.g., Black et al., 2022; Graves et al., 2022; Luisetti et al., 2019; Smeaton et al., 2021; Smeaton & Austin, 2022), shallow water coastal systems, embayments, such as harbours and fjords, and the continental shelf are identified consistently as important and potentially vulnerable repositories of stored carbon. This has led to increasing discussion about the importance of 'Blue Carbon' as an ecosystem service provided by the marine environment in mitigating global anthropogenic climate change (Graves et al., 2022) and perhaps contributing to national and subnational greenhouse gas emission inventories and reporting (Zhao et al., 2022). The focus on 'Blue Carbon' has mainly been on coastal habitats, such as seagrasses (Apostolaki et al., 2022; Oreska et al., 2018), macrophytes (Filbee-Dexter & Wernberg, 2020; Krause-Jensen et al., 2018; Krause-Jensen & Duarte, 2016; Marx et al., 2021; Ortega et al., 2019) and other higher plants, such as mangroves (Bulmer et al., 2020), but has not been without criticism as the mechanisms for effective carbon sequestration (i.e., removal from contact with the atmosphere) by Blue Carbon and other marine Carbon Dioxide Removal (m-CDR) strategies are more fully explored (e.g., (Bach et al., 2021; Ho, 2023; Hurd et al., 2022). There is growing recognition, however, that marine sediments also provide an effective mechanism for sequestering carbon, but in shallow environments such carbon repositories are particularly vulnerable to disturbance and therefore arguably worthy of consideration for protection (e.g., (Luisetti et al., 2020; Sala et al., 2022; 2021).

From further analysis of our newly compiled OC database for the Aotearoa New Zealand EEZ, shallow water environments (0-50 m) only account for ~2% of the total OC stocks in surface (0-10 cm) marine sediments within the EEZ (Table 5-1). However, the highest carbon density values are found in harbours and especially particular fjords (e.g., 11.7 kg C/m^2 in Doubtful Sound, Fiordland), although on average such OC storage values were typically ~0.5-0.6 kg/m^2 across all depth ranges (Table 5-2). The high values from the fjords is not surprising given the observations from previous studies in such fjordic settings (Cui et al., 2016b; Ramirez et al., 2016; Smith et al., 2015), and are comparable with the findings in the UK studies. The western Scottish coast and lochs/fjords and Irish fjords in particular were identified as hosting substantial carbon stocks, (Smeaton & Austin, 2019) and therefore more vulnerable to seafloor disturbance (Black et al., 2022; Luisetti et al., 2019). Such shallow environments are also recognised as hosting more reactive OC that will be prone to remineralisation if disturbed (Smeaton & Austin, 2022).

The mid- to outer continental shelf (50-200 m water depths) in the Aotearoa New Zealand EEZ contributes about 111 Mt OC or ~6% to the total EEZ OC stocks in surface marine sediments (Table 5-1). In comparison, the continental slope (200-1500 m) is a more significant repository of OC, accounting for an order of magnitude more OC stocks than the shallower environments (i.e., ~490 Mt OC or ~26% of the total EEZ OC inventory) (Table 5-1). The largest OC stocks, however, are in deep-water environments greater than 1500 m water depth due to their large areal extent in the EEZ. These environments contribute about two-thirds of the EEZ OC stocks, with ~1249 Mt OC or ~66% (Table 5-1). In the global comparison derived by Atwood et al. (2020), the continental shelf and other coastal regions comprise ~12% of the total sediment carbon stocks, with continental slopes representing ~7% and deeper (abyssal and hadal) environments dominating the inventory with ~80%. In the Aotearoa New Zealand context, there appears to be significantly less OC residing in continental shelf sediments (6% cf. 12%) and more OC in continental slope sediments than the global averages (26% cf. 7%). Correspondingly, marine sediments in deeper waters around Aotearoa New Zealand are a little less than but comparable to the global average for these environments (66% cf. 80%).

Table 5-1: Estimated Organic Carbon (OC) stocks (Mt) within surface marine sediments (0-10 cm) in the Aotearoa New Zealand EEZ, including the 12 NM Territorial Sea[a], grouped in depth bands. Calculations exclude areas within the 200 NM EEZ and 12 NM Territorial Seas that could not be modelled in the present study. “No Fjords” data are calculated by excluding analyses from inside the fjords of Fiordland.

Depth band (m)	Area within EEZ (km^2)	% Area within EEZ (%)	Area of modelled %OC (km^2)	% Area of EEZ OC stocks (%)	Estimated OC stock (Mt)	Estimated OC stock (no Fjords) (Mt)	% Estimated Total OC stock (%)	% Estimated Total OC stock (no Fjords) (%)
0-50 (coast-inner shelf)	60,237	1.46	57,509	1.40	34.36	33.45	1.82	1.93
50-200 (mid-outer shelf)	215,399	5.23	193,029	4.68	111.17	106.56	5.89	6.16
200-1500 (slope)	1,289,758	31.30	977,849	23.73	491.40	478.38	26.05	27.65
1500-EEZ (bathyal-hadal)	2,554,969	62.01	2,172,879	52.74	1,249.31	1111.57	66.23	64.25
EEZ	4,120,363	100	3,401,266	82.55	1,886.24	1,730.00	100	100

[a] excluding areas within the 200 NM EEZ and 12 NM Territorial Seas that could not be modelled in the present study.

Table 5-2: Estimated Organic Carbon (OC) stocks (Mt/km² and kg/m²) and Average %OC within surface marine sediments (0-10 cm) in the Aotearoa New Zealand EEZ, including the 12 NM Territorial Sea[a], grouped in depth bands. Calculations exclude areas within the 200 NM EEZ and 12 NM Territorial Seas that could not be modelled in the present study. "No Fjords" data are calculated by excluding analyses from inside the fjords of Fiordland. Standard deviation is given in brackets.

Depth band (m)	Estimated OC stock per unit area (Mt/km² x 10^{-3})	Estimated OC stock (no Fjords) per unit area (Mt/km² x 10^{-3})	Average of OC storage (kg/m²)	Average OC storage (no Fjords) (kg/m²)	Average percentage of OC (%)	Average percentage of OC (no Fjords) (%)
0-50 (coast-inner shelf)	0.600	0.582	0.600 (0.421)	0.584 (0.338)	0.52 (0.36)	0.51 (0.32)
50-200 (mid-outer shelf)	0.576	0.552	0.576 (0.348)	0.552 (0.272)	0.50 (0.28)	0.48 (0.24)
200-1500 (slope)	0.503	0.489	0.503 (0.307)	0.489 (0.275)	0.51 (0.26)	0.50 (0.25)
1500-EEZ (bathyal-hadal)	0.575	0.512	0.580 (0.492)	0.512 0.304)	0.62 (0.36)	0.58 (0.29)
EEZ	0.555	0.509	0.555 (0.440)	0.509 (0.295)	0.58 (0.34)	0.55 (0.28)

[a] excluding areas within the 200 NM EEZ and 12 NM Territorial Seas that could not be modelled in the present study.

In terms of areal extent, the OC storage in various depth ranges seem to match the proportions that these environments are found in the EEZ (e.g., 0-50 m coast to inner shelf environments comprise ~1.5% of the total EEZ area and host ~1.4% of the total EEZ OC stocks (Table 5-1). Across all depths of the EEZ the average OC storage is consistent (0.5-0.6 kg/m²), and only slightly higher in coast to inner shelf environments (Table 5-2). The lowest OC storage by area is in continental slope areas (0.5 kg/m²), despite hosting about a quarter of the total EEZ OC stocks (Table 5-1). This could be driven by the complex bathymetry associated with such areas, especially along the east coast of Te Ika-A-Māui North Island due to the Hikurangi Subduction Margin associated with the active plate boundary, and the persistence of ocean flows along the eastern shelf-break and slope from the northern tip of the island to the southern end of Te Waipounamu South Island (Chiswell et al., 2015; Stevens et al., 2021). These observations are similar to those made in the UK EEZ (Smeaton et al 2021), with coastal and inshore environments providing slightly more OC storage on average than continental shelf and deeper waters (i.e., ~1-2 kg/m² cf.0.4-1 kg/m², their Table 3). The OC areal storage in the Aotearoa NZ EEZ, however, appears to be overall less than that estimated for the UK at around ~0.5-0.6 kg/m² (Table 5-2).

5.3 Offshore areas that are vulnerable to disturbance and the fate of remobilised OC

The present study portrays a first-approximation, snap-shot of the OC stocks in surficial marine sediments around Aotearoa NZ. It does not attempt to consider the more dynamic features of OC cycling in terms of OC production (or supply), transport, deposition and burial. While as a percentage of the total EEZ stocks, the highest amounts are found in environments deeper than 1500 m (Table 5-1), these depositional settings are characterised by different processes than those in coastal and shelf areas, which account for less than 7% of the total carbon stocks (Table 5-1). For example, natural processes of disturbance (see Section 5.4) are likely more prevalent in shallow systems, where productivity, turnover, replenishment and burial of OC stocks is expected to be faster than in deeper water environments.

Sala et al. (2021) estimated that a total of 400 Mt of sedimentary C, equivalent to 1470 Mt of aqueous CO_2, may be released from marine sediments due to global bottom trawling in a single year. They equated this value to 15-20% of the atmospheric CO_2 absorbed annually by the ocean, despite comprising only 0.02% of the total global marine sediment carbon stocks. After nine years of 'continuous' trawling, this OC release was modelled to decline and eventually stabilise at about 580 Mt CO_2 (160 Mt C) as sediment carbon stocks were progressively depleted. Aspects of this approach and subsequent statements were criticised heavily (Hiddink et al., 2023; Hilborn & Kaiser, 2022) and were then refuted by the authors (Atwood et al., 2023; Sala et al., 2022). The criticism levelled by Hiddink et al. (2023) suggested that the potential OC release from marine sediments could be overestimated by 2-3 orders of magnitude by Sala et al. (2021). This was disputed by Atwood et al. (2023), who asserted similar or at most one order of magnitude difference, based on the theoretical, rather than empirical degradation rate (*k*) data used by Hiddink et al. (2023) to dispute the Sala et al. (2021) findings.

Regardless of these disagreements, it is apparent that the likely fate of sediment OC released from sediments by seafloor disturbances, such as bottom trawling, is an important consideration when evaluating whether such activities will have a deleterious environmental impact or not. Any seafloor disturbance, natural or anthropogenic, has the potential to resuspend OC-rich materials in surface sediments into the water column (O'Neill et al., 2013; O'Neill & Summerbell, 2016) and to expose recalcitrant or refractory OC in deeper sediments to oxygen-rich overlying waters (Epstein et al., 2022; Rijnsdorp et al., 2016), leading to increases in OC remineralisation and concomitantly reductions in sediment OC preservation (e.g., (Arndt et al., 2013; Chen et al., 2022; Hedges & Keil, 1995; LaRowe et al., 2020). Such seafloor disturbances can also:

- Cause changes to the physical structure and composition of marine sediments (Kaiser et al., 2002; O'Neill & Ivanović, 2016);
- Alter biogeochemical processes and elemental cycling in the sediments and overlying waters (Breimann et al., 2022; Duplisea et al., 2001; Tiano et al., 2019); and
- Modify sediment community composition and biomass through direct mortality or indirectly by changing the trophic response to the disturbance (e.g., increasing the abundance of scavengers and detritivores) (Hiddink et al., 2017; Jennings et al., 2001) or affecting community ecosystem functioning (Ramalho et al., 2020).

Reductions in the preservation potential of OC in marine sediments will have negative implications for the effectiveness of such environments to act as loci for natural carbon sequestration (Arndt et al., 2013; Hedges & Keil, 1995; Mcleod et al., 2011). Released sedimentary OC back into the water column will be available for degradation and remineralisation, with the potential to produce excess CO_2 (and other greenhouse trace gases, such as N_2O and CH_4) due to microbial respiration and chemical oxidation of the released OC substrates (Bianchi et al., 2018; Burdige, 2007). These processes will also increase ocean acidification and in the process of also consuming oxygen, thereby potentially contribute to ocean deoxygenation (e.g., Gao et al. 2019). Particularly in shallow waters there is potential for these degradation products to be transferred back into the atmosphere across the air-sea interface, therefore increasing atmospheric greenhouse gas-sensitive emissions.

The fate of previously stored OC in the form of released CO_2 is difficult to quantify but it is likely that, if excess dissolved inorganic carbon (DIC) and associated regenerated nutrients reach surface waters, a proportion could be utilised by phytoplankton during photosynthesis to increase primary production. The increase in DIC could also lead to increased ocean acidification (decreasing pH), while a proportion could re-equilibrate with the atmosphere and become a potential new marine source of CO_2. Obviously, such processes will be more likely to have an impact if the sediment disturbance occurs in shallow, well-mixed waters on the continental shelf and coastal embayments, such as estuaries, harbours, bays and fjords. Such relatively shallow coastal features, and fjords in particular (Smith et al., 2015), have been recognised as regional and globally significant loci for carbon storage and potentially vulnerable to anthropogenic seafloor disturbance (Bianchi et al., 2018; Black et al., 2022; Cui et al., et al., 2016; Hinojosa et al., 2014; Smeaton et al., 2021). Similarly, continental shelves are being recognised increasingly as potentially important sites for carbon sequestration and storage (Chen & Borges, 2009; Muller-Karger et al., 2005), especially in relation to the burgeoning interest in coastal Blue Carbon (Diesing et al., 2017, 2021; Graves et al., 2022; Legge et al., 2020; Luisetti et al., 2019).

In the Aotearoa New Zealand context, where we have a continental margin setting that sits astride an active plate boundary, with highly erodible geology, uplifting mountainous terrain and strong rainfall patterns in a temperate latitude maritime climate (Gomez et al., 2003; Hicks et al., 2011; Jiao et al., 2017; Scott et al., 2006), it is recognised that the contribution of terrigenous organic matter to marine carbon stocks, especially in coastal systems, could be significant (e.g., (Brackley et al., 2010; Burdige, 2007; Kniskern et al., 2014; Muller-Karger et al., 2005). For example, Gibbs et al. (2020) showed that there was more efficient transfer of terrestrial OC down the Hokitika Canyon on the west coast Te Waipounamu South Island, with terrestrial signals in biomarker isotopes observed up to 200 km offshore. These observations were contrasted by more limited transfer and increasing dilution by marine-derived OC within 25 km of the coast in the Kaikōura Canyon on the opposite eastern side of the island (Gibbs et al. 2020). Terrestrial OC is likely to be more refractory and therefore have different reactivities and hence lower potential for remineralisation and burial than marine-derived OC (Arndt et al., 2013; Burdige, 2005, 2007). Given the likely high contribution of terrestrial OC to carbon stocks on such continental margins as Aotearoa New Zealand, source characterisation of organic matter should be factored into future assessments of OC stocks in marine sediments.

In the Aotearoa New Zealand case, while the highest OC densities are observed in shallow harbours and fjords (data not shown, although environments in the 0-50 m water depth range typically had higher average OC storage values, see Table 5-2)s), it appears that continental slope sediments are a more important repository for OC, accounting for almost 30% of the total OC stocks that we were able to model within the EEZ. These observations are consistent with previous observations from other continental margins (e.g., Muller-Karger et al., 2005), and reflects the highly productive nature of such environments (e.g., Verity et al., 2002). Although, bottom trawling on the continental slope (200-1500 m water depths) is pervasive (Figure 4-7), vulnerability remains low to moderate at most locations, except off southern Westland, where the highest vulnerability values (and low variance) were observed (Figure 4-9B, Figure 4-2). This vulnerability appears to be driven by the substrate conditions, high OC content and relatively low levels of fishing effort on the continental slope, suggesting that this area could be further investigated to evaluate how OC storage protection could be implemented. The robustness of this interpretation would also benefit from improved sample density, especially offshore. Nonetheless, areas where there is historically high bottom trawling activity, such as the Chatham Rise and along the eastern side of Te Ika-a-Māui, OC vulnerability is overall moderate in scale across the whole domain (Figure 4-9B). The OC content in these more vulnerable areas ranges from 2-3% on the continental slope and within the canyon systems of the Hikurangi margin (including Kaikōura) to ~1-2% on the upper flanks and crest of the Chatham Rise

(Figure 4-2). Given that most of the OC sampling in these regions has been undertaken during the main period of bottom trawling it is likely that the OC stocks in these areas are already affected by anthropogenic seafloor disturbance, although in the case of the Chatham Rise, consideration needs to also be given to natural processes of sediment resuspension and redistribution by bottom currents (e.g., Nodder, 2012). The effect of long-term bottom trawling on upper continental slope environments has been demonstrated to lead to a smoothing of the seafloor morphology and hence reduction in benthic habitat heterogeneity, coupled with increased downslope transport of fine-grained sediment (Puig et al., 2012) and potential accumulation of ephemeral, fresh organic matter, with high remineralisation and turn-over rates (Paradis et al., 2019). These considerations would serve to reduce the permanence of OC sequestration in such areas, which comprise a significant repository of moderately vulnerable OC stocks in the Aotearoa New Zealand region (Table 5-1).

