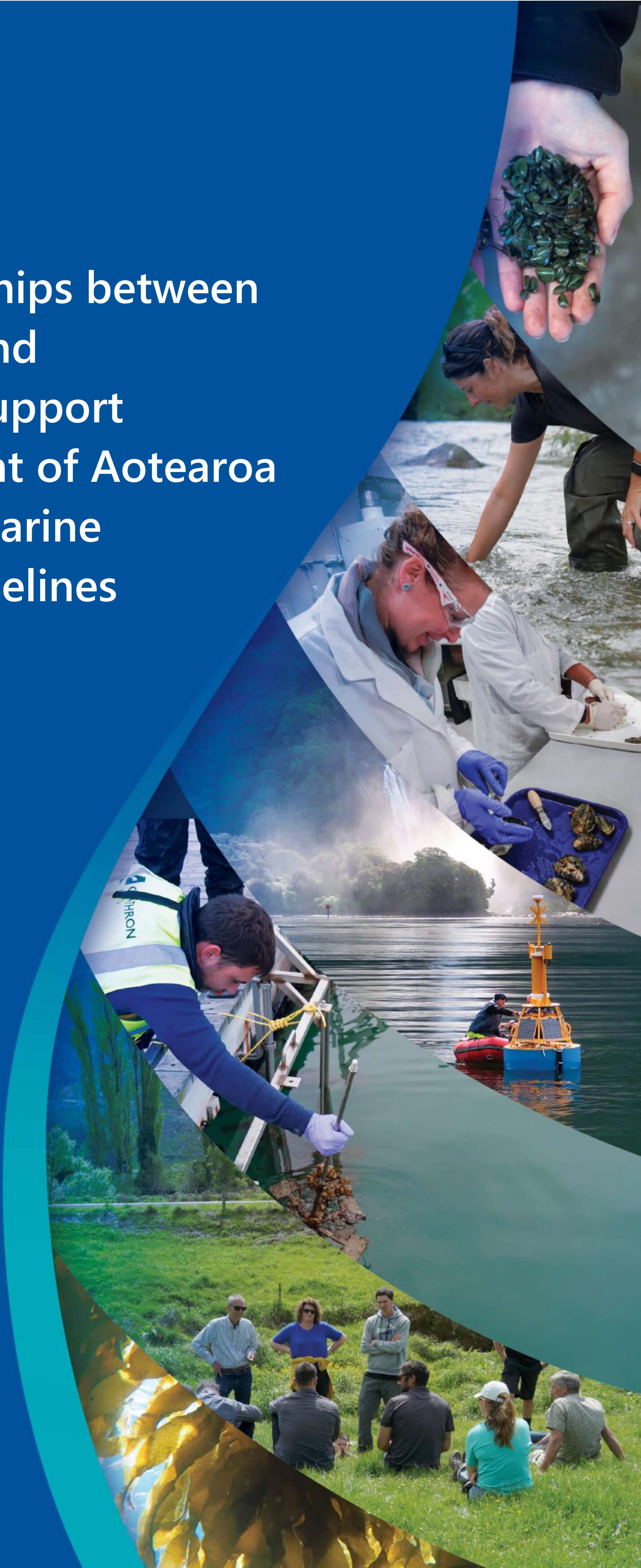
Assessing relationships between ecological health and sedimentation to support potential refinement of Aotearoa New Zealand's estuarine sedimentation guidelines

Cawthron Report 4150



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REVIEWED AND APPROVED FOR RELEASE BY: Grant Hopkins

PROJECT NUMBER: 19046

ISSUE DATE: 27 June 2025

RECOMMENDED CITATION: Clark D, Ho M, Atalah J, Hewitt J, Ellis J. 2025. Assessing relationships between ecological health and sedimentation to support potential refinement of Aotearoa New Zealand's estuarine sedimentation guidelines. Nelson: Cawthron Institute. Cawthron Report 4150. Prepared for Ministry for the Environment.

Assessing relationships between ecological health and sedimentation to support potential refinement of Aotearoa New Zealand's estuarine sedimentation guidelines

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Prepared for Ministry for the Environment

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Executive summary

In 2015, the Ministry for the Environment (MfE) commissioned the development of estuarine sedimentation guidelines, leading to the inclusion of a default guideline value (DGV) for estuarine sediment accretion rate (SAR) in the 2018 revision of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZWQ Guidelines). The SAR DGV was based on experimental data from short-term sediment deposition events, due to a lack of long-term, spatially extensive datasets linking annual SAR to ecological health. In response to the growing body of data collected since then, MfE commissioned Cawthron Institute to collate and analyse these data to evaluate whether SAR and sediment mud content can be reliably linked to estuarine ecological condition and whether the existing DGV for SAR should be refined.

The resulting national dataset combined SAR and mud content data with macrofaunal community information, yielding 710 unique observations from 79 intertidal sites across 32 estuaries in Aotearoa New Zealand. These sites spanned a broad geographic range and a diversity of estuary types, within-estuary locations and tidal elevations.

We first examined the spatial and temporal variation in sediment accretion data. Next, we assessed whether different methods of calculating SAR influenced our SAR estimates. Finally, we applied a weight-of-evidence approach to investigate the relationship between SAR and ecological health. This included modelling changes in macrofaunal communities, ecological indicators and key estuarine taxa along gradients of SAR, calculated over short (1–2-month), medium (1-year) and long (5-year and 10-year) time frames.

Despite the breadth of the dataset, our analyses found no strong or consistent relationships between SAR and macrofaunal community structure, ecological health indicators or the abundance of key species. In contrast, sediment mud content showed much clearer and more consistent relationships with ecological condition. This aligns with previous research and reinforces the use of mud content as a more reliable and relatively easily measured proxy for sediment-related ecological stress.

The lack of relationship is likely due to the high spatial and temporal variability of SAR, measurement limitations and the complex nature of estuarine ecosystems, where multiple interacting stressors influence ecological communities. While SAR can still offer insight into sediment dynamics – particularly when collected and interpreted in a standardised and site-specific manner – it is not suitable as standalone indicator of ecological condition.

Consequently, we recommend the continued use of the current sedimentation DGV as a contextual reference rather than a strict threshold, and urge caution in interpreting SAR-based thresholds without considering local site conditions and other measures of sedimentation stress. Further work could be done to try to tease apart the relationship between SAR and ecological health, and recommendations are provided in this report.

This study underscores the need for targeted, long-term datasets and more integrated approaches that combine physical and biological indicators to better understand and manage sediment-related impacts in estuarine environments.

1. Introduction

In 2015, the Ministry for the Environment (MfE) commissioned the development of estuarine sedimentation guidelines, which were later incorporated into the 2018 revision of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZWQ Guidelines; formerly ANZECC).[1] This work led to the development of a default guideline value (DGV) for estuarine sediment accretion rates (SAR) specific to Aotearoa New Zealand (Townsend and Lohrer 2015). At the time, insufficient data were available to properly examine the relationships between annual SAR and local biological effects. Consequently, the DGV was derived from experimental data on event-scale sediment deposition.

Since the 2015 report, SAR data have been collected from estuaries across Aotearoa New Zealand. MfE has now engaged Cawthron Institute (Cawthron) to compile a subset of these data and investigate relationships between SAR, sediment mud content and ecological health. Given that the objective of this work is to produce recommendations to refine the current DGV for estuarine sedimentation rates, the analysis and discussion focuses primarily on SAR rather than mud content. In this report, we use sediment macrofaunal communities as our measure of ecological health as they are particularly vulnerable to sedimentation and integrate the effects of stressors over time.

1.1 Sedimentation

Coastal sedimentation is the process by which sediments – such as boulders, cobble, gravel, sand, silt, clay and organic material – are transported and deposited by water, wind or ice in coastal environments. This process is fundamental to shaping coastal landscapes, contributing to the formation of features such as beaches, sandbars, deltas, tidal flats and estuaries. Fine, unconsolidated sediments are naturally occurring particles less than 2 mm in diameter and are commonly classified by size: sand (0.0625–2 mm), silt (0.0039–0.0625 mm) and clay (< 0.0039 mm). Fine-grained sediments comprising silt and clay are generally referred to as mud.

Sediments enter estuaries via multiple pathways, including land-based inputs delivered by rivers and ocean sources transported by waves and tidal currents. Once within the estuary, sediments may settle out of the water column, move along the seafloor as bedload or remain in suspension. The fate of these sediments is governed by complex interactions between freshwater inflows (e.g. McKergow et al. 2010) and a range of oceanographic processes, such as tidal currents (e.g. Brown and Davies 2010), wave action (e.g. Green et al. 1997), residual circulation (e.g. Bolle et al. 2010) and intertidal drainage (e.g. Fagherazzi et al. 2008). Estuaries are commonly classified into different types based partly on these hydrodynamic characteristics (e.g. Hume et al. 2016; Robertson et al. 2016a), meaning that sediment transport and deposition patterns can vary depending on estuary type. Sedimentation also varies within individual estuaries, as well as over time.

While sedimentation is a natural process, human activities in the catchment can accelerate rates of sedimentation to coastal environments. Catchment deforestation, including conversion to agriculture,

[1] https://www.waterquality.gov.au/anz-guidelines/your-location/new-zealand

horticulture or urbanisation, generally results in elevated sediment run-off from the land, with a high proportion of sediment being delivered during storm and flood events (Hume and McGlone 1986; Oldman 2009). Human activities within the coastal environment, such as aquaculture, channel dredging and the construction of structures, can also affect sedimentation processes.

Coastal environments in Aotearoa New Zealand experience particularly high sedimentation rates because the country is tectonically active, with steep terrain, fragile soils, short rivers and streams, intense rainfall and relatively recent deforestation (Green et al. 2021). In many parts of Aotearoa New Zealand, sedimentation rates have increased by several orders of magnitude since European settlement (Handley et al. 2017; Hunt 2019a; Ministry for the Environment and Stats NZ 2019; PCE 2020). Climate change is projected to increase the frequency and intensity of storms and heavy rainfall in many regions, which is likely to lead to higher volumes of sediment reaching the coast and consequentially potentially higher sedimentation rates in the future.

High sedimentation rates are detrimental to the ecological health of estuaries (Thrush et al. 2004). Sedimentation alters the physical environment in two key ways: elevated suspended sediments increase water turbidity and reduce light penetration, while the deposition of fine sediments modifies grain size, affecting biogeochemical fluxes, as well as the porosity and stability of seafloor sediments (Norkko et al. 2002b). These physical changes can trigger a cascade of ecological effects, including shifts in species composition, loss of sensitive species, declines in diversity and altered productivity (Norkko et al. 2002b; Lohrer et al. 2004; Thrush et al. 2004; see review in Townsend and Lohrer 2015). Over time, the persistent accumulation of fine sediments can lead to widespread biodiversity loss and diminished ecosystem functioning as species are lost, habitats become homogenised and sandy habitats transition to muddy, high-sedimentation areas (Thrush et al. 2003). Concerningly, the legacy effects of accumulated sediment can endure for decades – or even centuries – despite efforts to reduce sedimentation.

1.2 Indicators of sedimentation stress

A range of indicators can be used to assess whether sedimentation may be affecting estuarine ecological health. These include SAR, sediment mud content, areal extent of muddy substrates, suspended sediment concentrations in the water column, and a range of ecological indicators. These indicators are discussed in more detail below, and further information can be found in Stevens et al. (2024) and Townsend and Lohrer (2015).

Sedimentation accretion rate

SAR refers to the thickness of sediment accumulation (or accretion) over a given period of time (Townsend and Lohrer 2015) and is the indicator we are focusing on in this report. SAR is primarily controlled by the availability of source material, delivery processes, and the capacity of estuaries to retain or export sediment (Jones 2008). Sediment accumulation does not occur at a constant rate on an estuarine flat; rather, there will typically be episodes of deposition and scouring within any given period. For example, an annual sedimentation rate of 3 mm/yr may reflect a variety of depositional and erosional processes, such as a discrete 3 mm storm-induced deposit, a net accumulation derived from 10 mm of deposition offset by 7 mm of subsequent erosion, a continuous background sedimentation of approximately 0.0082 mm/day, or various other combinations of sediment input and removal. Sedimentation rates can also vary across an estuary – areas with lower hydrodynamic energy (typically the upper reaches) tend to be more depositional, while areas that are more exposed to wind, waves and currents (often the central and outer reaches) generally have lower sedimentation rates. Measurement methods and threshold values for SAR are discussed in more detail in Section 1.3.

Sediment mud content

Sediment mud content is a measure of the silt and clay particle size fractions (< 63 µm) in the sediment and is included by most councils in their state of the environment (SOE) estuary monitoring programmes. Mud content has been shown to be a significant predictor of macrofaunal community composition (e.g. Norkko et al. 2002a; Thrush et al. 2003; Anderson 2008; Hewitt et al. 2012; Rodil et al. 2013; Ellis et al. 2015; Robertson et al. 2015; Ellis et al. 2017; Douglas et al. 2019; Clark et al. 2020). It is a simple and relatively inexpensive indicator that can be reliably measured and provides an integrated assessment of episodic sedimentation inputs (Stevens et al. 2024). The National Estuarine Monitoring Protocol (NEMP; Robertson et al. 2002) method is based on analysis of sediment samples collected from sediment cores (upper 20 mm) using wet-sieving, although some councils have used laser diffraction (rather than wet-sieving) to analyse mud content. Results can vary depending on the sample pre-treatment (e.g. removal of large sticks or stones, or dissolving organic material with 10% hydrogen peroxide) and analytical method used (Hunt and Jones 2019), so care needs to be taken to follow a consistent protocol. In addition to SOE monitoring of recently deposited sediments, historical baselines may be established through the analysis of vertical sediment profiles in conjunction with sediment ageing techniques (Stevens et al. 2024).

Areal extent of muddy substrates

The spatial extent of muddy substrates can also be used as an indicator of sedimentation. In this context, 'mud-elevated sediments' are defined as those containing more than 25% mud content (Stevens et al. 2024). The mud content of the sediment is typically qualitatively estimated in the field by experienced practitioners, with laboratory grain-size analysis carried out on samples from representative sites to validate these estimates. Muddy substrate boundaries are usually estimated at a coarse level through simple visual assessment, but greater accuracy can be gained by setting up fixed transects or stratified, random grid sampling. Like sediment mud content, the areal extent of muddy substrates is an integrated measure of sedimentation. Both the proportional extent of muddy substrate within the available intertidal area[2] and the change in the proportional extent of muddy substrates since the first accurate baseline can be used as indicator metrics.

Suspended sediment

The indicators of sedimentation described above (SAR, sediment mud content, areal extent of muddy substrates) are measures of fine sediments that are deposited on the seafloor. However, in some locations sediments can either remain in suspension because waves, currents or turbulence prevent

[2] Intertidal area outside of salt marsh

them from settling, or they can be resuspended from the seafloor. In these places, SAR and sediment mud content may be low, but the suspended sediment concentrations (SSC) may be high. Suspended sediments can negatively affect ecological communities, particularly those that are reliant on light (e.g. seagrass, microphytobenthos; Flowers et al. 2023) and / or have respiratory or feeding structures that could be clogged by mud (e.g. horse mussels; Ellis et al. 2002). SSC can be estimated by measuring the water clarity or light penetration using indirect optical methods, optical backscatter sensors, Secchi discs, photosynthetically active radiation (PAR) sensors or remote sensing. Although high SSC can persist in areas with substantial catchment or riverine inputs, SSC – like many water quality parameters – can fluctuate significantly over time. In particular, SSCs can spike to orders of magnitude above normal in the hours or days following a flood event (Ellis et al. 2002).

Ecological indicators

The primary purpose of monitoring sedimentation is to prevent adverse effects on the ecological health and functioning of estuaries. As such, it is important to monitor the ecological communities themselves to ensure they remain healthy and are performing their ecological roles. This is particularly true in estuarine environments, where ecological communities are exposed to a range of natural and human-induced pressures and may vary in their vulnerability to sedimentation. Given the diverse ways sediment stress can affect estuarine systems, focusing directly on ecological responses is a logical and effective approach. Furthermore, ecological monitoring is more likely to capture sedimentation impacts caused by major storm events – episodic occurrences that are often missed by other indicators but can have long-lasting effects on the community.

A range of ecological indicators can be used to assess the effects of sedimentation, many of which are based on macrofaunal communities living in estuary sediments. These communities are commonly used to assess ecological health because they respond relatively rapidly to stressors, integrate the effects of multiple stressors over time, and are composed of a diverse range of species with differing functional roles, trophic levels and sensitivities (Pearson and Rosenberg 1978; Dauer 1993; Borja et al. 2000).

Simple univariate diversity metrics, including species richness, Pielou's evenness (Pielou 1966) and Shannon–Wiener diversity (Shannon 1948), calculated from macrofaunal community data, can be interpreted using frameworks such as the Pearson and Rosenberg (1978) model of macrobenthic succession to provide a general indication of ecological health. However, these indices lack specificity to identify causes of degradation and can have limited sensitivity to environmental change.

More targeted approaches involve tracking the abundance of mud-sensitive and mud-tolerant species, offering clearer insights into how ecological communities are responding to sedimentation. This can be taken a step further by calculating indices that score communities based on the proportion of taxa belonging to different sedimentation sensitivity groups (e.g. RI-AMBI or NZ hybrid AMBI; Robertson et al. 2016b). Similar approaches can be used to summarise changes in ecological functioning. For example, the traits-based index (TBI; Rodil et al. 2013) scores communities based on the richness of macrofaunal taxa in seven functional groups, which are known to respond to changes in sediment mud content and heavy metal contaminant concentration.

Multivariate approaches, such as the National Mud Benthic Health Model (BHM; Clark et al. 2020), retain all information on taxa and their relative abundances. These methods generally offer greater sensitivity than univariate metrics, enabling earlier detection of environmental change. The Mud BHM has been adopted as a national indicator of estuarine health on the Land, Air, Water, Aotearoa (LAWA) website. Its stressor-specific design makes it useful for targeted sedimentation management.

1.3 Sediment accretion rate

While a range of indicators can be used to assess sedimentation stress in estuarine environments, the focus of this report is SAR because that is the indicator for which a DGV was proposed in the 2015 ANZECC Estuarine Sedimentation Guidance report by Townsend and Lohrer (2015). Below we provide more detail on how SAR is measured, and threshold values being used guide interpretation of SAR.

Measurement

SAR is defined as 'the change in average annual sediment level at site-specific estuary locations' (Stevens et al. 2024), and is usually measured in millimetres per year (mm/yr). It provides a quantitative estimate of sedimentation as it measures the vertical change to a substrate surface over time. The method typically involves measuring changes in bed height from a given reference point using sediment rods, traps or plates, which can provide sedimentation estimates on a yearly scale. Because SAR represents a rate of change, it requires at least two depth measurements – an initial baseline and a subsequent measurement taken after a known time interval – to calculate the change in sediment depth over time.

Sediment plates are widely used by regional authorities across Aotearoa New Zealand. These are large (e.g. 30 cm × 30 cm), flat plates that are buried at a known distance (often 20 cm) beneath the sediment surface (Hunt 2019b). While variations in sediment plate deployment exist, generally plates are levelled and the initial depth of sediment above the plates is measured. Future measurements are made by inserting a probe into the sediment until the plate is reached to determine accretion or erosion rates (Stevens et al. 2024). Localised surface irregularities above the plate and scouring also need to be accounted for when taking measurements (e.g. by taking multiple measurements to obtain a representative site average or by use of a straight edge to average surface irregularities).

There are three main considerations when measuring SAR using sediment plates (Hunt 2023):

- **Temporal scales** – sedimentation occurs over complex temporal scales, with short-term fluctuations between samples often exceeding the long-term average rate.
- **Spatial variability** – differences in sedimentation across plates indicates that single plate measurements may not be representative of a given site. Furthermore, differences between sites indicate that single site measurements are unlikely to accurately represent estuary-wide SAR.
- **Operational challenges** – in erosional environments, plates may become exposed or tilt due to scour.

Temporal variation in sedimentation can be addressed by measuring sediment depths repeatedly over long time frames, which increases the size of the dataset and the ability to detect long-term trends. Townsend and Lohrer (2015) recommend monthly to quarterly monitoring, while Hunt (2019b) advises that annual measurements are sufficient providing the monitoring is undertaken for at least 10 years. Sediment depth measurements need to be accurate and precise to detect small changes (e.g. millimetres) in seabed elevation against a background of high natural variation. For this reason, sediment plate measurements should be used primarily as a measure of long-term sedimentation rates. Although significant, short-term episodic sedimentation events (e.g. storms) can often be discerned, Hunt (2019b) notes that tracking sedimentation at the event scale using sediment plates would be prohibitively time-consuming as it would require very frequent measurements to be undertaken.

Due to the high spatial variability in SAR across an estuary, care needs to be taken when determining sediment plate locations and interpreting results. Townsend and Lohrer (2015) recommend setting up plates in depositional zones and mid-estuarine areas, where sediment is more likely to accumulate, and avoiding exposed areas, where plates may be uncovered due to sediment erosion. They also advise against averaging sedimentation rates across an estuary and suggest examining sites individually instead. Many councils include multiple sites per estuary to assess SAR in representative parts of the estuary. They also commonly address site-scale spatial variation by deploying multiple plates at a site, and assess localised (within-plate) variation in sediment surface irregularities and plate measurement precision by taking replicate depth measurements at each plate.

Sediment plate data can be supplemented with historical coring and dating methods to generate a long-term understanding of historical or natural sedimentation rates, providing multiple lines of evidence if measurements converge.

Thresholds

In the absence of data examining the relationships between annual SAR and estuary health, Townsend and Lohrer (2015) developed the DGV for estuarine sedimentation using expert knowledge of the effects of sedimentation events on ecological condition. The proposed DGV was 2 mm of sediment accumulation per year above the natural annual SAR for the estuary, or part of estuary, at hand. Natural sedimentation was defined as the rate under native-forested catchment and was included in the DGV definition to account for estuaries or parts of estuaries with naturally high rates of sedimentation. Natural sedimentation rates can be estimated from sediment core dating or modelling of sedimentation rates in catchments prior to deforestation.[3] However, natural sedimentation rates for a given area of interest will often be unknown. When this occurs, Townsend and Lohrer (2015) recommend using the natural sedimentation rate from a comparable estuary, if one can be identified, or in the absence of any information, using a conservative approach of 0 mm/yr, which translates to a DGV of 2 mm/yr.

The DGV was recently developed into SAR thresholds by Stevens et al. (2024) as part of a review of estuarine ecological indicators commissioned by MfE (Table 1). For these thresholds, the DGV was used to define the threshold point between 'Fair' and 'Poor'. The authors caution that the remaining threshold points are not well underpinned by ecological data collected in Aotearoa New Zealand or overseas, but may be useful for environmental managers seeking guidance on SAR as a means of

[3] Noting that modelling without any sediment core data to validate the models would not be very robust.

understanding and improving estuarine ecological health. They note that the threshold between 'Poor' and 'Very Poor' (10 mm/yr) is the most uncertain and could be anywhere between 5 mm/yr and 10 mm/yr.

Table 1. Recommended sediment accretion (SAR) thresholds for Aotearoa New Zealand estuaries proposed by Stevens et al. (2024).

Average annual SAR (mm/yr)	Ecological quality status			
	Good	Fair	Poor	Very Poor
If assumed natural SAR ≤ 1 mm/yr	0 to 1	≥1 to 3	≥3 to 10	≥10
mm/yr above natural SAR	0	> 0 to 2	≥2 to 10	≥10
Narrative	No to minor stress on sensitive organisms	Moderate stress on some species and a risk of sensitive macroinvertebrate species being lost	Significant, persistent stress on a wide range of aquatic organisms	A likelihood of local extinctions of keystone species and loss of ecological integrity

Both Townsend and Lohrer (2015) and Stevens et al. (2024) recommend that the DGV and thresholds are refined by further examining the relationship between annual SAR and estuary health. They also caution that considering SAR on its own will be insufficient for managing sediment effects in estuaries. Instead, the DGV and thresholds should be used within a wider framework that considers the full range of pathways that sediment stress can manifest in estuaries (outlined in Section 1.2) as well as the cumulative effects of other stressors occurring within the system. Townsend and Lohrer (2015) also make the point that effective management of estuarine sedimentation would benefit from stronger connections between catchment processes and their downstream effects on sedimentation patterns and ecological impacts within estuaries.

2. Methods

Understanding the spatial and temporal variability of indicators is crucial to their effectiveness. Indicators that exhibit high variability are not fit for purpose – unless that variability can be accounted for through the measurement of covariates. Therefore, we first examined the spatial (within-plate and between-plate) and temporal (within-year and between-year) variation in sediment accretion data. Next, we assessed whether different methods of calculating SAR influenced our SAR estimates. Finally, we applied a weight-of-evidence approach to investigate the relationship between SAR and ecological health, with the aim of refining the estuarine sedimentation rate DGV. This included modelling changes in macrofaunal communities, ecological indicators and key estuarine taxa along gradients of sediment accretion rate and, in some cases, mud content.

2.1 Data collation and standardisation

Understanding the relationship between SAR and ecological health requires paired sediment accretion and macrofauna data collected from the same location at a similar time, as well as baseline sediment accretion data to enable calculation of SAR. We compiled data from a range of estuary types across the country, representing a broad gradient of sediment accretion rates – from low to high. Sites ranged in their within-estuary site location (upper reaches, mid-estuary, outer reaches) and tidal elevation.

Macrofauna / mud dataset

Macrofauna and sediment mud content data were sourced from two places:

- **Cawthron's National Estuary Monitoring dataset** (Berthelsen et al. 2020), which contains estuarine ecological monitoring data collected between 2001 and 2016, largely acquired from regional councils and unitary authorities around Aotearoa New Zealand.
- **Cawthron's National Benthic Health Model (BHM) dataset**, which contains macrofauna, sediment mud content and sediment metals data from 13 regional councils and unitary authorities across Aotearoa New Zealand.

The combined macrofauna / mud dataset contained 2,099 site/times (i.e. unique observations) across 80 estuaries and 399 sites. Macrofauna were standardised to align with the taxa categories used in the National BHMs (Clark et al. 2020; Clark 2022) and abundance data were averaged across individual replicates for each site/time. The number of macrofauna replicates at each site ranged from 3 to 16. Additional macrofauna and sediment mud content data are available, but it was not within the scope of this project to collate these data.

Sediment accretion dataset

Sediment accretion data measured using sediment plates were sourced directly from regional councils and unitary authorities. Data were provided by Northland Regional Council, Auckland Council, Waikato

Regional Council, Bay of Plenty Regional Council, Hawke's Bay Regional Council, Greater Wellington Regional Council, Nelson City Council, Tasman District Council, Otago Regional Council and Environment Southland. In most cases, sediment accretion data were provided in a raw format (i.e. as sediment depths) to allow us to examine spatial and temporal variability. To expediate data collation and standardisation, we focused on collating sediment accretion data that could be paired with macrofauna data from the two datasets described above. Additional paired sediment accretion and macrofauna data are available but would require standardisation before they could be used in further investigations. Sediment accretion data from Bay of Plenty Regional Council were not included in the dataset because the macrofauna data associated with the sediment plates were sieved to only 1 mm rather than 0.5 mm, so were not comparable to the rest of the dataset.

The sediment accretion dataset contained 1,908 site/times across 34 estuaries and 93 sites. Most of the sites (69%) had a 'cluster' sediment plate design, where multiple plates (typically 2–4) were positioned either at a similar distance from the macrofauna sampling location, or along a short 25–30 m transect bordering the fine-scale monitoring site from which the macrofauna samples were collected. The remaining sites either had a single sediment plate (18%) or used a transect design (13%), with up to six plates spaced across 200–500 m. Replicate depth measurements per plate ranged from 3 to 45, with most replicate measurements ranging from 3 to 15. Where only three replicate depth measurements were taken, a straight edge was used to average out localised surface irregularities over a sediment plate. For each site, council scientists provided additional metadata indicating its within-estuary location (outer reaches, mid-estuary, upper reaches), tidal elevation (low, mid, high), overall health (poor, fair, good) and the presence or absence of vegetation.

Combined macrofauna / SAR / mud dataset (final dataset)

Calculation of a SAR for our study required at least two sediment depth measurements: one paired with the macrofauna sampling event, and at least one earlier (baseline) measurement to determine sediment accumulation over time. Sediment accretion data were paired with macrofauna and sediment mud content data by matching the macrofauna sample collection date[4] with the closest prior sediment sampling date. Site/times were excluded from the dataset if the closest prior sediment sampling date was more than a year before the macrofauna samples were collected. Site/times were classified as 'offset' if the closest prior sediment sampling date was more than 60 days before the macrofauna was collected.

Our focus was on calculating the amount of sediment that has been deposited at, or eroded from, a site in the period leading up to when the macrofauna was collected. Both short-term and long-term changes in sediment accretion or erosion could affect ecological health; therefore, we calculated SAR over different time periods. Up to four SAR periods were calculated for each paired macrofauna / sediment site/time:

- **1–2-month SAR** (1–2 months beforehand) – short term
- **1-year SAR** (11–13 months beforehand) – medium term

[4] Only the month and year of the macrofauna sample collection was included in the dataset, so the macrofauna sample collection date was set as the last day of the month / year.

- **5-year SAR** (4.5–5.5 years beforehand) – long term
- **10-year SAR** (9.5–10.5 years beforehand) – long term.

SAR could not be calculated for site/times if there were no baseline sediment accretion data within the relevant period. If this was the case for all four SAR periods, that site/time was excluded from the dataset.

The SAR is the average net sediment accumulated at a site over the period leading up to the closest sediment sampling date and is reported as annual SAR (mm/yr). To calculate each SAR, replicate sediment depth measurements were first averaged across each individual sediment plate. Where all replicate depth measurements were zero or identical values,[5] the individual sediment plate for that site/time was removed from the dataset. The average sediment depths for each plate were then averaged across the number of relevant sediment plates at each site to provide an overall average sediment depth for a given site/time.

The number of sediment plates at each site ranged from one to six. At most sites, sediment depth data from all plates were relevant to the macrofauna samples, either because there was only one plate (single plate design) or because multiple plates were positioned at similar distances from where the macrofauna samples were collected (cluster design). At transect design sites, where plates were spaced over larger distances, only the two plates either side of where the macrofauna samples were collected were relevant.[6] Therefore, the overall average sediment depth for a given site/time was calculated using data from only these two plates. Information on the sediment plate design and which plates were used to calculate the SAR for each site is provided in Appendix 1.

The following equation was used to calculate the annual SAR for each site/time:

$$\text{Annual SAR (mm/yr)} = ((D_1 - D_2) / d) * 365$$

Where:
SAR is sediment accretion rate
D_1 is the average sediment depth for the closest sediment sampling date prior to the macrofauna sample collection date (if greater than a year, the data were excluded)
D_2 is the average sediment depth for the closest sediment sampling date within the time period of interest (baseline depth)
d is the number of days between the two sediment sampling dates.

Table 2 provides an example of which sediment sampling dates would be used to calculate D_1 and D_2 for each of the four SAR periods for a given macrofauna data collection date.

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[5] Several of the sampling occasions from the Waikato Regional Council dataset had identical replicate depth measurements across a sediment plate. This situation arose for two reasons. The first was when plates were buried too deep to measure and the '>' symbol was removed when the data were exported from their database. The second was when only a few accurate measurements were achievable (because of the depth of plate) and sediment surface was deemed to be uniform. In both these situations the data were removed from the final dataset before calculating site averages.
[6] Data exploration at these sites showed that the sediment accretion patterns varied.

Table 2. Example of sediment sampling dates that would be used to calculate D_1 and D_2 for four sediment accretion rate (SAR) periods for macrofauna data collected in October 2020. Red shading indicates the period over which the sediment has accreted but only the depths at the beginning and end of this period are used to calculate the SAR.

Date	Macrofauna	Sediment	1–2-month SAR	1-year SAR	5-year SAR	10-year SAR
19/10/2020	✓	✓	D_1	D_1	D_1	D_1
21/08/2020		✓	D_2			
01/10/2019	✓	✓		D_2		
24/01/2019		✓				
10/10/2018	✓	✓				
09/10/2017	✓	✓				
17/10/2016	✓	✓				
28/10/2015	✓	✓			D_2	
22/01/2015	✓	✓				
09/10/2014	✓	✓				
31/01/2014	✓					
07/10/2013	✓	✓				
15/01/2013	✓	✓				
17/10/2012	✓	✓				
25/01/2012	✓	✓				
27/10/2011		✓				
24/01/2011		✓				D_2

Site/times in the final macrofauna / SAR / mud dataset are those where sediment was sampled within a year of the macrofauna samples being collected and the sediment sampling dates enabled the calculation of at least one of the four SAR periods. Once the dataset was collated, a final check was carried out to ensure that sediment plates in the dataset had not been reburied or replaced during the period over which the SARs were calculated for that site. Where this did occur, SARs were recalculated using the correct sediment depth data (e.g. the depth of the reburied plate), or if this was not possible (e.g. because the plate was lost and replaced during that period), the SAR for that period was removed from the final dataset. Site/times were also removed if there were notes in the raw data that indicated they were not a reliable measure of long-term sediment accretion (e.g. monitoring of sediment plates in Ruakākā Estuary was eventually discontinued because it was a high-energy site and the plates kept going missing; sediment plates in Jacobs River and New River Estuaries were covered by thick layers of *Gracilaria* algae in some years). Site/times that had notes relating to fish or ray pits, mangroves, seagrass presence, mounds, a heterogeneous bed or measurements made around footprints were retained in the dataset as these types of data would likely be included when councils report SARs for their region.

On some occasions, one of the sediment plates at a site could not be found, so the average was calculated from the remaining sediment plates at that site. At sites with transect sediment plate designs, average sediment depth often varied substantially between plates, meaning that the omission of one of the plates had a large effect on the site average.[7] Therefore, where one of the plates was missing from a transect design site, the site average for both time periods used to calculate the SAR (D_1 and D_2) was calculated from the same plates (i.e. if a site had two plates and Plate 1 was missing for D_2, the site average for both D_1 and D_2 would be calculated from the average sediment depth at Plate 2 for both sampling occasions).

2.2 Exploring sediment accretion variability

The number of plates, replicate depth measurements per plate, frequency of measurements within a year and sampling plate design (transect, cluster of plates or single plate) varied between councils / unitary authorities. These differences in sampling design provided an opportunity to explore how sediment accretion varied across space and through time. It is important to note that exploratory analyses described in this section were carried out using sediment depth data, rather than SAR. Sediment depths were used because: (1) SARs could not be reliably calculated for individual replicate points within a plate due to the lack of a consistent baseline replicate; and (2) SARs were generated later, based on average sediment depths across all plates at each time point. As a result, some offset between plates is expected, depending on their initial burial depth. Patterns of sediment accretion and erosion between plates should therefore be interpreted with this limitation in mind. For this reason, we do not directly compare within- and between-plate variation. However, variation in sediment depth within and between years can be compared, as the same plates were included in these comparisons.

Spatial variation in sediment accretion

Both Environment Southland and Waikato Regional Council had multiple plate replicates per site (i.e. 2–6) and multiple within-plate replicate depth measurements (i.e. 5–45). We used these datasets to explore spatial variability of sediment depths (i.e. between and within plates). We first plotted the multiple plates for each site through time, separated by sediment plate design (i.e. cluster or transect), to look at sediment depth variability, focusing here on trends through time rather than the absolute sediment depth values. We then looked at within-plate variability using coefficient of variation (% CV). The replicate sediment depth measurements were first averaged across each sediment plate to calculate the within-plate average and standard deviation (SD). Where replicate depth measurements were zeros,

[7] The omission of a plate affected our site-level SAR estimates because we first averaged sediment depths across plates before calculating SAR from the two time points. Had we instead calculated SARs for each plate individually and then averaged them, the impact of the missing plate would have been smaller. Where no plates are missing, the site average is identical.

these were treated as NAs. To calculate the within-plate CV, the SD of depth measurements was divided by each corresponding within-plate average. The within-plate CVs were then averaged for each site/time. We plotted each site's average and overlaid each point with the within-plate CV (vertical bar) to visualise measurement variability.

The following equation was used to calculate the CV (%) for each plate:

$$\mathrm{CV}\ (\%) = \left(\frac{\mathrm{SD}}{\mathrm{mean}}\right) \times\ 100$$

Where:
CV is the coefficient of variation expressed in percent
SD is the standard deviation of the plate
Mean is the average of replicate depth measurements per sediment plate.

Temporal variation in sediment accretion

Northland Regional Council, Auckland Council and Waikato Regional Council sampled sites at least two or more times per year. We used these datasets to explore the temporal variability of sediment depths (between and within year) using CV. We selected sites where there were two or more sampling events within a year and two or more between-year sampling events. The within-plate averages were first averaged across all sampling events within a year / site to calculate the within-year average (i.e. annual average) and SD. No weighting was applied to account for different numbers of sampling events within a year. To calculate the within-year CV, the within-year SD was divided by the annual average / site. The within-year CVs were then averaged by site to obtain one value for the site-averaged within-year CV. The between-year calculations were similar: the annual averages / site were averaged to calculate each site average. Then the SDs of the annual averages / site were divided by the site average to calculate the between-year CV.

Overall patterns in sediment accretion

Time series of averaged sediment depths were also plotted by site to assess how sedimentation changed over time. Each plot was fitted with a trend line to indicate the overall rate of sediment change at a site over time, which can be indicative of sediment accumulation or erosion. The timing of large storm events was indicated by vertical dotted lines, and the timing of macrofauna sample collection (in our dataset) were indicated by red rug marks. Note that these plots are intended to provide a general indication of overall sediment accretion or erosion patterns at each site. As these data are sediment depths, and have not yet been converted to SAR values, the final quality control checks on the combined macrofauna / SAR / mud dataset (described in Section 2.1) have not yet been completed. As a result, the data include instances where plates were reburied or replaced, as well as site/time combinations that may not reliably reflect long-term sediment accretion. Additionally, site averages are based on raw data, with no adjustments made for missing plates.

2.3 Effect of calculation method on sediment accretion rates

Our approach for calculating SAR (described above in Section 2.1) aligns with that used by many of the regional councils and unitary authorities across Aotearoa New Zealand, providing consistency with current national monitoring practices. An alternative approach involves fitting a linear model through sediment depth data at each site and using the slope as an SAR estimate (e.g. Hunt 2023). While this regression-based approach can offer a more robust estimate by incorporating available data between the baseline (D_2) and closest (D_1) sediment sampling dates, we opted for the simpler method to ensure comparability with many existing council datasets.

To assess whether the two approaches yielded comparable SARs, we also applied the regression approach by fitting linear models to average sediment depth data for each site over the relevant period (i.e. 1–2 months, 1 year, 5 years and 10 years). As for the simple method, this resulted in up to four SARs for each paired macrofauna / sediment site/time, depending on data availability.

For the regression method, sediment depth data were treated in the same way as for the simple SARs: averaged per plate, uniform or zero-only replicates excluded, then averaged across each site. Linear models were fitted to these site-level mean depths over time, and slopes were multiplied by 365 to convert from mm/day to mm/year.

SARs from the two methods were compared using Pearson correlation coefficients, where an R value close to 1 would indicate strong agreement between methods, and p values < 0.05 would be considered statistically significant.

2.4 Response of the macrofaunal community to sedimentation

The relationship between the macrofaunal community and SAR was investigated using two approaches: canonical analysis of principal coordinates (CAP) and distance-based linear modelling (DistLM). To account for potential differences in community response to different sediment regimes, each SAR dataset (1–2 months, 1 year, 5 years, 10 years) was further subdivided into site/time combinations where sediment was accreting (SAR > 0) or eroding (SAR < 0). Site/times where sediment depth measurements were offset relative to macrofaunal sampling or where grain size was measured using laser diffraction or was unknown were removed before conducting these analyses. Multivariate analyses were carried out in PRIMER.

Canonical analysis of principal coordinates

CAP (Anderson and Robinson 2003; Anderson and Willis 2003) was used to model the relationship between macrofaunal community structure (i.e. the composition and relative abundance of taxa) and SARs. CAP enables a constrained ordination based on any dissimilarity or distance measure and identifies axes that best discriminate along an environmental gradient. All CAP analyses were performed using square-root transformed Bray–Curtis dissimilarities of macrofaunal community data (Bray and Curtis 1957), with 9,999 permutations. The square-root transformation – commonly used to downweight the influence of highly abundant taxa (Clarke and Gorley 2015) – was applied to reduce the influence of highly abundant taxa while still allowing variation in relative abundance to influence the analysis, as this was considered important for assessing changes in estuary health. Separate CAP models were constructed for each SAR period and sediment regime (accretion or erosion). Canonical correlations (*r*) were used to evaluate the strength of the relationship between macrofaunal community structure and SARs.

