Waikato Regional Council Technical Report 2019/29

Subtidal seagrass surveys at Slipper and Great Mercury Islands

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

Waikato REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

Prepared by:
Dana Clark and Dan Crossett (Cawthron Institute)

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

September 2019

Document #: 14824276

Peer reviewed by:

Michael Townsend Date September 2019

Approved for release by:

Mike Scarsbrook Date September 2019

SUBTIDAL SEAGRASS SURVEYS AT SLIPPER AND GREAT MERCURY ISLANDS

DANA CLARK, DAN CROSSETT

Prepared for Waikato Regional Council

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Paul Gillespie

APPROVED FOR RELEASE BY:
Grant Hopkins

ISSUE DATE: 31 July 2019

RECOMMENDED CITATION: Clark D, Crossett D 2019. Subtidal seagrass surveys at Slipper and Great Mercury Islands. Prepared for Waikato Regional Council. Cawthron Report No. 3347. 32 p. plus appendices.

EXECUTIVE SUMMARY

Subtidal seagrass meadows are rare in New Zealand and are now largely restricted to offshore islands. This report summarises the results of subtidal seagrass surveys at two islands off the coast of the Coromandel Peninsula that were carried out for the Waikato Regional Council in May 2019. We mapped the extent of the seagrass meadows at South Bay, Slipper Island and Huruhi Harbour, Great Mercury Island and collected information on key parameters that indicate the health and condition of seagrass (seagrass cover, leaf length, above-ground biomass) as well as indicators of stress (cover of macroalgae and epiphytes and the severity and prevalence of fungal wasting disease). Results were compared with previous surveys, as well as other seagrass meadows within New Zealand, with the aim of understanding how these subtidal meadows have changed over time and providing a baseline for variables not previously measured.

The seagrass meadow at South Bay, Slipper Island (0.19 km^2) was 2–6 times larger than estimates from previous surveys and was found to extend into the neighbouring bay. Differences in extent between surveys are likely a result of improved mapping techniques in the current survey, although temporal fluctuations may have also contributed. The health and condition of the seagrass meadow appears comparable with that observed in 2004, with winter biomass higher than recorded in intertidal seagrass meadows elsewhere in New Zealand and leaf length at the upper end of subtidal values.

Seagrass meadow extent (0.09 km^2) at Huruhi Harbour, Great Mercury Island appears to have declined significantly (83%) since 1975, particularly in the upper reaches of the harbour. Almost no seagrass was found north of the jetty on the eastern side of the harbour, although it was recorded here as recently as 2004. Seagrass was also observed in the neighbouring Parapara Bay, covering a similar area as estimated in 1975. The health and condition of the seagrass at Huruhi Harbour appears to have improved since 2004; however, this could be an artefact of survey design because subtidal portions of the meadow (which are not subjected to the stress of exposure at low tide) were more represented in the 2019 survey. Above-ground biomass at Great Mercury was at the lower end of average values observed elsewhere in New Zealand, and while leaf length was at the lower end of the range observed in subtidal meadows, it was greater than observed in many intertidal meadows.

Epiphyte cover was low at both sites (1% cover) and where macroalgae was present it did not appear to have a significant shading effect on seagrass plants. The prevalence (35–38%) and severity (< 1% cover) of the fungal wasting disease *Labyrinthula* was also similar between sites. Although disease symptoms were relatively minor, green areas of 'healthy-looking' tissue can also be affected by *Labyrinthula*, therefore, these meadows may still be exposed to considerable photosynthetic stress.

In this study, we trialled three visual biomass assessment techniques as a non-destructive and rapid method for future sampling. Visual biomass ranks and seagrass cover estimated using the dots-on-rocks (DOR) approach were found to be the best proxies for harvested above-ground biomass (R^2 = 0.75, 0.73, respectively). Seagrass cover estimated using the Braun-Blanquet method was a slightly poorer predictor of above-ground biomass (R^2 = 0.63) but the most time-efficient approach. For future surveys, we suggest using seagrass cover, estimated using the DOR or Braun-Blanquet method, as a proxy for above-ground biomass because these approaches are more time efficient and likely to be less affected by observer variation than the visual biomass assessment technique.

Given the unique nature of these offshore subtidal seagrass meadows, we recommend continuing to monitor their extent and condition to enable early detection of change and timely management action. The Slipper and Great Mercury Island seagrass meadows have been shown to be important for supporting biodiversity and fish populations. They represent some of the only subtidal seagrass meadows documented in New Zealand, therefore, consideration should be given to further protection for these areas.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1. INTRODUCTION

Subtidal seagrass meadows are rare in New Zealand, with most seagrass now found only in intertidal areas of estuaries. While subtidal seagrass beds may have once been common in subtidal channels of sheltered estuaries, permanently submerged meadows in New Zealand are now primarily restricted to offshore islands (Turner & Schwarz 2006a). The Waikato region has three known areas of subtidal seagrass; Huruhi Harbour[1] (Great Mercury Island), South Bay (Slipper Island) and Whangapoua Harbour. The Huruhi Harbour and South Bay beds were surveyed in the 1970s (Grace & Whitten 1974; Grace & Grace 1976) and in 2004 (Schwarz et al. 2006) and were recently checked by divers in 2017.

Waikato Regional Council (WRC) commissioned the Cawthron Institute to carry out a non-destructive field survey of the subtidal seagrass meadows at Huruhi Harbour and South Bay. The aim of the survey was to delineate the extent of the subtidal seagrass meadows and describe the ecological health and condition of the meadows.

New Zealand has only one species of seagrass, *Zostera muelleri* (previously known as *Z. capricorni* or *Z. novaezelandiae*; Jacobs et al. 2006). Seagrass meadows are recognised as having high ecological value and are regarded as one of the most valuable coastal ecosystems in terms of the ecological services they provide (Costanza et al. 1997). They are highly productive habitats, supporting the wider coastal area via net export of organic material (Hailes 2006) and accounting for 15% of the net global CO_2 uptake by marine biota (Duarte & Chiscano 1999). Seagrass beds also act as a sink for terrestrially-derived nutrients (Short 1987) and stimulate nutrient cycling (Pellikaan & Nienhuis 1988). Their rhizomes and roots stabilise the sediment, while the three-dimensional canopy promotes sediment deposition, contributing to improvements in water quality (Fonseca 1996; Heiss et al. 2000).

The structure provided by seagrass meadows, in what is often an otherwise homogenous, soft-sediment environment, also influences the diversity, abundance and spatial distribution of flora and fauna (Henriques 1980; Turner et al. 1999; van Houte-Howes et al. 2004). At Slipper Island, twice as many taxa and more than three times the number of individuals have been found within the seagrass bed compared with adjacent bare sediments (Schwarz et al. 2006). The seagrass bed also provided sleeping grounds for a number of fish species, including adult red mullet and northern bastard red cod (*Pseudophycis breviuscula*; Schwarz et al. 2006). Seagrass meadows also provide important nursery functions for juvenile fish (Morrison et al. 2014a) and there is evidence that subtidal beds may be more important in this role than intertidal beds (Morrison & Francis 2001). The seagrass beds at Great Mercury Island were found to support high abundances of sand gobies, juvenile yellow-eyed mullet and

[1] Called Huruhi Bay by Schwarz et al. (2006)

snapper, with juvenile snapper densities the highest recorded in any habitat in New Zealand (Schwarz et al. 2006).