Since many shallow harbours and embayments are presently excluded from fishing activities, seafloor disturbance and therefore vulnerability in this study could be regarded as minor (Figure 4-9, Figure 4-10 and Figure 4-11). In such environments, however, other anthropogenic activities, such as anchoring, dredging, offshore infrastructure and aquaculture, could be additional factors to consider (see Section 5.4 and Figure 3-3).

5.4 Other potential impacts – natural and anthropogenic disturbances

While bottom fishing is arguably the most pervasive and repetitive anthropogenic activity affecting the seafloor environment of continental margins globally (Atwood et al., 2023; Dayton et al., 1995; Epstein et al., 2022; Hiddink et al., 2017, 2023; Palanques et al., 2001; Puig et al., 2012; Sala et al., 2021; Thrush et al., 1998), other human activities could potentially also impact such habitats.

Given that globally (Amoroso et al., 2018; Hiddink et al., 2017, 2023; Rijnsdorp et al., 2016; Sala et al., 2021) and around Aotearoa New Zealand (Baird & Mules, 2021; Black & Tilney, 2015), bottom trawling activity Is restricted mainly to water depths shallower than 1500 m (Figure 4-7), the potential for disturbance due to this activity in deeper water is negligible to zero (Figure 4-9). While there is a drive to explore and exploit deep-water fish stocks (Pauly et al. 2003), the potential for increasing deep-sea mining of seabed minerals is also a potential threat to maintaining the integrity of seafloor carbon stocks as is existing sediment mining activities in continental shelf waters (e.g., sand and gravel extraction, diamond mining off Namibia). The degree to which marine sediments in all environments are effective in storing carbon is important as human endeavours continue to increasingly look to the sea for resources (Jouffray et al., 2020).

Applied across all of these facets is the threat of anthropogenic global climate change, which will be critical in the development and implementation of future management strategies to limit the detrimental impacts of human activities in the marine environment (Levin et al., 2020). There is the potential for the loci of marine aquaculture and fishing to change in the future as plankton communities and fish populations move geographically in response to the changing physical environment (e.g.,Franco et al., 2020). In coastal systems, with rising sea-levels, landward shifts in OC depositional habitats, such as mudflats, seagrass beds, macroalgae (seaweed) forests, mangroves and coastal swamp areas, improved water quality and sediment delivery and ecosystem restoration will lead to an enhancement of the blue carbon potential of such environments (Lovelock & Reef, 2020). Other climate change-related stressors will also impact the integrity of marine sediments and their capacity to act as effective carbon sequestration pools. For example, ocean acidification will lead to a shallowing of the depth at which carbonate minerals in marine sediments dissolve (Ilyina & Zeebe, 2012), with likely effects on the biogeochemical processes and hence OC preservation potential of these seafloor environments (Ravaglioli et al., 2019). Oxygen deoxygenation due to ocean warming may arise from reductions in O_2 solubility (e.g., Gao et al., 2019), or from nutrient delivery from terrestrial sources, such as agricultural run-off, causing increased primary production and O_2 uptake during enhance organic matter remineralisation (e.g., Zeldis et al., 2022); these processes may actually promote OC preservation.

There is an opportunity to relate baseline estimates of OC stocks in marine sediments to the episodic transfer of sediment, nutrients, pollutants and organic matter from rivers to the sea either by anthropogenic forcings, resulting from poor land management practices, leading to increased erosion and sediment delivery to the coast, or by natural processes, such as submarine landslides and evolution of debris flows and turbidity currents during earthquake ground-shaking events. In particular, it is recognised that organic matter content and reactivity in marine sediments is controlled to a large extent by its association with mineral surfaces (such as clays) and specific mineral associations (Arndt et al., 2013; Hedges & Keil, 1995; Mayer, 1994). These factors may be important in the Aotearoa NZ context given the large amount of fine-grained suspended sediment delivered from the land to the coast (Hicks et al., 2011). For example, the east coast of Te Ika-a-Māui North Island, especially Tairāwhiti, has rivers that discharge a significant proportion of the county's sediment yield to the coast, accounting for ~40% of the 209 Mt/y annual sediment yield nationally (Hicks et al., 2011). Episodic high sediment events occur on this coast, delivering particulate OC to the coast (Scott et al., 2006), as observed historically in sediment records (Gomez et al., 2003), and as represented in recent times by Cyclone Bola in March 1988 and most recently with Cyclone Gabrielle in 2023. The organic-rich, terrestrially-derived deposit arising from the Cyclone Bola floods led to the deposition of a 1-10 cm thick flood layer that was rapidly buried by sediments deposited under less extreme conditions (Brackley et al., 2010), providing an effective mechanism for sequestering terrestrially derived OC on the continental shelf. Such flood-related deposits on the inner and mid-Tairāwhiti Poverty Bay shelf are characterised by higher %OC contents than typical non-flood deposits (0.5-3.5% cf. <0.5%), with the terrestrial component at shelf and upper slope sites in the order of 20-30% of the total OC pool (Brackley et al., 2010; Kniskern et al., 2014). A single flood event on this coast can deliver 9-39 Kt OC to the shelf, comprising 2-9% terrestrial carbon, that represents 7-30% of the annual discharge from the flooding river, in the case the Waipaoa River (Kniskern et al., 2014). Similarly, ground-shaking from the November 2016 M_w 7.8 Kaikōura earthquake caused wholesale evacuation of seafloor materials and deeper substrates from the head of the Kaikōura Canyon (Mountjoy et al., 2018) that led to a powerful turbidity current that swept sediment from the canyon source over 650 km down the canyon-connected, deep-sea Hikurangi Channel (Howarth et al., 2021). Over 7 Mt OC was transferred from the canyon to the deep-sea (Mountjoy et al., 2018), which contributed an additional 2-3% of OC to the seafloor environment in the resulting turbidity current deposit (Nodder, NIWA unpublished data).

Another factor that could be used to account for the relative vulnerability of sediment OC stocks to disturbance is whether natural processes may affect the burial and preservation potential of OC. Specifically, regions where physical disturbance by waves and/or bottom currents can affect how much OC is deposited and accumulates on the seafloor will also affect relative vulnerability, compared to disturbance by anthropogenic activities. Obviously, areas in the shallow coast where wind and swell waves can periodically resuspend seafloor sediments, especially in mud-dominated environments, could have high natural vulnerability, such as in harbours and estuaries like Tauranga (De Lange & Healy, 1990; Pratt et al., 2014) and Waitemata harbours (Green, 2008). Strong tidal currents, as in Te Moana-o-Raukawakawa Cook Strait (Heath, 1978; Stevens, 2014; Stevens et al., 2021), are also known to transport even large grains (sand, cobbles) at the seafloor (Carter et al., 1991), thereby affecting the ability of OC to settle and become buried in the seafloor. In this system, only the deeper parts of the canyons in the strait are characterised by muddy sediments (Lamarche et al., 2011; Lewis & Mitchell, 1981; Lucieer & Lamarche, 2011), and are shown to be repositories for OC (Figure 4-2, Figure 4-4C) that are moderately vulnerable to bottom trawling fishing activity, compared to areas in the ~300 m-deep Narrows that are dominated by coarser substrates (Figure 4-9, Figure 4-11C).

In shallow embayments and harbours, especially offshore from port facilities, anchoring and propeller wash associated with shipping can potentially have local but significant impacts on the seafloor (Broad et al., 2020; Davis et al., 2016; Watson et al., 2022). These areas are also subject to offshore port infrastructure (Bugnot et al., 2021) and associated dredging and other harbour maintenance that can impact directly the seafloor either during channel deepening of the seabed along shipping lanes or by the physical dumping of sediment at spoil dumping grounds (Blake et al., 2009; Virtasalo et al., 2018). Increased tourism by large cruise ships, especially into vulnerable environments that have otherwise relatively low human impacts or high ecological value, such as in Fiordland and Akaroa Harbour, could exacerbate seafloor disturbances, leading to the mobilisation of OC in these exceedingly high OC marine sediments. In contrast, pollution inputs from accidental oil spills or point-source contamination in shallow environments can enhance natural OC stocks, and even in deep-water habitats, as was observed during the Deepwater Horizon oil spill disaster in the Gulf of Mexico in 2010 (e.g., Beyer et al., 2016).

Offshore infrastructure is associated with the energy (e.g., oil and gas platforms and pipelines, windfarms) and aquaculture sectors, whose activities can also impact the seabed, especially during the commissioning and decommissioning phases of construction or ongoing due to associated activities, such as servicing by tender vessels. The benthic footprint of aquaculture facilities includes physical disturbance during installation and maintenance, the modification of currents and sediment transport due to the presence of the aquaculture structure (Plew et al., 2005) and biodeposition, which adds OC to the benthic environment, and can lead to alterations to biogeochemical processes and faunal communities beneath the built structures (Hartstein & Rowden, 2004; Hartstein & Stevens, 2005). Windfarms are a relatively recent phenomena in near-coastal settings for which the environmental impacts are well-recognised (Clark et al., 2014; Hernandez-Estrada et al., 2021), with new technological and engineering developments and space considerations in the coastal zone also tending to push such activities into deeper water, where the largest proportions of OC stocks in the EEZ lie (Table 5-1; i.e., from 20-40 m to >100 m water depths) (Farr et al., 2021).

Seabed mining for offshore sediment resources, such as aggregate, placer or mineral deposits, directly impacts the seafloor environment by extracting and removing seabed materials and substrates. For example, in Aotearoa NZ, extraction of aggregate sand occurs offshore Pakiri Beach, Northland (Hicks et al., 2002; Hilton & Hesp, 1996), and various companies have evaluated the potential of offshore placer deposits, such as ironsands in the South Taranaki Bight (Anton & Kim, 2015), and mineral-rich deposits, such as phosphorites on the Chatham Rise (Nielsen et al., 2015). Deeper water environments may also be impacted as exploration for various important and precious elements and metals, such as gold, silver, colbalt, manganese and rare earth elements, develops (e.g., (Glasby & Wright, 1990; Takaya et al., 2018). These practices would disrupt the benthic environment and consideration of the possible impacts such activities might have on important OC sediment stocks should be evaluated.

Telecommunication and power cables are laid on or ploughed and buried in the seabed, stretching across ocean basins and between island nations or across waterways within nations (Carter et al., 2014). It is estimated that globally the installation of telecommunication cables have disturbed in the order of 3-11 Mt OC in water depths up to 2000 m (Clare et al., 2023). Figure 3-3 shows the location of existing and planned cable route corridors, numbering less than twenty in the Aotearoa NZ EEZ. These activities can be regarded as having a “one-off” impact on carbon stocks during cable installation, unlike other human practices in the marine environment, such as bottom trawling, anchoring, dredging and seabed mining. In some cases, they may have a positive effect as they are often associated with protection zones that restrict any activities, such as dredging or fishing, as for the power cable between the two main islands of Aotearoa New Zealand (Carter et al., 1991) and the telecommunication cable corridor running offshore in Hauraki Gulf (see Figure 3-3).

Areas that are excluded from human activities on the basis of legislation in the Aotearoa New Zealand context, such as marine reserves and benthic protection areas and seamounts closures, or by indigenous customary rights (taiāpure/rāhui/mātaitai) are also valuable in their protection of ecosystem services delivered by the marine environment (MacDiarmid et al., 2013) as well as protecting and conserving important marine biological communities (Edgar et al., 2014; Epstein & Roberts, 2023). In fact, Sala et al. (2021) argued for “a conservation planning framework to prioritize highly protected MPAs in places that would result in multiple benefits today and in the future”, advocating for a reduction in bottom trawling to increase carbon sequestration by marine sediments (but see discussion: (Hilborn & Kaiser, 2022; Sala et al., 2022)).

5.5 Improving estimates of OC storage in marine sediments

Improvements of the OC storage estimates by marine sediments globally and regionally will deliver positive outcomes in terms of understanding the functioning of the marine carbon cycle and how it might change in the future in the face of global climate change. This improved knowledge will ensure better outcomes with regard to marine spatial planning, ensuring that valuable seafloor OC stocks are suitably protected and not subject to unnecessary disturbance that could lead to reductions in the capacity of the oceans to efficiently absorb and sequester atmospheric CO_2. There is a need for the development of effective strategies to manage marine OC sediment stocks to maintain the ecosystem services that they offer humanity, such as carbon sequestration, denitrification (i.e., reduction of nitrous oxide, a potent greenhouse gas, to N_2), nutrient fluxes and as substrates for important species, including taonga and kai moana. Such management strategies could include establishing marine areas with high carbon stocks that are protected from human activities, such as marine reserves and other marine protected areas (e.g., (Atwood et al., 2020; Sala et al., 2021) or recognising the importance of offshore carbon repositories to national emissions inventories and ecosystem-economic accounting (e.g., Avelar et al., 2017; Luisetti et al., 2020). It is noted that the vulnerability of different depth zones to other human-induced stressors, such as sedimentation, pollution and climate-related sea-level rise, will also be important considerations in future management strategies, related to sedimentary OC stocks, especially in the coastal blue carbon context (e.g., Vanderklift et al., 2022).

Better understanding of location-specific processes affecting organic matter preservation in the Aotearoa NZ region are required due to the complex seascape in which marine sediments are accumulating. Quantification of the interactions of sediment OC stocks with oceanography (currents, primary production, vertical fluxes), biogeochemistry, oxygen conditions in the water column and sediments, sediment accumulation rates, biological communities and anthropogenic stressors, and in particular how all of these processes vary across water depth from the coast to the deep-sea.

While the present study is the first to derive an estimate of the OC stocks in marine sediments on the scale of the Aotearoa New Zealand EEZ, the calculations and subsequent results should be viewed with some caution. Compared to the less areal extent and more comprehensive sediment databases available to other comparable studies (e.g., (Black et al., 2022; Diesing et al., 2017, 2021; Legge et al., 2020; Luisetti et al., 2019; Smeaton et al., 2021; Smeaton & Austin, 2022), our estimates should be regarded as first-order approximations only. Future estimates would benefit greatly by continuing to develop and expand the new national OC database that has been compiled for the present study, ensuring the application of ongoing and robust data collection protocols, curation and database management techniques, and making the data openly available to other researchers and interested parties. In addition, significant data gaps, in particular in deep water environments off Fiordland and Campbell-Bounty Plateau, need to be addressed by new sampling efforts if future analyses are to result in more accurate outcomes. In addition, localised “hot spots” of potential OC accumulation, such as submarine canyons, may not be captured in the EEZ-scale and extrapolation methods applied in the present study; further work is needed to address the relative importance of these small-scale bathymetric features as possible hosts of valuable OC stocks.

6 Conclusions

Marine sediments are one of the largest repositories of organic carbon (OC) on Earth, and play a vital role in regulating climate change by storing carbon on timescales of thousands to millions of years if left undisturbed (Atwood et al., 2020; Estes et al., 2019). Historically persistent and ongoing physical seafloor disturbance by anthropogenic activities, such as bottom trawling (Hiddink et al., 2017, 2023), have the potential to release OC from sediments, with the opportunity for this carbon to be remineralised, thereby offsetting the absorption efficiency of the oceans for atmospheric CO_2 (Sala et al., 2021).

Based on the methods developed and utilised initially by Black et al. (2022) for the UK EEZ, we have compiled a new database of OC measurements in marine sediments around Aotearoa New Zealand. For the first time, an EEZ-scale inventory of sedimentary OC is available, from shallow harbours and estuaries to deep-water abyssal plains and subduction trenches. The magnitude of the OC stocks in the top 10 cm of marine sediments throughout the Aotearoa New Zealand EEZ is at least 1890 Mt OC for the areas of the EEZ that our statistical methods were able to robustly extrapolate to, and as much as 2240 Mt OC, making assumptions of the OC content in those areas that we were not able to model satisfactorily. This represents about 1% of the estimated global OC stocks in marine sediments (Atwood et al., 2020). These carbon stocks are distributed unevenly across the EEZ with shallow coastal and continental shelf environments (0-200 m water depths) accounting for only ~7%, compared to ~12% globally. A substantial amount of carbon (~26%) resides in New Zealand continental slope sediments (200-1500 m), about four-times more than global estimates for the same environments (Atwood et al., 2020). Due to the large area of the EEZ deeper than 1500 m, a substantial amount of OC is captured in deep-water sediments (~69%, ~1250 Mt), a similar proportion as for the global sedimentary OC inventory for abyssal, basin and hadal environments (~79%).