CAP score plots were colour-coded by estuary type (based on New Zealand Coastal Hydrosystem (Hume et al. 2016) and Estuary Trophic Index (ETI; Robertson et al. 2016a) classifications), region, within-estuary site location (outer reaches, mid-estuary, upper reaches) and tidal elevation (low, mid, high) to assess whether patterns emerged that might indicate these factors influenced the relationship between community structure and SAR.

Distance-based linear modelling

DistLM (Anderson et al. 2008) was used to model the relationship between the macrofaunal community data and three predictor variables to determine the relative influence of SAR on community structure. Predictors included SAR (both raw and $\log_{10}$-transformed) and sediment mud content (log-transformed using the natural log). Like the CAP models, separate models were constructed for each SAR period and sediment regime (accretion or erosion). DistLM produces two outputs: marginal and sequential tests. The marginal tests indicate how much each variable explains when taken alone, ignoring all other variables, while the sequential tests are the conditional tests of individual variables carried out in the order specified. The models used a forward selection procedure (R^2 selection criteria), which began with a null model containing predictor variables. The predictor variable with the best R^2 value was chosen first, followed by the variable that, together with the first, improves the selection criterion the most, and so on.

2.5 Response of key taxa and ecological indicators to sedimentation

We modelled how ecological indicators and the abundance of key macrofaunal taxa changed along SAR and sediment mud content gradients to assess potential relationships among these variables and identify any thresholds associated with significant declines. Ecological indicators included species richness (S), Pielou's evenness (J), Shannon–Wiener diversity (H') and Mud BHM scores (Table 3). Twelve taxa were selected for modelling based on their cultural and functional importance and their sensitivity or tolerance to mud (Table 4). While many benthic macrofauna are known to respond to changes in sediment mud content, their sensitivity or tolerance to changes in SAR may differ; however, species-specific responses to SAR remain poorly documented. As such, these taxa were selected as a representative suite that may show detectable responses to both gradients.

Two statistical approaches were used to model the response of these indicators and key taxa; change point detection and generalised additive models (GAMs). Due to the large number of plots produced, we only display plots for the 5-year SAR dataset in the main body of the report, with plots for the remaining SAR time periods (1–2 month SAR, 1-year SAR and 10-year SAR) provided in Appendices 6 and 8. The 5-year SAR time period was chosen because several taxa and ecological indicators showed significant changes in response to SAR at this temporal scale, based on results from both the change point detection and generalised additive models.

Table 3. Ecological indicators selected for modelling.

Indicator	Description	Range	Reference
Species richness (*S*)	Total number of taxa at a site/time.		
Pielou's eveness (*J*)	A measure of equitability, or how evenly the individuals are distributed among the different species / taxa.	0 (even distribution of taxa) to 1 (uneven distribution or dominance by a few taxa).	Pielou (1966)
Shannon–Wiener diversity (*H*)	A diversity index that describes, in a single number, the different types and amounts of animals present in a collection. Varies with both the number of species and the relative distribution of individual organisms among the species.	0 (communities containing a single species) to > 5 (communities containing many species and each with a small number of individuals).	Shannon (1948)
Mud Benthic Health Model (Mud BHM) scores	Indicates the impact of sedimentation on macrofaunal communities relative to other estuarine sites across Aotearoa New Zealand.	1 (least impacted) to 6 (most impacted).	Clark et al. (2020)

Table 4. Key taxa selected for modelling.

Taxon	Common name	Selection rationale
Amphibola crenata	Mud snail	Culturally important, mud tolerant
Aonides sp.	Polychaete worm	Mud sensitive
Austrohelice sp. / *Hemigrapsus* sp. / *Hemiplax* sp.	Crabs	Mud tolerant
Austrovenus stutchburyi	Cockle	Culturally and functionally important, tolerant of a broad range of sediment grain sizes
Capitella sp. / Oligochaeta	Polychaete and oligochaete worms	Mud tolerant
Cossura sp.	Polychaete worm	Prefers sediments that are not too muddy and not too sandy
Halicarcinus sp.	Crab	Mud tolerant
Heteromastus filiformis / *Barantolla lepte*	Polychaete worms	Prefers sediments that are not too muddy and not too sandy
Macomona liliana	Wedge shell	Functionally important, mud sensitive
Paphies australis	Pipi	Culturally and functionally important, mud sensitive
Phoxocephalidae	Amphipod	Generally prefer sandier sediments
Prionospio aucklandica	Polychaete worm	Prefers sediments that are not too muddy and not too sandy

Change point detection

SAR values were binned at 1 mm intervals to standardise comparisons across sampling periods. Abundance values within each SAR bin were averaged and then ordered along the SAR gradient for each taxon and period. Single change points were detected using the Lepage method from the *cpm* package (Ross 2015), with an average run length (ARL_0) of 500 and a 20-observation start-up period during which no change is signalled. Due to the limited sample size in the 1–2-month SAR period (n = 44), change point detection was not conducted as the data were considered insufficient for reliably detecting significant shifts. Taxa abundance was plotted against SAR bins, with vertical lines indicating the SAR at which the single change point was detected.

Generalised additive models

GAMs (Wood 2017) were used to assess how the abundance of individual taxa and ecological indicators (S, J, H and Mud BHM; Table 3) responded to SAR and mud content. Exploratory analysis revealed no consistent patterns to indicate that estuary type, region, within-estuary site location or tidal elevation influenced the relationship between taxa abundances or ecological indicators and SAR, so models were fitted without these terms. Separate GAMs were fitted for each taxa–SAR period and ecological indicator–SAR period combination, using log (x + 1)-transformed abundance or log (x + 1)-transformed indicator values as the response variables, and including smooth terms for SAR and mud content. Each smooth term used a basis dimension of k = 3 to minimise the risk of overfitting. Models were fitted using the *mgcv* package (Wood 2004; Wood 2011) in R (R Core Team 2024).

We estimated the first derivatives of each smooth term to identify significant changes in taxa abundance and indicator values along SAR and mud content gradients, using the *gratia* library (Simpson 2024) in R. Responses were considered significant where the 95% confidence intervals of the derivative did not include zero (Simpson 2018). To visualise results, we produced partial dependence plots with estimated smooths and confidence intervals, and overlaid derivative plots to highlight significant trends.

3. Results

3.1 Summary of data used in the study

The combined macrofauna / SAR / mud dataset contained 710 site/times (i.e. unique observations) from 79 intertidal sites across 32 estuaries in Aotearoa New Zealand (Figure 1, Table 5). Calculation of a SAR requires at least two sediment depth measurements: one paired with the macrofauna sampling event, and at least one earlier (baseline) measurement to determine sediment accretion over time. Of the 710 site/times in the dataset, 90% had the paired sediment depth measured within 2 months prior to macrofauna sampling, while the remaining 10% had measurements taken 3–12 months earlier (i.e. measurement of the sediment depths was offset from the macrofauna collection by a few months). The number of macrofauna replicates per site/time ranged from 6 to 12.

The dataset covered a broad geographic spread, with most observations from Auckland (40%) and Waikato (41%), reflecting long-term monitoring efforts in those regions. Estuary types were also diverse, although observations were dominated by the three most common estuary types in Aotearoa New Zealand: permanently open tidal lagoons (Class 7A, 26%), shallow drowned valleys (Class 8, 43%) and deep drowned valleys (Class 9, 29%). According to the Estuary Trophic Index estuary typology (Robertson et al. 2016a), most observations were split between shallow intertidal dominated estuaries (SIDE, 57%) and deeper subtidal dominated estuaries with longer residence times (DSDE, 41%).

Within-estuary site location data were available for 90% of observations, with 54% located in mid-estuary areas and the rest evenly divided between upper (20%) and outer (26%) estuary reaches. Tidal elevation information was provided for 86% of site/times; 57% were at mid-tide, 42% at low tide and only 1% at high tide.

Most observations (89%) came from unvegetated sites, with sites containing seagrass contributing just 1% of the dataset and the remainder lacking information on vegetation cover. Site health, as assessed by council scientists, was rated Poor at 21% of site/times, Fair at 52% of site/times, Good at 14% of site/times and unknown at the remainder of site/times. More detailed information on the sites contained in the combined macrofauna / SAR / mud dataset can be found in Appendix 1.

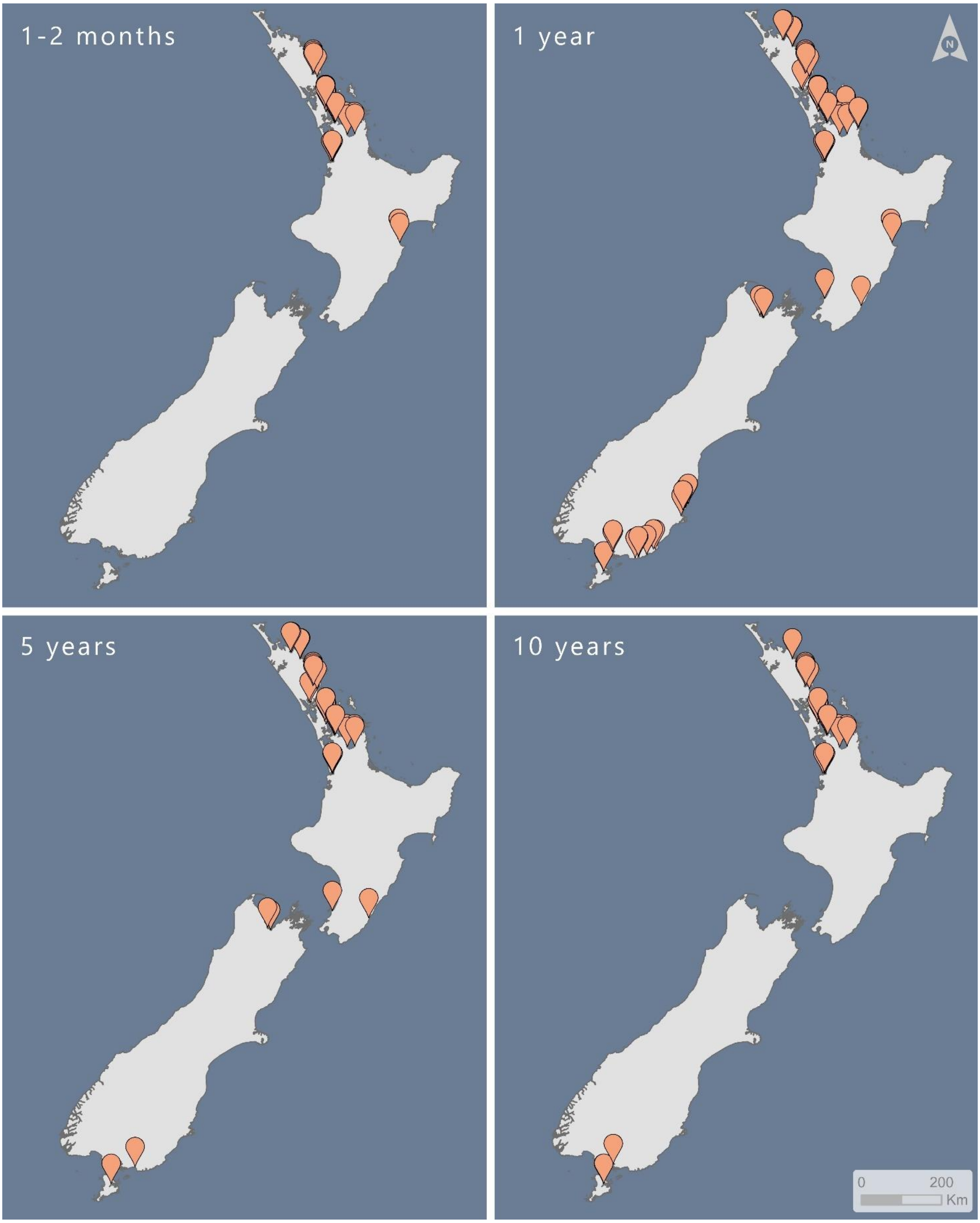


Figure 1. Maps of Aotearoa New Zealand showing the locations of sites included in the combined macrofauna / SAR / mud dataset. Panels are separated by SAR period.

Table 5. Summary of combined macrofauna / SAR / mud dataset. Offset refers to site/times (i.e. unique observations) where the paired sediment depths were measured 3–12 months prior to macrofauna sampling. For all other site/times, paired sediment depths were measured within 2 months prior to macrofauna sampling. Estuary types are classified using the New Zealand Coastal Hydrosystems Classification (Hume et al. 2016) and the Estuary Trophic Index (Robertson et al. 2016a). Percentage values refer to the percentage of site/times in each SAR-period dataset.

SAR period	Number of observations	Regions	Estuary types
1–2 months	**Site/times:** 44 (0% offset) **Sites:** 35 **Estuaries:** 13	Northland (11%), Auckland (39%), Waikato (32%), Hawke's Bay (18%)	**Hume:** 7A (36%), 8 (45%), 9 (14%), NA (5%) **ETI:** SIDE (68%), DSDE (27%), SSRTRE (5%)
1 year	**Site/times:** 310 (10% offset) **Sites:** 76 **Estuaries:** 31	Northland (9%), Auckland (43%), Waikato (32%), Hawke's Bay (4%), Wellington (2%), Nelson (< 1%), Tasman (2%), Otago (4%), Southland (5%)	**Hume:** 6A (< 1%), 6B (< 1%), 7A (33%), 8 (41%), 9 (24%), NA (< 1%) **ETI:** SIDE (62%), DSDE (35%), SSRTRE (2%)
5 years	**Site/times:** 225 (12% offset) **Sites:** 37 **Estuaries:** 18	Northland (12%), Auckland (42%), Waikato (42%), Wellington (< 1%), Tasman (2%), Southland (< 1%)	**Hume:** 6A (< 1%), 6B (< 1%), 7A (21%), 8 (46%), 9 (32%) **ETI:** SIDE (54%), DSDE (44%), SSRTRE (1%)
10 years	**Site/times:** 131 (11% offset) **Sites:** 29 **Estuaries:** 13	Northland (5%), Auckland (28%), Waikato (64%), Southland (2%)	**Hume:** 7A (12%), 8 (45%), 9 (43%) **ETI:** SIDE (47%), DSDE (53%)

Fewer short-term SAR observations (1–2 months; n = 44) were available compared to longer-term SAR periods (n = 131–310). Variability in SAR was highest in the 1–2-month dataset and declined as the SAR calculation period increased (Table 6). For instance, SAR values over 1–2 months ranged widely from -274.9 mm/yr to 243.3 mm/yr, whereas SAR values calculated over a 10-year period ranged from -9.7 mm/yr to 16.4 mm/yr. Average SAR values across the four datasets ranged from 0.14 mm/yr to 2.61 mm/yr, with particularly high variation associated with the 1–2-month dataset (Table 6). SAR values across regions, estuary types, within-estuary site locations and tidal elevations are provided in Appendix 2. Sediment mud content at site/times in the dataset ranged from 0.3% to 97%. The relationship between sediment mud content and SAR was weak (Figure 2).

Table 6. Summary of sedimentation accretion rates (SARs in mm/yr) across different SAR periods. The number of observations for each factor is denoted by *n*.

SAR period	*n*	Minimum	5th percentile	Mean	SD	95th percentile	Maximum
1–2 months	44	-274.86	-213.67	0.14	117.63	190.08	243.33
1 year	310	-120.16	-29.43	2.61	23.53	40.28	127.98
5 years	225	-21.61	-10.39	1.72	8.08	17.27	27.02
10 years	131	-9.70	-6.60	0.55	5.27	8.86	16.44

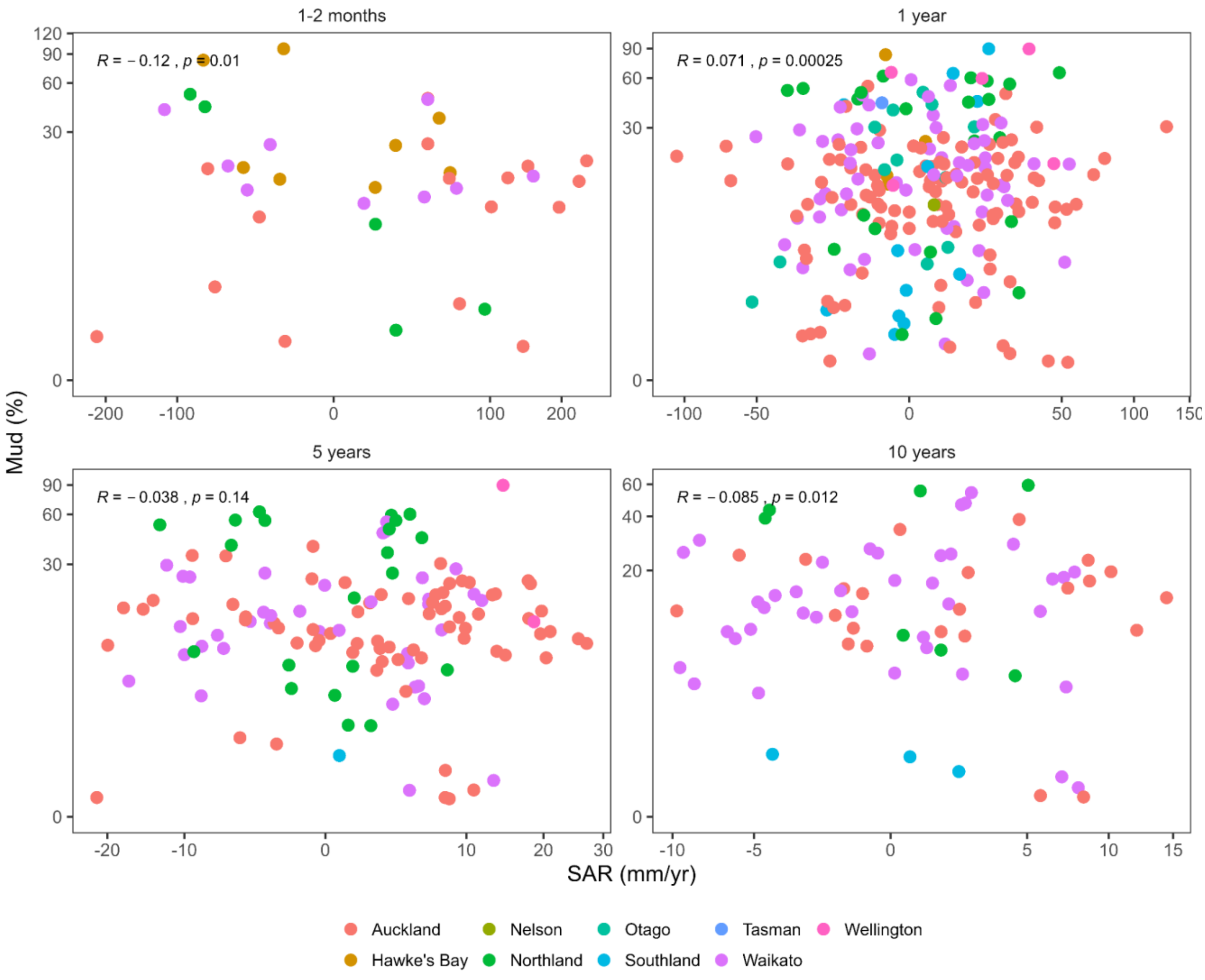


Figure 2. Scatter plots showing the relationship between sediment mud content (%) and sediment accretion rate (SAR; mm/yr), with SAR calculated over four time periods. Data are coloured-coded by region.

3.2 Sediment accretion variability

Spatial variation in sediment accretion

Sites with a clustered plate design often showed similar sediment accretion patterns across replicate plates (Figure 3A and B, Appendix 3). However, this was not true in all cases. For example, at Kaeo River (Northland), two plates located approximately 30 m apart initially showed similar sediment accretion patterns, but following ex-Tropical Cyclones Lusi and Ita in 2014, significantly more sediment erosion was recorded at the lower plate compared to the upper plate (Figure 3C). Similarly, at Site A in the Pleasant River Estuary (Otago), sediment accretion patterns varied considerably between the four plates (Figure 3D) across a distance of only 20 m.

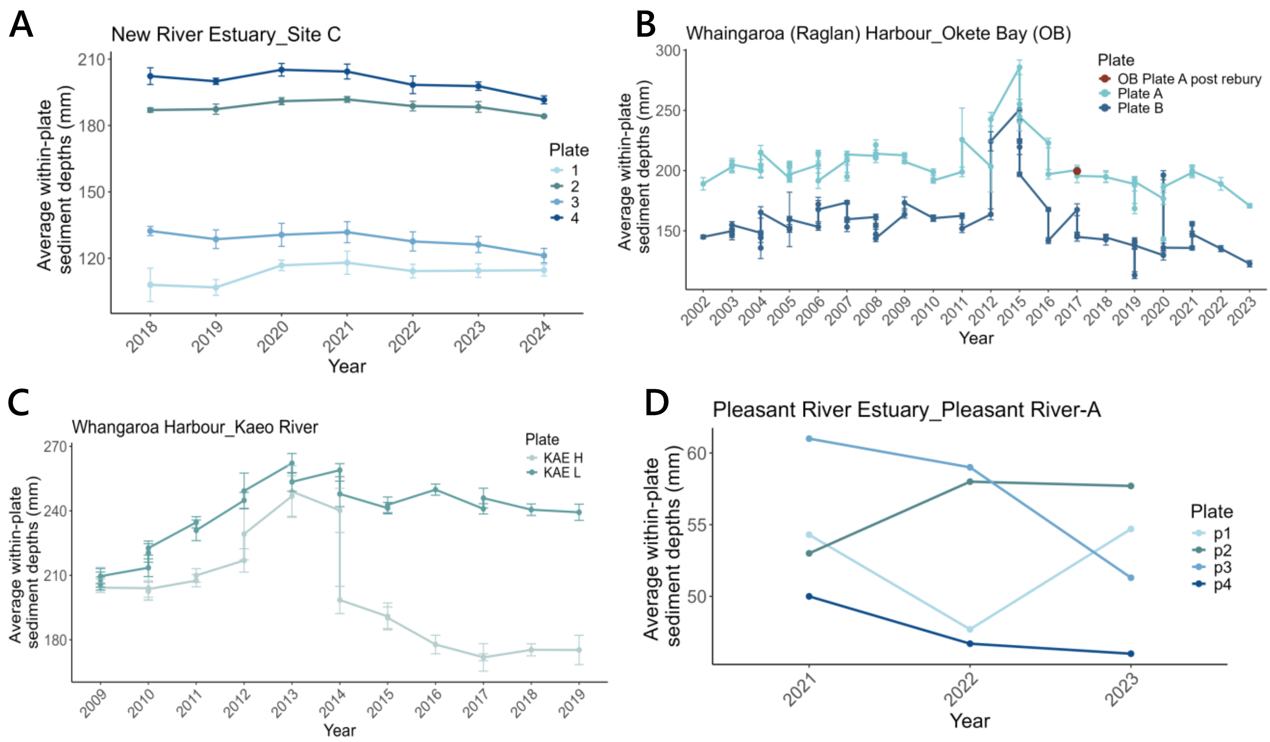


Figure 3. Average sediment depths at four sites with a 'cluster' sediment plate design. Coloured lines indicate average sediment depth (± standard deviation) for individual plates. At some sites, similar patterns in sediment accretion were observed between plates (panels A and B), while at others, different trends were observed (panels C and D). Note that these plots show sediment depth, rather than sediment accretion rate, so we would expect to see some offset between plates depending on how deep they were initially buried. See Appendix 3 for plots of sediment depths through time for other sites.

Waikato Regional Council had 15 sites across five estuaries with a transect plate design. Transect designs are used at these sites to capture the spatial variation in SAR in a particular part of the estuary. As expected, sediment accretion patterns typically varied between plates within each site (Figure 4B–D, Appendix 3). Due to the high variability in sedimentation observed across transects, SAR calculations for these sites were based only on the two plates located closest to the macrofauna sampling area, ensuring a more accurate reflection of local sediment conditions.

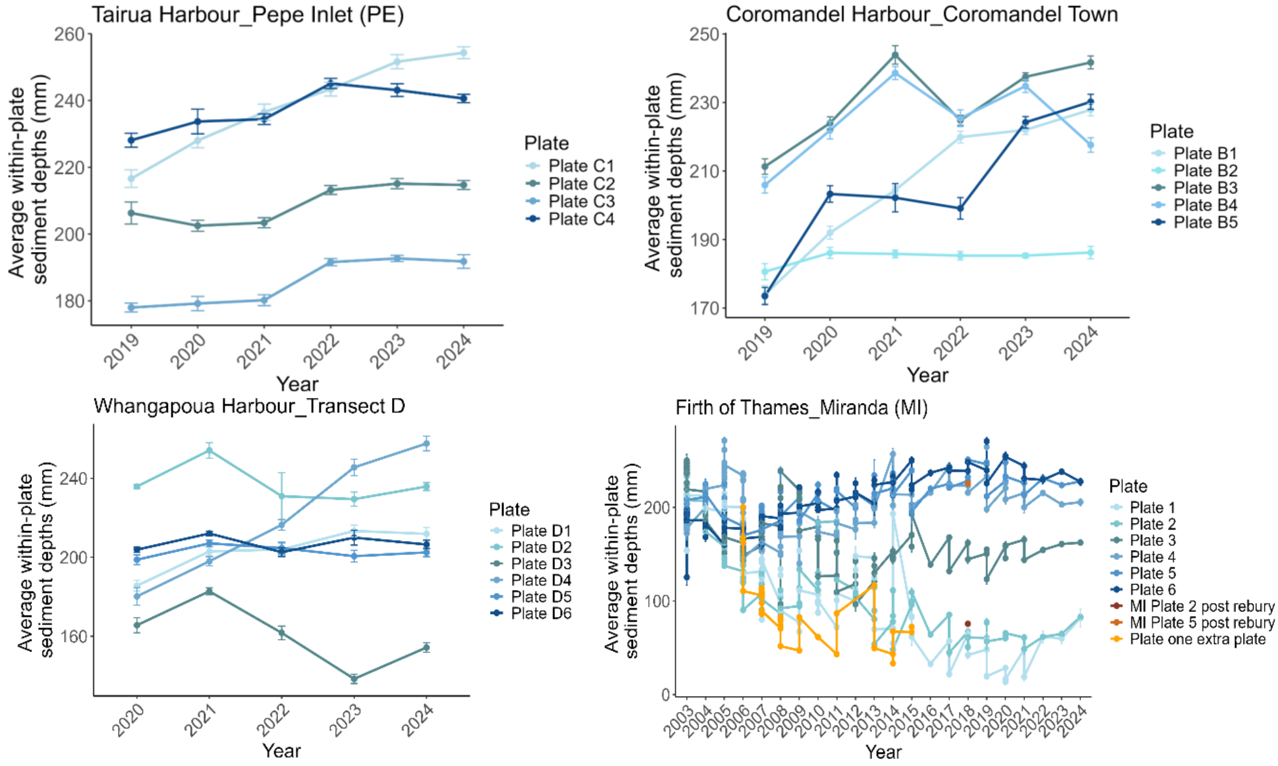
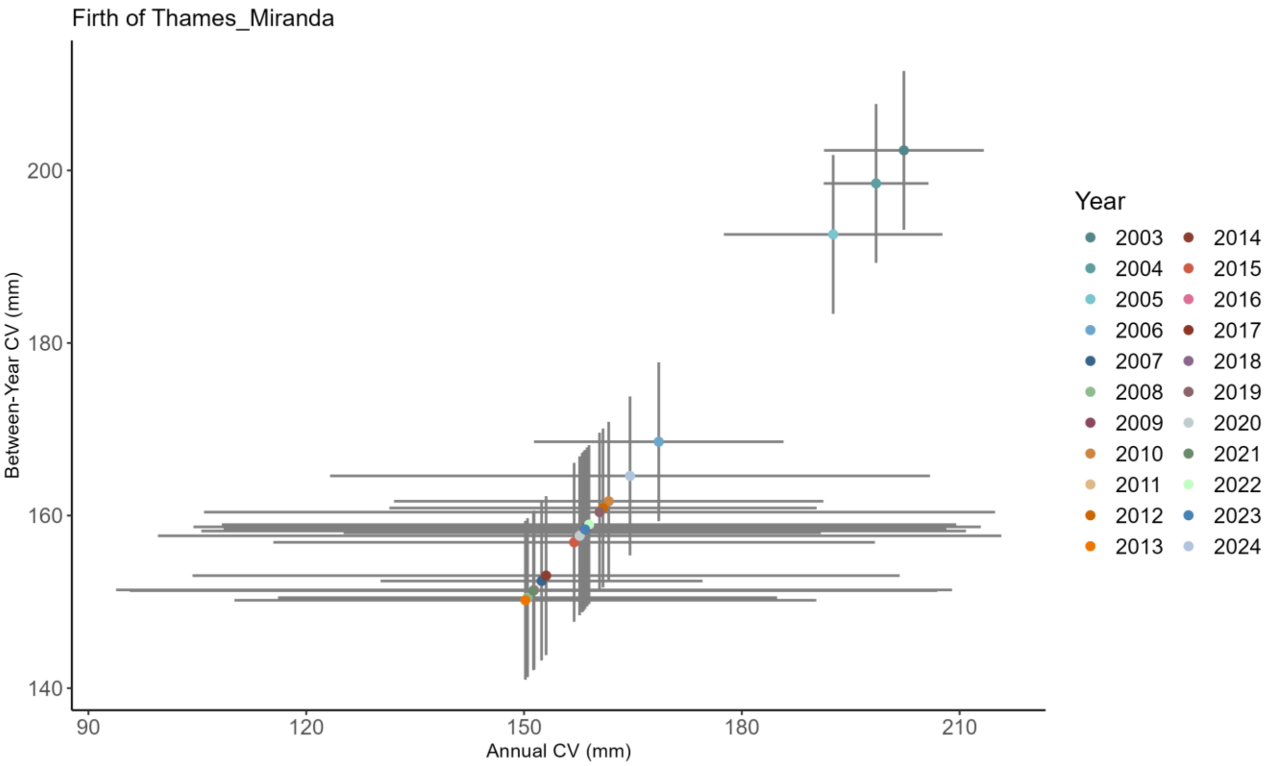


Figure 4. Average sediment depths across four of 15 sites in Waikato with a transect plate design. Coloured lines indicate average sediment depth (± standard deviation) for individual plates. (A) Pepe Inlet was one of the few sites that showed similar sediment accretion patterns between plates, while Coromandel Town, Whangapoua Harbour and Miranda (B–D) provide examples of highly variable sediment accretion patterns between sites across time. Note that these plots show sediment depth, rather than sediment accretion rate, so we would expect to see some offset between plates depending on how deep they were initially buried. See Appendix 3 for plots of sediment depths through time for other sites.

Sediment depths measured within a plate exhibited low variability (Appendix 4), meaning it was appropriate to average replicate depth measurements for each plate prior to calculating SAR. This approach allowed us to standardise SAR calculations across datasets, as some councils provided data where replicate depth measurements had already been averaged.

Temporal variation in sediment accretion

For the majority of sites, sediment depths measured within a single year exhibited higher variability than those measured between different years, similar to patterns shown at two representative sites in Figure 5. See Appendix 4 for CV plots of other sites.



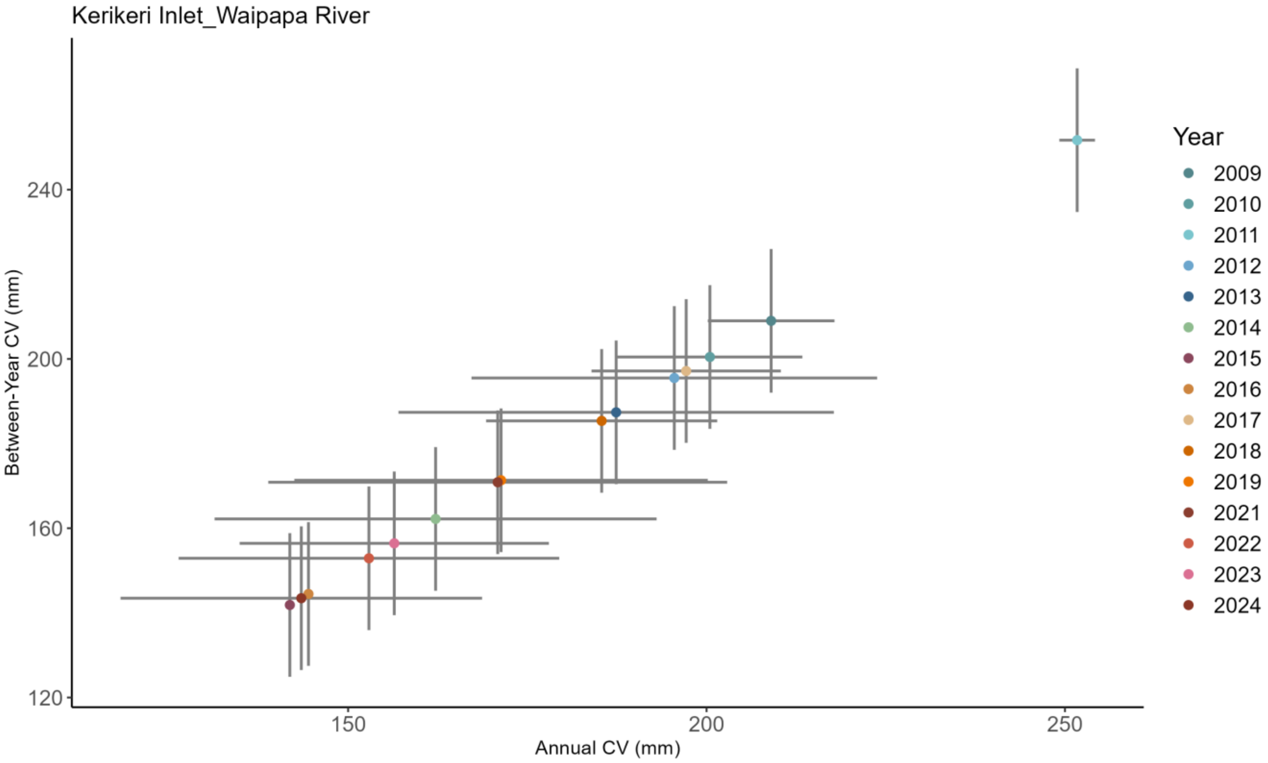


Figure 5. Within-year (annual) and between-year coefficient of variations (CVs) for two example sites, one in Waikato (top: Miranda) and one in Northland (bottom: Waipapa River). See Appendix 4 for CV plots of other sites.

Overall patterns in sediment accretion

The time-series plots of averaged sediment depths provide a general indication of sediment accretion and erosion patterns, and showed mixed trends across sites (Figure 6). Some sites showed no strong long-term directional change. Others exhibited sharp spikes in sediment accretion following storm events, but these patterns were not consistent across all storms. For instance, both Okete Bay (Waikato) and Otaika Flats (Northland) experienced major storms in 2011 (ex-Tropical Cyclone Wilma) and 2014 (ex-Tropical Cyclones Lusi and Ita), with sediment depths peaking between 2012 and 2016 before dropping sharply (Figure 6A and B). However, without site-specific notes and observations, it is difficult to confirm whether these storms were the primary drivers of the observed sedimentation changes. At Okete Bay, for example, a temporary establishment of Asian date mussels disrupted typical sedimentation patterns.

The majority of the sites showed an increasing positive trend, indicating long-term sediment accretion at these sites. For example, Haroto Bay (Waikato) and Kaiaua (Waikato) both displayed sediment accretion over time but with high interannual variability and notable increases around 2015 in Kaiaua (Figure 6C and D). Interestingly, a high number of sites showed a negative long-term trend, indicating ongoing erosion of sediments (Figure 6E and F). See Appendix 5 for time-series plots of all sites.

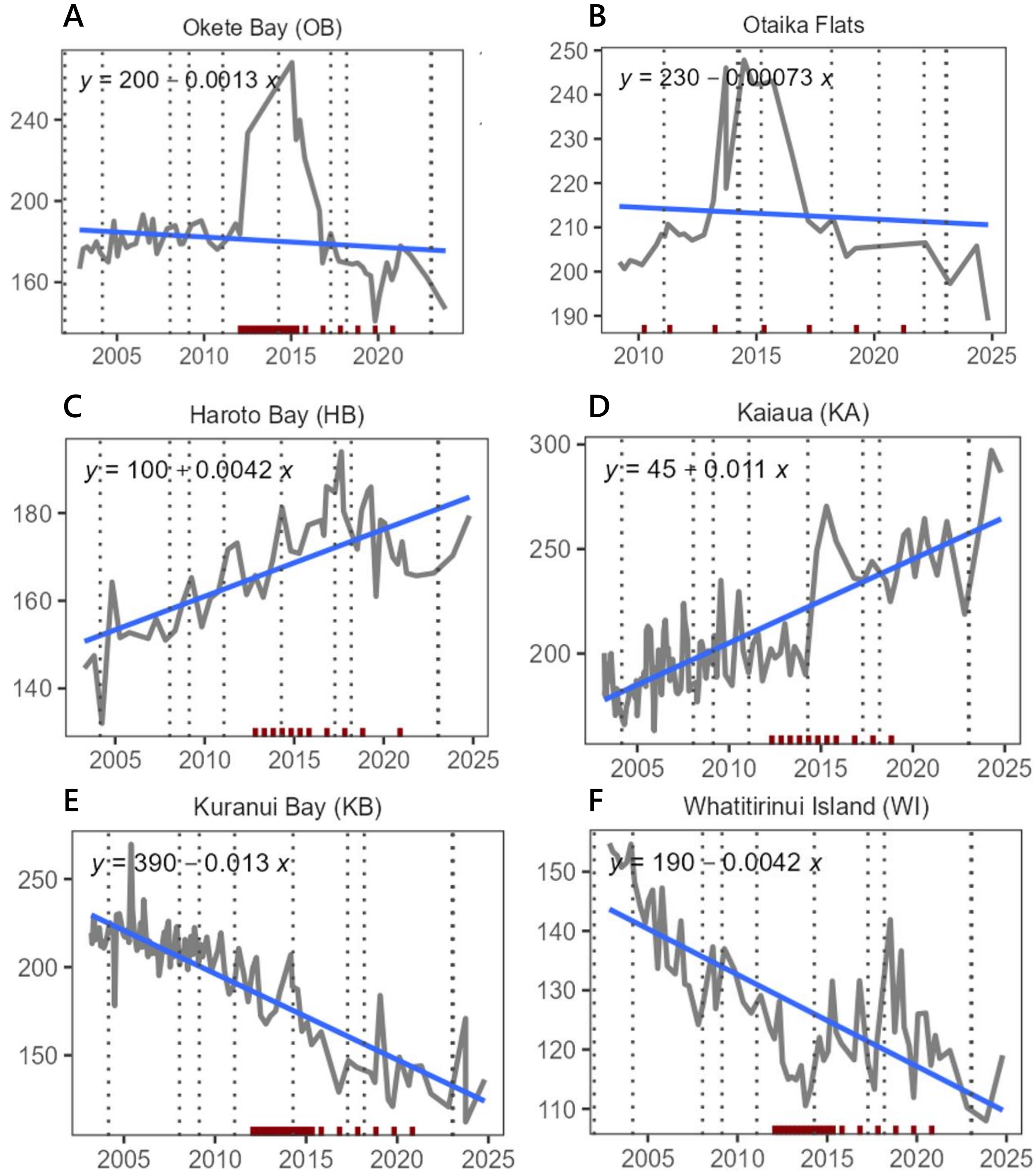


Figure 6. Time-series plots of averaged sediment depths (mm; y-axis) over time (year; x-axis) for selected sites. Each panel shows data from a single site, with linear trend lines (solid), storm events (dotted vertical lines) and macrofauna sampling events (red rug marks). Panels A and B show examples of sites with no clear long-term change in sediment depth. Panels C and D illustrate sites with an increasing trend, indicating long-term sediment accretion. Panels E and F show sites with a decreasing trend, indicating erosion. These plots provide a general indication of sediment accretion and erosion patterns at each site. Final quality control checks on the combined macrofauna / SAR / mud dataset (see Section 2.1) have not yet been completed. Data may include plates that were reburied or replaced, as well as site/time combinations that are not reliable indicators of long-term sediment accretion. Site averages are based on raw values and have not been adjusted for differences in the number of contributing plates. See Appendix 5 for time-series plots of all sites.

