Changes in soft sediment microtopography as indicators of macrofauna activity in the Whangateau estuary

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Abstract

Marine habitats are some of the largest habitats on earth which host a wide range of organisms that can each play central roles in ecosystems. Soft sediment systems are dynamic and subject to various amounts of change over time in response to disturbances. As a result, it is important to develop cost-effective tools that can be used to analyze the ecological state of soft sediment systems for optimal management. In this study, sediment surface microtopography was used as an indicator of macrofauna activity in the Whangateau Estuary as a way to assess ecosystem functionality. To provide a uniform starting point to gauge the rates of change for microtopograhic features, at each site surface features were gently flattened by smoothing the sediment surface with a piece of wood, with one location being left unsmoothed to act as a control. Laser scanning was then carried out on the smoothed locations to obtain a range of images using an RGB device. To assess the rates of microtopographic features, observations were carried out twice a day around 12 hours apart. Laboratory analysis was carried out on sediment samples collected from the Whangateau estuary to also investigate whether sediment organic or mud content had any significant impact on rates of change across the sites. Overall sediment mud content showed some levels of correlation with organism activity, however, the effects overall were insignificant.

Contents

Chapter 1: General Introduction

1.1 Importance of soft sediment systems

Marine soft sediments comprise one of the largest habitat types on earth hosting a wide range of organisms that play central roles in ecosystems. Soft sediment ecosystems consist of mud, and sand, and provide a habitat for a variety of different benthic species. The macrofauna that makes up soft sediment communities mainly consists of mollusks, crustaceans, and annelids. These ecosystems also provide a range of important services in both an ecological and economic sense. Ecologically, they can provide various important services, including flood control, carbon sequestration and acting as breeding habitats (Lee et al. 2017, Dungan et al. 2018, Barbier 2017). They also play an important role in protecting our shorelines by reducing wave energy and as a result, erosion. Additionally, areas with mangroves also protect against pollution by acting as a waste sink through absorbing waste discharge. Economically, soft sediment systems allow for commercial activities namely recreational fishing, and tourism. Well-managed soft sediment systems also play an important role in maintaining biodiversity. With the different macrofauna that inhibit soft sediment systems, and their different roles in constructing different habitats, proper maintenance of soft sediment systems is necessary to maintain biodiversity, and subsequently the structure of marine soft sediments (Ellingsen 2002, Solan et al 2008,). As demand for marine resources continues to grow, disturbances to soft sediment communities and rates of activity will also be further impacted (Blažauskas et al. 2015, Nabe et al. 2018). Hence, the assessment of biodiversity in soft sediment systems is an essential factor in understanding how these systems respond to change over time.

1.2 Impact of Organism traits on soft sediment functions and services

Soft sediment systems are largely modified by different organisms that reside in these environments. Functional Traits of different organisms, also play a large role in how they can impact ecosystem services. These are defined as the biological traits of different species which can impact how ecosystems function. Factors such as behavioral traits can increase the resistance of a species to disturbances that could contribute to ecosystem resilience (Gladstone-Gallagher et al. 2019). Additionally, different organisms' feeding modes can significantly impact the physical environments and functionality of soft sediment systems (Thrush et al. 2021, Middelburg 2017). Suspension feeders are classified as groups that ingest food particles that are suspended in water. They also create habitats for other animals via the production of shell or tube structures in addition to regulating benthic and pelagic systems. Suspension feeders can use their gill structures to create water currents, filter particles, and act as a filter for water clarity (Safi et al 2007, Kiorboe & Mohlenberg 1981). Deposit feeders are defined as organisms that ingest sediments and absorb organic matter, and include groups such as bivalves and gastropods (Lopez et al 1989, Deposit feeders impact soft sediment characteristics through the process of excretion. Furthermore, deposit feeders play roles in changing grain sizes of the sediment surface through excavation (Levin et al 1997, Wilson & Cohen 1993). Another feeding mode that can also potentially influence the grain size of sediment includes the predator/prey group (Fauchauld & Jumars 1979). Predators and Scavengers can disturb the sediment by seeking prey excavating through the sediment (Thrush et al. 2021). The extent to which sediment is modified is also dependent on the size of the predator, as well as the prey. The movement of fine sand into the site of excavation from the sediment surface can change the grain size of the sediment. Organisms with different traits often have different forms of bioturbation that can have large impacts on soft sediment systems (Jones et al 1994).

1.3 Forms of Bioturbation and its effects on ecosystems.

Bioturbation is the reworking of sediment by organisms, often caused through burrowing or ingestion of sediments (Biles et al 2003), and can result in a wide range of different effects on soft sediment systems. This includes affecting sediment porosity through burrowing activities, subsequently affecting habitat characteristics such as sediment moisture and aeration (Saaltink et al 2019). Burrowing activities can enhance or lower sediment stability through changes in sediment microtopography reducing compaction and enhancing erosion or conversely decreasing erosion by creating tube mats or enhancing microphyte production (Orvain et al 2004). Additionally, burrowing also improves the rate at which oxygen is exchanged within the sediment and across the sediment-water interface which can reduce harmful environmental conditions for some organisms, such as anoxic habitats (Lohrer et al, 2004, Kristensen, 2000).

Bioturbation is a crucial feature towards the formation of habitable marine habitats in soft sediments through changing and creating different microtopographic features of a particular site (Mermillod et al 2011). Bioturbation can also alter CO_2 and O_2 levels across the sediment-water interface (Howarth et al 1996,). Furthermore, organisms that cause bioturbation play important roles in contributing to the ecosystem by altering living conditions for themselves and other organisms (Biles et al 2002, Gabet et al, 2003). Microphytobenthos can also play important roles in enhancing the process of bioturbation (Stal 2010). In addition to stabilizing sediments and improving water quality, they also can act as food sources for bioturbators. Bioturbators that feed on microphytobenthos can result in enhanced oxygen generation which can enhance the bioturbation process (Gilbert, Tait, Osborn, & Widdicombe, 2011)

Bio-irrigation is classified as a form of solute transport that is a result of the reworking of sediment by organisms. Bio-irrigation can play a large role in altering environmental gradients as benthic organisms flush their burrows with overlying water to remove toxic substances (Benoit et al 2009, Aller 1988). Bioturbation and its different forms also play large roles in altering the surface features of soft sediment environments. Irrigation and burrowing both lead to the formation of vertical burrows and mounds in the system. Additionally, bioturbation also enables more efficient nutrient cycling, the process where matter is transferred between living and non-living parts of an environment. It is a key component that keeps many ecosystems in balance by keeping factors such as excessive nutrients in check (Alo 2008, Howarth et al 2011)

1.4 Microtopography

Microtopography refers to the slight irregularities of the surface of the earth, leading to slight elevations of the land surface (Roy et al 2005,). The use of microtopographic features as a way to monitor rates in which different species rework their environment following disturbances can be a flexible and quick method that incorporates information on both the animals living in the sediment, and their level of activity. Microtopographic measures can also be used to gauge the level of bioturbation in soft sediment ecosystems, and subsequently measure the before and after effects of physical disturbances that impact species that drive bioturbation (Stefanoudis et al 2016, Meysman et al 2006). Furthermore, using microtopography to monitor surface features of soft sediments could be a useful factor in determining different species that reside in soft sediments ecosystems and their activity based on the alteration of surface features (Roy et al 2005)**.** Similarly, monitoring micro topographic surface features could also be used as an indicator for environmental change (Mueller & Tarnocai 1999). Effective indicators to gauge changes in environmental gradients and biological activity include metrics that include the roles of bigger and rare organisms in the ecosystem. Additionally, gauging the speed at which organisms rework the environment can also be an effective indicator to observe the functionality of ecosystems (Zawada et al 2010, Pratchett et al 2008,). Furthermore, the use of microtopographic features as a way to measure habitat recovery rates can be a low-cost method for monitoring the biodiversity of different taxa groups residing on soft sediment ecosystems.

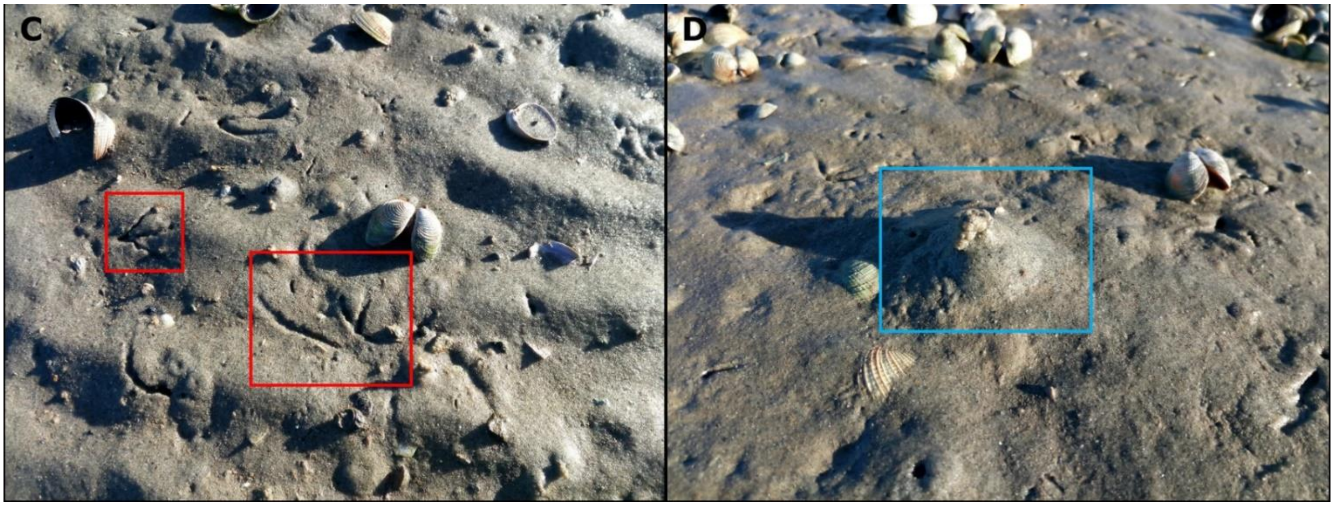


Figure 1: Examples of mounds highlighted in blue, and feeding tracks highlighted in red created by different soft sediment organisms (figure from Schenone & Thrush 2020).

1.5 Relevance of surface features to Ecosystem functions

Ecosystem functions are the result of the biological and chemical processes carried out by different organisms residing in these environments (Naeem et al 1994). Surface features are closely linked to functions and organisms in soft sediment systems such as bioturbation and traits. The topography of the sediments can be linked to several important factors that are essential for the long-term stability of these systems such as different organism traits and interactions between groups (Jones & Frid 2009, Rhoads 1970). Organisms with different traits have varying impacts on ecosystem functions, depending on factors such as size and feeding modes. Areas in soft sediment systems with complex topography such as areas with large depressions or mounds could result in higher richness, additionally, these areas may see higher rates of organism interaction as well as indicating higher levels of biological activity. Furthermore, areas with larger mounds could also be indicators of different traits of certain organisms such as size, shape, and feeding behavior (Thrush et al. 2021, Gray 1981). The traits of organisms can have a significant impact on the stability of surface features such as burrows, while the movement of organisms during feeding can result in the alteration of sediment stability and texture.

Morphological and feeding traits along with the mobility of organisms can have significant impacts on surface topography, for example creating mounds, burrows, and pits on the sediment surface during their feeding process (Thrush et al. 2021, Volkenborn et al. 2009). Furthermore, the size of different organisms is linked to burrow size, which impacts the sediment surface to different levels. The feeding modes of different organisms also impact surface features. Grazers such as snails can create patterns and trails on the surface as they move, these trails can alter the textures of the sediment and create ridges in addition to depressions. (Needham et 2012, Rhoads & Young 1970).

1.6 Vulnerability of soft sediment systems to disturbance

Soft sediment systems are dynamic and organisms that reside in these environments are subject to various amounts of change over time. These systems can be exposed to different major disturbances through natural causes, or human activity (Kaiser et al 2006, Borja et al 2010). Natural disturbances such as storms have a drastic impact on soft sediment systems with excess rain altering salinity and oxygen levels of the water quality within these environments (Deslyva 1986). Disturbances can also have lasting impacts on ecosystem functions within soft-sediment systems.