Seagrass meadows have declined in extent worldwide (Short & Wyllie-Echeverria 1996), and New Zealand is no exception (Inglis 2003). Between the 1920s and 1970s, significant declines in seagrass extent took place in estuaries and harbours around Whangarei, Auckland, Whangamata, Tauranga and Christchurch (Inglis 2003). Subtidal seagrass beds have been particularly affected, with 90% of subtidal seagrass lost in Tauranga Harbour (Park 1999), which suggests conditions have become less suitable for the growth of permanently submerged plants (Inglis 2003).

Causes of seagrass loss are often attributed to declines in water clarity and quality associated with human activities. In particular, increased sediment and nutrient loads can degrade the light environment through increased water turbidity and the stimulation of phytoplankton, macroalgae and epiphytes (Short & Wyllie-Echeverria 1996). Seagrass beds can also be impacted by the release of toxic compounds in coastal waters (e.g. oil spills, industrial discharge) and direct mechanical damage from activities such as dredging, coastal development and anchoring (Short & Wyllie-Echeverria 1996). Other factors that may impact seagrass meadows include severe storms, overgrazing and/or competition from natural or introduced species and fungal wasting disease (Matheson et al. 2009).

Fungal wasting disease is caused by the marine slime mould *Labyrinthula zosterae* and is thought to be responsible for the catastrophic die-off of *Zostera marina* meadows along the Atlantic coasts of North America and Europe during the 1930s (Ralph & Short 2002). *Labyrinthula* was detected in New Zealand in the 1960s and may have been linked to widespread losses of seagrass in harbours during this period (Armiger 1964). Since then, *Labyrinthula* has been found in seagrass populations throughout New Zealand (Armiger 1965; Woods & Schiel 1997; Ramage & Schiel 1999; Gillespie et al. 2012a, 2012c, 2012b; Berthelsen et al. 2016; Šunde et al. 2017). Blooms may occur when conditions are favourable (low light, warm temperatures, high salinity; Ralph & Short 2002) and seagrass may be more susceptible when it is stressed due to adverse environmental conditions or anthropogenic impacts (Turner & Schwarz 2006a). Recent research has demonstrated that seagrass is more vulnerable to infection by *Labyrinthula* when exposed to elevated nitrate concentrations and herbicides, providing support for the hypothesis that disease outbreaks may be linked to increased use and runoff of fertilisers and herbicides (Hughes et al. 2018).

Given the vulnerability of seagrass meadows to environmental change, effective management of these habitats requires the collection of accurate information on their distribution and condition (McKenzie et al. 2001; Turner & Schwarz 2006a). This study maps the extent and location of the seagrass meadows at South Bay, Slipper Island and Huruhi Harbour, Great Mercury Island. At each site, we collected information on key parameters that indicate the health and condition of seagrass (seagrass cover, leaf length, above-ground biomass; Duarte & Kirkman 2001) as well as indicators of stress (cover of macroalgae and epiphytes and the severity and prevalence of fungal wasting disease). Results were compared with previous surveys, as well as other seagrass meadows within New Zealand, with the aim of understanding how these subtidal meadows have changed over time and providing a baseline for variables not previously measured. We also trialled the use of visual biomass assessment techniques as non-destructive and rapid method of estimating above-ground biomass.

2. METHODS

2.1. Study areas

Slipper and Great Mercury islands are situated off the eastern coast of the Coromandel Peninsula, New Zealand (Figure 1). A private resort occupies most of Slipper Island, which is located 8 km southeast of Pauanui. Great Mercury is privately-owned, pest-free, and one of the Mercury Islands, 35 km north of Whitianga. Survey timing was comparable with the May–June 2004 survey; South Bay, Slipper Island, was surveyed on 21 May 2019 and Huruhi Harbour, Great Mercury Island, was surveyed on 22 May 2019. Tidal ranges (spring) at Slipper and Great Mercury islands are 2.05 m and 2.24 m, respectively (NIWA 2019). All subsequent references to 'Slipper' and 'Great Mercury' refer to these bays unless otherwise stated.

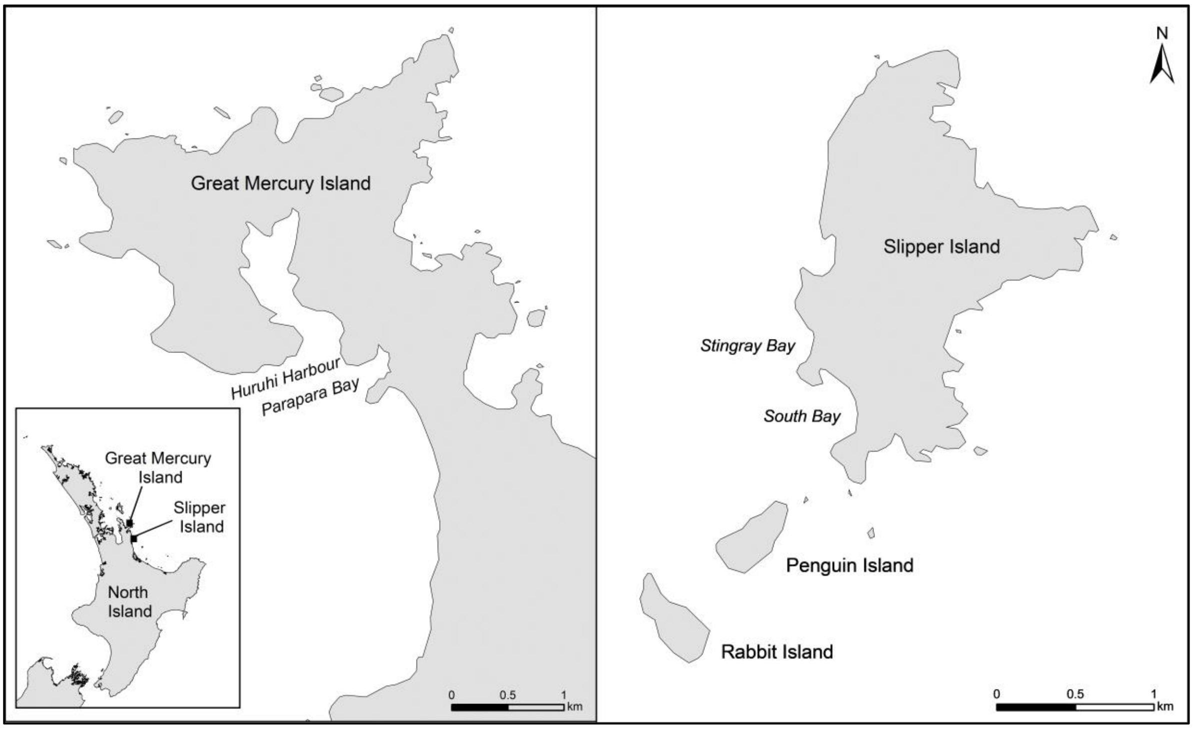


Figure 1. Great Mercury (left) and Slipper (right) islands, offshore from the Coromandel Peninsula, New Zealand. Seagrass meadows were surveyed in Huruhi Harbour and Parapara Bay, Great Mercury Island and Stingray and South bays, Slipper Island (black areas).