3.3 Effect of calculation method on sediment accretion rates

We found that the method of calculation had minimal impact on the SAR values, with correlations between the two approaches ranging from 0.82 to 0.97 (Figure 7). Strongest correlations were observed in the 1–2-month and 1-year SAR datasets (R = 0.93 and 0.97, respectively), likely due to the similarity in the underlying data used for SAR estimation. For example, in the 1–2-month SAR dataset, the regression line was typically fitted using only two data points, making it effectively identical to the simple calculation method. At sites where data are collected annually, a similar situation applied to the 1-year SAR values, with just two data points used for these regressions.

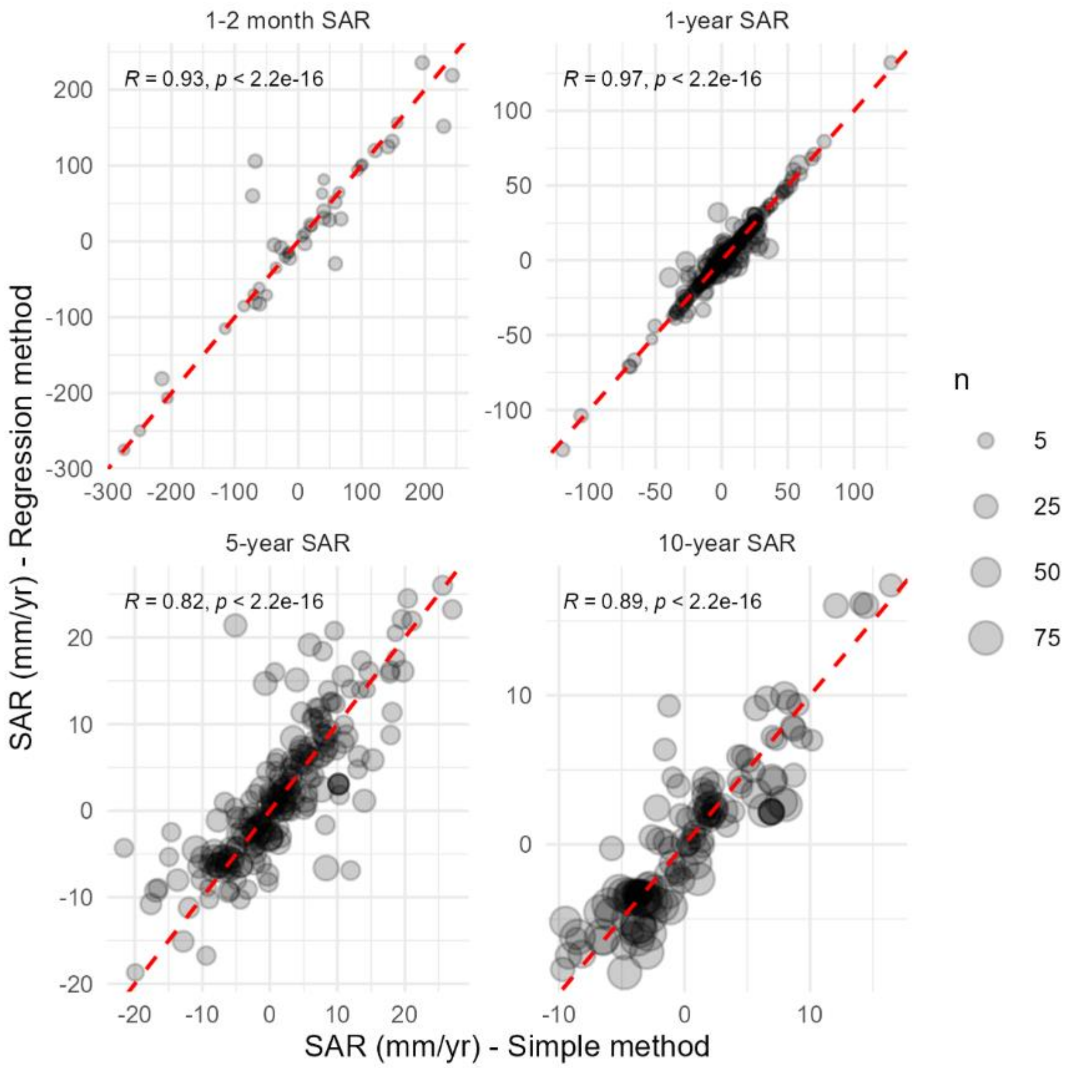


Figure 7. Scatter plots of sediment accretion rates (SARs) calculated using two methods: a simple two-point calculation, and a linear regression based on all available data within each period. The dashed red line indicates the 1:1 line, representing perfect agreement between the two methods. Higher Pearson correlation coefficients (R) indicate similarity between SAR values derived from the two calculation methods. p values < 0.05 denote statistically significant correlations and n refers to the number of observations. SAR values were calculated across four time periods preceding macrofauna sampling: 1–2 months, 1 year, 5 years and 10 years.

3.4 Response of macrofaunal communities to sedimentation

Canonical correlation values (*r*) indicated that the relationship between SAR and macrofaunal community structure was weak across most SAR time periods and sediment regimes (r = 0.16–0.54; Tables 7 and 8). The exception was the 1–2-month SAR dataset at site/times experiencing sediment accretion, where SAR was a strong predictor of macrofaunal community structure (r = 0.98). No clear patterns were observed to suggest that estuary type, region, within-estuary site location or tidal elevation influenced the relationship between community structure and SAR; results are therefore not presented.

Results from the DistLM showed that SAR explained relatively little of the variation in the macrofaunal community compared to sediment mud content (Tables 7 and 8). Marginal tests showed that at accreting site/times, mud content explained 11.3–15.6% of the variation in community structure and SAR explained less than 1–5.6%. At site/times dominated by erosion, mud content explained 8.2–24.9% of the variation and SAR only 1.6–7.2%. In sequential DistLM models, mud content consistently emerged as the best predictor of community structure.

Among the SAR datasets, the 1–2-month SAR had the highest canonical correlation (r = 0.98) and greatest explanatory power (5.6%) in the DistLM marginal tests at site/times where sediment was accreting. In contrast, at erosional sites the 5-year SAR dataset produced the highest canonical correlation (r = 0.56), and in the DistLM the highest explanatory power for SAR was in the 10-year SAR dataset (7.2%). These differences could reflect the contrasting nature of different sediment regimes: for example, accretion may occur through short-term depositional events, while erosion could reflect longer-term processes – potentially indicating a return to equilibrium following historical sediment accumulation.

Table 7. Results of canonical analysis of principal coordinates (CAP) and distance-based linear modelling (DistLM) for site/times where sediment was accreting (positive sedimentation accretion rate values). *n* = number of observations, *r* = canonical correlation between sediment accretion rate (SAR) and macrofaunal community.

Parameter	1–2-month SAR	1-year SAR	5-year SAR	10-year SAR
CAP				
n	23	149	101	57
r	0.975	0.253	0.430	0.512
DistLM				
n	23	122	76	41
Marginal tests				
Mud (ln) SAR (raw)	15.6% 5.6%	11.3% < 1.0%	11.8% 4.1%	13.0% 3.7%
Sequential tests (using forward selection)				
	Mud (ln): 15.6% + SAR: 5.8%	Mud (ln): 11.3% + SAR: 1.0%	Mud (ln): 11.8% + SAR: 4.1%	Mud (ln): 13.0% + SAR 3.2%

Table 8. Results of canonical analysis of principal coordinates (CAP) and distance-based linear modelling (DistLM) for site/times where sediment was being eroded (negative sedimentation accretion rate values). *n* = number of observations, *r* = canonical correlation between sediment accretion rate (SAR) and macrofaunal community.

Parameter	1–2 month SAR	1-year SAR	5-year SAR	10-year SAR
CAP				
n	21	117	77	59
r	0.162	0.317	0.562	0.453
DistLM				
n	21	91	43	31
Marginal tests				
Mud (ln) SAR (raw)	24.9% 2.5%	8.2% 1.6%	10.9% 5.6%	9.0% 7.2%
Sequential tests (using forward selection)				
	Mud (ln): 24.9% +SAR (log_{10}): 2.7%	Mud (ln): 8.2% + SAR: 1.7%	Mud (ln): 10.9% + SAR: 6.2%	Mud (ln): 9.0% + SAR: 7.2%

3.5 Response of key taxa and ecological indicators to sedimentation

Change point detection

When interpreting these results, it should be kept in mind that the change point detection method that we used requires a minimum of 20 observations before identifying a change in abundance and is limited to detecting only the first significant change point. As mentioned in Section 2.5, change points were not calculated for the 1–2-month SAR dataset due to insufficient data. The highest number of taxa with detected changes in abundance occurred at the 1-year SAR, where 10 out of 12 taxa showed evidence of change (Appendix 6). Fewer taxa showed changes in abundance in the 5-year SAR (seven taxa; Figure 8) and only one taxon showed a change for the 10-year SAR (Appendix 6).

In the 1-year SAR dataset (Appendix 6), 10 taxa exhibited change points, with shifts detected from -19 mm to +46 mm. For example, the *Austrohelice / Hemigrapsus / Hemiplax* group showed a change at 22 mm, the *Capitella /* Oligochaeta group at 13 mm, and *Heteromastus filiformis / Barantolla lepte* at 46 mm. Conversely, changes in *Cossura* and *Halicarcinus* abundances were detected at negative SAR: -19 mm and -11 mm, respectively. For the 5-year SAR (Figure 8), change points were identified for seven taxa, with shifts detected between 1 mm and 27 mm. For instance, *Heteromastus filiformis* / *Barantolla lepte* abundance changed at 27 mm, while *Macomona liliana* shifted at 6 mm. Several taxa, such as *Aonides*, *Austrovenus stutchburyi* and *Capitella /* Oligochaeta, showed no change. For the 10-year SAR (Appendix 6), *Amphibola crenata* was the only taxon with a detected change, showing a shift in abundance at 10 mm.

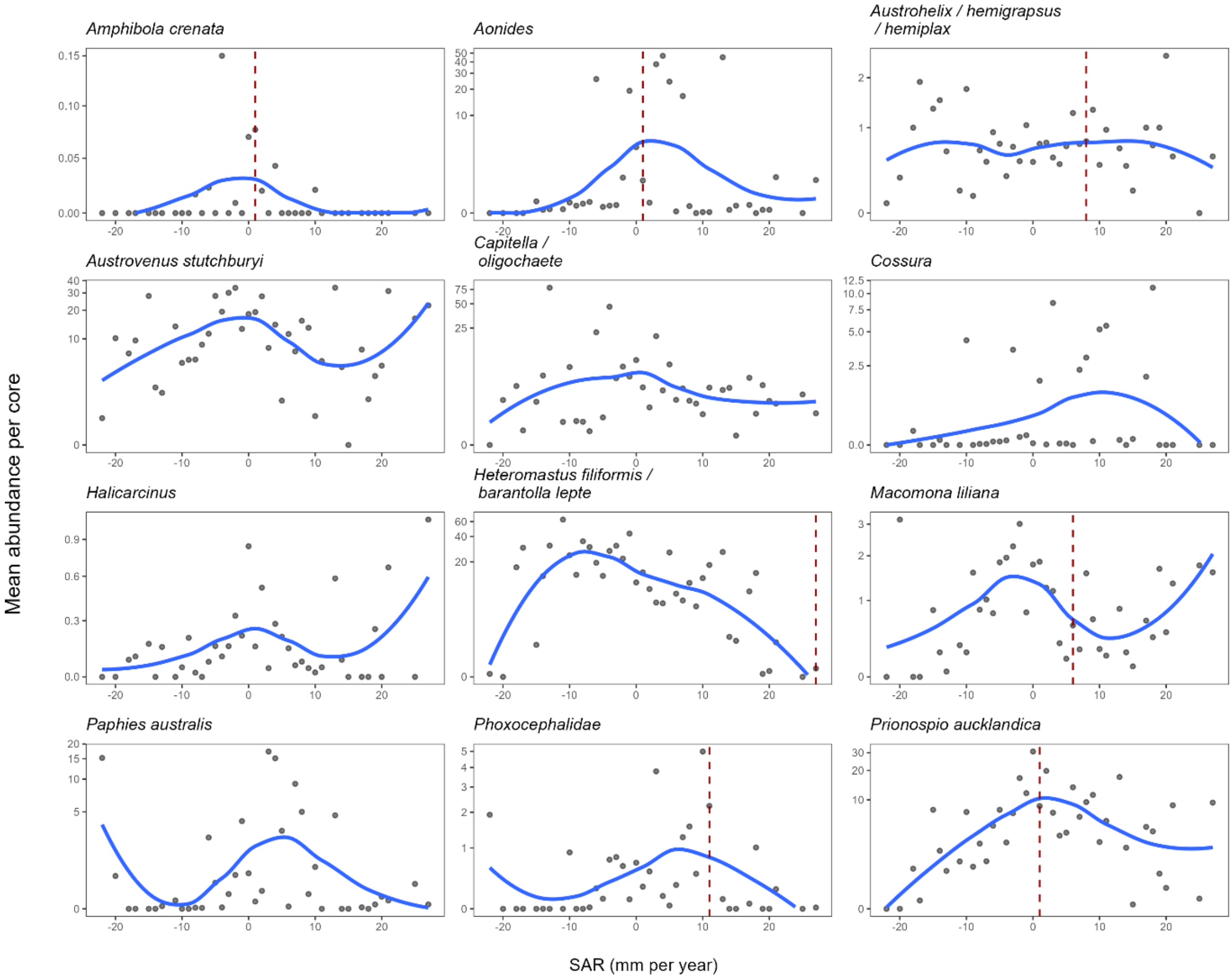


Figure 8. Plots showing the location of significant changes in macrofauna taxa abundance (indicated by dashed red lines) along 5-year SAR gradients, as identified using change point detection analysis. Blue lines are LOESS curves, included to aid visualisation of non-linear trends, but are not part of the change point analysis. See Appendix 6 for plots for other SAR periods.

Generalised additive models: key taxa

The explained deviance of the GAMs varied across taxa and SAR periods (Appendix 7). For the 1–2-month SAR, deviance values ranged from 0.02 to 0.45 (median 0.16), with the *Austrohelice / Hemigrapsus / Hemiplax* group showing the highest deviance explained and Phoxocephalidae the lowest. Over the 1-year SAR, explained deviance ranged from 0.02 to 0.30 (median 0.095), while for the 5-year SAR it ranged from 0.01 to 0.28 (median 0.155). In both periods, *Paphies australis* had the highest explanatory power and Phoxocephalidae remained among the lowest. For the 10-year SAR, explained deviance ranged from 0.02 to 0.42 (median 0.145), again with a maximum for *P. australis* and with *Halicarcinus* recording the lowest value.

SAR had fewer significant effects on species abundance compared to mud content, with its influence becoming more apparent over longer timescales. No species showed a significant response ($p > 0.05$) to the 1–2-month SAR (Appendix A8.1).

For the 1-year SAR (Appendix A8.1), only *Cossura* abundance was significantly affected by SAR ($p < 0.001$). *Cossura* partial dependence plots showed the weakest effect at intermediate SAR values, with responses increasing towards both low and high ends. A significant rate of change was indicated by the first derivative of the smooth term. However, most data points clustered near the centre, so model predictions are less reliable at the extremes. In addition, there was marginal effect of 1-year SAR on *Austrovenus stutchburyi* abundance ($p = 0.07$), with the first derivative of the smooth term indicating changes at the extremes of the SAR range.

The 5-year SAR (Figure 9) had a significant effect on the *Heteromastus filiformis / Barantolla lepte* group ($p < 0.001$), with abundance declining sharply from positive SAR values. In contrast, *Prionospio aucklandica* abundance increased significantly up to zero SAR values ($p < 0.04$).

The 10-year SAR GAMs (Appendix A8.1) showed significant declines in *Heteromastus filiformis / Barantolla lepte* abundance ($p < 0.001$), and significant increases in *Paphies australis* ($p < 0.02$) and Phoxocephalidae ($p < 0.01$). The rate of increase for the latter was steepest from slightly erosional (negative SAR) conditions up to 15 mm/year.

Most of the significant changes did not align with ecological expectations. The exception was the response of *Prionospio aucklandica* to 5-year SAR, as this species generally prefers sediments that are not too sandy and not too muddy, suggesting it may thrive in places with intermediate SAR levels.

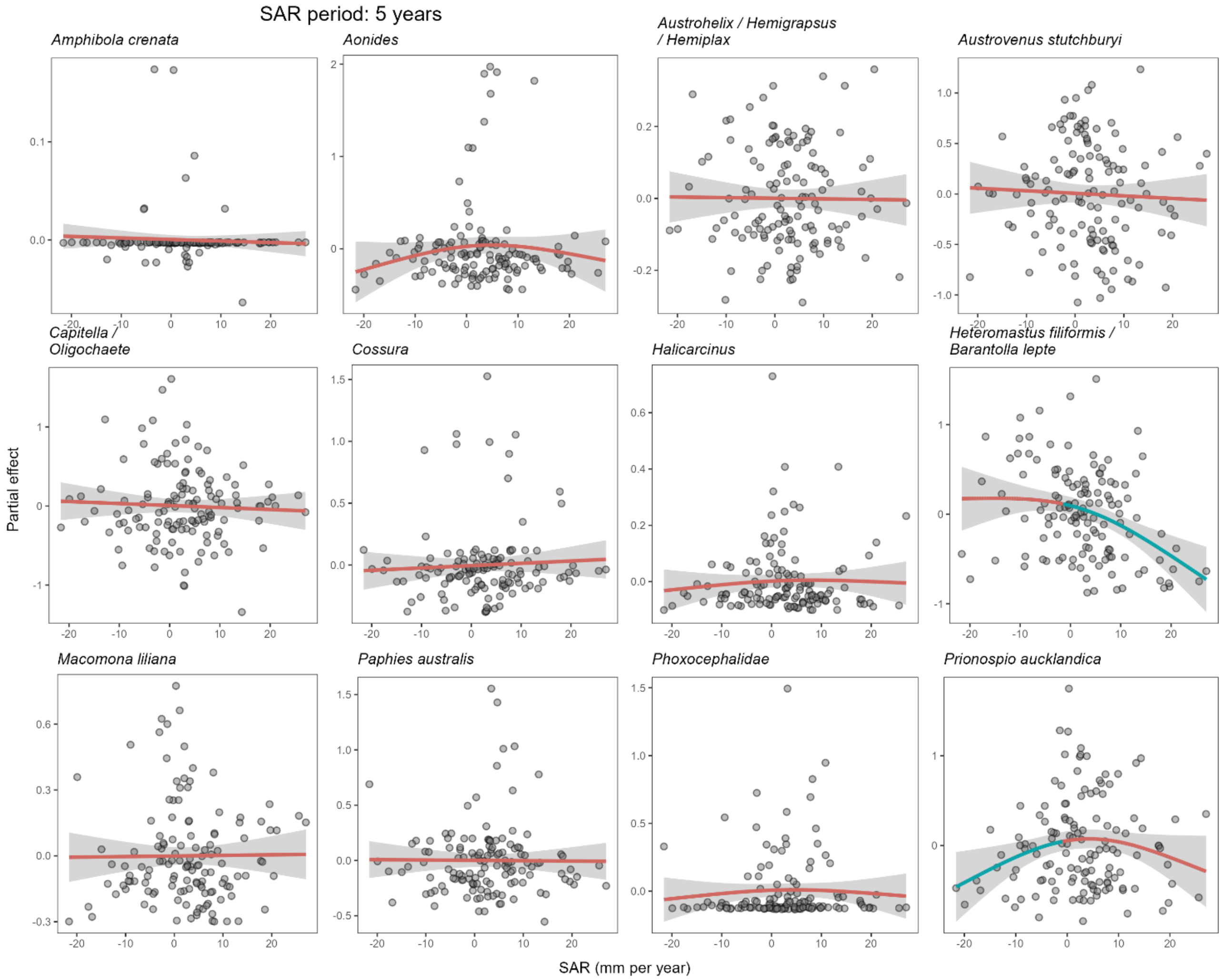


Figure 9. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 5-year SAR and macrofauna taxa abundance. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor. See Appendix A8.1 for plots for other SAR periods.

In contrast, mud content had a stronger and more widespread effect on species abundance than SAR (Appendix 7). For the 1–2-month SAR (Appendix A8.2), the abundance of five species was significantly affected by mud content. The 1-year (Appendix A8.2) and 5-year SARs (Figure 10) influenced the abundance of 11 species, while for the 10-year SAR (Appendix A8.2), eight species showed significant effects. In contrast to SAR, significant changes generally aligned with ecological expectations for these taxa with respect to sediment mud content, and relationships were more consistent between SAR periods.

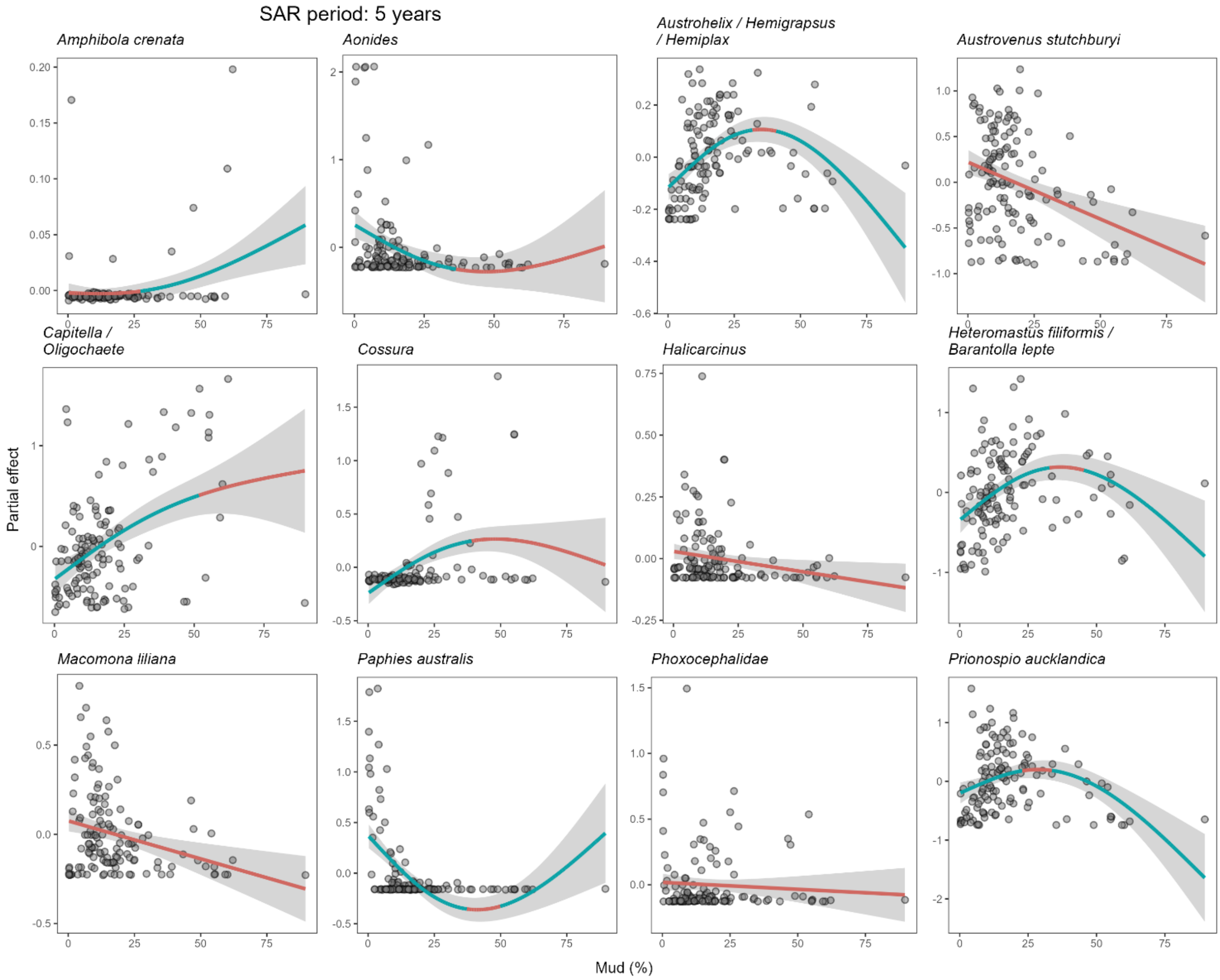


Figure 10. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and macrofauna taxa abundance in the 5-year SAR dataset. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor. See Appendix A8.2 for plots for other SAR periods.

Generalised additive models: ecological indicators

The explained deviance of the GAMs varied across ecological indicators and SAR periods (Appendix 7). For Shannon–Wiener diversity (*H*), deviance explained ranged from 0.10 to 0.23 and was highest at the 5-year SAR. Evenness (*J*) showed lower explanatory power, ranging from 0.04 to 0.14 and also peaking at the 5-year SAR. Species richness (*S*) consistently showed higher deviance explained, with 0.29, 0.35 and 0.34 for the 1-year, 5-year and 10-year SARs, respectively. The Mud BHM showed the highest deviance explained across all indicators, ranging from 0.62 to 0.67. As expected, most of this explanatory power was attributed to mud content, while SAR accounted for less than 0.1 of the deviance.

Significant relationships between mud content and ecological indicators were detected across most SAR periods (Appendix A8.1). Mud content was strongly associated with Mud BHM in all SAR periods (Appendix A8.2). Species richness also showed consistent and significant responses to mud. Shannon–Wiener diversity had weaker but still significant responses to mud, particularly at the 1-year and 10-year periods (Appendix A8.2). Evenness showed a significant relationship only at the 1-year and 5-year periods ($p < 0.001$; Figure 11 and Appendix A8.2), but it was not the pattern we expected to see. SAR was also a significant predictor for several indicators, especially at the 5-year period (Figure 12) for *S* ($p < 0.001$), *H* ($p = 0.03$) and Mud BHM ($p = 0.01$), and at the 10-year period (Appendix A8.1) for Mud BHM and *S*. However, the negative relationship between SAR and Mud BHM scores was not what we would expect to see.

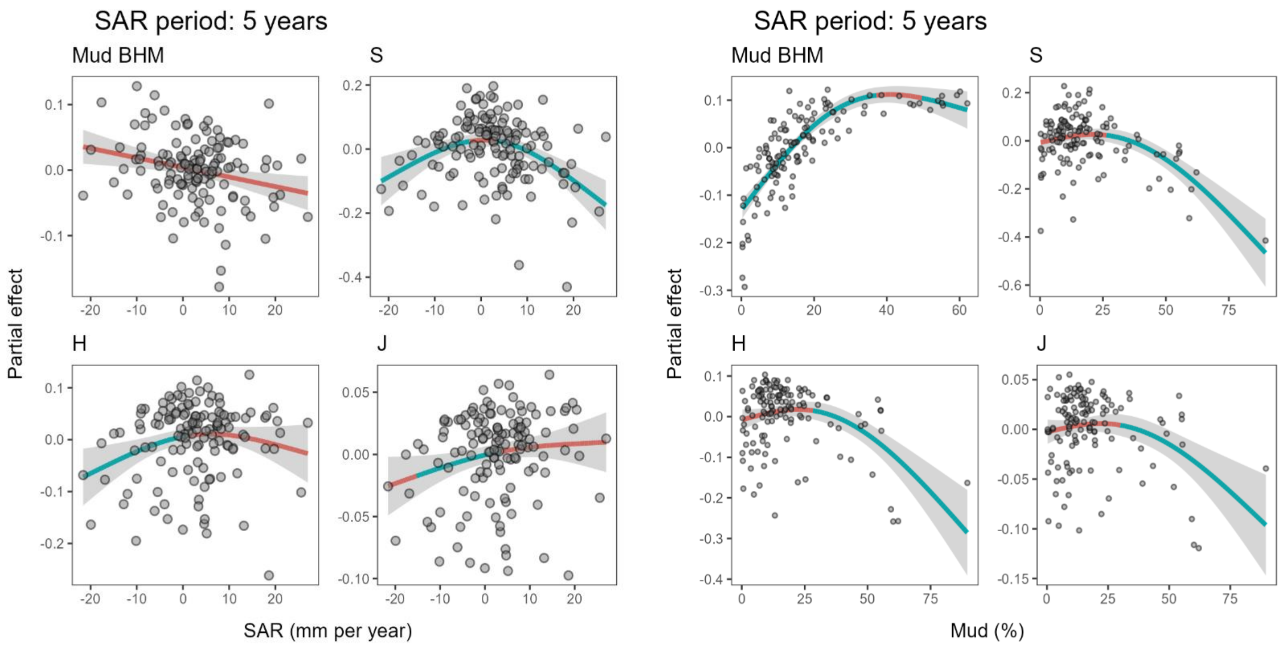


Figure 11. Partial dependence plots for sediment accretion rate (SAR; left) and sediment mud content (right) from generalised additive models showing the relationship between these parameters and ecological indicator values in the 5-year SAR dataset. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor. See Appendix A8.1 and A8.2 for plots for other SAR periods.

4. Discussion

4.1 Relationship between sediment accretion rate and ecological health

The objective of this study was to assess whether there is a relationship between sediment accretion rates (SAR), sediment mud content and ecological health, and to provide recommendations for refining the current DGV for estuarine sedimentation rates. However, no clear relationship was found between the amount of sediment accumulation and macrofaunal communities, ecological indicators or the abundance of key taxa. The outcome was consistent regardless of whether short-term (1–2-month), medium-term (1-year) or long-term (5- and 10-year) SARs were considered. While significant change points and relationships were found between some taxa or ecological indicators and SAR for some SAR time periods, these patterns were inconsistent and did not always align with ecological expectations. In all cases, sediment mud content was a better predictor of ecological health than SAR.

The weak or lack of relationship between SAR and ecological health is perhaps not surprising, as SARs are often highly variable in space and time, and it is difficult to accurately measure very small (e.g. millimetres) changes in seabed elevation against a background of high natural variation. As discussed in Section 1.2, SAR can also vary significantly depending on the location of sediment plates within the estuary, with differences often occurring over relatively small spatial scales.

Sediment accumulation also varied substantially over time, with many sites alternating between periods of accretion and erosion. These patterns are primarily driven by weather events (e.g. rainfall, wind) and hydrodynamic processes (e.g. waves, currents), which are, in turn, influenced by seasonal changes and broader climatic cycles (e.g. El Niño–Southern Oscillation). This high temporal variability means that the timing of sampling relative to seasonal patterns or storm events could have a significant impact on the SAR estimated for a site, particularly when measured infrequently or over a short time period. Our analysis of sediment accretion variability supports this, showing that at many sites the variability in sediment depth within a single year was greater than the variability between years. Our SAR estimates assume a constant rate of change over the specified period (i.e. they were calculated from the difference between two depths divided by the number of days), whereas in reality sedimentation is likely to have occurred in episodic events. These events may have occurred shortly before the macrofauna sampling or months to years earlier, introducing a potential mismatch between the timing of physical changes in the sediment and macrofaunal responses.

The sediment plate sampling design can also influence the precision and accuracy of SAR measurements. Factors such as whether SARs were estimated from a single plate or multiple plates, the number of replicate depth measurements taken per plate and the proximity of the plates to where the macrofauna samples were collected can all affect the results. For example, at two sites in the Firth of Thames macrofauna samples were collected between two sediment plates recording opposing long-term SAR trends – sediment accretion at one and erosion at the other (Hunt 2023). In such instances, the location of the macrofauna samples may be experiencing little or no net sediment change, a condition that is poorly represented by the sediment plate data, particularly on occasions when measurements were obtained from only one of the two plates.

In addition to site design differences, a range of operational issues can affect measurements. These include plates tilting or becoming uncovered; accidental disturbance (e.g. stepping on plates); surface irregularities caused by bioturbators, fish and rays; smothering by seaweed; encroachment by mangroves or Asian date mussels; and plates being submerged at the time of sampling. We removed data where field notes indicated that the measurements would not provide a reliable estimate of long-term sediment accretion (e.g. smothering by thick *Gracilaria* algae). However, we cannot be certain that all such issues were consistently reported. For instance, sediment plates at Pūkorokoro / Miranda in the Waikato Region were affected by a shifting chenier ridge that migrated through the monitoring area over a decade, but this was not clearly recorded in the data provided as it would be difficult to discern in the field. We chose to retain data where notes indicated issues such as fish or ray pits, mangroves, seagrass presence, mounds, a heterogeneous bed or measurements made around footprints, as it is likely these data would be included when councils report SARs for their region.

Although such measurement challenges are a concern in all monitoring programmes, particular caution is needed when estimating SARs due to their reliance on a baseline depth. Any changes to monitoring protocols or site conditions during the measurement period can significantly influence SAR estimates. For example, we observed substantial differences in sediment depth between plates at some of the sites with transect designs,[8] meaning that the omission of a plate (e.g. due to it being submerged or missing) had a disproportionate effect when calculating the average of the two plates relevant to the macrofauna. Where this was clearly the case, we attempted to manually adjust the SAR estimates by ensuring that the site averages for both time periods used in the SAR calculation were based on the same set of plates. This approach was possible because we calculated SAR using only two time points, allowing us to manually match plate data across periods. However, this is not feasible when using a regression-based approach to estimate SAR, as it relies on multiple time points. In such cases, accounting for missing or inconsistent plate data becomes more challenging. While it is possible to exclude plates with incomplete records, doing so would result in a substantial loss of data, potentially undermining the spatial and temporal coverage of the dataset.

In addition to the variability inherent in estimating SARs, macrofaunal communities themselves exhibit high natural variability. Community composition reflects an integrated measure of ecological health, capturing not only the effects of sedimentation but also the cumulative influence of multiple stressors that may co-occur at a site. These stressors often interact in complex, non-linear and multiplicative ways (Crain et al. 2008; Darling and Côté 2008; deYoung et al. 2008). Moreover, macrofaunal communities are influenced by a range of natural, temporally dynamic factors operating at multiple spatial scales – locally (e.g. wind-wave exposure, sediment grain size, salinity; Snelgrove 2001) and regionally or globally (e.g. temperature, climate patterns; Engle and Summers 1999; Hewitt et al. 2016; Denis-Roy et al. 2020) – as well as by temporal processes such as recruitment dynamics. While it is possible to disentangle this complex web of factors (e.g. Clark et al. 2021), this variability could obscure relationships between sedimentation rates and ecological health.

[8] Sediment plates are often buried at different depths for a good reason (e.g. the presence of a hard shell layer in the sediment).

The potential mismatch between the timescales over which sediment accumulates and those over which macrofaunal communities respond warrants further discussion. Both processes operate across multiple temporal scales. Each estuarine site has a unique sedimentation history that spans decades to centuries, shaped by long-term background accumulation and punctuated by short-term fluctuations driven by storm events, land-use changes or other episodic disturbances. While we attempted to capture this variation by calculating SAR over multiple time periods, even the 10-year SAR cannot fully account for the impacts of longer-term historical sedimentation. For example, sediment plate measurements at Kuranui Bay in the Firth of Thames indicate consistent erosion over the past 20 years. But this likely fails to reflect a longer history of substantial deposition that is gradually being removed by wave action as the system shifts toward equilibrium with current sediment supply (Hunt 2023). In contrast, macrofaunal communities, typically respond to environmental conditions over shorter timescales. While the long-term sediment history influences which taxa can persist at a site, community composition is more likely to reflect recent changes occurring over the scale of months. Unfortunately, our analysis did not clarify whether short-term or long-term sedimentation has the greatest influence on ecological health, as no meaningful relationships were detected for any of the time periods assessed.

4.2 Suitability of guideline threshold values for sedimentation

Given the lack of a clear relationship between SAR and ecological health, we are unable to provide further refinement to the current DGV for estuarine sedimentation rate. The DGV of '2 mm/yr above the natural annual sedimentation rate for the estuary, or part of estuary, at hand' is based on experimental data on the responses of macrofaunal communities to fine-sediment deposition following rainstorm events (Townsend and Lohrer 2015). In the absence of further empirical evidence, we suggest continuing to use this DGV, as it offers a reference point for understanding changes in SAR within the context of potential impacts on ecological health. Additional context on contemporary sedimentation rates around Aotearoa New Zealand can be drawn from the current study, which recorded sedimentation rates between -27 mm/yr and 36 mm/yr at most (90%) site/times. However, extreme rates as low as -274 mm/yr and as high as 243 mm/yr were also observed. Our study highlights the significant variability in sedimentation rates, which are highly dependent on the location of sediment plates, the timing of measurements and the timeframe over which SAR is calculated. Therefore, we stress that the DGV should only be used to trigger further investigation and to help interpret results in context.

Even if we had been able to find clearer relationships between SAR and ecological health, it is unlikely that a single value would have been applicable for all estuarine sites across Aotearoa New Zealand because estuarine state and responses are highly place- and context-specific. For example, upper reaches of estuaries may be able to cope with greater levels of sedimentation than areas closer to the estuary mouth, certain estuary types may be adapted to cope with higher levels of sedimentation, and sites that are under pressure from multiple stressors may have less resilience to cope with sedimentation stress. Exploratory analysis indicated that estuary type, within-estuary location, tidal elevation and region did not affect the relationship between SAR and macrofaunal communities, key taxa or ecological indicators; however, these factors were not formally tested. In addition, with climate change expected to alter sediment dynamics over time, we expect that relationships between SAR and ecological health may change in the future – underscoring the potential value of adopting more precautionary guidelines.

Although our study does not offer empirical evidence to evaluate the SAR thresholds proposed by Stevens et al. 2024), it does provide additional context for understanding those thresholds. Notably, erosion of sediment, rather than deposition, was recorded at 45% of site/times in our dataset. The proposed thresholds focus solely on the impacts of sediment accretion, and by overlooking erosional values they suggest that negative SAR values are either not a concern or may even be beneficial. However, in ecological terms any deviation from normal conditions can have consequences for community structure. Given that climate change may increase the frequency of erosion events through sea-level rise and intensified wave action, it is important to consider the implications of erosion in future assessments of sediment dynamics. As with the DGV, we strongly encourage that these thresholds are viewed as reference values for interpreting results, rather than rigid limits.

4.3 Limitations and future work

The ability to detect relationships between SAR and ecological health is highly dependent on the availability and quality of data. The dataset used in this study was relatively large (n = 710 unique observations), spanning a broad SAR gradient and encompassing a diverse array of regions, estuary types, within-estuary site locations and tidal elevations. While additional data are available that could potentially be incorporated with more time and resources, we believe it is unlikely that doing so would substantially alter the conclusions of our analysis. Similarly, although we could have used a regression-based approach to estimate SARs, our comparison showed that both methods produced similar results, suggesting that the choice of approach would not have materially affected our findings.

To meet the primary objective set by the MfE, which was to refine the national DGV for SAR, a national-scale analytical approach was essential. This required incorporating data from a wide range of sites across Aotearoa New Zealand, rather than limiting the analysis to a small number of locations with sufficient temporal data. To enable this, we adopted a space-for-time substitution approach, using spatial variation in SAR to infer how a single site might respond to changes in sedimentation over time, even in the absence of long-term SAR data. While commonly used in ecological studies, this approach introduces variability that could obscure potential relationships between SAR and ecological health. Future work could benefit from focusing on a sub-set of sites with robust paired SAR and macrofauna datasets and well-established time series, particularly where there have been marked changes in SAR. This would allow for more targeted assessments of ecological responses over time. Additionally, although we conducted a preliminary analysis of how estuary type, region, within-estuary site location and tidal elevation influenced the SAR–ecological health relationship, these factors warrant further investigation.

Our analysis also considered whether macrofaunal communities reflected SAR conditions only in the months or years preceding sampling. It did not account for the state of the macrofaunal community at the beginning of each SAR measurement period. Incorporating this baseline information could help resolve temporal mismatches between SAR and ecological condition. Similarly, exploring macrofaunal turnover or rates of change alongside SAR could help identify parallel shifts in community structure. Historical data – such as from dated sediment cores – could also provide insights into pre-contemporary impacts and how they influence present-day conditions.

We assessed ecological health by examining changes in macrofaunal community structure, ecological health indicators, and the abundance of ecologically, functionally and culturally important species. However, functional redundancy and resilience are also critical components of ecological health (Gammal et al. 2023). These could be explored further through analysis of functional traits or by using indicators that reflect ecosystem functioning, such as the traits-based index (Rodil et al. 2013). The RI-AMBI (also called the NZ hybrid AMBI; Robertson et al. 2016b), calculated using eco-groups based on taxa responses to changes in mud and organic carbon, is another ecological indicator that could be explored in future studies.