1.7 Impacts on sediment composition on organism behavior.

Following disturbance events, sediment compositions may be altered resulting in a variety of different impacts on organisms that reside in soft sediment systems. Storms and associated sediment runoff from land can create thicker layers of terrestrial fine sediments, which can cause mass mortality, in addition to reducing ecosystem functions (Mermillod 2011, Lorher et al 2013). In instances where mud particles are reworked into sediment surfaces, pore spaces become clogged and the permeability of sediments reduced (Mitchener &Torfs 1996, Bartzke et al 2013). Additionally, the presence of inorganic clay or silt in sediments can cause organisms to expend more energy to remove unnecessary particles (Smit et al 2008). Suspended sediments may also influence the production of different soft sediment organisms through filtering seawater (Thrush et al 2004). Furthermore, increased mud content in sediment surfaces can also result in a reduction in biodiversity and a loss in ecosystem functions by creating habitats that are more beneficial to certain species (McCartain et al 2017, Thomas et al 2022). The alteration of sediment grain size through the addition of mud can also impact the behavior of different organisms such as the rates at which different feeding modes are carried out (McCartain et al 2017).

1.8 Importance of rapid ecosystem assessment tools

The development of rapid ecosystem assessment tools allows for quick assessment of different indicators that reflect factors such as biodiversity, water quality, and sediment quality (Meyer et al 2015, Peh et al 2013). These tools are particularly important for soft sediment systems, which are dynamic and subject to rapid changes at short notice. Coastal soft sediment habitats are often heterogeneous and subject to multiple stressors, requiring extensive sampling, further emphasizing the need for fast and cost-effective sampling. Microtopography can be altered as a result of disturbance, changes in species composition, or changes in animal activity. Thus, if we can assess microphotography quickly this may provide a useful rapid assessment tool for many soft-sediment habitats. Rapid and simple methods could play a large role in reducing time and people power and allow for a greater focus on additional factors. This paper utilizes the technique developed by Azhar et al. (2022) for the rapid imaging of sediment surfaces which focuses on a low-cost approach for measuring different surface characteristics of soft sediments. The development of rapid ecosystem assessment tools is necessary to match the growing demand for marine resources and its impacts on soft sediment systems if they are to be maintained (Peh et al 2013, Anderson et al 2012)

1.9 Aim of Study

This study aimed to determine whether changes in surface topography could be used as an indicator of the activity levels of different organisms residing in soft sediments. To do this I looked at rates of change in smoothed vs intact sediments. Looking at sediment reworking rates following disturbances could also be an important low-cost method for augmenting the long-term management of soft sediment systems. Further, the study aimed to determine whether different rates of microtopography change could be detected in sites with different sediment types (i.e. mud and sand).

2.0 Hypothesis

If sediment microtopographic changes are a good indicator of organism activity rates, then the rate of change of microtopographic sediment features is expected to be higher at the disturbed plots regardless of site. Rates of change are also expected to be higher at plots with larger grain sizes, as this promotes bioturbation rates.

Chapter 2: Methods

2.1 Study Area

This study was carried out in the Whangateau harbor in northern New Zealand. The estuary is an open tidal lagoon located on the northeast coast, which acts as a feeding ground for both migratory and endemic species. The catchment has a mixture of native and exotic forests covering the catchment. Intertidal sand flats cover 85% of the estuary and cover 750 hectares in area, which host a diverse community of macrofauna. Within the estuary, 15 sites were chosen that had similar shellfish and mound producing worms, but differing mud content.

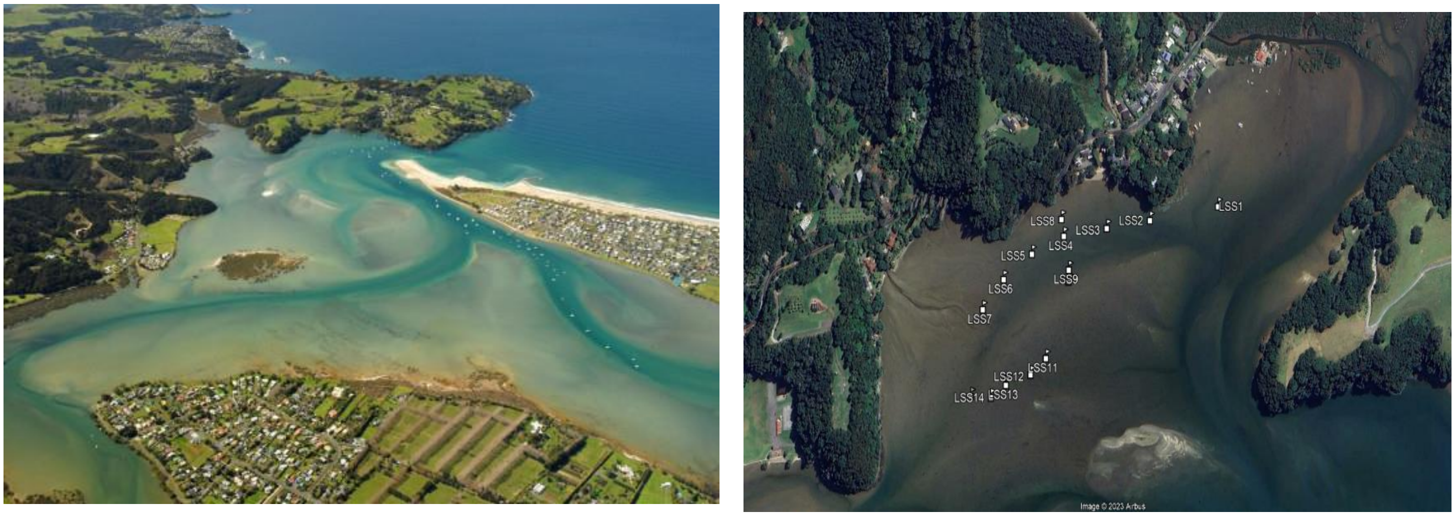


Figure 2a: Image of the Whangateau harbor (Left) where the fieldwork took place, and the sub-estuary 2b (Right), where the different sites were located, source google earth.

2.2 Field Work

To provide a uniform starting point to determine whether changes in microtopography can indicate organism activity levels and estimate the rates of change for microtopographic across sites, features at each site were gently flattened by smoothing the sediment surface with a piece of wood. This process was performed at 3 locations (1m x 0.5m) in each of the 15 sites. At each site as well as the 3 initially smoothed locations I also identified one area to act as a control, this was left undisturbed (Fig 2d). To assess the rate of change for microtopographic features, observations were made twice a day around 12 hours apart during the daytime low tide period, once during initial smoothing, and another observation was carried out at the end of the day. Laser scanning was carried out on the experimental plots of sediment (smoothed) from the experiment to obtain a range of depth images using an RGB-D device (2e). The laser line scanner device was used alongside a semi-opaque container to allow for rapid scanning of surface features.

Fig 2d: Example of a smoothed plot (disturbed) on the left, and the controlled plot (undisturbed) on the right showing differences in surface microtopography before and after smoothing.

Fig 2e: Asus Xtion Pro Live 3D RGB-D (Left) device from Azhar et al 2022. The device is placed in an opaque container (Right) to reduce sunlight infrared interference out in the field. The white opaque plastic allows diffused light to illuminate the surface during imaging.

2.3 Microtopography analysis

To analyze the sediment microtopography depth surface images were analyzed using a program(DSA) developed by Dr Mihailo Azhar, this was a refinement of the methods described in Azhar et al 2022. The DSA provided topographic information from each plot and derived a range of spatial heterogeneity statistics. Notable statistics included:

Peak Mean- which represents the average height of positive pixel values on the DSA program. Representing features such as mounds on the surface sediment, and could indicate a high level of activity from organisms.

Negative Topography – which showed areas of negative pixel values on the program, and could indicate the locations of burrows on the sediment surface, also could be an indicator of the location of depressions of the sediment surface.

SPK/SK and SVK/SK – Ratios of the peak heights and reduced valley depths, the extent of burrow beneath the sediment surface. Large SPK/SK values could imply deep burrows underneath the sediment surface, indicating the density at the sediment surface and could represent activities of larger organisms that make larger surface features.

SK – Indicated core roughness, . representing the overall features of the sediment surface, and could be influenced by factors such as sediment texture like grain size.

The SPK/SK metric was chosen to represent microtopography values over the other metrics presented in Azhar et al 2022. This metric was chosen was because it represented a ratio of peaks and valleys, which could include burrows and mounds, as well as their density. Other included metrics only represent some aspects of microtopography. For example, negative topography only showed negative pixel values on the DSA application which could only represent burrows. In contrast, a metric like Peak mean which represents positive pixel values, may only represent landforms such as mounds on the sediment surface.

Overall, the SPK/SK metric was chosen as it represents a larger amount of microtopography features. The representations of both burrows and mounds, on the DSA application also represent a wider range of organisms within the estuary and the different behavioral activities carried out to create surface features.

2.4 Lab Analysis

2.5 Sediments

The samples from the Whangateau estuary were taken from the 15 sites that were observed. 50 ml centrifuge tubes were filled with sediment from the corresponding site and analyzed for sediment characteristics that could have implications on the rate at which organisms reworked environments namely, size, porosity, and organic matter.

Sediment samples were placed into 15 containers for each site with the wet weights being recorded. The samples were then placed into a 60^{o}C oven for 7 days to dry the samples. After 7 days had elapsed, the samples were removed from the oven, and the dry weights for each sample were recorded. The following equation was then used to calculate the porosity of the sediment from each site.

$$P = 100\left(\frac{W - D}{V}\right)$$

In this equation, W represents the weight of the sediment, D represents the dry weight of the sediment, and V represents the volume of wet sediment.

2.6 Organic Matter

Empty foil dishes were labeled, one for each corresponding site, and placed into a 450^{o}C furnace for 4 hours. The pre-ashed foil dishes were then weighed to 4 decimal places. The sediment samples from each site were first homogenized, and then a spoonful of sediment was taken from each site and placed into the corresponding foil dishes. The dishes were then weighed, and then placed into a 450^{o}C furnace for 4 hours. After 4 hours had elapsed, the samples were then removed from the furnace and placed into a desiccator to cool. The cooled samples were then weighed again to 4 decimal places, and the following equation was used to calculate % of organic matter in the samples of each site observed.

$$SOM\% = 100(\frac{D-B}{D})$$

In this equation, D represents the dry weight of sediment, and B represents the burned weight of sediment (post furnace).

2.7 Grain Size

Grain size analysis was carried out using the Malvern method, with prior preparations being carried out on the sample sediments

Samples from the estuary that were gathered from the 15 sites were homogenized, and then 2 teaspoons of sediment per site were placed into 50ml centrifuge tubes. The tubes were then filled up with 6% H_2O_2 to the 50ml mark. The tubes were covered with aluminum foil and then left under a fume hood for one week.

After one week, the samples were then centrifuged for 5 minutes at 3500 rpm. DI water was then added to each sample up to the 45ml mark on the tubes, where the samples were reweighed and then centrifuged again. These steps were repeated 4 times for all the H_2O_2 to be removed from the samples. 5% Calgon was then added to the samples, and allowed to sit for a period of 24hrs. The samples were then analyzed through the Malvern, recording information such as grain size and sediment content.

2.8 Macrofauna community

Include methods for counting density of key species at the sites – 0.25 m2 was excavated at each site and sieved on 500um mesh. Key species of shellfish and large worms were laid out on a white tray and photographed and left at the site alive. In the lab, animals were identified and counted from the photos. This analysis confirmed that the sites had similar community types despite the differences in sediment properties.

2.8 Statistical Analysis

A 3-way repeated measures ANOVA was carried out between the treatment, site, and time, to investigate their impacts on the return of surface features following a disturbance. The ANOVA test was also used to see whether the process of smoothing the sediment surface had any significant impacts on organism activity compared to if sites were left undisturbed.

2.9 Macrofauna Community

To analyze the composition of macrofauna across each site, – 0.25 m2 of sediment at was excavated at each site and sieved on a 500um mesh. Key species of shellfish and large worms were laid out on a white tray and photographed and left at the site alive. In the lab, animals were identified and counted from the photos, based on different biological traits. This analysis confirmed that the sites had similar community types despite the differences in sediment properties.

