Physical and ecological impacts associated with mangrove removals using *in situ* mechanical mulching in Tauranga Harbour

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Cover photograph: Omokoroa Estuary, Tauranga Harbour, 10 months after mulching of mangroves (November 2010). Photograph by C. Lundquist (c.lundquist@niwa.co.nz)

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Contents

Executive summary

We surveyed trends in sediment characteristics and benthic communities after mechanical removal of mangroves and *in situ* mulch deposition in Tauranga Harbour. Our quantitative surveys in Waikaraka and Te Puna estuaries after mangrove removals revealed significant impacts on benthic communities, and few signs of recovery towards a typical sandflat (in terms of sediment characteristics or benthic community composition) over a 12 month period. Surveys in these and three other Tauranga Harbour estuaries also documented direct and indirect impacts associated with the deposition of mulch *in situ* following mechanical mangrove removal. These impacts included smothering of sediments and associated epifauna and infauna, resulting in persistent anoxic sediments, oxygen depletion to <80% saturation in the water column over large portions of the tidal cycle, nutrient release from mulch material, and macroalgal blooms stimulated by nutrients released from mulch zones.

Key findings are as follows:

- After 12 months, substantial mulch biomass still remained on site, with limited dispersal and decomposition of mulch material.
- Perimeters of mulched area showed very slow erosion of the mulch zone over 12 months (range 5-19% decrease in total area).
- Anoxic conditions persisted within surface sediments in the mulch zone for at least 12 months, except within 5-10 m of the seaward edge at some sites.
- No change from mud to sandier sediments was detected in the mulch zone during the 12 month survey.
- While some colonisation by macrofauna occurred, the resulting community was dominated by opportunistic species (oligochaetes, *Capitella* spp., and dipterid (fly) larvae), most of which are tolerant of anoxic conditions, and not representative of typical sandflat (or mangrove) communities.
- Macroalgal blooms were observed on all mulch sites, and on some occasions, reached 100% cover in large (>1 ha) patches at some locations.
- Laboratory experiments demonstrated high rates of nutrient release associated with the mangrove mulch.
- Field sampling of pore water nutrients confirmed laboratory predictions of elevated concentrations of phosphorus and ammonium associated with mulch zones in Waikareao and Waikaraka estuaries.
- Field sampling of water column oxygen saturation levels detected decreases in oxygen over both mulch zones and mangrove zones inshore of mulch zones.

1 Introduction

1.1 Background

In the past half century, mangroves have increased in extent in estuaries and tidal creeks throughout the upper half of the North Island (Morrisey et al. 2010). While mangroves are native and an integral part of functioning estuaries in northern New Zealand, their relative increase and association with fine sediments has resulted in an increasing number of consent applications for mangrove removals, with goals of estuarine areas returning to sandier, un-vegetated states (Green et al. 2003).

Legal and illegal removals have occurred to date in all four New Zealand regions where mangroves occur (Northland, Auckland, Waikato, and Bay of Plenty). Unfortunately, minimal information is available on long term recovery (and likelihood of success) of the clearings. While increased sediment loading into estuaries is clearly linked to increasing mangroves, we lack understanding of most aspects of mangrove clearing, including the physical and ecological processes underlying differences in the timing and likelihood of success of mangrove removals. For example, we would predict that hydrodynamic differences (e.g., wind-wave exposure, tidal currents) between sites might influence the natural removal of sediments and organic material that have built up within the mangrove habitat. Rehabilitation might also depend on the influence of further terrestrial-based sediment loading and freshwater influx, local sediment characteristics, and colonisation by organisms that will assist in the recovery process (e.g., via bioturbation). We also have poor understanding of potential barriers to restoration, such as sediments or organic material remaining from mangroves and how this might affect colonisation and successional processes of benthic communities. We also do not understand whether mangrove removal methods may indirectly affect neighbouring habitats including the overlying water column through deoxygenation and nutrient release. Finally, we have no understanding of far-field effects of these clearings via dispersal of any remaining mangrove material and erosion of fine sediments that might negatively impact shellfish beds and other neighbouring habitats. Information on all of these aspects of mangrove clearing are required in order to provide better advice to managers and community groups on suitable sites and "best practice" clearance techniques.

1.2 Objectives

1.2.1 NIWA's Aquatic Rehabilitation project

The broad objectives of the Mangrove project within NIWA's Aquatic Rehabilitation project are to:

- Determine if the recovery process at mangrove removal areas depends on site-specific features such as wave exposure, sediment inputs, and neighbouring habitats (including how much mangrove forest is left intact).
- Determine typical timelines and recovery trajectories for mangrove removals to return to sandier sediments when using the on-site mangrove mulching procedure with *in situ* disposal of mangrove mulch.

- Determine short and medium term impacts on adjacent macrofauna and estuarine health of mangrove removal and on-site mulching.

1.2.2 Tauranga Harbour field study

A resource consent to BOPRC to mulch mangroves in 11 sub-estuaries spread across Tauranga Harbour provided an ideal case study to quantify recovery trajectories at a range of sites within the harbour, determining the influence of variation in key physical and biological characteristics on success of mangrove removal. Mangroves were removed using a new *in situ* mechanical mulching technique, with total of ~110 ha mulched in 2010 and 2011. Mangrove trees were mechanically mulched using a tractor with a low psi rating to minimise sediment compaction. All sub-surface material was left intact, and mulch material was left on site.

We hypothesised that changes in local macrofaunal communities were likely, due to both direct impacts of smothering by mulch material or fine sediments released from binding by mangrove forests, and indirect, long-term effects of decomposition of mangrove material. Our experimental design concentrated on determining whether or not desired outcomes of mangrove removal occurred: 1) removal areas becoming more similar to sandflat zones in terms of both sediment characteristics and benthic communities; 2) mulch material disperses or decomposes rapidly, with no persistent anoxic zones due to remaining mulch material; 3) no signs of eutrophication (e.g., excess macroalgal growth); 4) no or limited mangrove recolonisation, and minimal need for maintenance by seedling removal; 5) no declines in neighbouring shellfish beds due to sediment or mulch erosion. A small number of macrofaunal and sediment cores were collected to supplement visual observations. As unanticipated impacts did occur as a result of mulch deposition, additional surveys and experiments were undertaken to investigate macroalgal blooms, nutrient release, and oxygen consumption.

Key measurements:

- Perimeter mapping of mulch zones.
- Transect sampling of mulched areas to determine changes in epifauna and infauna, oxic depth, mulch depth, and colonisation by seeds and seedlings.
- Benthic macrofaunal cores to determine changes in community structure.
- Cores to determine changes in mangrove mulch biomass remaining at the site.
- Sediment cores to determine changes in sediment grain size, organic matter content and chlorophyll *a* content.
- Shellfish condition surveys to investigate far field impacts on neighbouring habitats.
- Macroalgal surveys to quantify macroalgal blooms.
- Laboratory experimentation to determine nutrient release from mulch material.
- Oxygen surveys to quantify impacts on the water column.

- Sediment trap collections to determine if sediment and/or mulch material was eroding or dispersing away from the mulch zone.

2 Methods

2.1 Site selection

Six Tauranga Harbour estuaries (Omokoroa, Te Puna, Waikaraka, Matua, Waikareao, Welcome Bay) were visited in 2010 and 2011 to investigate effects of mangrove mulching with *in situ* deposition of mulch material. Three sites in each of three estuaries (Te Puna, Waikaraka, Waikareao) were chosen for quantitative monitoring over a 12 month period, including transect surveys and macrofaunal and sediment coring (Figure 2-1). These monitoring sites were chosen to maximise the ability to determine site characteristics that influence the likelihood of mangrove removals returning to sandier substrates. Individual sites within estuaries were chosen based on estimated similar size and width of mulch patches based on resource consent maps provided by the Bay of Plenty Regional Council (BOPRC). Unfortunately, delays due to longer time required to complete mulching meant that mulching in one of the three estuaries (Waikareao) was not completed during the same season as the other two estuaries (Waikaraka, Te Puna). As such, quantitative monitoring analyses are only presented for the two estuaries mulched in June-August 2010. Additional opportunistic surveys were performed in Omokoroa and Waikareao estuaries, including perimeter mapping, and macroalgal and water column oxygen saturation surveys. Oxygen saturation was also surveyed in Welcome Bay estuary prior to mangrove mulching at that site. Matua estuary was also visited regularly, and visual observations were recorded in photographs to document similarity of observed effects at this smaller mangrove removal site.

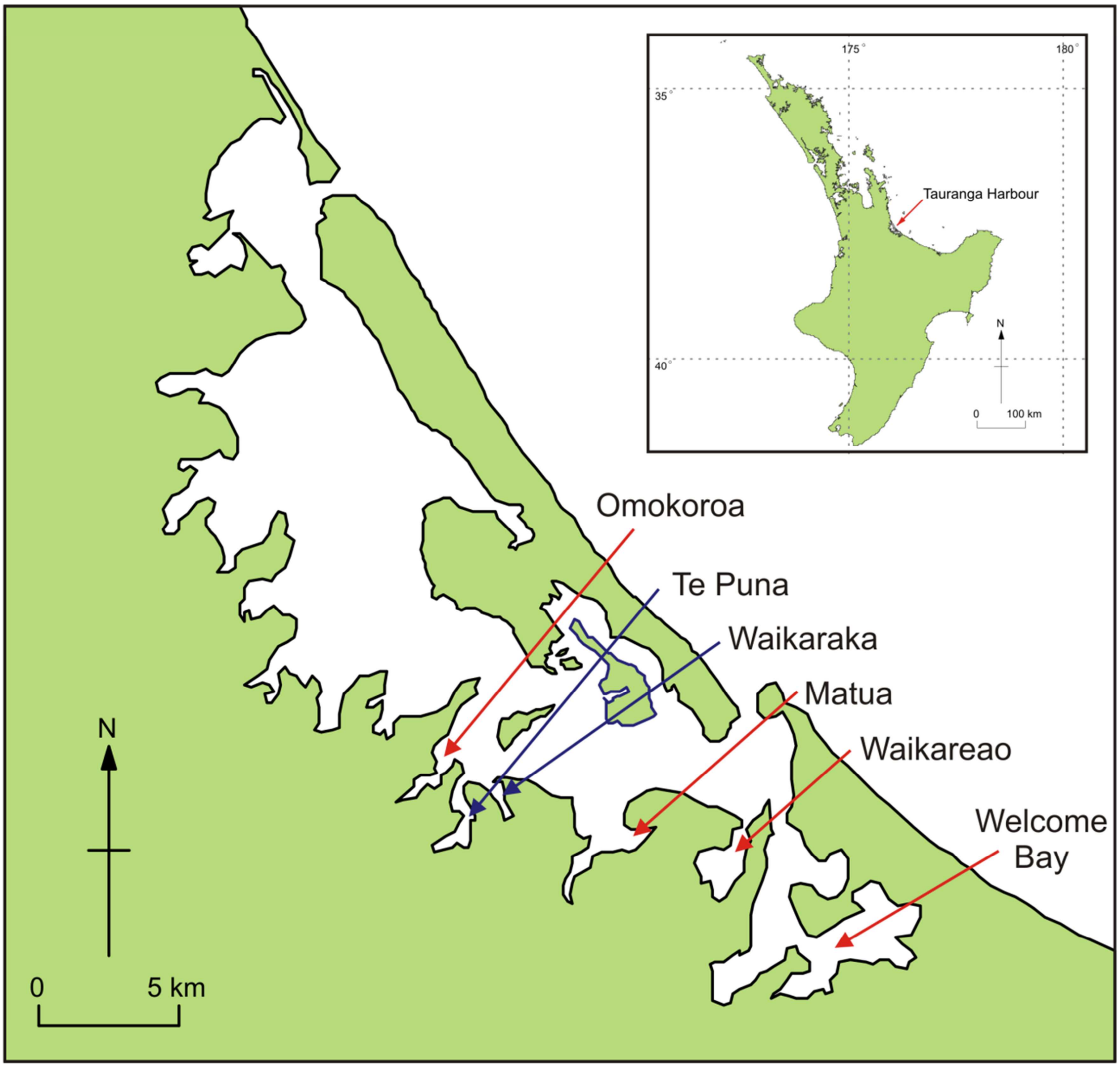

Figure 2-1: Map of the estuaries surveyed in Tauranga Harbour. Regular quantitative surveys occurred at Te Puna and Waikaraka, while other estuaries (Omokoroa, Matua, Waikareao, Welcome Bay) were surveyed opportunistically.

2.2 Perimeter mapping of mulch zones

To determine if the mulch zone was eroding over time, perimeters were mapped by walking within 1 m of the visible perimeter of the mulch patch, recording position using a hand-held GPS unit. Monitoring sites in Te Puna and Waikaraka estuaries were mapped on most sampling occasions. Opportunistic visits to other estuaries included further GPS perimeters. BOPRC provided initial perimeters of mulch zones for 4 estuaries: Omokoroa, Te Puna, Waikaraka, and Waikareao. Perimeters were mapped using ArcGIS and the area of each mulch zone was calculated to determine the percent change in area over time.

2.3 Transect sampling of mulched areas

At each of three mulch sites in Te Puna and Waikaraka estuaries, we sampled transects from sand through mulch to mangrove at four time periods: within one month prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching (Figure 2-2, Figure 2-3, Table 2-1). Both estuaries were also visited immediately (within one week) of the completion of mulching to confirm general characteristics at each site.

A standardised quadrat (0.5 x 0.5 m) was sampled at 10 locations along each transect from sand through mulch into mangrove zone. Quadrats were located at approximately 10 m intervals, with minor variation in length of transects if the area of the mulch zone differed from that predicted by resource consent maps. Our standard protocol sampled three quadrats in neighbouring sandflats outside the mulch zone (#1-3), one quadrat inside and within 2 m of the edge of the mulch zone (#4), three quadrats within the mulch zone (#5-7), one quadrat within the mangrove zone within 2 m of the mulch (#8), and 2 additional quadrats inside the mangrove forest (#9-10). Within each quadrat, visual observations were recorded for surface characteristics, and then measurements were taken by ruler to determine depth of sediment oxic layer and depth of remaining mulch material. Finally, quadrats were hand-raked to determine abundance of infaunal bivalves.

The following metrics were recorded for each 0.5 x 0.5 m:

- Number of visible crab holes.
- Number and species of epifauna on the surface, including primarily the gastropods *Amphibola, Zeacumantus, Diloma,* and *Cominella.* Counts of *Potamopyrgus* were not included in visual measurements, as they were not recorded reliably due to their small size.
- Infaunal bivalves >5mm, including *Austrovenus, Macomona*, and *Nucula.*
- Live and dead oyster shells.
- Proportion of surface covered by mangrove leaf litter.
- Proportion of surface covered by mulch, and depth of mulch layer (mm).
- Proportion of surface covered by macroalgae.
- Number of mangrove seeds and seedlings.
- Number of pneumatophores.
- Depth of oxic layer (mm).
- Sinkability, i.e., depth of footprints (cm depth).

We also made three shearvane and penetrometer readings within each habitat zone (sandflat, mulch, mangrove), and at the sandflat/mulch edge. Heights and trunk diameter at 10 cm above the sediment were measured for 10 mangrove trees at each site. Mean density of mangroves (2 m x 10 m area) were measured in July 2010 only.

One of three sites in each estuary had all mangroves cleared (Te Puna Site 1 and Waikaraka Site 3); therefore, all post-mulch collections include only 2 mangrove sites sampled per estuary. Also, we opportunistically sampled an historical manual mangrove removal area at Waikaraka site 3 that was directly adjacent to the mulched zone. According to the Waikaraka estuary care group, mangroves just outside of the Site 3 mulch removal area had been removed manually, and all mangrove material removed from the site. Intact stumps were clearly evident in the manual removal area, and suggested relatively sparse mangrove cover. Approximate dates of removals were not confirmed, but were suggested to be within 1 – 2 years prior to the mechanical mulching, with enough time to pass such that community groups had returned to the site to perform maintenance on stumps after some sediment erosion had occurred that resulted in stumps protruding over the sediment surface by 5-10 cm.

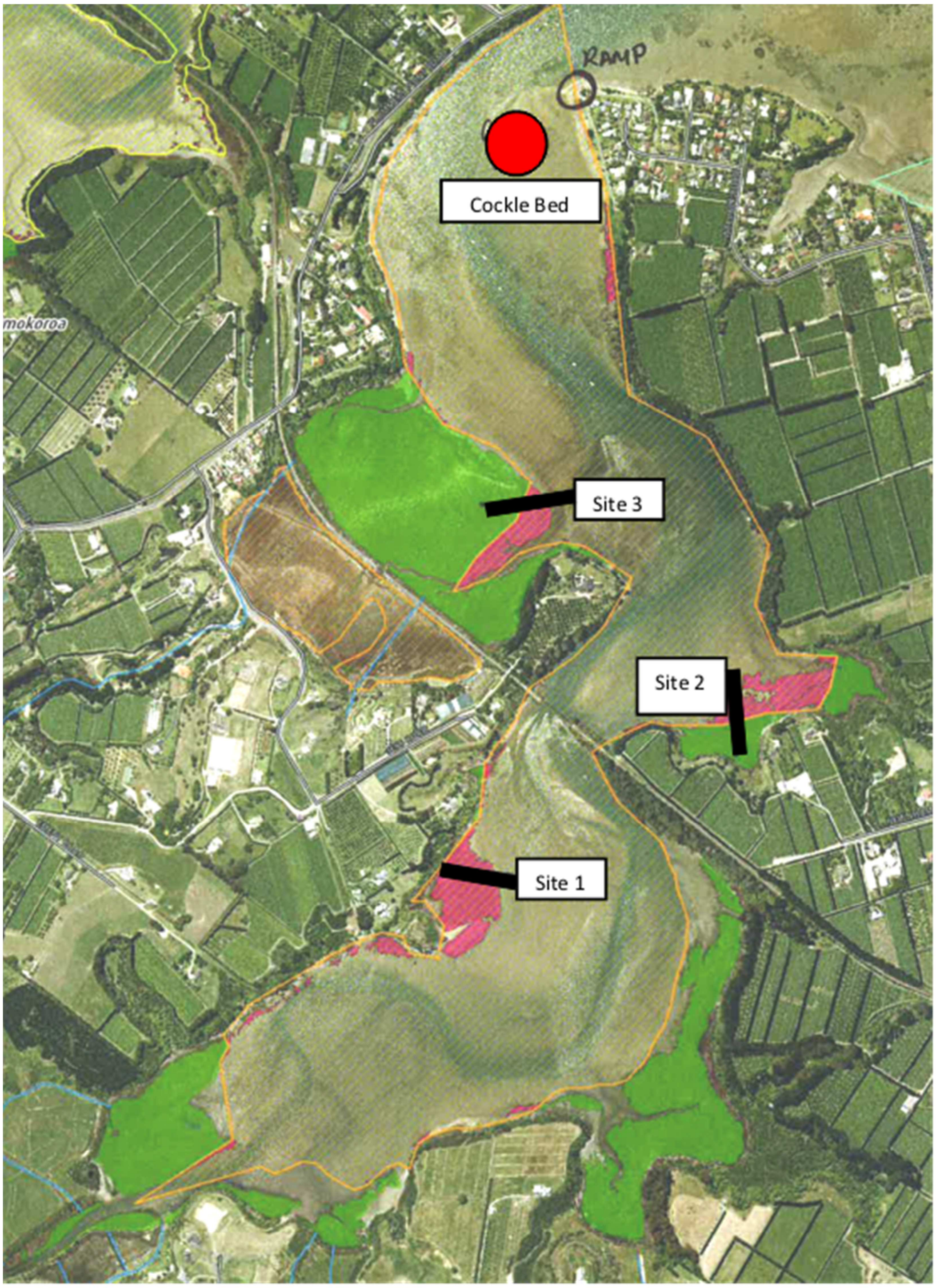

Figure 2-2: Aerial photograph of Te Puna estuary displaying sites (1-3) and transects (black line), cockle bed (red circle) and proposed areas of mangrove removal (pink) and remaining mangrove locations (green) (adapted from BOPRC resource consent application).

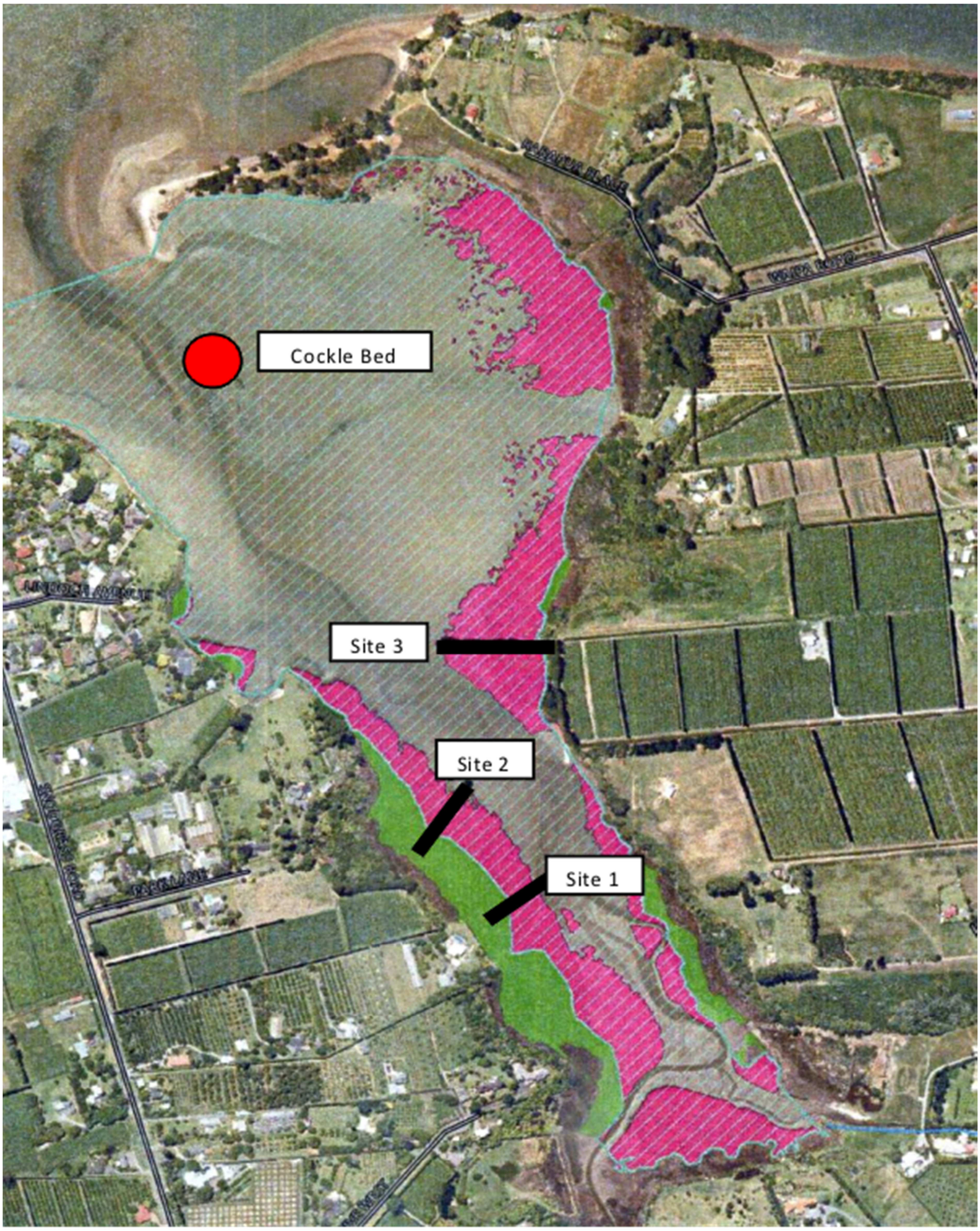

Figure 2-3: Aerial photograph of Waikaraka estuary displaying site (1-3) and transects (black line), cockle bed (red circle) and proposed areas of mangrove removal (pink) and remaining mangrove locations (green) (adapted from BOPRC resource consent application). Note that large amounts of the area defined as mangrove in the resource consent had already been manually cleared by estuary care groups, including a portion of site 3, and an area upstream of site 1.

Estuary	Transect	Quadrat	Latitude	Longitude
Waikaraka	1	1	37 40.048	176 03.933
		10	37 40.078	176 03.894
	2	1	37 39.942	176 03.856
		10	37 39.981	176 03.821
	3	1	37 39.847	176 03.811
		10	37 39.845	176 03.872
Te Puna	1	1	37 40.499	176 02.872
		10	37 40.497	176 02.814
	2	1	37 40.245	176 03.149
		10	37 40.290	176 03.173
	3	1	37 40.064	176 02.924
		10	37 40.056	176 02.871

Table 2-1: GPS coordinates of quadrats 1 and 10 along transects 1, 2 and 3 from Waikaraka and Te Puna estuaries.

2.4 Benthic macrofaunal cores

2.4.1 Benthic macrofauna

Benthic macrofaunal cores (13 cm diam., 15 cm depth) were taken from within sandflat, mulch and mangrove zones on 4 survey times: within one month prior to mulching, and at 3 months, 6 months and 12 months post-mulching. Three randomly placed cores were taken from each zone within 10 m of the main survey transect lines at each of the three sites in Waikaraka and Te Puna estuaries, with a total of 9 replicate cores from within each zone on each sampling occasion within each estuary.

Macrofaunal cores were sieved through a 500 µm mesh and the residues stained with rose bengal and preserved in 70% isopropyl alcohol in seawater. Sandflat samples were then rinsed and seived through a series of sieve sizes, and then sorted and stored in 50% isopropyl alcohol. Macrofauna were identified to the lowest taxonomic level practicable, usually to species.

Due to large amounts of vegetative material, mangrove and mulch samples were extensively rinsed and sieved as per above methods to remove as many macrofauna as possible from vegetative material. Larger vegetative material, for which rinsing successfully removed 100% of macrofauna, was removed from root material and set aside. The remaining root mass was subsampled (subsample proportion varying between samples with range of 10-50% of total remaining root mass) and the macrofauna identified (as above) and counted. The absolute abundance of each taxa within the core was then calculated as the count of each taxa divided by sub-sample proportion.

2.4.2 Bivalve size

After identification, shell lengths of individual *Paphies australis, Austrovenus stutchburyi* and *Macomona liliana* were measured and placed into size classes (<5 mm, 5 – 10 mm, then 10 mm increments).

2.4.3 Mulch biomass

As mulch was not observed to disperse from the sites within the predicted timeframe (less than one month post-mulching), we quantified the vegetative biomass in macrofaunal cores (13 cm diam., 15 cm depth) for the 6 and 12 month samples. After sorting, all vegetative material was air dried for one week on aluminium trays, and then oven dried at 70 ºC for approximately 4 days until dry weight stabilised.

Additional samples for mulch biomass were taken in August 2011 to determine spatial variability in mulch biomass at 4 estuaries: Waikaraka, Te Puna, Waikareao, Omokoroa. 13 cm diam., 15 cm depth cores were taken at three positions within the mulch zone (10 m from edge, centre of mulch zone, and 10 m from inside edge). These additional mulch biomass samples were collected within 50 m of each of the 3 monitoring transects in Waikaraka and Te Puna estuaries, and at 2 transects each in Waikareao and Omokoroa estuaries.

2.4.4 Statistical analyses

Community composition: All community analyses were performed on the sum of the 3 replicate cores collected in each zone (mangrove, mulch, sandflat) at each estuary site on each sampling occasion. Multivariate ordination of data was used to determine whether community composition was similar across zones, and if there were changes in community composition over the 12 month survey period. Ordinations of raw, log transformed and presence/absence data were conducted, using nonmetric multidimensional scaling based on Bray Curtis similarities (Clarke and Warwick 1994). Only the raw data ordinations are presented in this report as no differences in interpretation of patterns were apparent with the different transformations. Community composition at each site was also described based on the five most numerically dominant taxa.

Biodiversity: Univariate measures of biodiversity were also calculated for each zone at each estuary site at each sampling occasion. Number of species, number of individuals and the Shannon-Weiner index were calculated for each of three replicates, then averaged.

2.5 Sediment characteristics

Sediment characteristics (i.e., grain size, organic content and chlorophyll *a*) were assessed at each site on each sampling occasion. Within each zone (sandflat, mulch, mangrove), we randomly sampled sediment characteristics using two small sediment cores (2 cm deep, 2 cm diameter), one to determine grain size and organic content and the other for chlorophyll *a* analysis. The cores were kept frozen in the dark prior to being analysed as described below.

Grain size: The samples were homogenised and a subsample of approximately 5 g of sediment was taken and digested in ~ 9% hydrogen peroxide until frothing ceases. The sediment sample was then wet sieved through 2000 µm, 500 µm, 250 µm and 63 µm mesh sieves. Pipette analysis was used to separate the <63 µm fraction into >3.9 µm and ≤3.9 µm. All fractions were then dried at 60°C until a constant weight was achieved (fractions were weighed at ~ 40 h and then again at 48 h). Grainsize fractions were calculated as percentage weight of gravel/shell hash (>2000 μm), coarse and very coarse sand (500 – 2000 μm), medium sand (250 – 500 μm), fine and very fine sand (63 –250μm), silt (3.9 – 62.9 μm) and clay (≤3.9 μm). Mud content was calculated as the sum of the silt and clay content.

Chlorophyll *a*: Within one month of sampling, the full sample was freeze dried, weighed, then homogenised and a subsample (~5 g) taken for analysis. Chlorophyll *a* was extracted by boiling the sediment in 90% ethanol, and the extract processed using a spectrophotometer. An acidification step was used to separate degradation products from chlorophyll *a*.

Organic content: Approximately 5 g of sediment was placed in a dry, pre-weighed tray. The sample was then dried at 60°C until a constant weight was achieved (the sample was weighed after ~ 40 h and then again after 48 h). The sample was then ashed for 5.5 h at 400°C (Mook and Hoskin 1982) and then reweighed. Organic content was calculated as the difference in weight.

2.6 Macroalgal surveys

Opportunistic macroalgal surveys of species composition and percent cover occurred following observations of large blooms of macroalgae in mulch zones at the 6 month collection (Table 2-2). Four estuaries were sampled (Waikaraka, Te Puna, Waikareao, Omokoroa), with opportunistic collections from December 2010 through January 2012. We determined percent cover of macroalgae within a 0.25 m^2 quadrat at 5 m intervals on a transect running from 10 m inshore of the mangrove edge to 10 m outside of the sandflat edge of the mulch zone. Algal species were categorised into broad species categories, and identifications confirmed by an expert phycologist (W. Nelson, NIWA Wellington). Further genetic confirmation was undertaken as part of a collaboration with the University of Waikato (C. Gemmill; S. Pratt) to confirm a new record of *Percursaria percursa* (Ulvaceae) that had not previously been recorded on the North Island of New Zealand (Pratt et al. *in press*).

Table 2-2: Sampling dates for opportunistic macroalgal surveys.

	Date			
Estuary	**Dec-10**	**Aug-11**	**Nov-11**	**Jan-12**
Omokoroa	n/a	1 site, 1 transect	1 site, 3 transects	1 site, 3 transects
Waikaraka	2 sites, 3 transects at each site	2 sites, 1 transect at each site	3 sites, 2 transects at each site	3 sites, 2 transects at each site
Waikareao	1 site, 3 transects	1 site, 2 transects	1 site, 3 transects	1 site, 3 transects
Te Puna	2 sites, 3 transects at each site	2 sites, 1 transect at each site	n/a	n/a

2.7 Nutrient release laboratory experiment

To evaluate the potential for nutrient release in response to the presence and/or decomposition of mangrove mulch, a series of laboratory experiments were conducted in controlled temperature rooms. Chambers, containing layers of sediment, mangrove material, and sea water, were sealed and water samples extracted from the overlying water column over a seven day period. Water samples were measured for dissolved oxygen (DO) and nutrient chemistry (dissolved reactive phosphorus, ammonium and nitrate). Three sets of experiments were undertaken that involved investigations of the effects of:

1) temperature
2) age of the mulch, and
3) type of mangrove mulch material (roots, pneumatophores, woody debris).

The mangrove material and sediment used in these experiments were collected from the Waikareao estuary in Tauranga Harbour, and stored at 1˚C for 1-2 days prior to the experiment. Sediment was sieved on a 500 µm mesh to remove large animals (i.e., large cockles and polychaetes). Seawater was collected from Raglan Harbour and filtered through a 20 µm filter prior to use. Salinity remained constant over the course of the experiments (34-35 ppt).

For all experiments, three replicate controls (containing sediment and sea water) and three replicates of each treatment (containing sediment, mangrove treatment material and sea water) were used. To prepare for each experiment, plastic chambers (4.5 L volume) were double-lined with plastic bags and filled with sediment to a depth of 2 cm. For treatment replicates, a 5 cm layer of mangrove mulch material (mean weight of mulch material = 831.6 g) was then placed on top of the sediment, approximating depths of mulch material observed in the field. Experiments took place in controlled temperature rooms in the dark, and the chambers with sediment and mangrove material were stored overnight prior to initiation of the experiment to acclimatise to the controlled temperature room. At the start of the experiment, 2 L of filtered sea water was gently added to each mesocosm with sediment re-suspension minimised using bubble wrap. Nylon tubing was then inserted into each chamber, so that the end was approximately 2 cm above the sediment surface, the air was removed from the chamber, and the chambers and nylon tubing sealed. During the first day of the experiment (Day 0) water samples were extracted (without replacement of water volume, and minimising disturbance to the sediment) at times = 0, 1, 2, 3, 4 and 5 hours after experiment initiation. On subsequent days (Days 1, 2, 3, 5 and 7), only one water sample was taken at 24 hourly intervals. Water samples (60 mL) were extracted using a syringe, and samples were filtered into labelled containers and frozen for nutrient analyses. Approximately 1/3 of the total volume of water in the chamber was extracted for analysis during the course of the experiment. A DO reading was taken using a HACH Dissolved Oxygen meter (Model HQ40d) fitted with Luminescent Dissolved Oxygen Probe (Model LDO10105). Nutrient samples were only taken daily.

The first experiment examined the effect of temperature on nutrient release from mangrove mulch, and followed the experimental procedure with 3 replicates each of mulch and control at each of 3 temperatures (16, 20 and 24˚C). All temperature treatments used 2 week old mulch collected from Waikareao estuary.

The second experiment compared the effect of the age of the mangrove mulch on nutrient release, using mangrove mulch collected from Waikareao estuary at 2 weeks, 3 months and

5 months post mulching. For each treatment 'age', three control and three mulch treatment buckets were set up in a 20°C controlled temperature room.

The final experiment examined the effect of the type of mangrove mulch material (mulch, pneumatophores and roots) on nutrient release, comparing the 5 month old mangrove mulch with two additional mangrove material types (pneumatophores and roots), collected from intact mangrove forests in Waikareao estuary. Control and mangrove type treatments were set up in a 20°C controlled temperature room. For the pneumatophore treatment, approximately 8-10 pneumatophores (mean biomass of pneumatophores per replicate = 83.5 g) were placed on top of a 2 cm layer of sediment. For the root treatment, root material (mean biomass of root material = 30.6 g) was placed on top of a 2 cm layer of sediment, which was then buried by an additional 2 cm of sediment to approximate field observations of buried root mass. We opted to simulate *in situ* conditions of buried root mass, rather than placing roots on the surface in our controlled laboratory mesocosms. Root mass does naturally decompose within the sediments, so burial of roots does not prevent nutrient release.

Statistical analyses were performed using repeated measures analysis of variance in SAS (v. 9.1.3).

2.8 Field surveys of water column oxygen

As the laboratory nutrient experiments indicated a rapid decrease in oxygen when experimental treatments included mangrove mulch, we investigated *in situ* dissolved oxygen concentrations during a tidal cycle at Waikareao estuary in September 2010. Dissolved oxygen (DO) measurements were made at three locations: above the undisturbed sand at a distance of 10 m from the mulch zone; above the mulch zone in the centre of the zone; and 5 m into the mangrove zone. Measurements were taken every 15 min at 10 cm vertical intervals starting at 2.5 cm above the sediment surface (2.5, 12.5, 22.5, 32.5, 42.5, 52.5 and 62.5 cm above the sediment surface) starting at 0715 (during incoming tide, prior to high tide) and continued until 1030 (approaching mid-tide, after water levels had dropped such that no water remained on the mulch zone). Hand-held DO meters were used and intervals of 10 cm were marked with electrical tape on the probe cord to ensure measurements taken were accurately spaced. Optical dissolved oxygen sensors (D-Opto, Zebratech) were also placed at a depth of 10 cm at all 3 locations to get continuous readings throughout the sampling period. Unfortunately, the sandflat sensor malfunctioned and continuous data was only available for the mangrove and the mulch zone.

To determine spatial and temporal variability in deoxygenation patterns within the water column, and to evaluate vertical differences in deoxygenation heights, we performed additional observations of oxygen in the water column as part of a collaboration with the University of Waikato (C. Battershill). Continuous oxygen sensors were deployed in 3 Tauranga estuaries (Waikaraka, Waikareao, Welcome Bay) in March/April 2011. Oxygen levels in the water column were sampled for 2-3 days per estuary at three positions within each estuary (sandflat 10 m outside of mulch edge; centre of mulch patch at a distance of approximately 15-20 m inside the seaward edge; and 10 m inside mangrove forest inshore of the mulch zone). Sensors were placed 10 cm above the seafloor at the sandflat and mangrove site, and at 3 heights (5, 10, and 20 cm above the seafloor) in the mulch zone. Welcome Bay mangroves had not yet been mulched, and 'mulch' sensors were placed in sandflat habitat at a distance of 20 m from the edge of the mangrove forest and sandflat sensors were placed 40 m from the edge of the mangrove forest.