This study focused on understanding the relationship between SAR, sediment mud content and ecological health; however, SAR and mud content represent only two aspects of sediment-related stress in estuarine environments. As discussed in Section 1.2, other components can have significant ecological effects and should not be considered in isolation. For example, suspended sediment is currently not well monitored by councils, yet it can fluctuate rapidly and exert acute, short-term stress on benthic communities. Unlike SAR, which reflects longer-term patterns of deposition or erosion, suspended sediment dynamics are episodic and are not well captured by metrics such as mud content or SAR. Understanding the interactions between suspended sediment and accumulation dynamics – and how these combined stressors influence macrofaunal communities – is essential for a more holistic assessment of sedimentation impacts and for informing more effective estuarine management strategies.

4.4 Recommendations

Sediment plate data

Sediment plates can be a useful tool for indicating long-term trends in sediment accretion or erosion at a site, but these data are not a reliable proxy for ecological health. Our analysis found that sediment mud content was a much stronger predictor of macrofaunal community structure, ecological health indicators and the abundance of key taxa. The relationship between mud content and ecological health is well established in Aotearoa New Zealand, and grain-size data are also less variable and much easier to collect than sediment plate data. Therefore, if the primary goal is to assess ecological health, we recommend prioritising the measurement of mud content. That said, it is important to note that the most meaningful way to assess ecological health is to directly measure the ecological communities themselves.

Although we did not find a strong or consistent relationship between SAR and ecological health, we still see value in continuing to collect sediment plate data – provided it is done in a standardised manner and interpreted in an appropriate context. For example, these data could help validate catchment sediment models. Sediment plate data are highly variable across space and time, and this variability must be taken into account during interpretation. We support the recommendation by Townsend and Lohrer (2015) that sediment plate data should not be averaged to produce a single estuary-wide SAR estimate. Instead, changes at individual sites should be interpreted in the context of each site's specific location and history, and alongside other measures of sedimentation stress (e.g. mud content, suspended sediment). If there is interest in further exploring the relationship between SAR and ecological health, we have outlined several additional analyses that could be undertaken (see Section 4.3).

Guideline threshold values

For now, we recommend continued use of the estuarine sedimentation DGV of '2 mm/yr above the natural annual sedimentation rate for the estuary, or part of the estuary, at hand' (Townsend and Lohrer 2015). Our recommendation is that this value is treated as a reference point for interpreting results, rather than as a strict environmental limit, and that it is used in conjunction with other indicators of sediment-related stress.

Calculation of sediment accretion rates

Our analysis showed that calculation of SARs using the simple two-data-point method employed in this study and a regression approach produced comparable results. However, the regression approach is more robust because it incorporates all available data points and smooths out anomalies caused by outliers. For instance, if the long-term trend at a site is one of erosion but one of the data points happened to be collected just after a storm, the two-point method might misleadingly suggest stability or accretion. These differences become particularly important when interpreting changes at a single site over time. Our recommendation is to always plot data to visualise trends, and where possible, follow the methods outlined by Hunt (2023) for calculating SARs. Hunt recommends fitting a linear trend line to averaged sediment plate data, calculating SAR from the slope of that line, and reporting 95% confidence intervals for the linear fit. This interval reflects confidence in the trend, not variability among replicate plates, and enables reporting results as 'X mm/yr ± X mm/yr',' which provides a useful indication of the reliability of the estimate. As the slope of a regression is most influenced by the values at either end of the time series, we recommended collecting measurements more frequently at the start of the time series (once the plate has properly bedded in), to improve the reliability of the estimated trend.

This regression approach assumes a constant rate of sediment accretion or erosion over the time series, which may not always be valid – particularly as climate change introduces greater variability into sediment regimes. However, including the confidence interval provides a helpful indication of the appropriateness of a linear model. For example, the spike in sedimentation observed in Okete Bay is clearly non-linear (see Appendix 5); in such cases, wide confidence intervals reflect the uncertainty of the SAR estimate. At sites like these, it may be useful to calculate a running mean through the dataset and identify inflection points where the trend can be segmented into separate linear periods with consistent SARs.

If data from a sediment plate are temporarily unavailable (e.g. due to submersion or the plate being missing), this must be accounted for when fitting a regression. If the plates are true replicates and exhibit similar SAR patterns over time, the omission of one plate may have minimal impact on the overall site average. However, if plates are located along a transect or subject to different sediment regimes – as is often the case – omitting a plate could significantly influence the site average and should be carefully considered. In these cases, the data point may need to be removed before fitting the regression line, or separate lines may need to be fitted for each plate.

If a plate is permanently lost and reinstalled, the time series should be restarted. In some cases, it may be possible to link the new record with the historical one, but this should be done cautiously and only when there is strong evidence that the new plate is in a comparable sedimentary environment. Given the high spatial variability in SAR, combining time series across different plate installations is not generally advisable.

Sampling design considerations

Compilation of sediment plate data from across the country revealed a wide range of sampling approaches. Most sites were located in mid-estuary zones, but a substantial number were in upper and outer estuary reaches. Tidal elevations were typically mid to low, with few sites situated at high-tide levels. While sites were generally unvegetated, a small number were located in seagrass meadows or in areas with encroaching mangroves. Site designs varied considerably in terms of the number of replicate depth measurements per plate, the number of plates deployed, the spatial arrangement of plates, and the distance between sediment plates and macrofaunal sampling locations. Some protocols included the use of a straight edge as a reference for sediment depth, while others did not. Sampling frequency generally ranged from monthly to annually, and the length of the datasets for each site ranged from a single sampling event to 23 years.

This variation in sampling design contributes to the high variability in SAR estimates. Standardising methods would help to reduce this variability and improve data comparability. We recommend leveraging the findings from this study, as well as conducting further analyses of the compiled dataset, to inform standardised monitoring protocols. For example, a precision analysis could help determine the optimal number of replicate measurements per plate. The variability in sediment depth trends observed between plates at some sites suggests that a single plate is unlikely to reliably represent SAR trends at a site. The variation between plates could be explored further by examining variability in SAR values, rather than sediment depths. We also observed that the time of year when measurements are taken may influence SAR estimates. This dataset could be further explored to assess the optimal sampling frequency and minimum time-series length required to produce meaningful SAR estimates. Further guidance on where to locate sites within an estuary would also help to provide comparable results.

However, we stress that even with fully standardised monitoring protocols, SAR is inherently variable – this is a fundamental characteristic of the data and should be acknowledged in both analysis and interpretation.

5. Conclusions

In conclusion, this study found no clear or consistent relationship between SAR and measures of ecological health, including macrofaunal community structure, the abundance of key taxa or ecological indicator scores. This outcome held true across short-, medium- and long-term SARs. The lack of relationship is likely due to the high spatial and temporal variability of SAR, measurement limitations, and the complex nature of estuarine ecosystems where multiple interacting stressors influence ecological communities. Mud content emerged as a far stronger and more reliable predictor of ecological health, reinforcing its value as a monitoring metric for that purpose. While SAR can still offer insight into sediment dynamics – particularly when collected and interpreted in a standardised and site-specific manner – it is not suitable as standalone indicator of ecological condition. Consequently, we recommend continuing to use the current sedimentation DGV as a contextual reference rather than a strict threshold, and urge caution in interpreting SAR-based thresholds without considering local site conditions and other measures of sedimentation stress, particularly ecological responses. This study underscores the need for targeted, long-term datasets and more integrated approaches that combine physical and biological indicators to better understand and manage sediment-related impacts in estuarine environments.

6. Acknowledgements

We thank the regional and unitary councils that provided data and contributed valuable insights during the analysis process. These included: Northland Regional Council, Auckland Council, Waikato Regional Council, Bay of Plenty Regional Council, Hawke's Bay Regional Council, Greater Wellington Regional Council, Nelson City Council, Tasman District Council, Otago Regional Council and Environment Southland. We also thank Barrie Forrest and Leigh Stevens (Salt Ecology) for providing data on behalf of several councils.

We are grateful to the external reviewers of this report – Drew Lohrer (NIWA), Leigh Stevens (Salt Ecology), Stephen Hunt (Waikato Regional Council) and Hannah Jones (MfE) – for their constructive feedback, and to Grant Hopkins (Cawthron Institute) for internal review.

7. Appendices

Appendix 1. Summary of data in the combined macrofauna / SAR / mud dataset

Table A1.1. Summary of sites within the combined macrofauna / SAR / mud dataset. Provided are the site and estuary names, years of macrofauna sampling, corresponding sediment accretion rate (SAR) periods for each site (grey shading), and details on the SAR sediment plate design (number of plates in parentheses). Also shown are the specific plates used to calculate average sediment depth, the most common number of within-plate replicate depth measurements (range of replicates in parentheses) and the number of macrofauna replicates used to determine average abundances for each site/time. Where only three within-plate replicate depth measurements were collected, a straight edge was typically used to average surface irregularities. Note that this table does not provide an exhaustive list of all macrofauna, SAR and sediment mud data collected councils at each site; rather, it reflects the data included in the combined macrofauna / SAR / mud dataset.

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
Northland Regional Council										
Kaipara Harbour	Te Kopua	2011, 2017					Cluster (2)	All	15	10
	Whakapirau	2011, 2017					Cluster (2)	All	15	10
Kerikeri Inlet	Kerikeri River	2010, 2011, 2015, 2019					Cluster (2)	All	15 (14–15)	10
	Pickmere Channel	2010, 2015, 2017, 2019					Cluster (2)	All	15	10
	Waipapa River	2010, 2011, 2015, 2017, 2019					Cluster (2)	All	15	10
Ruakākā	Tamure	2010, 2011, 2015, 2017, 2019					Cluster (2)	All	15	10

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
Whangārei	Hatea River	2010, 2011, 2013, 2015, 2017, 2019					Cluster (2)	All	15	9–10
	Mangapai River	2010, 2011, 2015, 2017, 2019					Cluster (2)	All	15	10
	Otaika Flats	2010, 2011, 2015, 2017, 2019					Cluster (2)	All	15	10
	Portland Reach	2010, 2011, 2013, 2015, 2017, 2019					Cluster (2)	All	15	10
Whangaroa Harbour	Kaeo River	2011, 2013, 2017, 2019,					Cluster (2)	All	15	10
	Kahoe River	2011, 2013, 2017, 2019					Cluster (2)	All	15 (14–15)	10
Auckland Council										
Mangemangeroa	MNG3	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023					Single (1)	All	5 (4–5)	6
	MNG6	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023					Single (1)	All	5 (4–5)	6
	MNG9	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2021					Single (1)	All	5 (4–5)	6

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
Ōkura	OKR3	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021					Single (1)	All	5	6
	OKR7	2010, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023					Single (1)	All	5	6
	OKR9	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2023					Single (1)	All	5	6
Ōrewa	ORW8	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2019, 2020, 2023					Single (1)	All	5	6
Pūhoi	PUH1	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021					Single (1)	All	5 (4–5)	6
	PUH4	2010, 2011, 2012, 2013, 2014, 2015, 2016					Single (1)	All	5 (4–5)	6
	PUH9	2010					Single (1)	All	5 (4–5)	6
Tūranga	TRN3	2022					Single (1)	All	5 (4–5)	6

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
	TRN7	2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023					Single (1)	All	5 (4–5)	6
Waikōpua	WKP3	2010, 2011, 2012, 2014, 2016, 2017, 2018, 2019, 2020, 2023					Single (1)	All	5 (4–5)	6
	WKP6	2010, 2011, 2012, 2014, 2016, 2017, 2018, 2019, 2020, 2021, 2023					Single (1)	All	5 (4–5)	6
	WKP8	2010					Single (1)	All	5 (4–5)	6
Waiwera	WWR2	2010					Single (1)	All	5 (4–5)	6
	WWR6	2010, 2014					Single (1)	All	5 (4–5)	6
Waikato Regional Council										
Coromandel Harbour	Awakanae Stream	2020					Transect (5)	3, 4	10	10
	Brickfield Bay	2020					Transect (4)	2, 3	10	10
	Coromandel Town	2020					Transect (5)	3, 4	10	10
	McGregor Bay	2020					Transect (4)	2, 3	10	10

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
Firth of Thames	Kaiaua	2012, 2013, 2014, 2015, 2016, 2017, 2018					Transect (6)	3, 4	10 (10 or 20)	12
	Kuranui Bay	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020					Transect (6)	3, 4	10 (10 or 20)	12
	Miranda	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020					Transect (6)	3, 4	10 (10 or 20)	12
	Thames (Gun Club)	2012, 2013, 2014, 2015, 2016, 2017					Transect (6)	3, 4	10 (9 – 20)	12
Tairua Harbour	Manaia Road	2020					Transect (5)	3, 4	10	10
	Oturu Stream	2020					Transect (3)	2, 3	10	10
	Pauanui	2020					Transect (4)	3, 4	10	10
	Pepe Inlet	2020					Transect (4)	2, 3	10	10
Whāingaroa (Raglan) Harbour	Haroto Bay	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2020					Cluster (4)	All	10 (9–20)	12
	Okete Bay	2012, 2013, 2015, 2016, 2017, 2018, 2019, 2020					Cluster (2)	All	10 (10–30)	12
	Ponganui Creek	2017, 2018					Cluster (4)	All	10 (10 or 20)	10

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
	Te Puna Point	2016, 2017, 2018					Cluster (4)	All	10 (9–20)	10
	Whatitirinui Island	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020					Cluster (4)	All	10 (9–45)	12
Hawke's Bay Regional Council										
Ahuriri Estuary	Ahuriri Estuary Plot_A[a]	2018, 2019, 2020, 2021					Single (1)	All	10 (5–10)	12
	Ahuriri Estuary Plot_D[b]	2018, 2019, 2020, 2021					Single (1)	All	10 (5–10)	12
	Ahuriri Estuary Plot_E[c]	2018, 2019, 2020, 2021					Single (1)	All	10 (5–10)	12
Waitangi Estuary	Waitangi Estuary Plot_A[d]	2018, 2019, 2020					Single (1)	All	10 (5–10)	12
Greater Wellington Regional Council										
Waikanae Estuary	Wkne A	2011, 2017					Cluster (4)	All	3	10
Whareama Estuary	Wha B	2009, 2010, 2016					Cluster (4)	All	3	10
Nelson City Council										
Waimea Inlet	Waimea-E	2020					Cluster (4)	All	3	10
Tasman District Council										
Waimea Inlet	Waimea-A	2011, 2014, 2015, 2016					Cluster (4)	All	3	10
	Waimea-B	2014					Cluster (4)	All	3	10

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
Otago Regional Council										
Blueskin Bay	Blueskin-A	2022					Cluster (4)	All	3	10
	Blueskin-B	2022					Cluster (4)	All	3	10
Catlins Estuary	Catlins-A	2018					Cluster (4)	All	3	10
	Catlins-B	2018					Cluster (4)	All	3	10
Pleasant River Estuary	PleasantRiver-A	2022					Cluster (4)	All	3	9
	PleasantRiver-B	2022					Cluster (4)	All	3	9
Shag Estuary	Shag-A	2018					Cluster (4)	All	3	10
	Shag-B	2018					Cluster (4)	All	3	10
Tautuku Estuary	Tautuku-A	2020					Cluster (4)	All	3	9
	Tautuku-B	2022					Cluster (4)	All	3	9
Waikouaiti Estuary	Waikouaiti-B	2018					Cluster (4)	All	3	10
Environment Southland										
Fortrose Estuary	Fortrose Estuary Site B	2019					Cluster (4)	All	5 (3–5)	10
Freshwater Estuary	Freshwater Estuary Site A	2010, 2011, 2013, 2020					Cluster (4)	All	5	10
	Freshwater Estuary Site B	2010, 2011, 2020					Cluster (4)	All	5	10
Haldane Estuary	Haldane Estuary Site A1	2010, 2011					Cluster (4)	All	5 (3–5)	10
	Haldane Estuary Site B	2020					Cluster (4)	All	5 (3–5)	10
New River Estuary	New River Estuary Site B	2021					Cluster (4)	All	5 (3–5)	10

Estuary	Site	Years macrofauna was sampled	1–2-m SAR	1-yr SAR	5-yr SAR	10-yr SAR	SAR site design	Relevant plates	Within-plate sediment depth replicates	Macrofauna replicates
	New River Estuary Site C	2021					Cluster (4)	All	5 (3–5)	10
	New River Estuary Site E	2021					Cluster (4)	All	5	10
	New River Estuary Site F	2021					Cluster (4)	All	5	10
Waikawa Estuary	Waikawa Estuary Site A	2020					Cluster (4)	All	5 (3–5)	10
	Waikawa Estuary Site B	2020					Cluster (4)	All	5 (3–5)	10
	Waikawa Estuary Site C1	2020					Cluster (4)	All	5	10

[a] Sediment plate site name is Ahuriri a off expressway 15m
[b] Sediment plate site name is Tyne Street 25m off corner of boardwalk
[c] Sediment plate site name is Ahuriri Meanee Quay 30.5m off corner of walkway
[d] Sediment plate site name is Waitangi Clive.

Table A1.2. Summary of sites within the combined macrofauna/SAR dataset. Provided are the site and estuary names, estuary type (classified using both the New Zealand Coastal Hydrosystems Classification [Hume et al. (2016) and the Estuary Trophic Index [Robertson et al. (2016a) and, where provided by councils, the within-estuary site location and tidal elevation, presence of substantial vegetation, site health (as assessed by council scientists) and geographic coordinates for each site.

Estuary	Estuary type	Site	Location	Elevation	Vegetation	Health	Latitude	Longitude
Northland Regional Council								
Kaipara Harbour	8 / SIDE	Te Kopua					-36.2050	174.2676
		Whakapirau					-36.1743	174.2378
Kerikeri Inlet	9 / SIDE	Kerikeri River					-35.2124	173.9729
		Pickmere Channel					-35.2070	173.9906
		Waipapa River					-35.2091	173.9757
Ruakākā	7A /SIDE	Tamure					-35.8940	174.4534
Whangārei	8 / SIDE	Hatea River					-35.7374	174.3404
		Mangapai River					-35.8260	174.3377
		Otaika Flats					-35.7743	174.3445
		Portland Reach					-35.8080	174.3551
Whangaroa Harbour	9 / SIDE	Kaeo River					-35.0664	173.7383
		Kahoe River					-35.0490	173.7116
Auckland Council								
Mangemangeroa	8 / DSDE	MNG3	Outer	Low	No	Fair	-36.9110	174.9555
		MNG6	Outer	Low	No	Poor	-36.9113	174.9534
		MNG9	Upper	Low	No	Poor	-36.9146	174.9488
Ōkura	7A / SIDE	OKR3	Outer	Low	No	Good	-36.6677	174.7297

Estuary	Estuary type	Site	Location	Elevation	Vegetation	Health	Latitude	Longitude
		OKR7	Mid	Low	No	Fair	-36.6710	174.7219
		OKR9	Upper	Low	No	Poor	-36.6737	174.7177
Ōrewa	7A / SIDE	ORW8	Mid	Low	No	Fair	-36.5976	174.6830
Pūhoi	7A / SIDE	PUH1	Outer	Low	No	Good	-36.5269	174.7100
		PUH4	Mid	Low	No	Good	-36.5303	174.7073
		PUH9	Upper	Low	No	Poor	-36.5256	174.6945
Tūranga	8 / SIDE	TRN3	Outer	Mid	No	Good	-36.9116	174.9633
		TRN7	Mid	Mid	No	Fair	-36.9230	174.9658
Waikōpua	8 / SIDE	WKP3	Outer	Low	No	Fair	-36.9048	174.9792
		WKP6	Mid	Low	No	Fair	-36.9050	174.9863
		WKP8	Mid	Low	No	Fair	-36.9074	174.9910
Waiwera	7A / SIDE	WWR2	Outer	Mid	No	Fair	-36.5418	174.7061
		WWR6	Mid	Low	No	Good	-36.5408	174.7026
Waikato Regional Council								
Coromandel Harbour	8 / SIDE	Awakanae Stream	Mid	Mid	Yes (seagrass)	Fair	-36.7954	175.4985
		Brickfield Bay	Mid	Mid	Yes (seagrass)	Fair	-36.7805	175.4932
		Coromandel Town	Mid	Mid	Yes (seagrass)	Poor	-36.7676	175.4926
		McGregor Bay	Mid	Mid	No	Poor	-36.7557	175.4825
Firth of Thames	9 / DSDE	Kaiaua	Mid	Mid	No	Fair	-37.1212	175.3008
		Kuranui Bay	Mid	Mid	No	Fair	-37.1191	175.5249

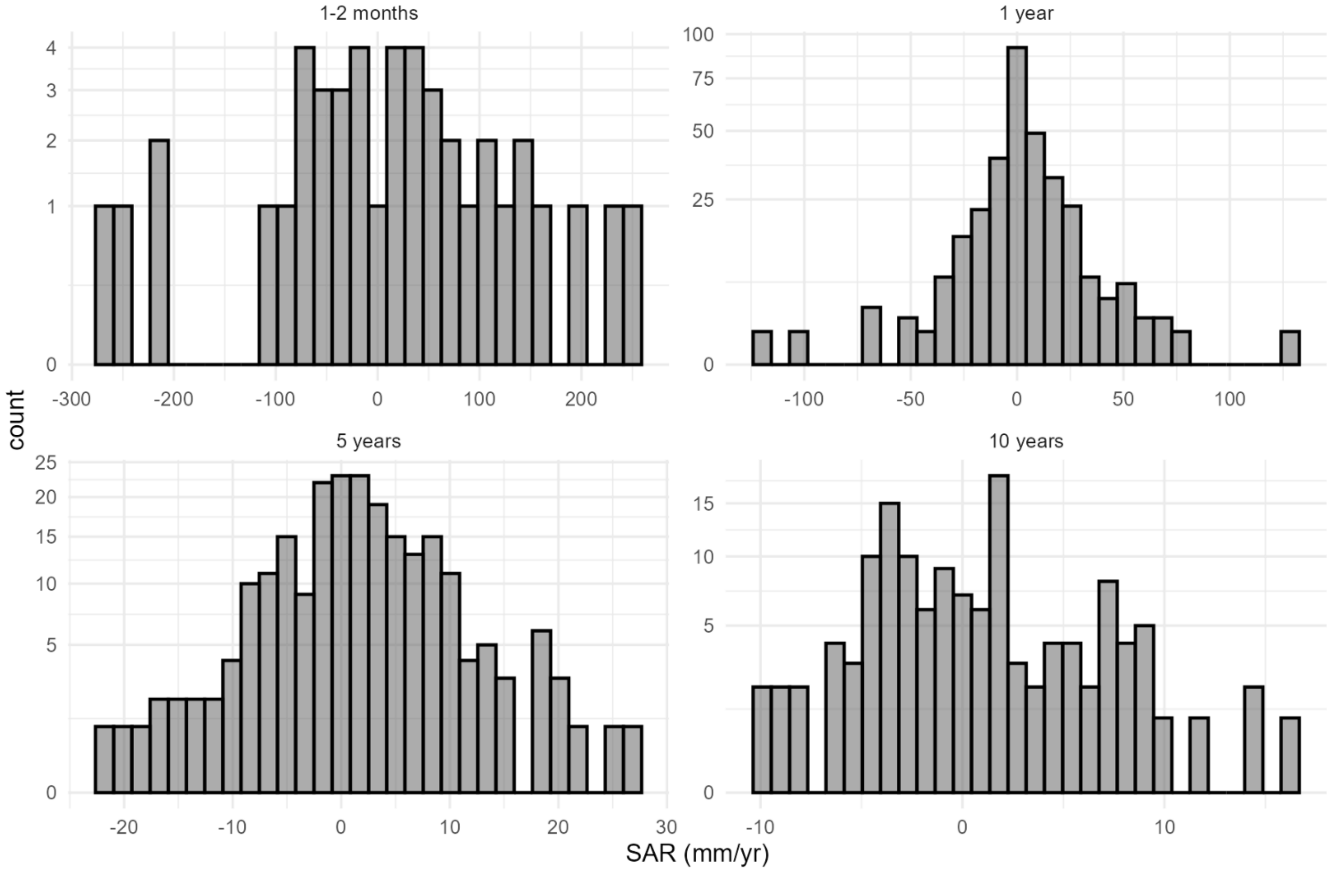
Estuary	Estuary type	Site	Location	Elevation	Vegetation	Health	Latitude	Longitude
		Miranda	Mid	Mid	No	Fair	-37.1808	175.3291
		Thames (Gun Club)	Outer	Mid	No	Good	-37.1597	175.5372
Tairua Harbour	7A / SIDE	Manaia Road	Outer	Mid	No	Good	-37.0025	175.8563
		Oturu Stream	Upper	Mid	No	Fair	-37.0306	175.8361
		Pauanui	Outer	Mid	No	Good	-37.0076	175.8577
		Pepe Inlet	Outer	Mid	No	Good	-37.0013	175.8446
Whāingaroa (Raglan) Harbour	8 / SIDE	Haroto Bay	Upper	Mid	No	Poor	-37.7871	174.9448
		Okete Bay	Mid	Mid	No	Poor	-37.7926	174.9174
		Ponganui Creek	Outer	Mid	No	Fair	-37.7850	174.8745
		Te Puna Point	Mid	Mid	No	Fair	-37.7778	174.9147
		Whatitirinui Island	Upper	Mid	No	Fair	-37.7640	174.9191
Hawke's Bay Regional Council								
Ahuriri Estuary	7A / SIDE	Ahuriri Estuary Plot_A[a]	Mid	Mid	No	Poor	-39.4838	176.8784
		Ahuriri Estuary Plot_D[b]	Mid	Mid	No	Poor	-39.4868	176.8866
		Ahuriri Estuary Plot_E[c]	Mid	Low	No	Poor	-39.4819	176.8847
Waitangi Estuary	NA / SSRTRE	Waitangi Estuary Plot_A[d]	Mid	Mid	No	Poor	-39.5727	176.9260
Greater Wellington Regional Council								
Waikanae Estuary	6B / SSRTRE	Wkne A	NA		No		-40.8733	175.0085
Whareama Estuary	6A / SSRTRE	Wha B	Mid		No	Fair	-41.0119	176.0928
Nelson City Council								

Estuary	Estuary type	Site	Location	Elevation	Vegetation	Health	Latitude	Longitude
Waimea Inlet	8 / SIDE	Waimea-E	Mid	Unknown	No		-41.3195	173.2058
Tasman District Council								
Waimea Inlet	8 / SIDE	Waimea-A	Mid	Unknown	No		-41.3172	173.1826
		Waimea-B	Mid	Unknown	No		-41.2643	173.0878
Otago Regional Council								
Blueskin Bay	7A / SIDE	Blueskin-A	Mid	Unknown	No		-45.7280	170.5778
		Blueskin-B	Mid	Unknown	No		-45.7388	170.5733
Catlins Estuary	7A / SIDE	Catlins-A	Outer	Unknown	No		-46.4769	169.6995
		Catlins-B	Upper	Unknown	No		-46.4723	169.6390
Pleasant River Estuary	7A / SIDE	PleasantRiver-A	Outer	Unknown	No		-45.5602	170.7230
		PleasantRiver-B	Mid	Unknown	No		-45.5522	170.7243
Shag Estuary	7A / SIDE	Shag-A	Outer	Unknown	No		-45.4803	170.8112
		Shag-B	Mid	Unknown	No		-45.4773	170.8078
Tautuku Estuary	7A / SIDE	Tautuku-A	Upper	Unknown	No		-46.5916	169.4193
		Tautuku-B	Upper	Unknown	No		-46.5902	169.4156
Waikouaiti Estuary	7A / SIDE	Waikouaiti-B	Mid	Unknown	No		-45.6251	170.6507
Environment Southland								
Fortrose Estuary	7A / SSRTRE	Fortrose Estuary Site B	Upper	High	No	Fair	-46.5630	168.7881
Freshwater Estuary	9 / SIDE	Freshwater Estuary Site A	Mid	Mid	Yes (seagrass)	Good	-46.9059	167.9775
		Freshwater Estuary Site B	Mid	Low	Yes (seagrass)	Good	-46.9045	167.9886

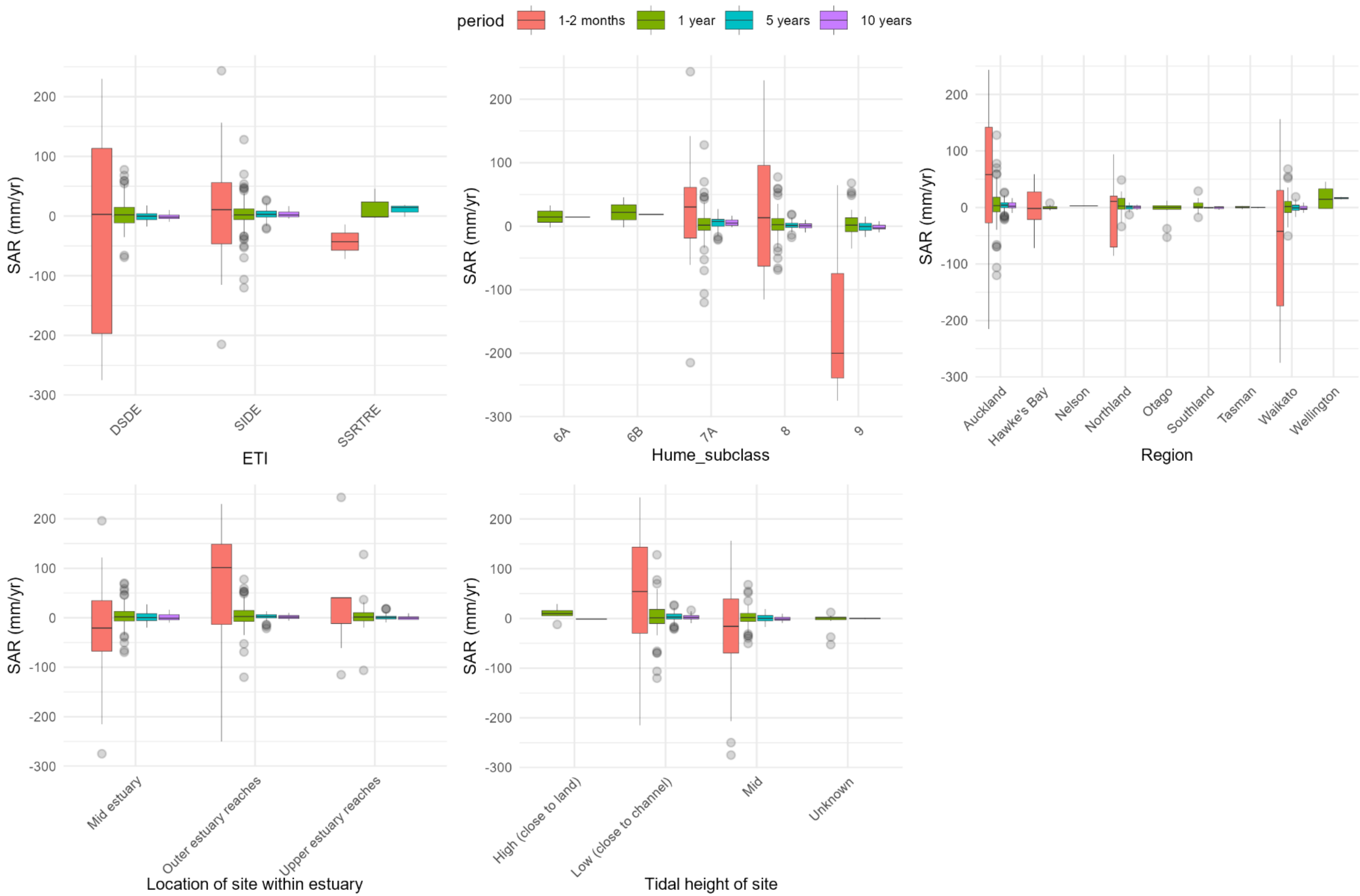
Estuary	Estuary type	Site	Location	Elevation	Vegetation	Health	Latitude	Longitude
Haldane Estuary	7A / SIDE	Haldane Estuary Site A1	Upper	High	No	Fair	-46.6427	169.0322
		Haldane Estuary Site B	Mid	Mid	No	Fair	-46.6479	169.0347
New River Estuary	8 / SIDE	New River Estuary Site B	Mid	Mid	No	Fair	-46.4770	168.3359
		New River Estuary Site C	Mid	High	No	Poor	-46.4764	168.3032
		New River Estuary Site E	Mid	High	No	Poor	-46.4753	168.3005
		New River Estuary Site F	Upper	High	No	Poor	-46.4404	168.3284
Waikawa Estuary	7A / SIDE	Waikawa Estuary Site A	Mid	Mid	No	Good	-46.6224	169.1452
		Waikawa Estuary Site B	Mid	Low	No	Good	-46.6285	169.1498
		Waikawa Estuary Site C1	Upper	High	No	Poor	-46.6090	169.1372

Appendix 2. Sediment accretion rate (SAR) variability

A2.1 Histograms of sediment accretion rate (SAR) across different SAR periods

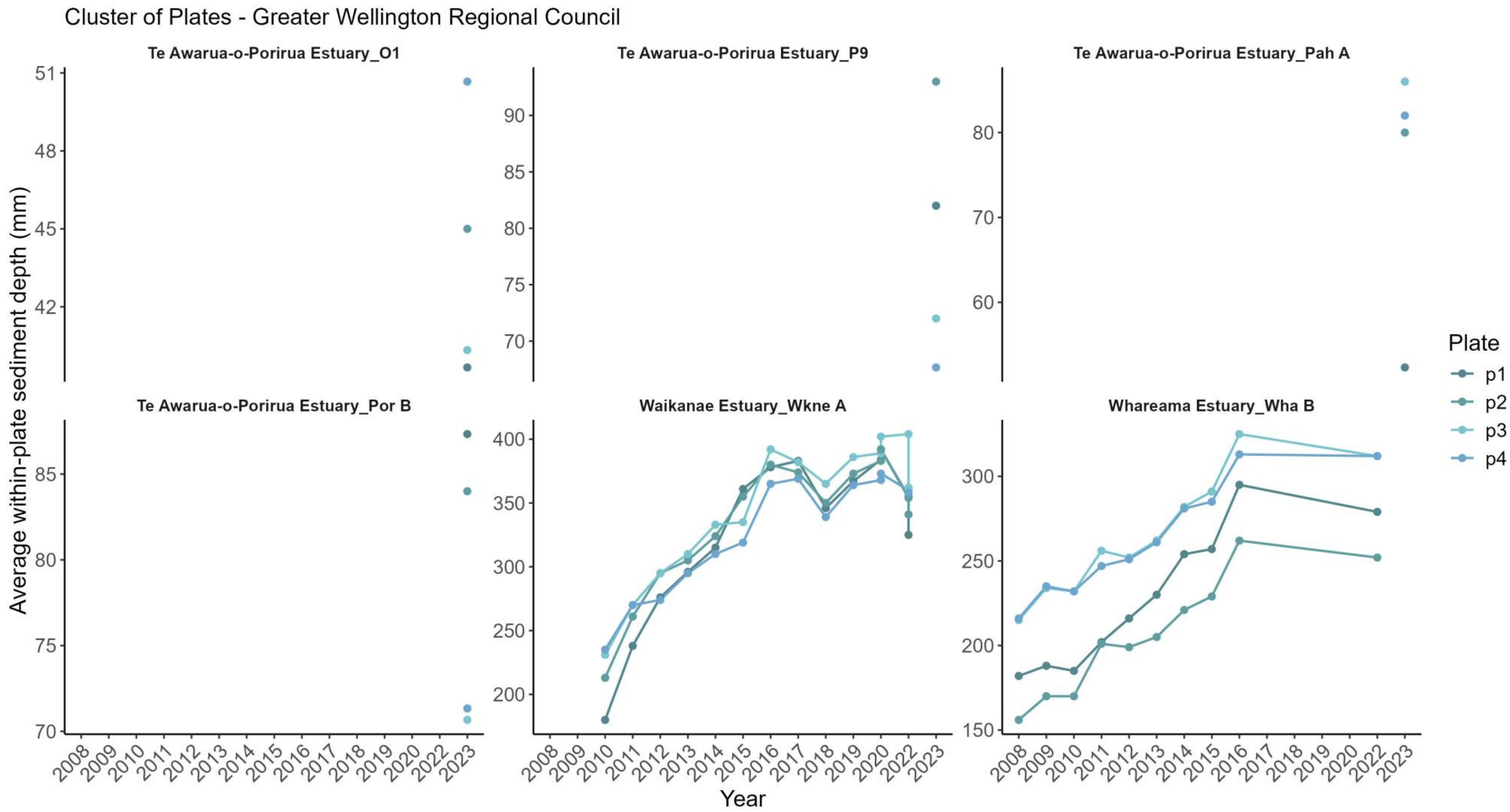


A2.2 Boxplots showing the range of sediment accretion rate (SAR) values across different estuary types, regions, within-estuary site locations and tidal elevations, separated by SAR period

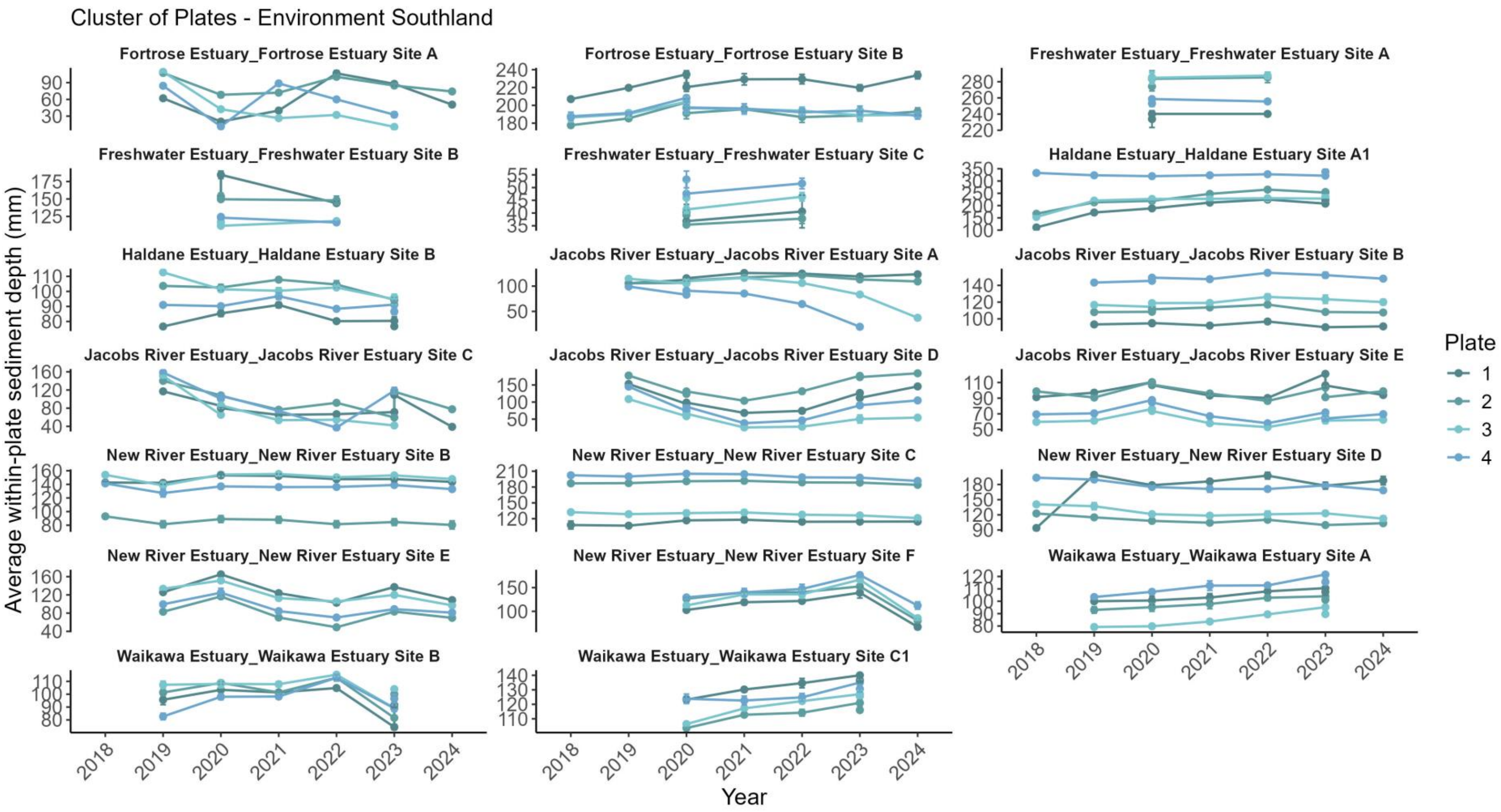


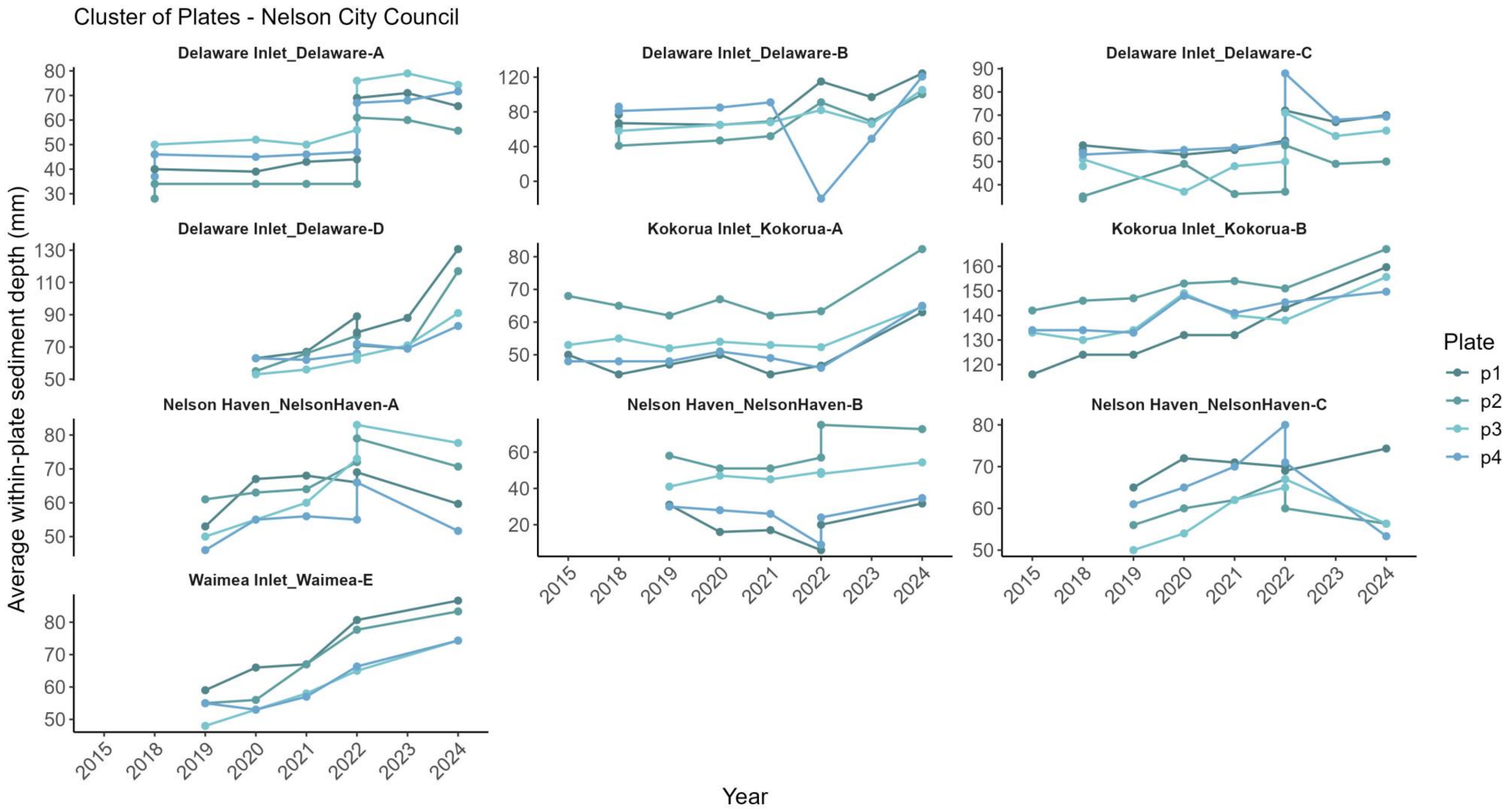
Appendix 3. Sediment depth variability by sampling design

Figure A3.1 (following pages). Sediment depth measurements (mm) at sites with a cluster sediment plate design. Coloured dots represent the averaged within-plate sediment depths (mean ± standard deviation), illustrating the variability in sediment accretion and erosion trends among replicate plates. Note that because these plots show sediment depth, rather than sediment accretion rate, we would expect to see some offset between plates depending on how deep they were initially buried. Final quality control checks on the combined macrofauna / SAR / mud dataset (see Section 2.1) have not yet been completed – some of these sites were later excluded. Some sites had extra plates or additional depth measurements after plates were reburied, which can be hard to see on the plots as they are one-off measurements.