Given that the most pervasive activity physically disturbing marine sediments is bottom trawling at water depths shallower than 1500 m, the vulnerability of OC to this anthropogenic activity was evaluated combining information from the new OC database in relation to assumed sediment type lability, particle sinking speeds and OC degradation rates as in Black et al. (2022). This analysis has led to the development of a vulnerability index for OC to bottom trawling that emphasises the likely impact of trawling on OC stocks in continental shelf and slope environments, particularly off south Westland, western Te Ara-a-Kiwa Foveaux Strait, Bounty Plateau, Chatham Rise and along the east coast from Kaikōura to Te Matau-a-Māui Hawke's Bay. The spatial extent of vulnerability models in this context is governed by the distribution of bottom trawling. In Aotearoa, bottom trawling is not permitted in harbours and fjords where numerous studies have revealed carbon densities are particularly high (Baird & Mules, 2021; Black & Tilney, 2015). As such, the logical continuation for analysing OC disturbance and vulnerability in Aotearoa should focus on shallow marine embayments, harbours and fjords, which host a range of cumulative anthropogenic activities that disturb the seabed and potentially OC stocks (e.g., dredging, anchoring). Furthermore, bottom trawling does not presently extend deeper than about 1500 m water depth. This highlights the need to measure and monitor environments that have not as yet been impacted by human activities, particularly deep-water habitats that remain the greatest repository of OC on Earth.

7 Recommendations

The following recommendations are made on the basis of improving estimates of the marine sediment contribution to OC storage around Aotearoa New Zealand:

1. Extend the study to include carbonate (or Inorganic Carbon) stocks, as shown by Smeaton et al. (2021) to be an important repository of marine carbon in the UK EEZ;

2. Incorporate natural disturbance indices (e.g., waves, tides, bottom currents) to put anthropogenic impacts into context;

3. Undertake a systematic sampling of areas where there are significant areas of the Aotearoa New Zealand EEZ that are data poor, particularly Campbell Plateau, offshore Fiordland-south Westland and Kermadec regions. Targeting likely 'hotspots' of OC storage to corroborate the interpolated data in the present study and to focus on smaller scale features, such as submarine canyons, that may not have been adequately captured in our OC modelling;

4. Standardise sampling (grabs vs sediment corers – gravity/piston vs box or multi-cores) and analytical methods to ensure the complete data coverage to generate the required model outputs (e.g., OC, TOM, dry bulk density, grain-size, regionally specific OC lability and degradation and accumulation rate data) and perform such measurements on archived samples (where available);

5. Conduct a data levelling exercise to account for the variability introduced by the different analytical methods used to generate the compiled OC data;

6. Interrogate more fully the Fisheries New Zealand bottom trawl footprint data to reveal the potential impacts of different fishing gear types as undertaken by other studies (e.g., Black et al. (2022);

7. Undertake direct measurements of sediment OC accumulation and burial rates, as well as CO_2 efflux and sediment oxygen consumption rates, as measures of OC remineralisation (e.g., Stratmann et al. (2019), to quantify the magnitude and efficacy of carbon sequestration and storage by marine sediments. There is also a paucity of information on organic matter sources (e.g., terrestrial vs marine) and reactivity (lability) and the processes driving OC preservation in the Aotearoa NZ region;

8. Address database scales especially as the large Aotearoa New Zealand EEZ requires considerably more sampling effort to develop comprehensive databases of a similar scale as those available to the Smeaton et al. (2021) and Black et al. (2022) studies in the UK EEZ. While initial investigations of existing international databases indicated a paucity of data for the Aotearoa New Zealand and SW Pacific Ocean region (e.g., Seiter et al., 2004), future work should explore other international data repositories and compilations to incorporate into the new sediment OC database. In the Aotearoa New Zealand context there is an extra need for new sample collections, especially on the Campbell-Bounty Plateau, where there is a lack of sediment data, especially from regions of moderately high fishing intensity;

9. Better sample and characterise potentially vulnerable shallow harbours, embayments and fjords for other anthropogenic impacts that disturb the seabed, other than bottom trawling, such as seabed mining, anchoring, cable laying, dredging and spoil dumping, etc.

Considerations could also be given to quantifying the OC stocks in the 12 NM Territorial Seas, within existing and proposed Marine Protected Areas and within coastal Blue Carbon contexts;

10. Ensure that the data compiled by the present study has longevity by implementing national databases, using standard methods of data management and curation, with open-access data policies to ensure maximum leverage and coverage. Efforts should also be made to provide these data to international databases, such as MOSAIC ("Modern Ocean Sediment Archive and Inventory of Carbon', http://mosaic.ethz.ch/); and

11. Consider region- or depositional setting-specific OC characteristics, in particular focussing on what factors might be driving the observed OC patterns, such as oceanography (currents, primary production, vertical fluxes), bottom dissolved oxygen concentrations and oxygen exposure times, sediment accumulation rates, sediment redox conditions, biological community structure and function, terrestrial versus marine sources, etc. Given the complex and heterogenous nature of seafloor environments in the Aotearoa NZ EEZ it is likely that the relationships used in the OC proxy development in the present paper will vary between sites due to location-specific processes affecting OC accumulation and burial.

8 Acknowledgements

We would like to thank Geoffroy Lamarche (Chief Science Advisor to the Parliamentary Commissioner for the Environment) for his encouragement and support of the present study. The comprehensive and considered reviews provided by the three external reviewers (Richard Bulmer, Craig Smeaton and Tim Eglington) helped immensely to clarify our methods and focus on the important findings of our study – thanks to them for their obvious efforts in undertaking their extensive reviews.

Grateful acknowledgement and thanks are given to the various researchers who provided data for the new sediment OC data compilation: Richard Bulmer (Tidal Research Ltd), Dana Clark (Cawthron Institute), Carolyn Lundquist, Andrew Swales, John Zeldis, Sean Handley, Alan Orpin, Katie Maier, Sarah Seabrook, Rachel Hale, James Williams and Daniel Leduc (all NIWA). Thanks also to Richard O'Driscoll (Chief Scientist – Fisheries, NIWA), Alison MacDiarmid (Senior Regional Manager, NIWA) who provided internal reviews of the report, and to and Dan MacGibbon (NIWA) who provided input during various stages of the study. The MBIE-funded Oranga Taiao Oranga Tangata (OTOT) research programme (MAUX1502) is acknowledged for the provision of data from the National Estuary Dataset and Tauranga Subtidal Ecological Survey, provided by Dana Clark (Cawthron Institute). Similarly, the provision of unpublished data from the MBIE Smart Idea Blue Carbon project, led by Richard Bulmer (Tidal Research Ltd) with many collaborators, is also gratefully acknowledged.

Thanks to MPI-Fisheries New Zealand who provided the data as presented in Figure 4-7. These data were provided on the basis of information provided to MPI-FNZ from catch returns provided by fishers. MPI-FNZ does not accept responsibility for the completeness or accuracy of the information on which the present study report is based.

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Appendix A Dataset statistics

Statistics of compilation dataset (all data types)

▪ Number of sample sites:	11,618
▪ *Maximum distance from sample (within EEZ):	320 km (SW Pacific Basin)
▪ Southern-most samples:	~57.7° S (outside EEZ)
▪ Western-most samples:	~163° E (outside EEZ)
▪ Northern-most samples:	~30.5° N
▪ Eastern-most samples:	~174.5°W
▪ # of sites with surficial (< 10 cm) samples:	5,912 sites
▪ # of sites with surficial (< 20 cm) samples:	6,001 sites
▪ # of sites with surficial (<1 m) samples:	6,035 sites
▪ Total dataset area (10 km buffer):	~1.7 million km^2
▪ Total dataset area within EEZ (10 km buffer):	~1.4 million km^2
▪ Percentage of EEZ coverage (10 km buffer):	34%

Statistics of compilation dataset (grain size – Folk Class)

▪ Number of sample sites:	6,942
▪ *Maximum distance from sample (within EEZ):	390 km (Macquarie Ridge)
▪ Southern-most samples:	~54.6° S (outside EEZ)
▪ Western-most samples:	~159° E (outside EEZ)
▪ Northern-most samples:	~21.7° S
▪ Eastern-most samples:	~165°W
▪ # of sites with surficial (< 10 cm) samples:	5,912 sites
▪ # of sites with surficial (< 20 cm) samples:	6,001 sites
▪ # of sites with surficial (<1 m) samples:	6,035 sites
▪ Total dataset area (10 km buffer):	~1.7 million km^2
▪ Total dataset area within EEZ (10 km buffer):	~1.4 million km^2
▪ Percentage of EEZ coverage (10 km buffer):	34%

Statistics of OC data

- Number of samples (measured sites): 1,063
- Number of samples (including modelled values): 2,262
- *Maximum distance from sample (within EEZ): ~810 km (Southern Campbell Plateau)
- Southern-most sample: ~50° S
- Western-most sample: ~160.3° E (outside EEZ)
- Northern-most sample: ~26.5° S
- Eastern-most samples: ~171.5°W
- Total area of dataset (10 km buffer) 159,529 km^2
- Total area of dataset within EEZ 124,384 km^2
- Percentage of EEZ covered (10 km buffer) 3%
- Deepest sample (Recorded) 10,010 m (Kermadec Trench)
- Deepest sample (NZ Bathy 250m) 10,055 m (Kermadec Trench)
- Shallowest sample (Recorded) Intertidal zone

*Distance between points derived using "Distance Accumulation" tool in ArcGIS Pro (Geodesic distance WGS84 NIWA Albers projection [EPSG 9191]), these results are also shown in Appendix Figure A-1. Note these derivations do not account for multiple points from the same location (e.g., sediment samples at varying depths at the same site with unique site identification).

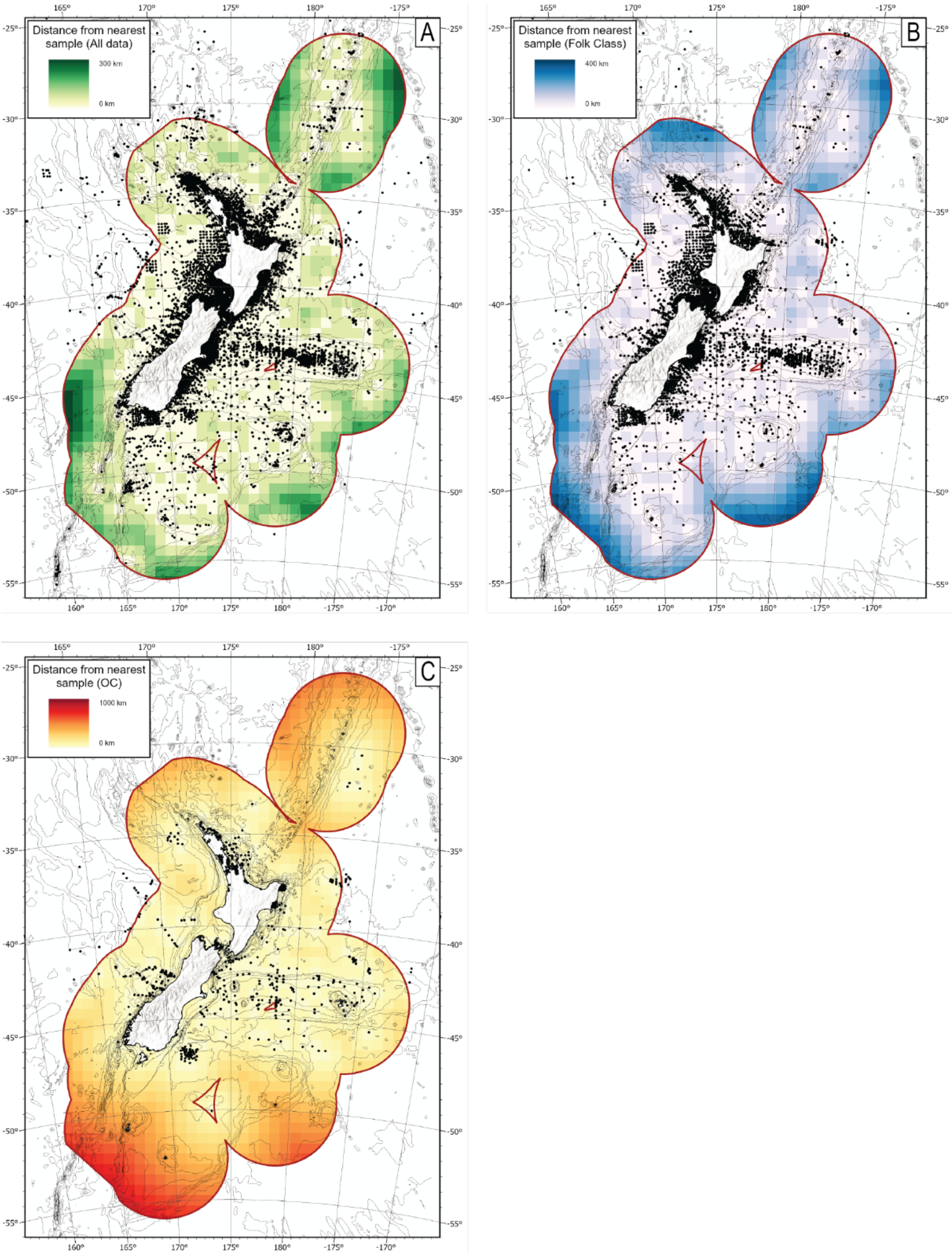

Figure A-1: Maximum distances from nearest sample sites across the New Zealand EEZ based on all available data . (A), grain size data for Folk classification (B), and organic carbon (C), respectively. Black dots in each panel show the distribution of the respective dataset.

Appendix B Organic Content Prediction Models and Exploratory Data Analysis

Data Treatments

Bivariate plots of each potential predictor variable versus dependent variable were assessed visually for linearity. Ordinary least squares regression (OLS) was also applied pairwise with each predictor variable. Residuals were visually interrogated for homoskedasticity, and Q-Q plots for normality of the data distribution.

Total Organic Carbon

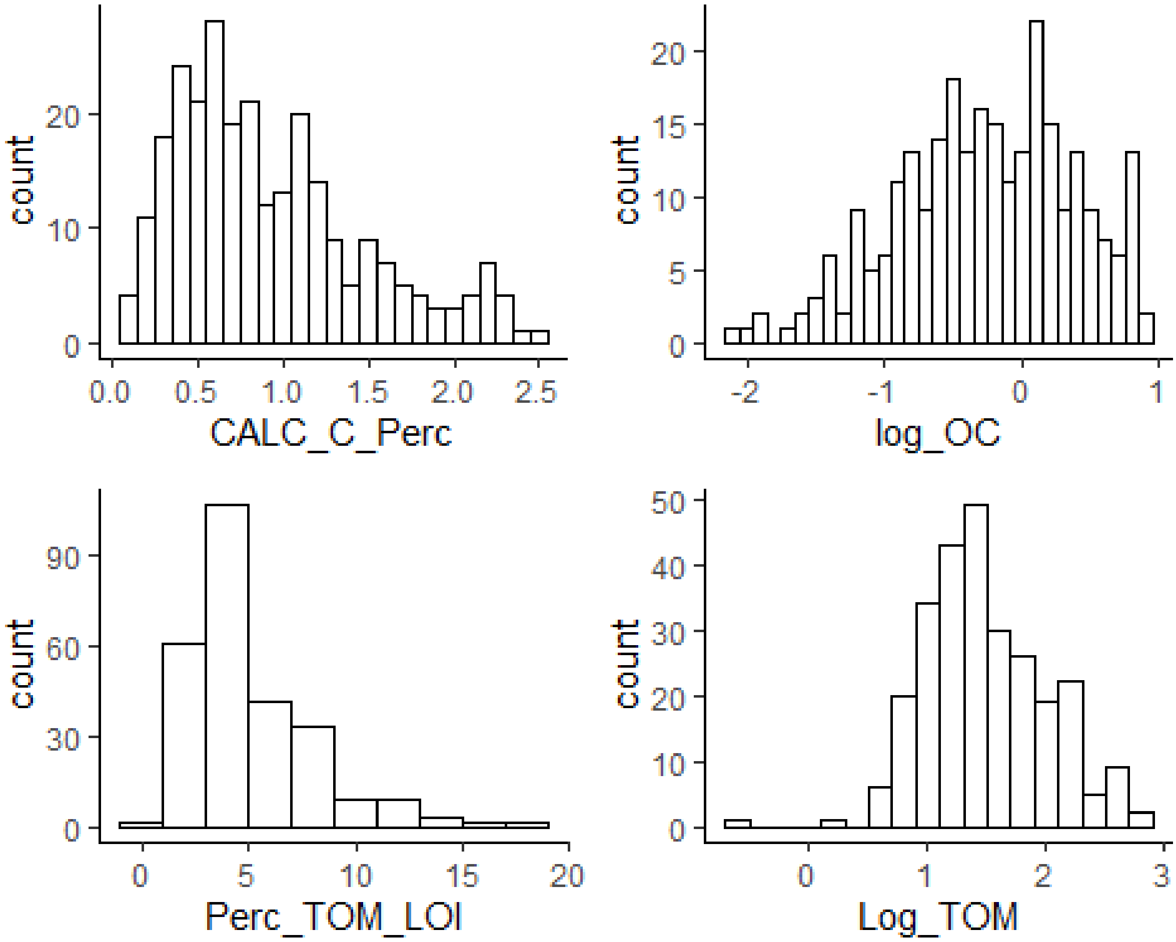

Figure B-2: Distribution of untransformed (left) and log transformed TOM% and OC% data. Note the shift from a right positive skew to more normal distribution upon transformation.