2.9 Cockle surveys

A cockle bed (*Austrovenus stutchburyi*) downstream of the mulched mangrove sites in both Te Puna and Waikaraka estuaries was identified and cockles were collected to analyse changes in density, size structure, and physiological condition. Cockle surveys were completed within one month prior to mulching, and 1 week, 3 months, 6 months and 12 months post-mulching. Cockle density was estimated by collecting and counting cockles from 10 randomly distributed 25 cm^2 quadrats. 100 cockles were measured (longest shell length, mm) to determine the approximate size structure of the cockle bed. 50 cockles ranging between 15-25 mm in length were collected for analysis of physiological condition. Condition was not determined for the 12 month survey.

Physiological condition was determined in the laboratory as part of a BScTech project with the University of Waikato (N. Webb). The length, width and depth (mm) of each cockle was measured. The flesh was dissected from the shell, and flesh and shell were dried separately in a 60ºC oven to a constant weight. The volume of each shell was measured and recorded in millilitres. Cockle condition weight and the condition volume were calculated using the following formulas:

$$CI_{flesh.\ shell.\ wt} = \frac{dry\ flesh\ weight\ (mg)}{dry\ shell\ weight\ (g)} \quad CI_{flesh.shell.\ vol.} = \frac{dry\ flesh\ weight\ (mg)}{shell\ cavity\ volume\ (ml)}$$

(Roper & Hickey, 1994)

The cockle condition weights and volumes were then averaged for each site and sampling time.

2.10 Sediment erosion

As part of a collaboration with a Bay of Plenty Polytech student (M. Robb), sediment traps were placed at two of the transect monitoring sites in Waikaraka (Sites 2 and 3) and Te Puna (Sites 2 and 3) to determine sedimentation rates shortly after mulching at each site. Three sediment traps were placed 10 m apart in each zone (sandflat, mulch, mangrove). Sandflat traps were placed 20 m out from the edge of the mulch zone, mulch traps were placed approximately 20 m into the mulch zone from the sandflat-mulch boundary, and mangrove traps were placed 10 m inside the mangrove-mulch boundary. Traps were allowed to stabilise for one week before sediment collection occurred to minimise effects of digging the trap on sedimentation rates. Traps were collected approximately every 10 days, with 4 collections made in Te Puna estuary, and 2 collections made in Waikaraka estuary between August and October 2010, with sampling beginning shortly after mulching was completed in each estuary. Sediment collections were dried to a constant weight at 100^0 C for 3-4 days.

3 Results

3.1 Perimeter mapping of mulch zones

In contrast to the mulching trial which demonstrated rapid dispersal of mangrove mulch within few tidal cycles (B. Rowson, BOPRC, pers. comm.), mulching on the larger scale of the resource consent to BOPRC resulted in mulch zones that only reduced by 5 – 19% over the period of the surveys (12 months). The Te Puna sites showed a proportional decrease in mulch zone area at sites 1 and 2 of -10.1% and -18.6%, respectively over 12 months (Figure 3-1, Table 3-1). Te Puna site 3 was only mapped at 3 months, showing a decrease of -1% at this site (Table 3-1). The Waikaraka sites showed smaller changes over time, with an initial spread of mulch outside the mulch zone detected at 3 months and 5 months post-mulching, and 12 month measurements being very similar to the initial measurements (Figure 3-2). As sites 1 and 2 were part of a contiguous mulch zone, perimeters were recorded for the combined zone. Maximum spread of the mulch zone at Waikaraka estuary was +8.2% for sites 1 and 2, combined, and +5.0% for site 3, with total change in mulch zone area at the end of the 12 month period of -5.6% at sites 1 and 2, combined, and -5.7% at site 3 (Table 3-1). Omokoroa and Waikareao estuaries both showed retraction of the mulch zone area, of -10.1% and -18.6%, respectively (Figure 3-3, Figure 3-4, Table 3-1). The Waikareao mulch zone edge was reasonably distinct, as were mulch boundaries at Te Puna and Waikaraka. In contrast, the Omokoroa edge was initially patchier, reflecting sparse mangrove coverage prior to mulching, particularly on the northern edge, resulting in sparse mulch coverage. We found it corresponding difficult to visually define the exact edge of this patchier boundary, and this was reflected in higher variability in our measured perimeter over the survey period.

	Area covered by mulch zone (m^2)				Proportion changed (%)		
Estuary	**Initial**	**Nov 2010**	**Mar 2011**	**Aug 2011**	**Nov 2010**	**Mar 2011**	**Aug 2011**
		~3 months	~6 months	~12 months	~3 months	~6 months	~12 months
Te Puna							
Site 1	31,788	30,824	32,289	28,582	-3.0	+1.6	-10.1
Site 2	23,592	20,448	ND	19,193*	-13.3	ND	-18.6*
Site 3	14,442	14,302	ND	ND	-1.0	ND	ND
Waikaraka							
Site 1 & 2	24,984	25,482	27,042	23,575	+2.0	+8.2	-5.6
Site 3	11,564	12,141	11,501	10,905	+5.0	-0.5	-5.7
Waikareao	16,046	14,749	13,415	13,057	-8.1	-16.4	-18.6
	Initial		**Sep 2010**	**Mar 2011**		**Sep 2010**	**Mar 2011**
Omokoroa			~6 months	~12 months		~6 months	~12 months
	73,210		61,895	65,805*		-15.5	-10.1*

Table 3-1: Proportional decrease in area of mulch zones at Te Puna, Waikaraka, Waikareao and Omokoroa estuaries. ND = no data collected. * = approximated based on incomplete map.

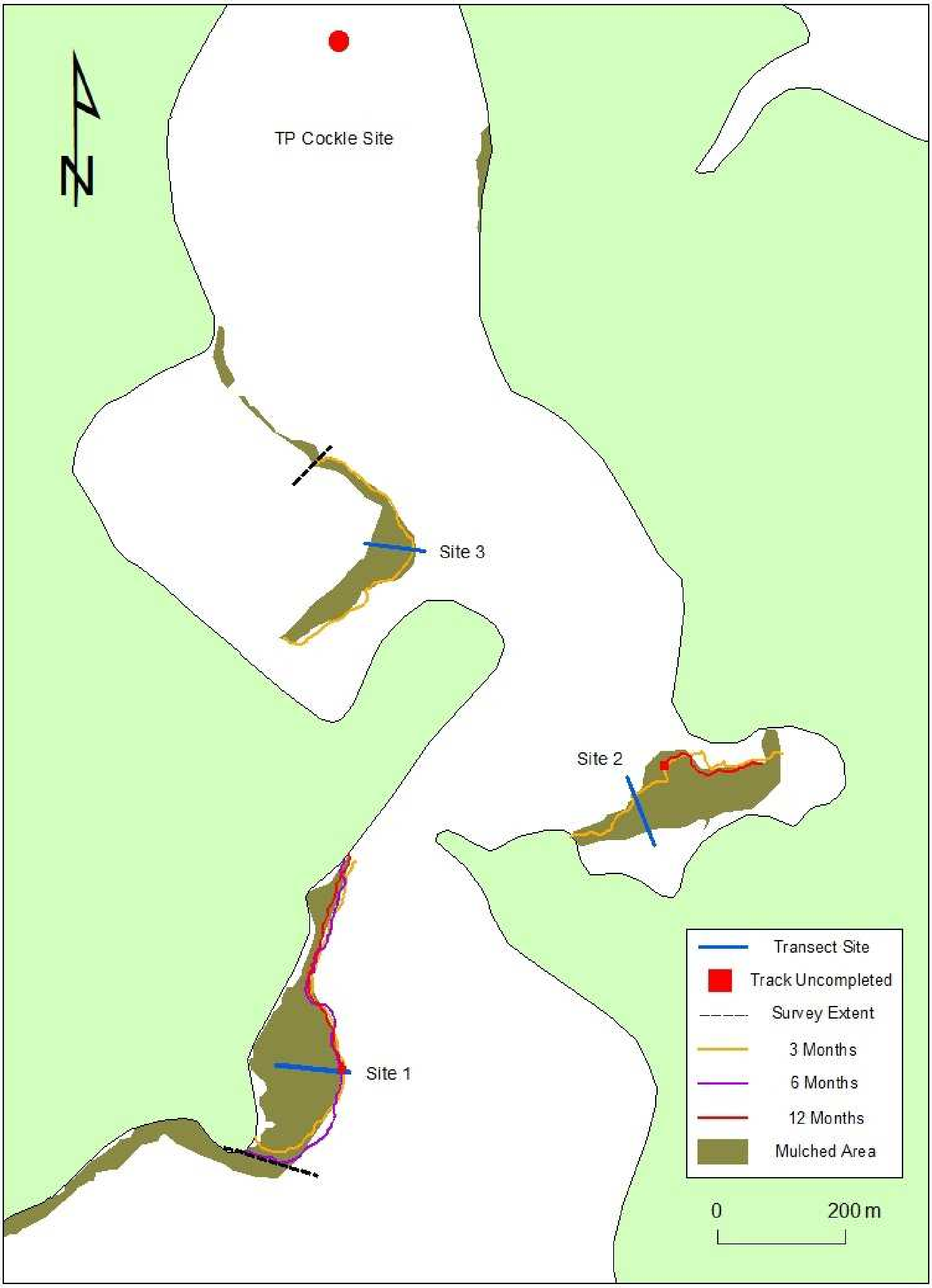

Figure 3-1: The extent of actual mangrove removal zone, and changing perimeter of the mulch zones over 12 months at Te Puna estuary. Te Puna was mulched from 1-28 July 2010, with sample perimeters measured approximately 3 months (November 2010), 6 months (February 2011), and 12 months (August 2011) after mulching.

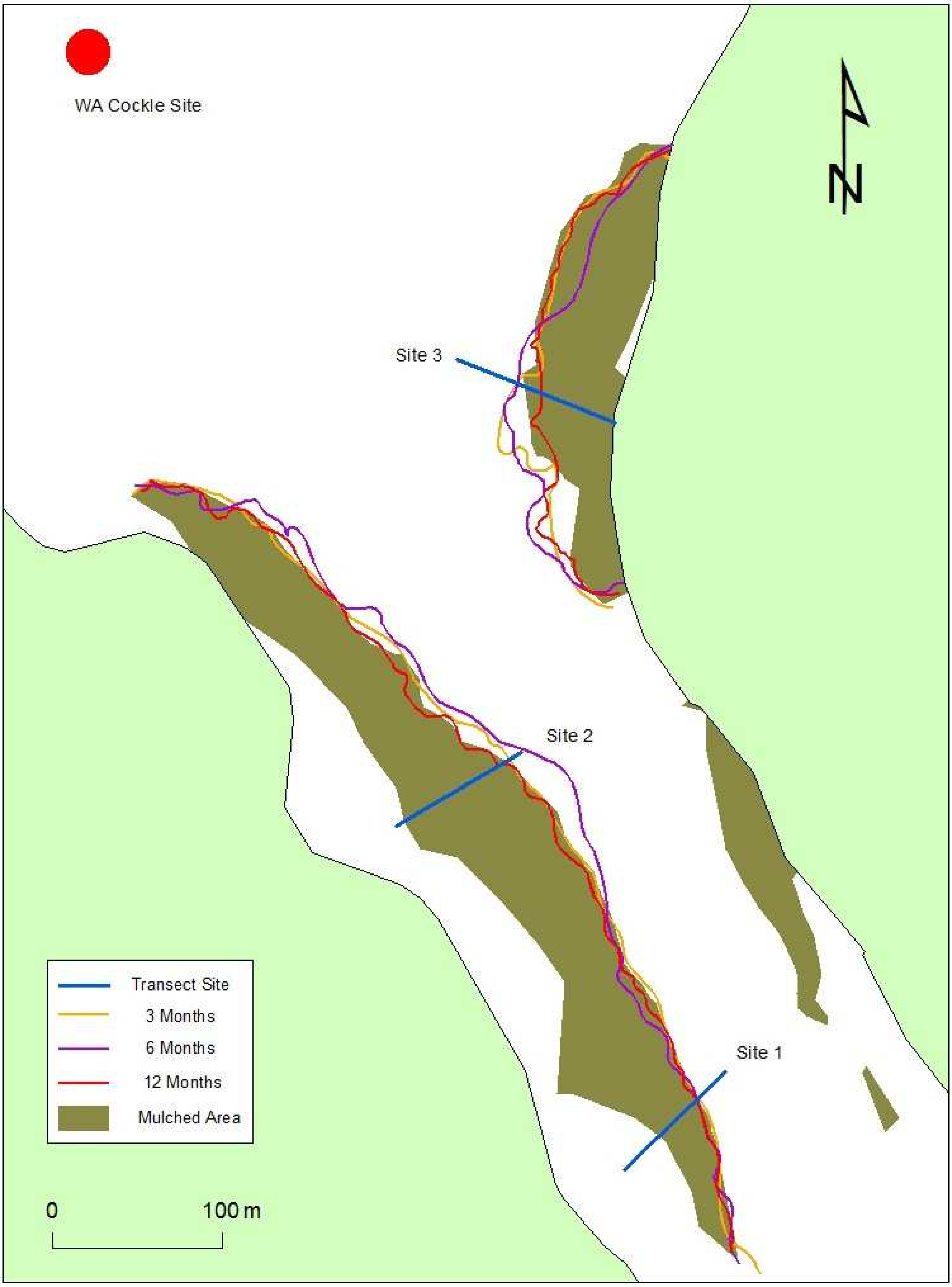

Figure 3-2: The extent of actual mangrove removal zone, and changing perimeter of the mulch zones over 12 months at Waikaraka estuary. Waikaraka was mulched from 29 July to 19 August 2010, with sample perimeters measured approximately 3 months (November 2010), 6 months (March 2011), and 12 months (August 2011) after mulching.

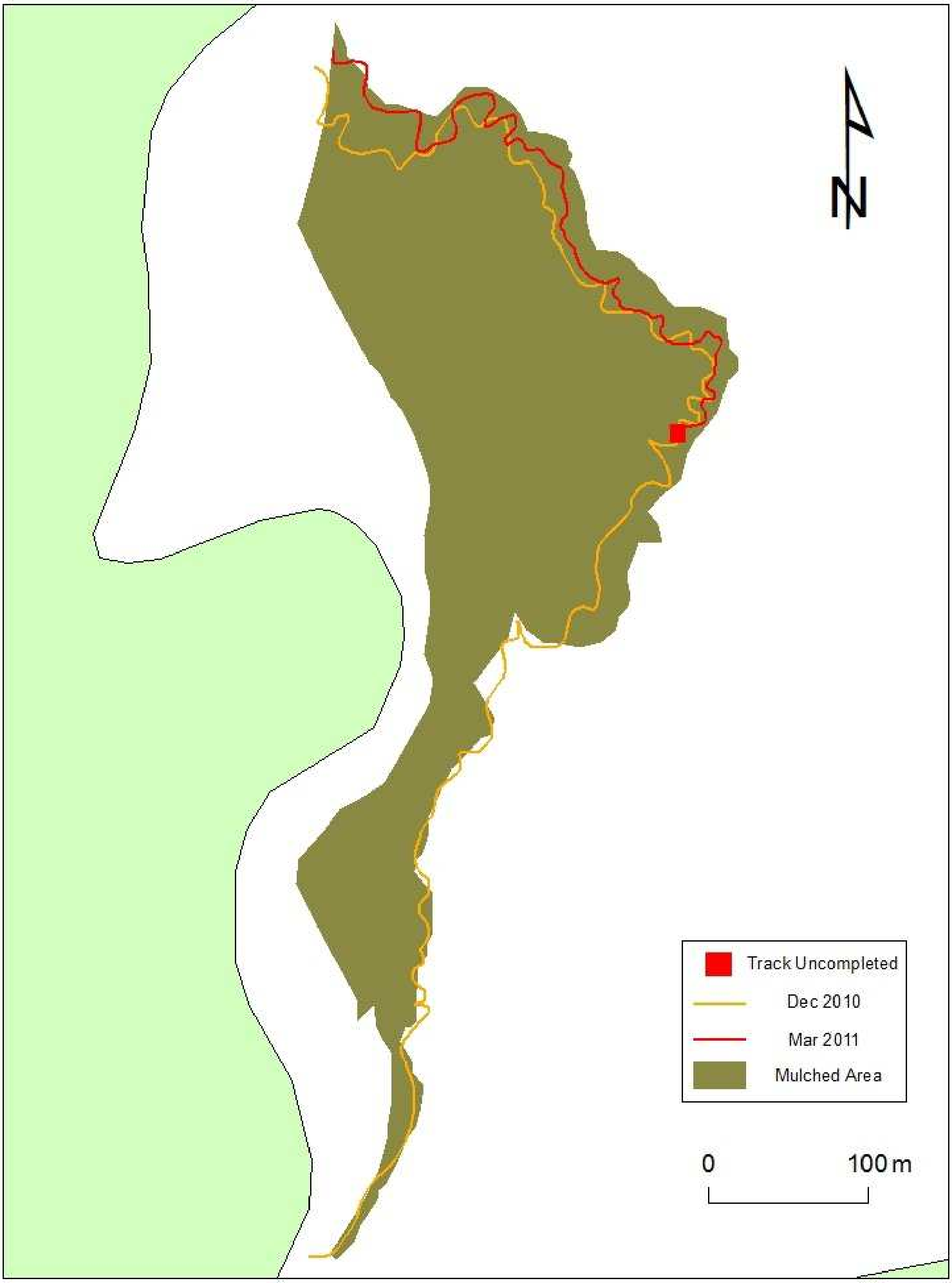

Figure 3-3: The extent of actual mangrove removal zone, and changing perimeter of the mulch zones at Omokoroa estuary. Omokoroa was mulched from 19 January to 18 February 2010, with sample perimeters measured in September 2010 and March 2011.

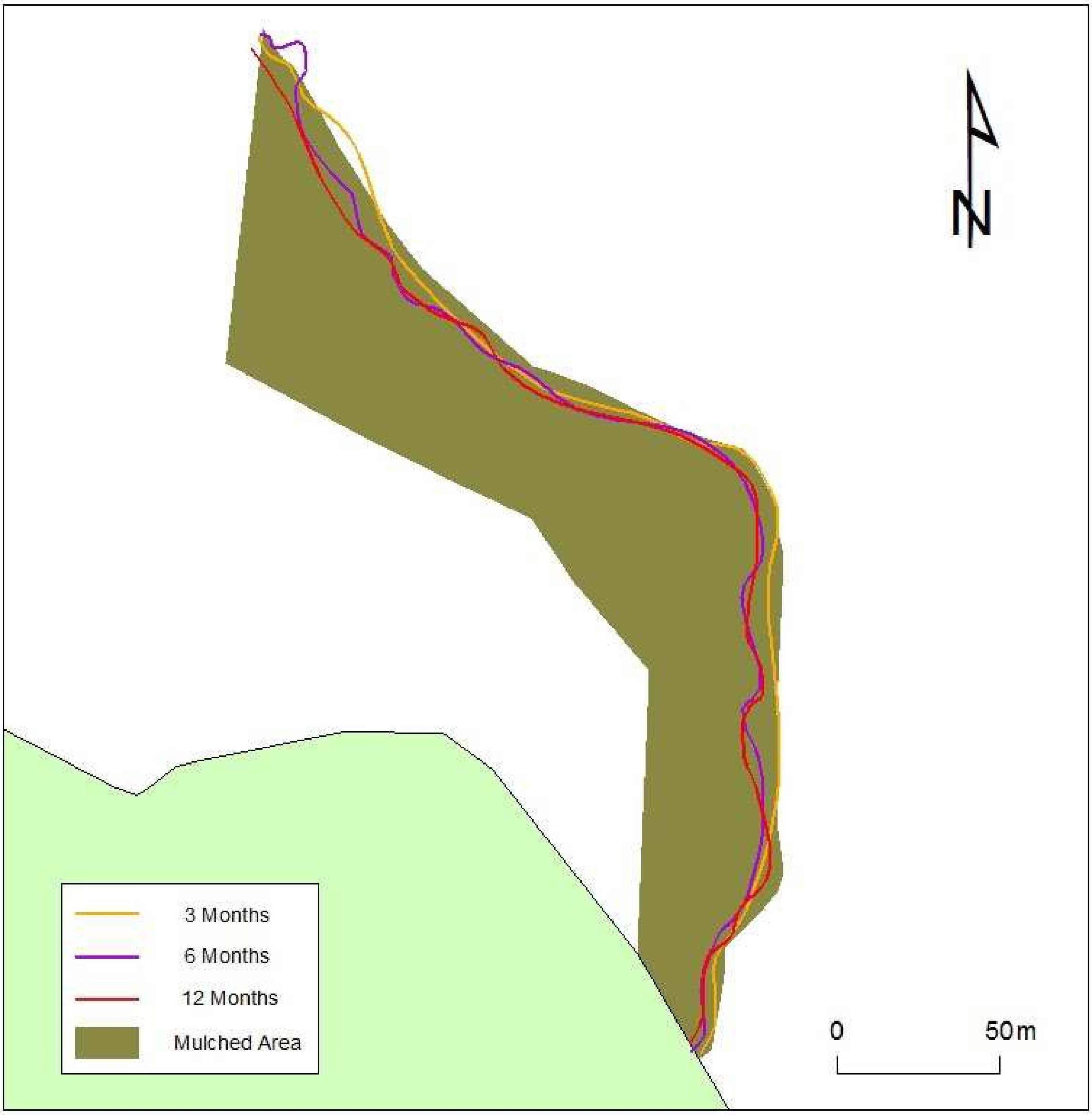

Figure 3-4: The extent of actual mangrove removal zone, and changing perimeter of the mulch zone over 52 weeks at one location in Waikareao estuary. This area in Waikareao was mulched from 23-31 August 2010, with sample perimeters measured approximately 3 months (November 2010), 6 months (March 2011), and 12 months (August 2011) after mulching.

3.2 Changes in epifauna and infauna, oxic depth, mulch depth, and mangrove colonisation

Measurements of the mean depth of the mulch layer also confirmed that mulch was still present over the 12 month survey period (Figure 3-5). At Te Puna, mulch depth decreased in depth at positions near the edge of the mulch zone from an average of approximately 40 mm to less than half that value. Smaller decreases in mulch depth were seen further from the edge of the mulch-sandflat zone at Te Puna, with depths of 30-40 mm remaining throughout the 12 month survey at mulch sites further inshore (Figure 3-5). Some mulch dispersal occurred shoreward into mangrove forests, but distance of dispersal of mulch into the mangrove forest was limited to the first 10 m (Figure 3-5). The pattern was similar at Waikaraka with slightly higher depths of mulch initially of 60-80 mm, decreasing to depths of 20-60 mm over 12 months (Figure 3-5). A similar pattern of decreasing depth near the edge of the sandflat-mulch zone was also observed at Waikaraka (Figure 3-5).

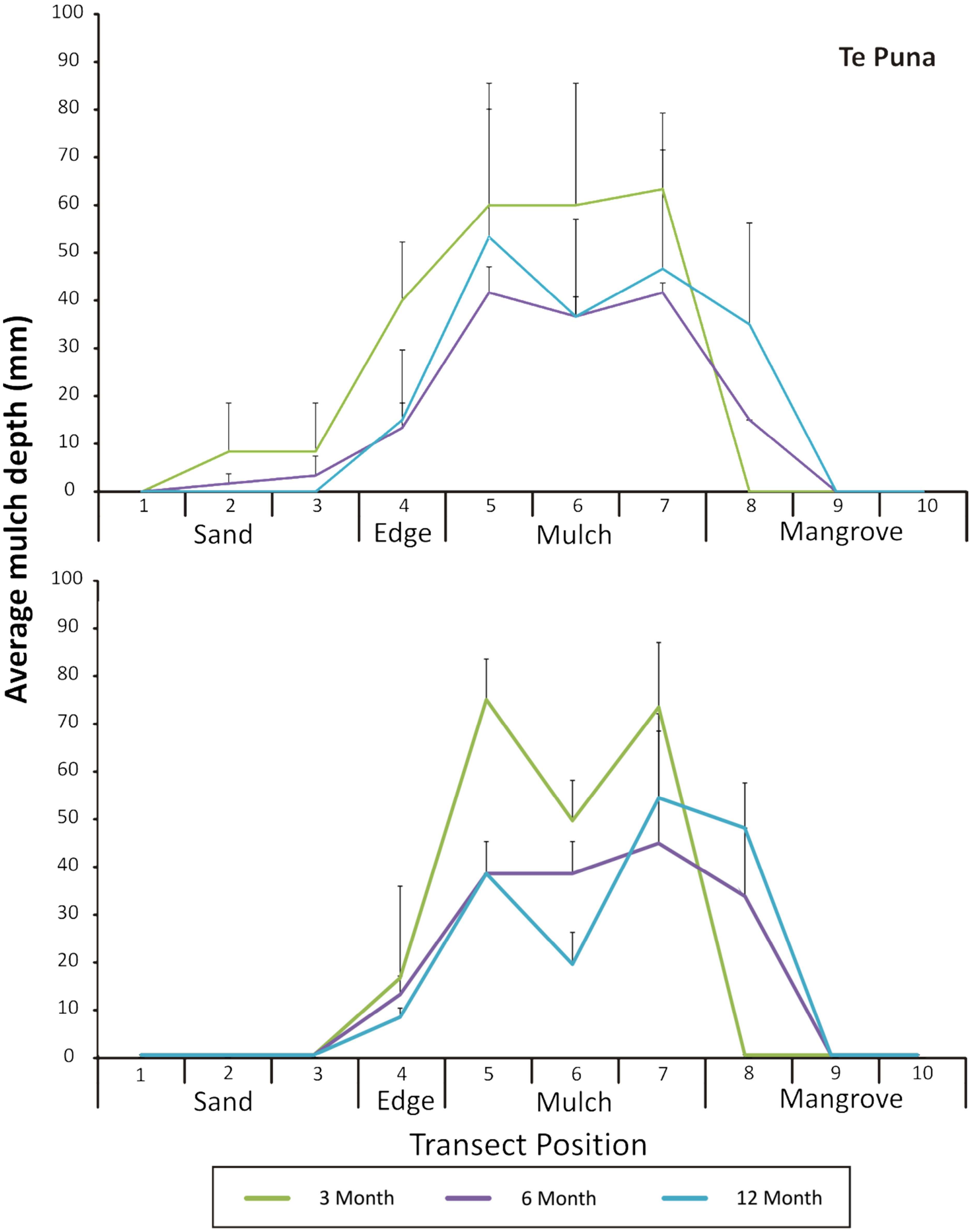

Figure 3-5: The mean depth (+SE) of the mulch layer (mm) sampled at Te Puna and Waikaraka estuaries, prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect position and habitat zones are denoted on the x axis.

Anoxia in mulch sediment was still apparent after 12 months, with initial oxic layers of < 1 mm being common within the mulch zone (Figure 3-6). While oxic depth was not measured in surveys prior to mulching, it is assumed that oxic depth would be similar to sandflat and mangrove measurements during the remainder of the 12 month survey. There was little change at both Waikaraka and Te Puna in depth of oxic layer in the mulch zone over 12 months, except at the sampling location located at the edge of the sandflat-mulch zone. Sediment anoxia was primarily limited to the mulch zone, with minimal impacts on sediment oxic zones in neighbouring sandflat and mangrove habitats which generally had 10-20 mm oxic depths (Figure 3-6). At most survey sites, the anoxic zone was immediately observed upon entering the mulch zone (within 1-2 m from the edge of mulch zone), though a few locations did show some recovery of oxic depth (e.g., to ~5 mm) within 10 m of the edge of the mulch zone over the 12 month survey period.

Occasionally, patches of sediment with higher oxic depths were observed within the mulch zone. Most often this was near the edge of mangroves where apparent sediment deposition zones have been created, but occasionally these sediment deposition zones occurred further shoreward within the mulch zone. It is unclear whether these sediments (usually deposited over mulch material) were a result of the sediment trapping ability of remaining mangrove biomass (primarily the mulch itself, but also remaining pneumatophores), or due to compaction from tractors resulting in lower relative height in some areas.

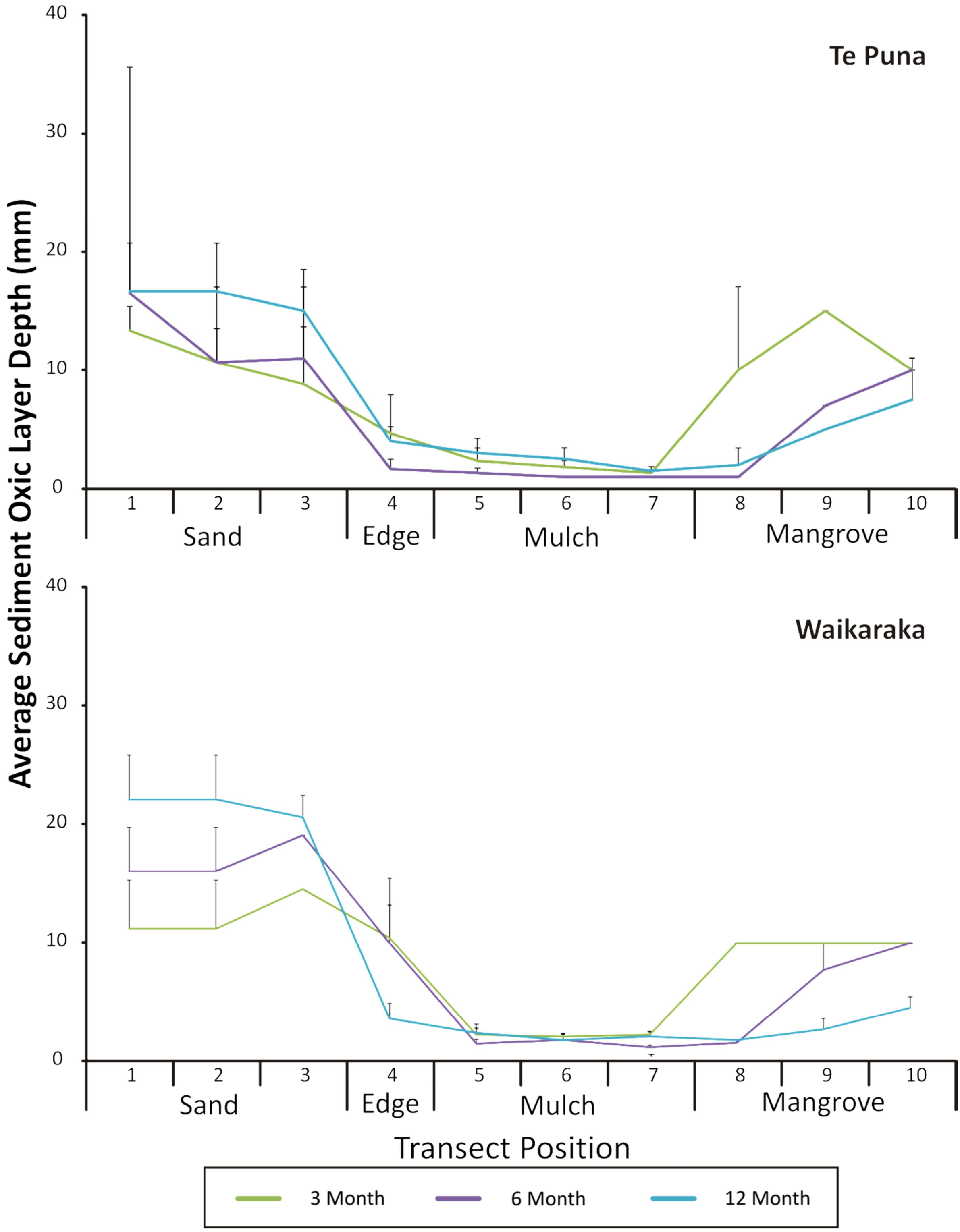

Figure 3-6: The mean depth (+SE) of the oxic layer (mm) sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

Crab burrows showed a pattern of generally high abundance at the edge of the mulch zone, and lower abundance within the centre of the mulch zone (Figure 3-7). Occasional high numbers of crab burrows were observed in neighbouring sandflat and at the edge of the mangrove zone at both sites during at least one sampling period. Highest numbers of crab burrows were observed in neighbouring sandflat habitats at all sites at the 12 month sampling time, with mean abundance of crab burrows at most positions being double that of baseline pre-mulch abundance. A large increase in burrows at the edge of the mulch-mangrove zone was also observed at 6 months at Te Puna.

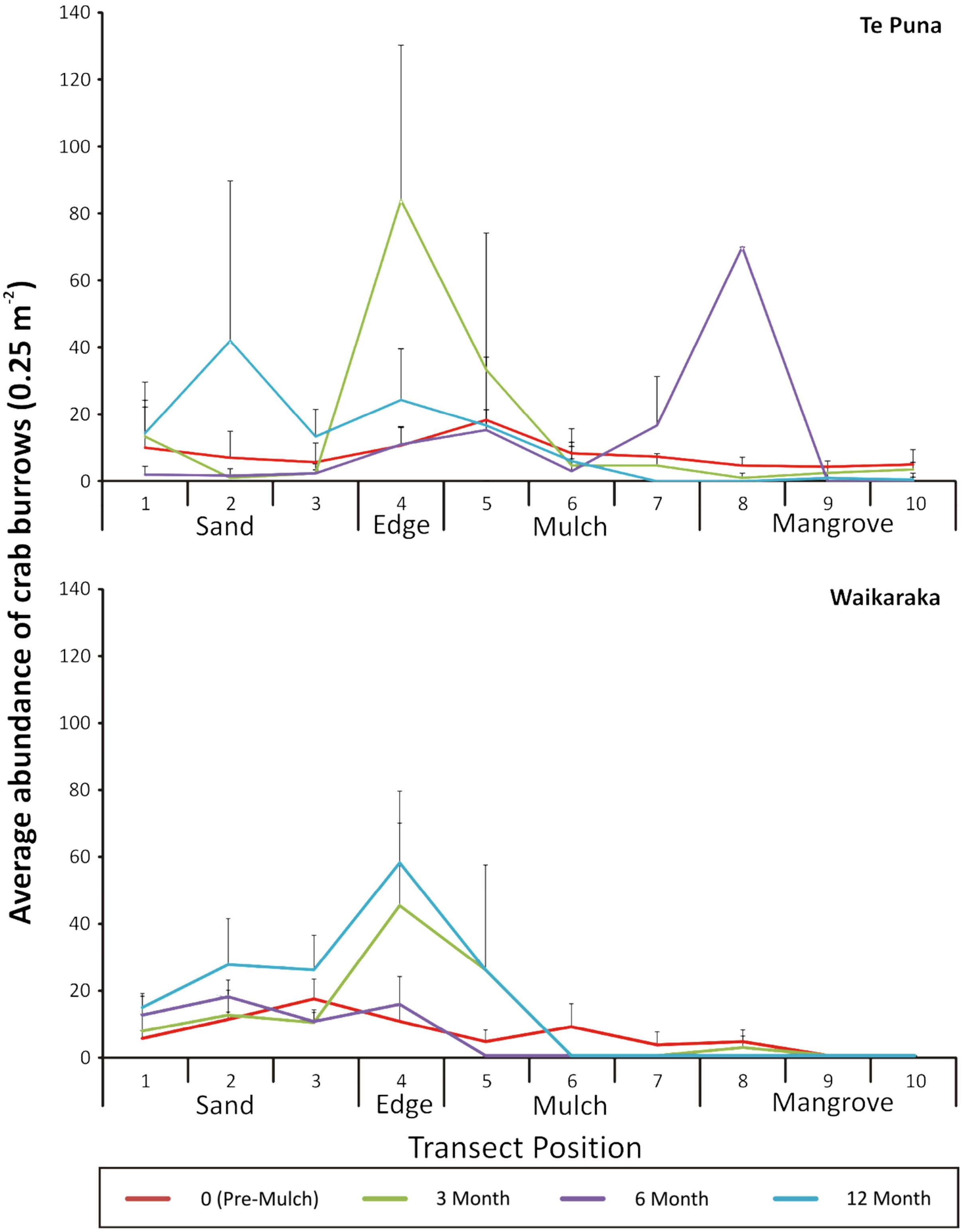

Figure 3-7: The mean abundance (+SE) of crab burrows sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

The abundance of gastropods and other epifauna (anemones, barnacles, oysters) in the mulch zone was lower than in neighbouring sandflat habitats (Figure 3-8). Biomass of epifauna in mangrove habitats was lowest of the three habitat zones, though these epifaunal counts did not include the small freshwater gastropod *Potamopurgus estuarinus* which was often present in large numbers in mangrove habitats. Abundance of *Potamopurgus estuarinus* was not included in visual counts of epifauna due to their small size making visual observations difficult, and temporal and spatial variability in abundance of this species were more accurately documented in macrofaunal core samples. The primary gastropod species observed in all habitat types was *Zeacumantus lutulentus*; other less abundant species included *Cominella glandiformis*, *Diloma subrostrata* and *Amphibola crenata* (mainly found in the mangroves and occasionally in the mulch zone). The sandflat zone had the highest abundance of epifaunal gastropods in both estuaries. Similar spatial patterns were observed in the mulch zone, with highest epifaunal abundance generally found near the sandflat-mulch edge, and decreased abundance at other mulch zone locations. At Te Puna, low numbers in the mulch zone (average of all 3 sites) continued throughout the sampling survey period (Figure 3-8), with the exception of a transect position 6 in the 3 month survey. Mean epifaunal abundance in mulch zones at Waikaraka also showed minimal recovery of epifauna to abundance levels at neighbouring sandflat habitats, with the exception of a transect position 6 in the 12 month survey (Figure 3-8).