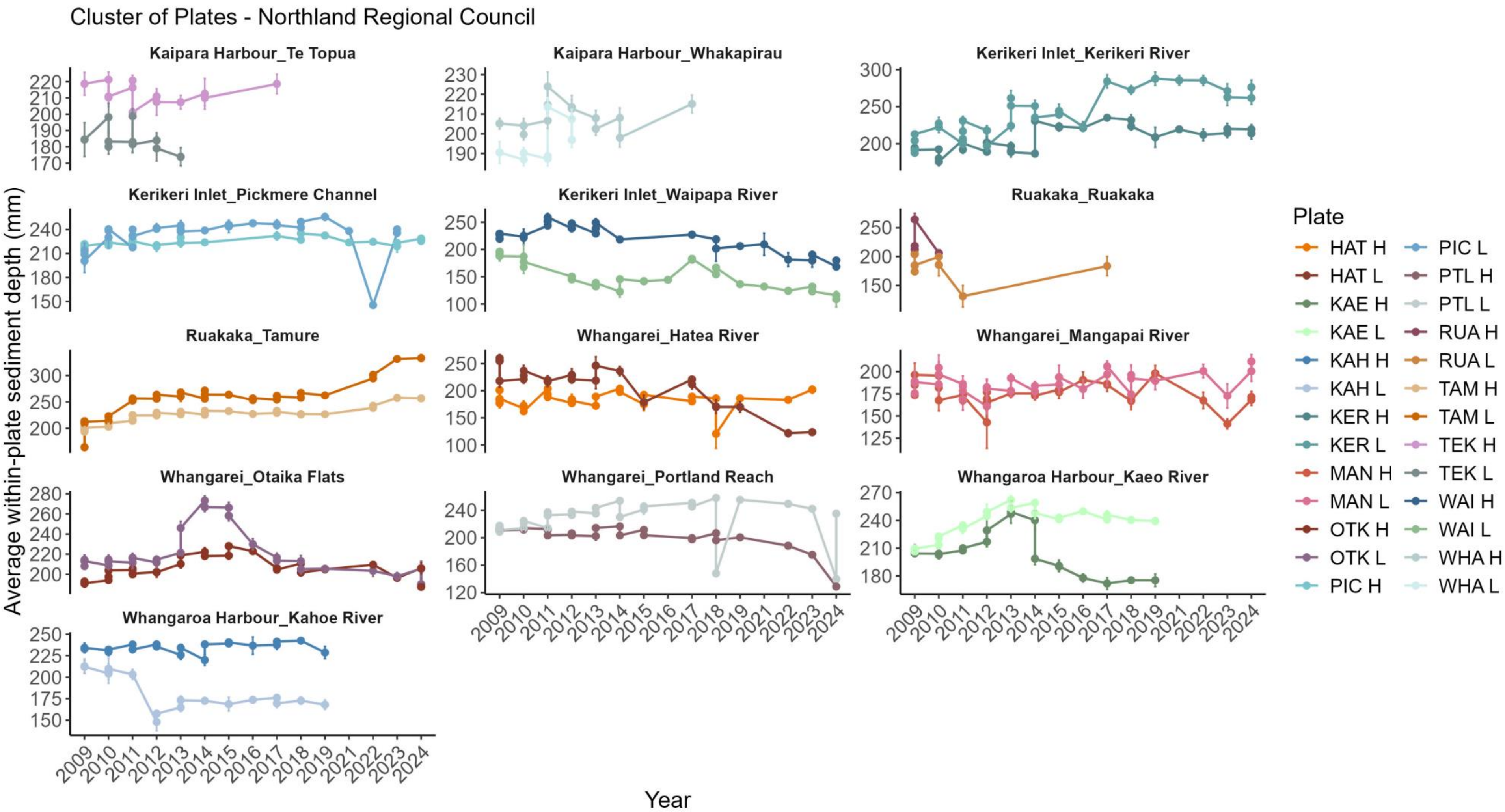


Cluster of Plates - Greater Wellington Regional Council
Te Awarua-o-Porirua Estuary_O1
Te Awarua-o-Porirua Estuary_P9
Te Awarua-o-Porirua Estuary_Pah A
Te Awarua-o-Porirua Estuary_Por B
Waikanae Estuary_Wkne A
Whareama Estuary_Wha B
Average within-plate sediment depth (mm)
Year
Plate
p1
p2
p3
p4

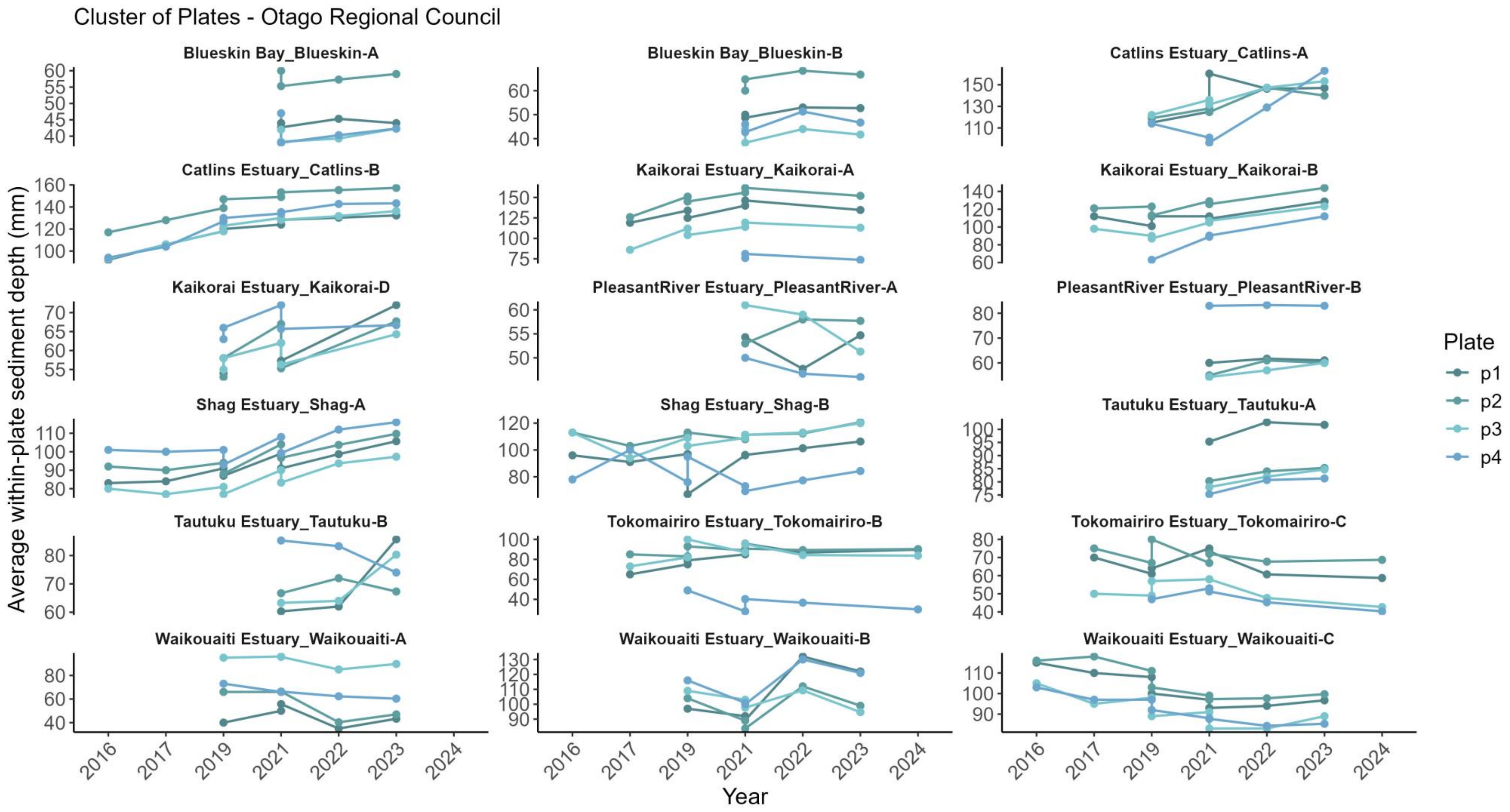

Cluster of Plates - Environment Southland
Fortrose Estuary_Fortrose Estuary Site A
Fortrose Estuary_Fortrose Estuary Site B
Freshwater Estuary_Freshwater Estuary Site A
Freshwater Estuary_Freshwater Estuary Site B
Freshwater Estuary_Freshwater Estuary Site C
Haldane Estuary_Haldane Estuary Site A1
Haldane Estuary_Haldane Estuary Site B
Jacobs River Estuary_Jacobs River Estuary Site A
Jacobs River Estuary_Jacobs River Estuary Site B
Jacobs River Estuary_Jacobs River Estuary Site C
Jacobs River Estuary_Jacobs River Estuary Site D
Jacobs River Estuary_Jacobs River Estuary Site E
New River Estuary_New River Estuary Site B
New River Estuary_New River Estuary Site C
New River Estuary_New River Estuary Site D
New River Estuary_New River Estuary Site E
New River Estuary_New River Estuary Site F
Waikawa Estuary_Waikawa Estuary Site A
Waikawa Estuary_Waikawa Estuary Site B
Waikawa Estuary_Waikawa Estuary Site C1
Average within-plate sediment depth (mm)
Year
2018
2019
2020
2021
2022
2023
2024
Plate
1
2
3
4



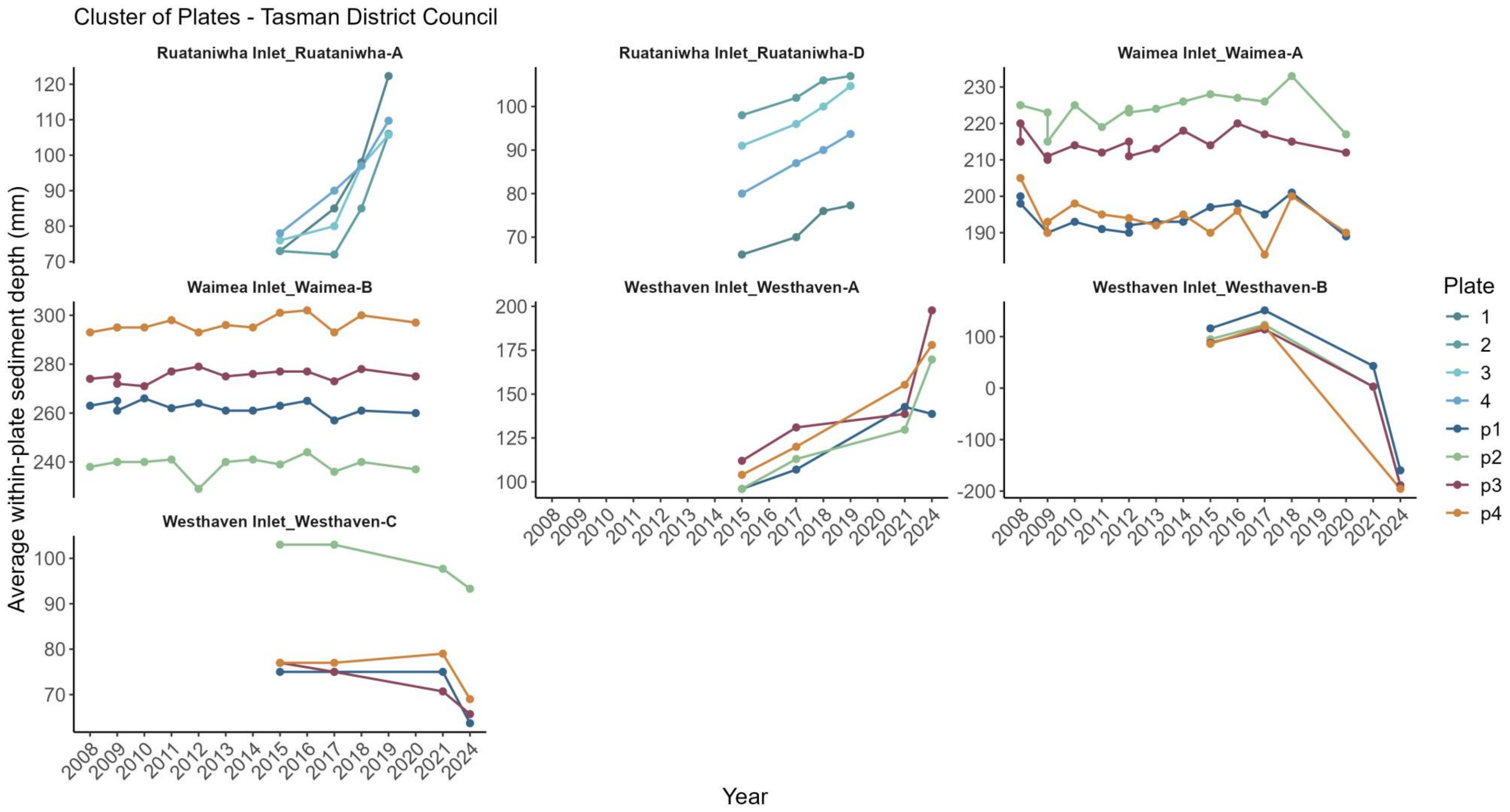
Cluster of Plates - Nelson City Council
Delaware Inlet_Delaware-A
Delaware Inlet_Delaware-B
Delaware Inlet_Delaware-C
Delaware Inlet_Delaware-D
Kokorua Inlet_Kokorua-A
Kokorua Inlet_Kokorua-B
Nelson Haven_NelsonHaven-A
Nelson Haven_NelsonHaven-B
Nelson Haven_NelsonHaven-C
Waimea Inlet_Waimea-E
Average within-plate sediment depth (mm)
Year
2015
2018
2019
2020
2021
2022
2023
2024
Plate
p1
p2
p3
p4



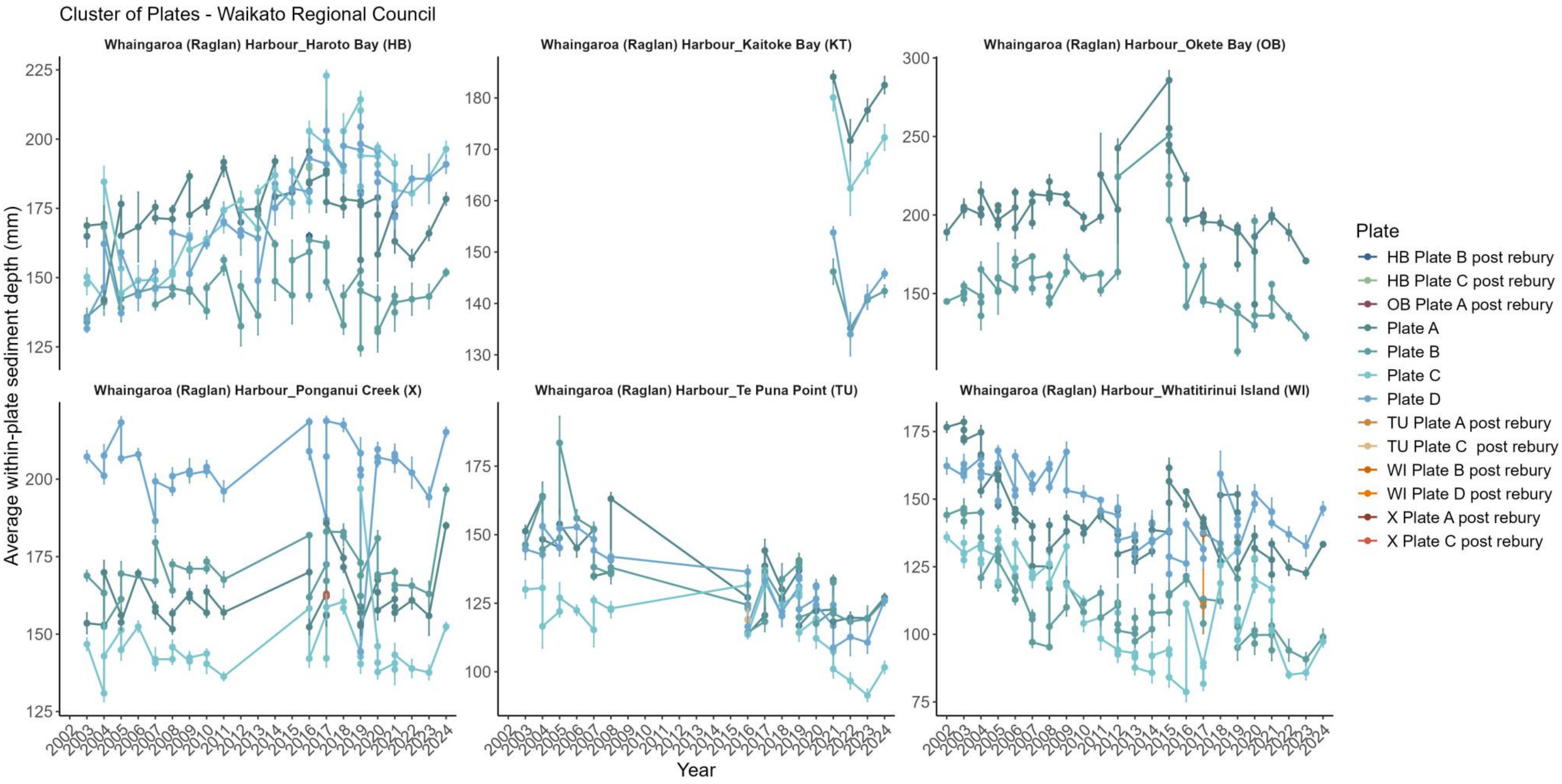
Cluster of Plates - Northland Regional Council
Kaipara Harbour_Te Topua
Kaipara Harbour_Whakapirau
Kerikeri Inlet_Kerikeri River
Kerikeri Inlet_Pickmere Channel
Kerikeri Inlet_Waipapa River
Ruakaka_Ruakaka
Ruakaka_Tamure
Whangarei_Hatea River
Whangarei_Mangapai River
Whangarei_Otaika Flats
Whangarei_Portland Reach
Whangaroa Harbour_Kaeo River
Whangaroa Harbour_Kahoe River
Average within-plate sediment depth (mm)
Year
Plate
HAT H
HAT L
KAE H
KAE L
KAH H
KAH L
KER H
KER L
MAN H
MAN L
OTK H
OTK L
PIC H
PIC L
PTL H
PTL L
RUA H
RUA L
TAM H
TAM L
TEK H
TEK L
WAI H
WAI L
WHA H
WHA L



Cluster of Plates - Otago Regional Council
Blueskin Bay_Blueskin-A
Blueskin Bay_Blueskin-B
Catlins Estuary_Catlins-A
Catlins Estuary_Catlins-B
Kaikorai Estuary_Kaikorai-A
Kaikorai Estuary_Kaikorai-B
Kaikorai Estuary_Kaikorai-D
PleasantRiver Estuary_PleasantRiver-A
PleasantRiver Estuary_PleasantRiver-B
Shag Estuary_Shag-A
Shag Estuary_Shag-B
Tautuku Estuary_Tautuku-A
Tautuku Estuary_Tautuku-B
Tokomairiro Estuary_Tokomairiro-B
Tokomairiro Estuary_Tokomairiro-C
Waikouaiti Estuary_Waikouaiti-A
Waikouaiti Estuary_Waikouaiti-B
Waikouaiti Estuary_Waikouaiti-C
Average within-plate sediment depth (mm)
Year
2016
2017
2019
2021
2022
2023
2024
Plate
p1
p2
p3
p4

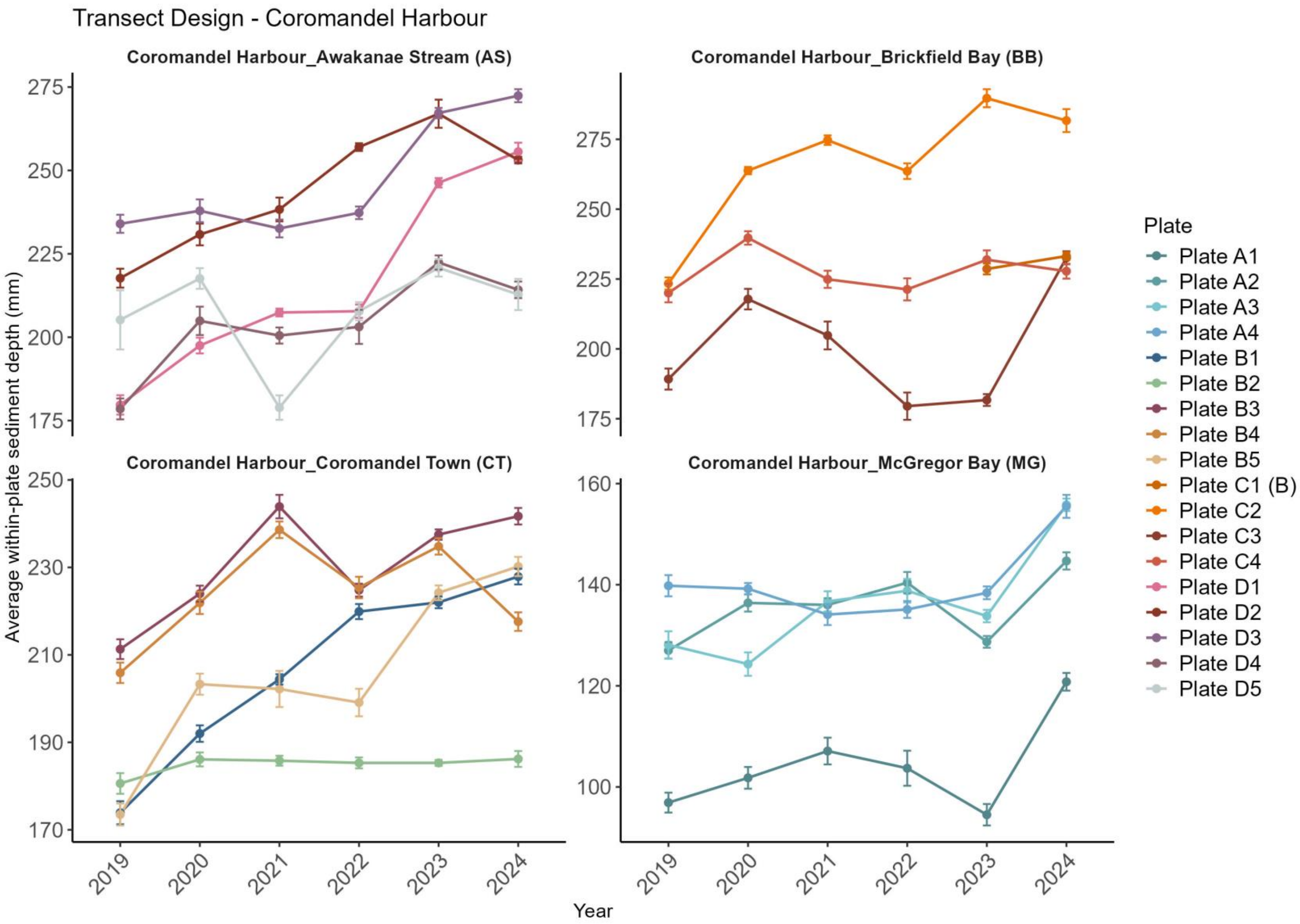


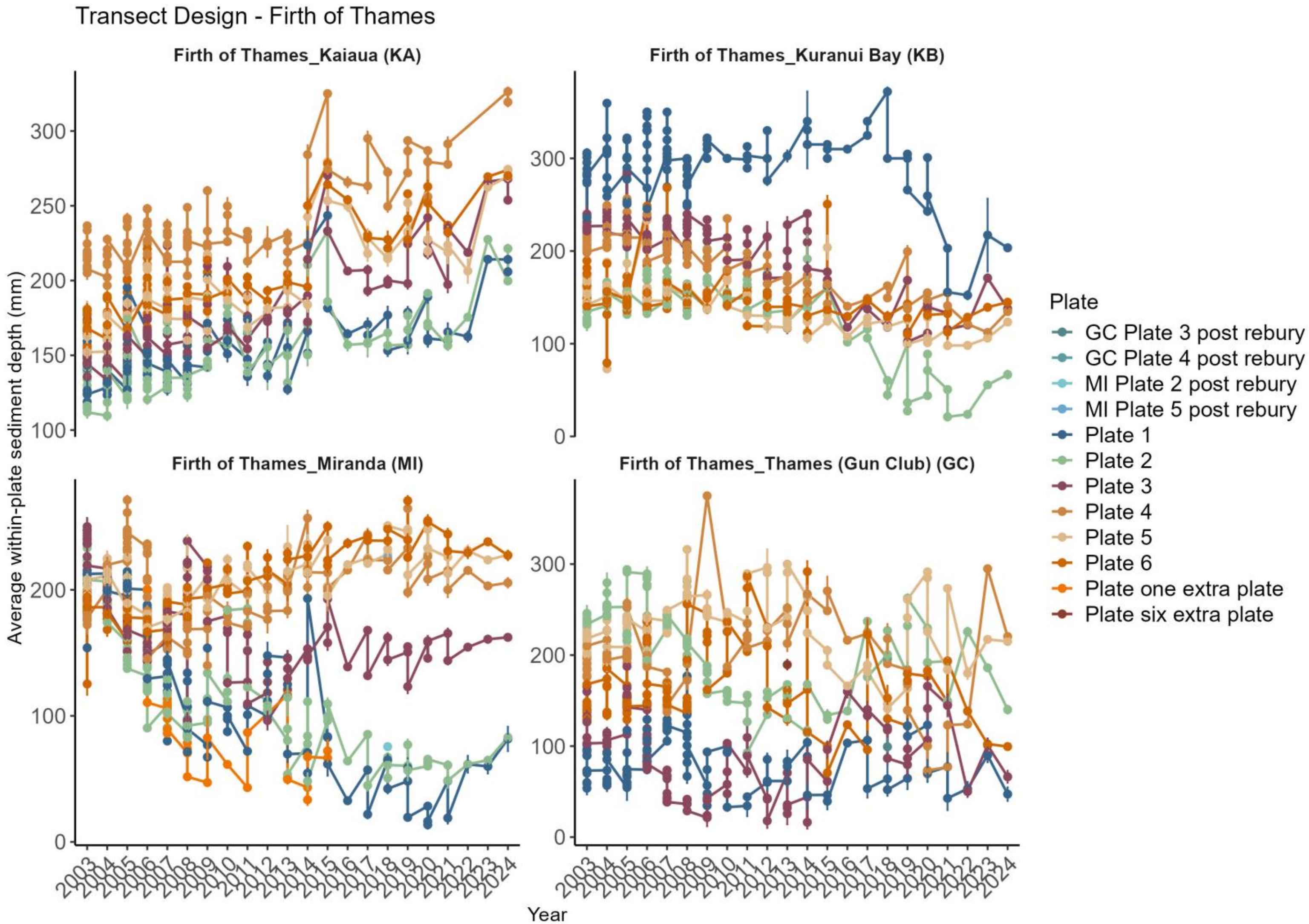
Cluster of Plates - Tasman District Council
Ruataniwha Inlet_Ruataniwha-A
Ruataniwha Inlet_Ruataniwha-D
Waimea Inlet_Waimea-A
Waimea Inlet_Waimea-B
Westhaven Inlet_Westhaven-A
Westhaven Inlet_Westhaven-B
Westhaven Inlet_Westhaven-C
Average within-plate sediment depth (mm)
Year
Plate
1
2
3
4
p1
p2
p3
p4

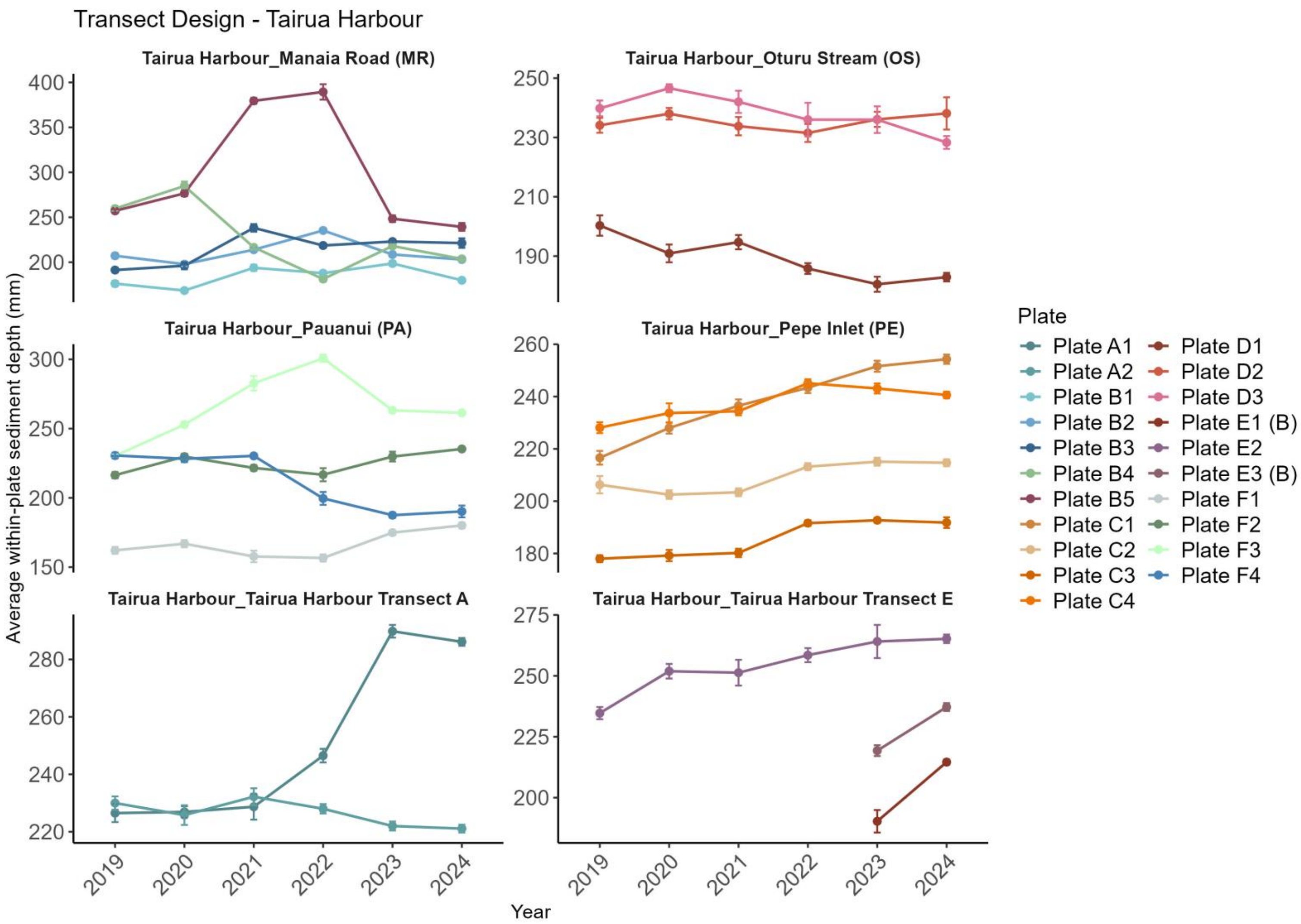


Cluster of Plates - Waikato Regional Council
Whaingaroa (Raglan) Harbour_Haroto Bay (HB)
Whaingaroa (Raglan) Harbour_Kaitoke Bay (KT)
Whaingaroa (Raglan) Harbour_Okete Bay (OB)
Whaingaroa (Raglan) Harbour_Ponganui Creek (X)
Whaingaroa (Raglan) Harbour_Te Puna Point (TU)
Whaingaroa (Raglan) Harbour_Whatitirinui Island (WI)
Average within-plate sediment depth (mm)
Year
Plate
HB Plate B post rebury
HB Plate C post rebury
OB Plate A post rebury
Plate A
Plate B
Plate C
Plate D
TU Plate A post rebury
TU Plate C post rebury
WI Plate B post rebury
WI Plate D post rebury
X Plate A post rebury
X Plate C post rebury

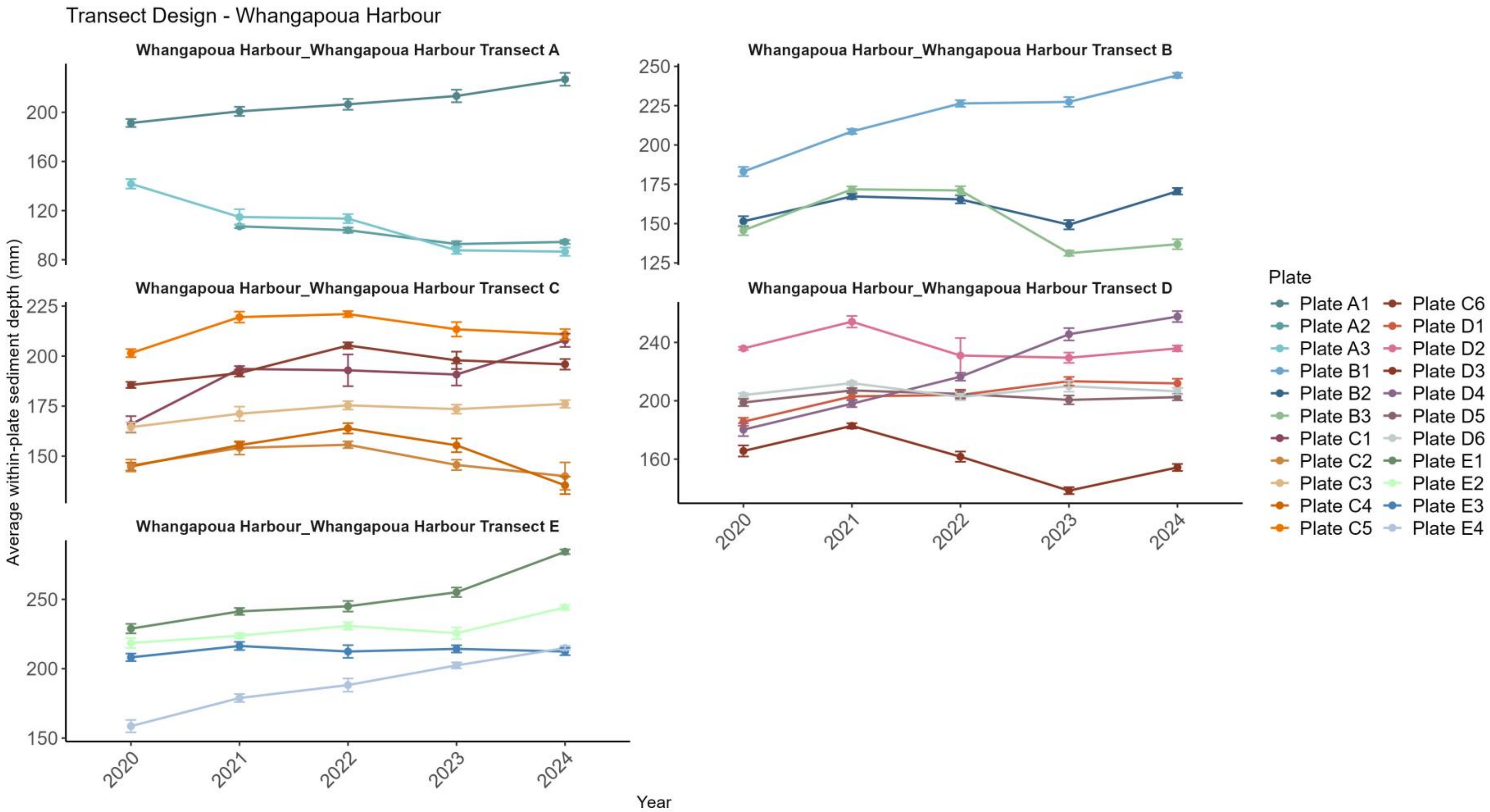
Figure A3.2 (following pages). Sediment depth measurements (mm) at sites with a transect sediment plate design. Coloured dots represent the averaged within-plate sediment depths (mean ± standard deviation), illustrating the variability in sediment accretion and erosion trends among replicate plates. Note that because these plots show sediment depth, rather than sediment accretion rate, we would expect to see some offset between plates depending on how deep they were initially buried. Final quality control checks on the combined macrofauna / SAR / mud dataset (see Section 2.1) have not yet been completed – some of these sites were later excluded. Some sites had extra plates or additional depth measurements after plates were reburied, which can be hard to see on the plots as they are one-off measurements.