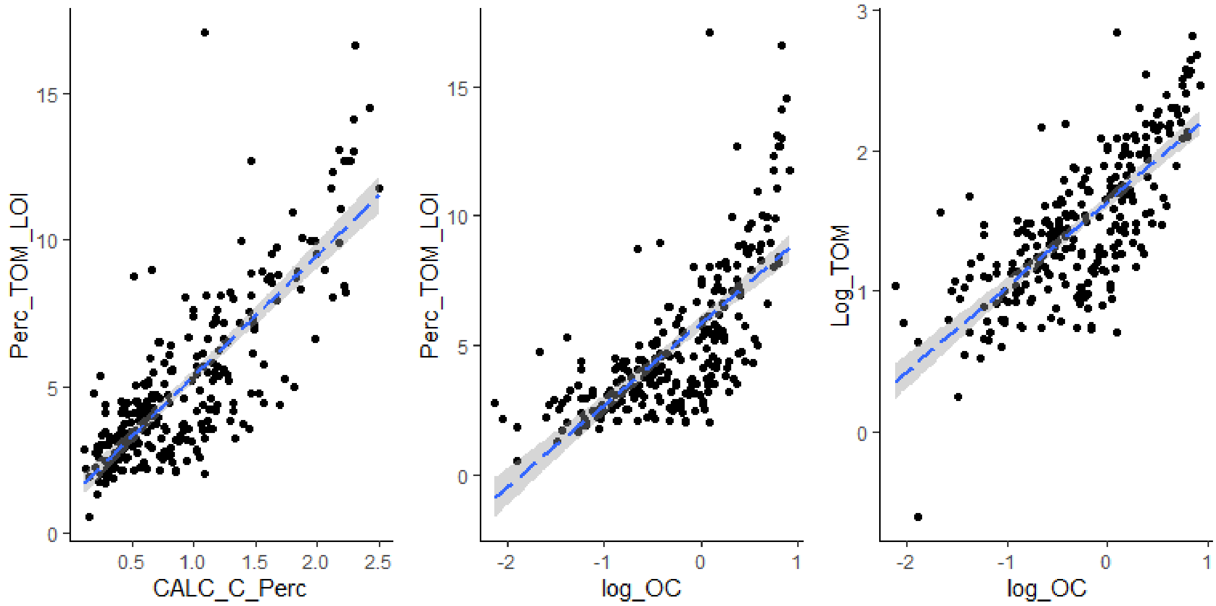

Figure B-3: Demonstration of linearity of untransformed vs. log transformed data between OC% and TOM%.

Regression output: OC vs TOM

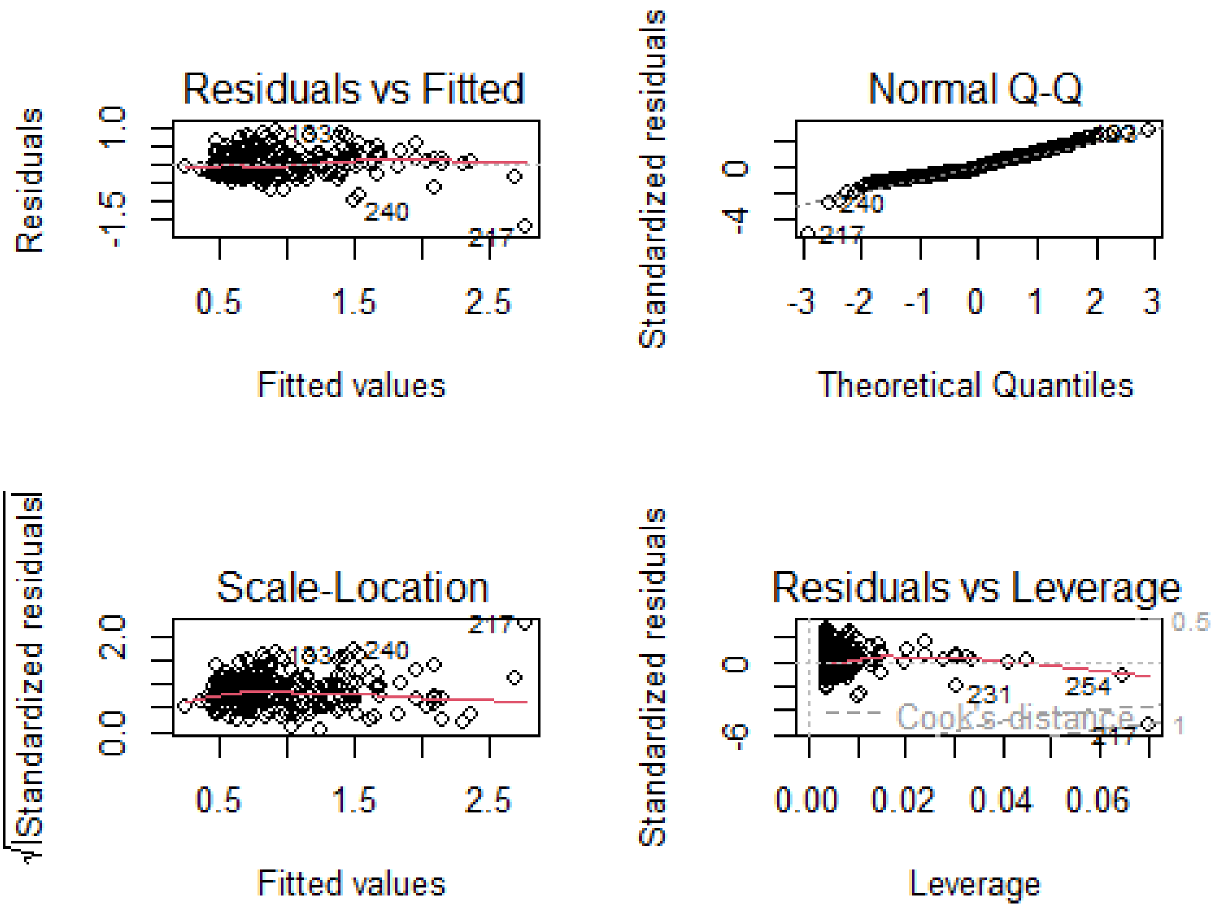

Figure B-4: Summary plots for the linear regression between OC% and TOM%.

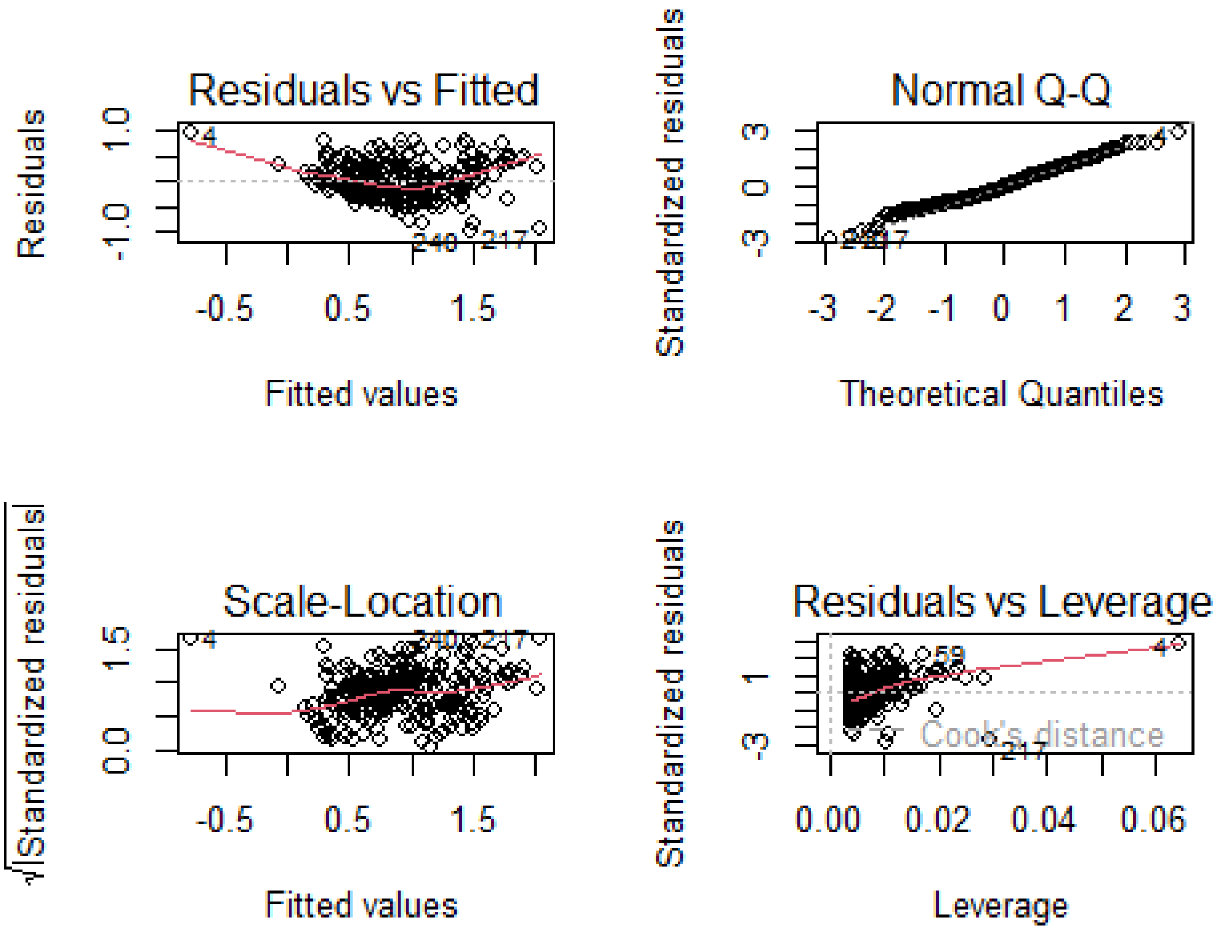

Figure B-5: Summary plots for the linear regression between log transformed OC% and log transformed TOM%.

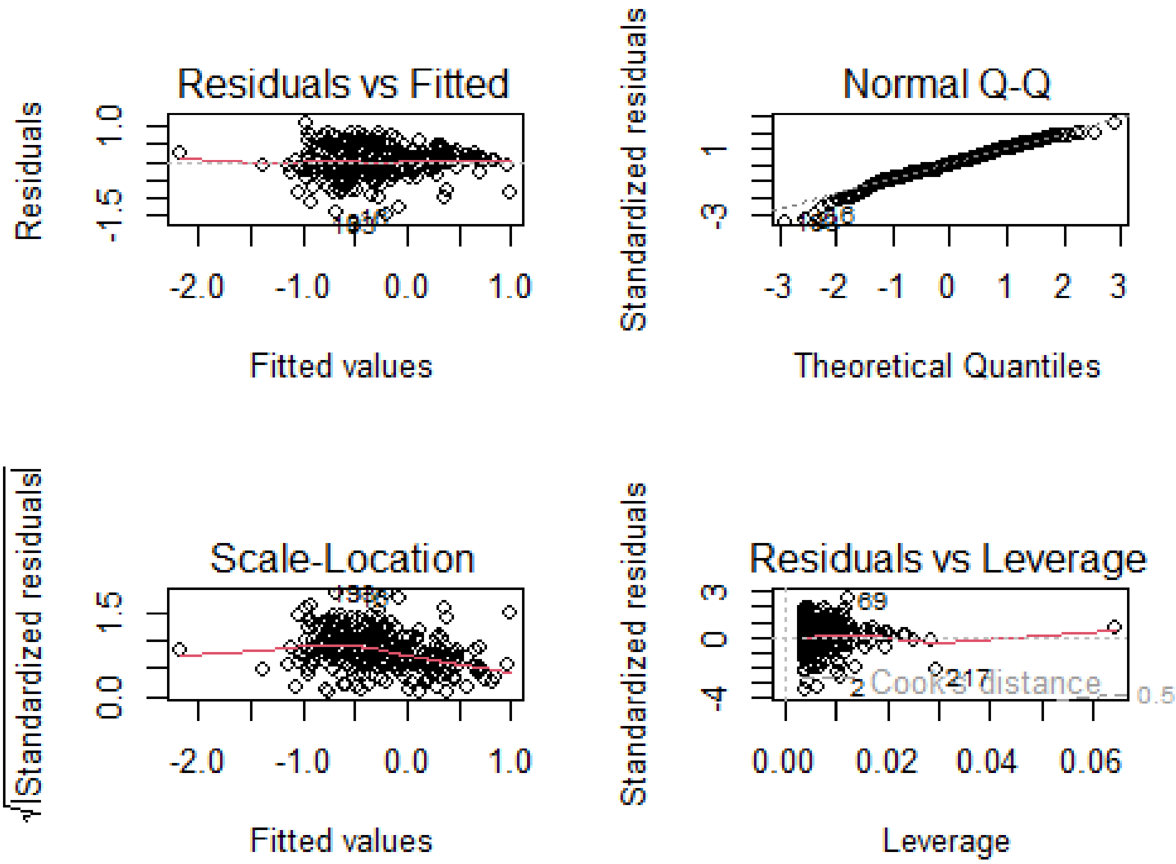

Figure B-6: Summary plots for the linear regression between OC% and log transformed TOM%.

Regression Output Summary Table

Ordinary Regression: TOM vs Organic Carbon			
	Dependent variable:		
	CALC_C_Perc		log_OC
	(1)	(2)	(3)
	OLSa	OLSa2	OLSa1
Perc_TOM_LOI	0.153***		
	(0.007)		
Log_TOM		0.824***	0.919***
		(0.041)	(0.051)
Constant	0.157***	-0.293***	-1.624***
	(0.042)	(0.065)	(0.079)
Observations	267	267	267
R^2	0.630	0.598	0.554
Adjusted R^2	0.628	0.597	0.553
Residual Std. Error (df = 265)	0.336	0.350	0.427
F Statistic (df = 1; 265)	450.564***	394.712***	329.823***
Note:	*p<0.1; **p<0.05; ***p<0.01		

Mud

The bivarate plots below demonstrate the effect of data transformation for proportional data types. The simple transformations open up the data and allow for improved linear model fitting across the entire dataset.