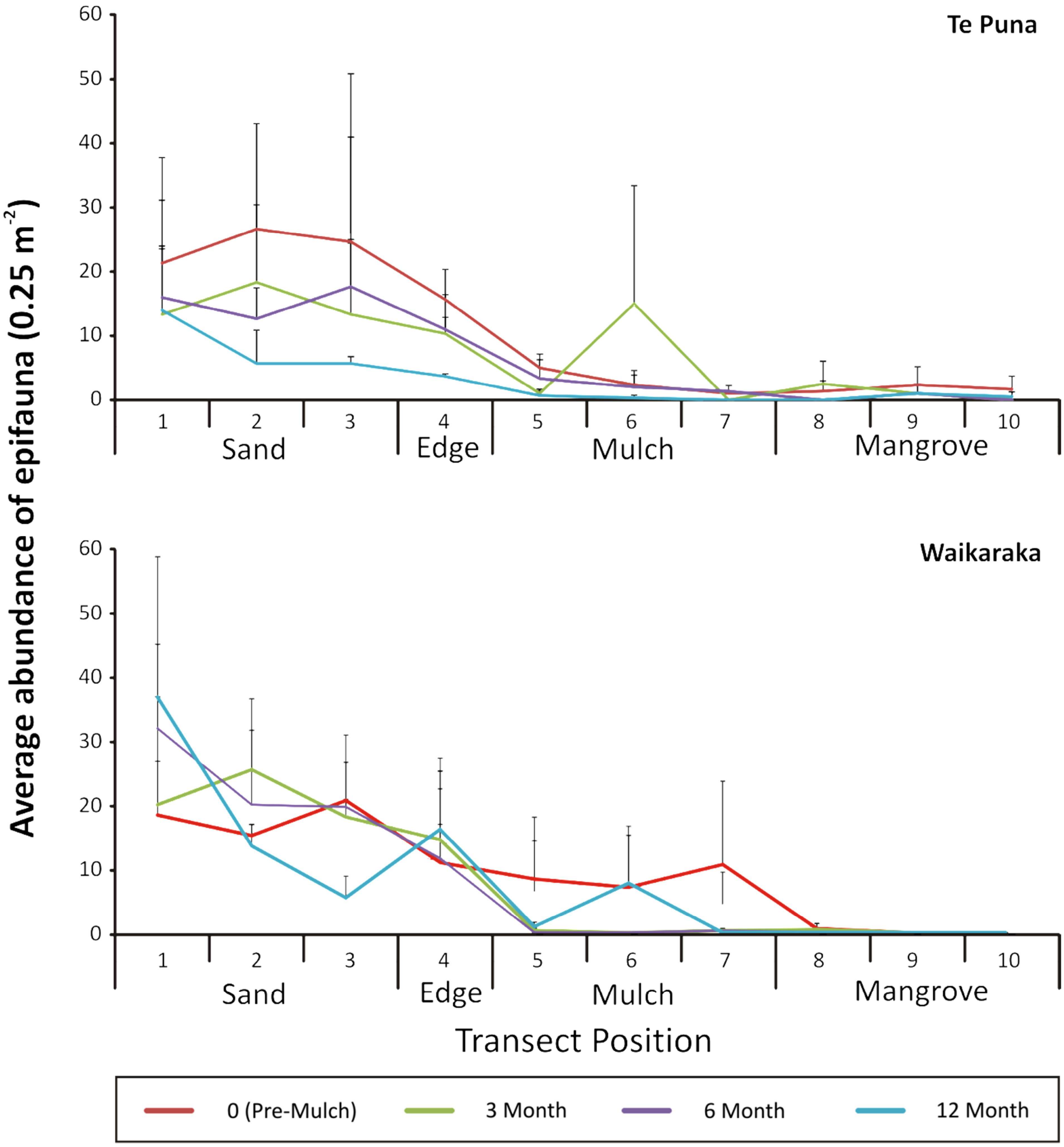

Figure 3-8: The mean abundance (+SE) of epifauna (excluding the gastropod *Potamopyrgus estuarinus*), sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

During pre-mulching surveys, bivalves were found primarily in the sandflat zone, with bivalves rarely found in quadrats in the mangrove zone (Figure 3-9). No bivalves (> 5 mm) were found in the mulch zone during the 12 months of post-mulch surveying. Bivalve species detected in quadrat surveys included primarily *Austrovenus stutchburyi* and *Macomona liliana*. Abundance of *A. stutchburyi* was about 4 times higher at Te Puna than at Waikaraka.

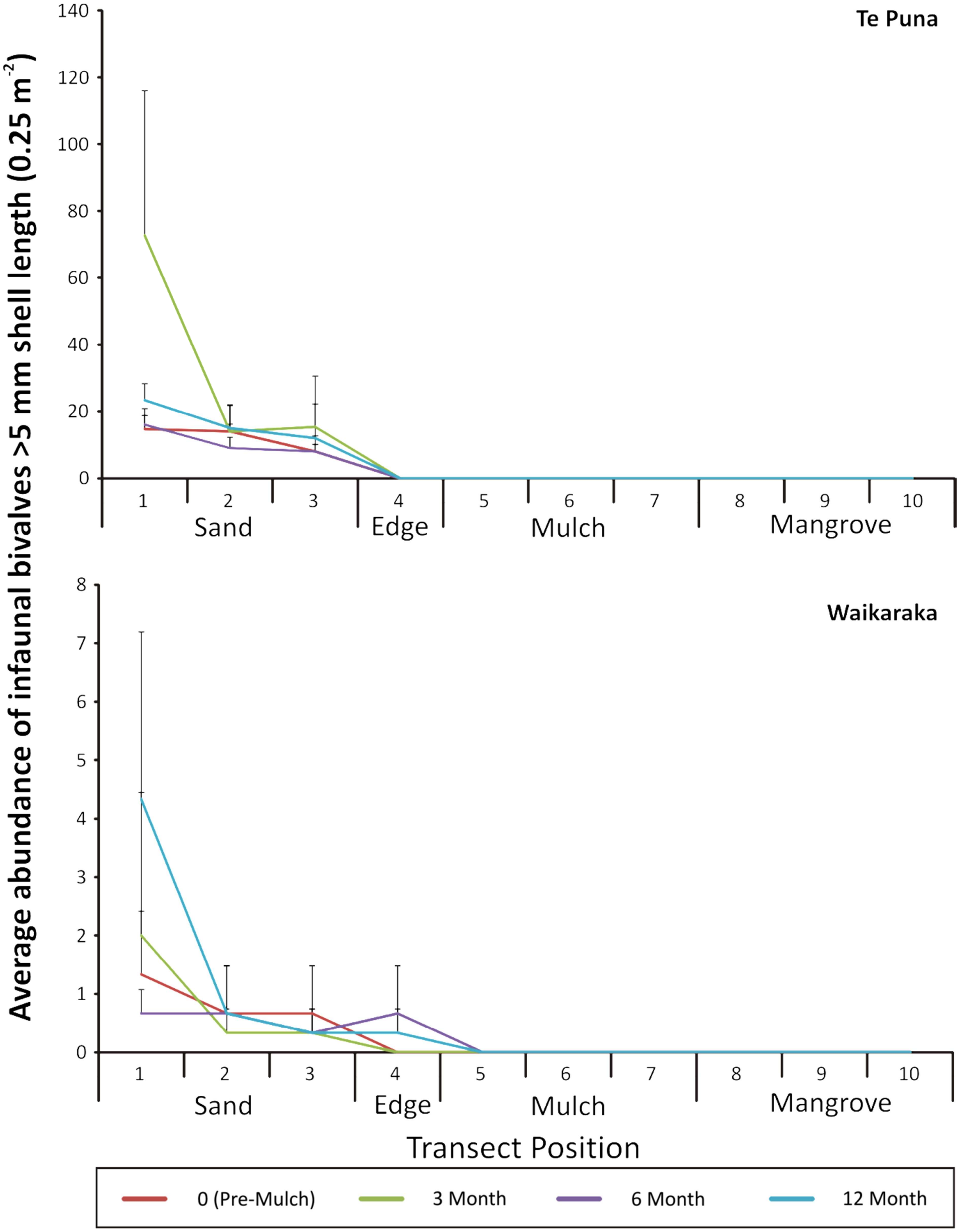

Figure 3-9: The mean abundance (+SE) of infaunal bivalves sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

Mangrove seeds and seedlings were common throughout mangrove habitats including the mulched area in the baseline survey (Figure 3-10). After mulching, seeds and seedlings were rare in the mulched area and adjacent sandflat during the 12 month survey period. Seeds and seedlings were rarely seen colonising the survey sites outside the remaining mangrove zone in the post-mulch surveys, with mean of < 1 seed or seedling observed at all transects in each estuary, whereas seedling abundance was ranged between 2-4 mangrove colonists per 0.25 m^2 quadrat at Te Puna, and 2-8 mangrove colonists per 0.25 m^2 at Waikaraka during the baseline survey prior to mangrove mulching (Figure 3-10).

Mangrove tree height and diameter showed no apparent changes at each site over the survey period, though mean tree height did vary between sites within estuaries (Table 3-2). No decreases were observed in density within the larger mangrove forest during the sampling period. However, we did see some die off of mangrove trees directly adjacent to the mulch area at some locations (e.g., Site 3 at Waikaraka, Waikareao). It is unclear whether this die off was related to mechanical impacts of the mulching mangrove (e.g., crushing below ground biomass of edge trees), or if it was related to sediment or water column conditions associated with the lack of dispersal of mulch biomass, or due to unrelated natural events.

		Height (cm)	Diameter (mm)	Density (number of trees > 20 cm per 20 m^2)
Te Puna	Site 1	115.0 (9.1)	36.2 (3.9)	23.7 (12.7)
	Site 2	122.3 (6.1)	43.2 (3.4)	12.0 (4.4)
	Site 3	68.4 (3.6)	34.1 (1.8)	19.0 (4.4)
Waikaraka	Site 1	113.0 (7.0)	40.8 (2.1)	20.3 (5.4)
	Site 2	87.7 (5.5)	30.5 (1.8)	24.3 (7.2)
	Site 3	93.2 (12.7)	44.1 (4.5)	10.5 (2.1)

Table 3-2: Average mangrove height and trunk diameter (cm) and density (SE).

Pneumatophores (visible at the sediment surface) showed minimal decrease in abundance throughout the sampling period (Figure 3-11). At 12 months post-mulching, relatively intact pneumatophores were still visible in high abundance at all mulched sites.

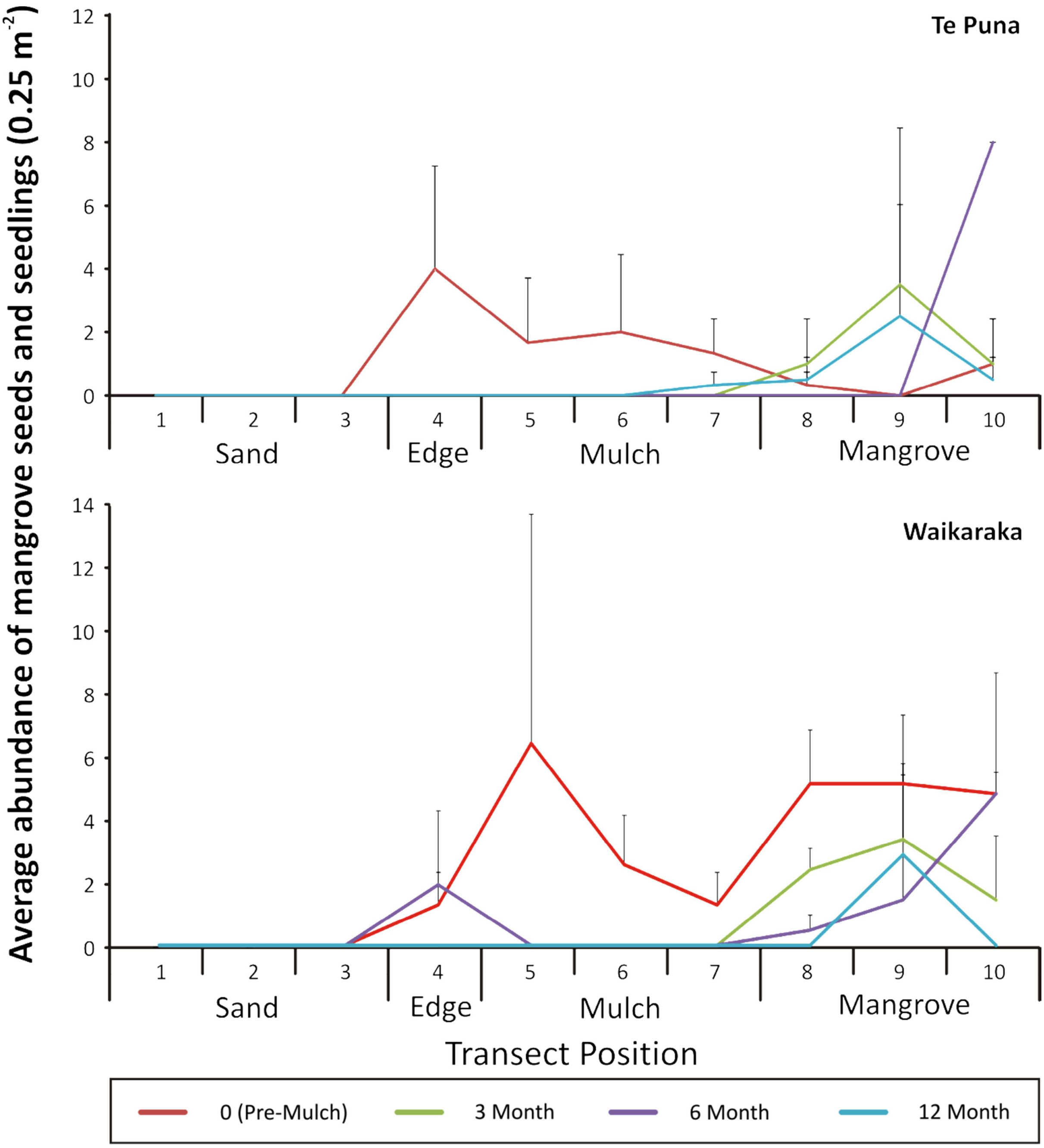

Figure 3-10:The mean abundance of mangrove seeds and seedlings (combined) (+SE), sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

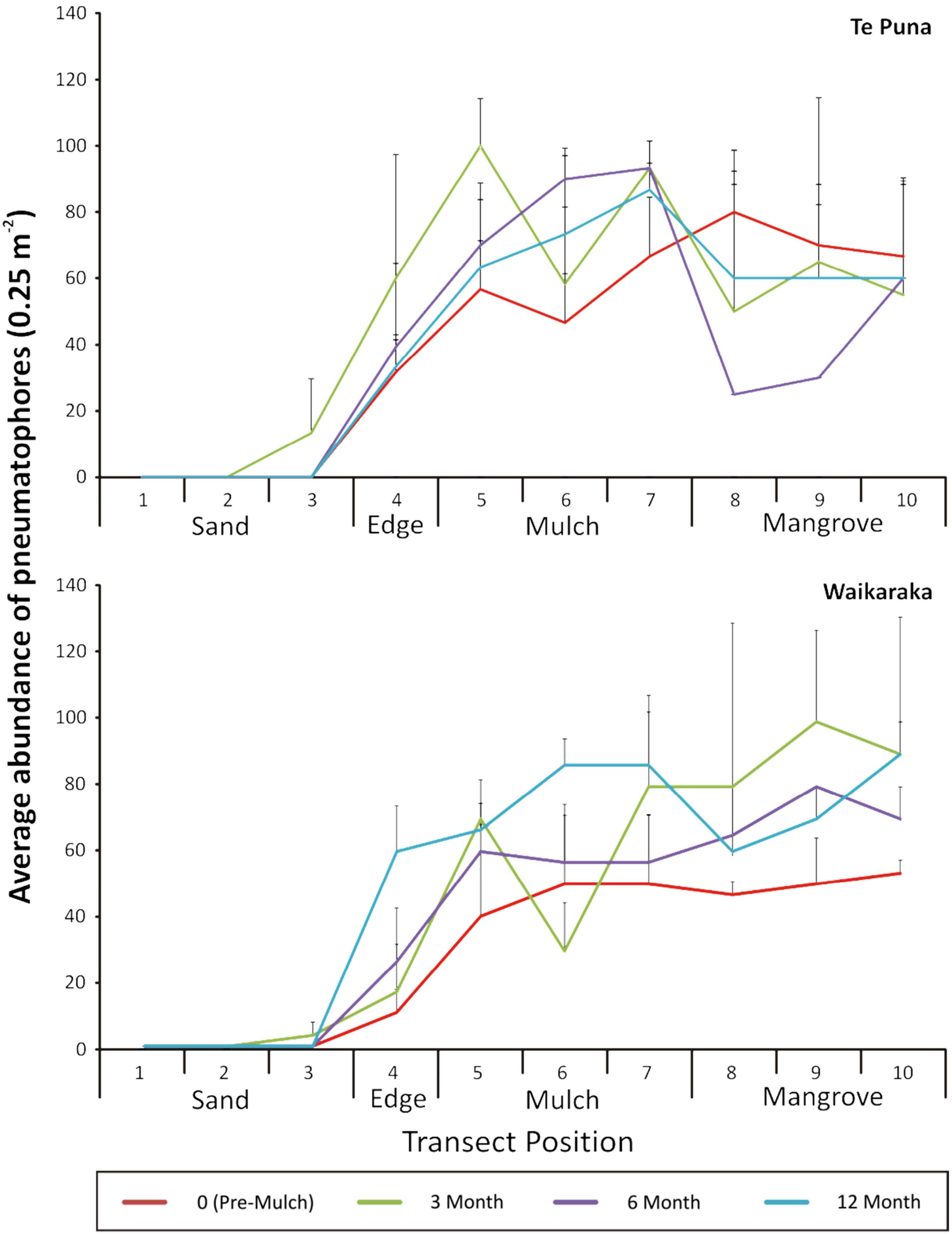

Figure 3-11:The mean abundance of pneumatophores (protruding at or above the sediment surface) (+SE), sampled at Te Puna and Waikaraka estuaries prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching. Transect number and habitat zones are denoted on the x axis.

Other sediment variables measured showed differences between all habitats, with sediment shear strength being largest in sandflat zones, and lowest in the mangrove zone, and mulch zone values usually lying in the middle of the range (Table 3-3). No apparent changes in sediment shear strength were detected over the 12 month survey.

Sediment compressibility measurements using a penetrometer showed highest measurements in sandflat zones, lower values in sandflat-mulch edge zones, and similar low values in both mulch and mangrove zones (Table 3-4). No apparent changes in sediment compressibility were detected over the sampling period in each zone.

		Sand	Edge	Mulch	Mangroves
Te Puna	Site 1	2.57 (0.27)	1.23 (0.23)	1.54 (0.28)	0.50 (0.19)
	Site 2	1.40 (0.25)	1.60 (0.15)	1.31 (0.31)	0.27 (0.12)
	Site 3	1.38 (0.11)	1.33 (0.18)	1.36 (0.25)	1.31 (0.15)
Waikaraka	Site 1	2.40 (0.26)	1.38 (0.25)	1.13 (0.13)	0.70 (0.08)
	Site 2	2.25 (0.21)	1.87 (0.19)	1.11 (0.23)	0.63 (0.15)
	Site 3	1.91 (0.26)	1.73 (0.20)	1.25 (0.24)	0.33 (0.10)

Table 3-3: Average sediment shear strength (kg cm^{-3}) (SE). Values are means of 3 replicates per survey time in each habitat zone at each sampling site.

		Sand	Edge	Mulch	Mangroves
Te Puna	Site 1	0.13 (0.01)	0.04 (0.02)	0.03 (0.01)	0.03 (0.01)
	Site 2	0.05 (0.01)	0.02 (0.01)	0.01 (0.01)	0.01 (0.00)
	Site 3	0.08 (0.01)	0.02 (0.01)	0.03 (0.01)	0.04 (0.01)
Waikaraka	Site 1	0.14 (0.01)	0.02 (0.01)	0.03 (0.01)	0.00 (0.00)
	Site 2	0.15 (0.01)	0.04 (0.01)	0.02 (0.01)	0.01 (0.00)
	Site 3	0.09 (0.01)	0.08 (0.01)	0.02 (0.01)	0.01 (0.01)

Table 3-4: Average sediment compression strength (kg cm^{-3}) (SE). Values are means of 3 replicates per survey time in each habitat zone at each sampling site.

3.3 Benthic macrofaunal communities

3.3.1 Number of individuals, number of species, Shannon-Weiner diversity

Benthic macrofaunal cores were sampled and all taxa identified to determine patterns in the number of individuals, taxa, and species richness, comparing baseline samples to those at 3, 6 and 12 months post-mulching. Patterns for individual species or taxonomic groups were also identified. At Te Puna, number of individuals, number of taxa, and Shannon-Weiner species diversity showed similar values between sites, and between sampling times in the sandflat zones (Figure 3-12, Figure 3-13, Figure 3-14). Waikaraka showed a slight increasing trend in number of individuals and number of taxa with sampling time, but similar Shannon-Weiner diversity metrics across sites and times (Figure 3-12, Figure 3-13, Figure 3-14).

Mangrove zones had generally similar number of individuals at Te Puna, with a slightly larger value for site 3 at 12 months post-mulching (Figure 3-12). Number of individuals in mangrove zones at Waikaraka showed high variability at site 3, and an increasing trend at sites 1 and 2, with high numbers at 6 and 12 months post-mulching (Figure 3-12). Numbers of individuals in undisturbed sandflat and mangrove habitats were of the same order of magnitude (Figure 3-12), often due to the large number of *Potamopyrgus estuarinus*. Number of species and Shannon-Weiner diversity was generally higher in sandflat compared to mangrove habitat zones, though there was high variability in values for both indices between sites and between sampling times, and some overlap in range of both values between zones (Figure 3-13, Figure 3-14).

The mulch zone was generally more similar to the mangrove zone in numbers of individuals, though high variability and apparent pulses of recruitment occurred at some sites at some but not all sampling times (e.g, Te Puna Site 1 at 12 weeks, Te Puna Site 2 at 6 months, Waikaraka sites 2 and 3 at 6 months) (Figure 3-12). Mean number of individuals was the same or lower at all mulch zones in both estuaries at 12 months compared to 6 months (Figure 3-12). Mean number of species at mulch sites showed at increasing trend at all sites in both estuaries, with numbers at 12 months being similar to that of mangrove habitats, and less than that found in adjacent sandflat zones (Figure 3-13). Shannon-Weiner diversity also showed increasing trends at mangrove sites, though variability in this metric between sites and sampling times was higher at Waikaraka sites than at Te Puna sites (Figure 3-14).

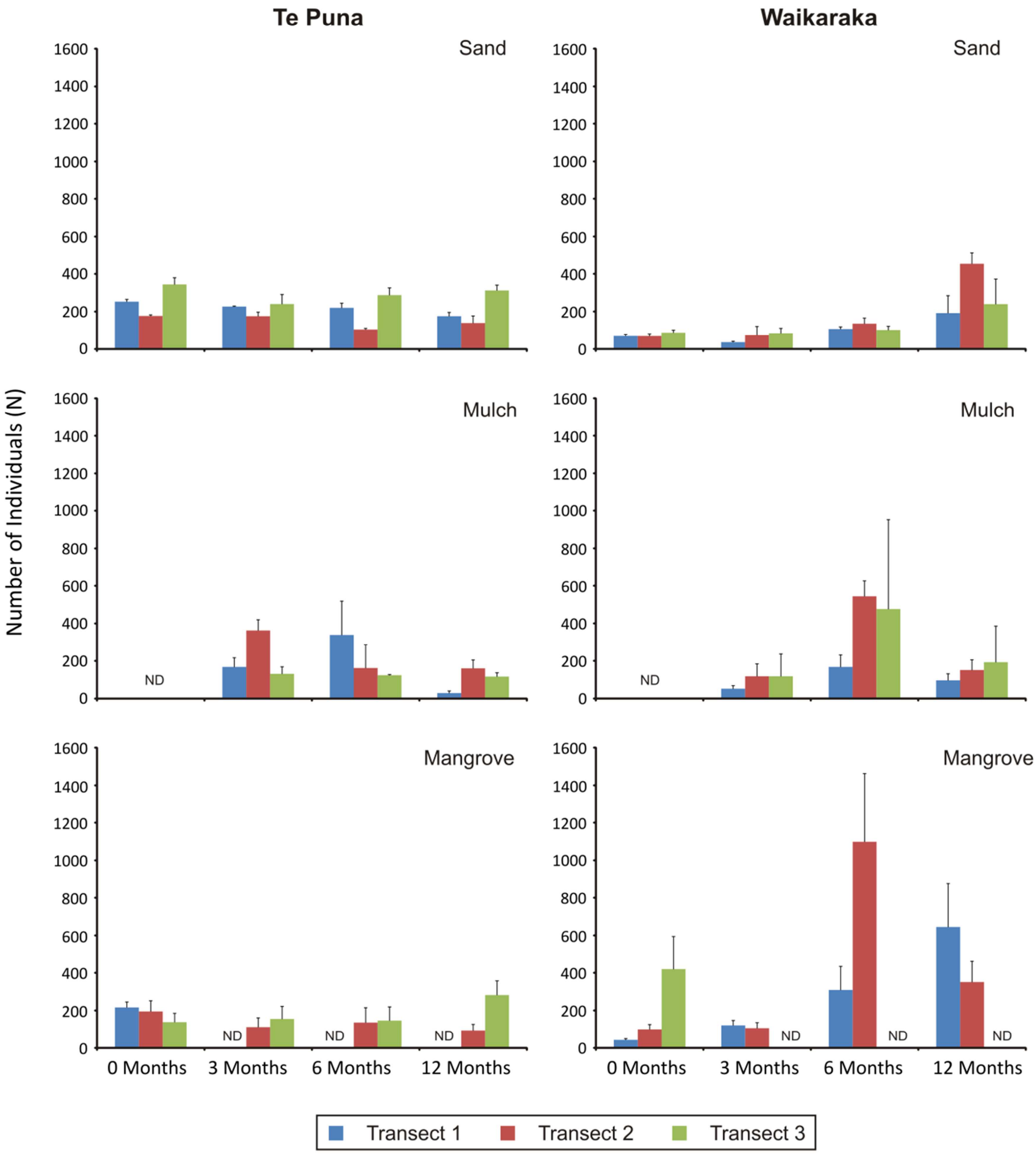

Figure 3-12: Total number of individuals in each habitat zone prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching, +SE. Numbers are given as the mean of three replicate cores (ND=no data collected).

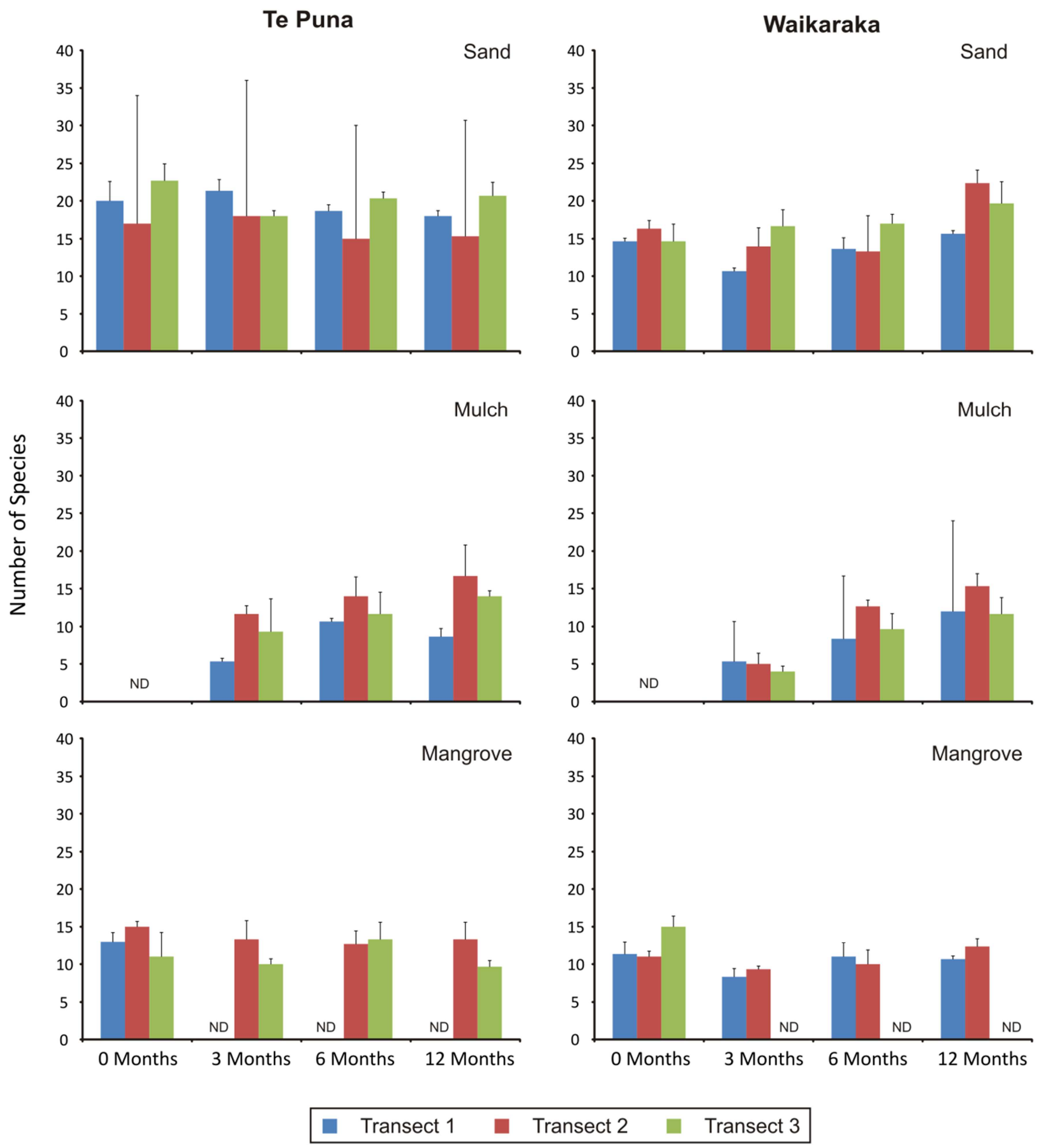

Figure 3-13: Total number of species in each habitat zone prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching, +SE. Numbers are given as the mean of three replicate cores (ND=no data collected).

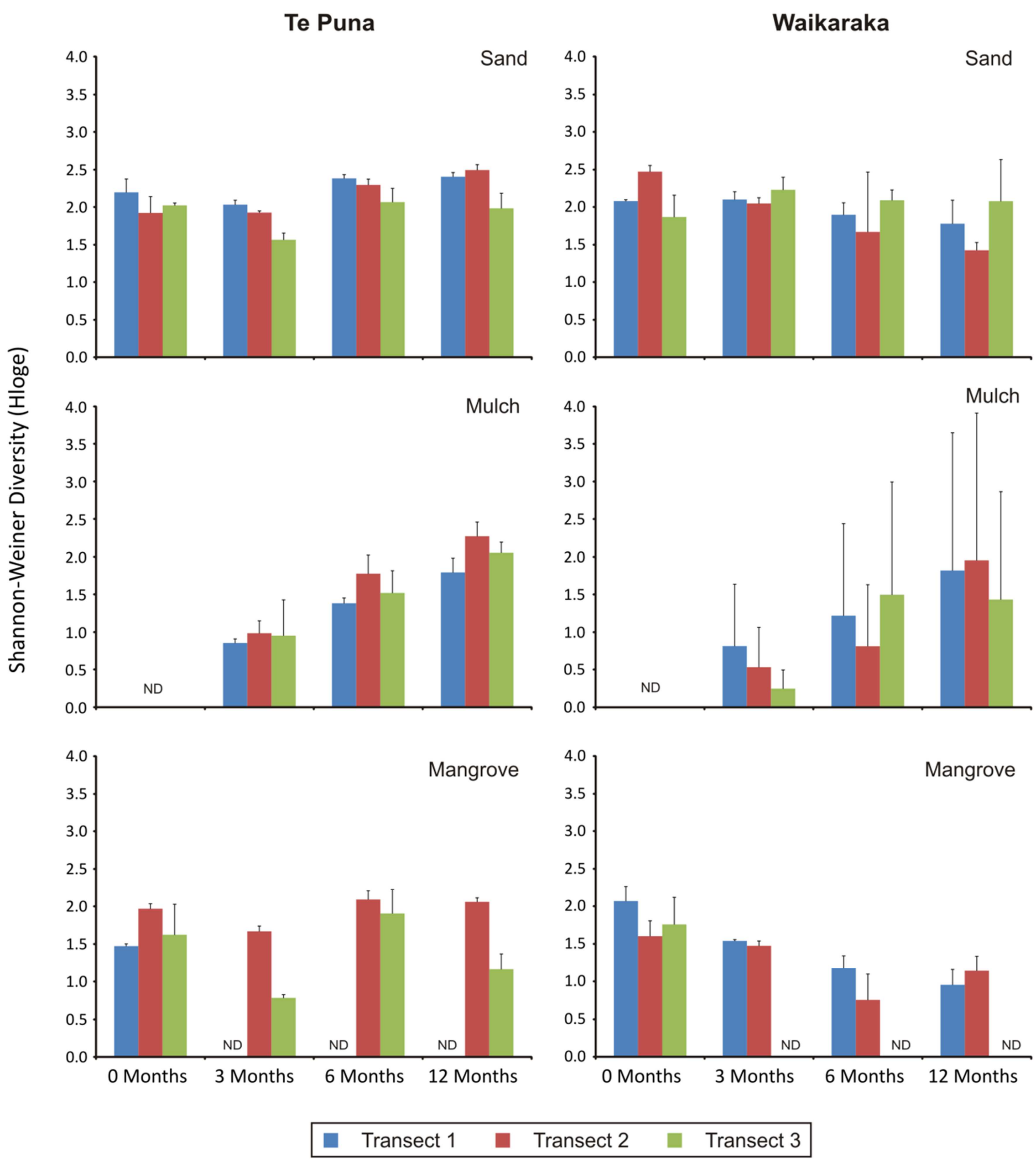

Figure 3-14: Shannon-Weiner Diversity in each habitat zone prior to mulching, and at approximately 3 months, 6 months and 12 months post mulching, +SE. Numbers are calculated based on the mean of three replicate cores (ND=no data collected).

3.3.2 Multivariate analyses of community structure

While univariate statistics of number of individuals, number of species, and Shannon-Weiner diversity indicate similarities between the sandflat, mangrove and mulch zones, as well as an increasing trend in the mulch zone, patterns shown by individual taxa and using multivariate statistics suggest broad separation of the three habitat zones, and do not imply that the mulch zones are trending toward either the sandflat or mangrove communities over time.

Multivariate analyses, based on abundance of individual macrofaunal species found at each site, showed high similarity between transects in sandflat zones within an estuary over all sampling times (Figure 3-15). Sandflat samples were tightly clumped for both Te Puna and Waikaraka (Figure 3-15), with no indication of change over time in sandflat community structure, and similarity across all three sandflat sites.

Mangrove samples showed very loose clustering of communities across both time and sites within each estuary, and clear dissimilarities with communities found in sand and mulch zones (Figure 3-15). Over time, the communities sampled at Te Puna mangrove site 2 were more similar to those sampled at Te Puna mangrove site 3, though the site 3 community appears to be shifting further from the mangrove cluster over time (Figure 3-15). The mangrove sites in Waikaraka estuary were loosely clustered, with some overlap with mulch sites but minimal overlap with sandflat zones (Figure 3-15).

We opportunistically sampled a 'manual' removal location at Waikaraka site 3, showing that these samples (anecdotally suggested by community group to be cleared 1-2 years prior to the mulching inshore of this site) generally clustered near the sandflat sites in Waikaraka estuary, with clustering near sandflat samples at 3 and 12 months, and within the loose mangrove site cluster at 0 and 6 months (Figure 3-15).

Mulch sites, in contrast, did not cluster with either sandflat or mangrove sites. At Te Puna, 3 month samples were tightly clumped, but distinct from other habitat zones. At 6 months, the mulch sites show more divergence between sites, and dissimilarity between sites increased further at 12 months, with sites 2 and 3 trending in similarity toward mangrove sites, and site 1 becoming more dissimilar from all sites (Figure 3-15). Waikaraka mulch sites also did not cluster with either sandflat or mangrove sites. Temporal clustering was strong, with communities sampled in mulch at 3 and 6 months having low dissimilarity, and both times clustering distinctly from mangrove or sandflat community clusters (Figure 3-15). 12 month community samples trended toward further dissimilarity from 3 and 6 month mulch samples, and also from sandflat samples, though the three mulch sites showed similarity in communities at 12 months (Figure 3-15).