Transect Design - Coromandel Harbour
Coromandel Harbour_Awakanae Stream (AS)
Coromandel Harbour_Brickfield Bay (BB)
Coromandel Harbour_Coromandel Town (CT)
Coromandel Harbour_McGregor Bay (MG)
Average within-plate sediment depth (mm)
Year
Plate
Plate A1
Plate A2
Plate A3
Plate A4
Plate B1
Plate B2
Plate B3
Plate B4
Plate B5
Plate C1 (B)
Plate C2
Plate C3
Plate C4
Plate D1
Plate D2
Plate D3
Plate D4
Plate D5

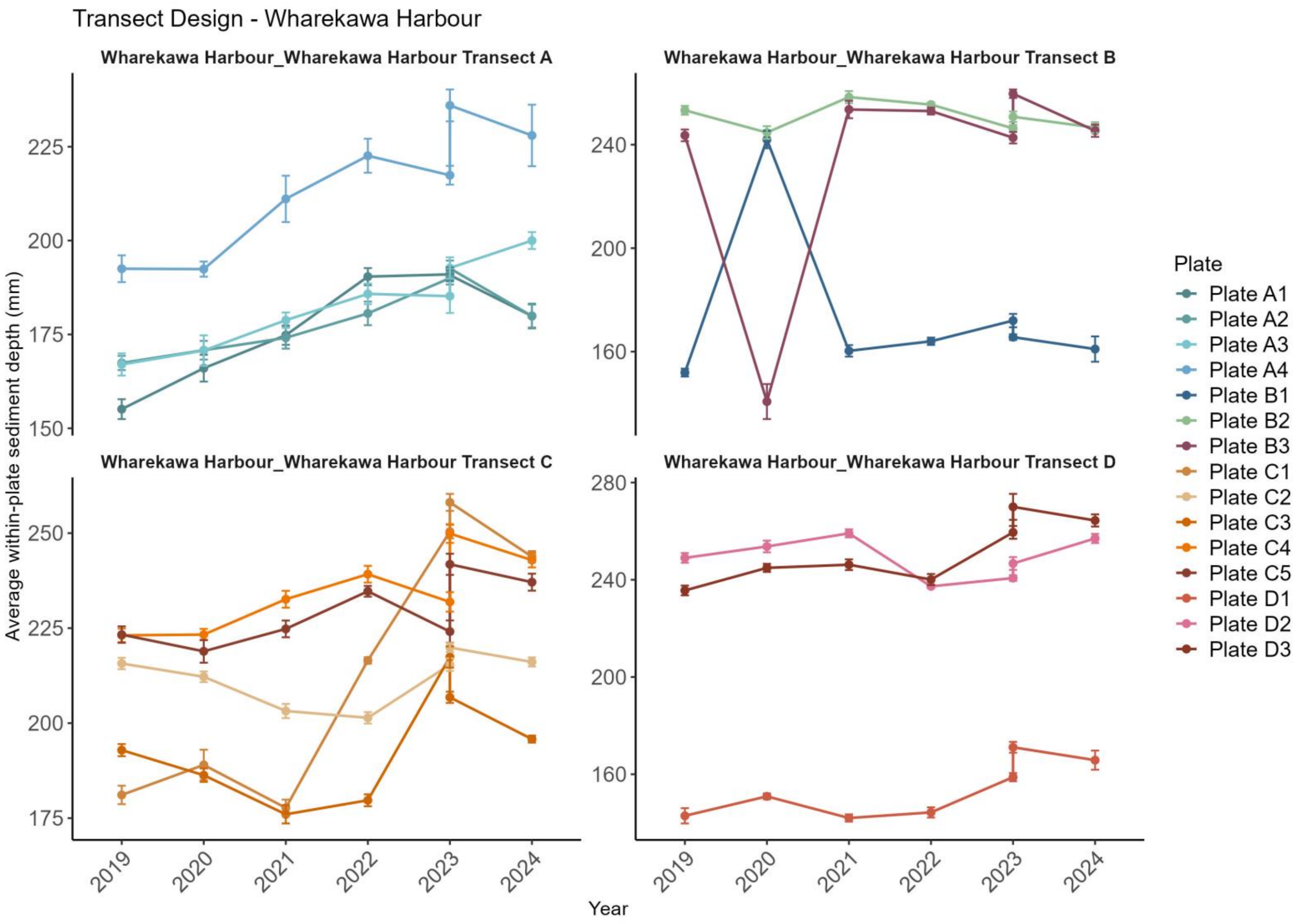

Transect Design - Firth of Thames
Firth of Thames_Kaiaua (KA)
Firth of Thames_Kuranui Bay (KB)
Firth of Thames_Miranda (MI)
Firth of Thames_Thames (Gun Club) (GC)
Average within-plate sediment depth (mm)
Year
Plate
GC Plate 3 post rebury
GC Plate 4 post rebury
MI Plate 2 post rebury
MI Plate 5 post rebury
Plate 1
Plate 2
Plate 3
Plate 4
Plate 5
Plate 6
Plate one extra plate
Plate six extra plate



Transect Design - Tairua Harbour
Tairua Harbour_Manaia Road (MR)
Tairua Harbour_Oturu Stream (OS)
Tairua Harbour_Pauanui (PA)
Tairua Harbour_Pepe Inlet (PE)
Tairua Harbour_Tairua Harbour Transect A
Tairua Harbour_Tairua Harbour Transect E
Average within-plate sediment depth (mm)
Year
Plate
Plate A1
Plate A2
Plate B1
Plate B2
Plate B3
Plate B4
Plate B5
Plate C1
Plate C2
Plate C3
Plate C4
Plate D1
Plate D2
Plate D3
Plate E1 (B)
Plate E2
Plate E3 (B)
Plate F1
Plate F2
Plate F3
Plate F4

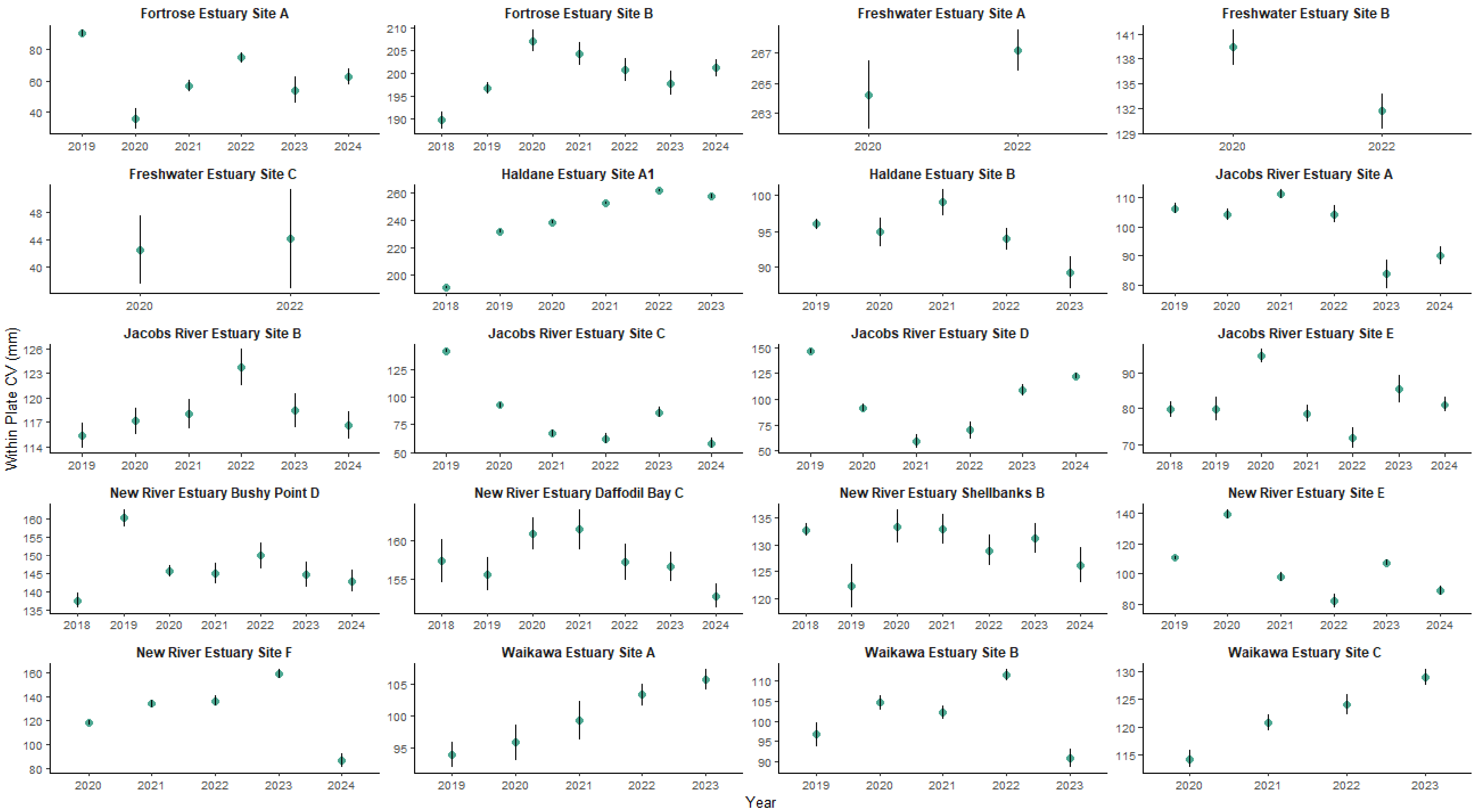


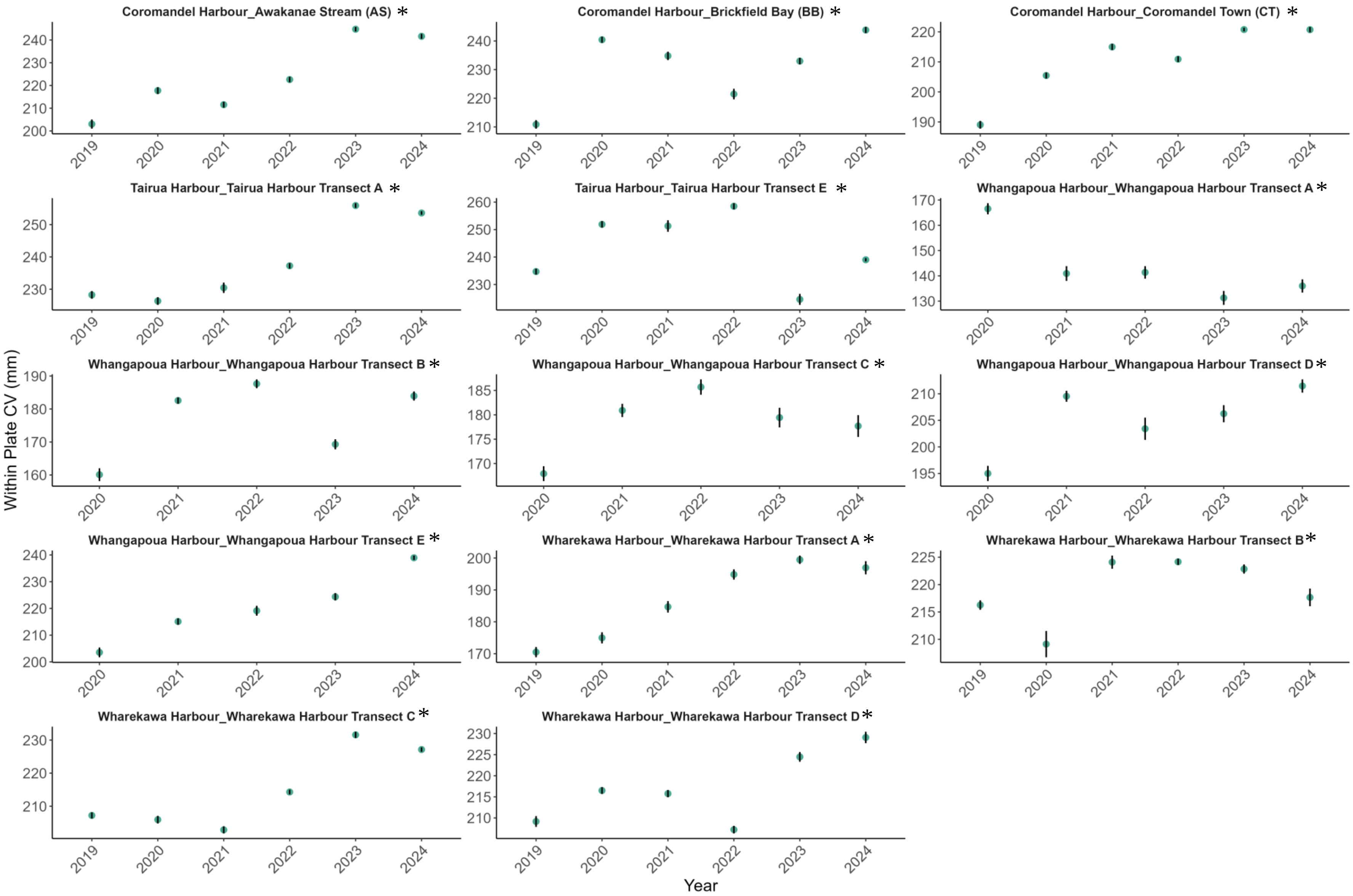
Transect Design - Whangapoua Harbour
Whangapoua Harbour_Whangapoua Harbour Transect A
Whangapoua Harbour_Whangapoua Harbour Transect B
Whangapoua Harbour_Whangapoua Harbour Transect C
Whangapoua Harbour_Whangapoua Harbour Transect D
Whangapoua Harbour_Whangapoua Harbour Transect E
Average within-plate sediment depth (mm)
Year
Plate
Plate A1
Plate A2
Plate A3
Plate B1
Plate B2
Plate B3
Plate C1
Plate C2
Plate C3
Plate C4
Plate C5
Plate C6
Plate D1
Plate D2
Plate D3
Plate D4
Plate D5
Plate D6
Plate E1
Plate E2
Plate E3
Plate E4

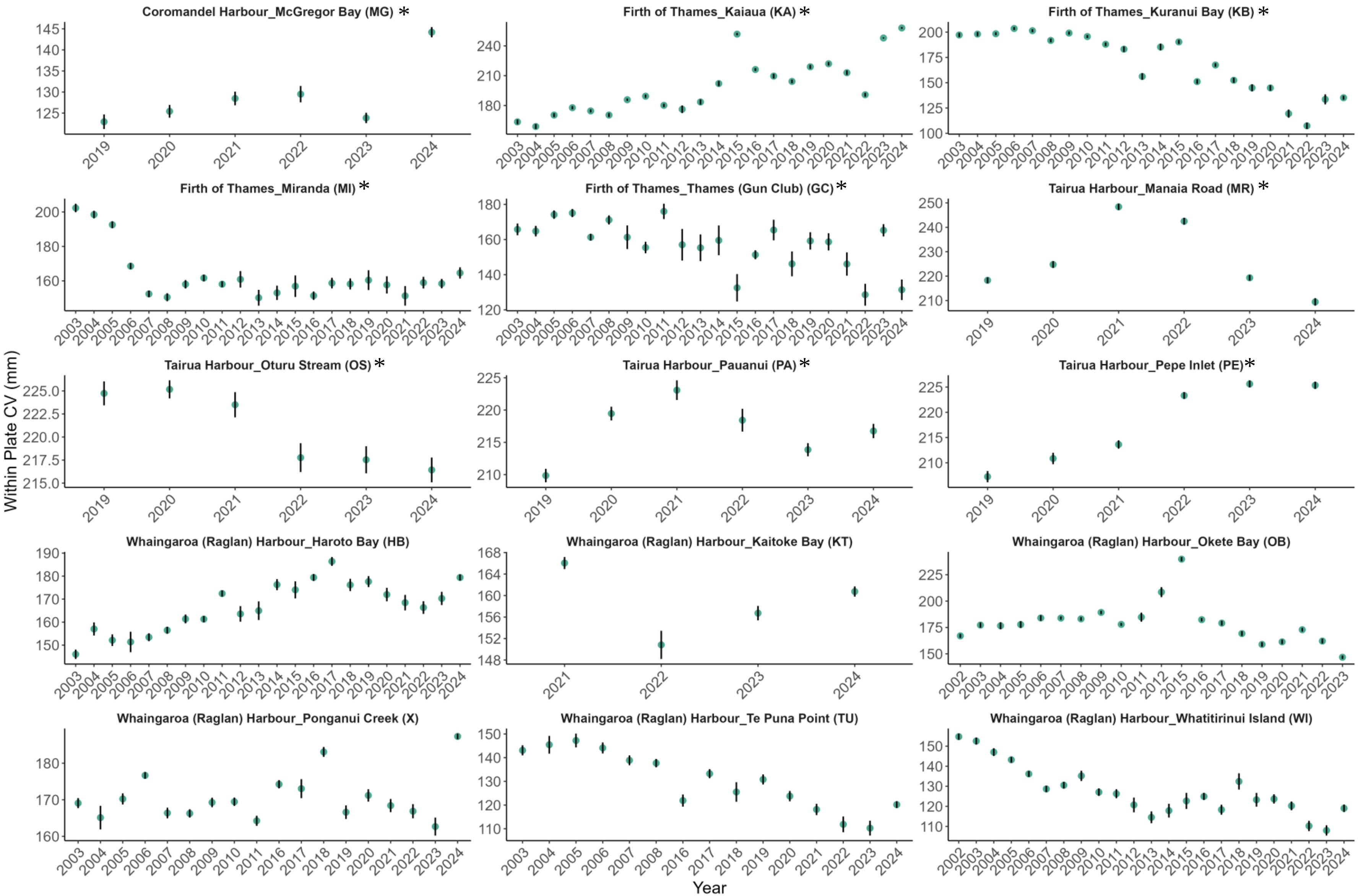

Transect Design - Wharekawa Harbour
Wharekawa Harbour_Wharekawa Harbour Transect A
Wharekawa Harbour_Wharekawa Harbour Transect B
Wharekawa Harbour_Wharekawa Harbour Transect C
Wharekawa Harbour_Wharekawa Harbour Transect D
Average within-plate sediment depth (mm)
Year
2019
2020
2021
2022
2023
2024
Plate
Plate A1
Plate A2
Plate A3
Plate A4
Plate B1
Plate B2
Plate B3
Plate C1
Plate C2
Plate C3
Plate C4
Plate C5
Plate D1
Plate D2
Plate D3

Appendix 4. Coefficient of variation plots

Figure A4.1 (following pages). Coefficient of variation (CV) in sediment depth measurements for selected sites in Southland and Waikato, illustrating both within-plate variability. Coloured dots represent averaged sediment depth measurements for each site/year. Within-plate CVs were calculated as the standard deviation (SD) of replicate depth measurements divided by their respective within-plate average, then averaged across plates. Most sites had a cluster plate design, and asterisks indicate sites with a transect design.

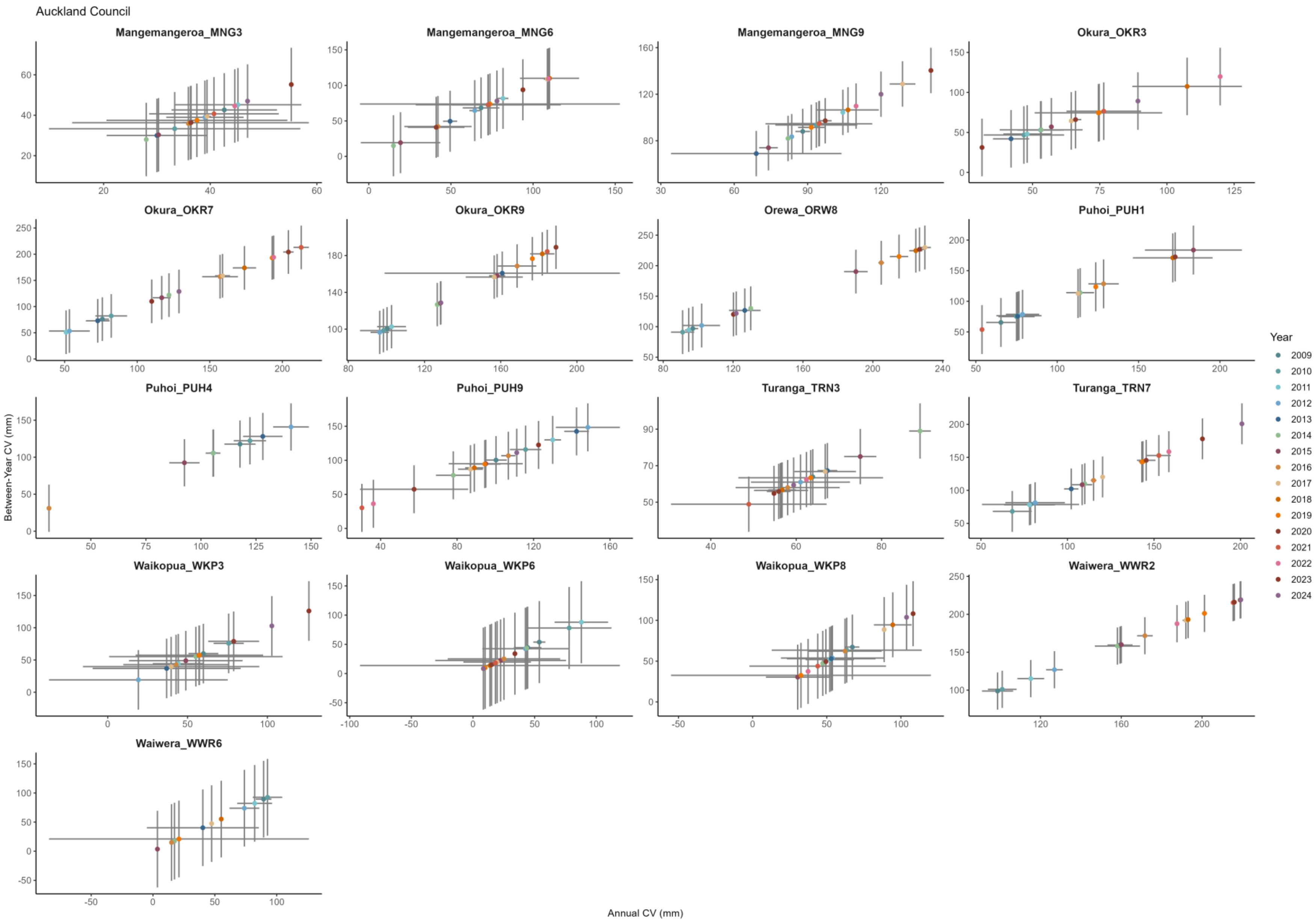

Fortrose Estuary Site A
Fortrose Estuary Site B
Freshwater Estuary Site A
Freshwater Estuary Site B
Freshwater Estuary Site C
Haldane Estuary Site A1
Haldane Estuary Site B
Jacobs River Estuary Site A
Jacobs River Estuary Site B
Jacobs River Estuary Site C
Jacobs River Estuary Site D
Jacobs River Estuary Site E
New River Estuary Bushy Point D
New River Estuary Daffodil Bay C
New River Estuary Shellbanks B
New River Estuary Site E
New River Estuary Site F
Waikawa Estuary Site A
Waikawa Estuary Site B
Waikawa Estuary Site C
Within Plate CV (mm)
Year

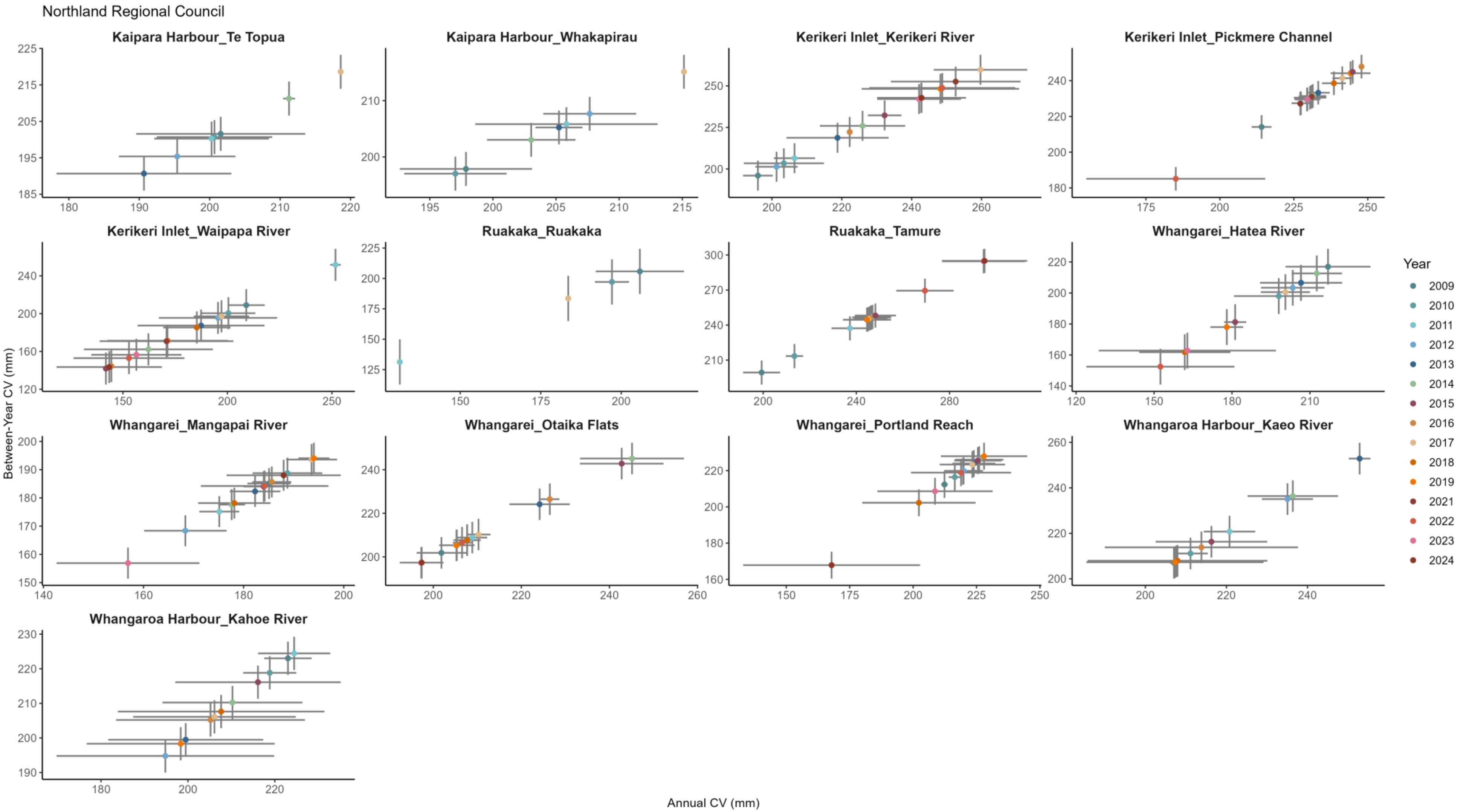

Coromandel Harbour_Awakanae Stream (AS) *
Coromandel Harbour_Brickfield Bay (BB) *
Coromandel Harbour_Coromandel Town (CT) *
Tairua Harbour_Tairua Harbour Transect A *
Tairua Harbour_Tairua Harbour Transect E *
Whangapoua Harbour_Whangapoua Harbour Transect A *
Whangapoua Harbour_Whangapoua Harbour Transect B *
Whangapoua Harbour_Whangapoua Harbour Transect C *
Whangapoua Harbour_Whangapoua Harbour Transect D *
Whangapoua Harbour_Whangapoua Harbour Transect E *
Wharekawa Harbour_Wharekawa Harbour Transect A *
Wharekawa Harbour_Wharekawa Harbour Transect B *
Wharekawa Harbour_Wharekawa Harbour Transect C *
Wharekawa Harbour_Wharekawa Harbour Transect D *
Within Plate CV (mm)
Year

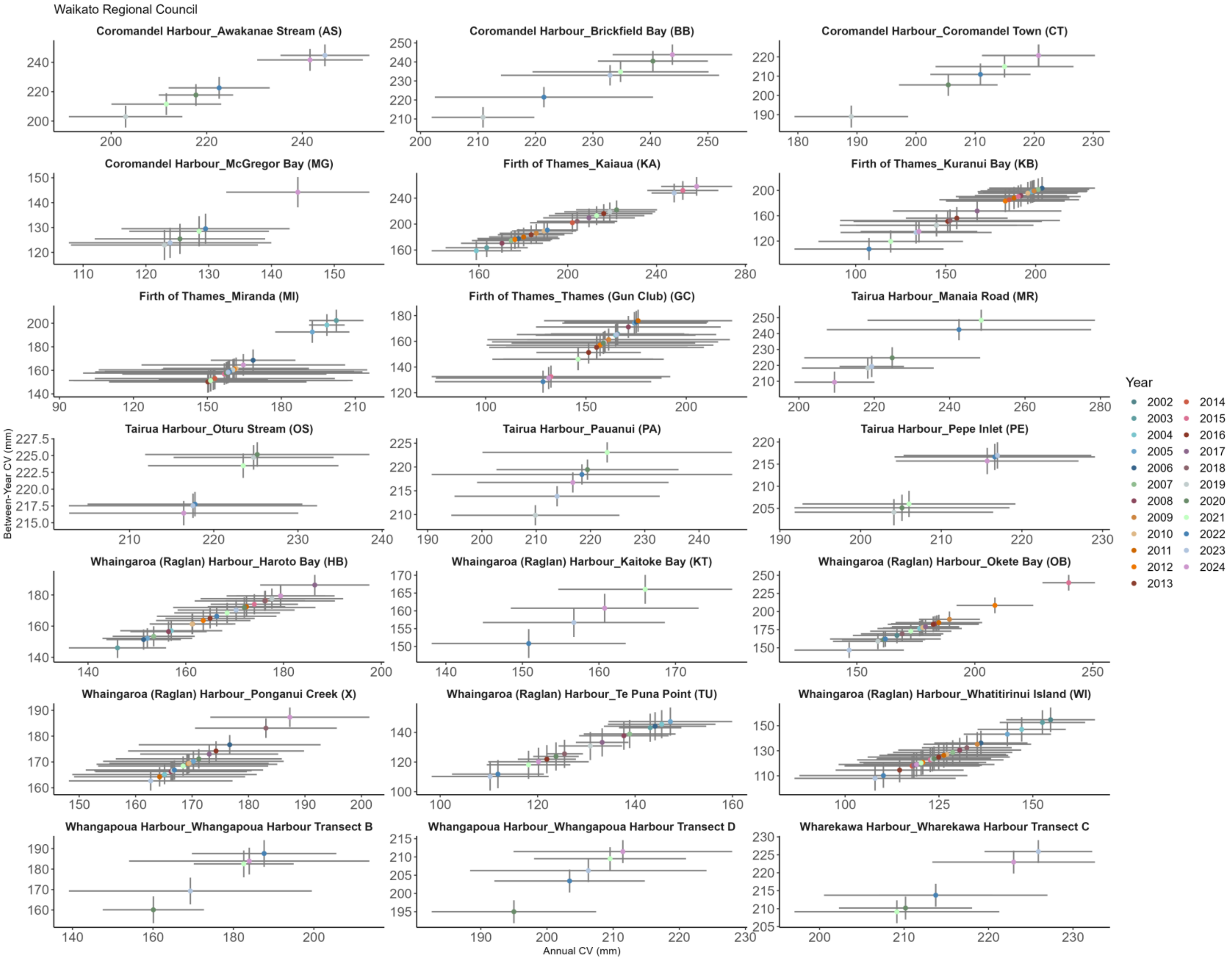


Coromandel Harbour_McGregor Bay (MG) *
Firth of Thames_Kaiaua (KA) *
Firth of Thames_Kuranui Bay (KB) *
Firth of Thames_Miranda (MI) *
Firth of Thames_Thames (Gun Club) (GC) *
Tairua Harbour_Manaia Road (MR) *
Tairua Harbour_Oturu Stream (OS) *
Tairua Harbour_Pauanui (PA) *
Tairua Harbour_Pepe Inlet (PE) *
Whaingaroa (Raglan) Harbour_Haroto Bay (HB)
Whaingaroa (Raglan) Harbour_Kaitoke Bay (KT)
Whaingaroa (Raglan) Harbour_Okete Bay (OB)
Whaingaroa (Raglan) Harbour_Ponganui Creek (X)
Whaingaroa (Raglan) Harbour_Te Puna Point (TU)
Whaingaroa (Raglan) Harbour_Whatitirinui Island (WI)
Within Plate CV (mm)
Year

Figure A4.2 (following pages). Coefficient of variation (CV) in sediment depth measurements for selected sites in Auckland, Northland and Waikato, illustrating both within-year (annual) and between-year variability. Coloured dots represent averaged sediment depth measurements for each site/year. Within-year CVs were calculated as the standard deviation (SD) of averaged within-year measurements divided by their respective annual average / site. The between-year CVs were calculated as the SD of annual site means divided by the overall site mean.

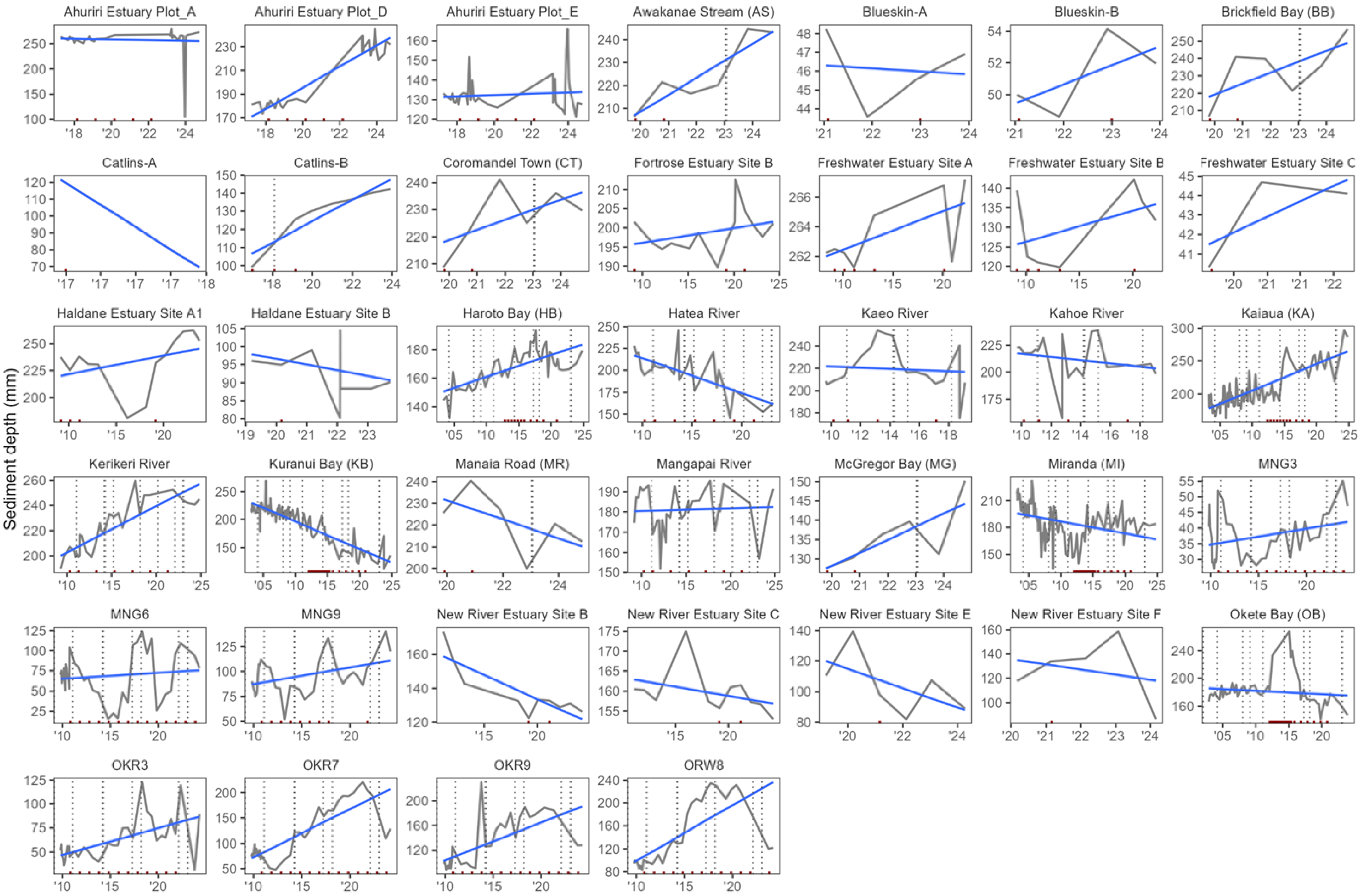

Auckland Council
Mangemangeroa_MNG3
Mangemangeroa_MNG6
Mangemangeroa_MNG9
Okura_OKR3
Okura_OKR7
Okura_OKR9
Orewa_ORW8
Puhoi_PUH1
Puhoi_PUH4
Puhoi_PUH9
Turanga_TRN3
Turanga_TRN7
Waikopua_WKP3
Waikopua_WKP6
Waikopua_WKP8
Waiwera_WWR2
Waiwera_WWR6
Between-Year CV (mm)
Annual CV (mm)
Year
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

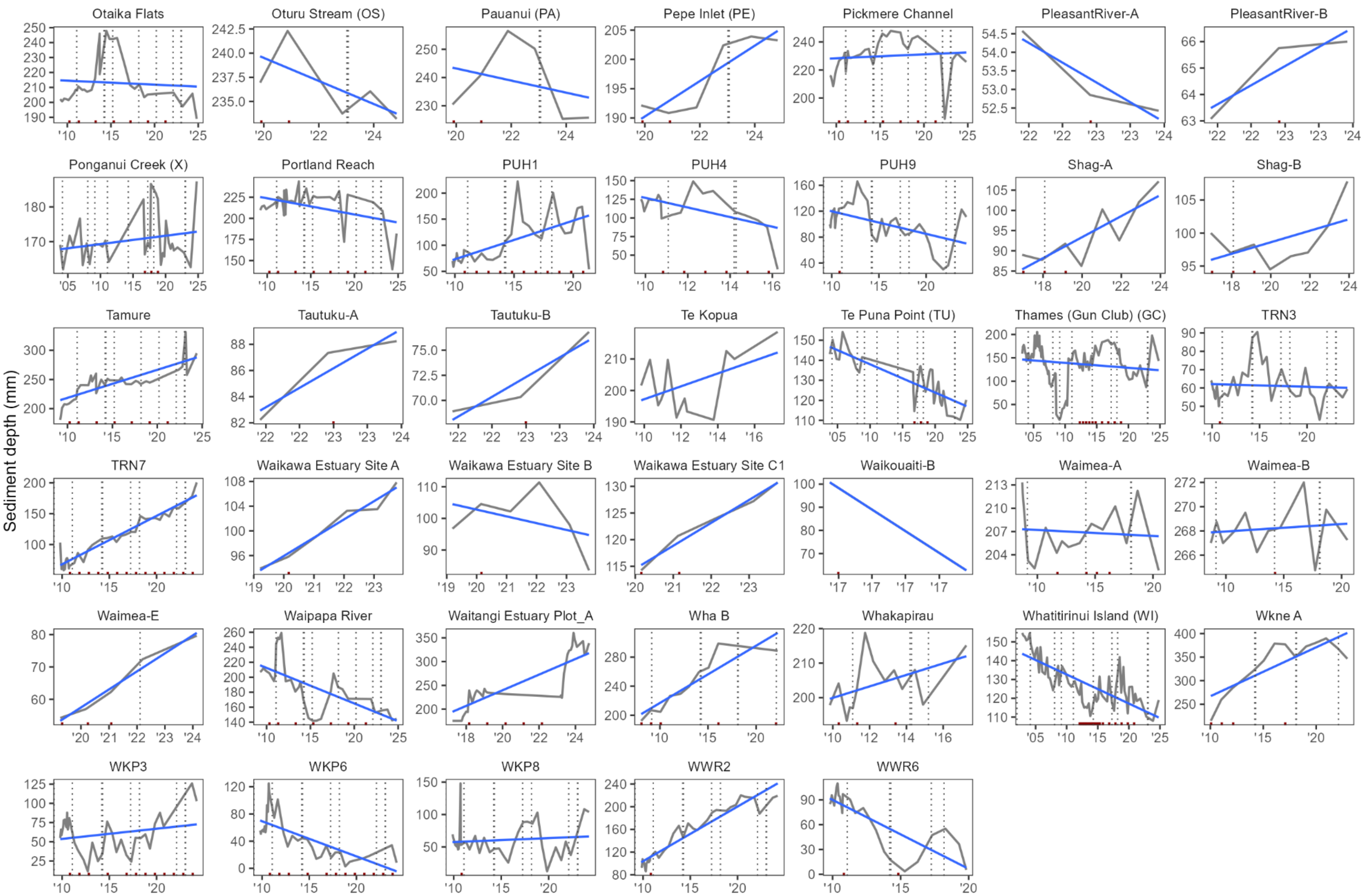

Northland Regional Council
Kaipara Harbour_Te Topua
Kaipara Harbour_Whakapirau
Kerikeri Inlet_Kerikeri River
Kerikeri Inlet_Pickmere Channel
Kerikeri Inlet_Waipapa River
Ruakaka_Ruakaka
Ruakaka_Tamure
Whangarei_Hatea River
Whangarei_Mangapai River
Whangarei_Otaika Flats
Whangarei_Portland Reach
Whangaroa Harbour_Kaeo River
Whangaroa Harbour_Kahoe River
Between-Year CV (mm)
Annual CV (mm)
Year
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2021
2022
2023
2024


Waikato Regional Council
Coromandel Harbour_Awakanae Stream (AS)
Coromandel Harbour_Brickfield Bay (BB)
Coromandel Harbour_Coromandel Town (CT)
Coromandel Harbour_McGregor Bay (MG)
Firth of Thames_Kaiaua (KA)
Firth of Thames_Kuranui Bay (KB)
Firth of Thames_Miranda (MI)
Firth of Thames_Thames (Gun Club) (GC)
Tairua Harbour_Manaia Road (MR)
Tairua Harbour_Oturu Stream (OS)
Tairua Harbour_Pauanui (PA)
Tairua Harbour_Pepe Inlet (PE)
Whaingaroa (Raglan) Harbour_Haroto Bay (HB)
Whaingaroa (Raglan) Harbour_Kaitoke Bay (KT)
Whaingaroa (Raglan) Harbour_Okete Bay (OB)
Whaingaroa (Raglan) Harbour_Ponganui Creek (X)
Whaingaroa (Raglan) Harbour_Te Puna Point (TU)
Whaingaroa (Raglan) Harbour_Whatitirinui Island (WI)
Whangapoua Harbour_Whangapoua Harbour Transect B
Whangapoua Harbour_Whangapoua Harbour Transect D
Wharekawa Harbour_Wharekawa Harbour Transect C
Between-Year CV (mm)
Annual CV (mm)
Year
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

Appendix 5. Time series of sediment depth at each site

Figure A5.1 (following pages). Temporal patterns in sediment depth (mm) at estuarine monitoring sites. Each panel shows time-series data from one site, with linear trends (solid lines), storm events (dotted vertical lines) and macrofauna sampling events (red rug marks). These plots provide a general indication of sediment accretion and erosion patterns at each site. Final quality control checks on the combined macrofauna / SAR / mud dataset (see Section 2.1) have not yet been completed. Data may include plates that were reburied or replaced, as well as site/time combinations that are not reliable indicators of long-term sediment accretion. Site averages are based on raw values and have not been adjusted for differences in the number of contributing plates.