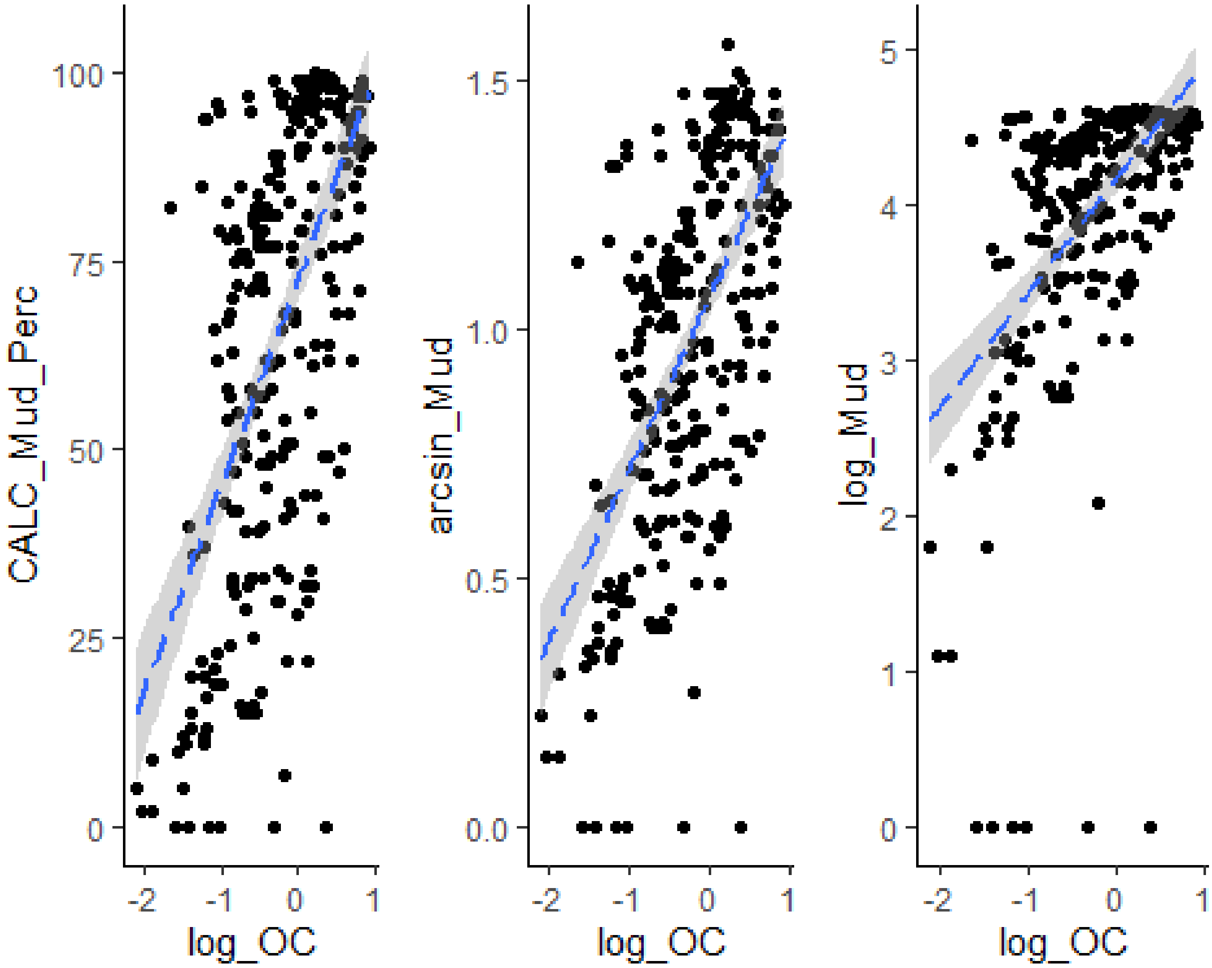

Figure B-7: Demonstration of linearity of untransformed vs. log and arcsin transformed data between OC% and Mud%.

Regression Output: OC vs Mud

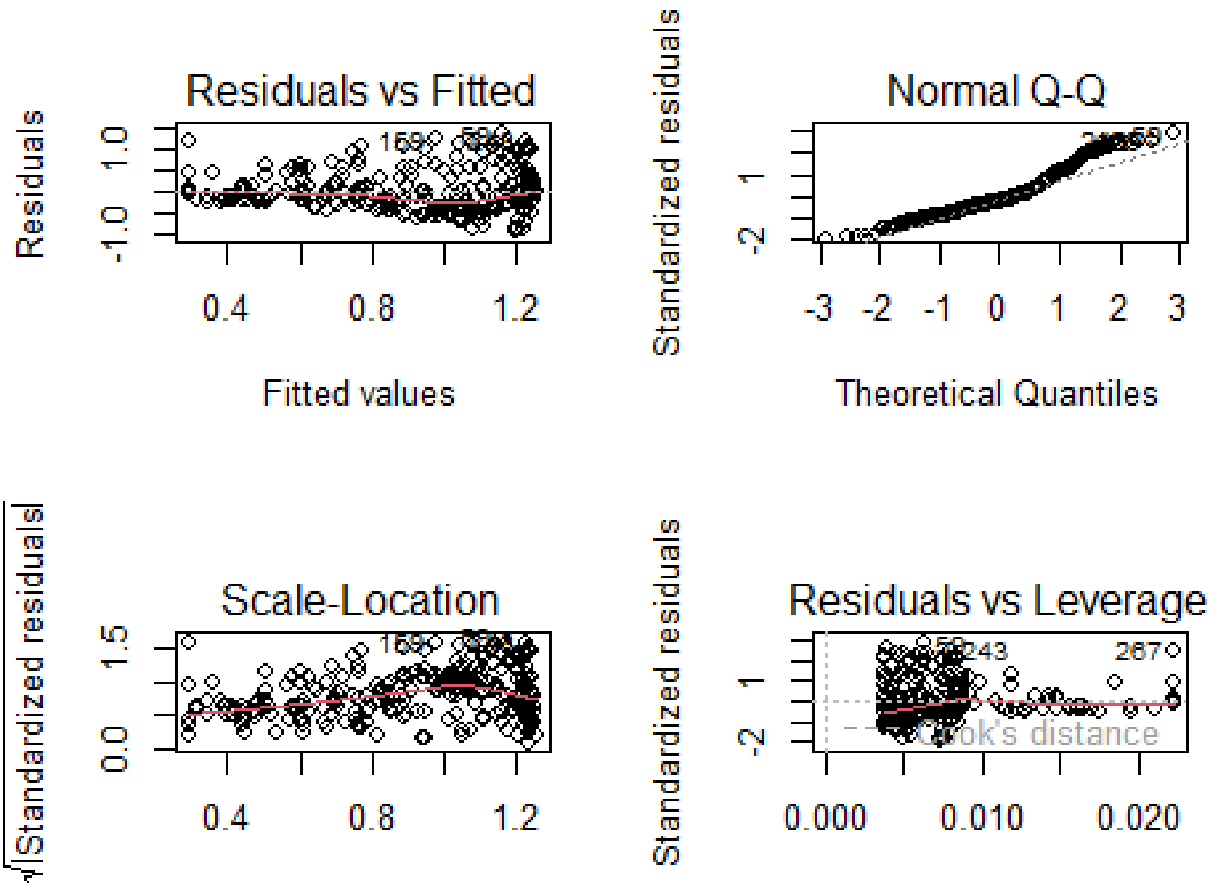

Figure B-8: Summary plots for the linear regression between OC% and mud%. Note the "trumpet" shaped residuals indicating homoscedasticity (non-equal variances).

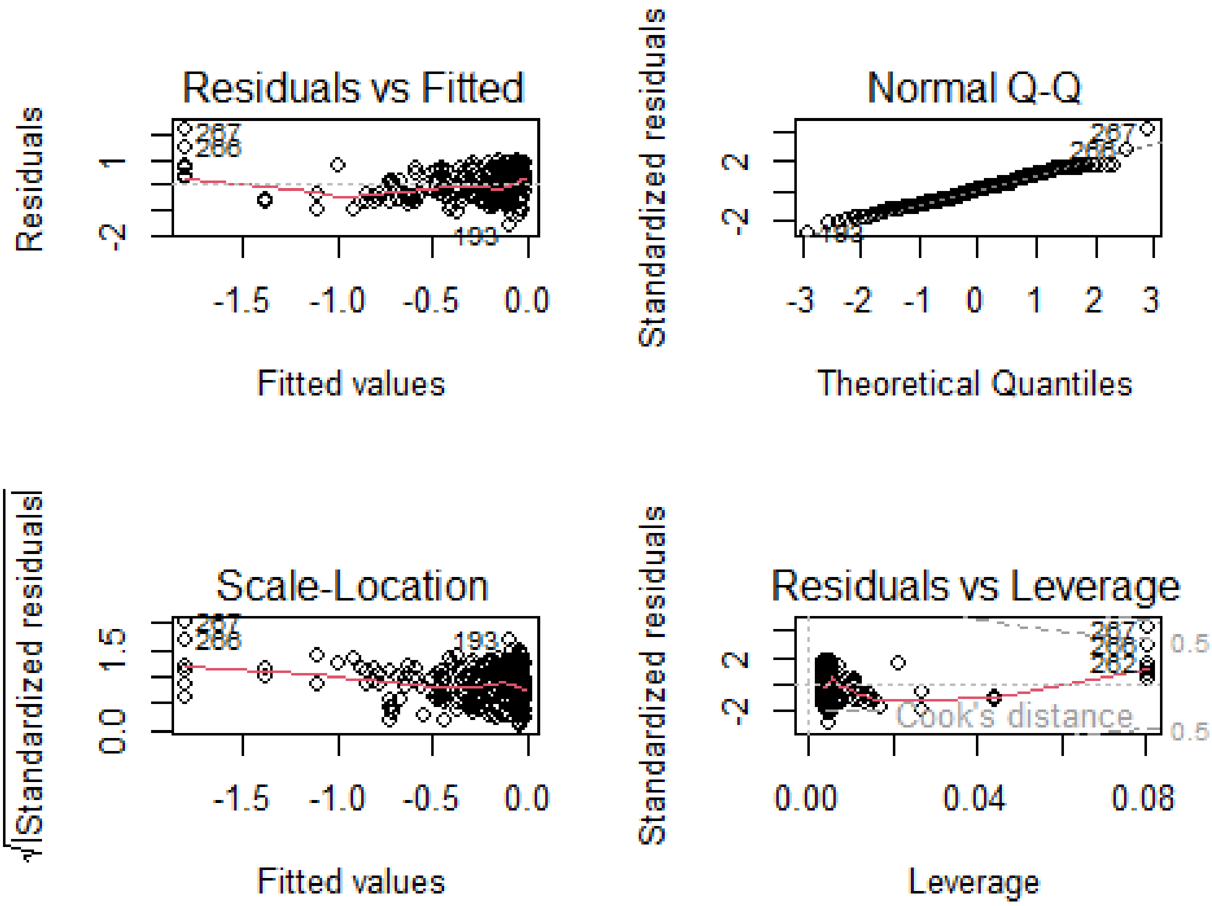

Figure B-9: Summary plots for the linear regression between log OC% and log mud%.

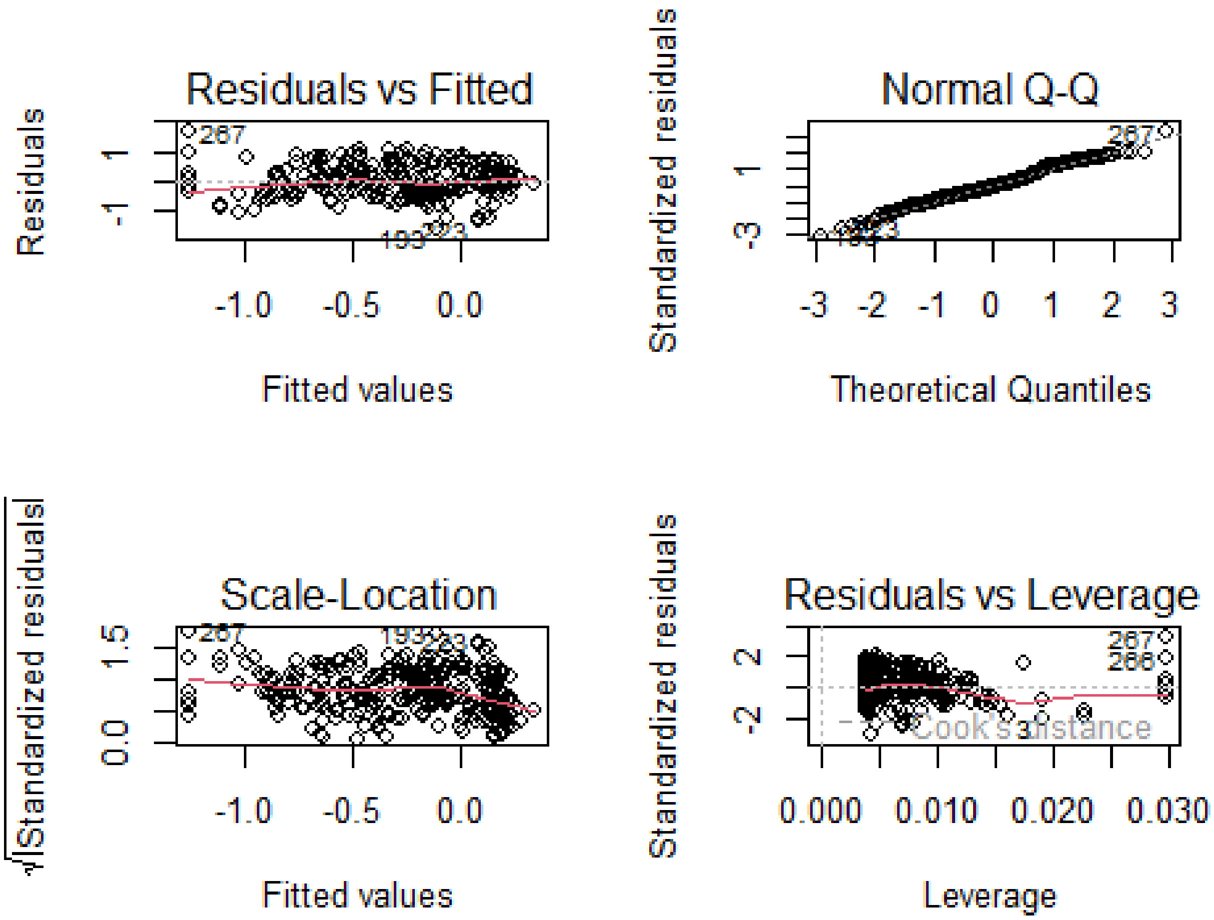

Figure B-10: Summary plots for the linear regression between log OC% and arcsin mud%. Note improvement on more equal distribution of the residuals and improvement on normal distribution of the residuals in the Q-Q plot.

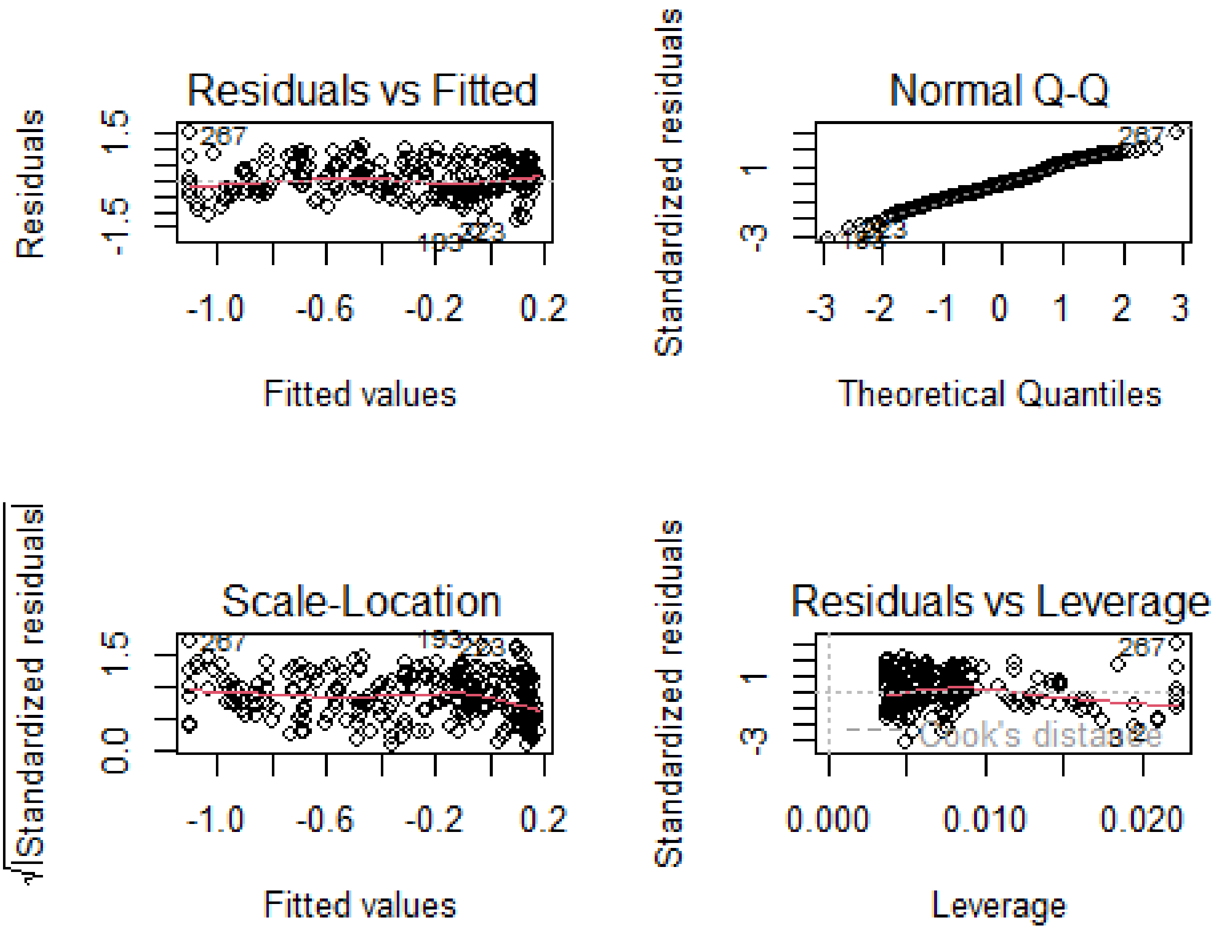

Figure B-11: Summary plots for the linear regression between log OC% and mud%. Note the log transformation of OC% improves most models.