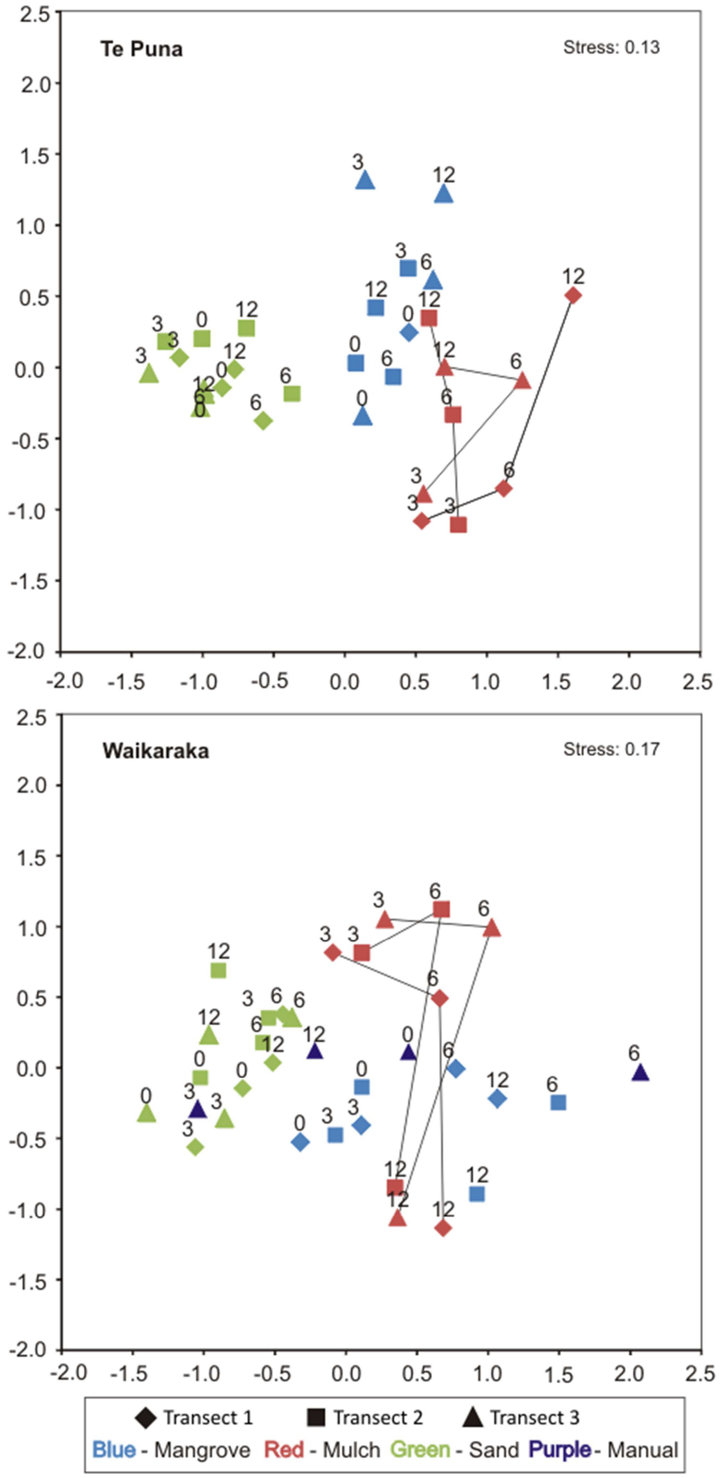

Figure 3-15:Multivariate analysis (MDS) of macrofaunal community structure at Te Puna and Waikaraka estuaries, prior to mulching, and at 3 months, 6 months and 12 months post mulching, in sandflat, mulch and mangrove habitat zones, and in opportunistically sampled manual clearing area.

The top ranked species found in each habitat zone explained much of the differences between zones in the multivariate analyses. Top ranked species combined over all Te Puna sandflat sites, and for all sample times, included three polychaetes, an oligochaete and a bivalve. Waikaraka sandflat sites included two other polychaete species, the same oligochaete, a gastropod, and a corophid amphipod (Table 3-5). These five species explained 74% and 62% of the similarity within each sandflat zone at Te Puna and Waikaraka, respectively. Mangrove sites were more similar between estuaries, with 3 top-ranked species (an oligochaete, a nereid polychaete and an amphipod) shared between Te Puna and Waikaraka, and both sites also having a corophid amphipod in the top 5 ranked species (Table 3-5). Te Puna mangroves also included a capitellid polychaete, and Waikaraka mangroves included the freshwater gastropod *Potamopyrgus estuarinus* which was present at some Waikaraka mangrove sites in high abundance (Table 3-5). Top 5 ranked species in mangrove explained 81% and 79% of the similarity within each mangrove zone at Te Puna and Waikaraka, respectively.

For mulch zones, one species (Oligochaeta Type 1) overlapped sand and mangrove zones in both estuaries (Table 3-5). Three species found in both estuaries in mulch zones were not ranked in sandflat or mangrove habitats (the freshwater insect larvae of *Ephydrella* sp. and Psychodidae, and the amphipod *Paracalliope* sp.). The capitellid polychaete *Capitella* sp. was top ranked in both mulch and mangrove zones at Te Puna, and the amphipod *Melita awa* was top ranked in both mulch and mangrove zones at Waikaraka. Top 5 ranked species in mulch zones explained 77% and 90% of the similarity within each mangrove zone at Te Puna and Waikaraka, respectively (Table 3-5).

	Te Puna	**Waikaraka**
Sand	*Heteromastus filiformis* (37%)	Oligochaeta Type 1 (18%)
	Prionospio aucklandica (14%)	*Ceratonereis* sp. (16%)
	Aonides trifida (10%)	*Scoloplos cylindrifer* (10%)
	Oligochaeta Type 1 (7%)	*Corophium* sp. (9%)
	Macomona liliana (6%)	*Zeacumantus lutulentus* (9%)
% Contribution	74%	62%
Mulch	Oligochaeta Type 1 (30%)	Oligochaeta Type 1 (45%)
	Capitella spp. (16%)	*Melita awa* (19%)
	Ephydrella sp. (13%)	*Capitella* spp. (13%)
	Psychodidae (12%)	*Paracalliope* sp. (8%)
	Paracalliope sp. (6%)	Psychodidae (5%)
% Contribution	77%	90%

	Te Puna	Waikaraka
Mangrove	*Corophium* sp. (34%)	*Potamopyrgus estuarinus* (32%)
	Oligochaeta Type 1 (21%)	*Melita awa* (22%)
	Ceratonereis sp. (10%)	Oligochaeta Type 1 (18%)
	Capitella spp. (8%)	*Paracorophium* sp. (9%)
	Melita awa (8%)	*Ceratonereis* sp. (6%)
% Contribution	81%	87%

Table 3-5: Percent contribution of the top 5 species (ranked by abundance) to the similarity of communities sampled within each zone (across sites and over time).

Patterns in abundance over time differed between habitat zones for different taxonomic groupings, but were generally similar between sites in both estuaries. Bivalves were abundant in sandflat zones, but exhibited low abundance in mangrove zones, although small *Austrovenus stutchburyi* (< 5 mm) were collected from mangroves at Waikaraka in 3 month samples, and from Te Puna in 6 month samples (Figure 3-16). Bivalves were collected in mulch samples at Te Puna sites 2 and 3 at 12 months, but were comprised of only low numbers of small (< 5 mm) juvenile bivalves (Figure 3-17, Figure 3-18).

Gastropods (excluding *Potamopyrgus estuarinus*) were generally highest in abundance in sand, and occurred at lower densities in mangroves and mulch zones (Figure 3-19). Species included primarily the gastropods *Zeacumantus* and *Amphibola* in sandflat sites. Few gastropods were found in mulch zones at Te Puna and Waikaraka, including primarily *Zeacumantus* and *Amphibola*. In contrast in mangrove sites at Waikaraka, *Potamopyrgus estuarinus* was found at high abundance and was by far the dominant species, with smaller numbers found in mulch zones in Waikaraka (Figure 3-20).

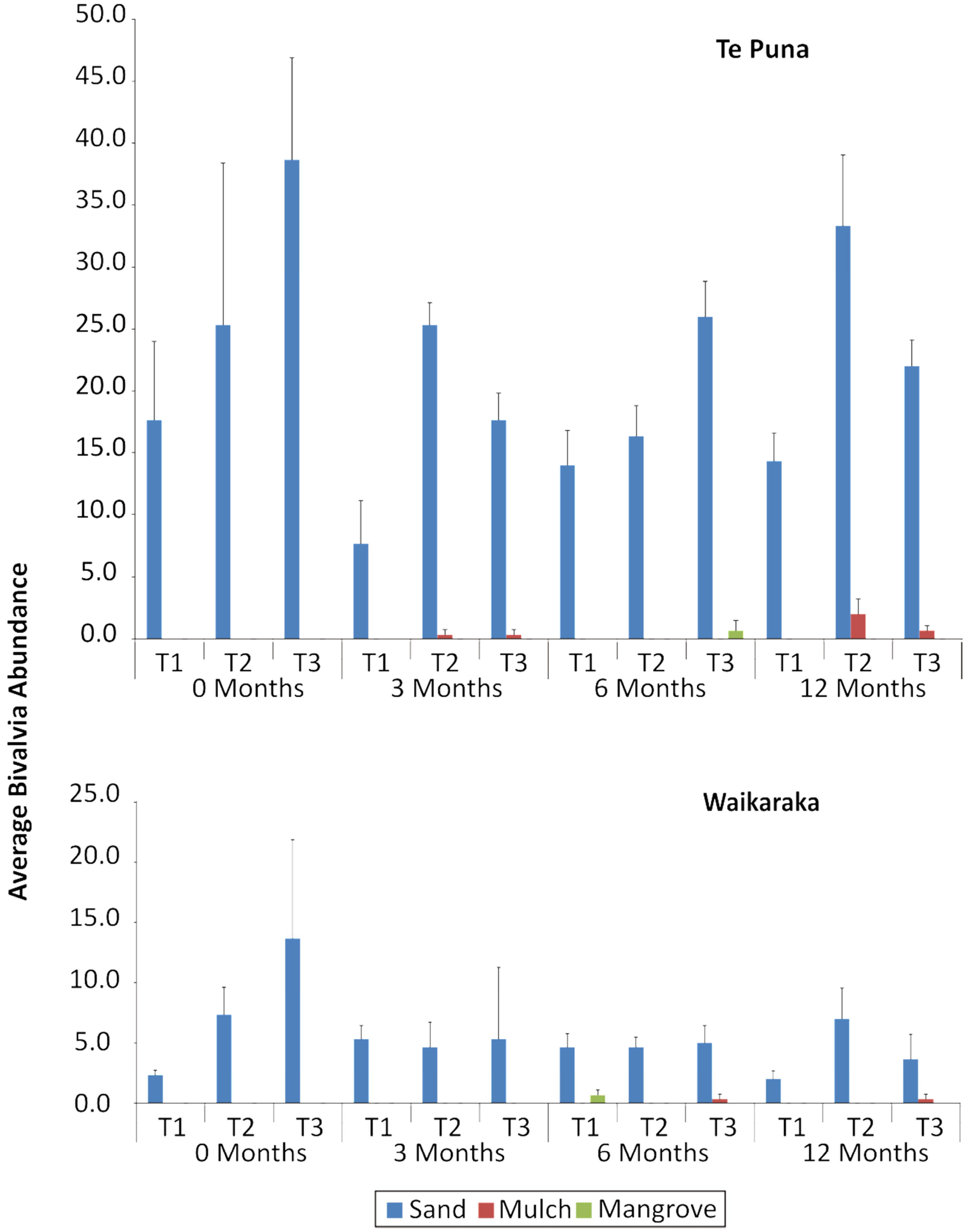

Figure 3-16:Mean abundance of bivalves per 13 cm core averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months), and at 3, 6 and 12 months post mulching, +SE.

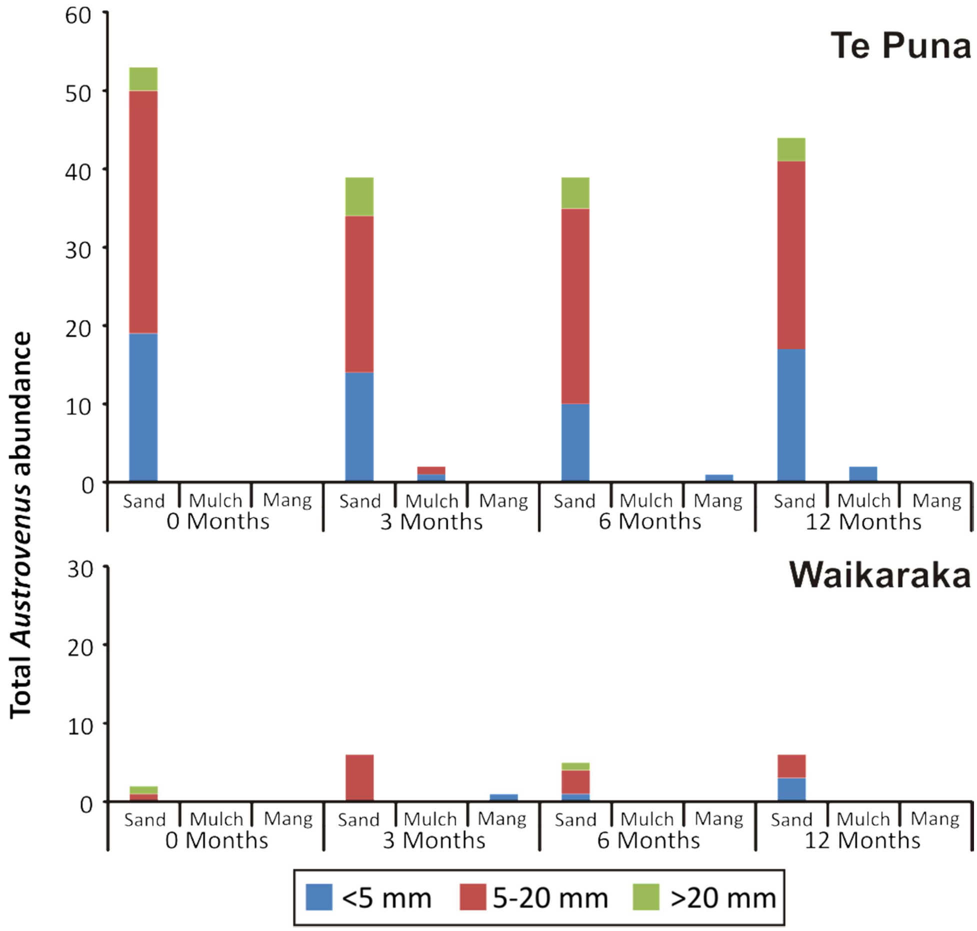

Figure 3-17:Total abundance and size distribution of *Austrovenus stutchburyi* sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months), and at 3 months, 6 months and 12 months post mulching.

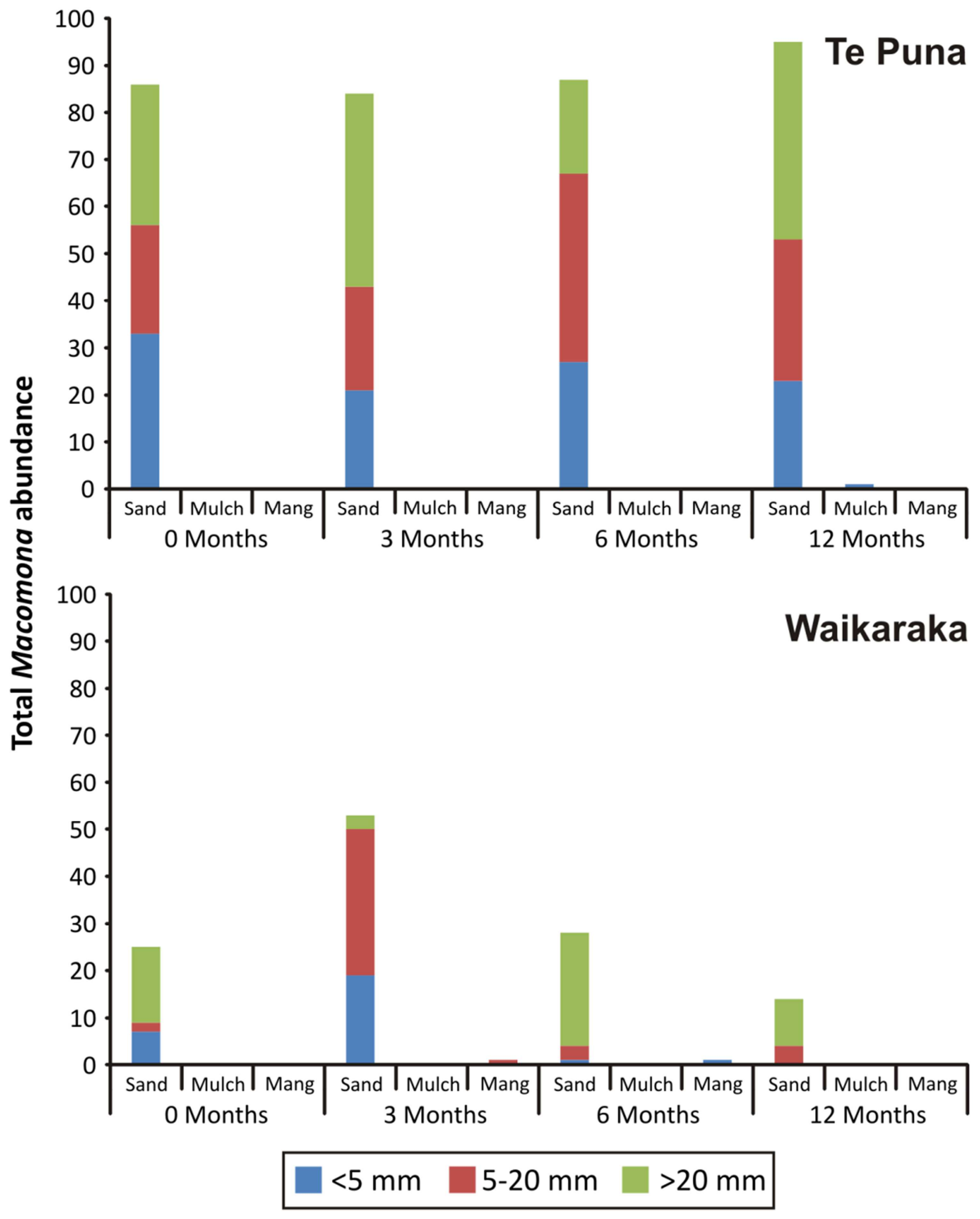

Figure 3-18: Total abundance and size distribution of *Macomona liliana* sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months), and at 3 months, 6 months and 12 months post mulching.

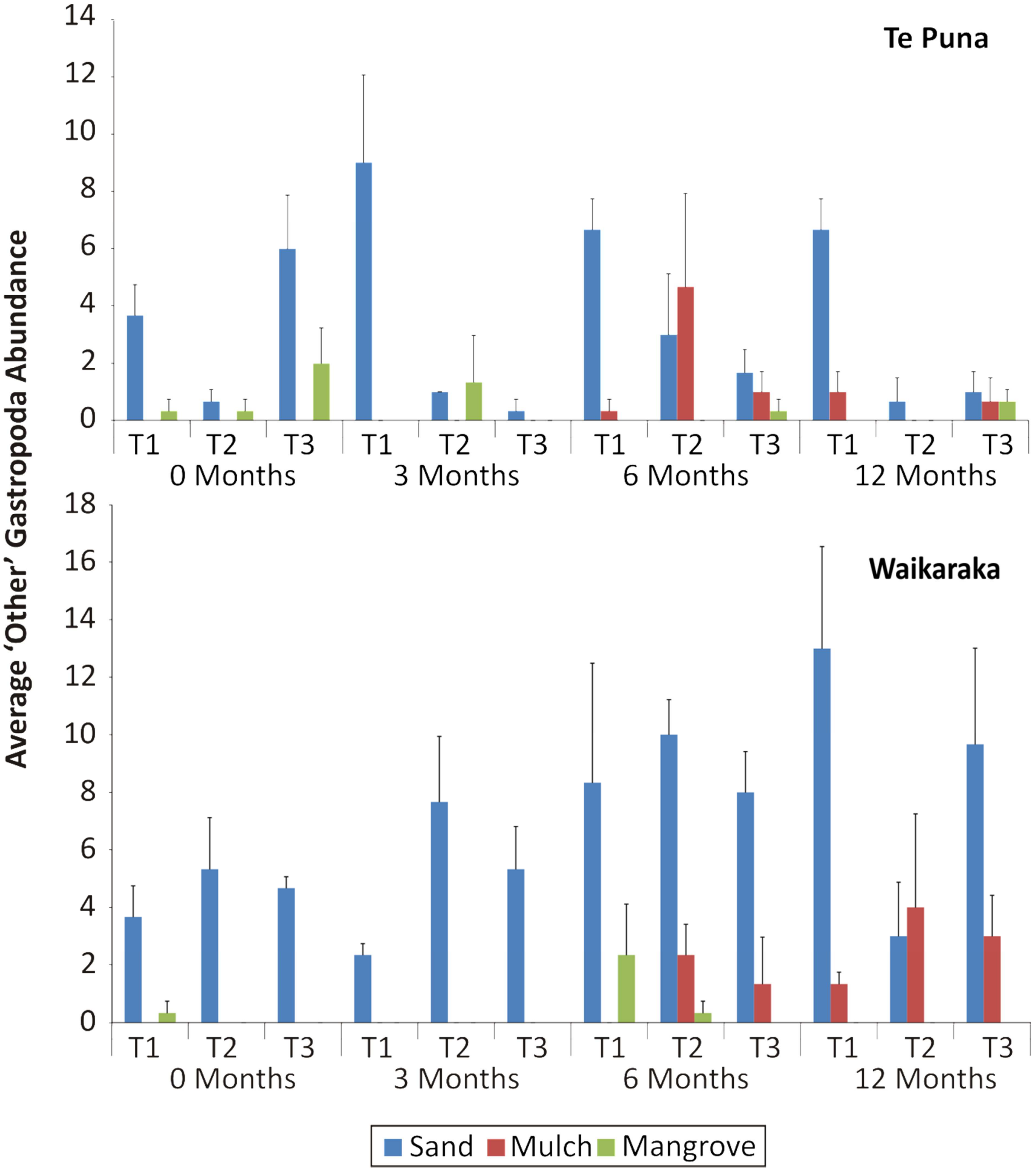

Figure 3-19:Mean abundance of gastropods (excluding *Potamopyrgus estuarinus*) (+SE) averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching.

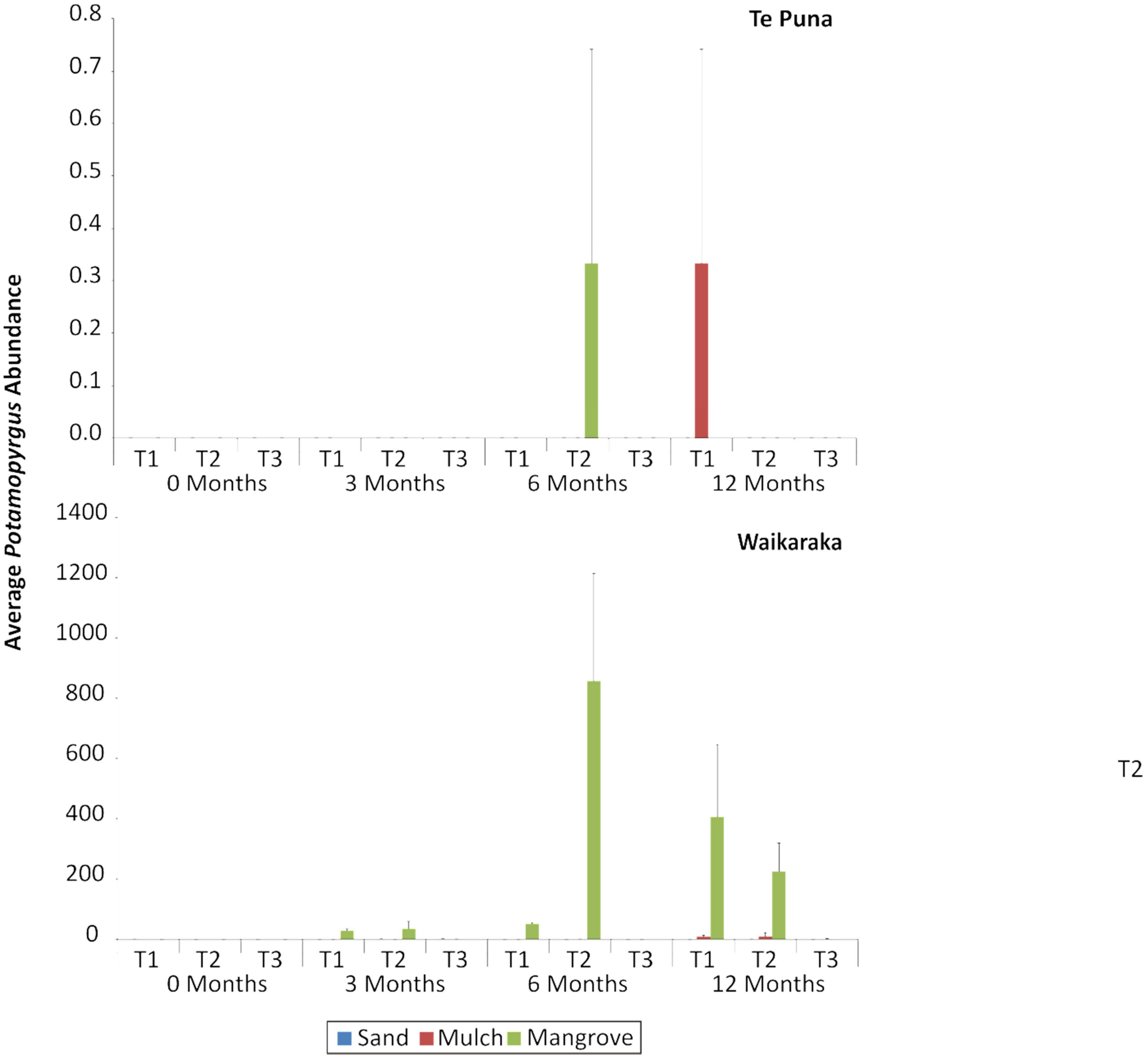

Figure 3-20:Mean abundance of *Potamopyrgus estuarinus* averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

Polychaete abundance was high in sand, mulch and mangrove habitats, with some sites showing temporal trends of increasing numbers over time in mulch habitats. Nereididae polychaetes showed similar numbers in sandflat zones throughout the sampling period, and high variability in abundance in the mangrove zone (Figure 3-21). Nereididae polychaetes showed early colonisation of mulch plots at the 3 month sample, with increasing numbers at most sites over time, but also high variability (Figure 3-21). 12 months after mulching, Nereididae polychaete abundance in mulch zones was less than half the abundance in neighbouring sandflats. Spionidae polychaetes showed higher abundance at Te Puna than at Waikaraka estuary in the sandflat zone, and high variability in abundance in the mangrove zone in both estuaries (Figure 3-22). Increasing abundance of Spionidae polychaetes over time was detected in sites 2 and 3 in both estuaries, but minimal colonisation occurred at site 1 in both estuaries (Figure 3-22). Capitellidae polychaetes were consistently common at the sandflat sites in Te Puna, primarily of the species *Heteromastus filiformis*, but were rare in the Waikaraka sandflat zone (Figure 3-23). At mangrove sites, Capitellidae polychaete species were represented by both *Heteromastus filiformis* and *Capitella* spp. In contrast, mulch sites were only represented by *Capitella* spp. in both estuaries. Peak abundance of *Capitella* spp. at mulch sites occurred at 6 months at all sites, though abundance at Waikaraka site 1 was substantially less than other sites (Figure 3-23). Oligochaeta were present at all survey sites, with generally higher abundance in mangrove than in sandflat zones (Figure 3-24). High abundance of Oligochaeta was recorded in mulch sites at 3 and 6 months; however, Oligochaeta were rare at most mulch sites at 12 months (Figure 3-24).

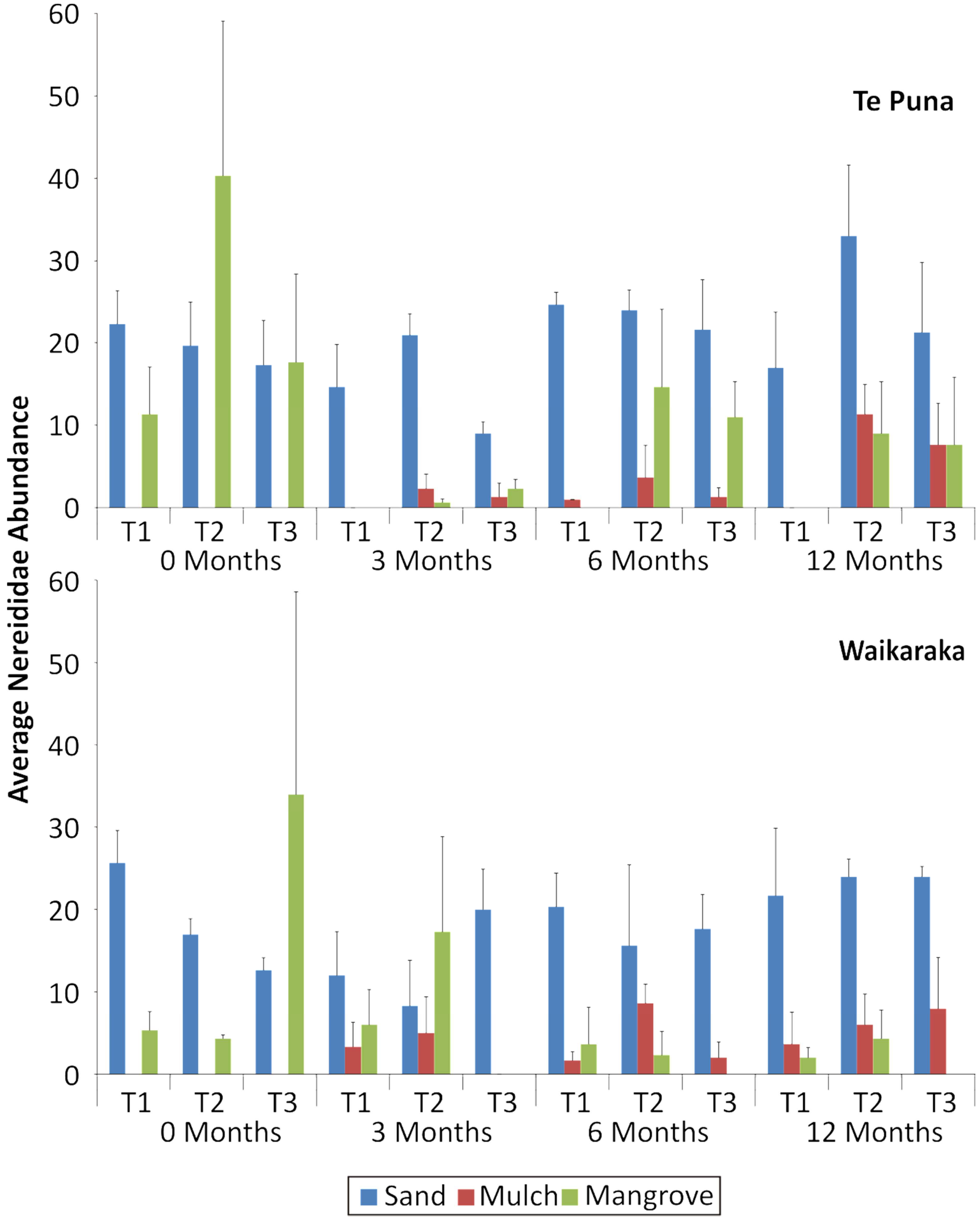

Figure 3-21:Mean abundance of Nereididae polychaetes averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

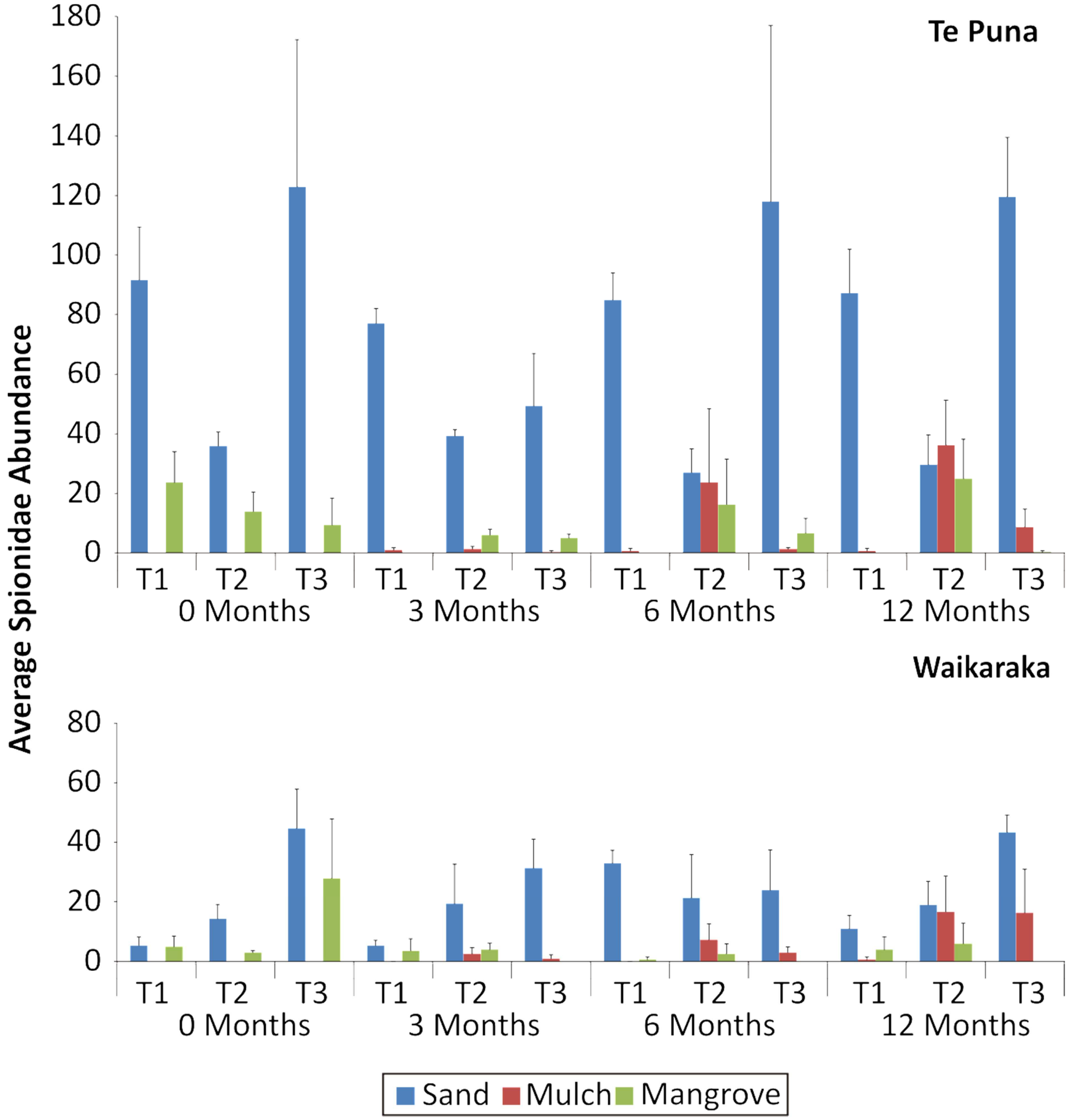

Figure 3-22:Mean abundance of Spionidae polychaetes averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

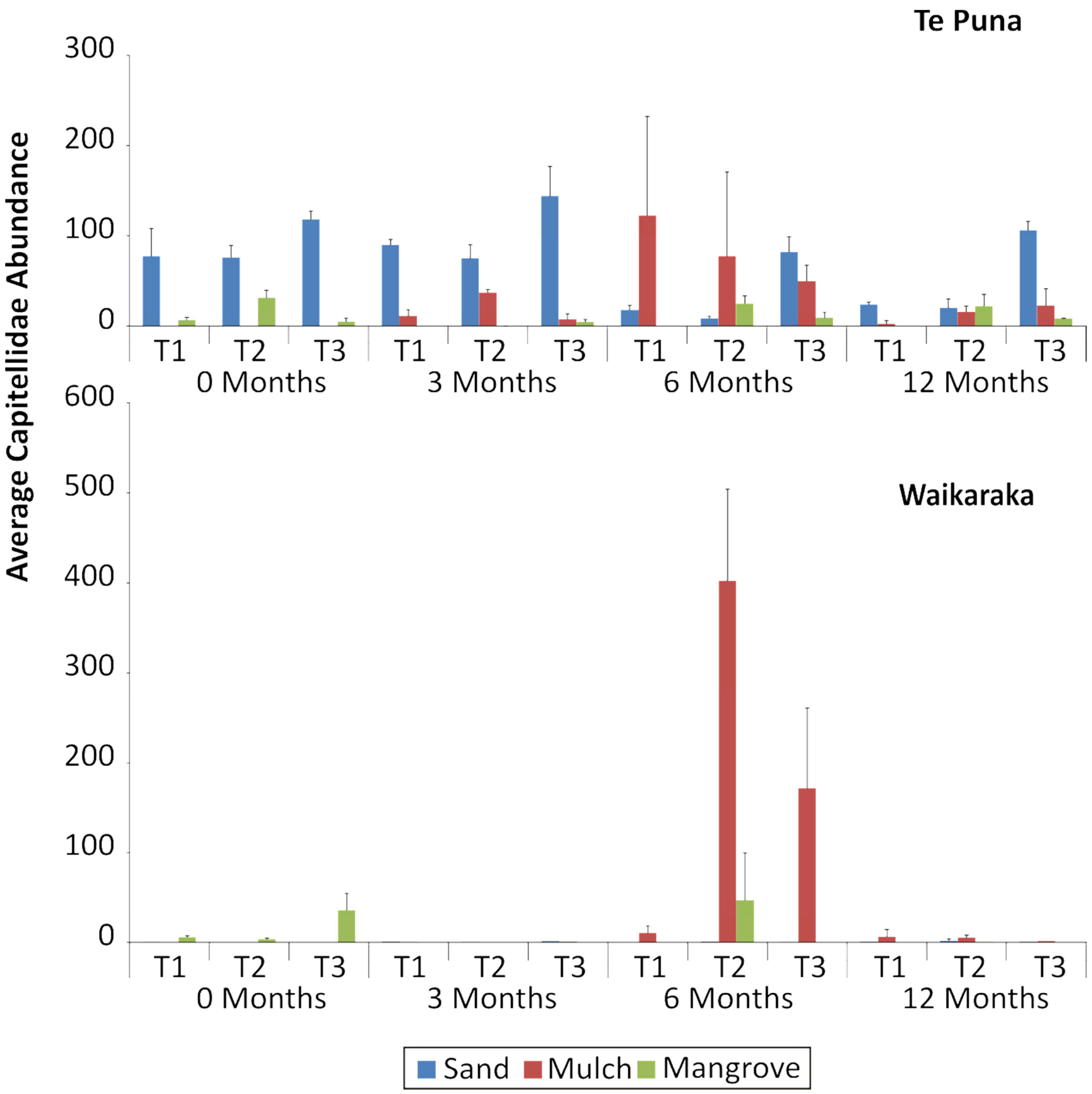

Figure 3-23:Mean abundance of Capitellidae polychaetes averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

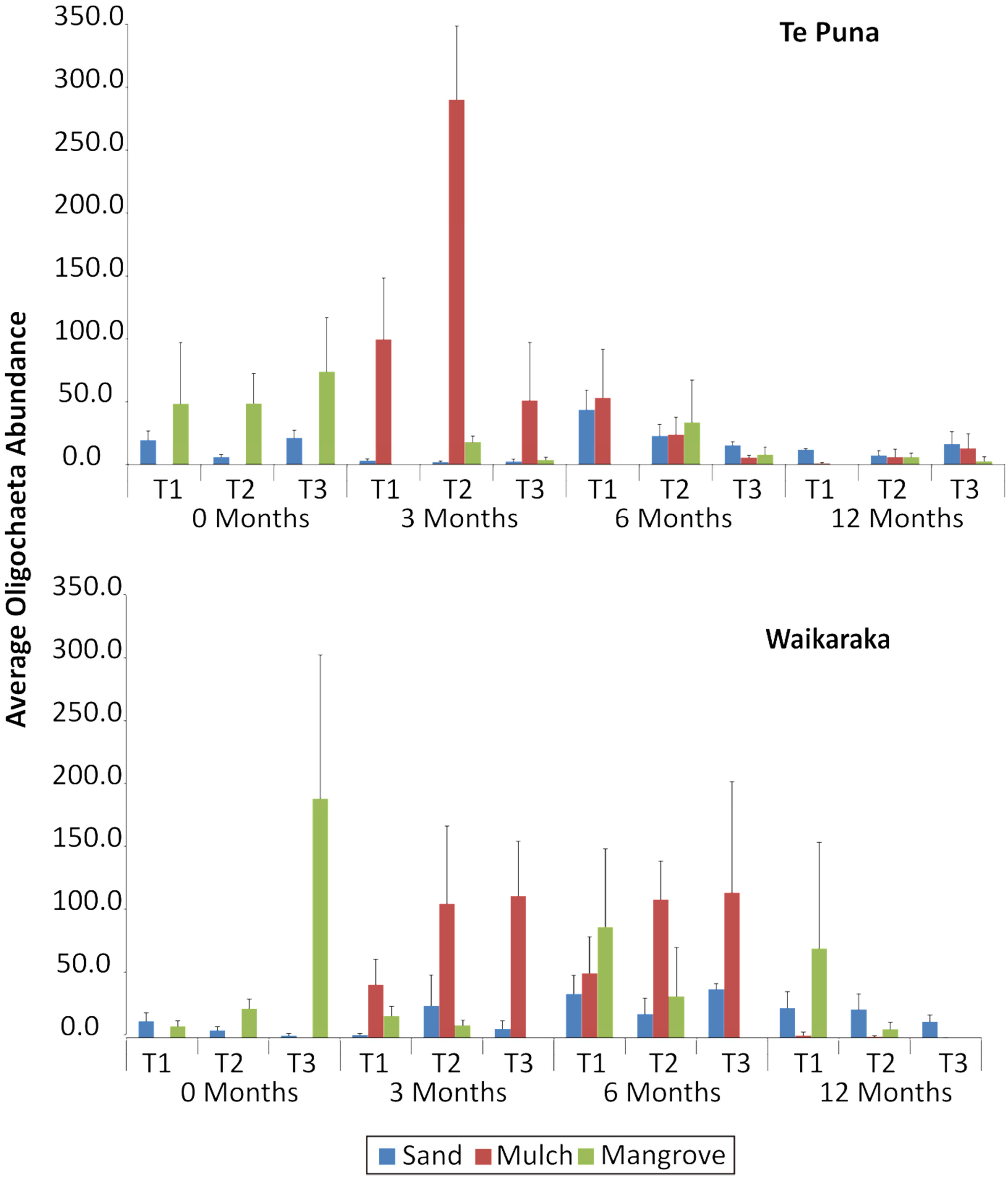

Figure 3-24:Mean abundance of Oligochaeta averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

Decapoda and Amphipoda abundance were generally low at the sandflat sites at Te Puna and Waikaraka, and were highly variable in the mangrove sites in both estuaries (Figure 3-25, Figure 3-26). Decapoda abundance was high in mulch sites at Te Puna at 3, 6 and 12 months post-mulching, whereas Decapoda abundance was only high at Waikaraka at the 12 month sampling time (Figure 3-25). High Amphipoda abundance was observed at all sites in Waikaraka at the 12 month sampling time (Figure 3-26). Amphipoda were generally observed only in low numbers in the mulch zone until 12 months post-mulching (Figure 3-26). Abundance of other crustacean taxa was generally highest at sandflat sites compared to other habitat zones. Other crustacean taxa were rarely recorded in mangrove zones in Te Puna, and occasionally recorded in mangrove zones in Waikaraka. Other crustacean taxa were recorded in mulch zones at Te Puna site 2 at 3 months, and at Te Puna sites 1 and 3 at 6 months, and at all Te Puna sites at 12 months. Waikaraka mulch zones only collected other crustacean taxa at site 3 at 6 months, and at all sites at 12 months.