Chapter 3 Results

3.0 Average SPK/SK values for disturbed and undisturbed plots

The rates of change for surface features were higher in disturbed plots compared to the undisturbed plot. Overall site and time had major impacts on the rate at which the surface features at the disturbed plots returned (Table 1). The rates of change for surface features varied per site, depending on the different environmental variables.

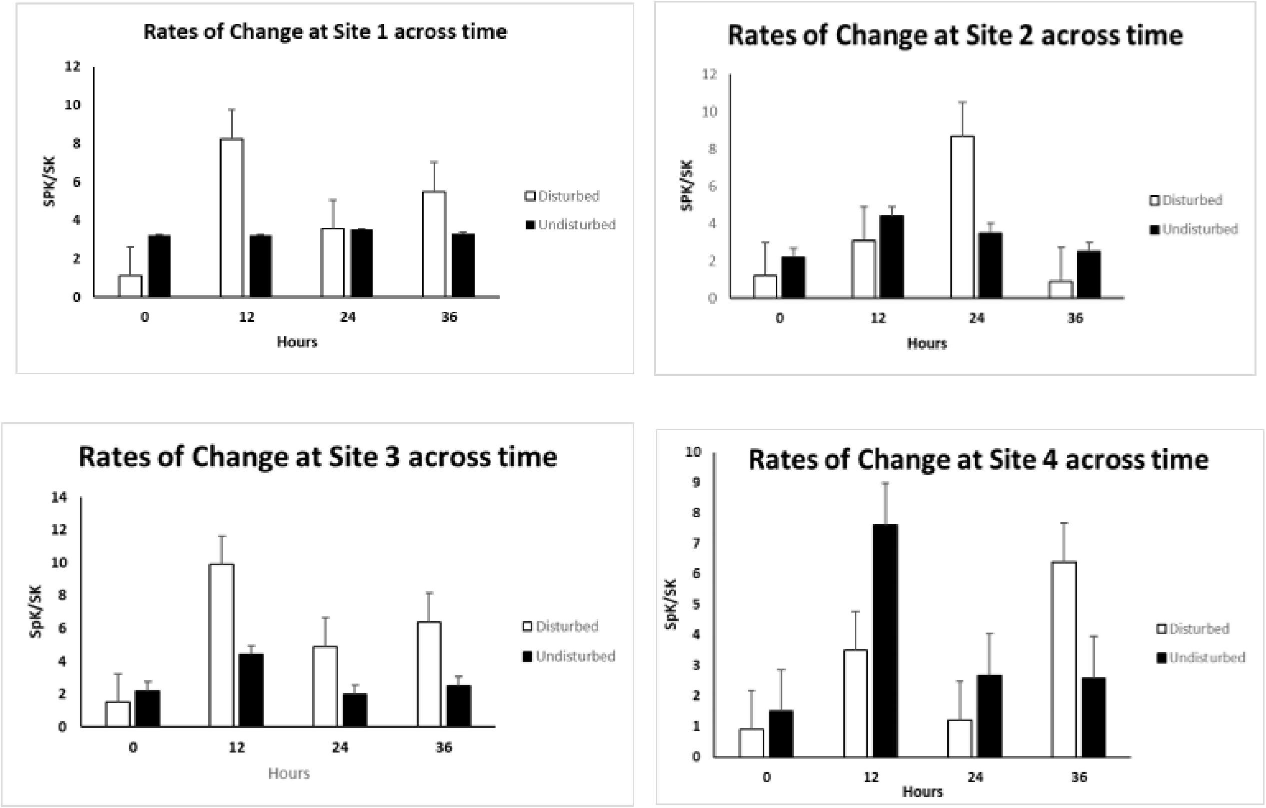


Fig 3a: Average microtopographic values showing rates of change for undisturbed vs. disturbed sediment patches at sites 1-4 over a period of 36 hours.

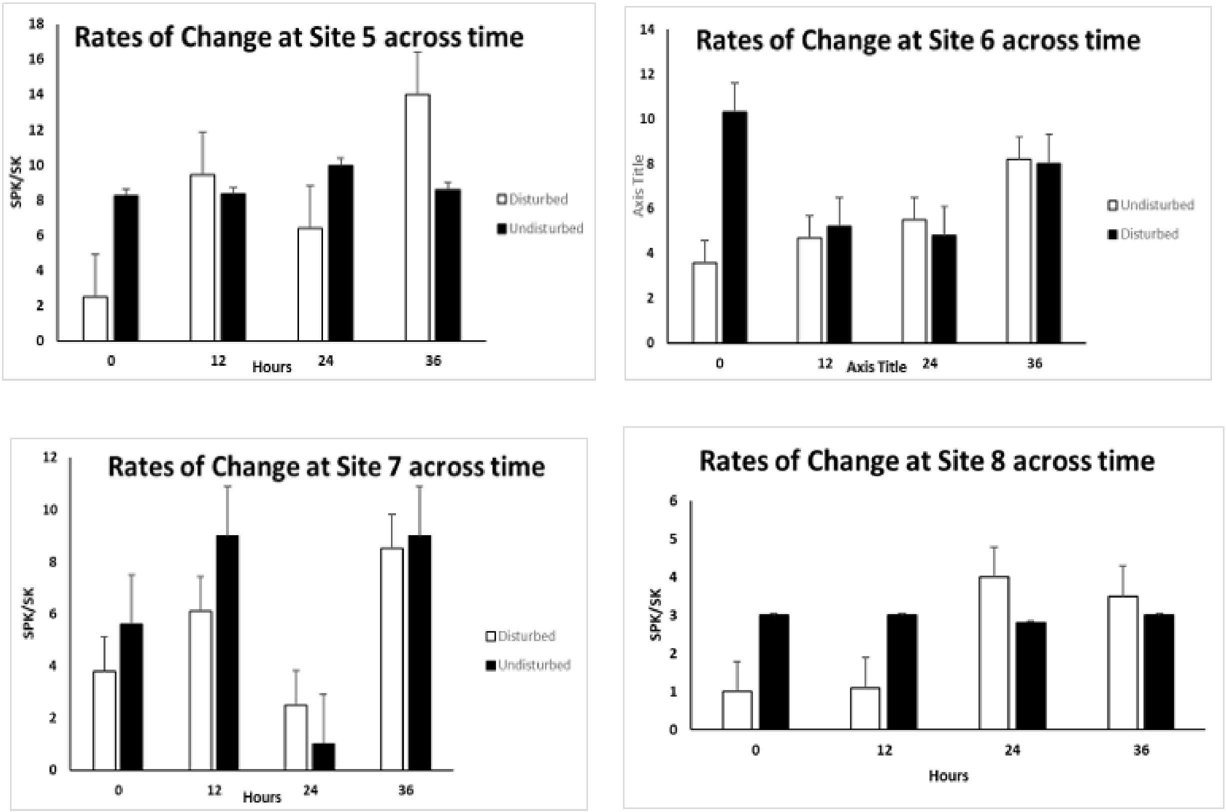


Fig 3B: Average microtopographic values showing rates of change for sediment patches at sites 5-8 over 36 hours.

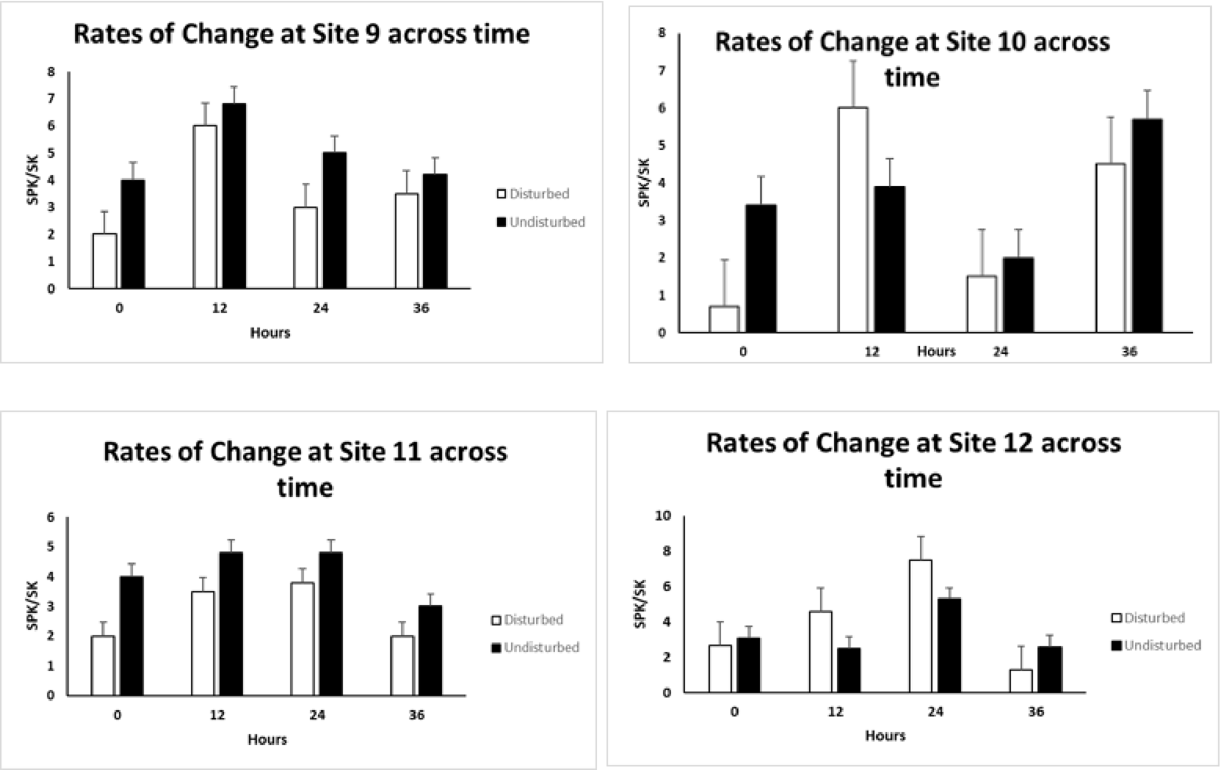
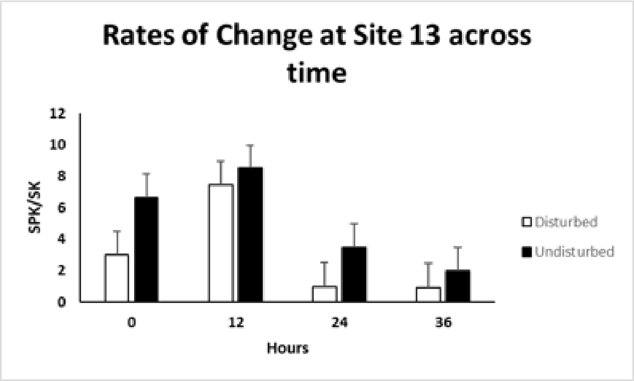
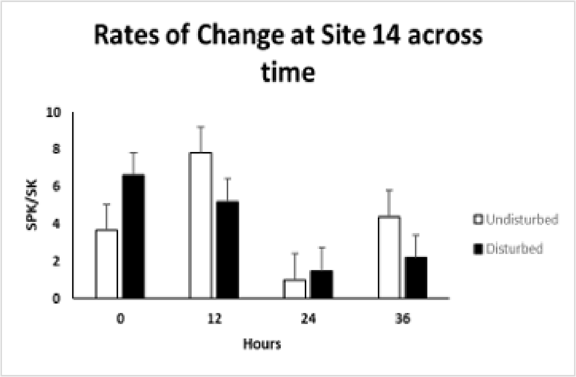


Fig 3C: Average microtopographic values showing rates of change for undisturbed vs disturbed sediment patches at sites 9-12 after 36 hours


Rates of Change at Site 13 across time
12
10
8
6
4
2
0
SPK/SK
0
12
24
36
Hours
□ Disturbed
■ Undisturbed


Rates of Change at Site 14 across time
10
8
6
4
2
0
SPK/SK
0
12
24
36
Hours
□ Undisturbed
■ Disturbed

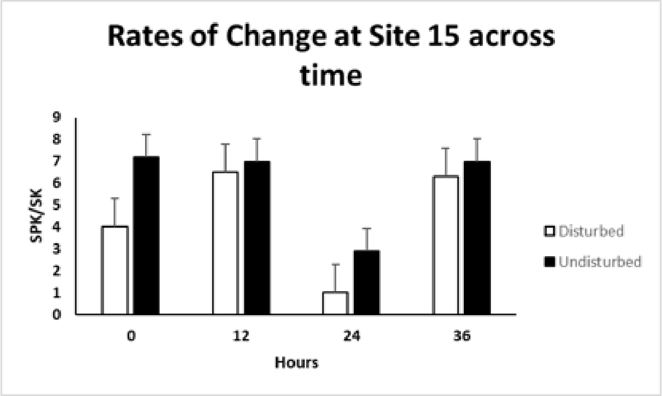

Rates of Change at Site 15 across time
9
8
7
6
5
4
3
2
1
0
SPK/SK
0
12
24
36
Hours
□ Disturbed
■ Undisturbed

Fig 3D: Average microtopographic values showing rates of change for undisturbed and disturbed sediment patches at sites 12-15 after 36 hours.