2.2. Mapping seagrass extent

Recent aerial photographs of the study sites were obtained from the Waikato Regional Aerial Photography Service (WRAPS; Slipper Island, 2017, Great Mercury Island 2012; Figure 2). Prior to going out in the field, seagrass meadow extent was digitised from the aerial photographs using GIS. Once in the field, the boundary of each seagrass meadow was ground-truthed by tracking the perimeter of the bed using a

GPS with single position fixes recorded every 5 seconds. Where water clarity was sufficient, seagrass extent was assessed by observers from the boat, while in deeper or more turbid areas a snorkeller judged the seagrass coverage.

Following previous survey methodology (Schwarz et al. 2006), seagrass meadow boundaries were determined as the point where seagrass cover exceeds 5%. As noted by Schwarz et al. (2006), this decision rule underestimates the potential niche available for seagrass growth (i.e. some plants will extend beyond this point) and does not take into account bare patches within the bed.

Seagrass extent was also estimated in two other bays—Stingray Bay, north of South Bay (Slipper Island) and Parapara Bay, east of Huruhi Harbour (Great Mercury Island)—but these areas were not mapped as thoroughly as South Bay and Huruhi Harbour as this was beyond the scope of the study.

2.3. Determining seagrass health and condition

Six temporary, 100 m long transects were laid within each seagrass meadow, with GPS points taken at the start and end of each transect so they can be revisited in the future (Appendix 1). At Slipper Island, the seagrass meadow was stratified into three depth strata and two transects were surveyed in each depth band (Figure 2). The seagrass meadow at Great Mercury was narrower so single transects were spread evenly across the depth gradient of the meadow (Figure 2).

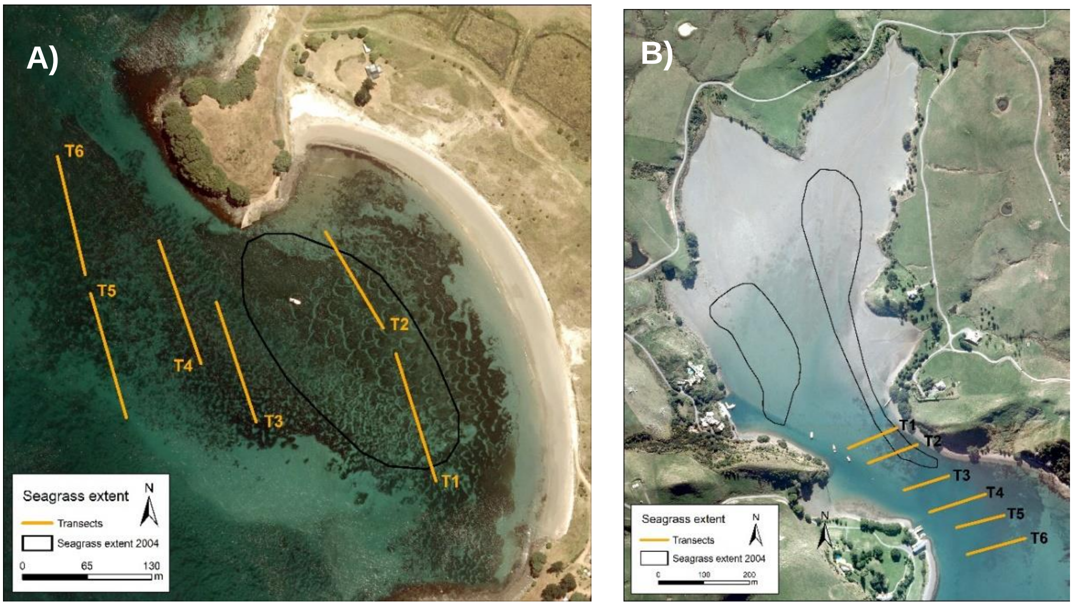


Figure 2. Transect locations surveyed at A) South Bay, Slipper Island and B) Huruhi Harbour, Great Mercury Island. Seagrass extent estimated during the 2004 survey is indicated by the black polygons and numbering indicates the start of each transect. Aerial imagery was supplied by Waikato Regional Council and is from 2017 (Slipper Island) and 2012 (Great Mercury Island).

Key parameters that indicate the ecological health and condition of seagrass (seagrass cover, leaf length and above-ground biomass; Duarte & Kirkman 2001) were quantified at fixed points by SCUBA divers. Cover of macroalgae and epiphytes and the presence and severity of fungal wasting disease were also recorded to provide indicators of stress.

2.3.1. Seagrass cover

Cover of seagrass was estimated within a 0.25 m^2 quadrat at 5 m intervals along each transect. Following Schwarz et al. (2006), cover was estimated *in situ* using the Braun-Blanquet cover scale (Braun-Blanquet 1932), which is an international standard for estimating seagrass cover that reduces observer bias. The technique involves estimating percent cover within five cover classes: 1 = 1–5%, 2 = 6–25%, 3 = 26-50%, 4 = 51–75%, 5 > 75% (Appendix 2). Concurrent photo-quadrats were also collected to provide a permanent record, which can be more accurately quantified later if required.

2.3.2. Seagrass leaf length

Canopy height characterises the structural role of the seagrass, including the habitat and refuge services these meadows provide. Seagrass leaf length was estimated within a ~0.02 m^2 quadrat at 10 m intervals along each transect. In each quadrat, we measured the maximum height of 10 haphazardly selected seagrass blades. Maximum height was chosen to be comparable with the 2004 survey.

2.3.3. Seagrass biomass

The structural role of seagrass depends largely on the amount of material it develops above and below ground. Biomass is a useful measure for monitoring because it responds to perturbation quickly and in a sufficient amount to be detected statistically (Duarte & Kirkman 2001). However, the collection of samples for biomass quantification is destructive, particularly for below-ground biomass, which requires the removal of rhizomes and roots.

Due to the sensitive nature of subtidal seagrass meadows, we carried out small-scale sampling of above-ground biomass only. The above-ground portion of the biomass is a more responsive indicator of disturbance than below-ground biomass and collection is less destructive, with bare patches recolonised within a few months (Duarte & Kirkman 2001). We wanted to test whether a visual estimate could be used as a proxy for above-ground biomass as a non-destructive and rapid method for future sampling. We tested three different visual measures: 1) visual assessment of above-ground biomass, 2) seagrass cover estimated using the Braun-Blanquet scale (refer Section 2.3.1) and 3) cover estimated using a dot-on-rocks (DOR) method (Meese & Tomich 1992), where presence or absence of seagrass was recorded across a grid of 30 points.