Regression Output Summary Table

Regression between transformed data slightly improves the linear model, but also improves normal distribution and heteroskedasticity of the residuals. The best performing model is log OC% vs. arcsine mud%.

Ordinary Regression: Mud v.s. Organic Carbon				
	Dependent variable:			
	CALC_C_Perc		log_OC	
	(1)	(2)	(3)	(4)
	OLSc	OLSc1	OLSc2	OLSc3
CALC_Mud_Perc	0.010***			0.013***
	(0.001)			(0.001)
log_Mud		0.385***		
		(0.038)		
arcsin_Mud			1.025***	
			(0.085)	
Constant	0.295***	-1.795***	-1.263***	-1.098***
	(0.071)	(0.154)	(0.089)	(0.077)
Observations	267	267	267	267
R^2	0.266	0.282	0.353	0.347
Adjusted R^2	0.264	0.280	0.351	0.345
Residual Std. Error (df = 265)	0.473	0.542	0.515	0.517
F Statistic (df = 1; 265)	96.200***	104.281***	144.826***	140.948***
Note:				*p<0.1; **p<0.05; ***p<0.01

Sand

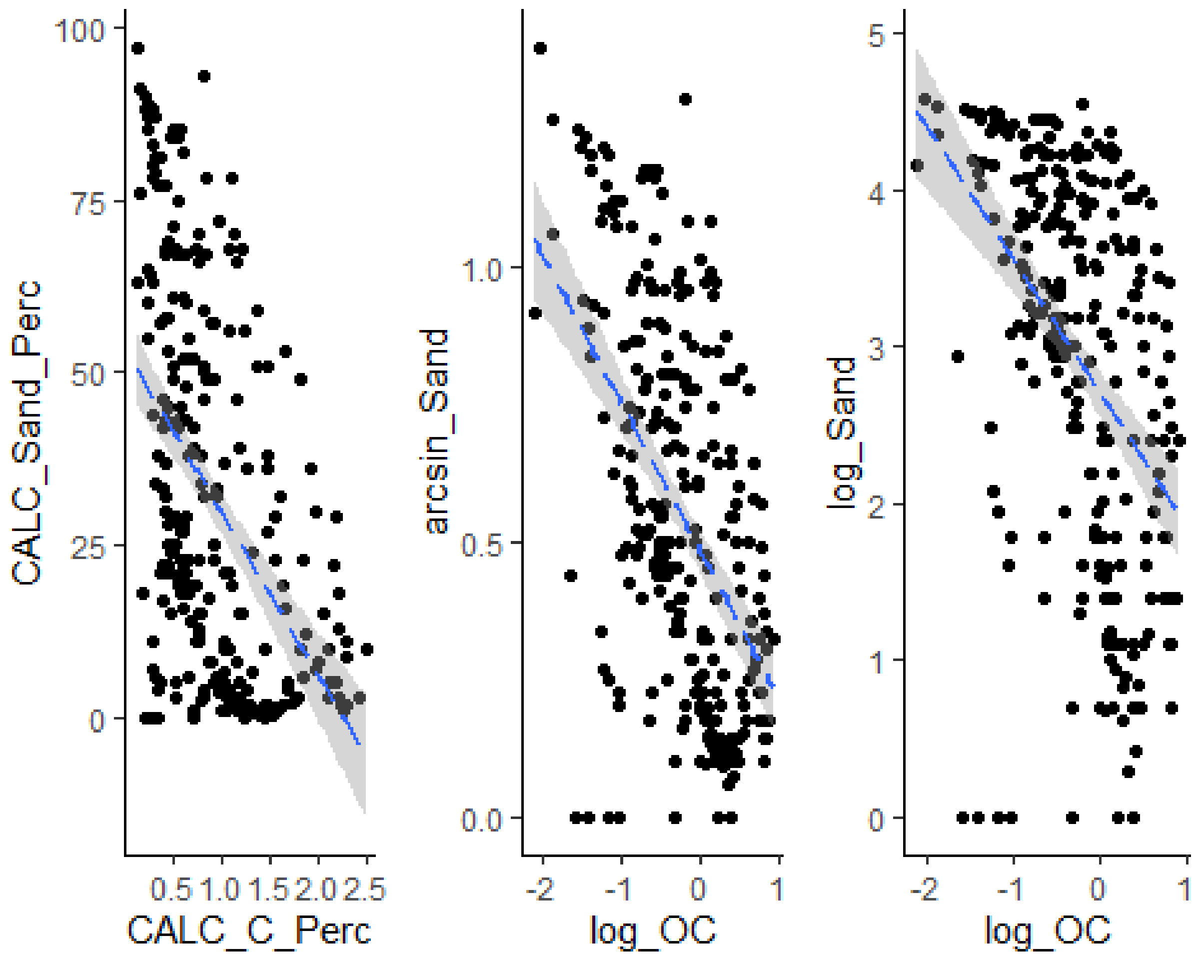

Figure B-12: Demonstration of linearity of untransformed vs. log and arcsine transformed data between OC% and Sand%.

Regression Output: OC vs Sand

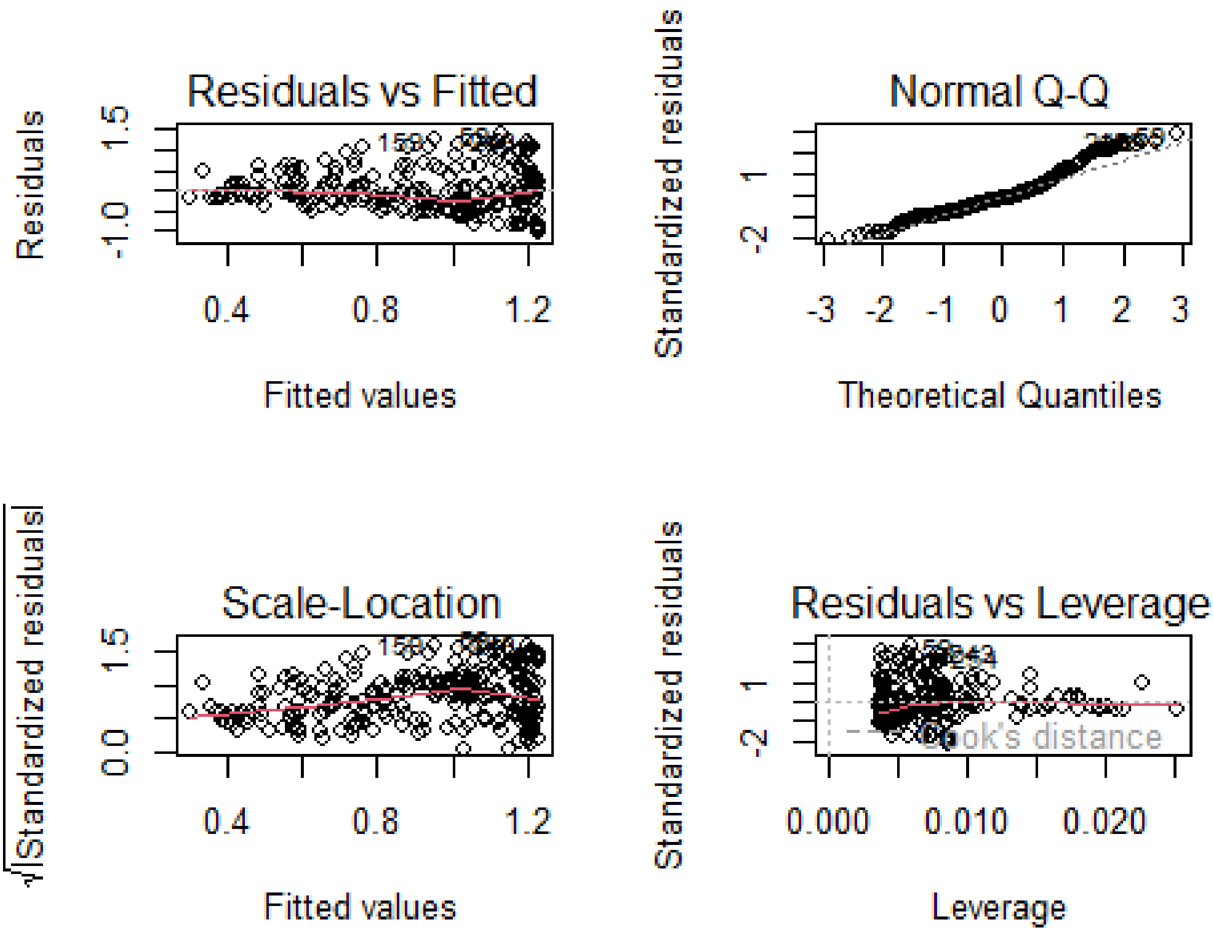

Figure B-13: Summary plots for the linear regression between OC% and sand%. Note the "trumpet" shape of the residuals indicating heteroskedasticity or unequal variance.

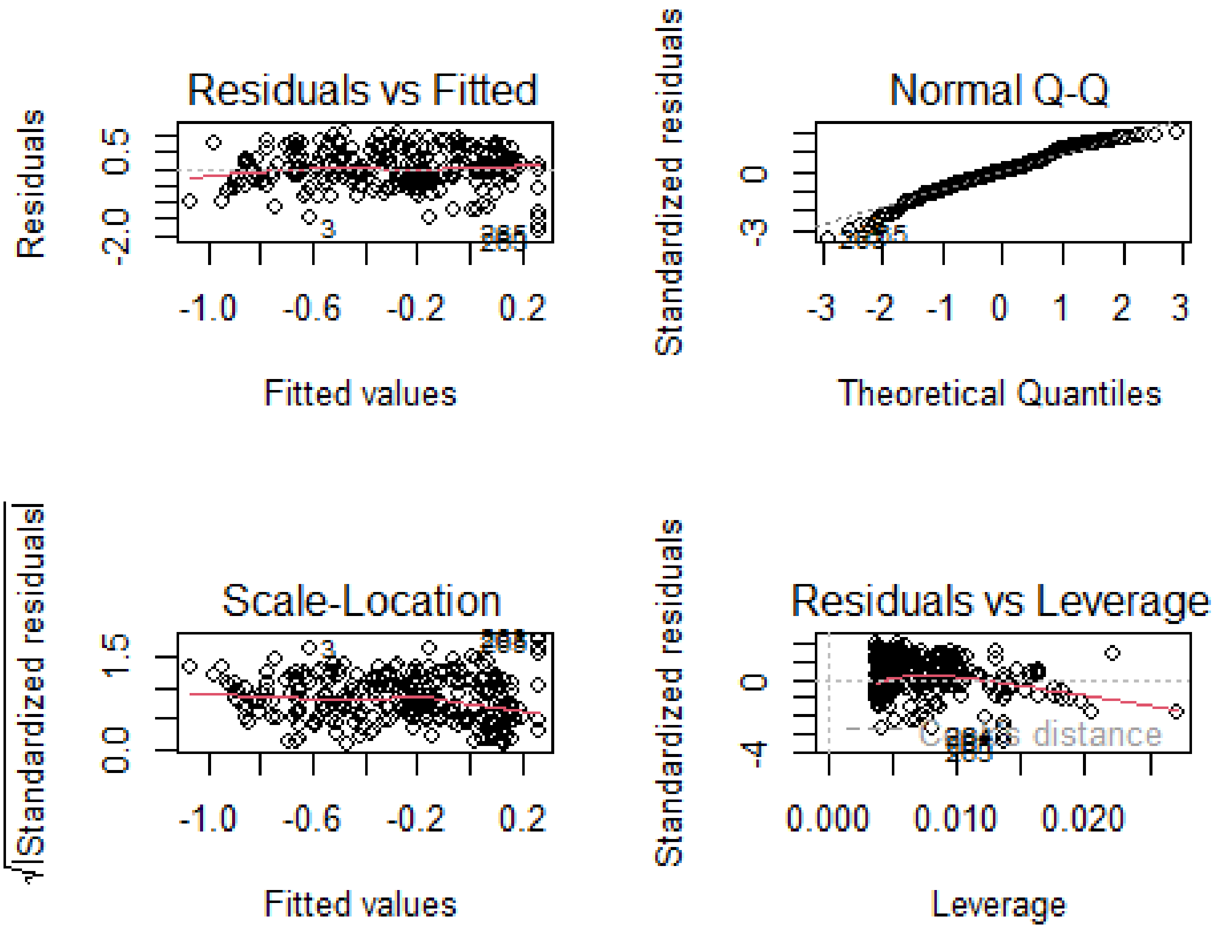

Figure B-14: Summary plots for the linear regression between log OC% and arcsine sand%. Note vast improvement in the residuals distribution as a result of the data tranaformation.

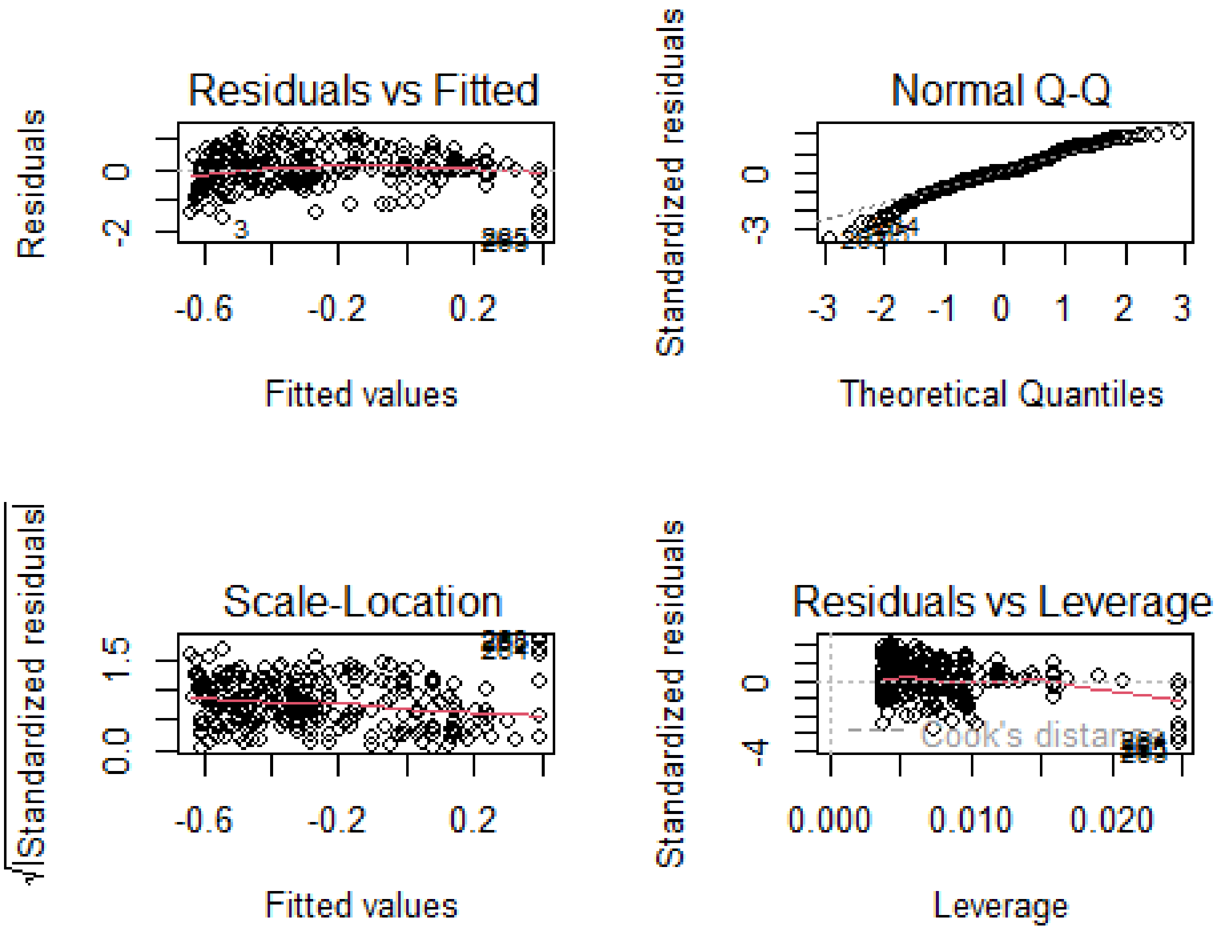

Figure B-15: Summary plots for the linear regression between log OC% and log sand%.