3.1 Sediment Characteristics Across Sites

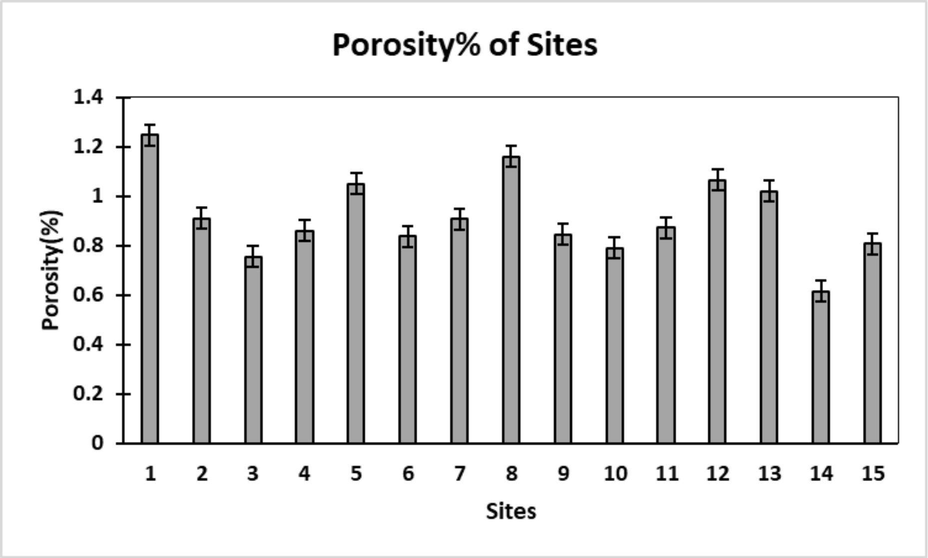


Fig 3E: Amount of Porosity across each sites

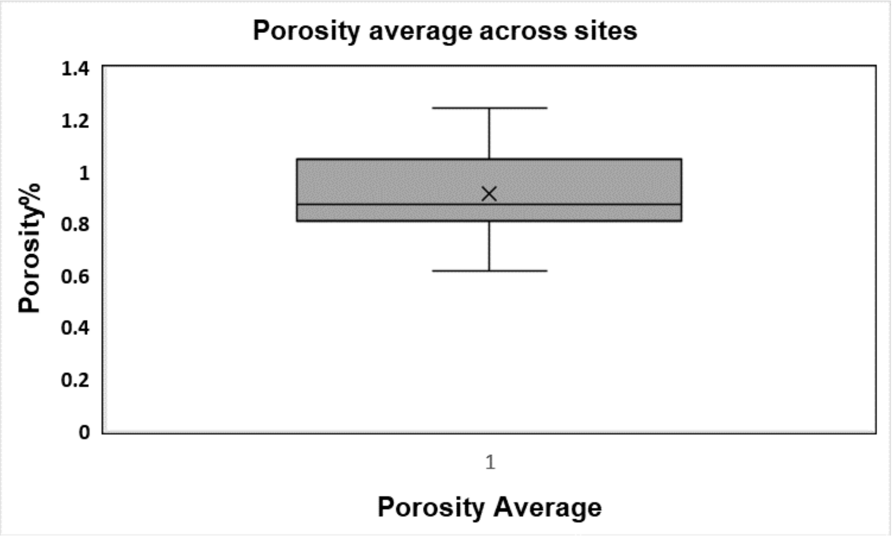


Fig 3F: Average amount of porosity across all sites

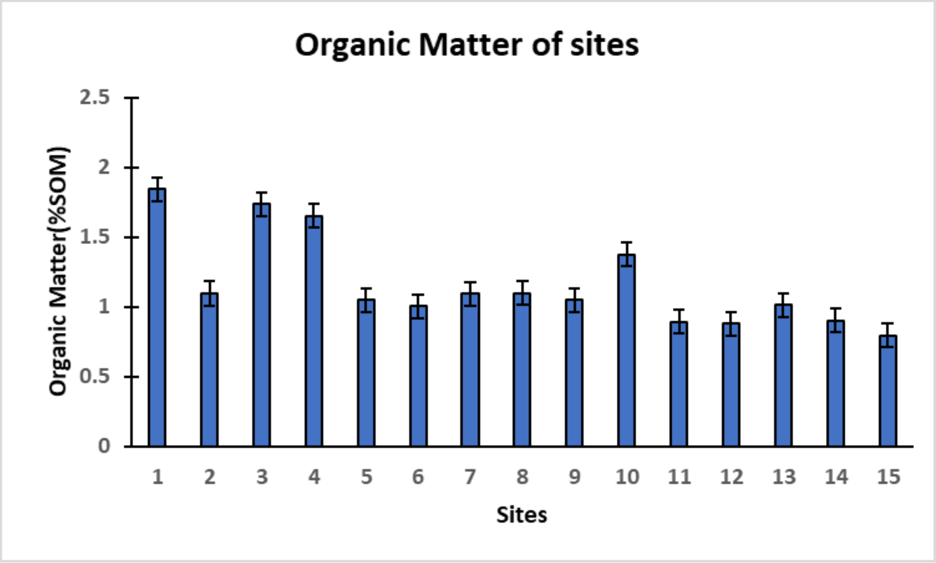


Fig 3G: Organic matter content across the 15 sites

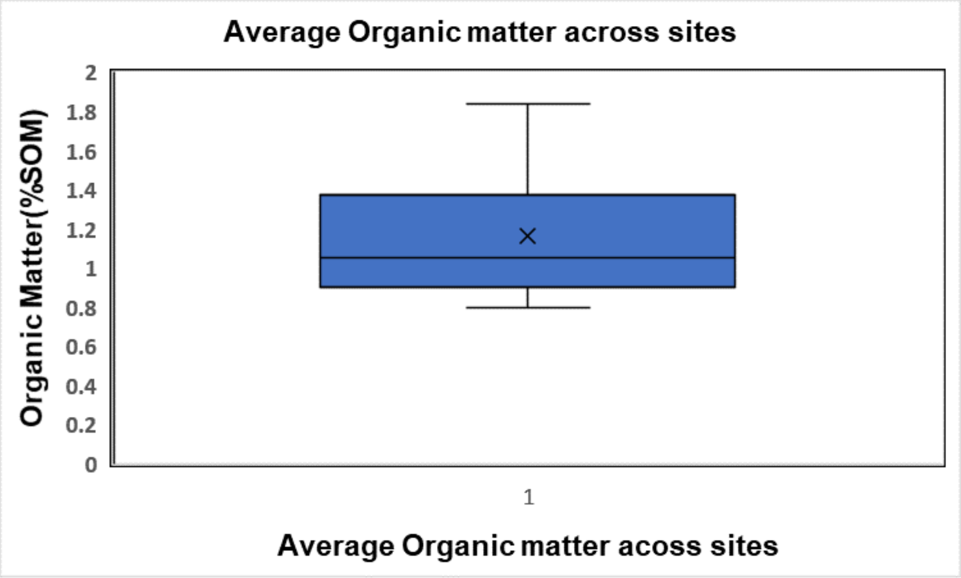


Fig 3H: Average Organic matter content across all sites.

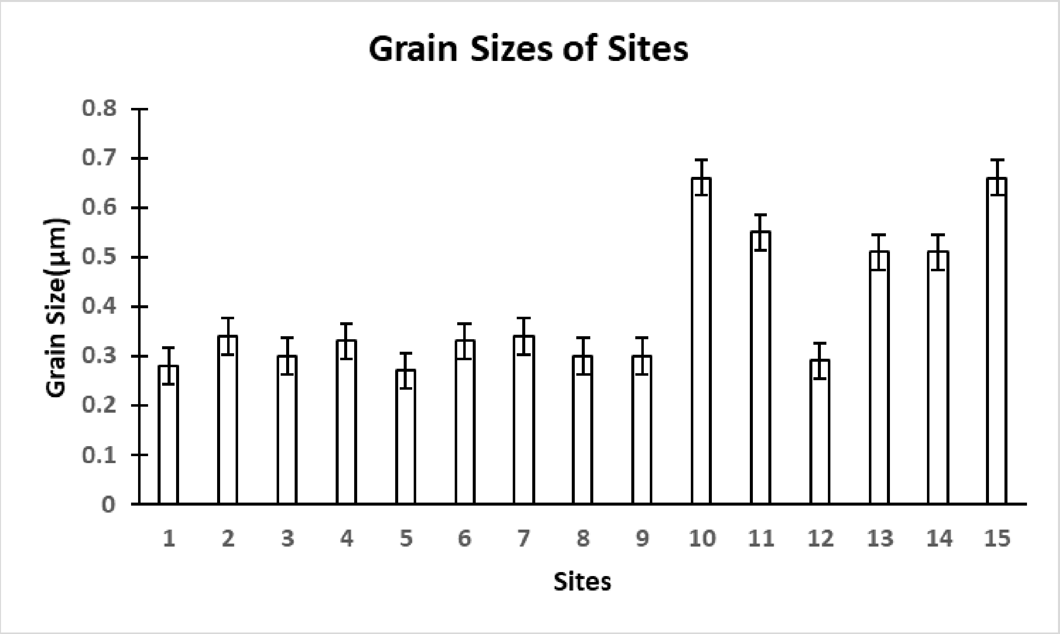


Fig 3I: Grain size of sediment across sites

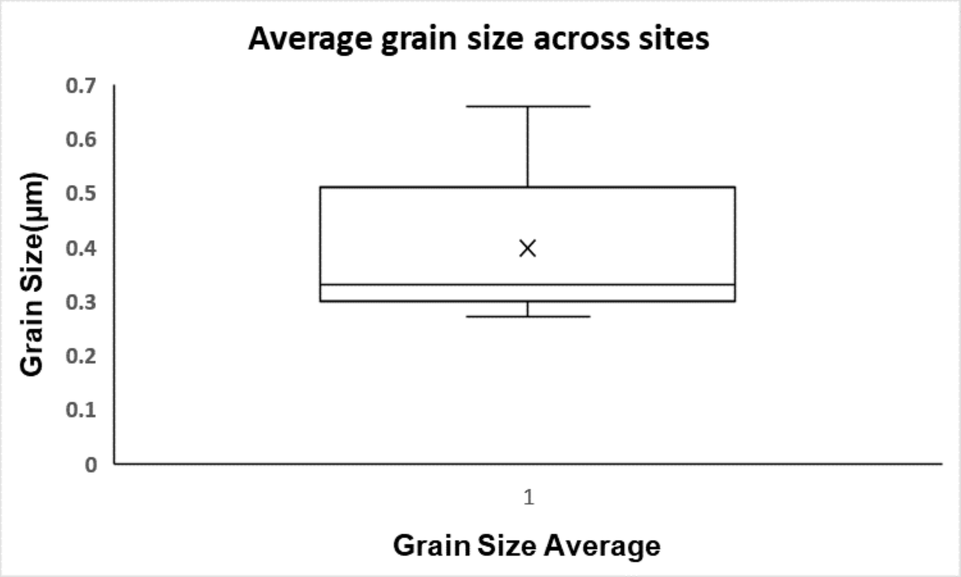


Fig 3J: Average grain size across the 15 sites

The average sediment characteristics varied per site, porosity ranged from 0.6% to 1.2%, with an average of 0.9% across all sites. Grain size ranged from 0.27mm to 0.66, with an average of 0.4. Organic matter ranged from 0.8% to 1.4% with an average of 1.2%

3.2 Disturbed and undisturbed differences

ANOVA assumptions were tested to ensure the data was evenly distributed, Normality was tested using the Shapiro test in R and resulted in a p-value of 0.1164, while homogeneity was tested using the Barlett test with a p-value of 0.23

In this study, the smoothing process had a significant impact on activity levels with treatment having a p-value of 0.04. Time also had a significant impact on the amount of surface features present with a p-value of 0.004. The location of the observed sites did not seem to have a significant impact, however, with p = 0.5. The interactions between time, treatment and site were all significant. From these results, it can be seen while not all of the treatment factors had a significant impact on rates of change, the interactions between the treatment factors were all significant. Overall, the smoothing treatment in addition to time had the largest impact on the return of surface microtopography, while site locations had a more limited impact.