For the visual assessment of biomass, we developed a set of standard ranks, which although likely to be less accurate than quantitative harvesting techniques, will allow more samples to be taken, ensuring that a representative area is assessed across the seagrass meadow. Following the methods of Mellors (1991), five reference quadrats were selected to represent a scale against which the above-ground biomass in each sample was compared. To develop the reference scale, quadrats were placed in different areas of the seagrass meadow, ranging from an area which was visually determined to have the highest biomass (Rank 5) to an area deemed to have the lowest biomass (Rank 1). Ranks 2 to 4 were placed in areas midway along this visual biomass gradient. Reference and sample quadrats were photographed so they can be referred to for future sampling (Appendix 3).

During the transect surveys, above-ground biomass was visually ranked and then harvested from two small (0.0225 m^2) quadrats per transect. Four additional biomass samples were collected at Slipper Island to ensure sufficient replicates across the full range of the biomass scale. Seagrass material was separated from the sediment and thoroughly rinsed through a 1-mm sieve to ensure the removal of attached sediment and invertebrates. Following Schwarz et al. (2006), seagrass material was oven-dried at 80 °C for 48 hours, then the dried samples were transferred to a desiccator, and once cool, were weighed on a balance.

Harvested dry weight biomass values were then compared to visual biomass estimates and seagrass cover estimated using the Braun-Blanquet method and the DOR method (refer Section 2.3.8).

2.3.4. Macroalgae cover

Macroalgae can shade seagrass plants and monitoring is essential as an early warning signal of seagrass growth limitations (Kirkman 1996). Cover of macroalgae was estimated within a 0.25 m^2 quadrat at 5 m intervals along each transect, using the Braun-Blanquet cover scale described earlier (Braun-Blanquet 1932).

2.3.5. Epiphyte/sediment cover

Like macroalgae, epiphytes can shade seagrass and monitoring their abundance can be a useful indicator of eutrophication within the seagrass meadow. A semi-quantitative scale (Appendix 4) was used to estimate the cover of epiphytes on 10 haphazardly selected seagrass blades within a ~0.02 m^2 quadrat at 10 m intervals along each transect. At Great Mercury Island, fine sediments were trapped by the epiphytes, contributing to light attenuation, and as it was difficult to discriminate between sediment and epiphytes, they were considered together at this site.

2.3.6. Fungal wasting disease

Fungal wasting disease is characterised by patches of darkened leaves (Burdick et al. 1993), with histological examination of leaves confirming the link with *Labyrinthula* cells (Berthelsen et al. 2016). Prevalence and severity of fungal wasting disease was estimated within a ~0.02 m^2 quadrat at 10 m intervals along each transect. In each quadrat, 10 seagrass blades were haphazardly selected and the presence and severity of *Labyrinthula* infection, as indicated by patches of darkened leaves, was ranked using the Wasting Index Key (Appendix 4; Burdick et al. 1993).

Seagrass samples from each site were sent out to a medical laboratory for histological processing. They were examined on return to Cawthron. Each site sample was subsampled into four histology cassettes; three contained *Z. muelleri* leaf blades with black/brown patches typical of *Z. muelleri* die-back and the fourth contained root material. All material was fixed in formalin seawater for 48 hours followed by standard histological processing to produce haematoxylin and eosin (H&E) -stained slides, which were observed under a microscope to confirm the presence of the *Z. muelleri* die-back pathogen, *Labyrinthula zosterae*. It was identified by its fusiform shape (~15 µm x 3 µm), purple-grey granular cytoplasm, and a large nucleus with a prominent nucleolus at the cell mid-point. Either side of the nucleus there is a vacuole of similar size to the nucleus.

2.3.7. Additional information

Photo-quadrats (0.25 m^2) were taken at 5 m intervals along each transect, concurrent with our *in situ* field estimates. This provides a permanent visual record of seagrass cover and biomass as well as the cover of macroalgae and epiphytes and the presence of fungal wasting disease. These indicators can be accurately quantified later if required. Video footage and depth information (reported as MSL depths) were also collected, and fauna incidentally observed within the seagrass meadows were noted.

2.3.8. Statistical analyses

Leaf length, epiphyte/sediment cover and fungal wasting disease severity were averaged at the quadrat level (10 blades per quadrat). Depth is known to be an important factor influencing seagrass meadow characteristics (Duarte & Kirkman 2001), so for each site a series of generalised additive models (GAMs) were fitted with depth as the independent variable and seagrass indicators (seagrass cover, leaf length, above-ground biomass, epiphyte/sediment cover, fungal wasting disease severity, fungal wasting disease prevalence) as the dependent variables. For fitting the GAMs, we used a beta regression family when the response variable was a proportion and an ordered categorical family when the response variable was categorical. These models allowed for including an interaction effect, and this was used to examine differences in seagrass indicators between sites. Where significant interactions between 'Site' and 'Depth' were found, separate models were fitted for each site.

In order to better understand significant differences between sites, Kruskal-Wallis rank sum tests were also performed on each of the indicators with only 'Site' as a factor (the effect of depth was not included). A Kruskal-Wallis was used because the data were not normally distributed. A zero above-ground biomass value at Slipper Island was omitted from the above analyses to be comparable with the 2004 survey, which only included biomass estimates from within seagrass patches. Statistical analyses were not carried out for macroalgal cover as no macroalgae was observed at Great Mercury Island.

To assess the effectiveness of the visual biomass assessment techniques, calibration curves were established by regressing quantitatively harvested above-ground dry weights (n = 28) against the corresponding visual score (visual biomass rank, seagrass cover assessed using the Braun-Blanquet scale or seagrass cover assessed using the DOR method) using GAM models. Following Mellors (1991), zero values were retained in the analysis as a measure of patchiness within the seagrass bed. When predicting biomass values using the regression equations, where low ranks predicted negative values, the smallest positive value determined by the accuracy of the balance (0.01 g) was inserted for that rank. Refer to Appendix 5 for full statistical results. All analyses were carried out using R (version 3.5.3; R Core Team 2019).

3. RESULTS

3.1. Seagrass extent

In 2019, the seagrass meadow at South Bay (Slipper Island) covered an area of c. 0.19 km^2, more than six times larger than the 0.03 km^2 area estimated in 2004 and more than twice the 0.07 km^2 area estimated in 1973 (Figure 3). Seagrass was relatively dense across most of the meadow, becoming patchier near the edges and with depth. The meadow extended to a maximum depth of 7.9 m (MSL) in 2019, deeper than the 5–6 m (MSL)[2] estimated in earlier surveys. In 2019, seagrass was also found to extend north into Stingray Bay (0.03 km^2 of total area) and was more extensive here than estimated in 1973 (Figure 3). As observed in 1973, the headlands of South Bay and the inner area of Stingray Bay were comprised of boulders covered with *Carpophyllum* macroalgae.