Sediment depth (mm)
Ahuriri Estuary Plot_A
Ahuriri Estuary Plot_D
Ahuriri Estuary Plot_E
Awakanae Stream (AS)
Blueskin-A
Blueskin-B
Brickfield Bay (BB)
Catlins-A
Catlins-B
Coromandel Town (CT)
Fortrose Estuary Site B
Freshwater Estuary Site A
Freshwater Estuary Site B
Freshwater Estuary Site C
Haldane Estuary Site A1
Haldane Estuary Site B
Haroto Bay (HB)
Hatea River
Kaeo River
Kahoe River
Kaiaua (KA)
Kerikeri River
Kuranui Bay (KB)
Manaia Road (MR)
Mangapai River
McGregor Bay (MG)
Miranda (MI)
MNG3
MNG6
MNG9
New River Estuary Site B
New River Estuary Site C
New River Estuary Site E
New River Estuary Site F
Okete Bay (OB)
OKR3
OKR7
OKR9
ORW8


Sediment depth (mm)
Otaika Flats
Oturu Stream (OS)
Pauanui (PA)
Pepe Inlet (PE)
Pickmere Channel
PleasantRiver-A
PleasantRiver-B
Ponganui Creek (X)
Portland Reach
PUH1
PUH4
PUH9
Shag-A
Shag-B
Tamure
Tautuku-A
Tautuku-B
Te Kopua
Te Puna Point (TU)
Thames (Gun Club) (GC)
TRN3
TRN7
Waikawa Estuary Site A
Waikawa Estuary Site B
Waikawa Estuary Site C1
Waikouaiti-B
Waimea-A
Waimea-B
Waimea-E
Waipapa River
Waitangi Estuary Plot_A
Wha B
Whakapirau
Whatitirinui Island (WI)
Wkne A
WKP3
WKP6
WKP8
WWR2
WWR6

Appendix 6. Change point detection plots

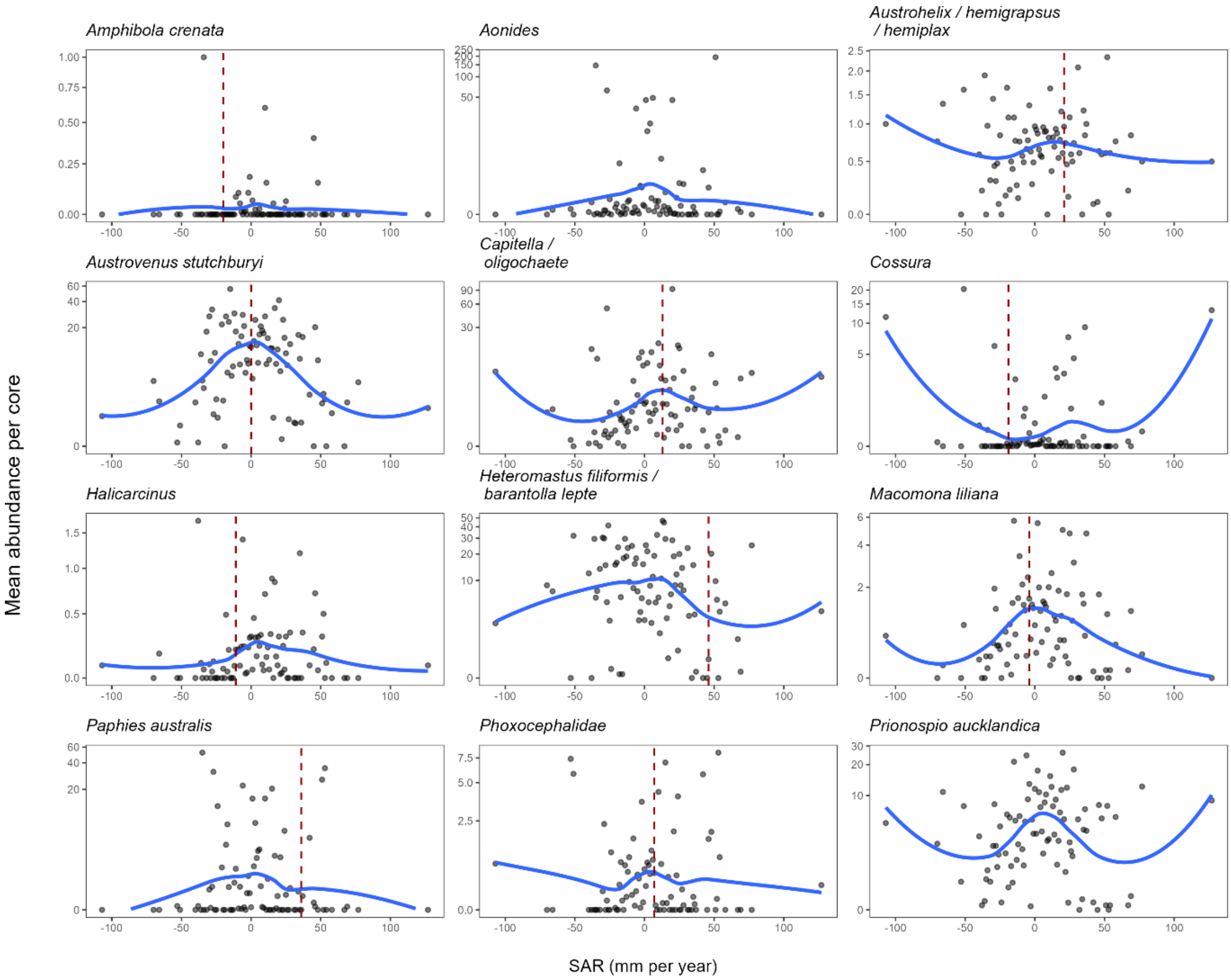


Figure A6.1. Plots showing the location of significant changes in macrofauna taxa abundance (indicated by dashed red lines) along 1-year SAR gradients, as identified using change point detection analysis. Blue lines are LOESS curves, included to aid visualisation of non-linear trends, but are not part of the change point analysis.

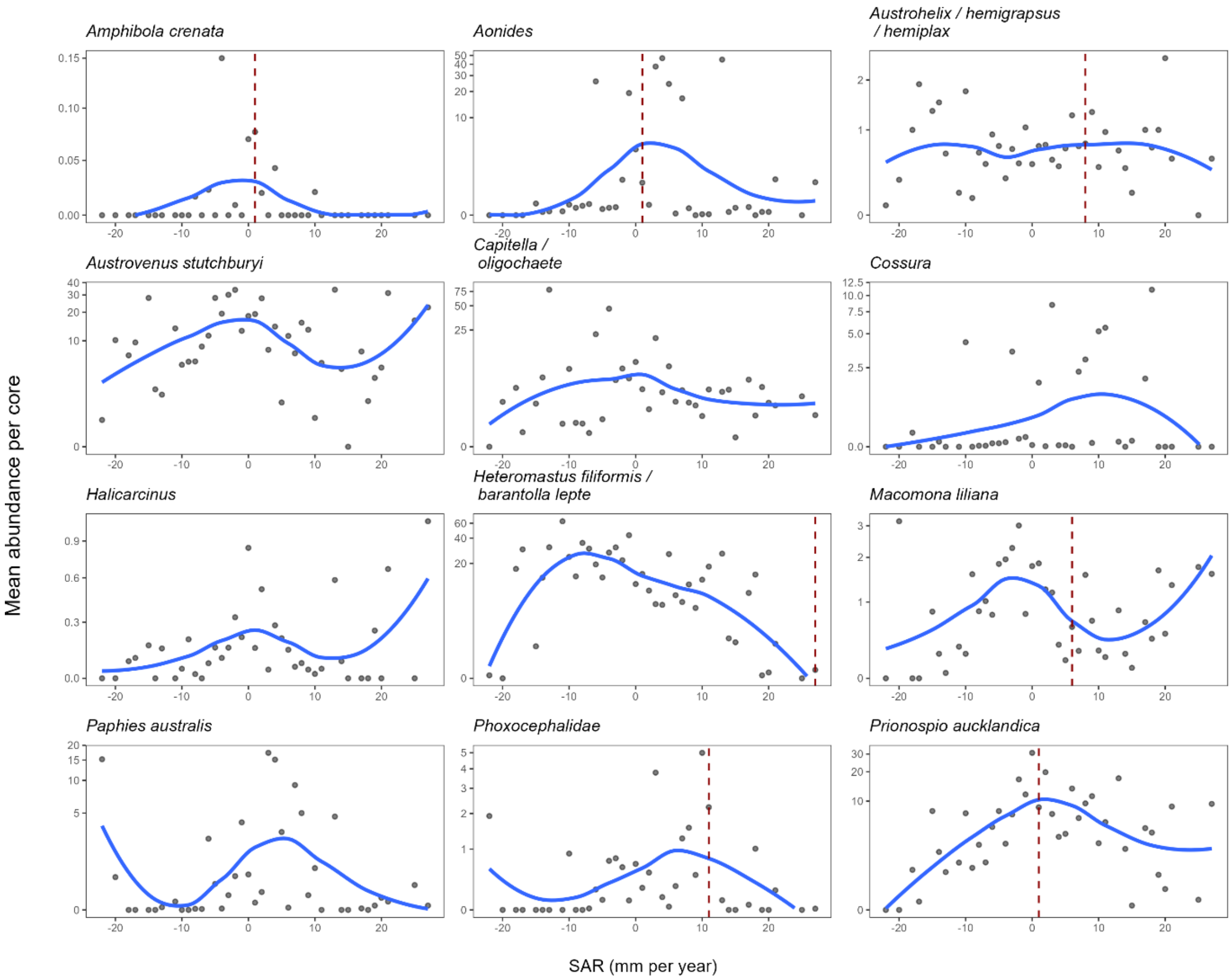


Figure A6.2. Plots showing the location of significant changes in macrofauna taxa abundance (indicated by dashed red lines) along 5-year SAR gradients, as identified using change point detection analysis. Blue lines are LOESS curves, included to aid visualisation of non-linear trends, but are not part of the change point analysis.

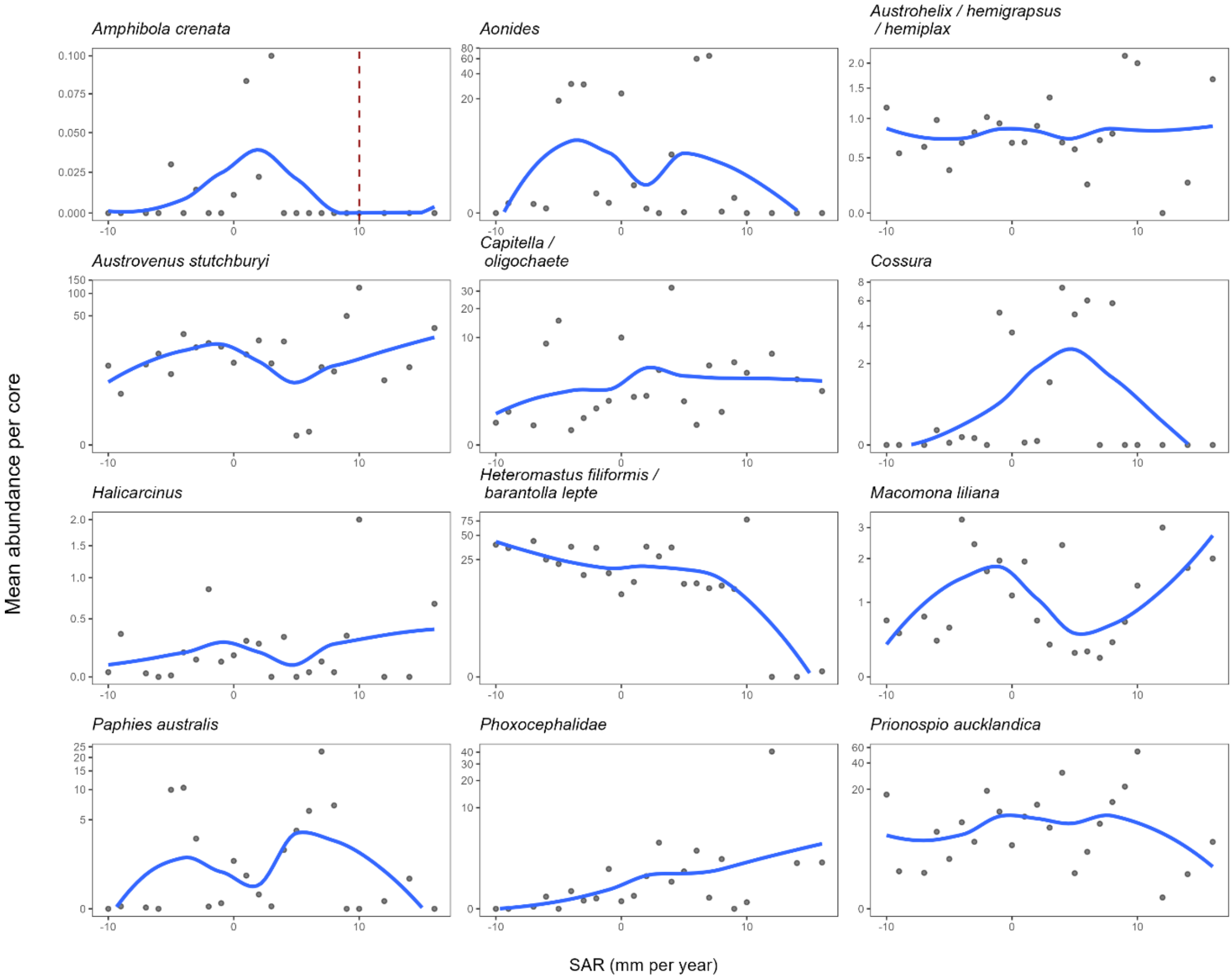


Figure A6.3. Plots showing the location of significant changes in macrofauna taxa abundance (indicated by dashed red lines) along 10-year SAR gradients, as identified using change point detection analysis. Blue lines are LOESS curves, included to aid visualisation of non-linear trends, but are not part of the change point analysis.

Appendix 7. Generalised additive model (GAM) summary and performance tables

A7.1 Generalised additive model (GAM) summary table for key taxa

Taxa	Period	Term	edf	ref.df	Statistic	*p*-value
Amphibola crenata	1–2 months	s(sar_mm_yr)	1	1	1.14	0.29
Amphibola crenata	1–2 months	s(mud)	1.66	1.89	1.41	0.32
Aonides	1–2 months	s(sar_mm_yr)	1.6	1.84	1.36	0.36
Aonides	1–2 months	s(mud)	1	1	2.38	0.13
Austrohelice / Hemigrapsus / Hemiplax	1–2 months	s(sar_mm_yr)	1	1	0.34	0.56
Austrohelice / Hemigrapsus / Hemiplax	1–2 months	s(mud)	1.96	2	13.5	< 0.001
Austrovenus stutchburyi	1–2 months	s(sar_mm_yr)	1	1	1.02	0.32
Austrovenus stutchburyi	1–2 months	s(mud)	1	1	11.1	< 0.001
Capitella / Oligochaeta	1–2 months	s(sar_mm_yr)	1	1	0.41	0.52
Capitella / Oligochaeta	1–2 months	s(mud)	1.52	1.77	1.07	0.46
Cossura	1–2 months	s(sar_mm_yr)	1.68	1.9	1.11	0.37
Cossura	1–2 months	s(mud)	1.75	1.94	2.91	0.11
Halicarcinus	1–2 months	s(sar_mm_yr)	1.09	1.17	0.06	0.94
Halicarcinus	1–2 months	s(mud)	1	1	2.58	0.12
Heteromastus filiformis / Barantolla lepte	1–2 months	s(sar_mm_yr)	1	1	1.06	0.31
Heteromastus filiformis / Barantolla lepte	1–2 months	s(mud)	1.87	1.98	3.59	0.04
Macomona liliana	1–2 months	s(sar_mm_yr)	1.15	1.28	0.65	0.55
Macomona liliana	1–2 months	s(mud)	1.76	1.94	9.1	< 0.001
Paphies australis	1–2 months	s(sar_mm_yr)	1	1	0.32	0.58
Paphies australis	1–2 months	s(mud)	1.85	1.98	6.11	0.01
Phoxocephalidae	1–2 months	s(sar_mm_yr)	1	1	0.17	0.68
Phoxocephalidae	1–2 months	s(mud)	1	1	0.44	0.51
Prionospio aucklandica	1–2 months	s(sar_mm_yr)	1	1	2.32	0.14
Prionospio aucklandica	1–2 months	s(mud)	1	1	1.31	0.26
Amphibola crenata	1 year	s(sar_mm_yr)	1	1	0.22	0.64
Amphibola crenata	1 year	s(mud)	1	1	7.75	0.01
Aonides	1 year	s(sar_mm_yr)	1	1	0.86	0.35
Aonides	1 year	s(mud)	1.79	1.96	10.5	< 0.001
Austrohelice / Hemigrapsus / Hemiplax	1 year	s(sar_mm_yr)	1	1	0.09	0.76
Austrohelice / Hemigrapsus / Hemiplax	1 year	s(mud)	1.98	2	25.95	< 0.001
Austrovenus stutchburyi	1 year	s(sar_mm_yr)	1.84	1.98	2.73	0.07
Austrovenus stutchburyi	1 year	s(mud)	1	1	32.55	< 0.001
Capitella / Oligochaeta	1 year	s(sar_mm_yr)	1	1	0.84	0.36
Capitella / Oligochaeta	1 year	s(mud)	1.74	1.93	7.66	< 0.001
Cossura	1 year	s(sar_mm_yr)	1.96	2	12.31	< 0.001
Cossura	1 year	s(mud)	1.94	2	17.02	< 0.001
Halicarcinus	1 year	s(sar_mm_yr)	1.2	1.35	1.23	0.36

Taxa	Period	Term	edf	ref.df	Statistic	*p*-value
Halicarcinus	1 year	s(mud)	1	1	12.83	< 0.001
Heteromastus filiformis / Barantolla lepte	1 year	s(sar_mm_yr)	1	1	0.3	0.58
Heteromastus filiformis / Barantolla lepte	1 year	s(mud)	1.97	2	15.92	< 0.001
Macomona liliana	1 year	s(sar_mm_yr)	1.7	1.91	1.37	0.3
Macomona liliana	1 year	s(mud)	1	1	15.59	< 0.001
Paphies australis	1 year	s(sar_mm_yr)	1	1	0.7	0.4
Paphies australis	1 year	s(mud)	1.98	2	45.83	< 0.001
Phoxocephalidae	1 year	s(sar_mm_yr)	1	1	0.05	0.82
Phoxocephalidae	1 year	s(mud)	1.17	1.31	3.8	0.06
Prionospio aucklandica	1 year	s(sar_mm_yr)	1	1	0.29	0.59
Prionospio aucklandica	1 year	s(mud)	1.95	2	12.33	< 0.001
Amphibola crenata	5 years	s(sar_mm_yr)	1	1	0.39	0.54
Amphibola crenata	5 years	s(mud)	1.79	1.95	5.5	< 0.001
Aonides	5 years	s(sar_mm_yr)	1.7	1.91	1.49	0.28
Aonides	5 years	s(mud)	1.83	1.97	8.11	< 0.001
Austrohelice / Hemigrapsus / Hemiplax	5 years	s(sar_mm_yr)	1	1	0.01	0.9
Austrohelice / Hemigrapsus / Hemiplax	5 years	s(mud)	1.96	2	15.2	< 0.001
Austrovenus stutchburyi	5 years	s(sar_mm_yr)	1	1	0.25	0.62
Austrovenus stutchburyi	5 years	s(mud)	1	1	18.32	< 0.001
Capitella / Oligochaeta	5 years	s(sar_mm_yr)	1	1	0.28	0.59
Capitella / Oligochaeta	5 years	s(mud)	1.63	1.87	18.97	< 0.001
Cossura	5 years	s(sar_mm_yr)	1	1	0.38	0.54
Cossura	5 years	s(mud)	1.89	1.99	15	< 0.001
Halicarcinus	5 years	s(sar_mm_yr)	1.38	1.62	0.54	0.67
Halicarcinus	5 years	s(mud)	1	1	5.89	0.02
Heteromastus filiformis / Barantolla lepte	5 years	s(sar_mm_yr)	1.8	1.96	10.82	< 0.001
Heteromastus filiformis / Barantolla lepte	5 years	s(mud)	1.94	2	11.32	< 0.001
Macomona liliana	5 years	s(sar_mm_yr)	1	1	0.01	0.9
Macomona liliana	5 years	s(mud)	1	1	11.17	< 0.001
Paphies australis	5 years	s(sar_mm_yr)	1	1	0.01	0.92
Paphies australis	5 years	s(mud)	1.96	2	25.44	< 0.001
Phoxocephalidae	5 years	s(sar_mm_yr)	1.45	1.7	0.44	0.68
Phoxocephalidae	5 years	s(mud)	1	1	0.56	0.46
Prionospio aucklandica	5 years	s(sar_mm_yr)	1.86	1.98	3.09	0.04
Prionospio aucklandica	5 years	s(mud)	1.95	2	10.1	< 0.001
Amphibola crenata	10 years	s(sar_mm_yr)	1	1	0.79	0.38
Amphibola crenata	10 years	s(mud)	1.75	1.94	1.6	0.17
Aonides	10 years	s(sar_mm_yr)	1	1	1.19	0.28
Aonides	10 years	s(mud)	1.91	1.99	11.98	< 0.001
Austrohelice / Hemigrapsus / Hemiplax	10 years	s(sar_mm_yr)	1	1	0.53	0.47
Austrohelice / Hemigrapsus / Hemiplax	10 years	s(mud)	1.96	2	14.34	< 0.001
Austrovenus stutchburyi	10 years	s(sar_mm_yr)	1	1	0.01	0.92

Taxa	Period	Term	edf	ref.df	Statistic	*p*-value
Austrovenus stutchburyi	10 years	s(mud)	1.87	1.98	3.5	0.03
Capitella / Oligochaeta	10 years	s(sar_mm_yr)	1	1	0.41	0.53
Capitella / Oligochaeta	10 years	s(mud)	1	1	9.43	< 0.001
Cossura	10 years	s(sar_mm_yr)	1.39	1.63	0.24	0.76
Cossura	10 years	s(mud)	1.04	1.09	10.14	< 0.001
Halicarcinus	10 years	s(sar_mm_yr)	1	1	0.14	0.71
Halicarcinus	10 years	s(mud)	1	1	1.04	0.31
Heteromastus filiformis / Barantolla lepte	10 years	s(sar_mm_yr)	1	1	8.99	< 0.001
Heteromastus filiformis / Barantolla lepte	10 years	s(mud)	1.94	2	9.89	< 0.001
Macomona liliana	10 years	s(sar_mm_yr)	1.08	1.16	0.01	0.97
Macomona liliana	10 years	s(mud)	1.52	1.77	0.68	0.38
Paphies australis	10 years	s(sar_mm_yr)	1	1	5.56	0.02
Paphies australis	10 years	s(mud)	1.95	2	21.63	< 0.001
Phoxocephalidae	10 years	s(sar_mm_yr)	1.37	1.6	5.09	0.01
Phoxocephalidae	10 years	s(mud)	1	1	0.94	0.34
Prionospio aucklandica	10 years	s(sar_mm_yr)	1.53	1.78	0.71	0.56
Prionospio aucklandica	10 years	s(mud)	1.94	2	6.59	< 0.001

edf = estimated degrees of freedom; ref.df = reference degrees of freedom.

A7.2 Generalised additive model (GAM) performance table for key taxa

Taxa	Period	df	logLik	AIC	BIC	Deviance	df.residual	nobs	adj.r.squared	npar	deviance_explained
Amphibola crenata	1–2 months	3.66	46.16	-82.99	-75.35	0.2	34.34	38	0.05	5	0.12
Aonides	1–2 months	3.6	-4.38	17.98	25.51	2.8	34.4	38	0.05	5	0.12
Austrohelice / Hemigrapsus / Hemiplax	1–2 months	3.96	23.53	-37.14	-29.02	0.64	34.04	38	0.4	5	0.45
Austrovenus stutchburyi	1–2 months	3	-27.54	63.08	69.63	9.48	35	38	0.2	5	0.24
Capitella / Oligochaeta	1–2 months	3.52	-24.48	58.01	65.41	8.07	34.48	38	0.01	5	0.08
Cossura	1–2 months	4.43	-13.86	38.59	47.48	4.62	33.57	38	0.11	5	0.2
Halicarcinus	1–2 months	3.09	47.28	-86.39	-79.69	0.18	34.91	38	0.02	5	0.07
Heteromastus filiformis / Barantolla lepte	1–2 months	3.87	-23.51	56.77	64.75	7.67	34.13	38	0.15	5	0.21
Macomona liliana	1–2 months	3.92	-6.67	23.18	31.24	3.16	34.08	38	0.27	5	0.33
Paphies australis	1–2 months	3.85	1.03	7.63	15.57	2.11	34.15	38	0.2	5	0.26
Phoxocephalidae	1–2 months	3	3.56	0.89	7.44	1.85	35	38	-0.03	5	0.02
Prionospio aucklandica	1–2 months	3	-18.53	45.07	51.62	5.9	35	38	0.07	5	0.12
Amphibola crenata	1 year	3	319.97	-631.94	-618.37	0.7	217	220	0.03	5	0.03
Aonides	1 year	3.79	-105.53	220.64	236.89	33.62	216.21	220	0.07	5	0.08
Austrohelice / Hemigrapsus / Hemiplax	1 year	3.98	123.31	-236.66	-219.77	4.2	216.02	220	0.18	5	0.2
Austrovenus stutchburyi	1 year	3.84	-157.22	324.14	340.57	53.79	216.16	220	0.14	5	0.15
Capitella / Oligochaeta	1 year	3.74	-138.17	285.83	301.93	45.24	216.26	220	0.05	5	0.06
Cossura	1 year	4.9	3.43	4.94	24.96	12.49	215.1	220	0.21	5	0.22
Halicarcinus	1 year	3.2	146.68	-284.96	-270.72	3.4	216.8	220	0.05	5	0.06
Heteromastus filiformis / Barantolla lepte	1 year	3.97	-162.23	334.38	351.24	56.29	216.03	220	0.12	5	0.13
Macomona liliana	1 year	3.7	-30.88	71.14	87.08	17.05	216.3	220	0.07	5	0.08
Paphies australis	1 year	3.98	-79.9	169.75	186.64	26.63	216.02	220	0.29	5	0.3
Phoxocephalidae	1 year	3.17	-36.11	80.55	94.7	17.89	216.83	220	0.01	5	0.02
Prionospio aucklandica	1 year	3.95	-147.86	305.62	322.44	49.4	216.05	220	0.1	5	0.11
Amphibola crenata	5 years	3.79	298.83	-588.09	-574.29	0.08	128.21	132	0.08	5	0.1

Taxa	Period	df	logLik	AIC	BIC	Deviance	df.residual	nobs	adj.r.squared	npar	deviance_explained
Aonides	5 years	4.54	-81.68	174.43	190.39	26.64	127.46	132	0.1	5	0.13
Austrohelice / Hemigrapsus / Hemiplax	5 years	3.96	71.33	-132.73	-118.42	2.62	128.04	132	0.18	5	0.2
Austrovenus stutchburyi	5 years	3	-98.62	205.24	216.77	34.44	129	132	0.11	5	0.13
Capitella / Oligochaeta	5 years	3.63	-88.28	185.83	199.2	29.45	128.37	132	0.19	5	0.21
Cossura	5 years	3.89	-30	69.79	83.89	12.18	128.11	132	0.17	5	0.18
Halicarcinus	5 years	3.38	94.09	-179.41	-166.78	1.86	128.62	132	0.03	5	0.05
Heteromastus filiformis / Barantolla lepte	5 years	4.74	-87.25	185.98	202.53	28.99	127.26	132	0.24	5	0.27
Macomona liliana	5 years	3	10.58	-13.17	-1.63	6.58	129	132	0.07	5	0.08
Paphies australis	5 years	3.96	-40.46	90.85	105.15	14.27	128.04	132	0.27	5	0.28
Phoxocephalidae	5 years	3.45	-3.52	15.94	28.76	8.15	128.55	132	0	5	0.01
Prionospio aucklandica	5 years	4.81	-95.96	203.52	220.26	33.08	127.19	132	0.16	5	0.18
Amphibola crenata	10 years	3.75	205.23	-400.97	-390.15	0.01	68.25	72	0.03	5	0.07
Aonides	10 years	3.91	-53.36	116.54	127.72	18.56	68.09	72	0.24	5	0.27
Austrohelice / Hemigrapsus / Hemiplax	10 years	3.96	41.59	-73.26	-61.98	1.33	68.04	72	0.28	5	0.31
Austrovenus stutchburyi	10 years	3.87	-59.46	128.65	139.73	21.98	68.13	72	0.07	5	0.11
Capitella / Oligochaeta	10 years	3	-45.71	99.42	108.53	15.01	69	72	0.1	5	0.12
Cossura	10 years	3.44	-10.73	30.33	40.43	5.68	68.56	72	0.12	5	0.15
Halicarcinus	10 years	3	42.77	-77.54	-68.43	1.29	69	72	-0.01	5	0.02
Heteromastus filiformis / Barantolla lepte	10 years	3.94	-49.43	108.74	119.99	16.64	68.06	72	0.28	5	0.31
Macomona liliana	10 years	3.6	-1.97	13.14	23.62	4.45	68.4	72	0	5	0.04
Paphies australis	10 years	3.95	-28.8	67.5	78.77	9.38	68.05	72	0.4	5	0.42
Phoxocephalidae	10 years	3.37	-7.4	23.54	33.49	5.18	68.63	72	0.11	5	0.14
Prionospio aucklandica	10 years	4.47	-52.97	116.89	129.34	18.36	67.53	72	0.14	5	0.18

Df = degrees of freedom used by the model; logLik = log-likelihood of the model – higher values indicate better fit; AIC = Akaike information criterion, used for model comparison – a lower value is better; BIC = Bayesian information criterion, used for model comparison – a lower value is better; Deviance = a measure of model fit; lower deviance implies a better model; Df.residuals = residual degrees of freedom – the difference between the number of observations and the estimated degrees of freedom used by the model; Nobs = number of observations in the dataset (sample size); Adj.rsquared = adjusted *R*-squared – proportion of deviance explained, adjusted for degrees of freedom, useful for comparing models of different complexity; Npar = number of parameters – total number of estimated parameters in the model (including smoothing parameters and intercept); Deviance explained = percentage of total deviance explained by the model.

A7.3 Generalised additive model (GAM) summary table for ecological indicators

Indicator	Period	Term	edf	ref.df	Statistic	*p*-value
mud_bhm	1–2 months	s(sar_mm_yr)	1	1	2.35	0.14
mud_bhm	1–2 months	s(mud)	1.95	2	24.77	< 0.001
S	1–2 months	s(sar_mm_yr)	1	1	0.21	0.65
S	1–2 months	s(mud)	1	1	13.94	< 0.001
H	1–2 months	s(sar_mm_yr)	1	1	1.43	0.24
H	1–2 months	s(mud)	1	1	4.99	0.03
J	1–2 months	s(sar_mm_yr)	1	1	3.89	0.06
J	1–2 months	s(mud)	1	1	0.04	0.84
mud_bhm	1 year	s(sar_mm_yr)	1.41	1.65	0.79	0.57
mud_bhm	1 year	s(mud)	1.98	2	169.19	< 0.001
S	1 year	s(sar_mm_yr)	1	1	0.87	0.35
S	1 year	s(mud)	1.93	2	32.08	< 0.001
H	1 year	s(sar_mm_yr)	1	1	1.1	0.29
H	1 year	s(mud)	1.71	1.92	10.42	< 0.001
J	1 year	s(sar_mm_yr)	1	1	2.36	0.13
J	1 year	s(mud)	1	1	7.84	0.01
mud_bhm	5 years	s(sar_mm_yr)	1	1	8.15	0.01
mud_bhm	5 years	s(mud)	1.98	2	114.94	< 0.001
S	5 years	s(sar_mm_yr)	1.95	2	11.66	< 0.001
S	5 years	s(mud)	1.95	2	21.64	< 0.001
H	5 years	s(sar_mm_yr)	1.84	1.97	3.23	0.03
H	5 years	s(mud)	1.94	2	14.19	< 0.001
J	5 years	s(sar_mm_yr)	1.49	1.74	3.63	0.08
J	5 years	s(mud)	1.87	1.98	6.55	< 0.001
mud_bhm	10 years	s(sar_mm_yr)	1	1	12.36	< 0.001
mud_bhm	10 years	s(mud)	1.94	2	54.43	< 0.001
S	10 years	s(sar_mm_yr)	1.9	1.99	4.57	0.02
S	10 years	s(mud)	1.97	2	14.1	< 0.001
H	10 years	s(sar_mm_yr)	1.82	1.97	3.38	0.06
H	10 years	s(mud)	1.92	1.99	4.82	0.01
J	10 years	s(sar_mm_yr)	1.57	1.81	2.19	0.21
J	10 years	s(mud)	1.74	1.93	1.26	0.28

edf = estimated degrees of freedom; ref.df = reference degrees of freedom.

A7.4 Generalised additive model (GAM) performance table for ecological indicators

Indicator	Period	df	logLik	AIC	BIC	Deviance	df.residual	nobs	adj.r.squared	npar	deviance_explained
mud_bhm	1–2 months	3.95	41.6	-73.29	-66.19	0.12	27.05	31	0.61	5	0.64
S	1–2 months	3	18.48	-28.97	-22.42	0.84	35	38	0.25	5	0.29
H	1–2 months	3	55	-102.01	-95.46	0.12	35	38	0.14	5	0.19
J	1–2 months	3	85.58	-163.16	-156.61	0.02	35	38	0.05	5	0.1
mud_bhm	1 year	4.39	288.24	-565.69	-547.7	0.76	203.61	208	0.62	5	0.62
S	1 year	3.93	155.18	-300.49	-283.76	3.14	216.07	220	0.23	5	0.24
H	1 year	3.71	214.17	-418.91	-402.92	1.84	216.29	220	0.09	5	0.1
J	1 year	3	378.09	-748.19	-734.61	0.41	217	220	0.03	5	0.04
mud_bhm	5 years	3.98	201.77	-393.58	-379.41	0.31	123.02	127	0.66	5	0.67
S	5 years	4.91	123.76	-235.71	-218.68	1.19	127.09	132	0.33	5	0.35
H	5 years	4.78	162.1	-312.63	-295.97	0.66	127.22	132	0.2	5	0.23
J	5 years	4.36	254.96	-499.2	-483.75	0.16	127.64	132	0.12	5	0.14
mud_bhm	10 years	3.94	112.76	-215.63	-204.6	0.15	65.06	69	0.65	5	0.66
S	10 years	4.87	67.44	-123.13	-109.75	0.65	67.13	72	0.31	5	0.34
H	10 years	4.74	89.89	-168.3	-155.24	0.35	67.26	72	0.15	5	0.19
J	10 years	4.31	139.15	-267.68	-255.59	0.09	67.69	72	0.05	5	0.09

Df = degrees of freedom used by the model; logLik = log-likelihood of the model – higher values indicate better fit; AIC = Akaike information criterion, used for model comparison – a lower value is better; BIC = Bayesian information criterion, used for model comparison – a lower value is better; Deviance = a measure of model fit; lower deviance implies a better model; Df.residuals = residual degrees of freedom – the difference between the number of observations and the estimated degrees of freedom used by the model; Nobs = number of observations in the dataset (sample size); Adj.rsquared = adjusted *R*-squared – proportion of deviance explained, adjusted for degrees of freedom, useful for comparing models of different complexity; Npar = number of parameters – total number of estimated parameters in the model (including smoothing parameters and intercept); Deviance explained = percentage of total deviance explained by the model.