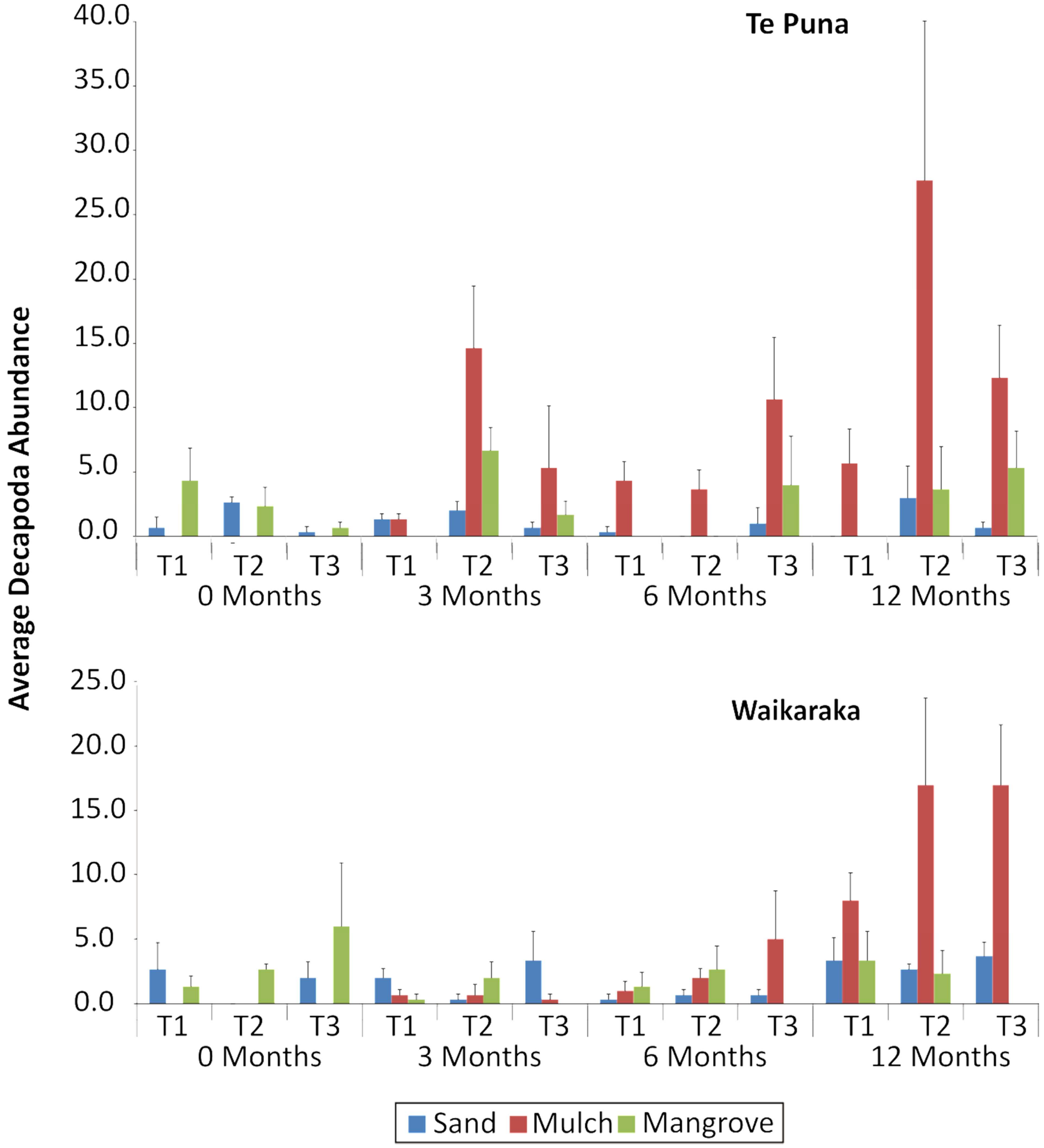

Figure 3-25:Mean abundance of Decapoda averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

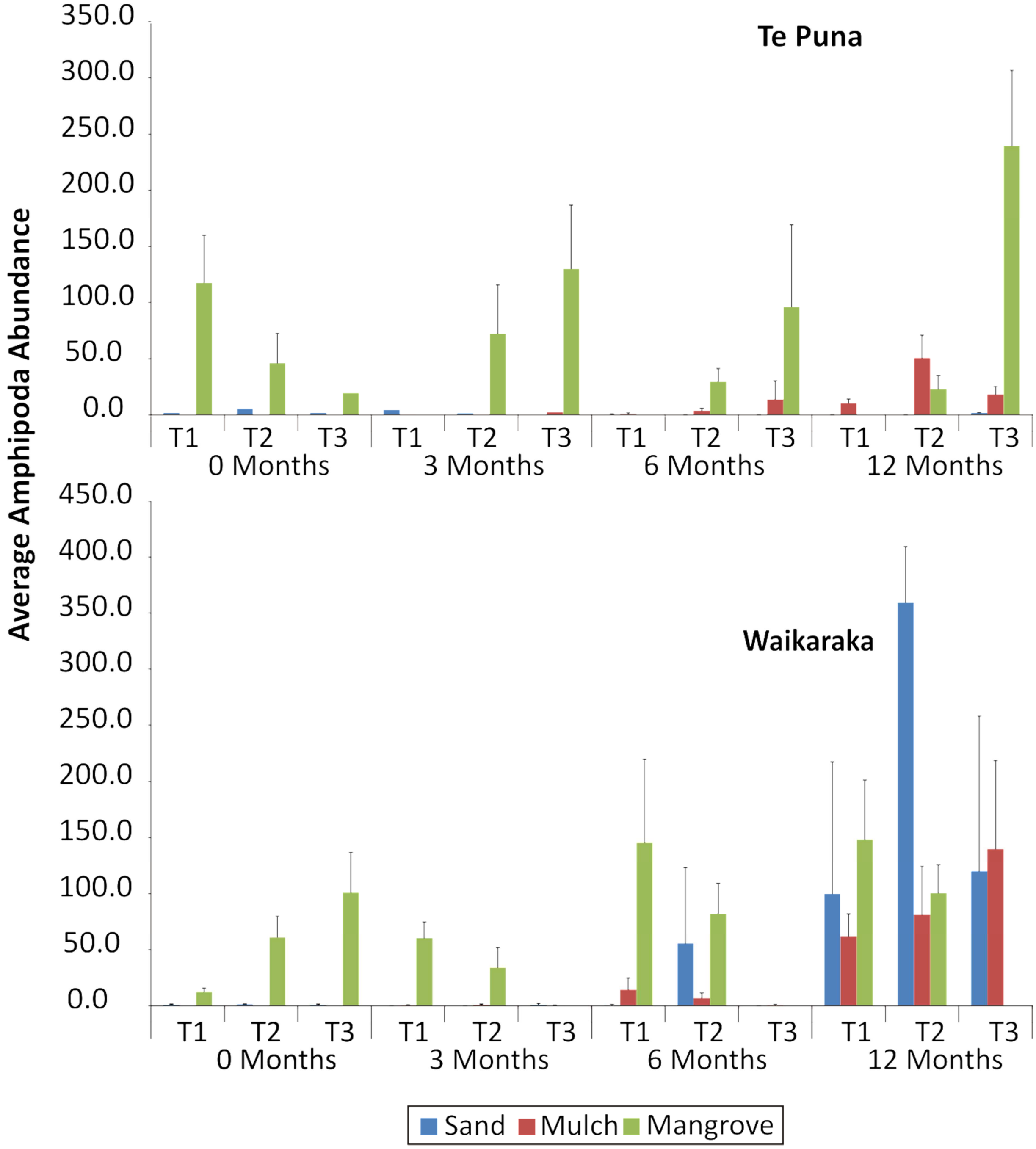

Figure 3-26:Mean abundance of Amphipoda averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

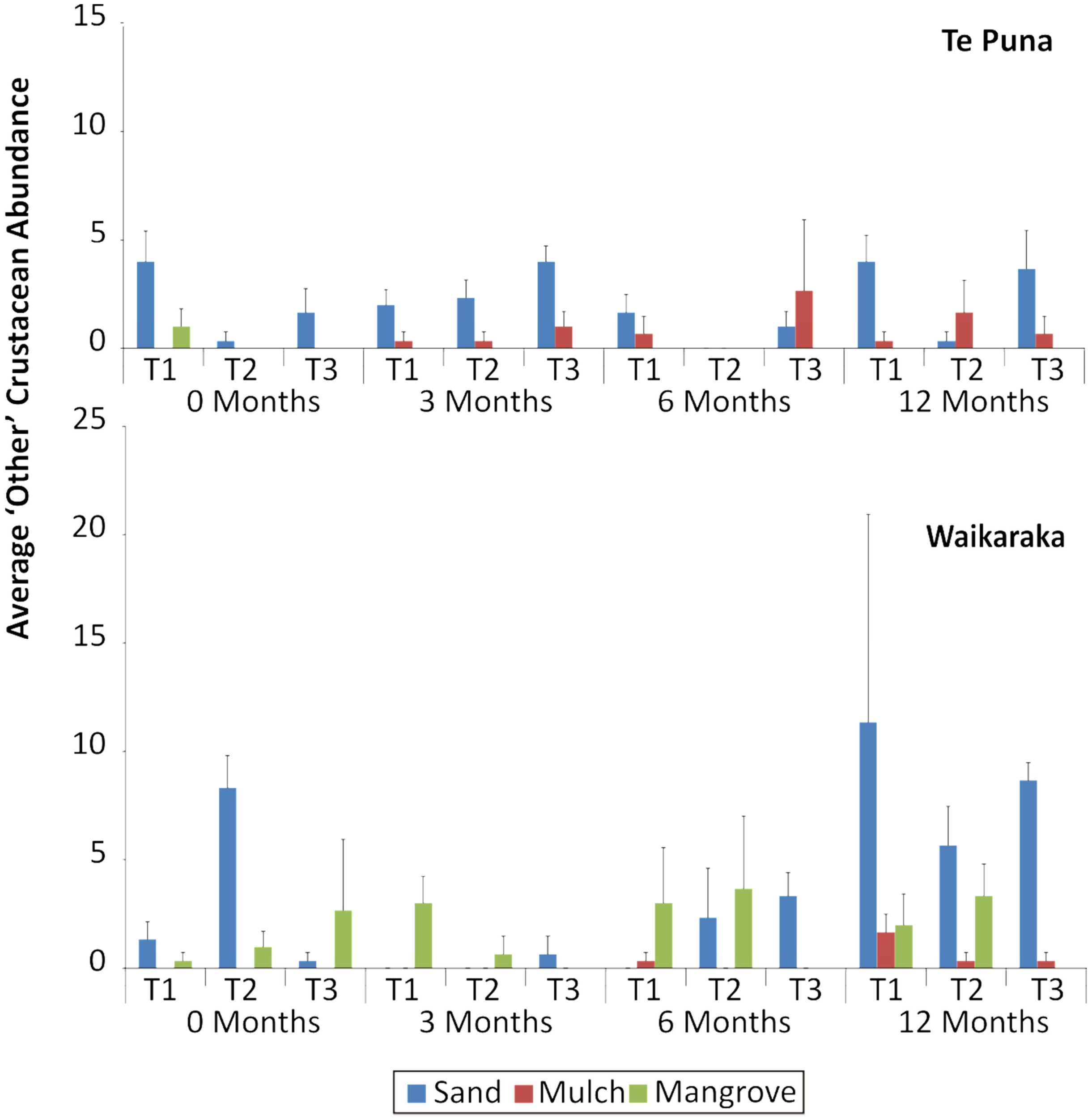

Figure 3-27:Mean abundance of other crustaceans (excluding Amphipoda and Decapoda) averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

"Terrestrial" taxa, including numerous insect larvae, were seasonally common in the mulch zone. Abundance of dipterid larvae of *Ephydrella* sp. peaked at both sites at 3 months post-mulching, with substantially higher abundance at the Te Puna sites (Figure 3-28). Other terrestrial taxa were also observed in macrofaunal cores from the mulch zone, including other dipteran adults, larvae and pupae, and chironomiidae, dolochopodidae, and psychodidae larvae (Figure 3-28). Abundances of other terrestrial taxa were highest in mulch zones at 6 months in both estuaries, with high abundances observed also in mangrove zones at 6 months in Waikaraka (Figure 3-28).

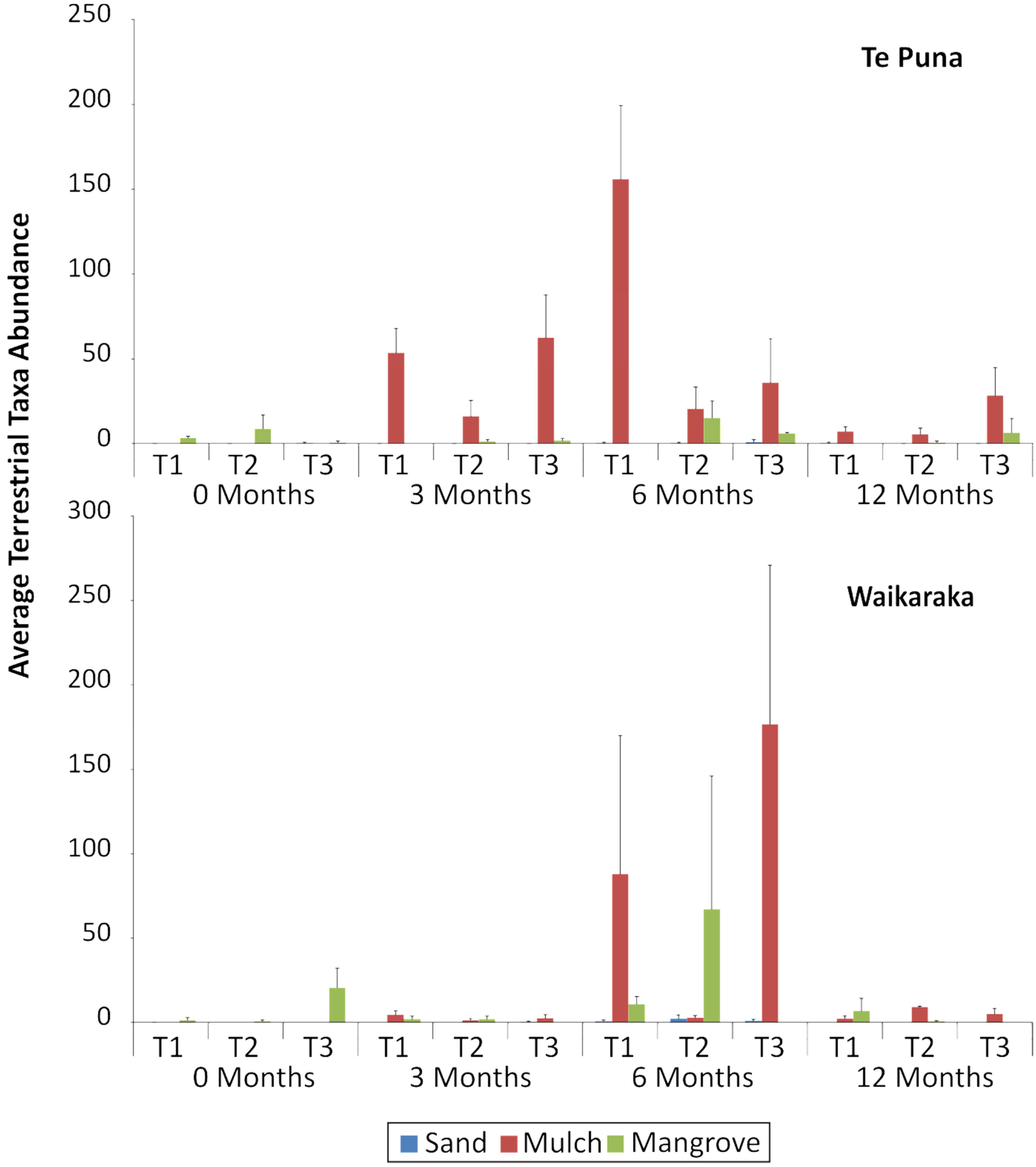

Figure 3-28:Mean abundance of terrestrial taxa averaged over three sites sampled at Te Puna and Waikaraka estuaries prior to mulching (0 months) and at 3, 6 and 12 months post mulching, +SE.

3.4 Mulch biomass remaining in macrofaunal cores

Substantial mulch biomass remained on cleared sites a year after mulching. While we measured the depth of mulch in our transect surveys at all sampling times, we did not measure mulch biomass from macrofaunal cores immediately after mulching occurred, or at the 3 month sampling time. Instead, this specific measurement of mulch biomass from macrofaunal cores was an opportunistic addition to our sampling methodology, included after it was clear that mulch was not dispersing from the sandflat. Regardless, we can use changes between 6 and 12 month biomass to infer trends in the decrease of mulch biomass. We note that our measurements included all vegetative biomass, e.g., woody debris, pneumatophores and root biomass, collected to a depth of 15 cm, and does not specifically separate out woody mulch or pneumatophore debris deposited on the sediment surface. We compare mulch biomass to vegetative biomass collected at 6 and 12 months from mangrove cores at each site.

Our comparison between 6 and 12 month samples suggests that vegetative biomass has stayed relatively constant at both Te Puna and Waikaraka estuaries between the 6 and 12 month sampling times, with no apparent decrease in either estuary (Figure 3-29). We did observe differences between sites, for example Site 2 at Te Puna had consistently lower vegetative biomass, but as this was also true for biomass in the mangrove cores, it probably reflects lower density of mangroves, and thus less mangrove mulch to be left at this site (Figure 3-29). There was also some variability in mulch biomass within each site, often associated with tracks left by the tractor. These resulting differences in height at the sediment surface may result in differential accumulation of mulch.

Within site comparisons of mulch biomass across the mulched area between all four estuaries after 12 months are shown in Figure 3-30. There was little difference in mulch biomass between cores collected at the seaward edge, the centre of the mulch zone, and the shoreward edge for three of the estuaries, though at Waikaraka mulch biomass was more variable and often higher at the inner edge (Figure 3-30).

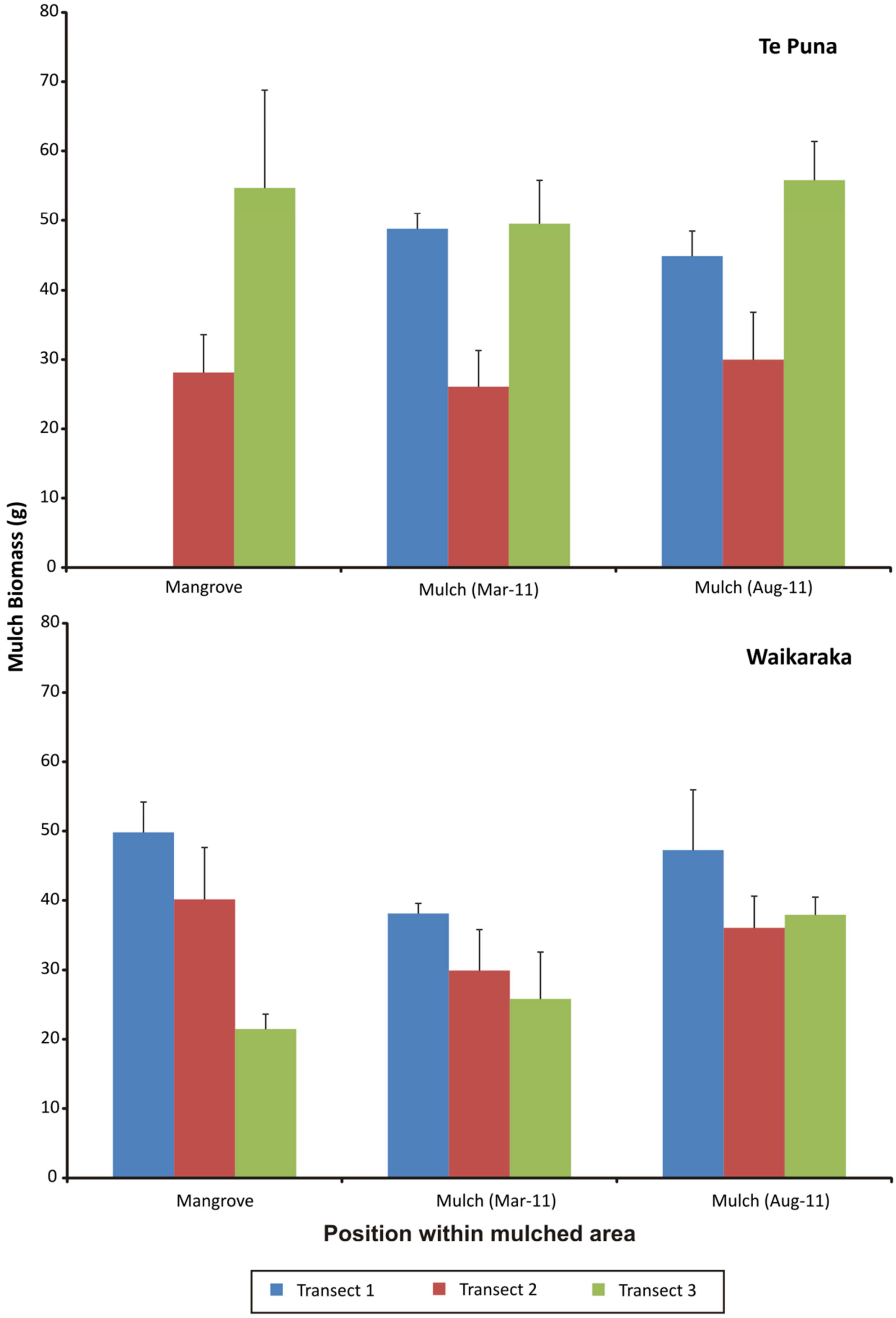

Figure 3-29: Mean mulch biomass (g) in 13 cm macrofaunal cores at 3 sites per estuary in Te Puna and Waikaraka estuaries, at 6 months and 12 months post mulching, compared to mangrove below ground biomass collected at the same sites, +SE.

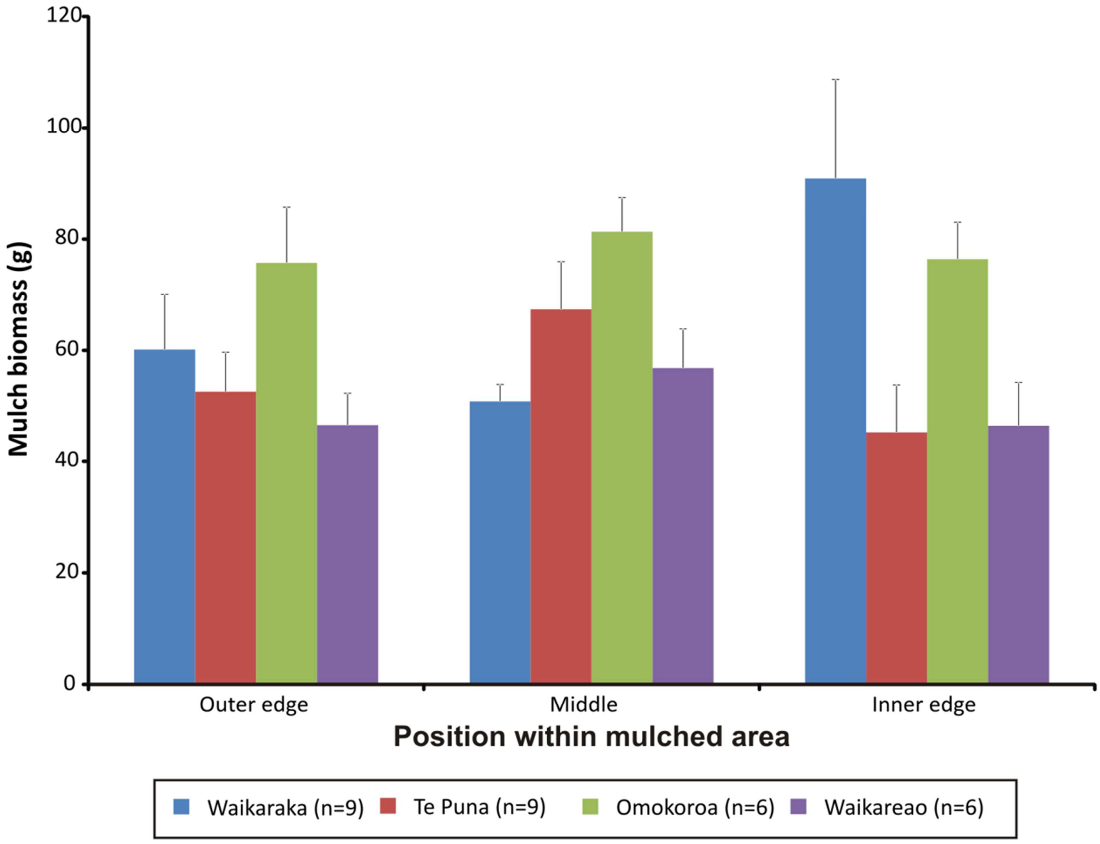

Figure 3-30:Mean mulch biomass remaining within the mulched area at Waikaraka, Te Puna, Omokoroa and Waikareao estuaries, 12 months post mulching, +SE.

3.5 Sediment characteristics

Both estuaries show a greater percentage of mud in the mulch and mangrove zones compared to the sand zone. In both estuaries, mud content was relatively consistent at sandflat sites, with an apparent increase in both estuaries at the 3 month sampling (Figure 3-31). In Te Puna a slight increasing trend in mud content occurred in mangrove habitat during the 12 month survey (Figure 3-31). Mulch zones were more similar to mangrove zones, with high mud content, and no apparent increasing or decreasing trend with time from mulching in either estuary.

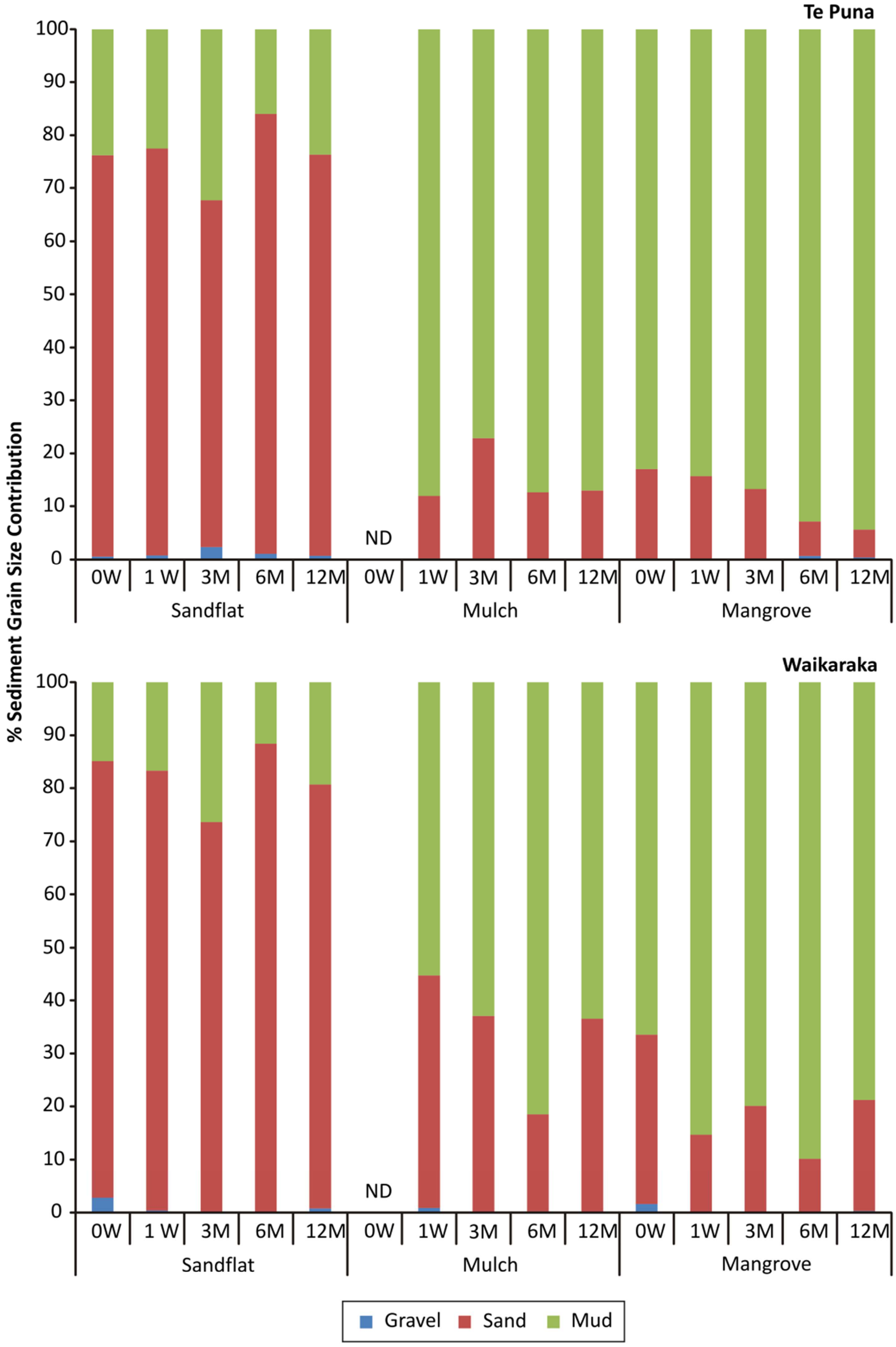

Figure 3-31: Percent sediment grain size contribution of gravel (>2000 µm), sand (63 –2000 µm)and mud (<u><</u>63 µm)within the Te Puna and Waikaraka estuaries prior to mulching (0W) and at 1 week (1W), 3 months, 6 months and 12 months (3M, 6M, 12M) post mulching.

Sediment chlorophyll α content was higher in mulch and mangrove zones compared to sandflat zones (Figure 3-32). No temporal patterns were observed at the sandflat zones during the 12 month survey (Figure 3-32). The sediment chlorophyll α level in the mangrove zone showed a slight increase over time, whereas sediment chlorophyll α in the mulch zone initially increased to its highest value at 3 months, and exhibited the lowest recorded value at 12 months in both estuaries (Figure 3-32).

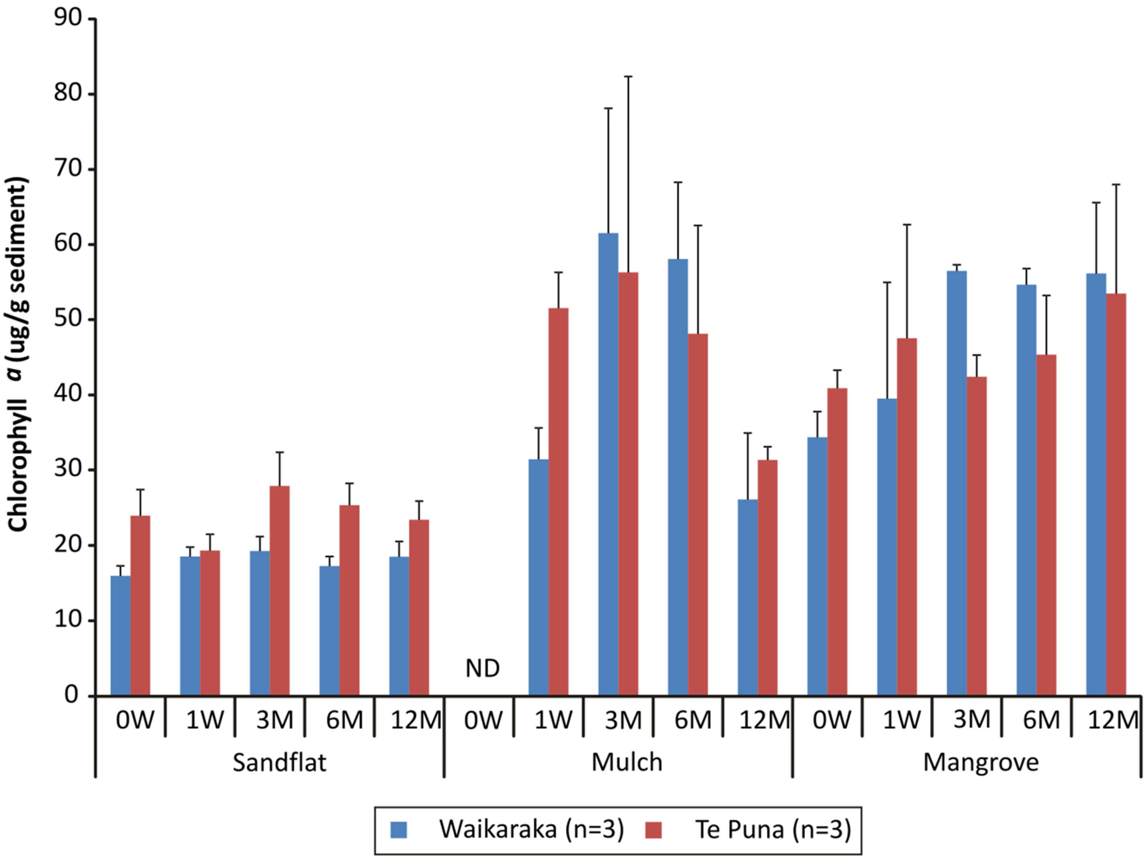

Figure 3-32:Mean sediment chlorophyll α content (μg/g) within the Waikaraka and Te Puna estuaries, prior to mulching (0W) and at 1 week (1W), 3 months, 6 months and 12 months (3M, 6M, 12M) post mulching, +SE.