Table 1: 3-way ANOVA results for the significance of treatment, time, and site.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	3	24.96	24.959	4.153	0.044
Time	3	50.15	50.147	8.344	0.004
Site	3	0.55	0.549	0.0914	0.5
Time:Treatment	3	88.2	60.1	0.003	0.02
Time:Site	3	85.1	55.2	1.34	0.001
Site:Treatment	3	65.3	72.4	2.123	0.04

Chapter 4 Discussion

4.1 Key Findings Summary

In this study, rates of change from disturbed plots were compared to undisturbed plots to investigate the rates of change in which surface topography was recovered. Sediment content between disturbed and undisturbed plots was also analyzed to investigate whether they had any impact on the rates of change for microtopographic features. Laboratory analysis was carried out on sediments that were collected from the 15 sites to observe how sediment composition varied per site.

The key findings of this study were that generally at disturbed plots, surface features returned at a higher rate on average compared to the undisturbed plots. Overall the smoothing of sediment patches often resulted in higher rates of change in which microtopography was recovered, compared to the sections of sediment that were left undisturbed. A 3 way repeated measures ANOVA was carried out between the treatment method, time, and plots to see whether these factors had any significant impact on the rates of change for surface features. The significance of the interactions between site, time and treatment indicate that rates of change in microtopographic features following a disturbance depend on the 3 variables. The composition of the sediment at each plot may also have had varying impacts on the rate of microtopographic rates of change.

4.2 Rate of Change at Disturbed and Undisturbed Plots

In this study, the locations that were smoothed showed higher rates of change in SPK/SK values. Contrasting the disturbed and undisturbed locations, SPK/SK values were higher for the majority of the smoothed plots compared to the undisturbed plots, which would suggest that the rate of rates of change for microtopographic features was higher at the disturbed plots (Fig 3A – 3D). The majority of disturbed plots showed higher changes in levels of SPK/SK values on average. A possible explanation for higher rates found at the smoothed locations could be due to the removal of surface features that needed to be rapidly replaced as a result of the role they have on different organism interactions. In contrast, at the undisturbed locations, prior microtopographic features may have already been established and left undisturbed. At some sites, the average SPK/SK values were higher at the undisturbed plots. This could be explained through the initial smoothing process, in which not all microtopographic features were completely smoothed at the undisturbed plots. This could also mean that the difference in rates of change for microtopography features could be attributed to other factors like sediment composition including grain size, amount of organic matter, and porosity present in each location.

4.3 Environmental Factors and Surface Features

The presence of porosity across the disturbed and undisturbed plots could have had varying impacts on the rates of change for surface features, depending on different factors. The higher levels of porosity in soft sediments could enable higher levels of activity with more room to maneuver during the reworking process (Gibson et al 2001). Additionally, sediments with higher porosity can impact the ease with which organisms can burrow through sediments. Higher porosity can enable easier movement through the sediment, and enhance bioturbation, creating a higher amount of microtopographic features. Porosity may also influence oxygen, with more space between pores allowing for enhanced oxygen flow, which also creates favorable conditions for bioturbation (Herman & Middelburg 1996, Volkenborn et al 2007).

Porosity can also affect microtopography through changing sediment characteristics, and environments (Lavoie & Holmes 1997, Glud et al 2003,). Sediments with higher levels of porosity in intertidal areas such as mangroves and estuaries have different impacts on different species. Larger spaces between sediment particles can act as habitats for various species, promoting biodiversity. This enables bioturbation to be carried out by different organisms, and modify the sediment resulting in surface features (Bertics & Ziebis 2006). Porosity can also lead to the formation of additional surface features within intertidal areas such as tidal pools. Sediments with lower porosity, retain water therefore, creating larger pools, while higher porosity sediments drain water faster, resulting in shallower and smaller pools (Attril & Warwick 2003, Netto et al 2003).

Porosity can also have some negative impacts on the microtopography of soft sediments. While sediments with higher porosity can help with the ease of bioturbation, they can also be subject to erosion during natural processes such as storm events (Berg et al 2001). The more porous sediments are more prone to erosion, and can potentially alter different surface features on the sediment (Billerbeck et al 2006). Furthermore, this can also impact how organisms can maintain their habitats such as burrows during disturbances. Habitat disruption can also lead to losses in biodiversity, and as a result, can impact bioturbation leading to the loss of surface features (Pawar 2016, O’hara et al 2021).

In addition to impacting microtopography, porosity can also play a role in the overall functionality of intertidal ecosystems, through impacting habitats and several different biological processes. Porosity also influences the effectiveness of which water is retained within the sediment. Higher levels of porosity swithin intertidal areas allow for better water infiltration, which is an important factor in the role of nutrient cycling (Nixon 1981). The oxygen of more porous sediments can promote biological activities such as bioturbation and respiration of the many intertidal species residing in these ecosystems.

From looking at figure 3E, sites 6 and 10, had slightly lower levels of porosity compared to the other sites. This could further explain the significance the treatment and time interaction had in this study on the rates of change for surface features observed across the sites. The lower levels of porosity can have negatively impacted organism activities such as bioturbation, impacting the rates in which surface features returned. As a result, 12 hours after the disturbance treatment, the amount of surface features at the disturbed plots were still lower than the surface features at the undisturbed plots. These results could show that lower levels of porosity had significant effects on the rates of change in surface features across sites.

Grain size can also have several impacts on the formation of surface features within intertidal ecosystems. Studies on benthic environments seem to suggest that rates in which activities that create surface features such as bioturbation are carried out are dependent on grain size, and the different stresses they can cause. (Wiesebron et al 2021, Gibson et al 2001). Finer grain sizes in soft sediments, often result in lower rates of bioturbation, which can be attributed to these sediments having decreased consistency, which negatively impacts the ability of different organisms to produce and maintain burrows. (Dashtgard et al 2008)

Additionally, grain size can influence the microtopography of soft sediments, through changing different sediment traits such as surface roughness, stability, and consolidation (Hogue & Miller 1981). Sediments with larger grain sizes often have a rough surface as a result of irregularities between the grain boundaries, while finer-grained sediments have a more even distribution of space. Different grain sizes of soft sediments can also impact the efficiency with which organisms can carry out activities that contribute towards the formation of surface features by influencing sediment stability (Tolhurst & Paterson 2002). Larger grain sizes are more stable and can impact the formation of surface features through activities such as bioturbation. In contrast, finer-grained sediments are not as stable, are more susceptible to the reworking of sediment particles, and can have more surface features as a result. Finally, different sediment grain sizes can also have impacts on cohesion, with finer-grained sediments having a higher level of cohesion as a result of spaces between the grain sizes (Johnson et al 2012, du Châtelet et al 2009).

The grain sizes of sediments, can also potentially have some negative impacts on soft sediment microtopography. Changes in grain size can influence different biological interactions between intertidal species by influencing distribution as a result of habitat suitability (Huston 1994, Hwang & Hong, 2007). Intertidal organisms, with burrowing behaviors, can depend on certain grain sizes to carry out bioturbation more effectively, and changes in sediment composition may negatively impact bioturbation rates and the formation of surface features (Dashtgard et al 2008, Volkenborn et al 2007). The changes in organism composition can affect predator-prey interactions and can contribute to the alteration of surface features (Dyer and Wright 2000). Additionally, the alteration of organism relationships can also have an impact on the functionality of ecosystems. Sediment Dynamics within intertidal areas may also be impacted by changing grain sizes can result in regular sediment transport and deposition, and as a result, this can also disrupt existing surface features created by organisms (Shuu & Collins 2001).

Furthermore, grain size can also have a significant impact on the behavior of organisms within intertidal areas. Feeding strategies, for instance, are a major factor that can be impacted by grain size, in areas of finer sediments filter feeders may be more common in contrast to coarser sediments where deposit feeders may be more abundant (Whitlatch 1980, Ahn & Choi 1998). Additional environmental factors that grain size can also impact can include, resistance to disturbances and recovery. Areas with finer-grained sediments are more susceptible to sediment transport, and to disturbances where this can occur such as storms (Pedreros & Michel 1996, Brand & Montreuil). Subsequently, this can increase the recovery time following disturbances in contrast to coarser sediments which can have more resistance to disturbance events.

From the effects of grain size strong factors that could correlate to the significance of time and treatment as seen in the ANOVA could include the change in grain size through sediment transport, and subsequent effects of bioturbation rates. The intertidal organisms can adapt their feeding behavior based on different feeding cycles and adapt to shifts in grain sizes over time. The dynamic behavior of different organisms can influence bioturbation rates, and rates in which surface features return following disturbances. In this study, the shifts in feeding strategies could explain the significance of time found in the ANOVA analysis. It is also possible that the significance of time on the formation of surface features may only be relevant after 12 hours from the initial smoothing period, as this process would have removed all surface features from the disturbed plots. In this sense it is possible that time would only be significant as some time has elapsed, enabling organisms to reform surface features. Additionally, these effects may also explain the significance of the treatment effect on the different plots that were investigated. The disturbed plots of sediment may also have had higher levels of porosity and organic matter compared to the undisturbed plots, which may be a significant factor explaining the higher rates of change in the surface features for the disturbed plots, from gv 3A-D.

The presence of organic matter in sediment can benefit bioturbation in different ways, creating more surface features. Organic matter can help provide stability within sediments, and remains of different marine organisms such as shells and corals, can add structure to the sediment, providing stability and promoting bioturbation. Furthermore, stabilized areas of sediment, can serve as habitats for intertidal organisms, which can create different surface features over time such as burrows and pits. Stabilized sediments are also more resistant towards the effects of erosion, and can promote the formation of topographic features. Organic matter also can act as a food source which can positively impact the behavior of burrowing organisms, and increase the rates at which surface features are created (Fanjul 2015, Garcia et al 2015). Organic matter can also have some negative impacts on bioturbation rates. Excessive amounts of organic matter can result in high levels of matter decomposition, and create toxic environments that can limit organism activity (Kristensen 2000, Jørgensen et al 2013). In this study, the amount of organic matter located at the different sites did not seem to strongly impact bioturbation rates and the return of microtopographic features.

Organic matter can also influence the microtopography of soft sediments through different factors in addition to possible impacts on bioturbation. Organic matter such as decaying plants can create mounds through accumulation, and subsequently lead to changes in elevation on the sediment surface (Anderson & Meyer 1986, Qiu et al 2019). In contrast, once this organic matter begins to decompose, this can result in areas of pits and depressions. Additionally, organic matter can also influence nutrient cycling in intertidal areas, this can overall improve the productivity of an ecosystem, leading to the development of microtopographic features (Cook et al 2004, Singh & Prasad 2005). Organic matter can also have negative effects on surface features. Changes in organic matter can alter the sediment's microbial communities and influence factors such as sediment stability. While organic matter can act as food sources for organisms that carry out bioturbation, too much can consume excessive amounts of oxygen, leading to anoxic conditions in the sediment (Middelberg & Herman 2001, Wu & Hinrichs 2018). This in turn also negatively impacts different organism groups and can affect the creation of micotopogrpahic features (Yallop & Wellsbury 2000, Böttcher et al 2000). Overall, organic matter can impact microtopography in intertidal areas based on different factors, ranging from the amount of organic matter to sediment types. Balancing organic matter is important for maintaining the health and stability of ecosystems.