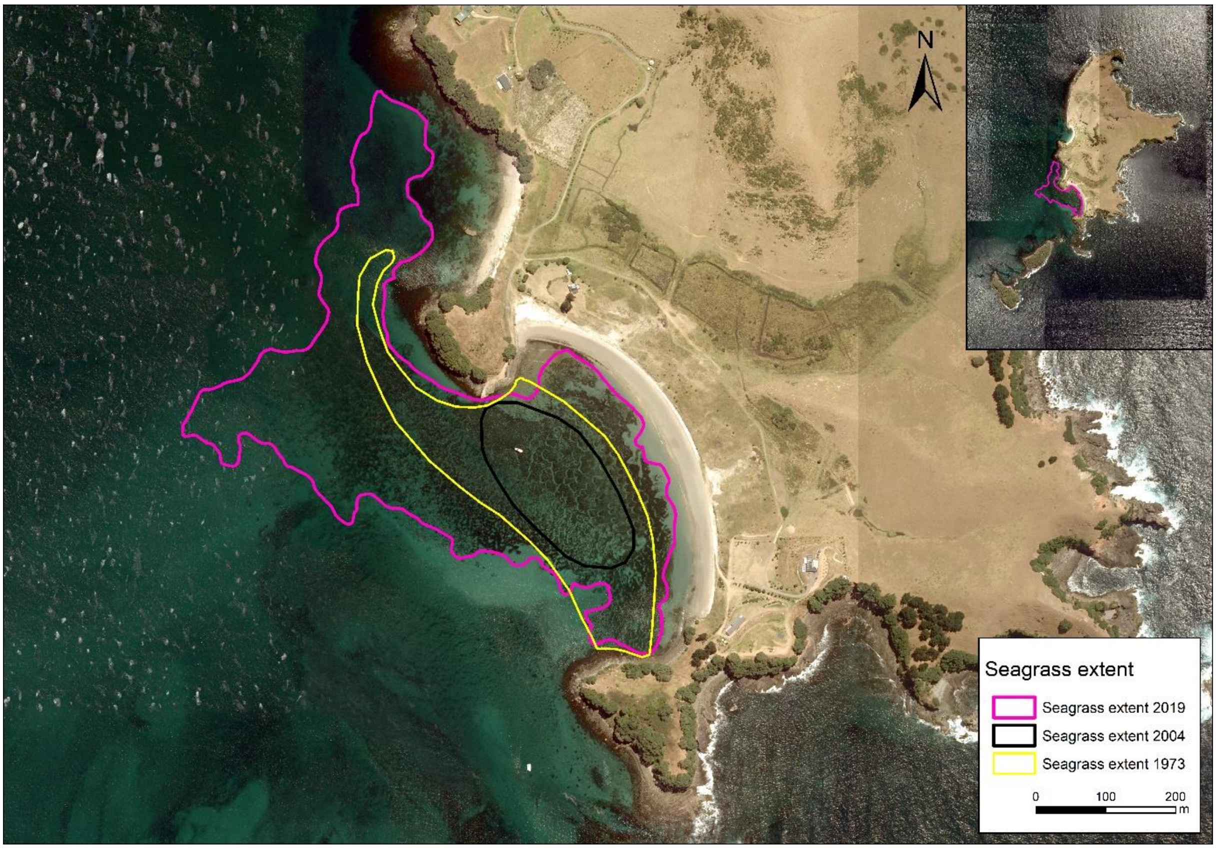


Figure 3. Extent of the seagrass meadow at South Bay (south) and Stingray Bay (north), Slipper Island, estimated in 2019, 2004 and 1973. Aerial imagery was taken in 2017 (supplied by Waikato Regional Council).

[2] Equivalent to 4–5 m below chart datum (recorded in the 2004). The 1973 survey estimated seagrass to extend to a depth of about 5 m but no reference to MSL or chart datum was given; we estimated the depth of their maximum extent to be about 7.0–7.5 m (MSL) based on depths recorded during the 2019 survey.

In 1975, the seagrass meadow at Great Mercury was thought to cover the entire harbour (0.52 km^2), including intertidal areas, with a maximum depth of approximately 5 m (Figure 5; Grace & Grace 1976). By 2004, the seagrass meadow appeared to have reduced considerably in size. Schwarz et al. (2006) described the meadow as a fringe around the intertidal region of the bay, extending to a maximum depth of 1.8 m (MSL)[3] and covering an area of 0.07 km^2. In 2019, we found no seagrass in the upper reaches of the harbour, with the meadow instead extending from the middle of the bay (2.5-3.0 m depth, MSL) to a maximum depth of 4.5 m (MSL) at the entrance to the harbour. The meadow covered an area of c. 0.09 km^2 and was thickest on the north-east side of the harbour, becoming patchier towards the western side of the harbour where the channel is, and as it becomes deeper towards the mouth of the harbour. None of the seagrass observed in 2019 would be exposed during spring low tides.

Subtidal seagrass was also reported in Parapara Bay, to the east of Huruhi Harbour, in the 1975 survey (Grace & Grace 1976). In 2019, a brief survey indicated that seagrass occupied most of the area within Parapara Bay (0.02 km^2), extending to a maximum depth of 5 m (MSL) and becoming more patchily distributed with depth (Figure 4). Taking into consideration mapping error, this area is comparable in size to the 0.03 km^2 mapped in 1975.