Organic content of the sediment was also higher in mulch and mangrove zones compared to sandflat zones (Figure 3-33). No temporal patterns were observed in sandflat, mulch or mangrove zones over the course of the survey (Figure 3-33).

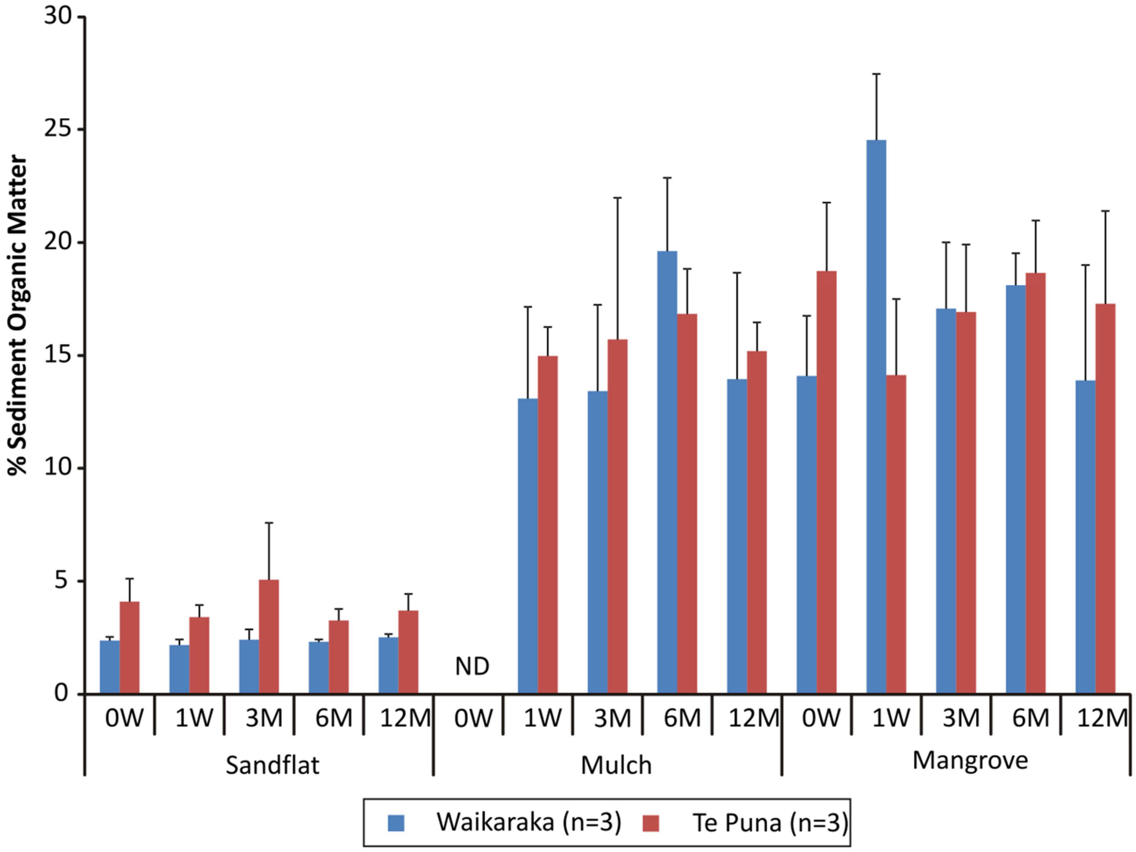

Figure 3-33: Percent sediment organic matter within the Waikaraka and Te Puna estuaries, prior to mulching (0W) and at 1 week (1W), 3 months, 6 months and 12 months (3M, 6M, 12M) post mulching, +SE.

3.6 Macroalgal blooms

Macroalgal blooms on mulched sites were opportunistically sampled in higher resolution transects than the standard transect monitoring methodology, after the blooms were observed at the November 2010 sampling occasion. Replicate macroalgal transects occurred within 100 m of the primary transect lines at each site, and width of patches varied by 10-20 m across this distance. General patterns were somewhat consistent with *Ulva* sp. (sheet form) (recognised as 'sea lettuce') most commonly occurring in abundance at the sandflat-mulch edge, and usually not being attached to mulch or pneumatophores, suggesting that it could be transported in from elsewhere in the harbour (Figure 3-34 to Figure 3-43). In contrast, other species were clearly attached to and were growing from mulch biomass or remaining pneumatophores, and most commonly were found in the shoreward region of mulch patches. Large blooms of these other macroalgae varied between being single species to multi-species patches, with all bloom algae being of the family Ulvaceae, and including primarily *Ulva* sp. (tubular form) (previously known as *Enteromorpha* spp.), and the filamentous species *Rhizoclonium* spp. and *Percursaria percursa*. Smaller brown algal species were occasionally found attached to pneumatophores at low abundance (usually <1% percent cover) at some sites.

Seasonal trends were apparent at some sites, with *Ulva* sp. (sheet form) being most abundant in spring and summer months. Some species replacement is suggested at Te Puna sites 1 and 2, and Waikaraka sites 1 and 2, with filamentous blooms recorded in December 2010 replaced by *Ulva* sp. (tubular form) at later sampling times in 2011 (Figure 3-34, Figure 3-35, Figure 3-36, Figure 3-37, Figure 3-38). Other sites did not show major shifts in macroalgal species composition over the sampling period (e.g., Waikaraka site 3, Omokoroa, Waikareao) (Figure 3-40, Figure 3-41, Figure 3-43).

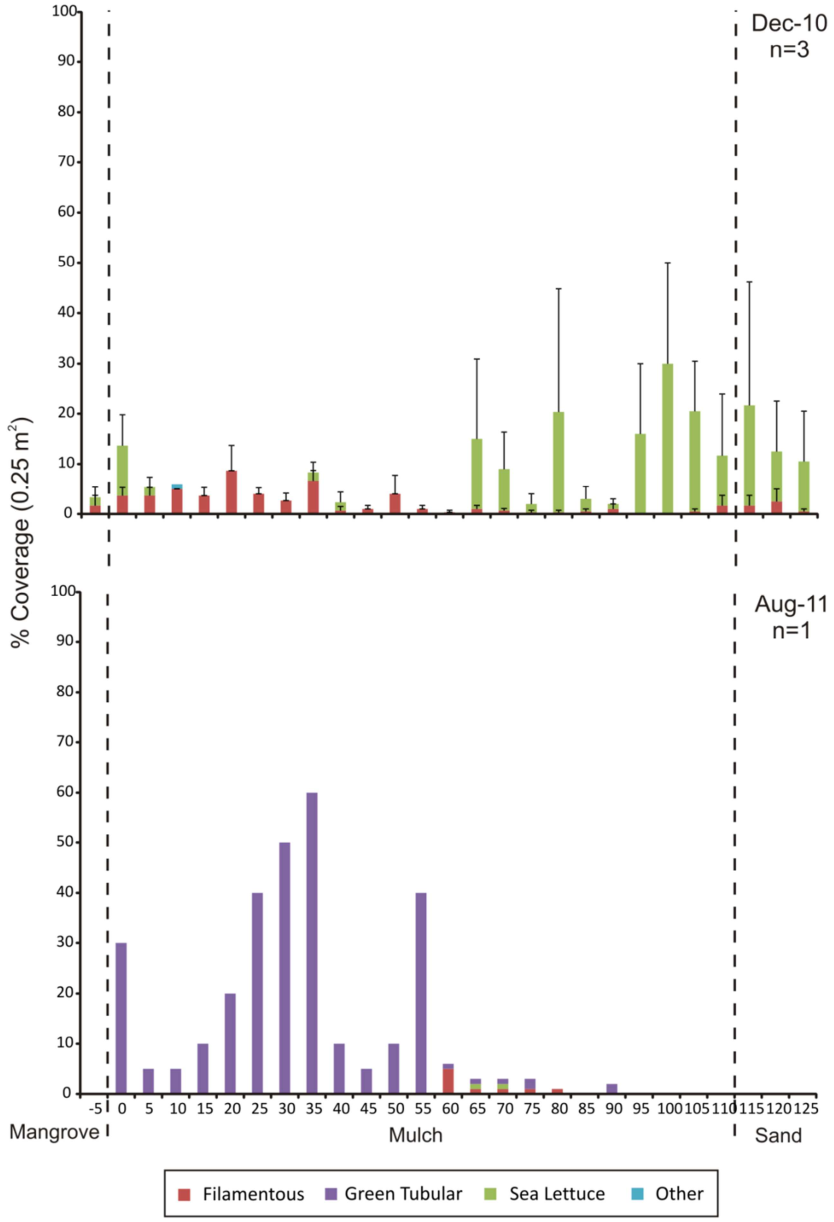

Figure 3-34:Macroalgal percent cover and species composition at Te Puna Site 1. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

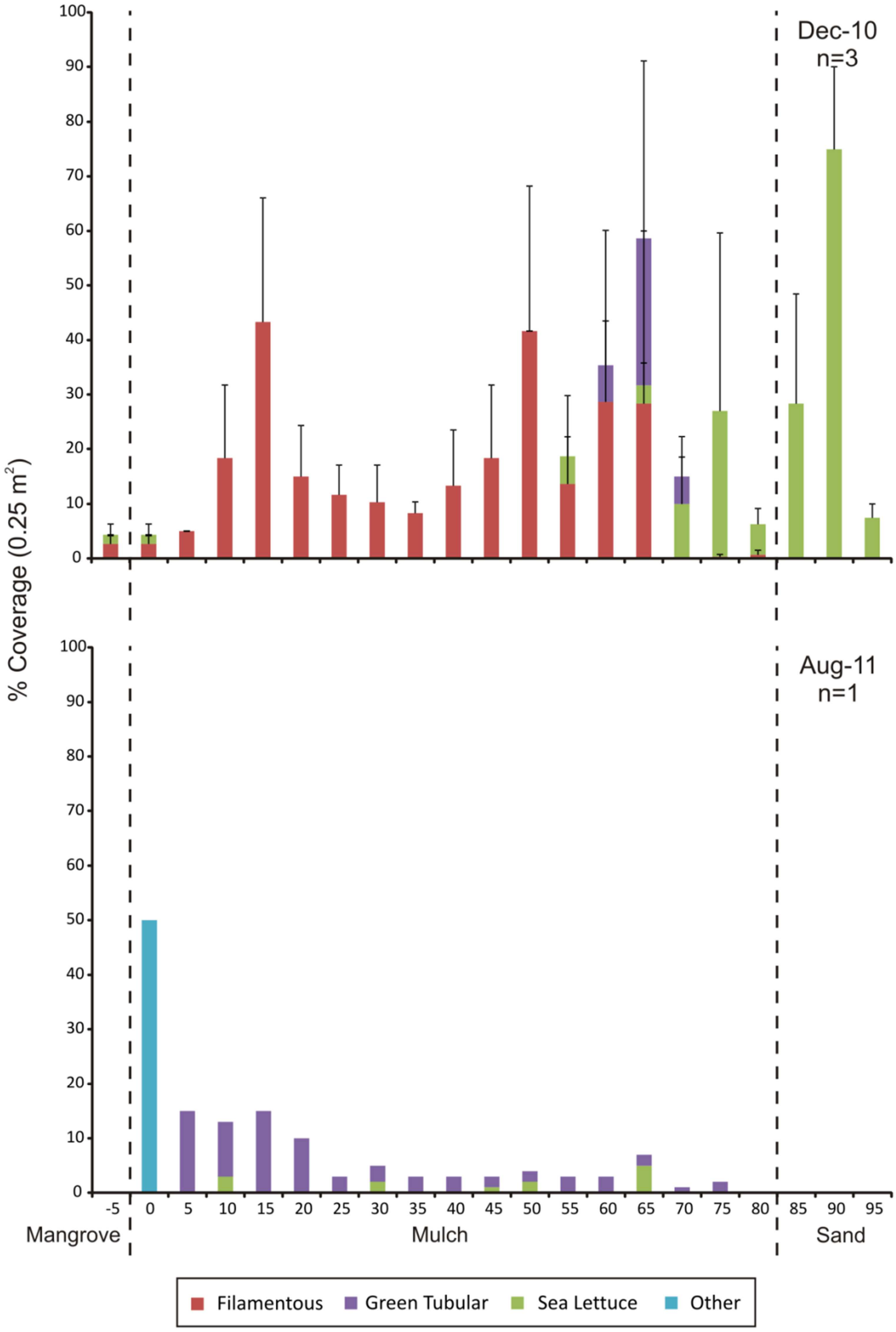

Figure 3-35: Macroalgal percent cover and species composition at Te Puna Site 2. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

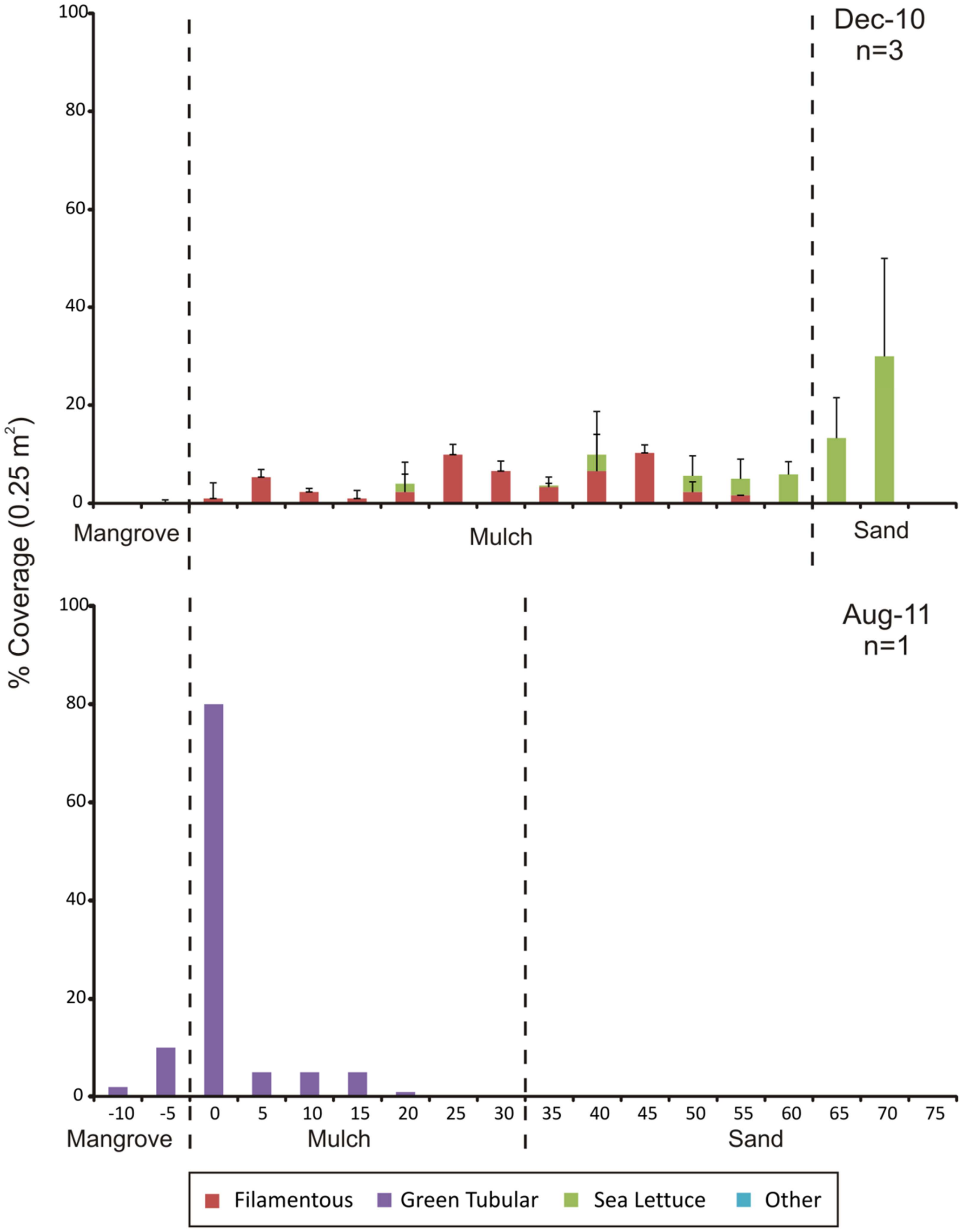

Figure 3-36:Percent cover of macroalgae and species composition at Waikaraka Site 1 in December 2010 and August 2011. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); ‘Other’ includes all other species observed, including primarily brown and red algae.

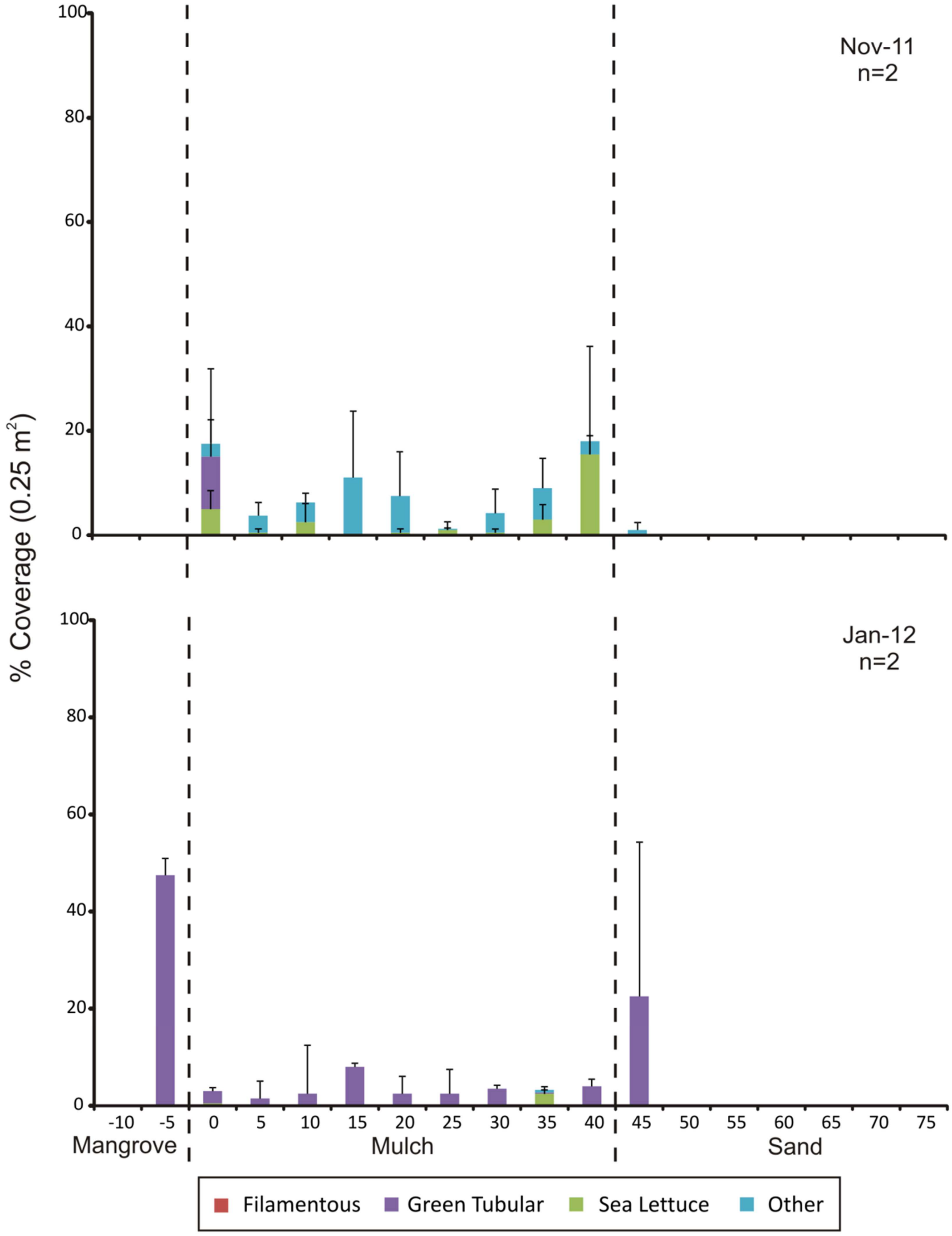

Figure 3-37: Percent cover of macroalgae and species composition at Waikaraka Site 1 in November 2011 and January 2012. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

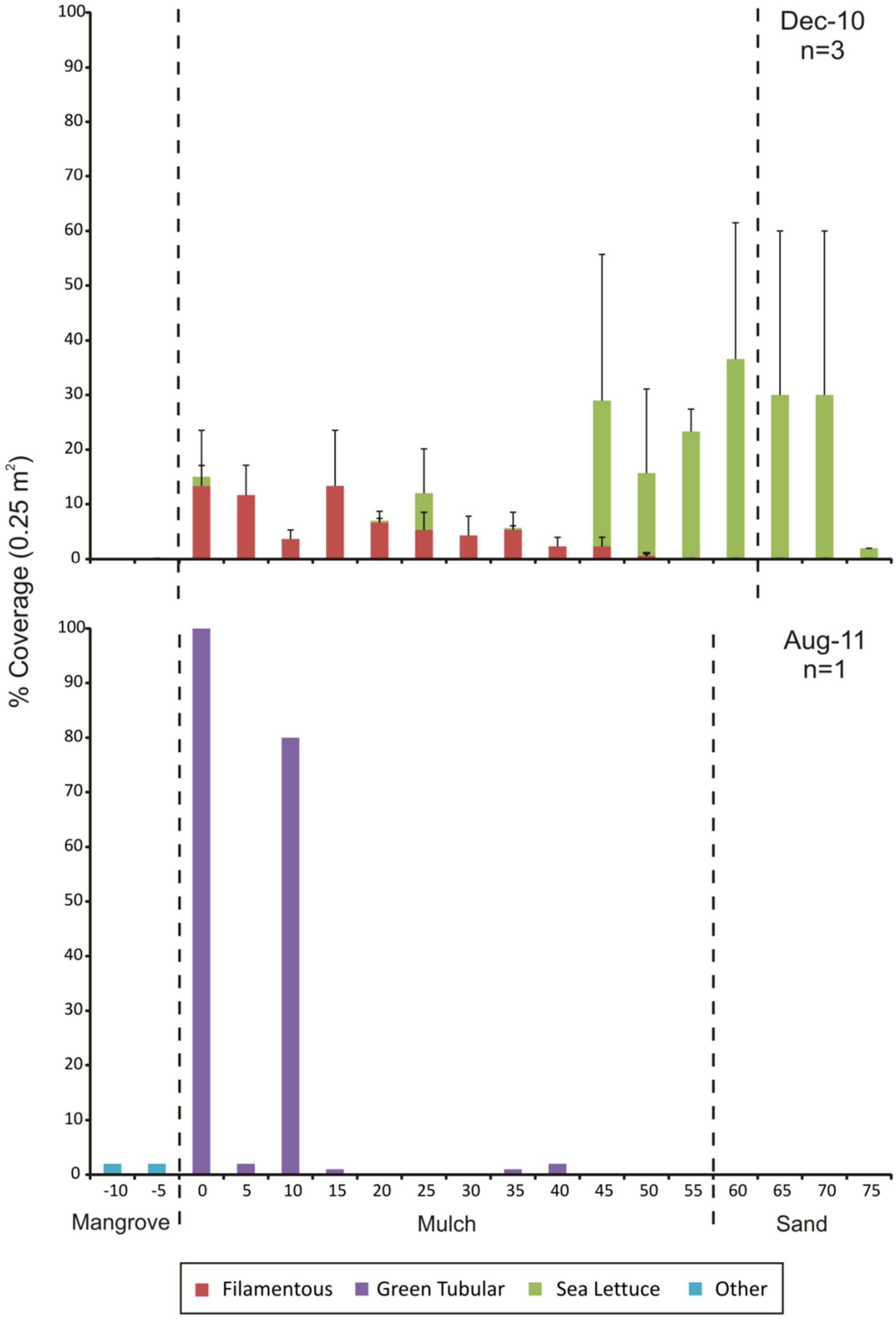

Figure 3-38:Percent cover of macroalgae and species composition at Waikaraka Site 2 in December 2010 and August 2011. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

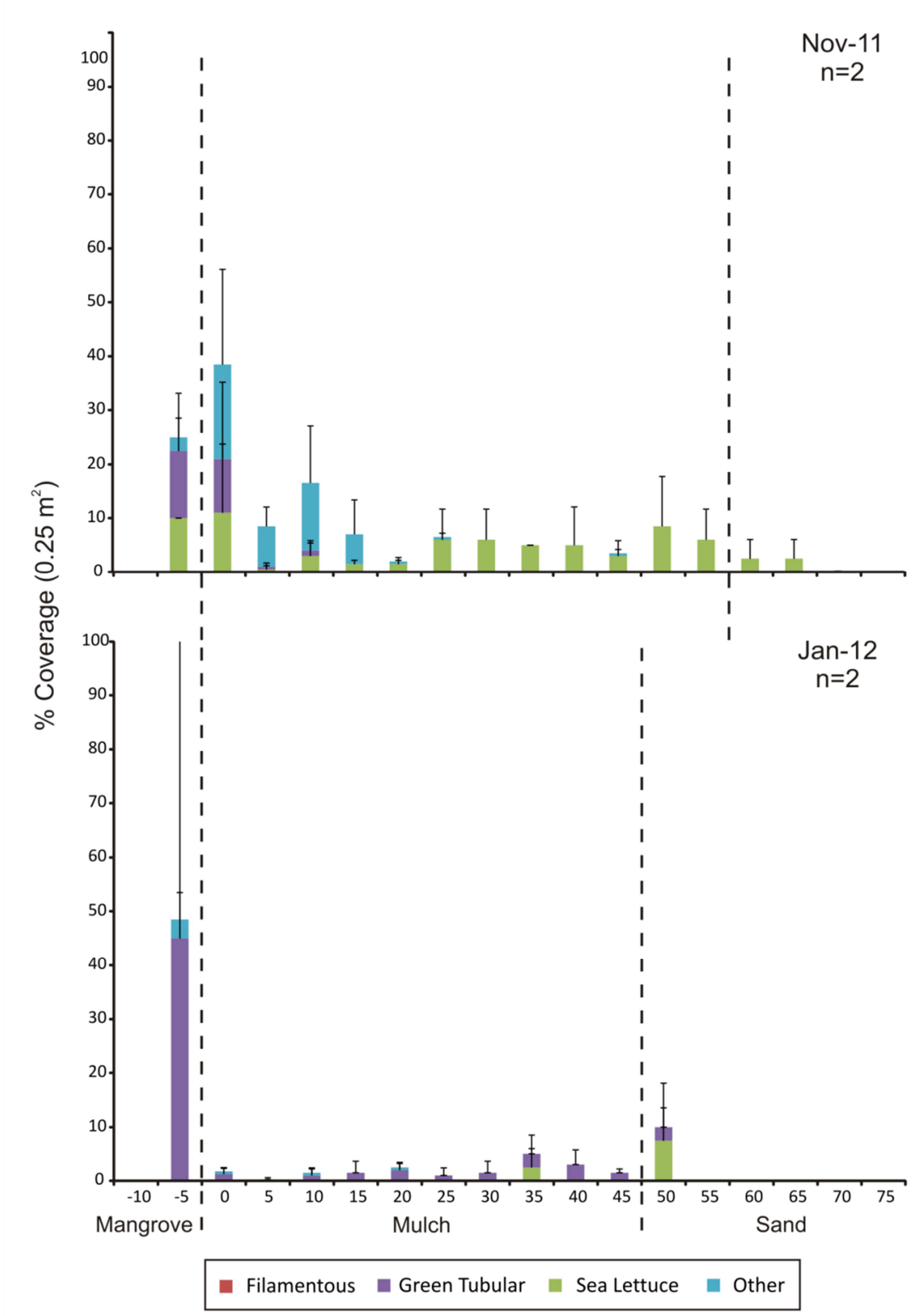

Figure 3-39: Percent cover of macroalgae and species composition at Waikaraka Site 2 in November 2011 and January 2012. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

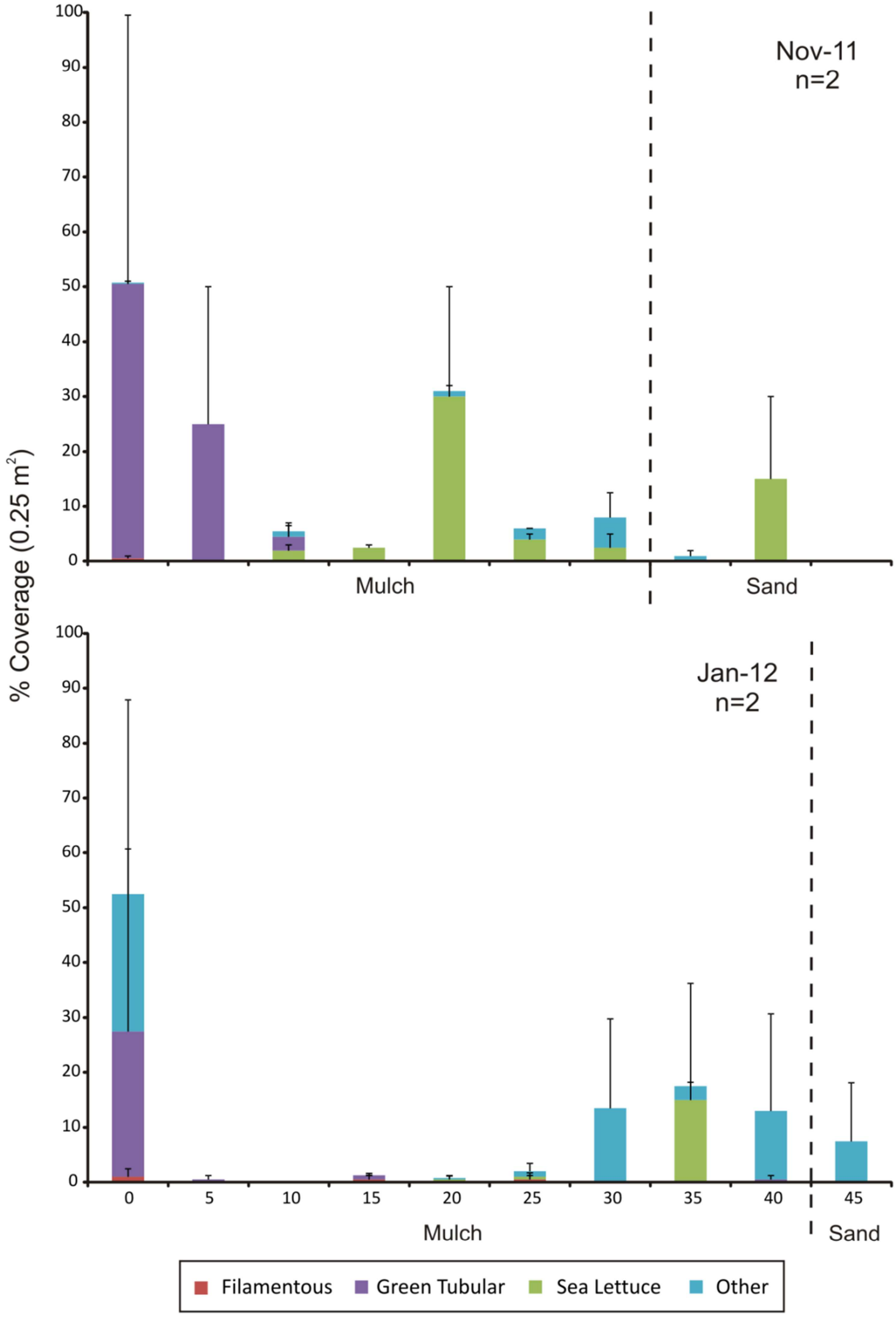

Figure 3-40:Percent cover of macroalgae and species composition at Waikaraka Site 3 in November 2011 and January 2012. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

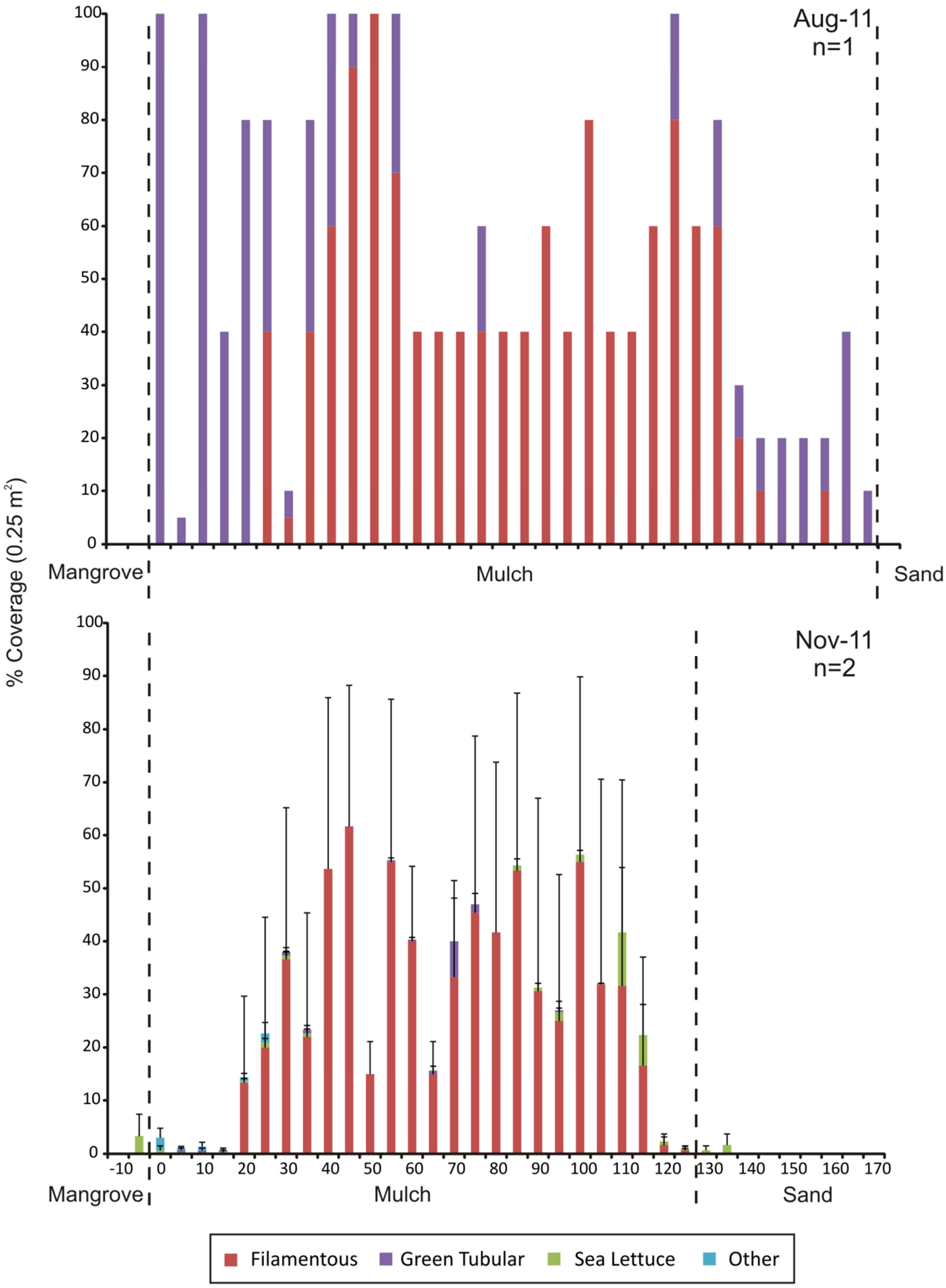

Figure 3-41:Percent cover of macroalgae and species composition at Omokoroa in August and November 2011. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

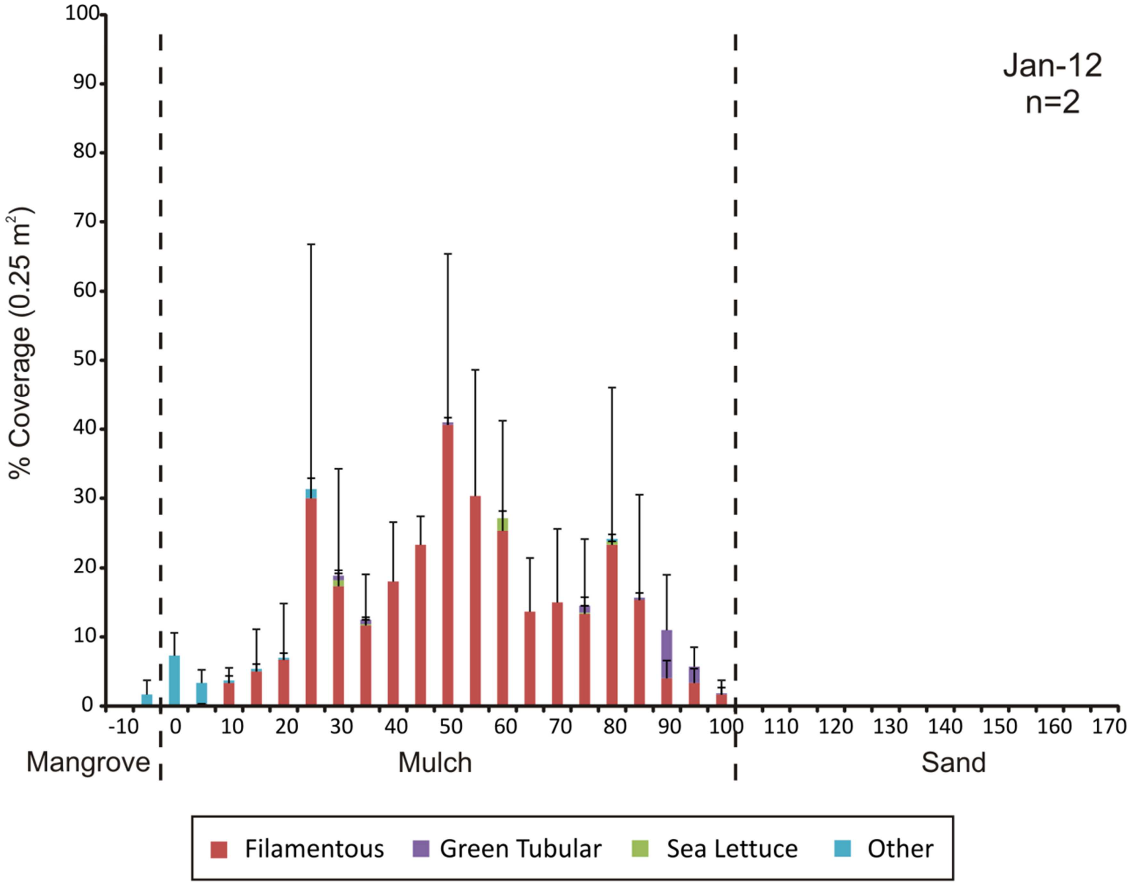

Figure 3-42: Percent cover of macroalgae and species composition at Omokoroa in January 2012. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