Looking at Figure 3G, Site 6 had a slightly lower level of organic matter compared to the other sites, while Site 10 had a slightly higher than average level of organic matter in comparison. While the undisturbed plots only had a slightly higher level of surface features compared to the disturbed plots at site 10, the difference was much more significant at site 6. This could potentially be explained by the lower levels of organic matter found at site 6 which also may have explained the significance that the treatment effect had on this study from the ANOVA analysis. Additionally, the shift in the organic matter along with the tidal cycles throughout the day may also have had possible impacts on the formation of microtopgrahic features, explaining the significance of time seem in the ANOVA.

4.4 Environmental Characteristics and rates of change

In this study, different environmental characteristics had a large impact at the rates in which activities such as bioturbation were carried out. This can be drawn from the analysis of the macrofauna communities at each site, which showed that the macrofauna community at each site were similar despite having different rates of change. A major reason that rates of change from where organisms worked to rework the environment following a disturbance were more effective at sites with fewer levels could be due to mud content in the sediment. Higher levels of mud content could largely limit rates of activity by impacting the activity of different organisms (McCartain et al. 2017), which can subsequently contribute to the rate at which surface features are restored. Additionally, other sediment features such as Organic matter and Grain size had a weaker impact on the recovery of microtopographic features. Other benthic studies have shown that porosity usually has significant impacts on the efficiency with which bioturbation is carried out, while organic matter and grain size have a weaker impact. Areas with higher levels of porosity generally have higher rates of bioturbation as this allows for organisms to have a better range of movement, in addition to increasing the ease with which they can burrow into sediments (Aller 1983, Ballard et al 2017). Grain size can have varying impacts that can affect the rate of bioturbation. Coarser sediments allow for better airflow, providing a suitable environment for bioturbation organisms. However, coarser sediments can also provide more resistance that can impact the ability of different organisms to create burrows. In contrast, finer-grained sediments may provide less resistance to burrowing however, they have lower permeability which can limit oxygen flow, and subsequently create a less ideal environment for bioturbation (Balsamo et al 2010, Martinez et al 2015). One particular relation in which organic matter could have about bioturbators could include acting as a food source for different organisms. Hence sediment rich in organic matter could attract and sustain a community of organisms that carry out bioturbation.

4.5 Impact of treatment, time, and sites on the rates of change for Surface Features.

The location of sites in this study this not have that much of a significant impact on the rates of change for surface features in comparison to the treatment methods, and time, with a p-value of 0.5. This would be expected as the different locations of the sites were not drastically different, with most sites containing similar amounts of mud and sand content. Time, however, had a significant amount of impact on the rates of change for surface features. From Figures 3a – 3d, the rates of change were mainly higher at the disturbed plots. This process would show active signs of biological activity such as bioturbation in the process to restore lost sediment features, and would also indicate a healthy ecosystem.

Treatment also had a significant impact on the amount of surface features that were present at each plot, with a p-value of 0.04, this would be expected as the initial smoothing process also removed any preexisting microtopographic features at each plot. However, the smoothing process also seemed to increase the rates of change in surface topography from looking at figures 3a – 3d, where the majority of the disturbed plots had a higher amount of surface features after 12 hours compared to the undisturbed plots which were left undisturbed in the experiment. Additionally, time also had a significant impact on the rates of change across the disturbed plots, with a p-value of 0.004. In this study, a possible explanation for the significance of time on the rates of change for surface features could include the time of day on which the treatment took place. The lower rates of change initially following the smoothing could be attributed to early hours when organisms wake and carry out critical biological activities such as bioturbation to create new microtomographic features.

4.6 Possible Impact of Environmental Characteristics on Time and Treatment

The disturbed plots across a majority of the 15 sites showed higher rates of change compared to the undisturbed plots after 12 hours following the smoothing process. However, at sites 6 and 10, there were a higher amount of surfaces at the undisturbed plots. The environmental characteristics at these sites may have impacted rates of change at the disturbed sites resulting in lower rates of change compared to the undisturbed plots. One such factor that could play a large role in rates of change, is the mud content present at the disturbed plots for sites 6 and 10. Mud content present in sites can have several different impacts on processes that create surface features such as bioturbation. High levels of mud content can reduce the stability of surface features such as burrows and bounds. Additionally, the cohesive nature of mud can result in difficulties for organisms that may rely on loose sediments for bioturbation (Grant &

Daborn 1994, Harris et al 2016). The lower rates of change at sites 6 and 10 for the disturbed plots can be attributed to higher levels of mud content within the sediment, where organisms could potentially have struggled to restore lost surface features through bioturbation, resulting in lower rates of change at the disturbed plots.

In this study, the smoothing treatment had a significant impact on the rates of change at the disturbed plots compared to the undisturbed plots p value = 0.004, with the disturbed plots having higher rates of change following the smoothing disturbance. This would suggest that the environmental characteristics had a positive impact on the disturbed sites, providing a more optimal environment to carry processes such as bioturbation to restore surface features. This could suggest that the grain sizes within the area of the disturbed plots may have been larger compared to the grain sizes located within the undisturbed plots. Finer grain sizes within the plots of disturbed sediments may have enabled organisms to carry out bioturbation more effectively, and subsequently have higher rates of change compared to the undisturbed plots. Furthermore, porosity levels may also have been higher on average in the disturbed plots compared to the undisturbed plots. As a result, this could also mean that the disturbed plots could have a wider range of organisms that can contribute to modifying sediment surface features and result in higher rates of change.

Time also had a significant impact on the rates of change in sediment surface features across the disturbed and undisturbed plots, with p value = 0.04. Different environmental characteristics can also impact time as intertidal areas are exposed to the regular rise and fall of tides. During high tides, waves can transport sediment which can flood areas and deposit fine sediments (Christiansen et al 2000, Ma et al 2019). As a result, this can create a more beneficial environment for organisms to carry out bioturbation and can create surface features. Additionally, this would also match the higher rates of change across a majority of the disturbed plots across the observed sites, as the initial smoothing period takes place during low tide, surface features returning 12 hours later with high tide, and the deposit of finer sediments. Time may also have had a major impact on the amount of porosity present in the sediment throughout the day. Similar to impacts on grain size, during high tide, water can infiltrate sediment at a higher rate causing sediments to be saturated with water and reduce their porosity, with sediments draining as water recedes following low tide and once again becoming porous. In this study, the significance of time could be explained through higher bioturbation rates in the early hours of the day during low tide, resulting in higher rates of change in the disturbed plots, with rates slowing down during high tide once sediments become less porous making bioturbation more difficult.

Finally, the different sites also had a significant impact on the treatment methods, and time, with Site: Treatment having a p value of 0.04, and Site: Time having a p value of 0.001. The significance of the interaction between treatment and site was to be expected, due to the largely different environmental conditions of each site seen from figures 3G, 3E and 3I. The variance in the amount of environmental characteristics would have had a large impact the rates in which bioturbation would be carried out at each site, therefore also having a major impact in rates of change across the disturbed vs undisturbed plots. Additionally, the significance of time: site can also be seen from figures 3A-D. Across a majority of the observed sites, rates of change were higher at the disturbed plots from 12-24 hours after the initial smoothing period. The rates of change increasing around 12-24 hours could potentially be attributed to the tidal cycles, during the day, and changes to environmental characteristics within the soil across each site as a result. The changes to sediment characteristics would also impact bioturbation, and result in different rates of change through a day, explaining the high and low periods seen in figures 3A-D.

4.7 Possible Uses as REA Tool

Rapid ecosystem assessments are an efficient method to gauge the ecological state of different benthic communities. With the dynamic state of soft sediment systems, it is important to develop rapid and simple methods to analyze environments quickly. This study showed that with the use of laser scanner analysis, data can be gathered and analyzed quickly at a relatively low cost and labor. In this study, Information on 15 different locations in the Whangateau estuary was gathered within a day, which could make the RGB-D method a consideration for the rapid gathering of data. With a larger group, it is possible that the number of locations scanned within a day could be largely increased. The results of this study show that RGG-D imaging can potentially be looked at as an REA tool, with its cost-effectiveness, and relatively quick analysis can be an option for environments where data collection by be costly or challenging. In instances where the health of ecosystems may be deteriorating, and time is a large restriction in obtaining information REA is an essential tool. It provides fast and informative information that can be used to make best-informed decisions on how to respond to different factors that may impact the health of ecosystems (Preskitt et al 2004, Sayre et al 1999). Additionally, for locations with a large area that could require a larger team to carry out, in addition to the use of different equipment that may require a significant amount of resources invested in comparison to an REA being carried out (O’Farrell et al 2012).

4.8 Advantages and Limitations of REA

One of the largest advantages of a rapid ecosystem assessment, is the flexible and relatively fast period in which it can be carried out. REAs can provide essential scientific information required to protect ecosystems such as species richness, habitat diversity, and certain species that may be facing threats (Patrick et al 2014). The time period in which REAs can be carried out can provide timely information for different decision-makers to decide on suitable actions that may be needed for conservation. Despite its advantages, some possible challenges may also arise when using this as a tool to analyze the state of different ecosystems. One such problem may include the issue of temporal changes to an ecosystem over time. To provide up-to-date information on different ecosystems, it may be necessary to carry out REAs frequently, which could also subsequently increase the cost.

4.9 Limitations and Future Studies

While this study made use of the rapid imaging process of the RGB-D device to gather information on estuary locations, the smoothing process used to create the smoothed locations sometimes produced inconsistent results. The smoothing process in this study by using a piece of wood removed most surface topography, however in some instances small mounds were still present after the smoothing process. This may have created some inconsistencies regarding the values of the metrics that were used to measure animal activity for the smoothed patches. Additionally, this study was carried out during the spring season, which may potentially limit the rates of change displayed by different organism groups through bioturbation. Future studies could look towards tools that could provide an even smoothing process to create consistent results. Furthermore, the study period could be expanded to include winter and summer months to gauge whether different temperatures could also be a driving factor that impacts rates of change.

5.0 Implications on Management

The dynamic state of soft sediment systems characteristics and organism populations are rapidly changing. While monitoring the state of ecosystems is important, it is also important to provide necessary information for management to minimize the impacts of different threats toward soft sediment ecosystems. As a result, finding low-cost and quick methods can be useful in providing up-to-date information about the health of different ecosystems as they change. The method developed by (Azhar et al 2022) can be an effective method that can be used to rapidly assess the state of soft sediment ecosystems, and determine whether subsequent actions need to be taken. This information can be to assess the risk that different ecosystems face in different situations. Additionally, different models can be created in order the predict the response of environments or organisms in response to disturbances. The current decision making process in terms of implementing solutions towards degrading ecosystems is delayed as a result of the current ecosystem analysis methods (Lee & Khim 2017), which may take a long time to complete. As a result, once solution has been reached it is possible environments or ecosystems may have reached an unrecoverable state. In contrast, the information from this study may be useful to different management teams in helping them make quick informed decisions , based on the current health of different environments. Fast and temporary solutions could be applied to different ecosystems that are under immediate threat from physical or natural disturbances, such as the construction of barriers or restriction on activities. Furthermore, if threats facing certain ecosystems or environments are not immediate concerns, long term solutions such as carefully considered policy changes could be considered in order without immediate concern.

5.1 Conclusions

The findings of this study indicate that the current functionality of the Whangateu Estuary is healthy, with high rates of change occurring after the initial smoothing period indicating that there is a high level of organism activity, restoring lost surface features at a rapid rate following a disturbance. The rates of change along with time across the observed sites following disturbances indicate that there are still major groups within the estuary in order to carry out bioturbation and restore lost surface features. The variation in the rates of change overtime also indicates that there is a high level of biodiversity within the estuary, with the varying rates of change potentially representing different organisms groups, and the rate in which they bioturbated. Additionally, the hypothesis on the study was met, with rates of change generally increased as more time passed from the initial smoothing period.

References

- Alho, C. J. R. (2008). The value of biodiversity. *Brazilian Journal of Biology*, *68*, 1115-1118

- Aller, R. C. (1983). The importance of the diffusive permeability of animal burrow linings in determining marine sediment chemistry. *Journal of Marine Research*, *41*(2), 299-322.