[3] Equivalent to 1 m below chart datum

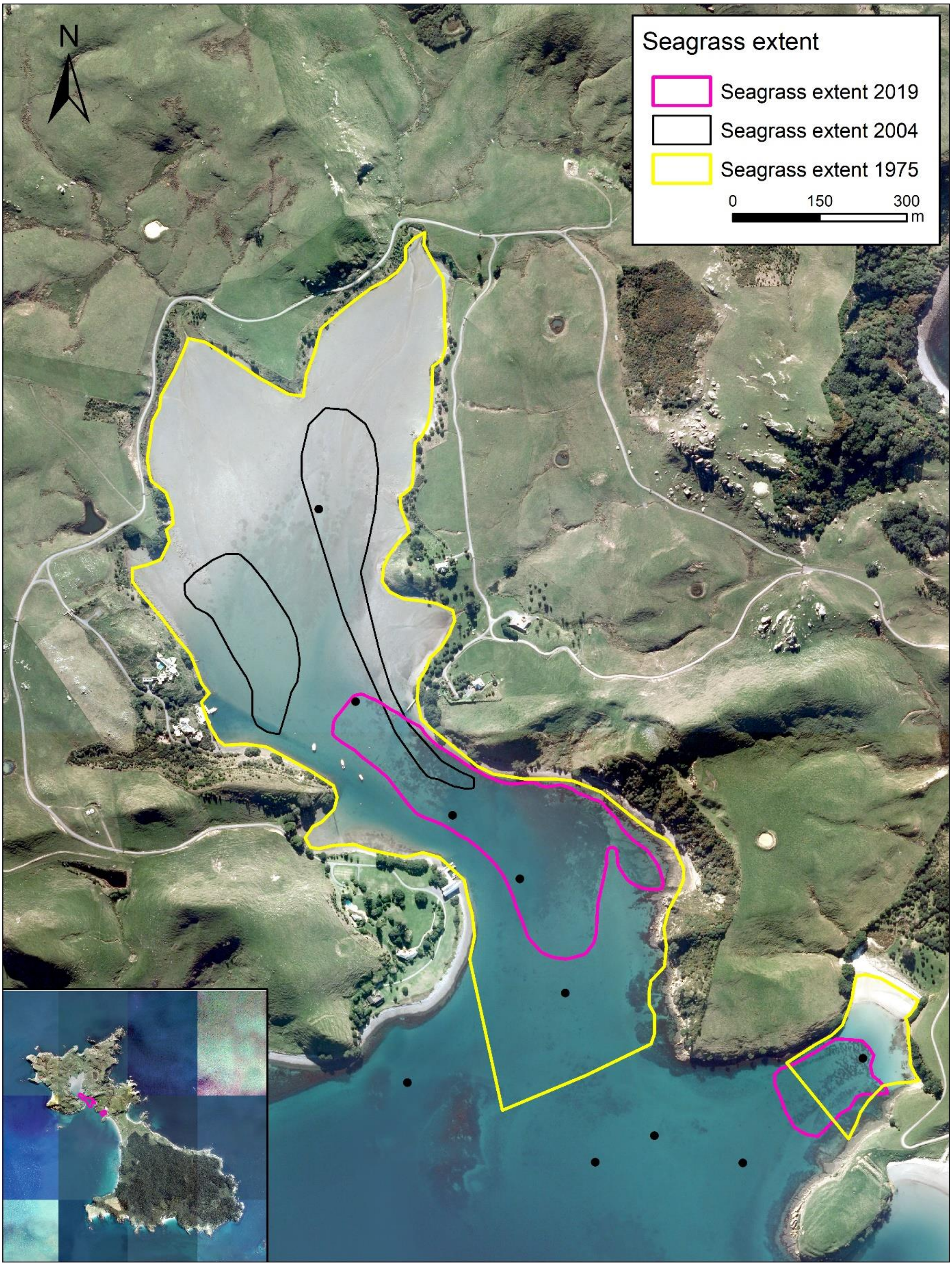


Figure 4. Extent of the seagrass meadows at Huruhi Harbour (north) and Parapara Bay (east), Great Mercury Island, estimated in 2019, 2004 and 1975. Black circles indicate the location of the 1975 sampling stations, Aerial imagery was taken in 2012 (supplied by Waikato Regional Council).

3.2. Seagrass health and condition

3.2.1. Indicators of seagrass condition

Indicators of seagrass condition were significantly higher at Slipper Island than Great Mercury (Figure 5 and Figure 6), with average values of 26–50% seagrass cover[4] (maximum > 75%), 118 gDW m^{-2} biomass (± 30 SE; range 9–382) and 215 mm leaf length (± 9.1 SE; 67–319)at Slipper Island. In comparison, average values for these indicators across the seagrass meadow at Great Mercury were 6–25% cover[5] (maximum 51–75%), 50 gDW m^{-2} biomass (± 10 SE; range 9–116) and 139 mm (± 6.9 SE; range 45–250) leaf length.

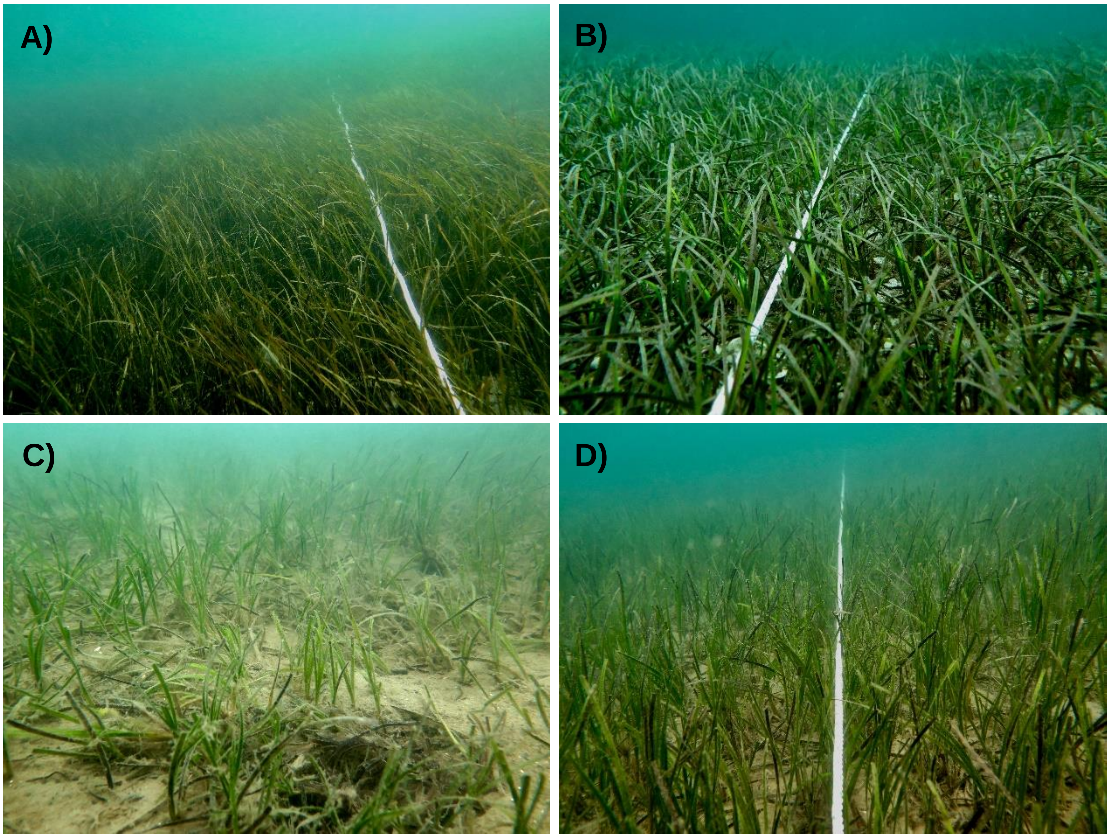


Figure 5. Seagrass meadows at South Bay (A: T1, B: T6), Slipper Island and Huruhi Harbour (C: T1, D: T4), Great Mercury Island.