Regression Output Summary Table

Ordinary Regression: Sand v.s. Organic Carbon			
	Dependent variable:		
	CALC_C_Perc	log_OC	
	(1)	(2)	(3)
	OLSd	OLSd1	OLSd2
CALC_Sand_Perc	-0.010^{***}		
	(0.001)		
arcsin_Sand		-0.951^{***}	
		(0.100)	
log_Sand			-0.224^{***}
			(0.029)
Constant	1.226^{***}	0.261^{***}	0.393^{***}
	(0.045)	(0.065)	(0.091)
Observations	267	267	267
R^2	0.224	0.255	0.189
Adjusted R^2	0.221	0.252	0.186
Residual Std. Error (df = 265)	0.487	0.553	0.576
F Statistic (df = 1; 265)	76.445^{***}	90.501^{***}	61.650^{***}
Note:	*p<0.1; **p<0.05; ***p<0.01		

Gravel

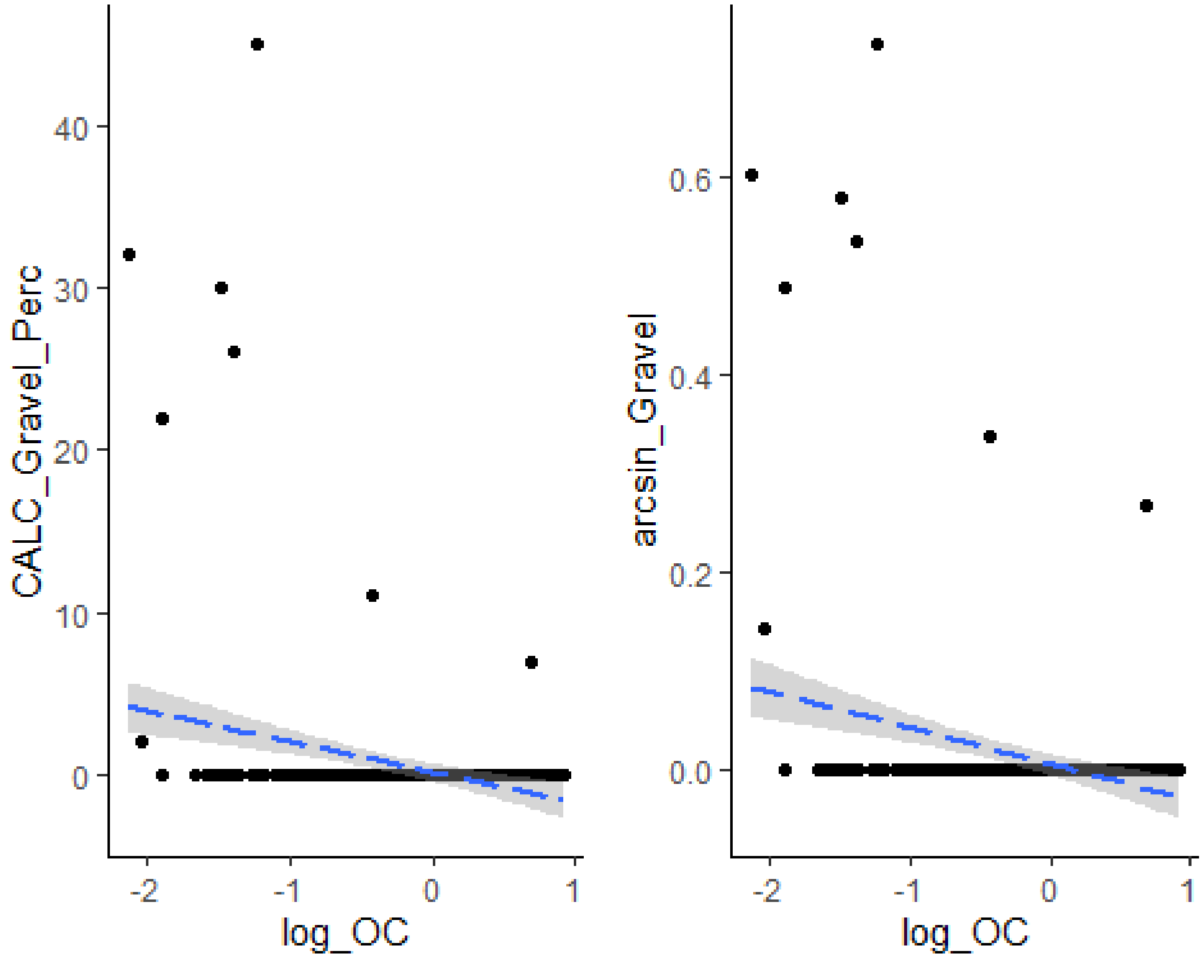

Figure B-16: Demonstration of linearity between log OC% and untransformed vs. transformed gravel%. vNote the high content of true zeroes in this variable.

Regression Output: OC v.s. Sand

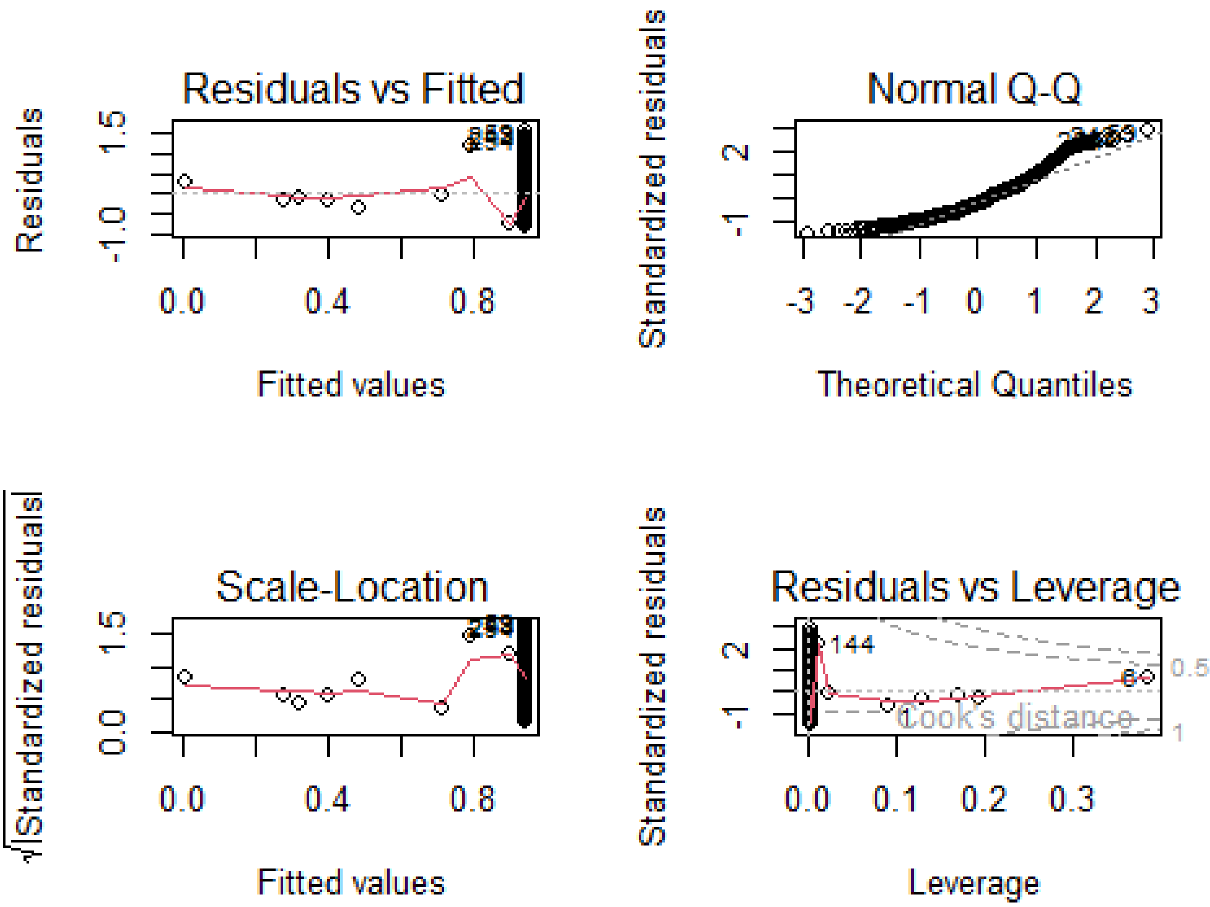

Figure B-17: Summary plots for the linear regression between OC% and Gravel%.

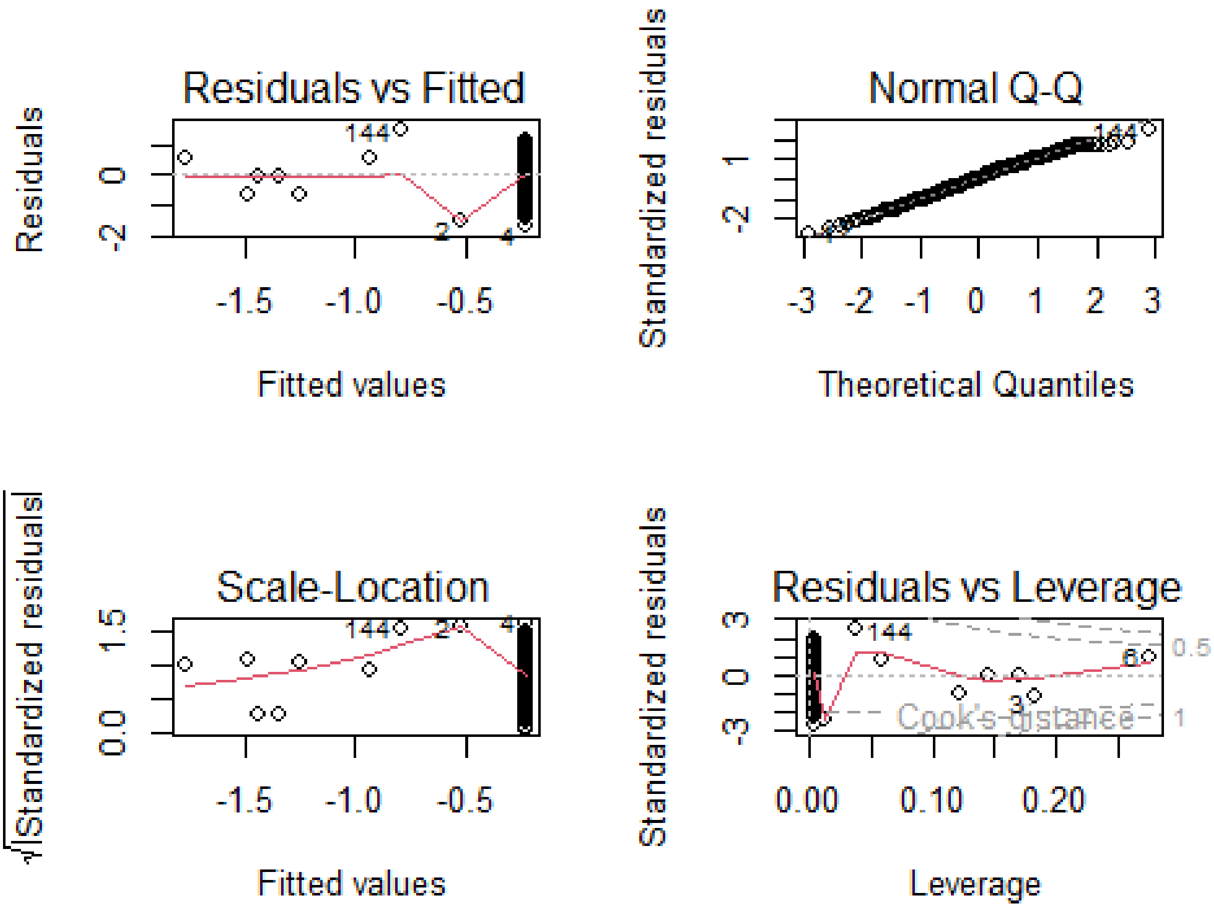

Figure B-18: Summary plots for the linear regression between log OC% and arcsine Gravel%.

Regression Output Summary Table

Ordinary Regression: Gravel v.s. Organic Carbon		
	Dependent variable:	
	OC Percentage	log_OC
	(1)	(2)
	OLSe	OLSe1
CALC_Gravel_Perc	-0.021***	
	(0.008)	
arcsin_Gravel		-2.108***
		(0.437)
Constant	0.949***	-0.220***
	(0.034)	(0.038)
Observations	261	261
R^2	0.029	0.082
Adjusted R^2	0.025	0.079
Residual Std. Error (df = 259)	0.544	0.606
F Statistic (df = 1; 259)	7.754***	23.226***
Note:	*p<0.1; **p<0.05; ***p<0.01	

Carbonate

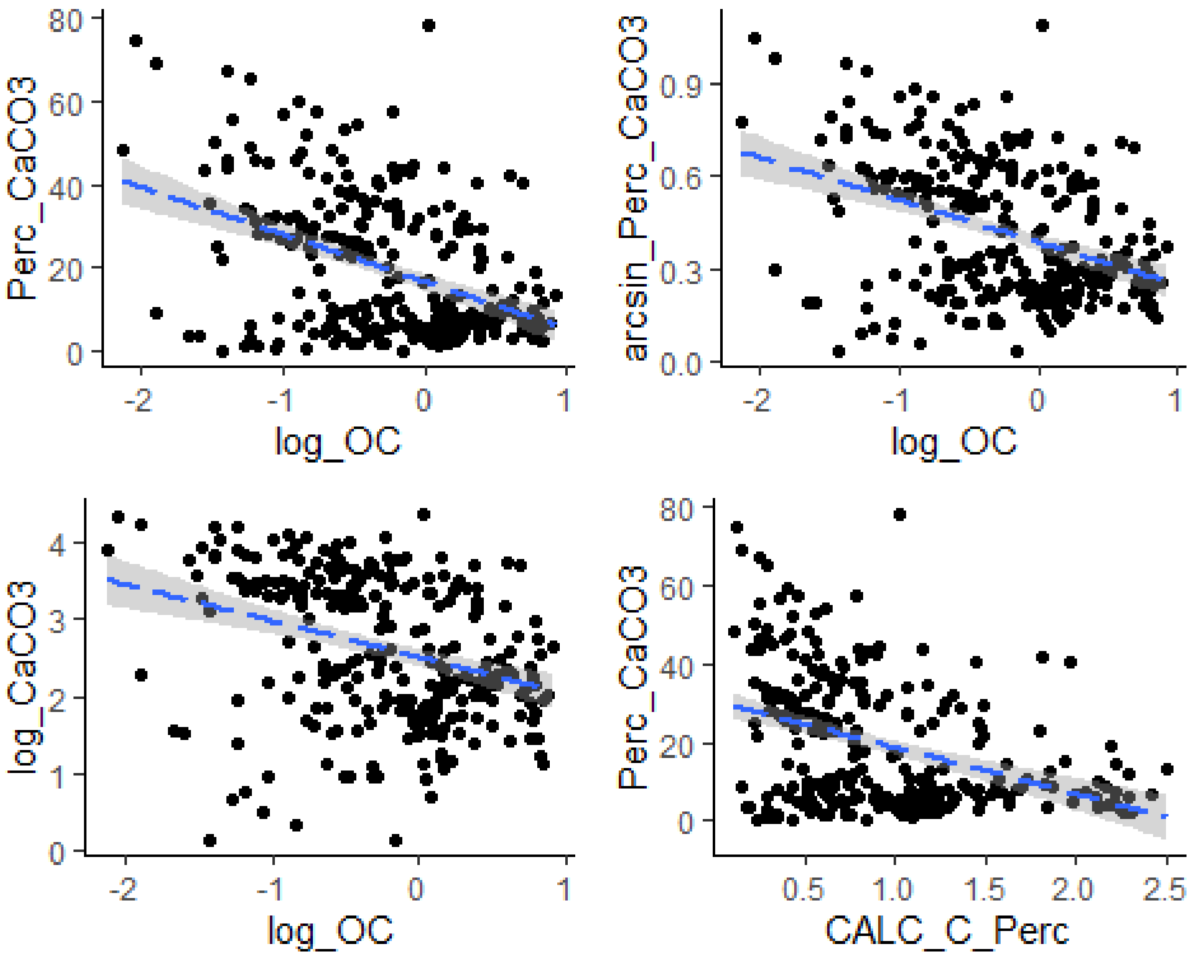

Figure B-19: Demonstration of linearity of untransformed vs. transformed data between OC% and CaCO3%.