- Anderson, F. E., & Meyer, L. M. (1986). The interaction of tidal currents on a disturbed intertidal bottom with a resulting change in particulate matter quantity, texture, and food quality. *Estuarine, Coastal and Shelf Science*, *22*(1), 19-29.

- Azhar, M., Hillman, J. R., Gee, T., Schenone, S., van der Mark, W., Thrush, S. F., & Delmas, P. (2022). An RGB-D framework for capturing soft-sediment microtopography. *Methods in Ecology and Evolution*, *13*(8), 1730-1745

- Ballard, M. S., & Lee, K. M. (2017). The acoustics of marine sediments. *Acoust. Today*, *13*(3), 11-18

- Barbier, E. B. (2017). Marine ecosystem services. *Current Biology*, *27*(11), R507-R510

- Bartzke, G., Bryan, K. R., Pilditch, C. A., & Huhn, K. (2013). On the stabilizing influence of silt on sand beds. *Journal of Sedimentary Research*, *83*(8), 691-703.

- Balsamo, F., & Storti, F. (2010). Grain size and permeability evolution of soft-sediment extensional sub-seismic and seismic fault zones in high-porosity sediments from the Crotone basin, southern Apennines, Italy. *Marine and Petroleum Geology*, *27*(4), 822-837

- Benoit, J. M., Shull, D. H., Harvey, R. M., & Beal, S. A. (2009). Effect of bioirrigation on sediment− water exchange of methylmercury in Boston Harbor, Massachusetts. *Environmental science & technology*, *43*(10), 3669-3674.

- Bertics, V. J., & Ziebis, W. (2009). The biodiversity of benthic microbial communities in bioturbated coastal sediments is controlled by geochemical microniches. *The ISME journal*, *3*(11), 1269-1285.

- Berg, P., Rysgaard, S., Funch, P., & Sejr, M. K. (2001). Effects of bioturbation on solutes and solids in marine sediments. *Aquatic Microbial Ecology*, *26*(1), 81-94.

- Billerbeck, M., Werner, U., Polerecky, L., Walpersdorf, E., DeBeer, D., & Huettel, M. (2006). Surficial and deep pore water circulation governs spatial and temporal scales of nutrient recycling in intertidal sand flat sediment. *Marine Ecology Progress Series*, *326*, 61-76.

- Biles, C. L., Paterson, D. M., Ford, R. B., Solan, M., & Raffaelli, D. G. (2002). Bioturbation, ecosystem functioning, and community structure. *Hydrology and Earth System Sciences*, *6*(6), 999-1005.

- Bonaglia, S., Marzocchi, U., Ekeroth, N., Brüchert, V., Blomqvist, S., & Hall, P. O. (2019). Sulfide oxidation in deep Baltic Sea sediments upon oxygenation and colonization by macrofauna. *Marine Biology*, *166*, 1-12.

- Bonnie Laverock, Jack A. Gilbert, Karen Tait, A. Mark Osborn, Steve Widdicombe; Bioturbation: impact on the marine nitrogen cycle. *Biochem Soc Trans* 1 February 2011; 39 (1): 315–320

- Borja, Á., Dauer, D. M., Elliott, M., & Simenstad, C. A. (2010). Medium-and long-term recovery of estuarine and coastal ecosystems: patterns, rates and restoration effectiveness. *Estuaries and Coasts*, *33*, 1249-1260

- Botsford, L. W., Castilla, J. C., & Peterson, C. H. (1997). The management of fisheries and marine ecosystems. *Science*, *277*(5325), 509-515

- Böttcher, M. E., Hespenheide, B., Llobet-Brossa, E., Beardsley, C., Larsen, O., Schramm, A., ... & Amann, R. (2000). The biogeochemistry, stable isotope geochemistry, and microbial community structure of a temperate intertidal mudflat: an integrated study. *Continental Shelf Research*, *20*(12-13), 1749-1769.

- Brand, E., Chen, M., & Montreuil, A. L. (2020). Optimizing measurements of sediment transport in the intertidal zone. *Earth-Science Reviews*, *200*, 103029

- Christiansen, T., Wiberg, P. L., & Milligan, T. G. (2000). Flow and sediment transport on a tidal salt marsh surface. *Estuarine, Coastal and Shelf Science*, *50*(3), 315-331.

- Claudet, J., & Fraschetti, S. (2010). Human-driven impacts on marine habitats: a regional meta-analysis in the Mediterranean Sea. *Biological Conservation*, *143*(9), 2195-2206.

- Cook, P. L., Revill, A. T., Butler, E. C., & Eyre, B. D. (2004). Carbon and nitrogen cycling on intertidal mudflats of a temperate Australian estuary. II. Nitrogen cycling. *Marine Ecology Progress Series*, *280*, 39-54

- Constable, A. J. (1999). Ecology of benthic macro-invertebrates in soft-sediment environments: a review of progress towards quantitative models and predictions. *Australian Journal of Ecology*, *24*(4), 452-476

- Dashtgard, S. E., Gingras, M. K., & Pemberton, S. G. (2008). Grain-size controls on the occurrence of bioturbation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *257*(1-2), 224-243.

- Dauwe, B., Middelburg, J. J., & Herman, P. M. (2001). Effect of oxygen on the degradability of organic matter in subtidal and intertidal sediments of the North Sea area. *Marine Ecology Progress Series*, *215*, 13-22

- DeSylva, D. (1986). Increased storms and estuarine salinity and other ecological impacts of the greenhouse effect. *Effects of changes in stratospheric ozone and global climate*, *4*, 153-164.

- du Châtelet, É. A., Bout-Roumazeilles, V., Riboulleau, A., & Trentesaux, A. (2009). Sediment (grain size and clay mineralogy) and organic matter quality control on living benthic foraminifera. *Revue de micropaléontologie*, *52*(1), 75-84.

- Duffy, J. E., Cardinale, B. J., France, K. E., McIntyre, P. B., Thébault, E., & Loreau, M. (2007). The functional role of biodiversity in ecosystems: incorporating trophic complexity. *Ecology letters*, *10*(6), 522-538

- Dugan, J. E., Emery, K. A., Alber, M., Alexander, C. R., Byers, J. E., Gehman, A. M., ... & Sojka, S. E. (2018). Generalizing ecological effects of shoreline armoring across soft sediment environments. *Estuaries and coasts*, *41*, 180-196.

- Dyer, K. R., Christie, M. C., & Wright, E. W. (2000). The classification of intertidal mudflats. *Continental Shelf Research*, *20*(10-11), 1039-1060.

- Ellingsen, K. E. (2002). Soft-sediment benthic biodiversity on the continental shelf in relation to environmental variability. *Marine ecology progress series*, *232*, 15-27.

- Fanjul, E., Escapa, M., Montemayor, D., Addino, M., Alvarez, M. F., Grela, M. A., & Iribarne, O. (2015). Effect of crab bioturbation on organic matter processing in South West Atlantic intertidal sediments. *Journal of Sea Research*, *95*, 206-216

- Fauchald, K., & Jumars, P. A. (1979). The diet of worms: a study of polychaete feeding guilds. *Oceanography and Marine Biology annual review*.

- Gabet, E. J., Reichman, O. J., & Seabloom, E. W. (2003). The effects of bioturbation on soil processes and sediment transport. *Annual Review of Earth and Planetary Sciences*, *31*(1), 249-273.

- Gérino, M., Stora, G., François-Carcaillet, F., Gilbert, F., Poggiale, J. C., Mermillod-Blondin, F., ... & Vervier, P. (2003). Macro-invertebrate functional groups in freshwater and marine sediments: a common mechanistic classification. *Vie et Milieu/Life & Environment*, 221-231.

- Gibson, R. N., Barnes, M., & Atkison, R. J. A. (2001). Functional group ecology in soft-sediment marine benthos: the role of bioturbation. *Oceanogr Mar Biol Annu Rev*, *39*, 233-267.

- Gladstone-Gallagher, R. V., Pilditch, C. A., Stephenson, F., & Thrush, S. F. (2019). Linking traits across ecological scales determines functional resilience. *Trends in ecology & evolution*, *34*(12), 1080-1091

- Glud, R. N., Gundersen, J. K., Røy, H., & Jørgensen, B. B. (2003). Seasonal dynamics of benthic O2 uptake in a semienclosed bay: Importance of diffusion and faunal activity. *Limnology and Oceanography*, *48*(3), 1265-1276.

- Gray, J. S. (1981). The ecology of marine sediments. *The ecology of marine sediments*

- Grant, J., & Daborn, G. (1994). The effects of bioturbation on sediment transport on an intertidal mudflat. *Netherlands Journal of Sea Research*, *32*(1), 63-72.

- Griffith, G. P., Fulton, E. A., & Richardson, A. J. (2011). Effects of fishing and acidification-related benthic mortality on the southeast Australian marine ecosystem. *Global Change Biology*, *17*(10),

- Harris, R. J., Pilditch, C. A., Greenfield, B. L., Moon, V., & Kröncke, I. (2016). The influence of benthic macrofauna on the erodibility of intertidal sediments with varying mud content in three New Zealand estuaries. *Estuaries and coasts*, *39*, 815-828.3058-3074.

- Howarth, R. W., Billen, G., Swaney, D. P., Townsend, A., Jaworski, N., Lajtha, K., ... Zhao-Liang, Z. (1996). Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. Boigeochemistry, 35, 75–139

- Howarth, R., Chan, F., Conley, D. J., Garnier, J., Doney, S. C., Marino, R., & Billen, G. (2011). Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Frontiers in Ecology and the Environment*, *9*(1), 18-26.

- Hogue, E. W., & Miller, C. B. (1981). Effects of sediment microtopography on small-scale spatial distributions of meiobenthic nematodes. *Journal of Experimental Marine Biology and Ecology*, *53*(2-3), 181-191

- Hassan, A., & Nawchoo, I. A. (2020). Impact of invasive plants in aquatic ecosystems. *Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation*, 55-73

- Huston, M. A. (1994). *Biological diversity: the coexistence of species*. Cambridge University Press

- Yoo, J. W., Hwang, I. S., & Hong, J. S. (2007). Inference models for tidal flat elevation and sediment grain size: a preliminary approach on tidal flat macrobenthic community. *Ocean Science Journal*, *42*, 69-79.

- Jones, D., & Frid, C. L. (2009). Altering intertidal sediment topography: effects on biodiversity and ecosystem functioning. *Marine Ecology*, *30*, 83-96.

- Johnson, B. D., Barry, M. A., Boudreau, B. P., Jumars, P. A., & Dorgan, K. M. (2012). In situ tensile fracture toughness of surficial cohesive marine sediments. *Geo-Marine Letters*, *32*, 39-48.

- Arndt, S., Jørgensen, B. B., LaRowe, D. E., Middelburg, J. J., Pancost, R. D., & Regnier, P. (2013). Quantifying the degradation of organic matter in marine sediments: A review and synthesis. *Earth-science reviews*, *123*, 53-86

- Kaiser, M. J., Clarke, K. R., Hinz, H., Austen, M. C., Somerfield, P. J., & Karakassis, I. (2006). Global analysis of response and recovery of benthic biota to fishing. *Marine Ecology Progress Series*, *311*, 1-14.

- Kiorboe, T., & Mohlenberg, F. (1981). Particle selection in suspension-feeding bivalves. *Mar. Ecol. Prog. Ser*, *5*(3), 291-296.

- Kristensen, E. (2000). Organic matter diagenesis at the oxic/anoxic interface in coastal marine sediments, with emphasis on the role of burrowing animals. In *Life at Interfaces and Under Extreme Conditions: Proceedings of the 33rd European Marine Biology Symposium, held at Wilhelmshaven, Germany, 7–11 September 1998* (pp. 1-24). Springer Netherlands

- Lavoie, D. L., Richardson, M. D., & Holmes, C. (1997). Benthic boundary layer processes in the Lower Florida Keys. *Geo-Marine Letters*, *17*, 232-236.

- Lee, S. Y., & Khim, J. S. (2017). Hard science is essential to restoring soft-sediment intertidal habitats in burgeoning East Asia. *Chemosphere*, *168*, 765-776.

- Lohrer, A. M., Rodil, I. F., Townsend, M., Chiaroni, L. D., Hewitt, J. E., & Thrush, S. F. (2013). Biogenic habitat transitions influence facilitation in a marine soft-sediment ecosystem. *Ecology*, *94*(1), 136-145.