Appendix 8. Generalised additive model (GAM) plots

A8.1 Partial dependence plots for sediment accretion rate (SAR)

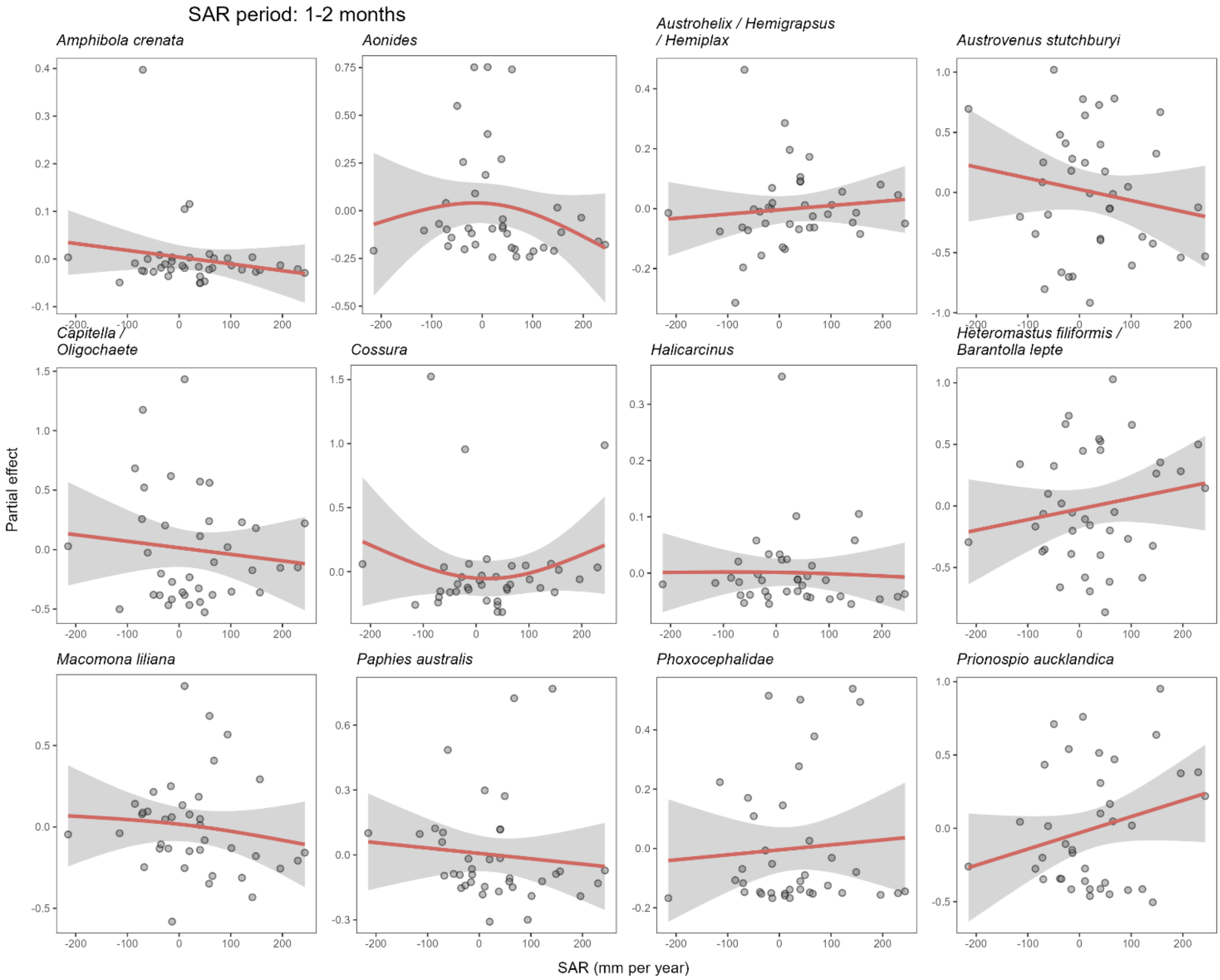


Figure A8.1. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 1–2-month SAR and macrofauna taxa abundance. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

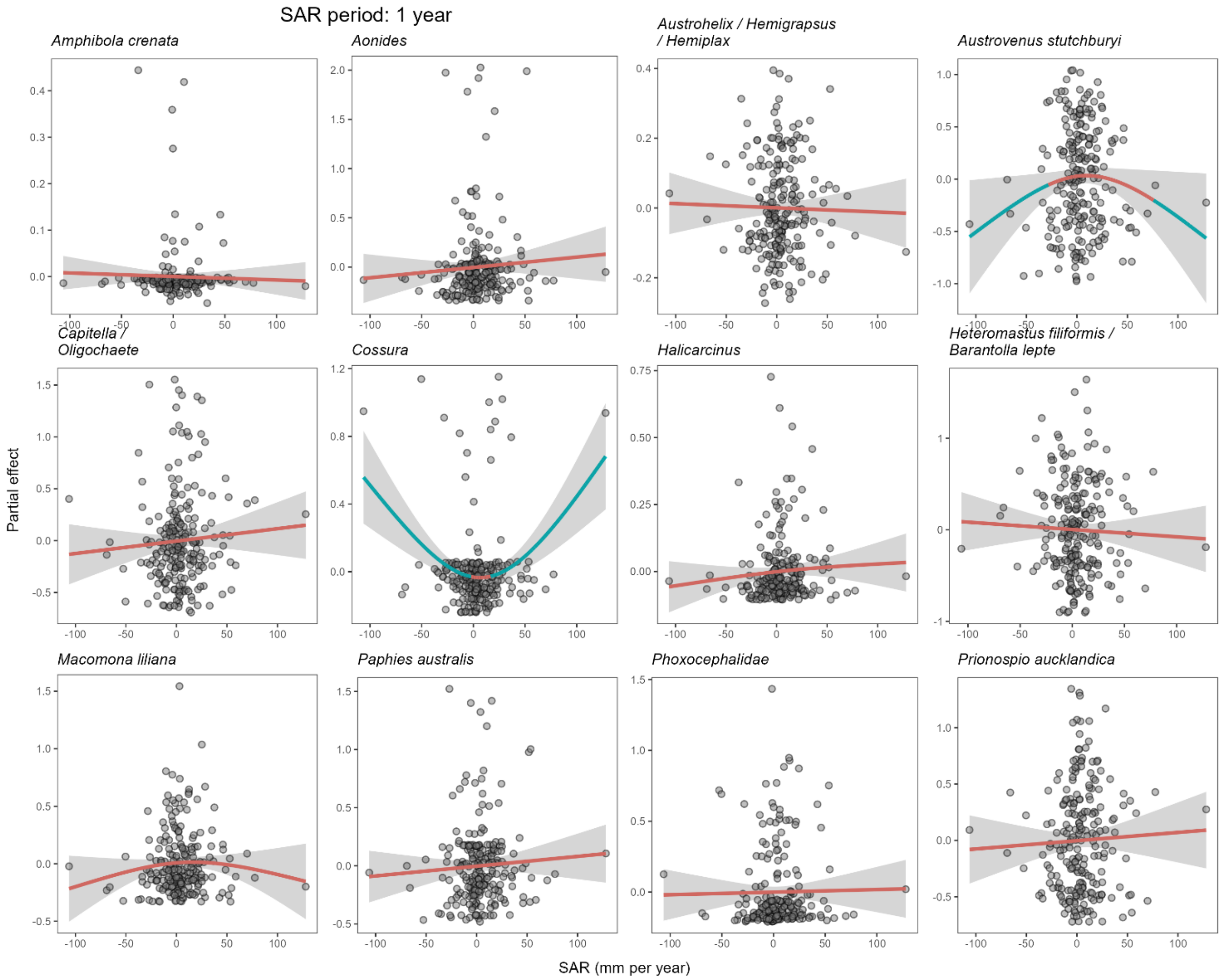


Figure A8.2. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 1-year SAR and macrofauna taxa abundance. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

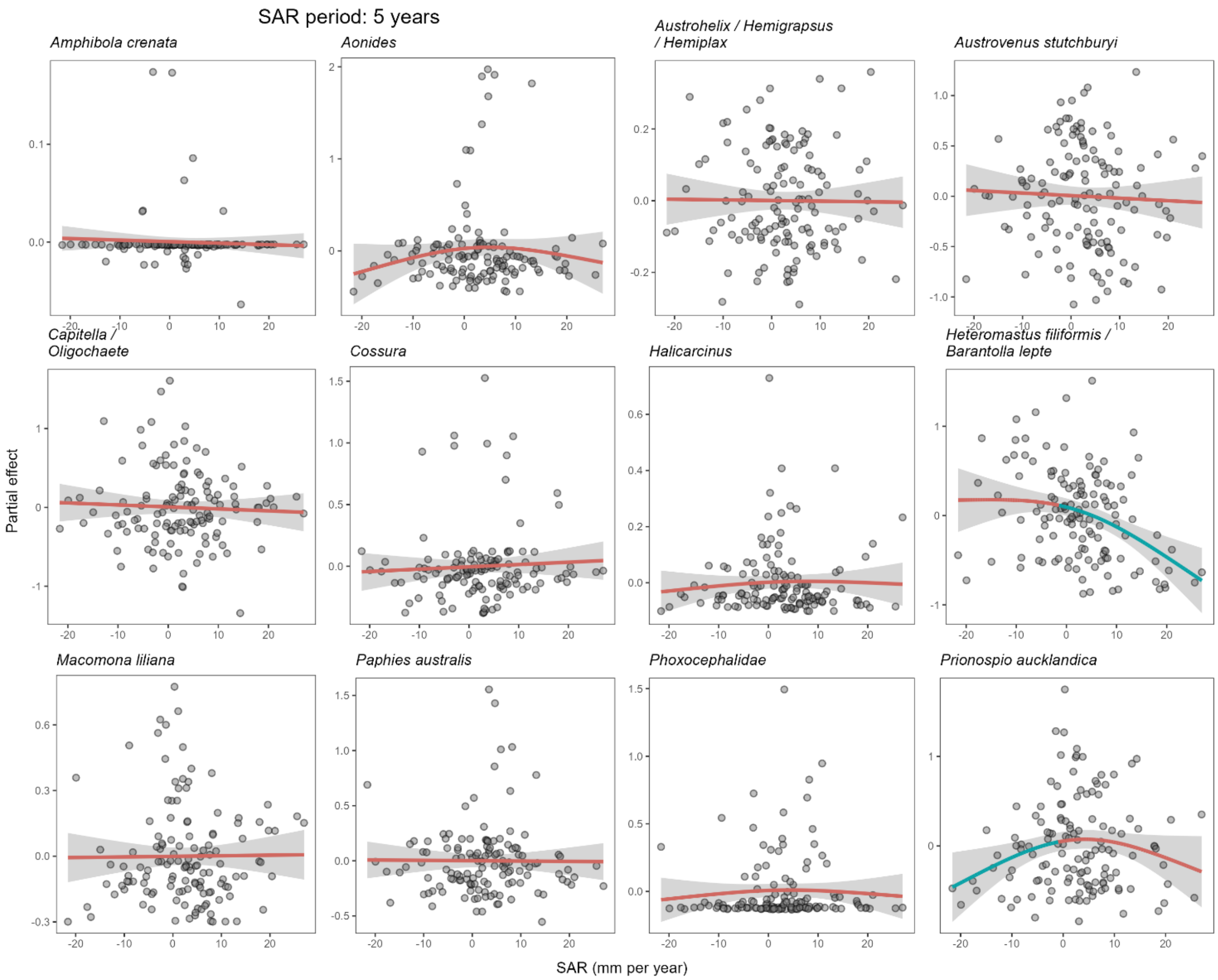


Figure A8.3. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 5-year SAR and macrofauna taxa abundance. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

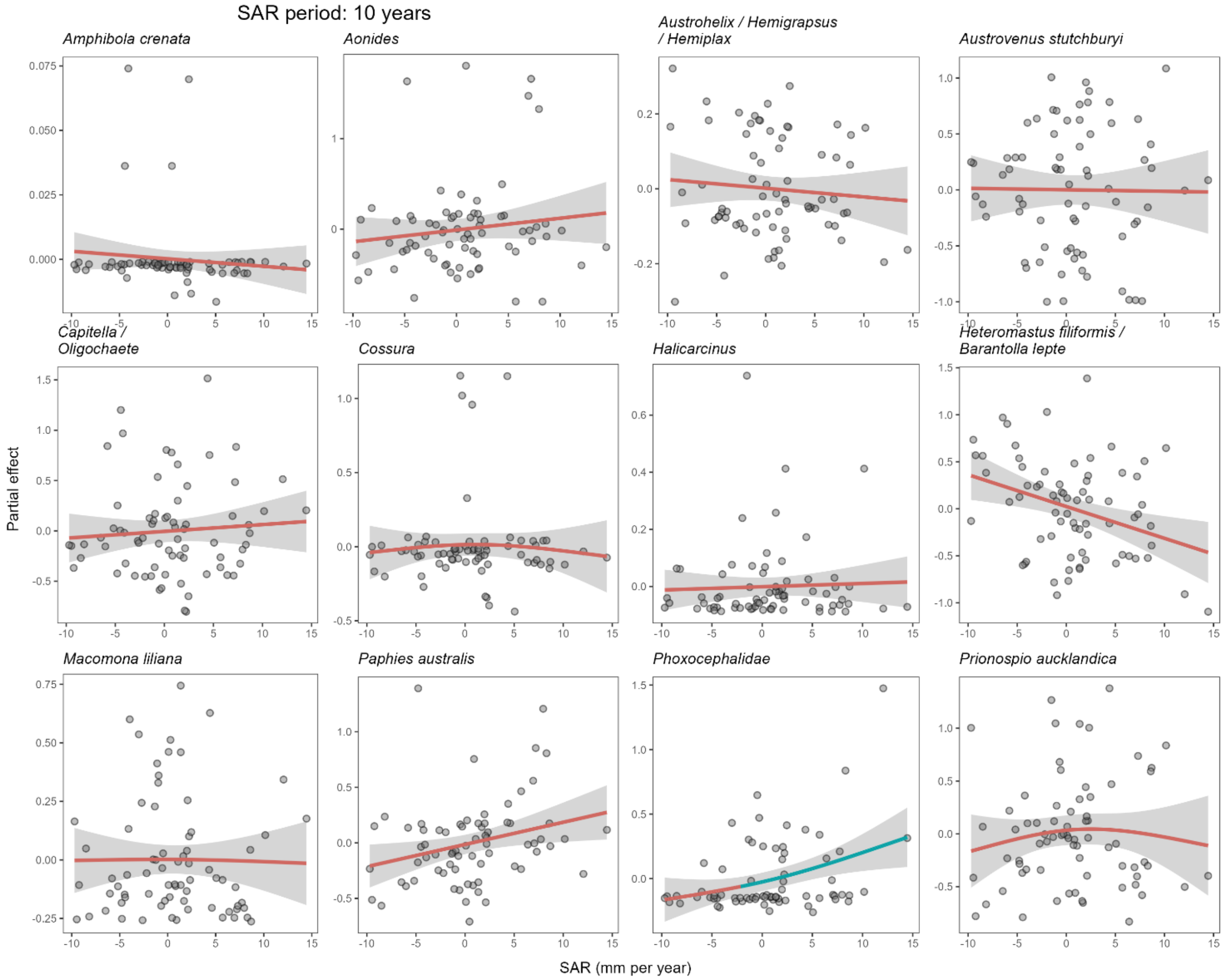


Figure A8.4. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 10-year SAR and macrofauna taxa abundance. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

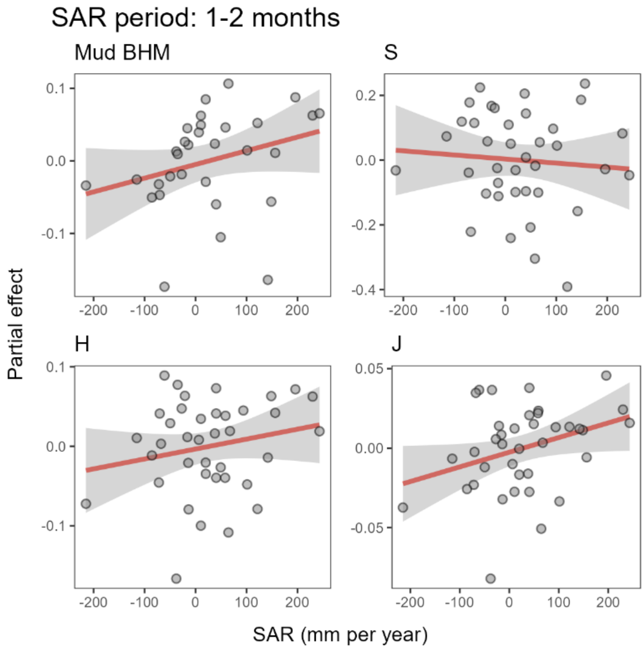


Figure A8.5. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 1–2-month SAR and ecological indicators. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

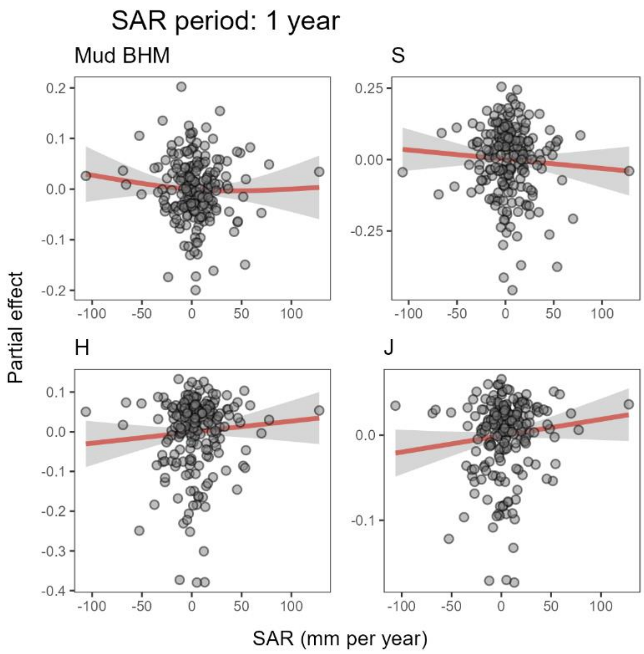


Figure A8.6. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 1-year SAR and ecological indicators. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

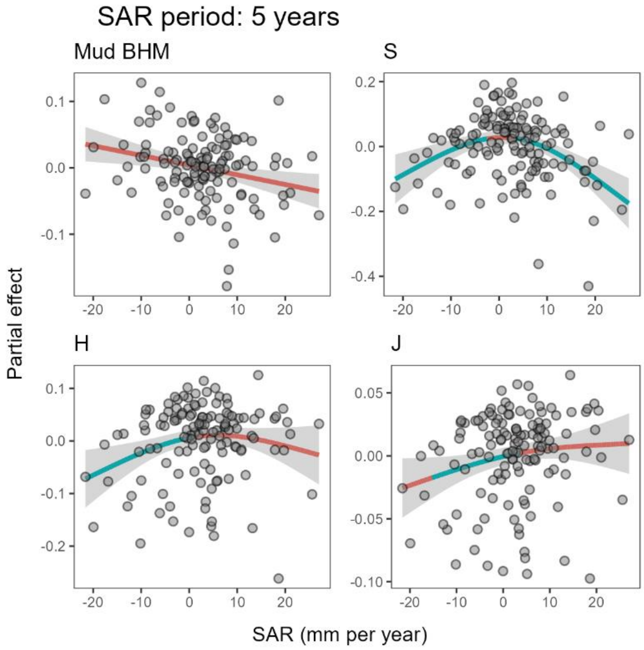


Figure A8.7. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 5-year SAR and ecological indicators. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

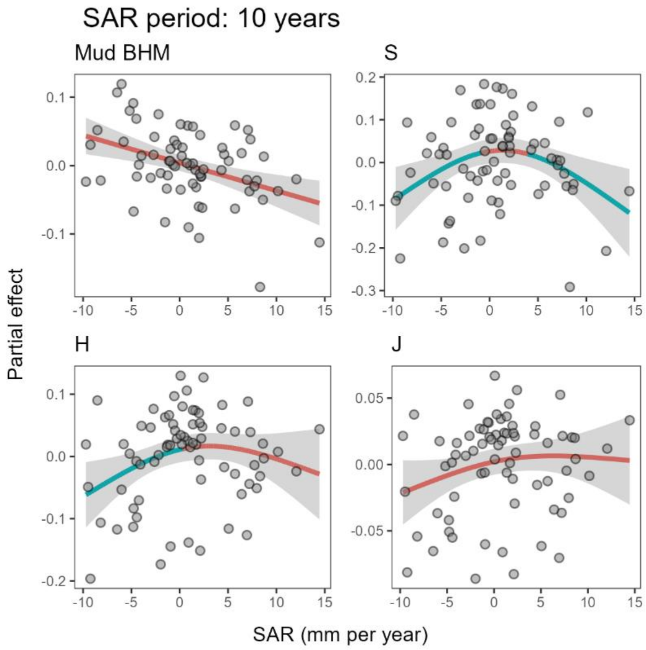


Figure A8.8. Partial dependence plots for sediment accretion rate (SAR) from generalised additive models showing the relationship between 10-year SAR and ecological indicators. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

A8.2 Partial dependence plots of sediment mud content

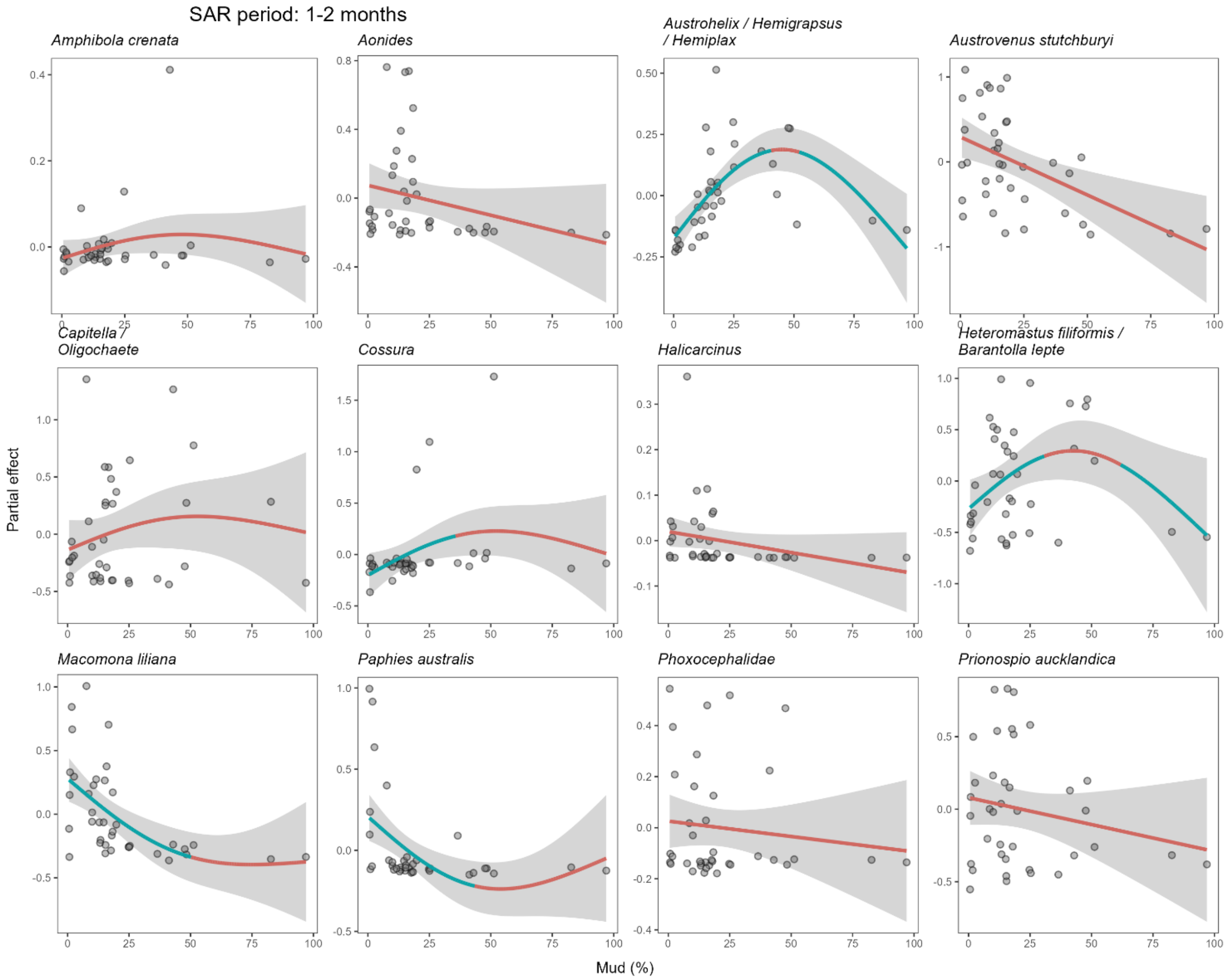


Figure A8.9. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and macrofauna taxa abundance in the 1–2-month SAR dataset. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

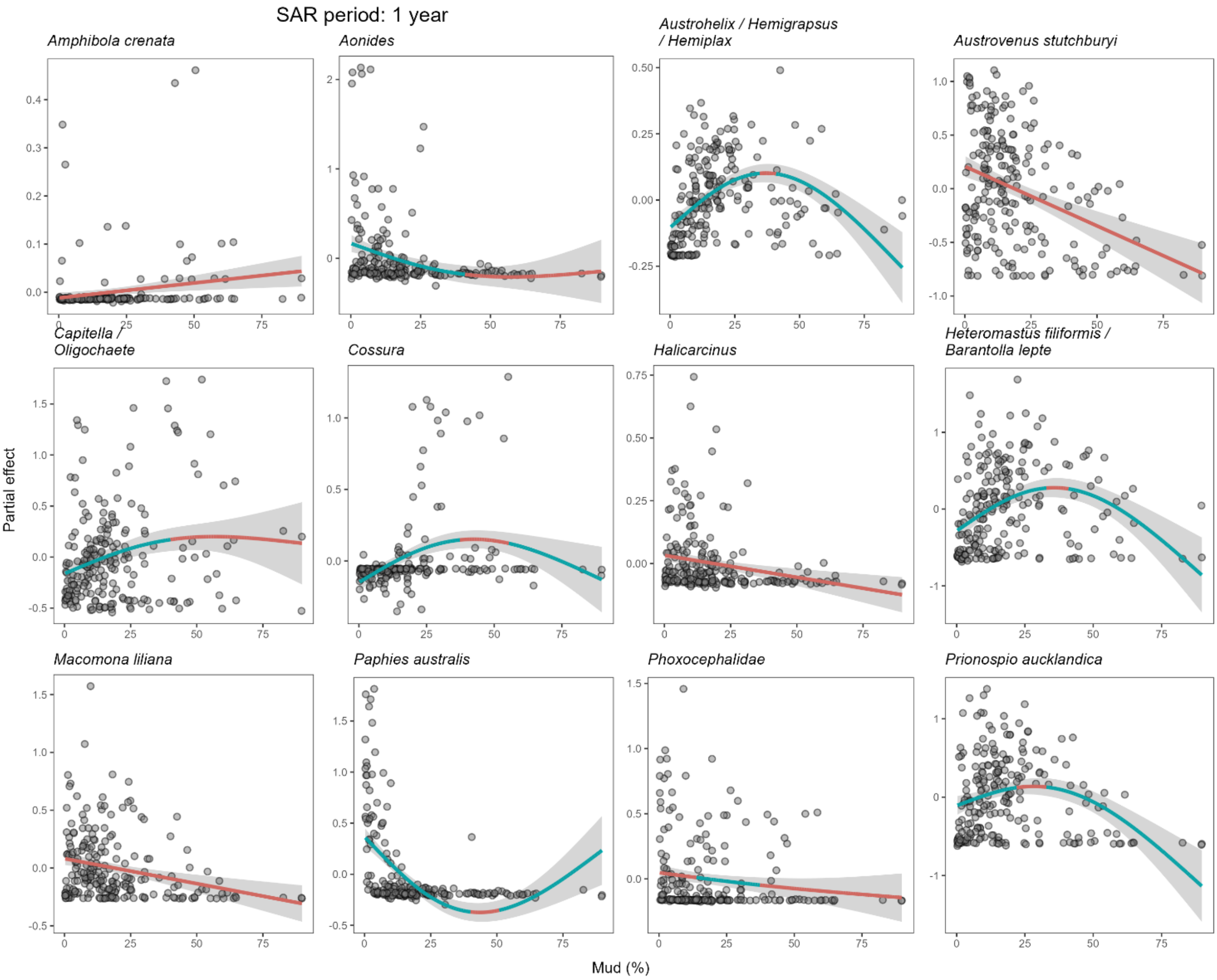


Figure A8.10. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and macrofauna taxa abundance in the 1-year SAR dataset. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

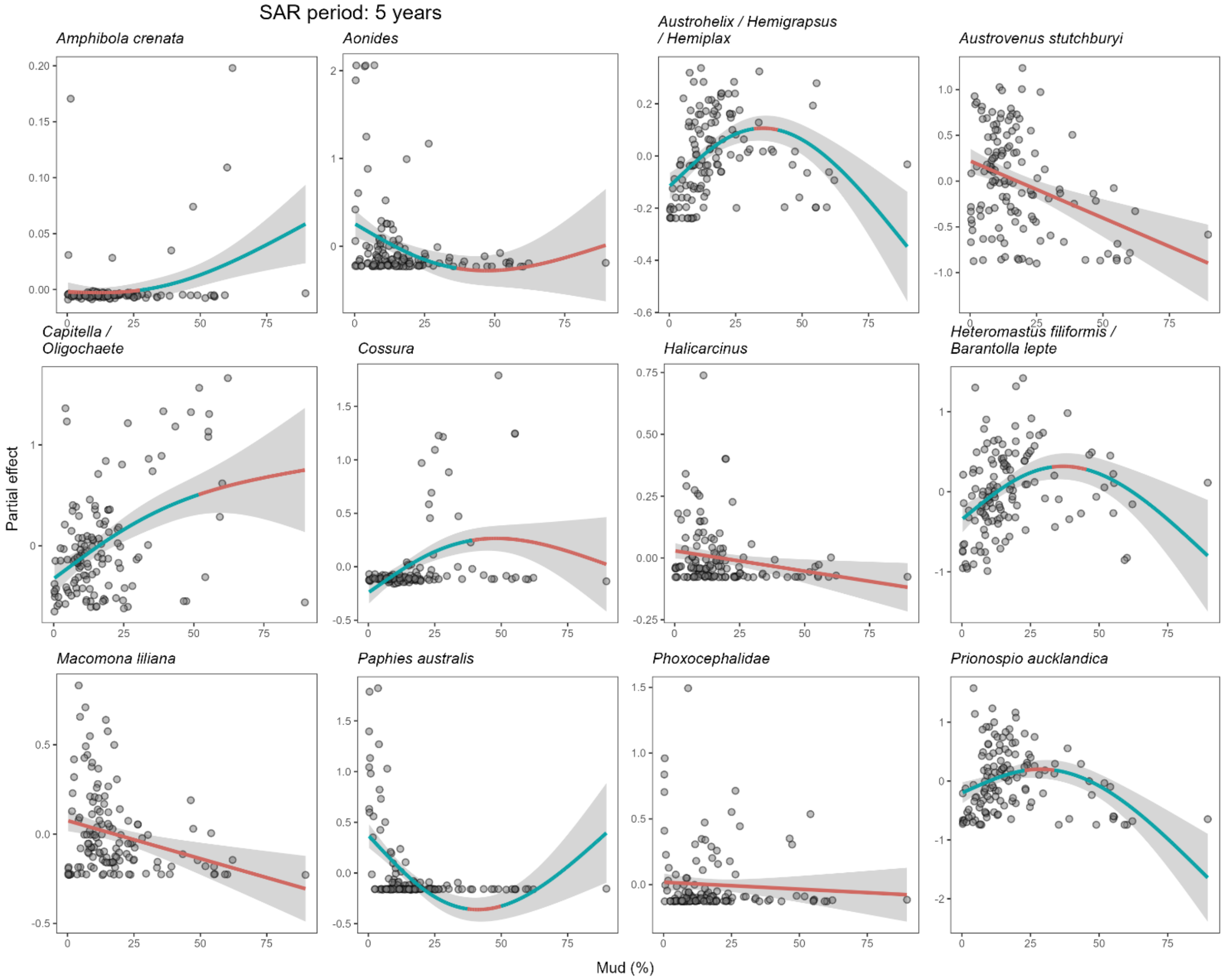


Figure A8.11. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and macrofauna taxa abundance in the 5-year SAR dataset. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

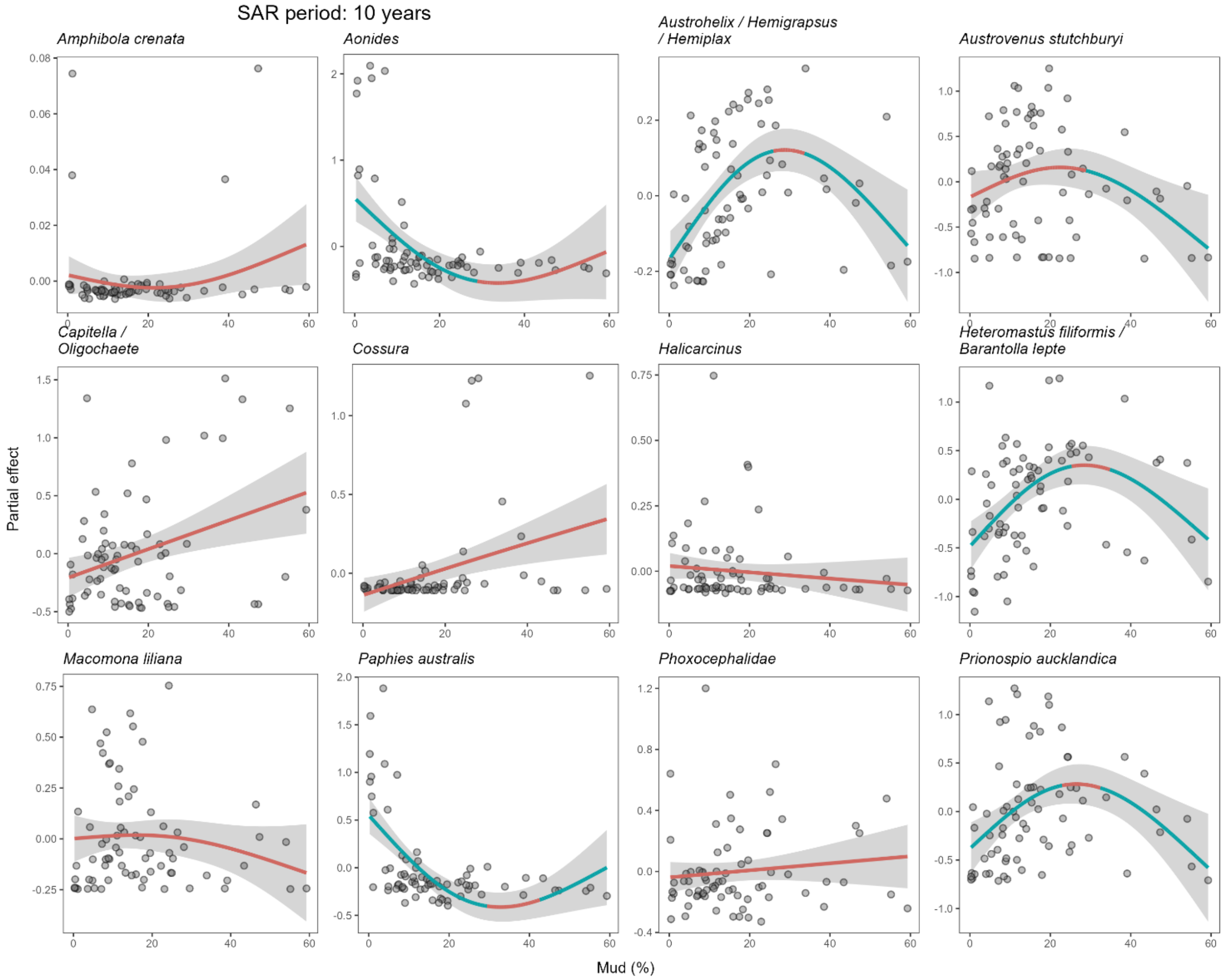


Figure A8.12. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and macrofauna taxa abundance in the 10-year SAR dataset. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

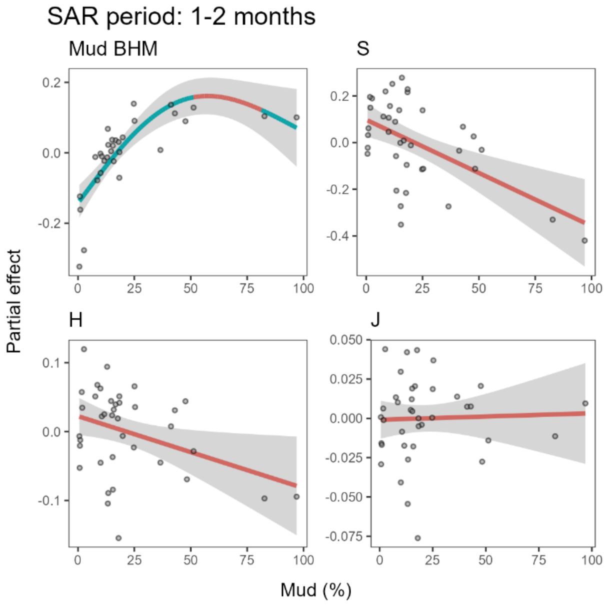


Figure A8.13. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and ecological indicators in the 1–2-month SAR dataset. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

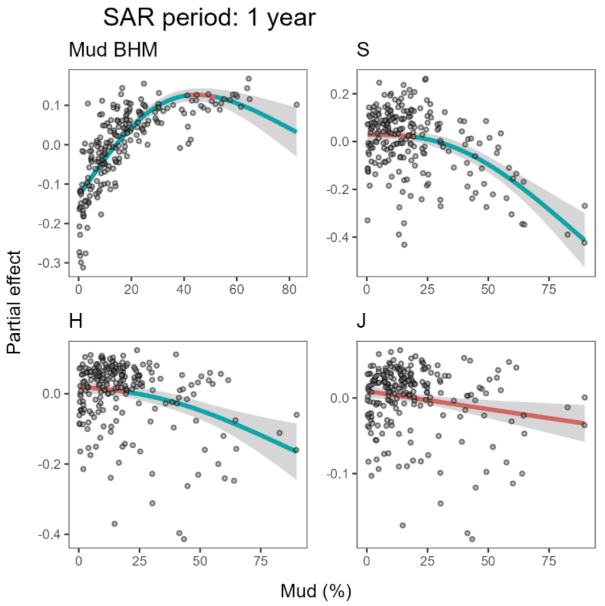


Figure A8.14. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and ecological indicators in the 1-year SAR dataset. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

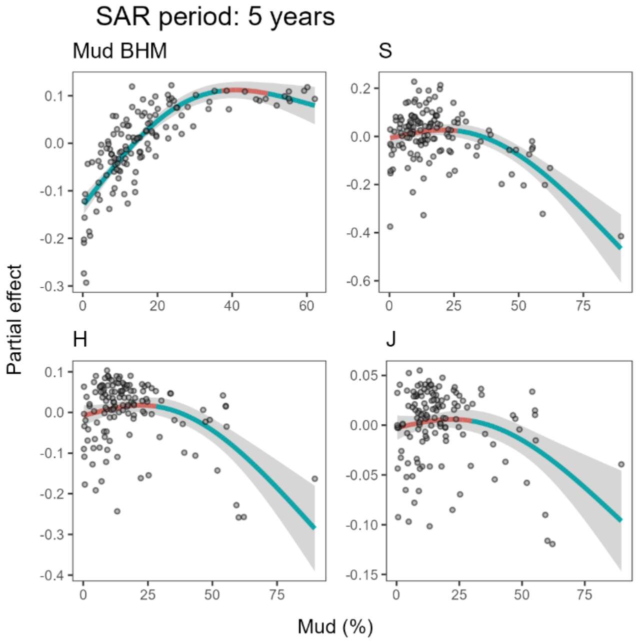


Figure A8.15. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and ecological indicators in the 10-year SAR dataset. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

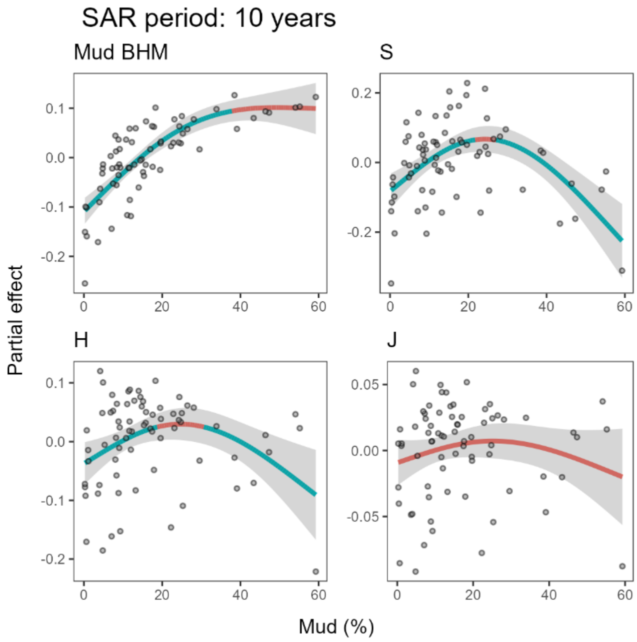


Figure A8.16. Partial dependence plots for sediment mud content from generalised additive models showing the relationship between mud content (%) and ecological indicators in the 10-year SAR dataset. Ecological indicators include the Mud Benthic Health Model (Mud BHM), species richness (S), Shannon–Wiener diversity (H) and Pielou's evenness. Lines represent fitted smooths, with areas of significant change (blue) identified by the first derivative of the smooth term. The y-axis is a unitless value that represents the contribution of the smooth term to the linear predictor.

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