[4] Seagrass Braun-Blanquet rank 3.2 (± 0.2 SE) at Slipper Island
[5] Seagrass Braun-Blanquet rank 2.3 (± 0.1 SE) at Great Mercury Island

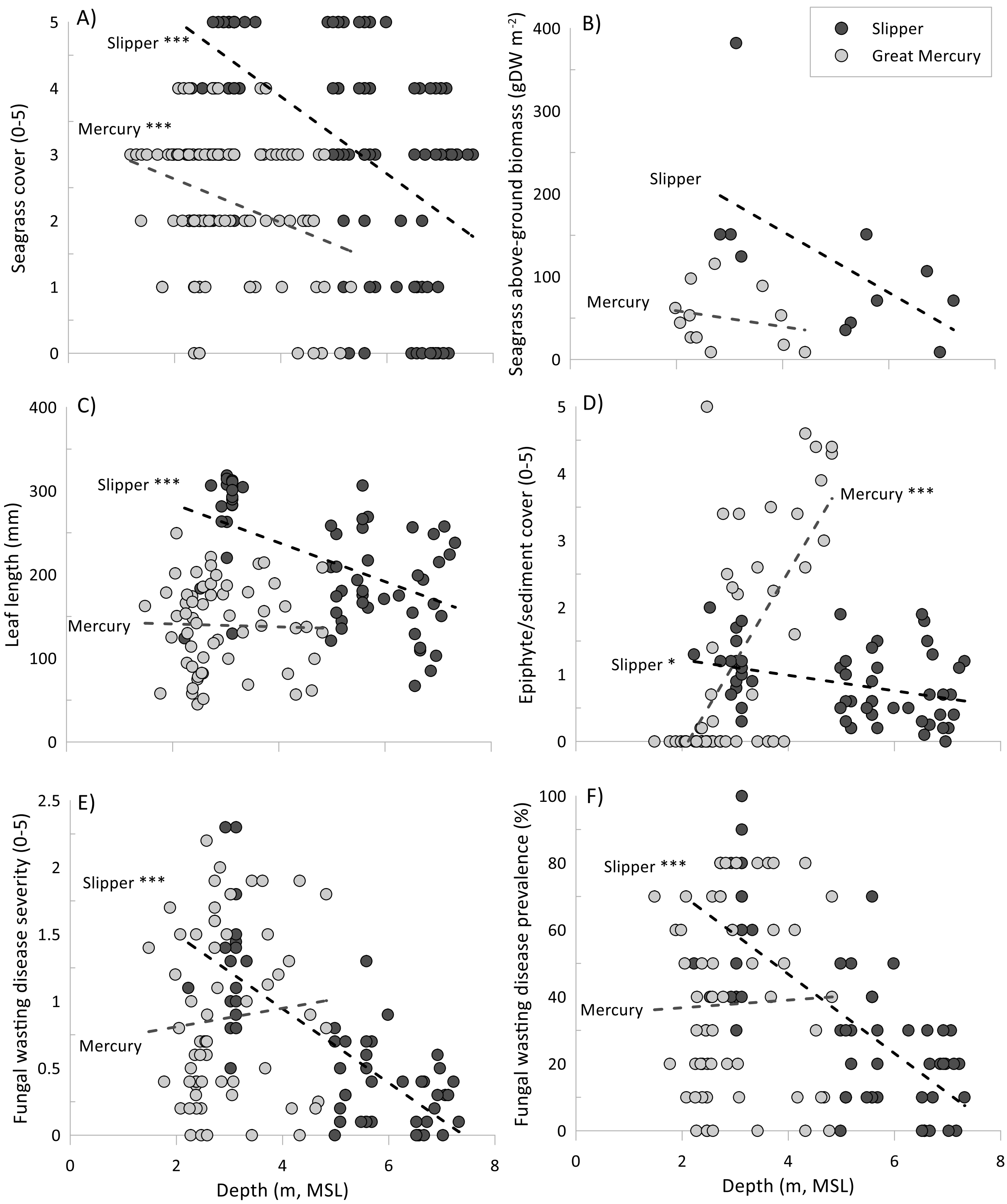


Figure 6. Seagrass health and stress indicators regressed against depth at two sites; South Bay, Slipper Island and Huruhi Harbour, Great Mercury Island. Indicators include A) seagrass cover (Braun-Blanquet scale), B) above-ground biomass (gDW m^{-2}), C) maximum leaf length (mm), D) epiphyte/sediment cover (0-5 scale), E) fungal wasting disease severity (wasting index, 0-5 scale) and F) fungal wasting disease prevalence (%). Replicates for leaf length, epiphyte/sediment cover and fungal wasting disease severity are a mean across 10 seagrass blades. GAMs have been fitted to the data and asterisks indicate the strength of the significance (*** $p < 0.001$, ** 0.01, * < 0.05) for the effect of depth on each site. All sites were significantly different from each other.

There was a significant ($p < 0.002$) decline in seagrass cover with depth at both islands, and this relationship was more evident at Slipper ($p < 0.001$). Here, average cover dropped from 51-75%[6] in the shallow transects (T1-T2) to 6-25%[7] in the deeper transects (T5-T6). The change in seagrass cover with depth was not as pronounced at Great Mercury Island, with both the shallow and the deep transects (T1-T2 and T4-6) having an average cover of 6-25% cover[8].

Leaf length also declined significantly ($p < 0.001$) with depth at Slipper Island, but this effect was not observed at Great Mercury. Average leaf length across shallow transects (T1-T2) at Slipper Island was 270 (± 13.2 SE) mm compared with 171 (± 13.7 SE) mm across deep transects (T5-T6). No effect of depth on seagrass biomass was observed at either island.

Above-ground biomass and leaf length were lower at Slipper Island in 2019, compared with 2004 when biomass averaged 155 (± 27 SE) gDW m^{-2} and mean leaf length was 288 (± 17) mm. However, the maximum biomass observed during the 2019 survey (382 gDW m^{-2}) was higher than the maximum sampled in 2004 (299 gDW m^{-2}). At Great Mercury, both biomass and leaf length were higher in 2019 than 2004 (36 ± 4.3 SE gDW m^{-2} biomass and 78 ± 3.0 SE mm leaf length).

3.2.2. Indicators of seagrass stress

Although epiphyte/sediment cover averaged 1% at both sites[9] (Figure 6), there was a significant difference between islands ($p < 0.01$), with Slipper dominated by encrusting coralline and red filamentous algae and epiphytes at Great Mercury comprising cyanobacteria covered with a fine layer of sediment (Figure 7). The relationship between epiphyte/sediment cover and depth differed between sites ($p < 0.001$). At Slipper Island, epiphyte/sediment cover decreased with depth ($p = 0.01$), while at Great Mercury the opposite trend was observed ($p < 0.001$). Macroalgae was uncommon at both sites with a coralline turfing species (Figure 7) only recorded at T5 and T6 at Slipper Island (maximum density 26–50%).