- Ma, B., Dai, Z., Pang, W., Ge, Z., Li, S., Mei, X., & Huang, H. (2019). Dramatic typhoon-induced variability in the grain size characteristics of sediments at a meso-macrotidal beach. *Continental Shelf Research*, *191*, 10400

- Martinez-Garcia, E., Carlsson, M. S., Sanchez-Jerez, P., Sánchez-Lizaso, J. L., Sanz-Lazaro, C., & Holmer, M. (2015). Effect of sediment grain size and bioturbation on decomposition of organic matter from aquaculture. *Biogeochemistry*, *125*, 133-148.

- McCartain, L. D., Townsend, M., Thrush, S. F., Wethey, D. S., Woodin, S. A., Volkenborn, N., & Pilditch, C. A. (2017). The effects of thin mud deposits on the behavior of a deposit-feeding tellinid bivalve: implications for ecosystem functioning. *Marine and Freshwater behaviour and physiology*, *50*(4), 239-255.

- Mermillod-Blondin, F. (2011). The functional significance of bioturbation and biodeposition on biogeochemical processes at the water–sediment interface in freshwater and marine ecosystems. *Journal of the North American Benthological Society*, *30*(3), 770-778.

- Meyer, S. T., Koch, C., & Weisser, W. W. (2015). Towards a standardized rapid ecosystem function assessment (REFA). *Trends in ecology & evolution*, *30*(7), 390-397

- Middelburg, J. J. (2017, April). To the bottom of carbon processing at the seafloor: towards integration of geological, geochemical, and ecological concepts (Vladimir Ivanovich Vernadsky Medal Lecture). In *EGU General Assembly Conference Abstracts* (p. 2283).

- Meysman, F. J., Middelburg, J. J., & Heip, C. H. (2006). Bioturbation: a fresh look at Darwin's last idea. *Trends in Ecology & Evolution*, *21*(12), 688-695

- Mitchener H, Torfs H. 1996. Erosion of mud/sand mixtures. Coastal Eng. 29:1–25

- Middelburg, J. J. (2017, April). To the bottom of carbon processing at the seafloor: towards integration of geological, geochemical and ecological concepts (Vladimir

- Ivanovich Vernadsky Medal Lecture). In *EGU General Assembly Conference Abstracts* (p. 2283).

- Molnar, J. L., Gamboa, R. L., Revenga, C., & Spalding, M. D. (2008). Assessing the global threat of invasive species to marine biodiversity. *Frontiers in Ecology and the Environment*, *6*(9), 485-492.

- Mueller, G., Broll, G., & Tarnocai, C. (1999). Biological activity as influenced by microtopography in a cryosolic soil, Baffin Island, Canada. *Permafrost and Periglacial Processes*, *10*(3), 279-288

- Nabe-Nielsen, J., van Beest, F. M., Grimm, V., Sibly, R. M., Teilmann, J., & Thompson, P. M. (2018). Predicting the impacts of anthropogenic disturbances on marine populations. *Conservation Letters*, *11*(5), e12563

- Naeem, S., Thompson, L., Lawler, S. *et al.* Declining biodiversity can alter the performance of ecosystems. *Nature* **368**, 734–737 (1994).

- Needham, H. R., Pilditch, C. A., Lohrer, A. M., & Thrush, S. F. (2013). Density and habitat dependent effects of crab burrows on sediment erodibility. *Journal of sea research*, *76*, 94-104

- Netto, Sérgio A., Martin J. Attrill, and Richard M. Warwick. "The relationship between benthic fauna, carbonate sediments, and reef morphology in reef-flat tidal pools of Rocas Atoll (north-east Brazil)." *Journal of the Marine Biological Association of the United Kingdom* 83.2 (2003): 425-432.

- Netto, S. A., Attrill, M. J., & Warwick, R. M. (2003). The relationship between benthic fauna, carbonate sediments, and reef morphology in reef-flat tidal pools of Rocas Atoll (north-east Brazil). *Journal of the Marine Biological Association of the United Kingdom*, *83*(2), 425-432

- Nixon, S. W. (1981). Remineralization and nutrient cycling in coastal marine ecosystems. In *Estuaries and nutrients* (pp. 111-138). Totowa, NJ: Humana Press.

- O’Hara, Casey C., Melanie Frazier, and Benjamin S. Halpern. "At-risk marine biodiversity faces extensive, expanding, and intensifying human impacts." *Science* 372, no. 6537 (2021): 84-87.

- O’Farrell, P. J., Anderson, P. M., Le Maitre, D. C., & Holmes, P. M. (2012). Insights and opportunities offered by a rapid ecosystem service assessment in promoting a conservation agenda in an urban biodiversity hotspot. *Ecology and Society*, *17*(3).

- Orvain, F., Sauriau, P. G., Sygut, A., Joassard, L., & Le Hir, P. (2004). Interacting effects of Hydrobia ulvae bioturbation and microphytobenthos on the erodibility of mudflat sediments. *Marine ecology progress series*, *278*, 205-223.

- Pawar, P. R. (2016). Anthropogenic threats to coastal and marine biodiversity: a review. *Int J Mod Biol Res*, *4*, 35-45.

- Patrick, B., McCllelan, R., Martin, T., Tocher, M., Borkin, K., McKoy, J., & Smith, D. (2014). Guidelines for undertaking rapid biodiversity assessments in terrestrial and marine environments in the Pacific.

- Peh, K. S. H., Balmford, A., Bradbury, R. B., Brown, C., Butchart, S. H., Hughes, F. M., ... & Birch, J. C. (2013). TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance. *Ecosystem Services*, *5*, 51-57.

- Pratchett, M. S., Munday, P. L., Wilson, S. K., Graham, N. A., Cinner, J. E., Bellwood, D. R., ... & McClanahan, T. R. (2008). Effects of climate-induced coral bleaching on coral-reef fishes—ecological and economic consequences. In *Oceanography and marine biology* (pp. 257-302). CRC Pres

- Pedreros, R., Howa, H. L., & Michel, D. (1996). Application of grain size trend analysis for the determination of sediment transport pathways in intertidal areas. *Marine geology*, *135*(1-4), 35-49.

- Preskitt, L. B., Vroom, P. S., & Smith, C. M. (2004). A rapid ecological assessment (REA) quantitative survey method for benthic algae using photoquadrats with scuba. *Pacific Science*, *58*(2), 201-209

- Qiu, D., Cui, B., Yan, J., Ma, X., Ning, Z., Wang, F., ... & Bai, J. (2019). Effect of burrowing crabs on retention and accumulation of soil carbon and nitrogen in an intertidal salt marsh. *Journal of Sea Research*, *154*, 101808.

- Rhoads, D. C. (1970). The influence of deposit-feeding organisms on sediment stability and community trophic structure. *J mar Res*, *28*, 150-178.

- Røy, H., Huettel, M., & Jørgensen, B. B. (2005). The influence of topography on the functional exchange surface of marine soft sediments, assessed from sediment topography measured in situ. Limnology and oceanography, 50(1), 106-112.

- Safi, K. A., Hewitt, J. E., & Talman, S. G. (2007). The effect of high inorganic seston loads on prey selection by the suspension-feeding bivalve, Atrina zelandica. *Journal of Experimental Marine Biology and Ecology*, *344*(2), 136-148.

- Sale, P. F., Feary, D. A., Burt, J. A., Bauman, A. G., Cavalcante, G. H., Drouillard, K. G., ... & Van Lavieren, H. (2011). The growing need for sustainable ecological management of marine communities of the Persian Gulf. *Ambio*, *40*, 4-17.

- Saaltink, R. M., Honingh, E., Dekker, S. C., Griffioen, J., van Riel, M. C., Verdonschot, P. F., ... & Wassen, M. J. (2019). Respiration and aeration by bioturbating Tubificidae alter biogeochemical processes in aquatic sediment. *Aquatic Sciences*, *81*, 1-13.

- Sayre, R., Roca, E., Sedaghatkish, G., Young, B., Keel, S., & Roca, R. (1999). *Nature in focus: rapid ecological assessment*. Island Press.

- Schenone, S., Thrush, S.F. Unraveling ecosystem functioning in intertidal soft sediments: the role of density-driven interactions. *Sci Rep* 10, 11909 (2020).

- Shephard, S., Brophy, D., & Reid, D. G. (2010). Can bottom trawling indirectly diminish carrying capacity in a marine ecosystem. *Marine Biology*, *157*, 2375-2381

- Shu, G., & Collins, M. (2001). The use of grain size trends in marine sediment dynamics: a review. *Chinese Journal of oceanology and Limnology*, *19*(3), 265-271.

- Singh, G., Ramanathan, A. L., & Prasad, M. B. K. (2005). Nutrient cycling in mangrove ecosystem: a brief overview. *Int J Ecol Environ Sci*, *30*, 231-244

- Smit, M. G., Holthaus, K. I., Trannum, H. C., Neff, J. M., Kjeilen-Eilertsen, G., Jak, R. G., ... & Hendriks, A. J. (2008). Species sensitivity distributions for suspended clays, sediment burial, and grain size change in the marine environment. *Environmental Toxicology and Chemistry: An International Journal*, *27*(4), 1006-1012.

- Soetaert, K., Herman, P. M., & Middelburg, J. J. (1996). A model of early diagenetic processes from the shelf to abyssal depths. *Geochimica et Cosmochimica Acta*, *60*(6), 1019-1040

- Solan, M., P. Batty, M. T. Bulling, and J. A. Godbold. 2008. How biodiversity affects ecosystem processes: implications for ecological revolutions and benthic ecosystem function. Aquatic Biology 2:289-301

- Stal, L. J. (2010). Microphytobenthos as a biogeomorphological force in intertidal sediment stabilization. *Ecological Engineering*, *36*(2), 236-245.

- Stefanoudis, P. V., Bett, B. J., & Gooday, A. J. (2016). Abyssal hills: Influence of topography on benthic foraminiferal assemblages. *Progress in Oceanography*, *148*, 44-55.

- Defew, E. C., Tolhurst, T. J., & Paterson, D. M. (2002). Site-specific features influence sediment stability of intertidal flats. *Hydrology and Earth System Sciences*, *6*(6), 971-982

- Veríssimo, H., Bremner, J., Garcia, C., Patrício, J., van der Linden, P., & Marques, J. C. (2012). Assessment of the subtidal macrobenthic community functioning of a temperate estuary following environmental restoration. *Ecological Indicators*, *23*, 312-322.

- Volkenborn, N., Polerecky, L., Hedtkamp, S. I. C., van Beusekom, J. E., & De Beer, D. (2007). Bioturbation and bioirrigation extend the open exchange regions in permeable sediments. *Limnology and Oceanography*, *52*(5), 1898-1909

- Wernberg, T., Smale, D. A., Tuya, F., Thomsen, M. S., Langlois, T. J., De Bettignies, T., ... & Rousseaux, C. S. (2013). An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nature Climate Change, 3(1), 78-82

- Whitlatch, R. B. (1980). Patterns of resource utilization and coexistence in marine intertidal deposit-feeding communities

- Wiesebron, Lauren E., Natalie Steiner, Claudia Morys, Tom Ysebaert, and Tjeerd J. Bouma. "Sediment bulk density effects on benthic macrofauna burrowing and bioturbation behavior." *Frontiers in marine science* 8 (2021): 707785.

- Wilson, R. S., Cohen, B. F., & Poore, G. C. (1993). *The role of suspension-feeding and deposit-feeding benthic macroinvertebrates in nutrient cycling in Port Phillip Bay*. Melbourne: CSIRO.

- Wu, W., Meador, T., & Hinrichs, K. U. (2018). Production and turnover of microbial organic matter in surface intertidal sediments. *Organic Geochemistry*, *121*, 104-113.

- Yallop, M. L., Paterson, D. M., & Wellsbury, P. (2000). Interrelationships between rates of microbial production, exopolymer production, microbial biomass, and sediment stability in biofilms of intertidal sediments. *Microbial ecology*, *39*, 116-127

- Zawada, D. G., Piniak, G. A., & Hearn, C. J. (2010). Topographic complexity and roughness of a tropical benthic seascape. *Geophysical research letters*, *37*(14)