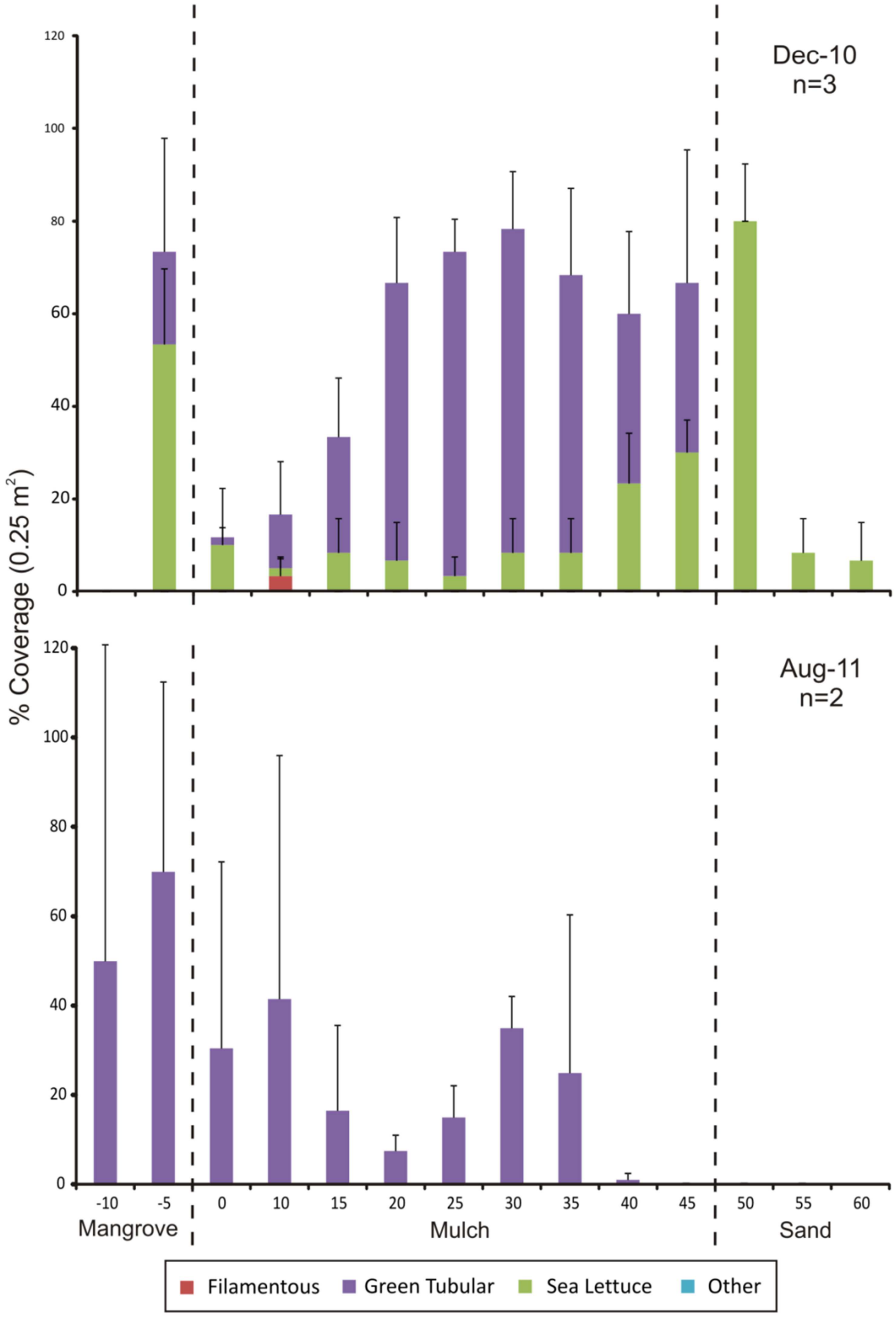

Figure 3-43:Percent cover of macroalgae and species composition at Waikareao in December 2010 and August 2011. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

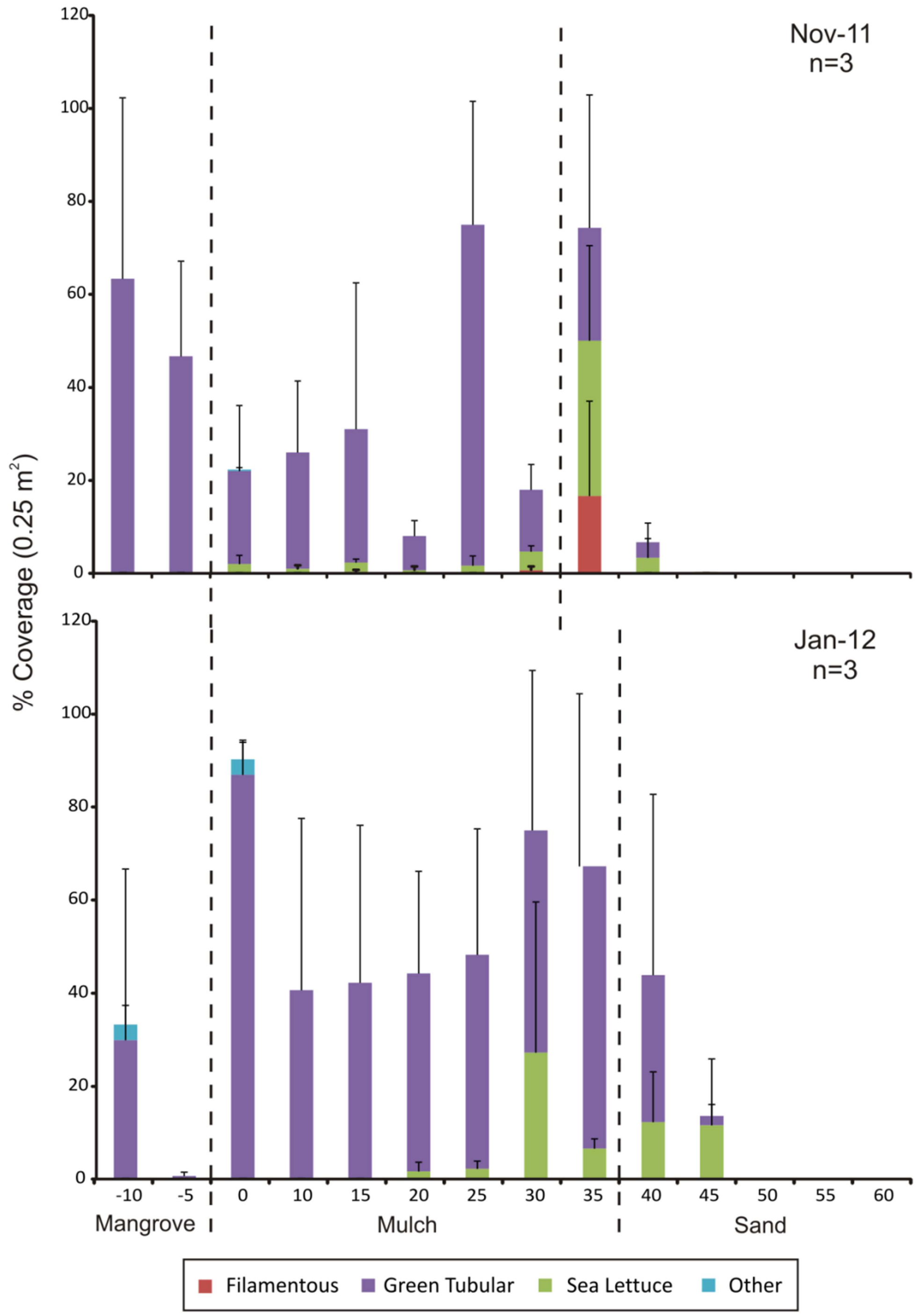

Figure 3-44: Percent cover of macroalgae and species composition at Waikareao in November 2011 and January 2012. Filamentous species including primarily *Percursaria percursa* and *Rhizoclonium* spp.; Green tubular refers to *Ulva* sp. (tubular); Sea lettuce refers to *Ulva* sp. (sheet); 'Other' includes all other species observed, including primarily brown and red algae.

3.7 Nutrient release from mulch material

Laboratory mesocosms were used to infer potential for nutrient release by mangrove mulch material. In the temperature experiment, dissolved oxygen (DO) was rapidly used in all mulch treatments, dropping to < 1 mg/L in less than 48 hours, compared to the control treatments (which stabilised at 5-6 mg/L after 48 hours, Figure 3-45). Nitrate (NO_3) concentrations also differed significantly between control and treatments on all days but day 0 ($p<0.0001$, Appendix B), with NO_3 concentrations decreasing rapidly in the mulch treatments (Figure 3-45). The most likely explanation for the disappearance of NO_3 is denitrification, whereby NO_3 is converted into N_2 gas in a series of steps during anoxic conditions and in the presence of organic carbon substrates. In contrast, NO_3 concentrations increased in control treatments, as the ammonium (NH_4) diffusing out of the sediment was likely being nitrified given the oxic conditions in the overlying water (Figure 3-45). In mulch treatments after oxygen was depleted, no further nitrifying activity occurred, and NH_4 was the primary form of nitrogen that remained. NH_4 concentrations increased in controls over the experimental time period, consistent with the expectation that NH_4 levels would reach an equilibrium based on microbial activity (Figure 3-45), though artefacts of the laboratory setting prevented this behaviour in some mesocosms. Pulses in NH_4 were observed in all treatment mesocosms, and are attributed to presence of the mulch material at the initiation of the experiment. This initial pulse of NH_4 includes contributions of both microbial activity through decomposition of mulch material, and sediment mineralisation. Once anoxic conditions occur in the treatment mesocosms, NH_4 concentrations would be expected to be mainly a function of sediment mineralisation processes and reach equilibrium conditions similar to control mesocosms (Figure 3-45). This is because it takes time for decomposition processes to become established on the mulch. NH_4 does appear to equilibrate to similar values of control mesocosms in two of the treatment temperatures, though the 16ºC temperature treatment dropped to low concentrations of NH_4; this is attributed to be an artefact of the laboratory setting. Phosphate is mobilised from the sediment under anoxic conditions, with release of dissolved reactive phosphate (DRP) significantly higher in treatment than in control mesocosms ($p<0.0001$, Appendix B, Figure 3-45).

Temperature had an effect on nutrient concentrations, with significant differences in NO_3 and NH_4 concentrations between controls at different temperatures for most experiment days, and significant interactions between treatment and temperature detected (Figure 3-45, Appendix B). DRP release increased significantly with increasing temperature in mulch treatments, and significant interactions between treatment and temperature were also found for DRP (Figure 3-45, Appendix B). Here, we infer that reduction of iron and manganese to soluble forms in the sediment was occurring under anoxic conditions, resulting in the release of DRP, and that this rate of release increased with increasing temperature. DO concentration was similar across control treatments, and demonstrated a slightly slower decline in the 16ºC treatment than in the warmer mulch treatment mesocosms (Figure 3-45).

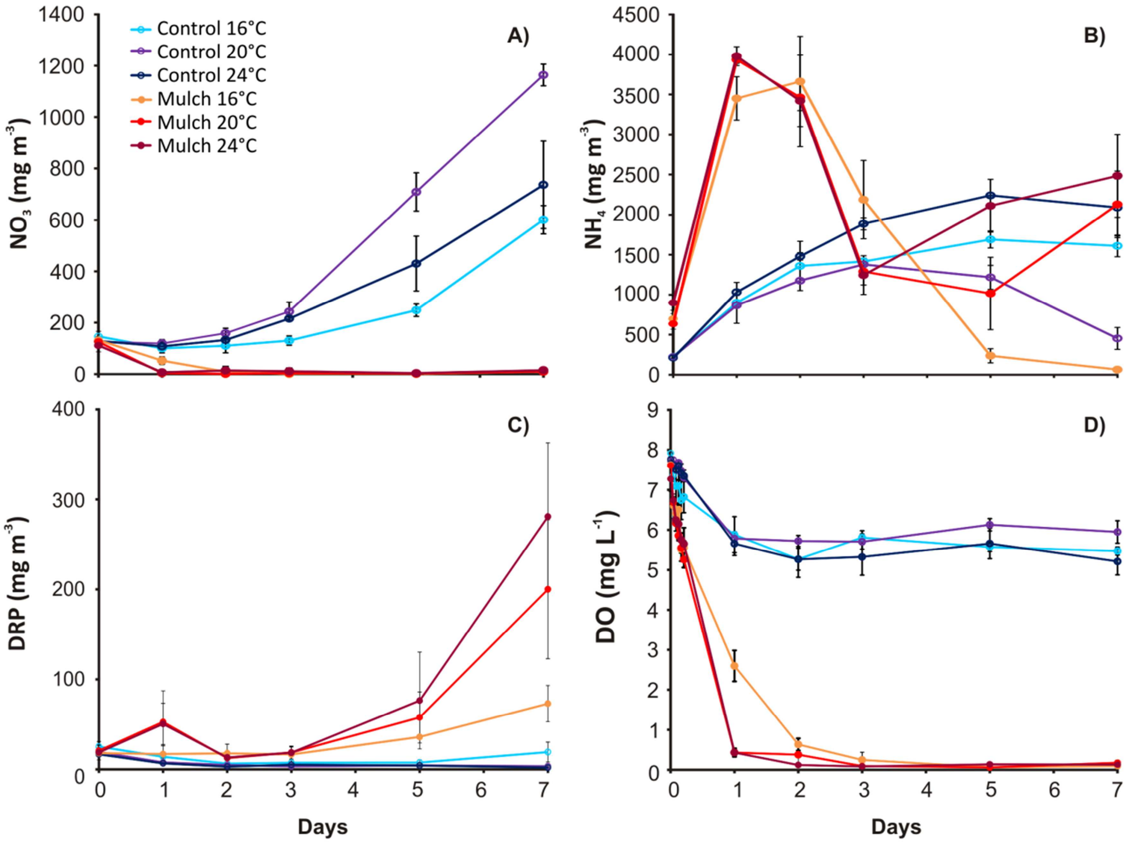

Figure 3-45:Temperature effects on oxygen and nutrient concentration in mangrove mulch laboratory mesocosms. A) Nitrate (NO_3); B) Ammonium (NH_4); C) dissolved reactive phosphorus (DRP); and D) dissolved oxygen (DO).

Patterns of DO, NO_3, NH_4 and DRP were generally similar in the 'mulch age' experiments, with significant differences between control and mulch treatments ($p<0.0001$, Appendix B, Figure 3-46). Age of mulch had significant effects on DRP release into the water column ($p<0.0001$, Appendix B), with almost an order of magnitude increase in phosphate measured in water samples with 5 month old mulch compared to 2 week old mulch (Figure 3-46). This is consistent with an increase in microbial populations associated with the decomposition process as the mulch ages. DO also was used more rapidly in 3 and 5 month old mulch treatments compared to 2 week old mulch treatments (Figure 3-46), also consistent with higher rates of microbial decomposition on the mulch. As in the temperature experiment, NO_3 decreased rapidly in treatment mesocosms, reflecting anoxic conditions (Figure 3-46).

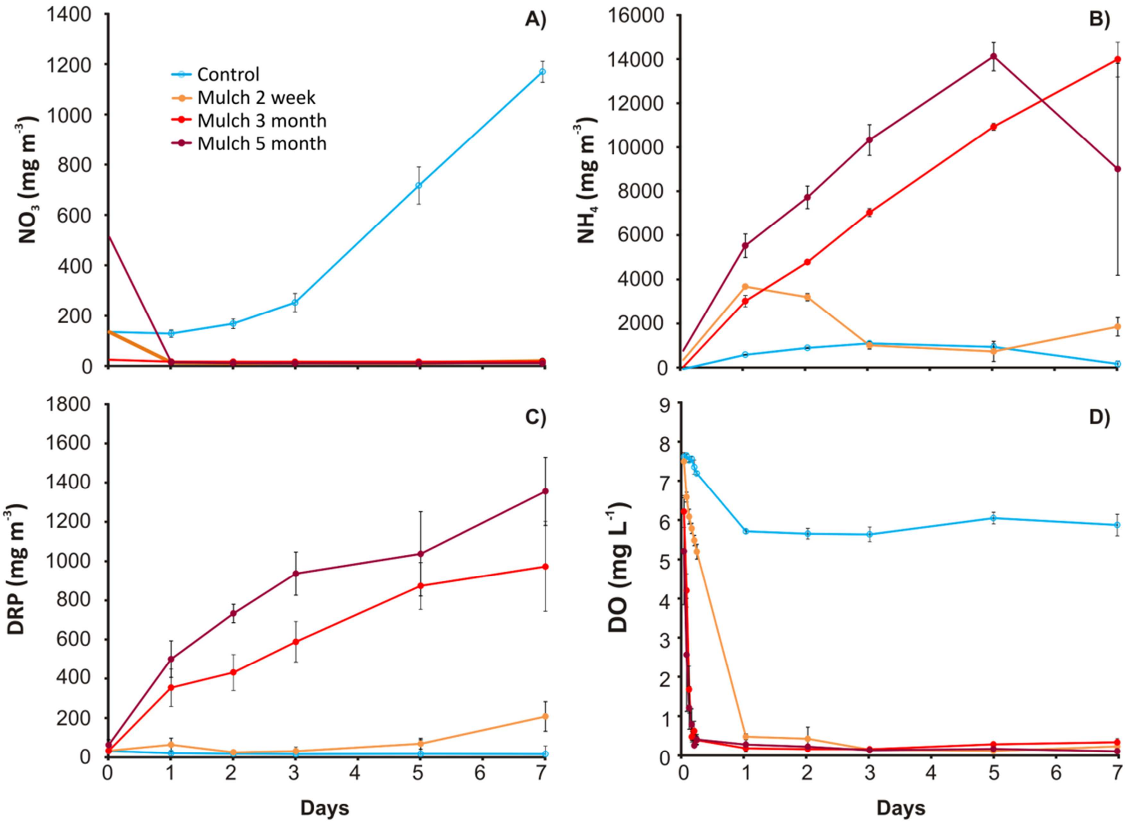

Figure 3-46:Mulch age effects on oxygen and nutrient concentration in mangrove mulch laboratory mesocosms. A) Nitrate (NO_3); B) Ammonium (NH_4); C) dissolved reactive phosphorus (DRP); and D) dissolved oxygen (DO).

Type of mangrove material also resulted in significant differences in nutrient release, with root treatments showing similarities to control treatments: no evidence of anoxic conditions caused by mangrove roots buried in the sediment; and minimal release of DRP from buried mangrove root material (Figure 3-47, Appendix B). As we replicated *in situ* conditions by burying roots rather than leaving roots on the surface of our mesocosms, this potentially reduced the chance for oxic decomposition of root material. We note that *in situ* decomposition of root material does occur for buried roots, but at a slower rate than for unburied root material (Gladstone-Gallagher 2012). In contrast, pneumatophore treatments showed similarities with mulch treatments, with evidence of anoxic conditions and rapid decreases in NO_3 suggesting no nitrification of NH_4 occurring. Release of DRP was almost an order of magnitude lower in pneumatophore mesocosms compared to mangrove mulch mesocosms (5 month old mulch) (Figure 3-47, Appendix B).

DRP releases from the decomposition of the root material in the sediment was likely to be sequestered by the iron and manganese at the sediment surface. Consequently, no increase in DRP would be expected, and this was not seen for phosphorus in the form of either DRP (Figure 3-47) or as total dissolved phosphorus (TDP) (Figure 3-48). Conversely, NH_4 from the decomposing roots would diffuse out of the sediment, showing an increase in NH_4 in root treatments relative to controls (Figure 3-47). Higher concentrations of NH_4 would contribute to higher total dissolved nitrogen (TDN) concentrations in root treatments (Figure 3-48).

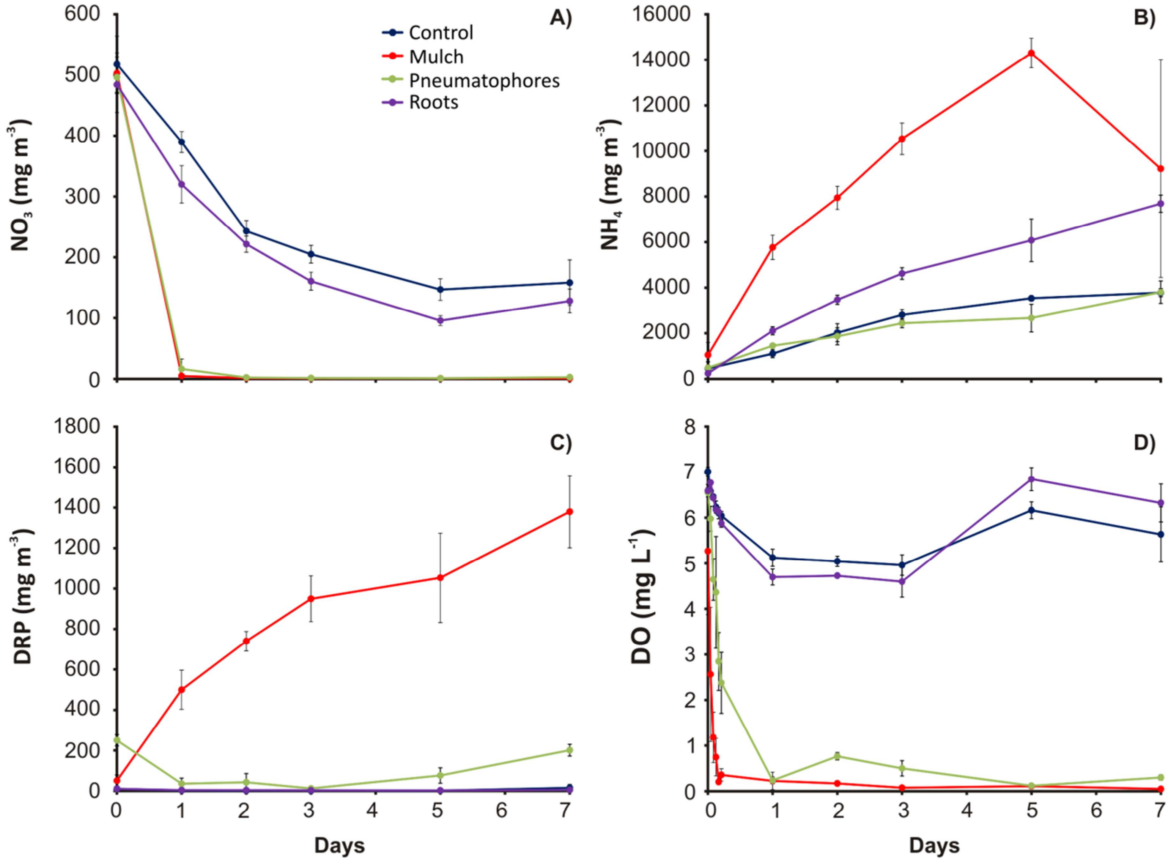

Figure 3-47:Mangrove material type effects on oxygen and nutrient concentration in mangrove mulch laboratory mesocosms. A) Nitrate (NO_3); B) Ammonium (NH_4); C) dissolved reactive phosphorus (DRP); and D) dissolved oxygen (DO).

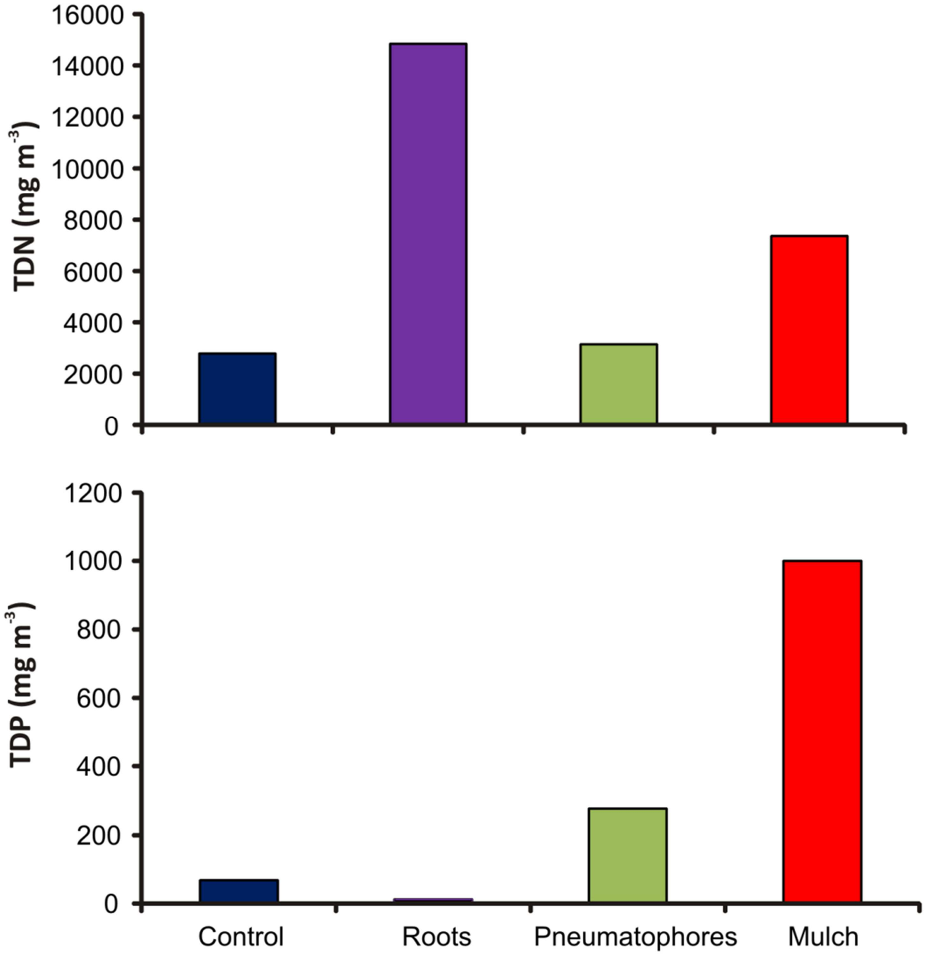

Figure 3-48: Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) from mangrove material experimental treatments.

Pore water measurements of NO_3, DRP and NH_4 show elevated concentrations at *in situ* mulching locations in Tauranga Harbour (Figure 3-49). High concentrations of DRP were detected in the sediment pore water at both sites tested where mangrove mulching had occurred (Waikareao and Waikaraka; *NB* mangroves had not yet been mulched at Welcome Bay at the time of sampling). Elevated levels of DRP were detected in pore water both within the mulch zone and within adjacent mangrove zones (Figure 3-49), consistent with DRP release under anoxic conditions in the sediment. At the Welcome Bay site (prior to mulching of mangroves), DRP concentrations in mangrove zones were similar to adjacent sandflat zones, suggesting that zones with live mangroves do not experience anoxic conditions that would result in release of DRP. Instead, it is more likely that the elevated DRP concentrations detected in and near mulch deposition sites are associated with mangrove mulching.

In addition, while not the purpose of the sampling presented in this report, the pre-mulching data from Welcome Bay suggests high nitrate concentrations indicative of historical leaching from septic tanks (Figure 3-49).

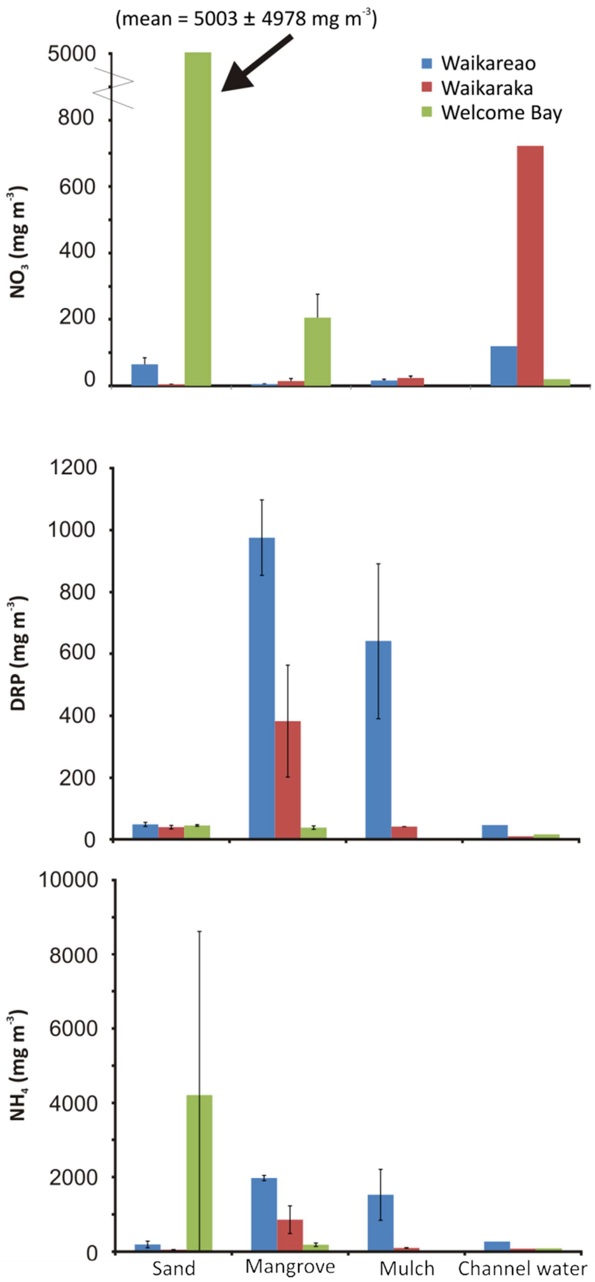

Figure 3-49:Pore Water samples collected from Waikareao, Welcome Bay and Waikaraka estuaries in March 2012. NB Welcome Bay had not yet been mulched at the time of sampling.

3.8 Water column dissolved oxygen saturation

To determine if mulch material might be resulting in decreases in water column oxygen saturation, the dissolved oxygen saturation (%DO) of the overlying water column was measured in September 2010 at different heights about the sediment surface at Waikareao estuary over a mulch zone, and over neighbouring sandflat and mangrove zones. As per Park (2011a,e), we use ANZECC guidelines for the protection of aquatic life (southeast Australia) which require that oxygen saturation is maintained at or above 80% DO. Oxygen saturation was lowest closest to sediment surface, and lower inside mangrove than neighbouring mulch, as expected (oxygen would be removed from the water travelling over the mulch zone before it entered the mangrove zone). The mean %DO of water in the mangrove and mulch zones show a similar pattern of decrease in %DO between 0-20 cm above the sediment (Figure 3-50). There was no decrease in %DO above this in the mangrove zone; however, the mulch zone showed %DO continued to decrease to approximately 40 cm above the bed (Figure 3-50).

%DO in the mangrove and mulch zones remained similar to water overlying the sandflat until the tide turned, and no further incoming harbour/ocean water moved onto the site (Figure 3-50). Decreases in oxygen saturation occurred throughout the receding tide, with oxygen saturation levels decreasing below 50% at both mangrove and mulch sites by the end of the tidal cycle. In contrast oxygen saturation directly above the sand zone was consistent at 80-90 %DO at all tested depths over the period of the experiment (Figure 3-50). We note that we did not measure the entire tidal cycle at the sand zone site to determine if a decline occurred in oxygen saturation when the depleted water from the mulch and mangrove zone flowed past the sandflat site on ebb tide, as we discontinued measurements when water levels were approximately 20 cm at the sandflat site.

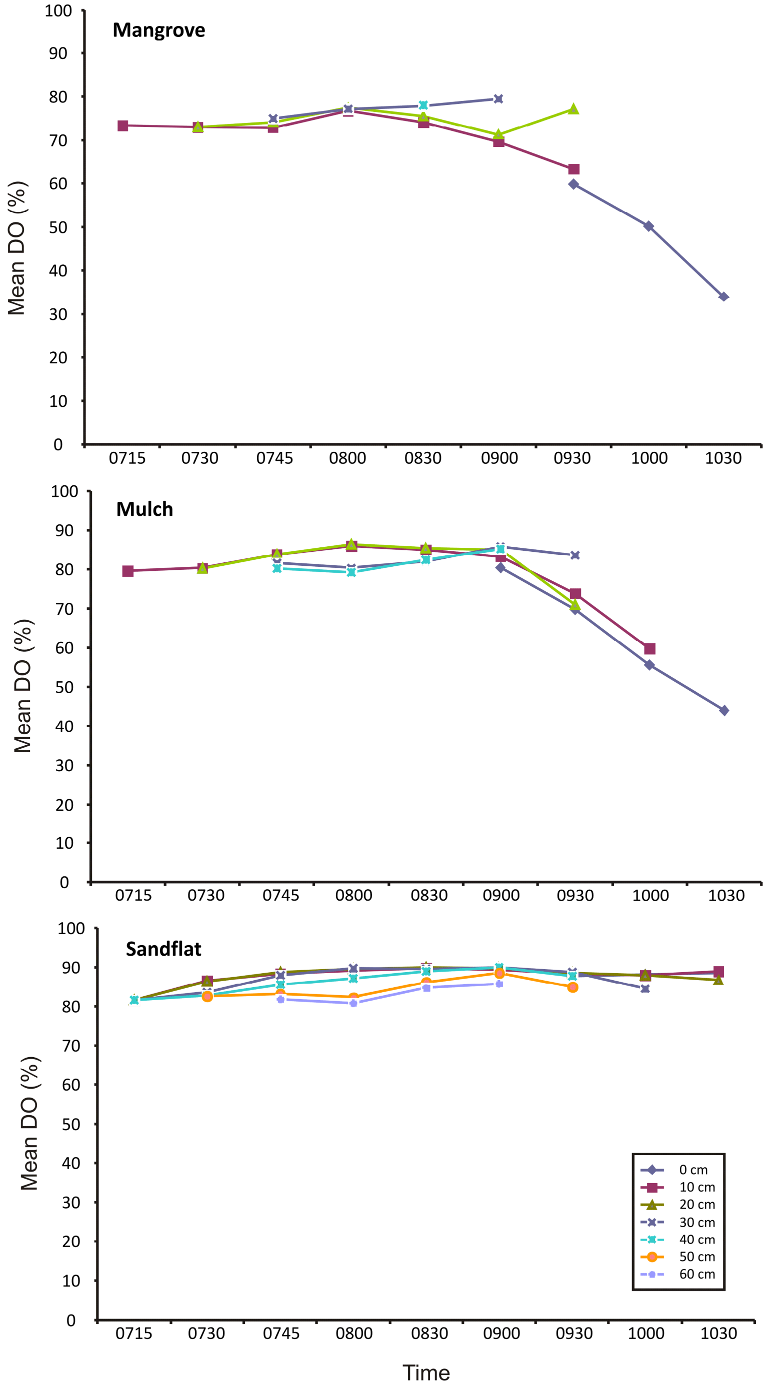

Figure 3-50:Mean percent saturation of Dissolved Oxygen of the water overlying the undisturbed sand flat, mulched mangrove and undisturbed mangroves within Waikareao estuary, depths measured at 2.5, 12.5, 22.5, 32.5, 42.5, 52.5, and 62.5 (legend denotes distance from lowest sampling depth of 2.5 cm).

Continuously sensed data showed similar patterns for sensors located at approximately 12.5 cm above the sediment surface, with declines observed at both mulch and mangrove sites (Figure 3-51). While the sandflat sensor malfunctioned, concurrent vertical measurements at the sandflat suggest DO saturation showed no declines over the tidal cycle at the sandflat site 10 m from the edge of the mulch zone (Figure 3-50).