Regression Output: OC vs Carbonate

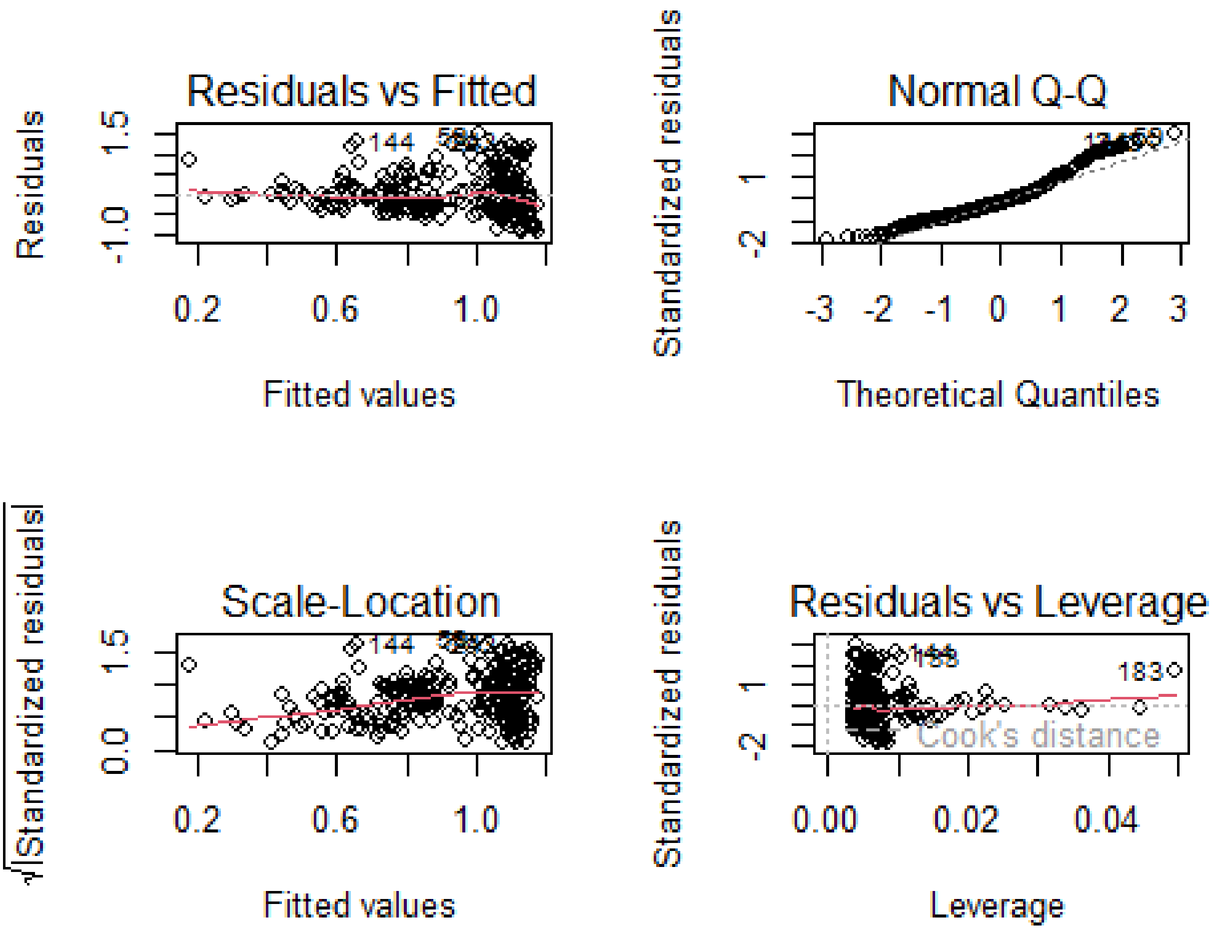

Figure B-20: Summary plots for the linear regression between OC% and Carbonate%.

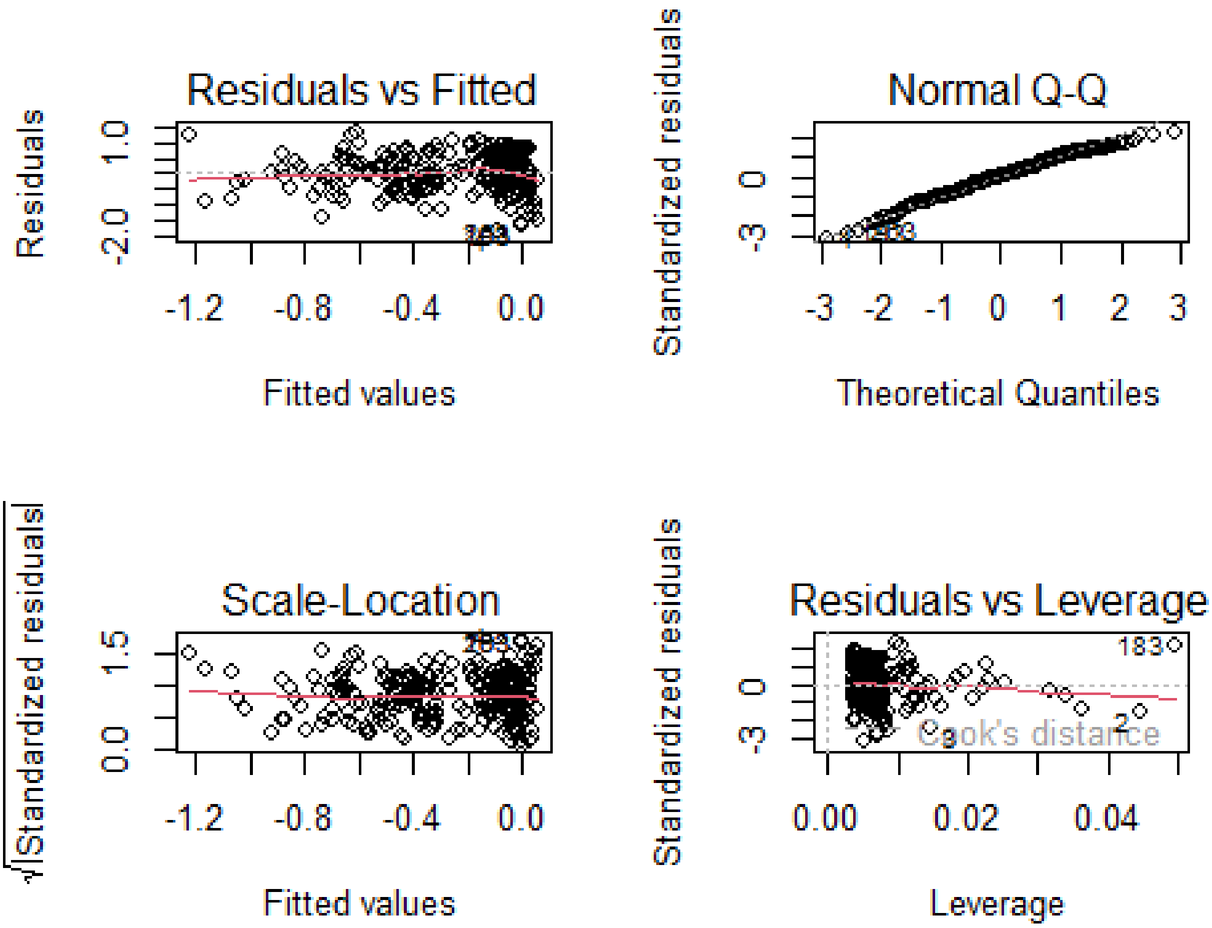

Figure B-21: Summary plots for the linear regression between log OC% and Carbonate%.

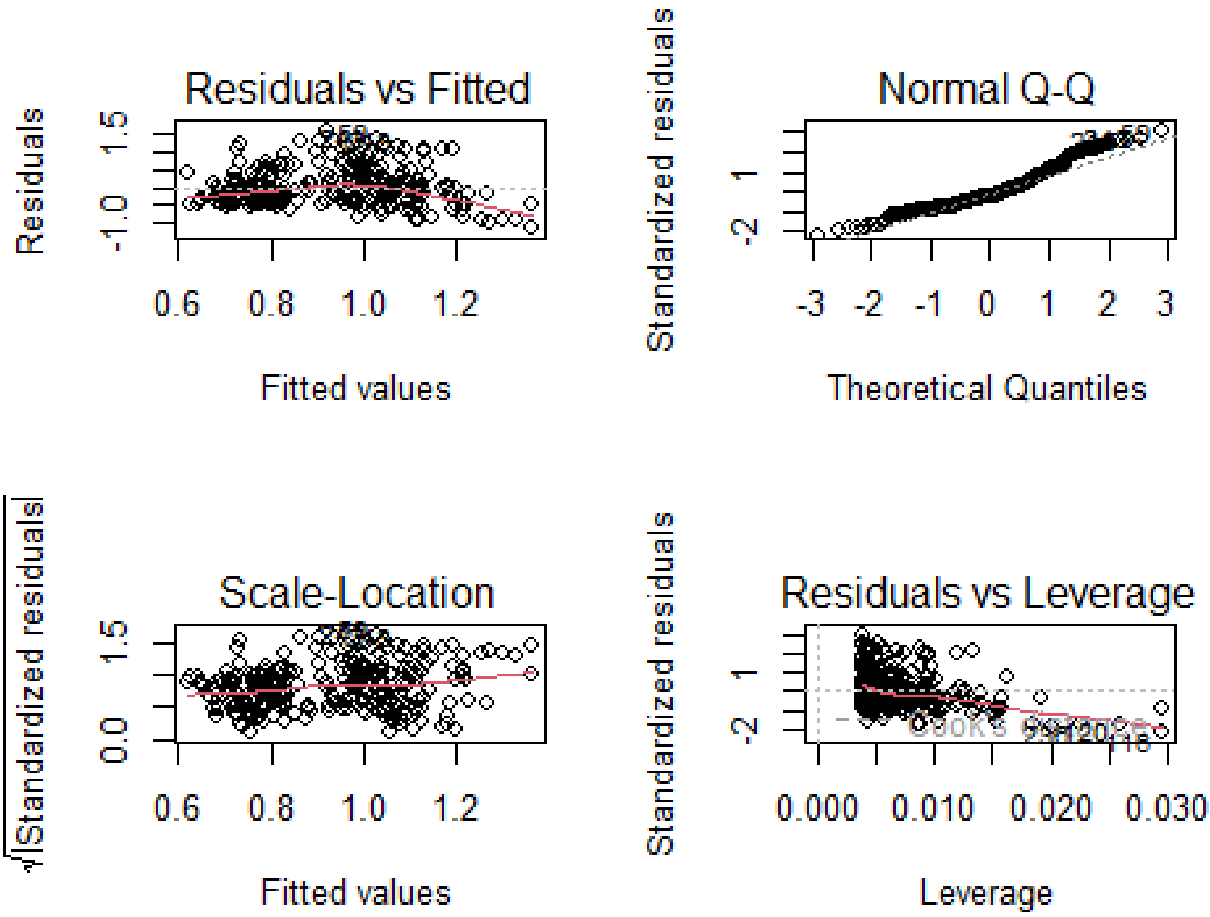

Figure B-22: Summary plots for the linear regression between log OC% and log Carbonate%.

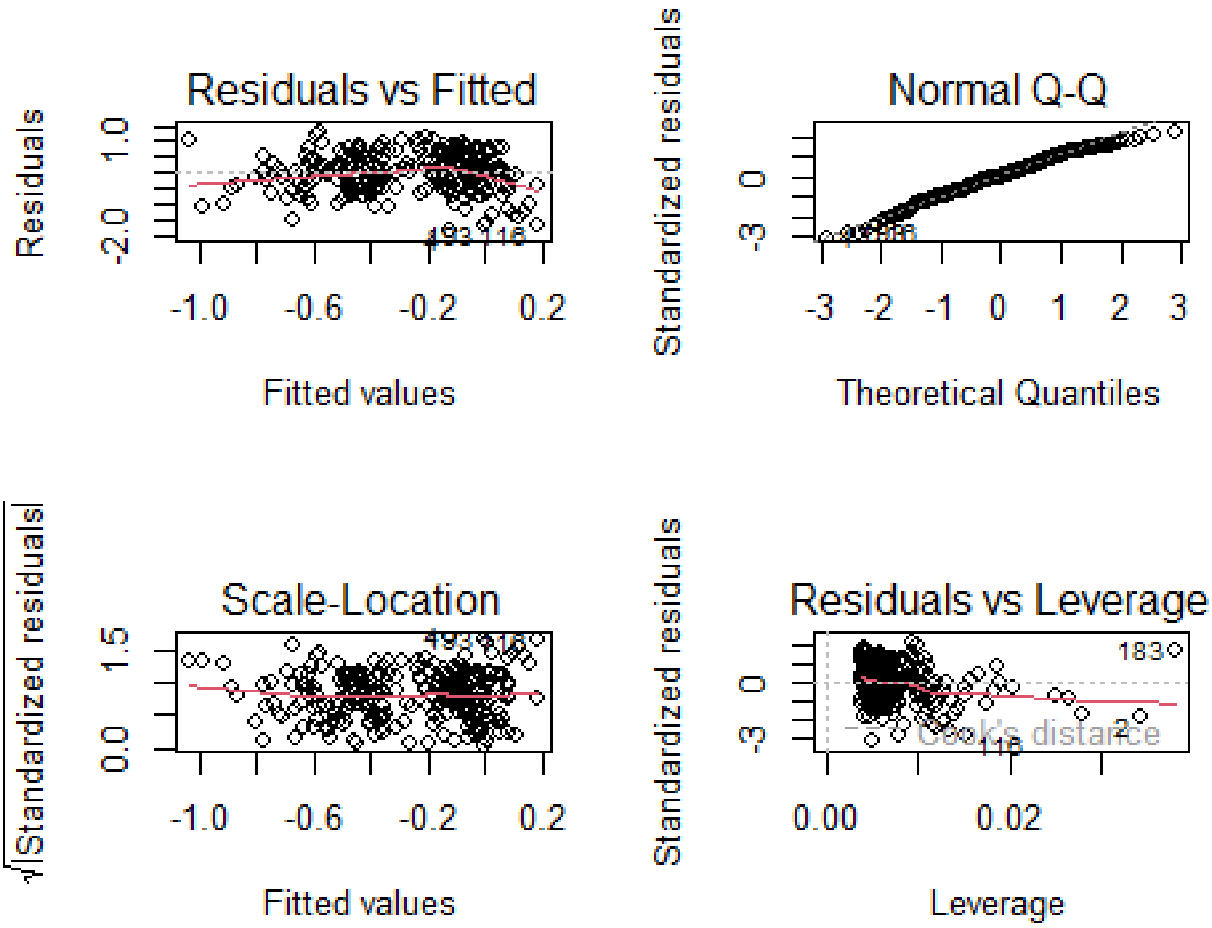

Figure B-23: Summary plots for the linear regression between log OC% and arcsine Carbonate %.

Regression Output Summary Table

Ordinary Regression: CaCO3 v.s. Organic Carbon				
	Dependent variable:			
	CALC_C_Perc	log_OC	CALC_C_Perc	log_OC
	(1)	(2)	(3)	(4)
	OLSg	OLSg1	OLSg2	OLSg3
Perc_CaCO3	-0.013***	-0.017***		
	(0.002)	(0.002)		
log_CaCO3			-0.181***	
			(0.034)	
arcsin_Perc_CaCO3				-1.209***
				(0.162)
Constant	1.191***	0.082	1.409***	0.257***
	(0.048)	(0.053)	(0.095)	(0.077)
Observations	261	261	261	261
R^2	0.163	0.208	0.098	0.177
Adjusted R^2	0.160	0.205	0.094	0.174
Residual Std. Error (df = 259)	0.505	0.563	0.524	0.574
F Statistic (df = 1; 259)	50.342***	68.187***	28.048***	55.731***
Note:				*p<0.1; **p<0.05; ***p<0.01

Appendix B references

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