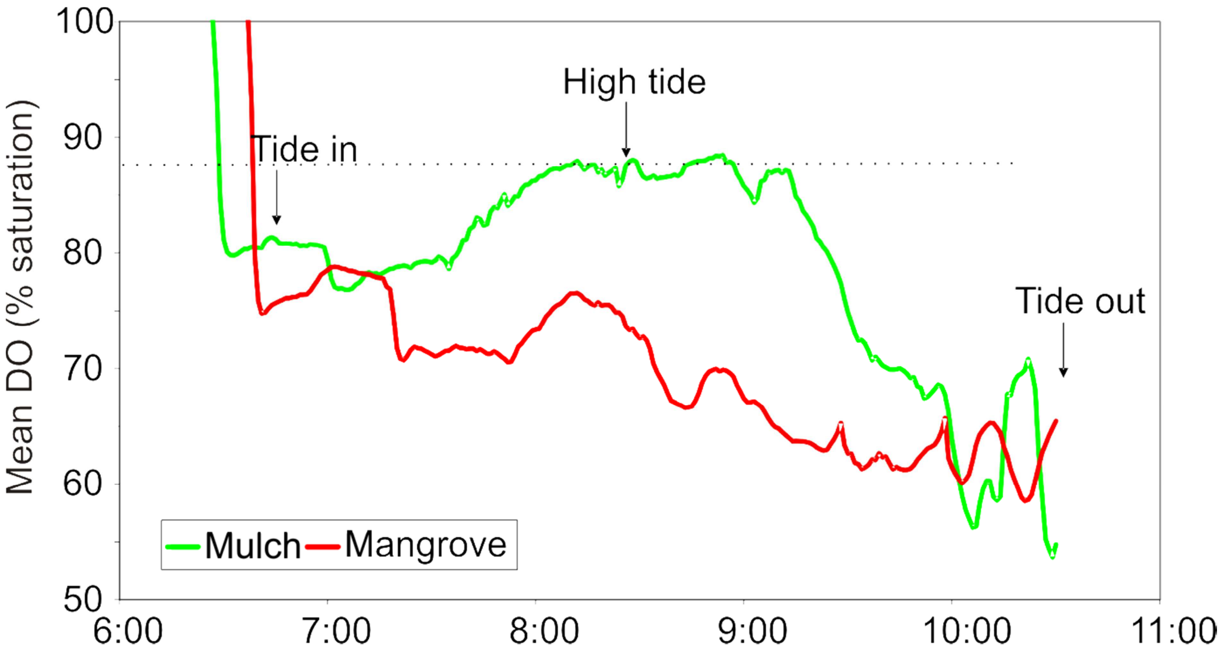

Figure 3-51:Mean Dissolved Oxygen percentage saturation (DO) of the water overlying the mulched mangrove and intact mangroves within Waikareao estuary, measured at 12.5 above the sediment surface. Dotted line suggests DO level at sandflat site based on measurements in Figure 3-50.

Additional continuous oxygen sensor measurements over mulch zones in Waikareao and Waikaraka estuaries in March and April 2011 showed similar decreases in dissolved oxygen saturation, and also documented diurnal variations in oxygen declines at most sites (Table 3-6). Oxygen saturation generally reached lowest levels closest to the seafloor. Oxygen saturation was usually lowest inside mangrove zones, presumably as all water reaching the mangrove site had to pass over the mulch zone during which some deoxygenation occurred. Decreases in oxygen saturation above sandflat zones were generally low in Waikaraka, with 0, 0 and 12% of the tidal cycle having values <80% saturation during the three night tides sampled, and 23 and 40% of the tidal cycle having values <80% saturation during the two daytime tides sampled (Table 3-6). Waikareao, in contrast, showed clear diurnal variation, with all values at the sandflat site measuring above 80% saturation during daytime observations, and 100, 92 and 98% of the tidal cycle experiencing oxygen saturation below 80% during the three evening tides sampled (Table 3-6).

Supersaturation (i.e., DO > 100% saturation) was common during summer daytime conditions, attributed to photosynthetic oxygen production by phytoplankton, microphytobenthos and macroalgae being greater than heterotrophic oxygen demand (Table 3-6). Regardless, the day-night comparisons demonstrate that, without the contributions of primary producers (e.g., conditions that would be experienced regularly at night, during cloud cover, and during autumn/winter), oxygen saturation does decline over mulch zones to levels below 80% oxygen saturation for a large portion of the tidal cycle when the tide is in.

Welcome Bay was chosen as a ‘control’ site for the oxygen survey; however, this site showed similar patterns with respect to declines in oxygen saturation over incoming and outgoing tide (Figure 3-49). While these declines could imply that oxygen declines occur naturally in mangrove ecosystems in New Zealand estuaries, the high concentrations of nitrate measured in pore water samples collected in Welcome Bay suggest that these declines may instead be associated with eutrophication in this estuary. Sampling of water column oxygen saturation in additional intact mangrove ecosystems, while not done as part of this study, would be valuable to allow comparison of natural rates of oxygen decline during tidal cycles to sites with mechanical mulching.

Estuary	High (Slack) Tide Time	%DO	Sandflat 10cm	Mulch 5cm	Mulch 10 cm	Mulch 20 cm	Mangrove 10 cm
Waikaraka	2125 Night	Max	106.76	102.41	99.32	101.04	89.15
		Min	83.63	**51.08**	**57.88**	**72.25**	**59.18**
		Time <80% DO	0%	42%	36%	20%	55%
	0915 Day	Max	96.15	80.93	75.41	77.56	71.80
		Min	**67.78**	**57.80**	**60.03**	**59.09**	**42.81**
		Time <80% DO	40%	91%	100%	100%	100%
	2140 Night	Max	96.67	92.31	88.07	89.82	75.93
		Min	**73.46**	**43.21**	**47.02**	**65.49**	**41.51**
		Time <80% DO	12%	51%	56%	25%	100%
	1000 Day	Max	89.80	94.43	87.43	98.39	79.44
		Min	**71.48**	**66.06**	**66.28**	**71.52**	**62.44**
		Time <80% DO	23%	58%	73%	59%	100%
	2215 Night	Max	99.35	89.06	87.99	90.75	90.95
		Min	83.32	81.08	**77.27**	**79.65**	**70.82**
		Time <80% DO	0%	0%	30%	7%	64%
Waikareao	0415 Night	Max	74.27	74.74	78.90	ND	ND
		Min	**43.88**	**50.99**	**58.43**	ND	ND
		Time <80% DO	100%	100%	100%		
	1635 Day	Max	162.07	153.79	149.77	ND	ND
		Min	119.09	124.48	112.52	ND	ND
		Time <80% DO	0%	0%	0%		
	0505 Night	Max	85.42	76.71	87.62	ND	ND
		Min	**53.80**	**66.79**	**65.35**	ND	ND
		Time <80% DO	92%	100%	95%		
	1725 Day	Max	124.74	126.91	123.06	ND	ND
		Min	94.54	111.51	103.07	ND	ND
		Time <80% DO	0%	0%	0%		
	0600 Night	Max	81.31	89.42	84.47	ND	87.75
		Min	**42.23**	**37.24**	**52.01**	ND	**58.02**
		Time <80% DO	98%	81%	96%		94%
Welcome Bay (prior to mulching)	1850 Dusk	Max	129.49	135.24	131.67	131.67	133.92
		Min	92.14	97.61	95.45	**70.13**	**59.66**
		Time <80% DO	0%	0%	0%	7%	6%
	0700 Dawn	Max	80.78	79.83	82.07	84.07	78.58
		Min	**59.01**	**58.84**	**55.3**	**54.89**	**52.45**
		Time <80% DO	93%	100%	86%	82%	100%
	1920 Dusk	Max	127.90	138.48	134.81	131.75	129.71
		Min	99.77	96.21	99.86	86.27	**61.84**
		Time <80% DO	0%	0%	0%	0%	7%
	0755	Max	76.64	81.42	77.98	84.66	76.23

Estuary	High (Slack) Tide Time	%DO	Sandflat 10cm	Mulch 5cm	Mulch 10 cm	Mulch 20 cm	Mangrove 10 cm
	Dawn	Min	**57.02**	**61.32**	**58.94**	**52.89**	**52.08**
		Time <80% DO	100%	94%	100%	81%	100%
	2040	Max	131.20	140.81	139.21	135.51	125.59
	Dusk	Min	88.20	83.56	86.39	85.57	**65.17**
		Time <80% DO	0%	0%	0%	0%	10%
	0835	Max	89.38	93.52	86.26	89.78	92.18
	Dawn	Min	**76.37**	80.69	**75.79**	**72.00**	**67.41**
		Time <80% DO	7%	0%	55%	6%	40%

Table 3-6: Maximum and minimum dissolved oxygen measurements at Waikaraka, Waikareo and Welcome Bay estuaries in sandflat, mulch and mangrove zones in March/April 2011. Measurements were taken at 5, 10 and 20 cm above the sediment surface in mulch zones, and at 10 cm only in sandflat and mangrove zones. ND = no data collected as tide did not reach the height of the sensor. Shaded regions represent night time conditions. Values <80% oxygen saturation are in bold. High (slack) tides were estimated as the mid-point of the tidal cycle while water was over the sensor.

3.9 Shellfish physiological condition

Cockle physiological condition, mean density and population size class distribution were measured to determine if there were far field impacts of mulching on neighbouring shellfish habitats at Te Puna and Waikaraka estuaries. Cockle condition (weight and volume) was variable over the sampling period, with a marked drop in flesh weight at Te Puna at the 3 month survey, but return to baseline levels for both weight and volume in the 6 months survey (Figure 3-52).

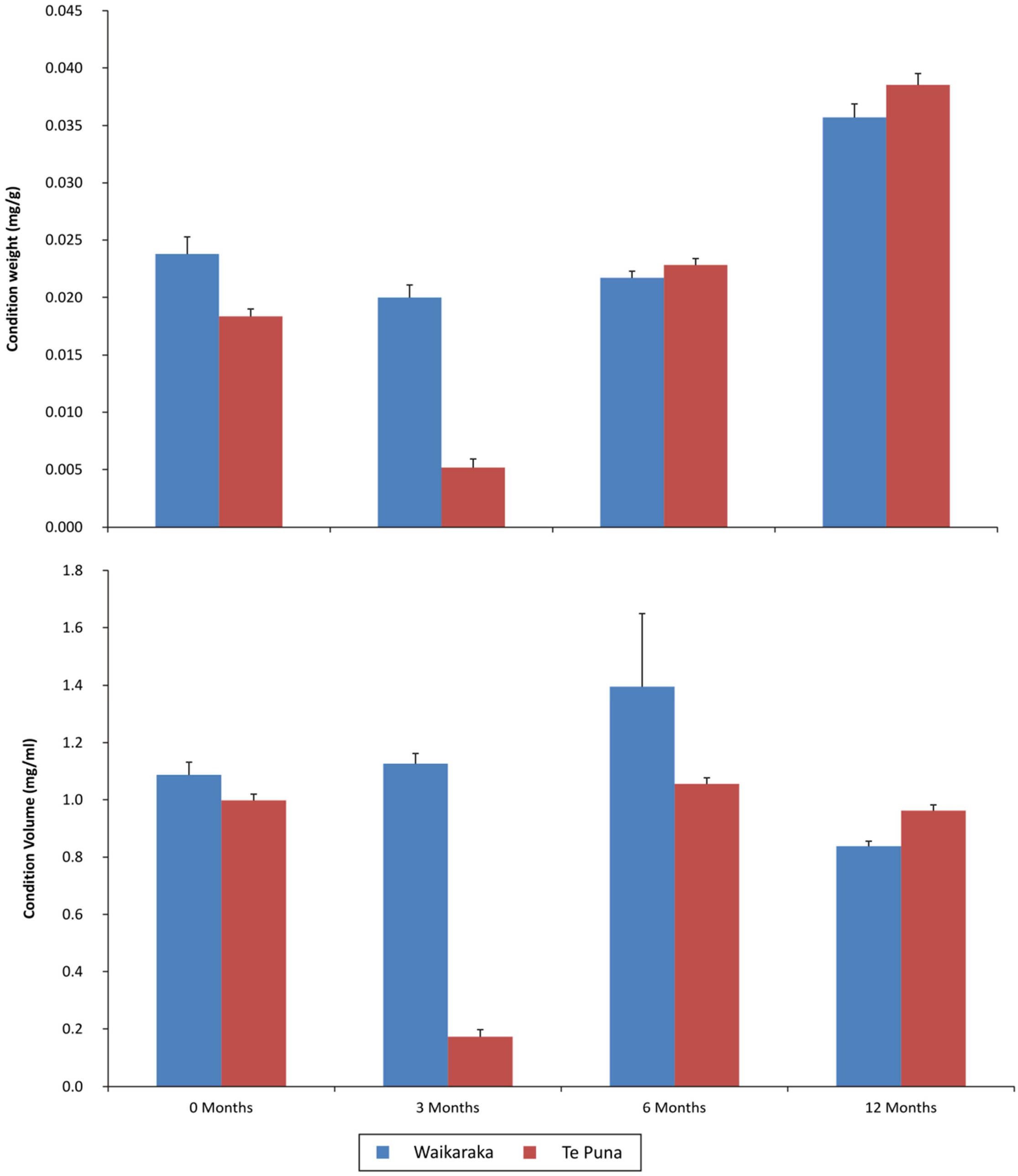

Figure 3-52: The mean weight and volume of cockles (n=50) collected from Waikaraka and Te Puna Estuaries, prior to mulching (0 months), and 3, 6, and 12 months post mulching, +SE .

Mean cockle density did not decrease over time, though cockle density was significantly higher at Te Puna than at Waikaraka throughout the sampling period (Figure 3-53).

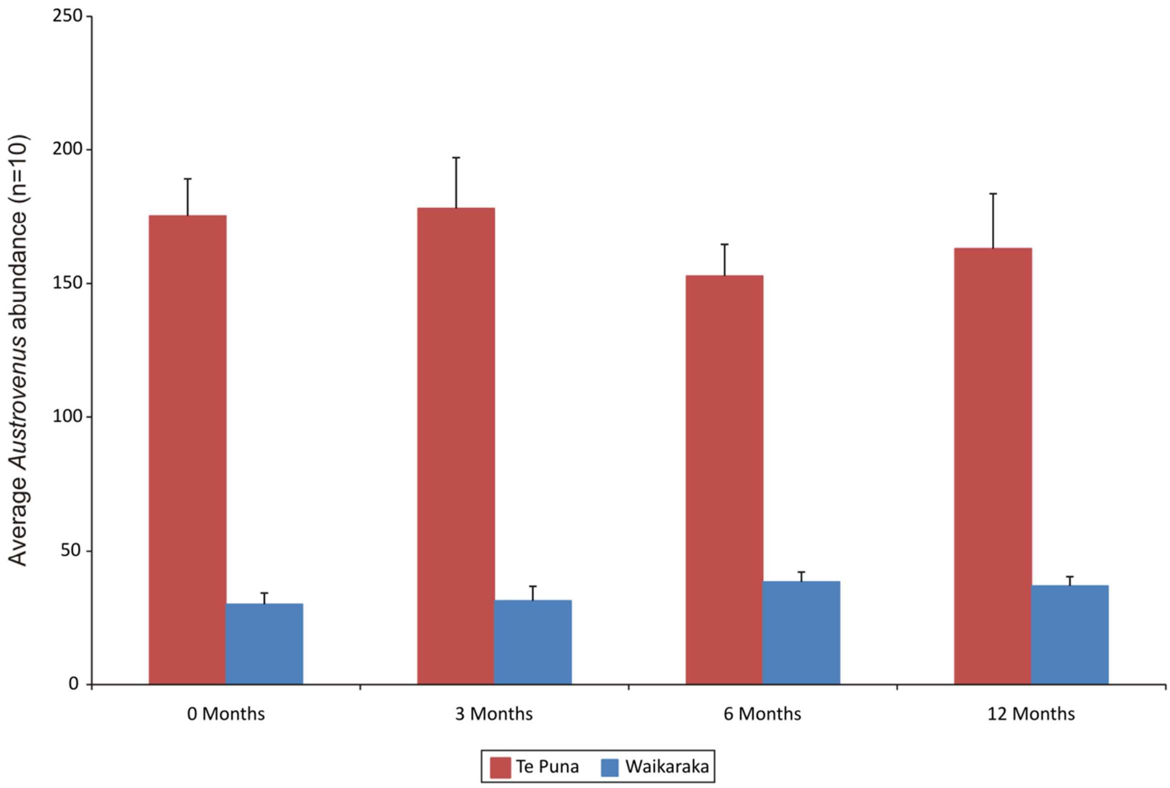

Figure 3-53: Average abundance of *Austrovenus stutchburyi* (n= 10 x 0.25 m^2 quadrats) collected from the cockle collection sites at Te Puna and Waikaraka estuaries.

Size distributions of cockles show expected seasonal variability over time, but no obvious changes that could be attributed to mangrove mulching (Figure 3-54). Cockles were slightly larger at Te Puna than at Waikaraka (Figure 3-54).

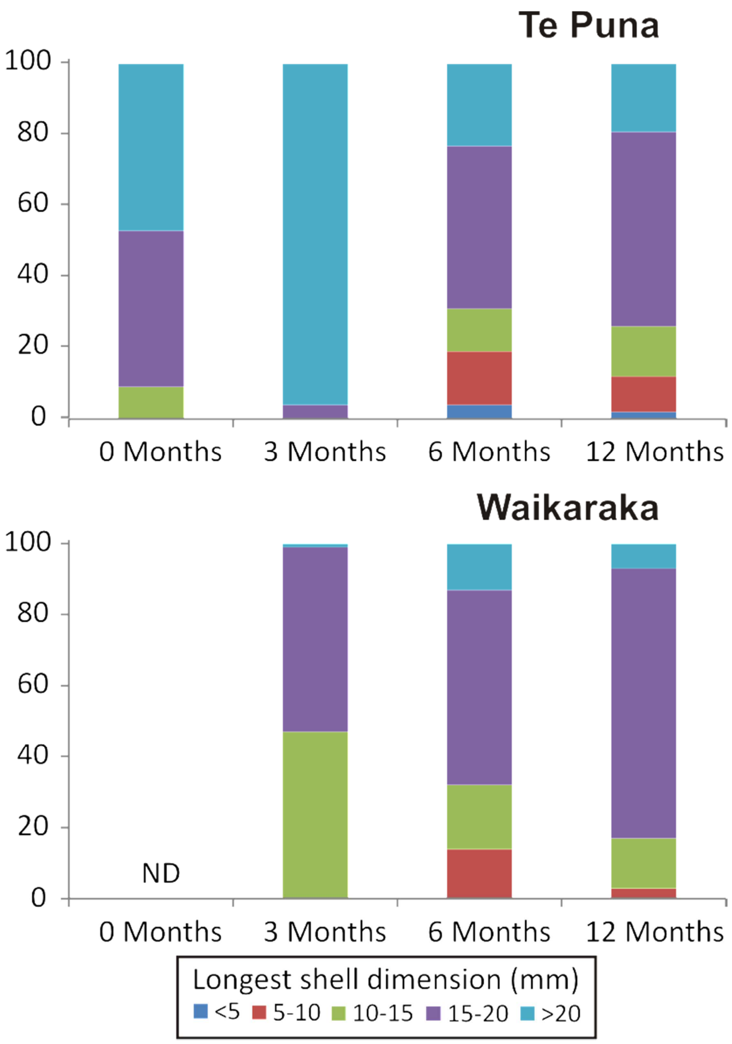

Figure 3-54: Size class distribution of *Austrovenus* at Te Puna and Waikaraka before mulching commenced (0 months) and at 3 months, 6 months, and 12 months post-mulching (n=100).

3.10 Sediment erosion

Sediment trap collections showed minimal evidence of erosion of mulch or sediments from the mulch zone. Trapped sediment weights were similar between zones (mangrove, mulch, sandflat), with lowest sedimentation rates in mangrove traps, and higher sedimentation in mulch and sandflat traps, though none of these differences were significant (Figure 3-55, Figure 3-56, Figure 3-57, Figure 3-58, Figure 3-59). Variability in sedimentation was both spatial (between sites and between estuaries), as well as temporal at some sites, likely due to local variability in wind-waves and sediment deposition.

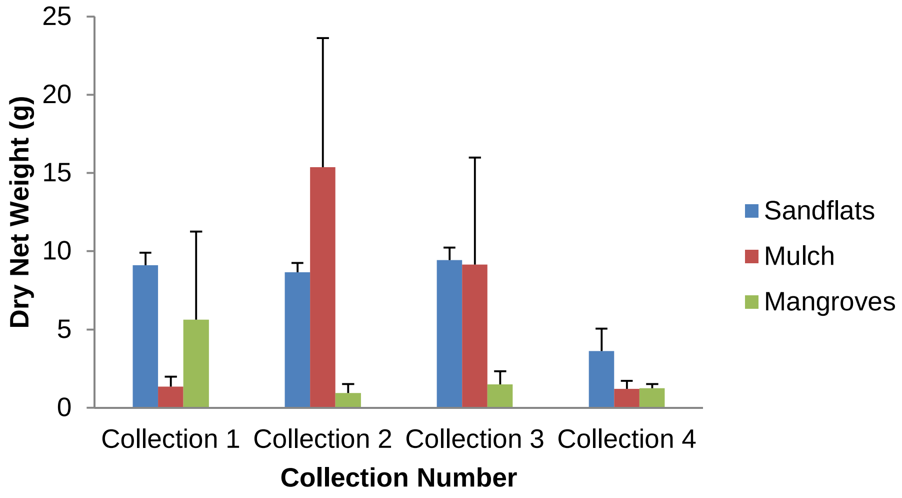

Figure 3-55:Mean dry weight (g) of sediment collected in sediment traps at Te Puna Site 2. Each collection represents total sediment weight collected in a 4 cm diameter trap over ~10 days.

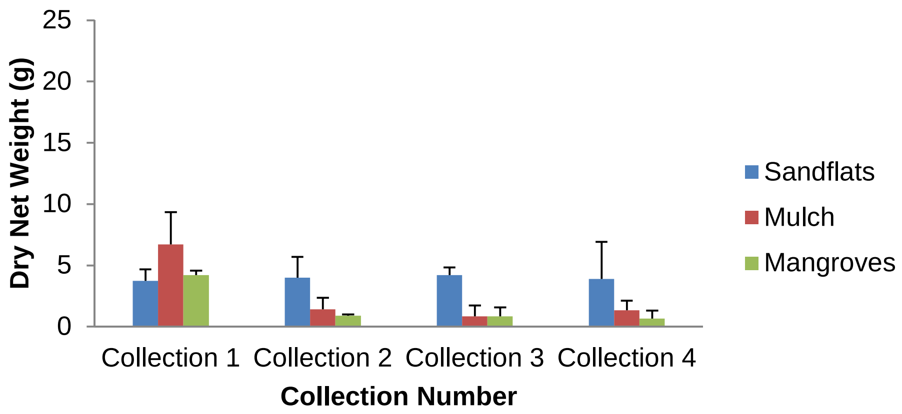

Figure 3-56:Mean dry weight (g) of sediment collected in sediment traps at Te Puna Site 3. Each collection represents total sediment weight collected in a 4 cm diameter trap over ~10 days.

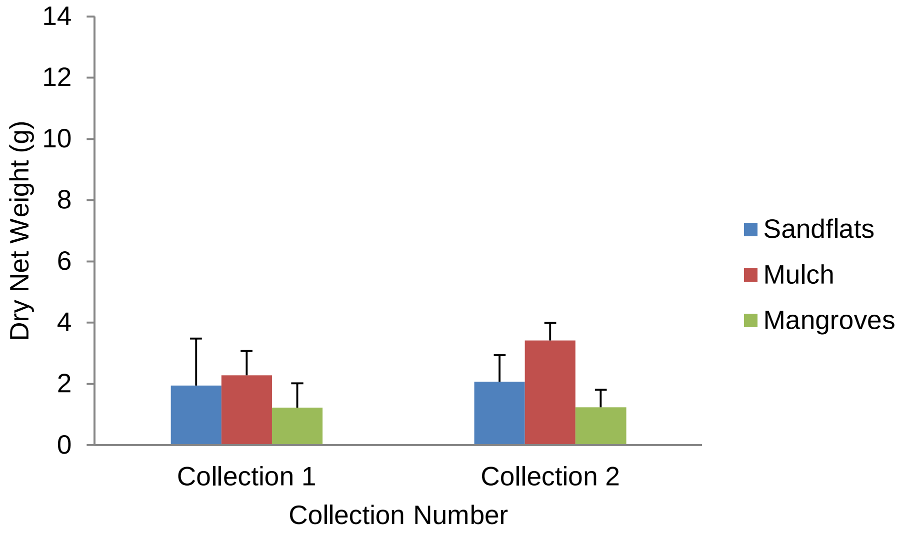

Figure 3-57:Mean dry weight (g) of sediment collected in sediment traps at Waikaraka Site 2. Each collection represents total sediment weight collected in a 4 cm diameter trap over ~10 days.

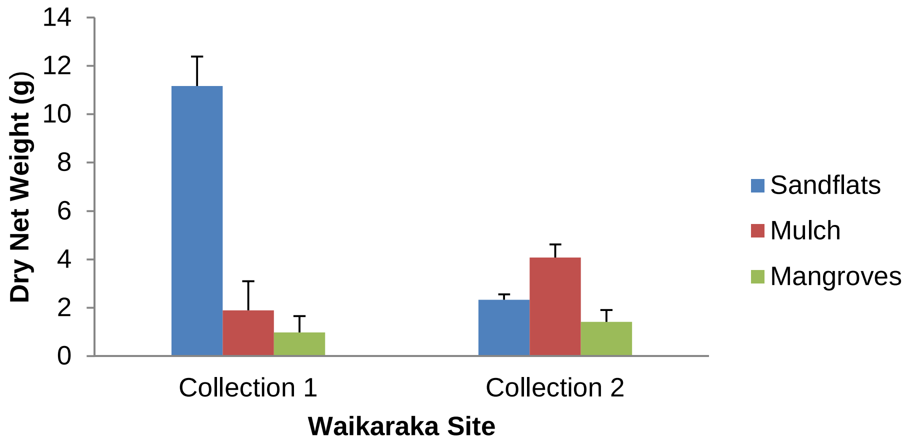

Figure 3-58:Mean dry weight (g) of sediment collected in sediment traps at Waikaraka Site 3. Each collection represents total sediment weight collected in a 4 cm diameter trap over ~10 days.

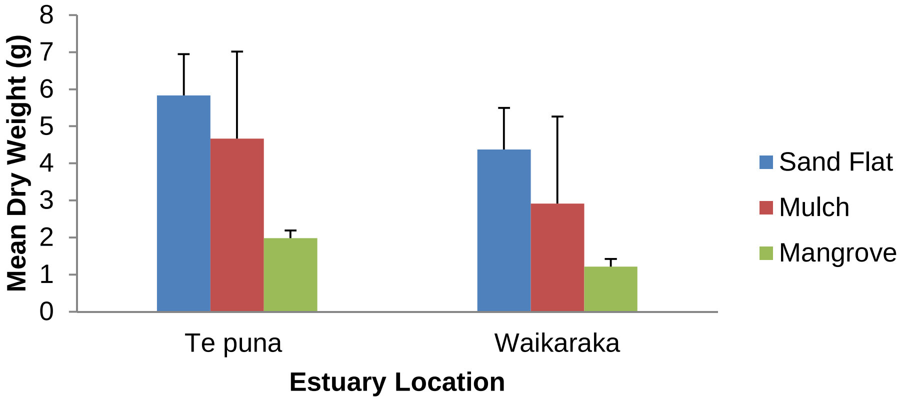

Figure 3-59:Mean dry weight (g) of sediment collected in sediment traps at Te Puna and Waikaraka estuaries.

4 Summary and discussion

4.1 Persistence of mulch material

The primary goal of mangrove removal in Tauranga Harbour is to restore open estuary sandflat conditions in areas that have been colonised by mangroves since the 1960s. A sandier substrate is anticipated to increase the area of suitable habitat for wading and roosting birds and marine life; increase visual amenity values; and increase public access by removing a dense monoculture of mangroves extending up to 100 metres from the shoreline (Resource Consent Application #65505).

Our 12 month survey implies that mangrove mulching using a mechanical tractor and depositing mulch *in situ* results in minimal recovery towards a sandflat community over a 12 month period. After 12 months, substantial mulch biomass still remained on site, with limited dispersal and decomposition of mulch material. Three methods were used to track persistence of mulch material: transect surveys measuring vertical depth of mulch material, measured perimeters of mulch zones, and core samples to determine mulch biomass. While vertical depth of mulch has decreased at some sites, it is possible this is due to compaction rather than any change in mulch material remaining. Perimeters of mulched area showed very slow erosion of the mulch zone over 12 months (range 5-19% decrease in total area), with mulch biomass relatively consistent throughout the mulch zone except for within 5-10 m of the seaward edge, and no apparent decrease in mulch biomass between 6 and 12 month samples. Measurements of decomposition rates of mangrove materials in Whangamata Harbour suggest that wood and root material will take years to break down (Gladstone-Gallagher 2012).

Unfortunately, the results of the small scale mulching trial by BOPRC showed minimal similarities to the actual mulching that took place, in that the mulch trial predicted immediate dispersal of mangrove material. We expect this is primarily due to the size of the actual mangrove removal zones compared to the small size of the trial, but may also be related to the behaviour of the mechanical tractor, which while rated at low psi, instead showed evidence of substantial long-term tracks, and presumably associated compaction of sediments along with the mulch that was deposited on the surface, as the tractor tended to move back and forth repeatedly over a site during the process of removing mangroves. It is also difficult to compare our results to estimates of mulch biomass remaining on site before and after mitigation at Waikareao estuary, as BOPRC methodology did not remove mulch to a standard depth, and used hand removal methods only, limiting quantification of mulch biomass in their survey to large woody debris only, and minimising collection of root and pneumatophore biomass as well as smaller woody debris (Park 2011b,c).

In terms of far-field impacts, sediment erosion and mulch dispersal appeared minimal from mulch sites, implying minimal physical impacts of increased sediment deposition or turbidity related to mulching on neighbouring habitats. Brief increases in mud content were detected in neighbouring habitats (mangroves, sandflats) at the 3 month survey, but returned to baseline grainsize characteristics in the 6 month survey. A decline in shellfish condition was detected at Te Puna at the 3 month survey, though shellfish condition had returned to baseline levels by the 6 month survey, and the limited sampling was not sufficient to separate natural or seasonal changes in cockle condition from any changes associated with mangrove mulching.

4.2 Physical effects of mulching

Anoxic sediments were associated with the mulch zone and the anoxia persisted for at least the 12 months of the survey, except within 5-10 m of the seaward edge at some sites. Oxic layer depths in the mulch zone were severely reduced, often to <2 mm, though oxic depth was not affected at neighbouring sandflat and mangrove zones. Other sediment metrics (mud content, organic content, chlorophyll content, and sediment cohesiveness) continued to be more similar to mangrove than near-by sandflat zones, and no change from mud to sandier sediments was detected in the mulch zone during the 12 month survey. Our results show similarities to the lack of change in sediment grainsize measured by BOPRC at Waikareao estuary, with only minor decreases in mud content that were unlikely to be statistically significant (Park 2011d, Park 2012). In contrast, results collected by BOPRC at Matua estuary show clear changes in mud content after mangrove removal toward sandier sediments (Park 2011d, Park 2012). We suggest recovery at Matua estuary is poorly representative of other sites where mechanical mulching occurred, due to the very small size of mangrove removals at Matua (1.2 ha in total) relative to the large total size (540 ha) and exposure of the estuary. Mulch mitigation at the Waikareao estuary monitoring site could also potentially limit its representativeness of long-term recovery dynamics after mechanical mulching (Park 2011d, Park 2012).

4.3 Benthic community

Transect surveys of all faunal groups (gastropods, bivalves), except crabs, showed minimal colonisation of the mulch zone through 12 months. Crab burrows increased both in neighbouring sandflat and within the mulch patches after mangrove removal, often with highest abundance at the edge of the mulch zone. Other taxa showed more delayed colonisation.

Macrofaunal core samples indicate that while some colonisation is occurring, the resulting community is formed of opportunistic species, most of which are tolerant of anoxic conditions. Benthic communities in mulch zones were dominated by oligochaetes, *Capitella* sp., and dipterid (fly) larvae including *Ephydrella* sp. and Psychodidae, whereas sandflat sites included spionid polychaetes, gastropods, and bivalves as dominant taxa. By 12 months, communities in mulched sites were generally not becoming more similar to nearby sandflat communities, and generally showed distinct communities compared to both mangroves and sandflats. In contrast, opportunistic sampling of a manual mangrove removal location at Waikaraka Site 3 showed similarities in benthic community composition to nearby sandflat communities in the Waikaraka estuary. While univariate metrics such as species richness and number of individuals did show increases over time at most sites, multivariate comparisons of benthic community composition suggest that colonising species are primarily disturbance-tolerant species, and that the mulch zones are not trending toward sandflat community composition.

Our benthic community results are similar to those collected by BOPRC at 5 months post-mulching at Waikareao estuary (Park 2011d), with observations of minimal colonisation by benthic fauna; though, we would disagree with Park's interpretation of his results as a recovery trend. Monitoring at Matua and Waikareao was repeated by BOPRC in January 2012, suggesting further colonisation by benthic communities, though the fauna at mulched sites appears more similar to neighbouring mangrove sites (Park 2012). Mulch zones at both estuaries were dominated by the freshwater gastropod *Potamopyrgus estuarinus* that is common in the neighbouring mangrove sites, and had poor representation of taxa typical of sandflat habitats such as estuarine gastropods and bivalves. We do, however, agree with Park that the BOPRC mangrove removal monitoring includes just a preliminary analysis of two estuaries, and that “a comprehensive review of all the Tauranga Harbour sites where mangrove removal has been conducted needs to be undertaken” (Park 2011d).

4.4 Unanticipated impacts

Macroalgal blooms were observed on all mulch sites, and on some occasions, reached 100% cover in large (>1 ha) patches at some locations. Seasonal and between-site variability in macroalgal abundance was apparent. However, all macroalgal bloom species were Ulvaceae, an algal family known to respond to increased nutrient concentrations with increasing growth rates. While *Ulva* sp. (sheet form, aka sea lettuce) was detected at the edge of many patches, and could potentially have washed in from outside the mulch patches, most macroalgal blooms consisted of other species (*Ulva* sp. (tubular form); filamentous species such as *Rhizoclonium* spp. and *Percursaria percursa*) which were clearly attached to pneumatophores or remaining mulch material, and growing directly on site. It is also of interest that *P. percursa* had previously not been documented on New Zealand’s North Island (Pratt et al. in press).

Laboratory experiments demonstrated high rates of nutrient release associated with the deposition/decomposition of mangrove mulch, resulting in elevated concentrations of phosphorus and ammonia in the water column. Field sampling of pore water nutrients confirmed laboratory predictions of elevated concentrations of phosphorus and ammonia associated with mulch zones in Waikareao and Waikaraka estuaries. Laboratory results also suggest that nutrient release is associated with both bacterial decomposition of mangrove mulch and sediment mineralisation due to the anoxic conditions associated with mulch zones. We recommend additional field surveys of water column nutrient concentrations, and chamber experiments to quantify rates of in situ nutrient release from mulch zones.

Field sampling of water column oxygen saturation levels detected decreases in oxygen concentrations below 80% saturation over both mulch zones and mangrove zones inshore of mulch zones. Our sampling was more comprehensive that that undertaken by BOPRC (Park 2011a,e). First, as BOPRC samples were only taken during daylight hours, photosynthetic oxygen production may have compensated for oxygen consumption associated with the decomposition of mulch material, though decreases in BOPRC samples did occur over their sampling period. Secondly, it is important to measure oxygen dynamics throughout the tidal cycle, not just at incoming or high tide, as the strongest decreases we observed were in the latter half of the tidal cycle, when the water column over the mulch zone was no longer being refreshed with influx of harbour water. Regardless, we recommend further sampling of an intact mangrove habitat, as our sampling did not include an adequate control site (due to high nitrate concentrations in Welcome Bay), to determine if declines in oxygen saturation occur over a tidal cycle in intact mangrove habitats.

4.5 Comparison to other methods

Our understanding of recovery after mangrove removal in New Zealand estuaries is limited, as long-term trajectories in sediment characteristics and benthic community structure are poorly documented at most mangrove removal sites. Anecdotal evidence suggests a few areas have returned to sandier habitats in ~5 years since clearing (e.g., Patiki Bay, Whangamata (Coffey 2002); hand cleared areas only in Matua, Waikaraka and Waikareao estuaries, Tauranga (C. Lundquist, pers. obs.). However, other sites (e.g., Moanaanuanu estuary in Whangamata Harbour) have not returned to sandier habitats (Felsing 2006, Stokes 2009). Site-specific factors that are anticipated to affect the return to sandflats after mangrove removal include differences in hydrodynamics (wind-wave exposure, tidal currents), terrestrial-based sediment inputs, freshwater influx, and local sediment characteristics. Sites that have returned to sandflats are generally located in exposed areas with high fetch or near tidal creeks with strong tidal currents. In addition, the scale of all mangrove removal efforts prior to mechanical mulching in Tauranga Harbour has been small (generally <0.5 ha per annum).

Benthic community recovery has been limited at the sites that have been monitored for benthic community changes after mangrove removal. Lower abundance but increased number of species was observed at Pahurehure Inlet (unpublished monitoring report, Auckland Council). Recovery after non-mechanical clearing of a small mangrove area (0.26 ha fringe) was associated with rapid decreases in mud content and colonisation by benthic macrofauna, though long-term trends were confounded by a large sediment deposition event associated with development projects in the local catchment (Alfaro 2010). Observations of manual removal sites at Waikaraka and Matua estuaries adjacent to mechanical clearing areas suggest the potential for rapid change (within 5 years) to sandflat communities at many of these locations when using non-mechanical removal methods, and strongly contrast with observations of recovery trajectories with the mechanical mulching and *in situ* disposal method.

In comparison to other natural disturbance events in estuaries such as catastrophic sediment deposition from large storm events, numerous experiments by NIWA in intertidal and shallow subtidal New Zealand estuaries suggest at least partial, if not full, recovery from disturbance after 6 months to 2 years, with recovery time dependent on depth of deposited sediment (Thrush et al. 2003, 2004, 2008). While some, though not all, non-mechanical mangrove removal trajectories have shown positive recovery trends over similar timelines, the mechanical removals monitored here, at Waikaraka and Te Puna in Tauranga Harbour, are not trending toward sandflat habitats in either benthic community or sediment properties, and instead are demonstrating properties of limited oxic zones and depauperate opportunistic faunal communities.

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Appendix A Site photos

Te Puna, August 2011 (C. Lundquist)

Waikaraka, August 2011 (C. Lundquist)

Omokoroa estuary, August 2011 (C. Lundquist)






Waikareao estuary, November 2011 (C. Lundquist)






Appendix B Statistical results

Available upon request.