[6] Seagrass Braun-Blanquet rank 4.3 (± 0.1 SE) at across T1 & T2 Slipper Island
[7] Seagrass Braun-Blanquet rank 1.9 (± 0.2 SE) at across T5 & T6 Slipper Island
[8] Seagrass Braun-Blanquet rank 2.0 (± 0.1 SE) at across T1 & T2 and 2.4 (± 0.2) across T5 & T6 at Great Mercury Island
[9] Epiphyte cover rank 0.9 (± 0.1 SE) at Slipper and 1.1 (± 0.2 SE) at Great Mercury

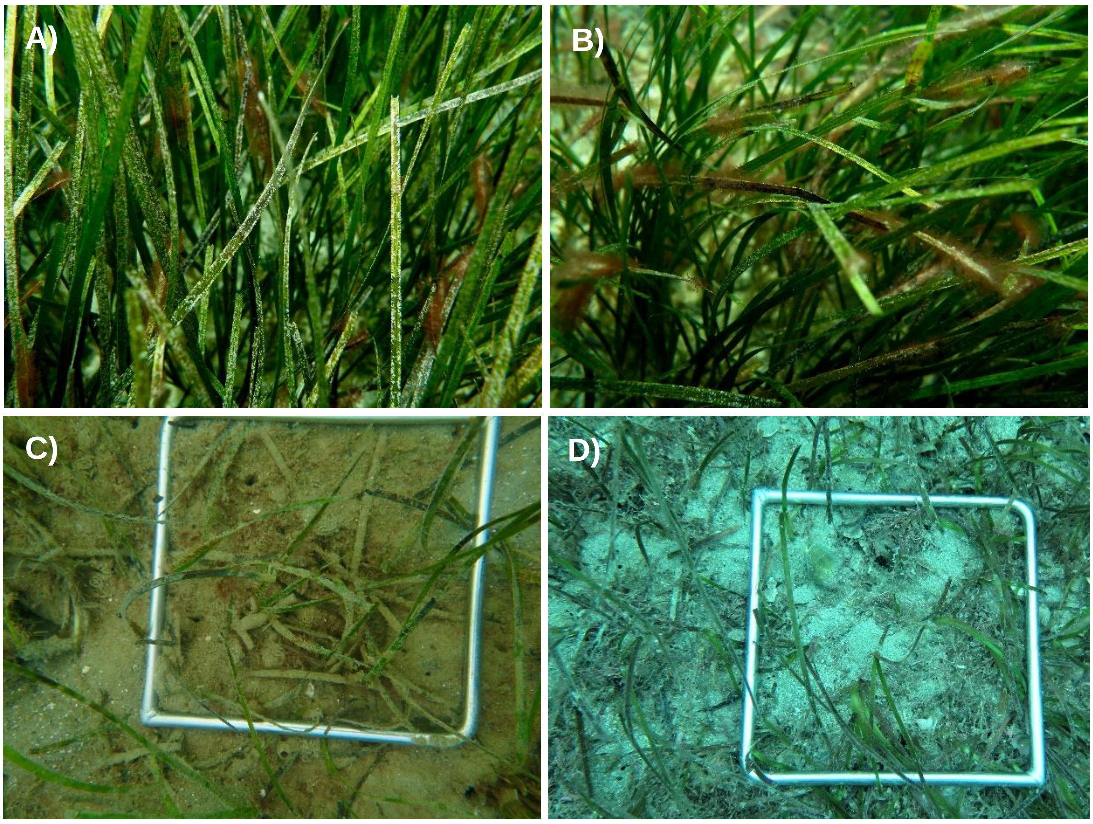


Figure 7. Example photographs of epiphytes/sediment and macroalgae. A) and B) encrusting coralline and red filamentous algae at Slipper Island T1, C) cyanobacteria and sediment at Great Mercury T6, D) coralline turfing algae observed along T5 and T6 at Slipper Island.

Prevalence of the fungal wasting disease *Labyrinthula* (Figure 8) was 35% (± 3.4 SE) at Slipper Island and 38% (±3.5 SE) at Great Mercury, with a severity of less than 1% cover at both sites[10] (Figure 6). Prevalence and severity of fungal wasting disease declined significantly ($p < 0.001$) with depth at Slipper Island, with 62% (± 4.4 SE) prevalence and 1–10% cover[11] across shallow transects (T1–T2) compared to deeper transects (T5–T6) where prevalence was only 14% (± 3.1 SE) and severity much less than 1% cover[12]. No trend between fungal wasting disease and depth was observed at Great Mercury Island. Examination of histological slides confirmed the presence of *Labyrinthula zosterae* cells which were patchily distributed in all samples, with lower numbers observed in the root tissue compared with the blades.

[10] Fungal wasting disease severity rank 0.7 (± 0.1 SE) at Slipper and 0.9 (± 0.1 SE) at Great Mercury
[11] Fungal wasting disease severity rank 1.3 (± 0.1 SE) at Slipper T1-T2
[12] Fungal wasting disease severity rank 0.3 (± 0.1 SE) at Slipper T5-T6

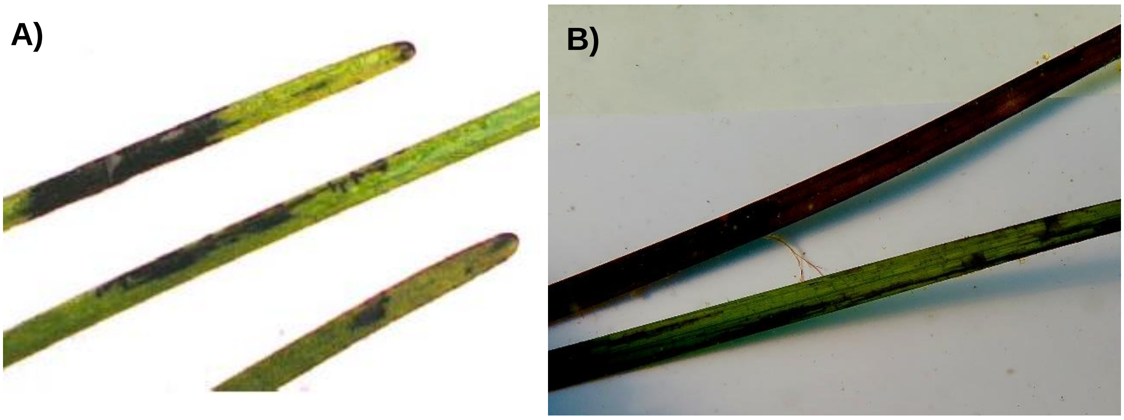


Figure 8. Photographs showing the presence of the fungal wasting disease *Labyrinthula* on seagrass blades. A) Example photograph from Ralph and Short (2002) and B) infected blades from Huruhi Harbour, Great Mercury Island (present study). The presence of infection is indicated by darkened patches.

3.2.3. Visual biomass assessment

The visual biomass assessment techniques were tested on 28 samples ranging from 0 to 382 gDW m^{-2} above-ground biomass. Visual biomass ranks and seagrass cover estimated using the DOR method explained the most variance in quantitative biomass (R^2 = 0.75, 0.73, respectively) while seagrass cover estimated using the Braun-Blanquet method explained less variation (R^2 = 0.63). Similarly, correlations between quantitative biomass and visual techniques were highest for the visual biomass ranks and seagrass cover estimated using DOR (r = 0.87) and lower for the Braun-Blanquet method (r = 0.80). Visual biomass ranks gave the closest average biomass estimate to the harvested samples for Slipper Island (110 vs. 108 gDW m^{-2}) while seagrass cover (DOR method) was the best proxy for Great Mercury (57 vs. 50 gDW m^{-2}), however, all measures had large confidence intervals. The only biomass estimate available for extrapolation across a greater number of samples was seagrass cover estimated using the Braun-Blanquet method (*n* = 125), and this also gave similar values to the harvested biomass (Slipper 110 vs.108 gDW m^{-2}; Great Mercury 58 vs. 50 gDW m^{-2}) but with considerably better precision (Table 1).

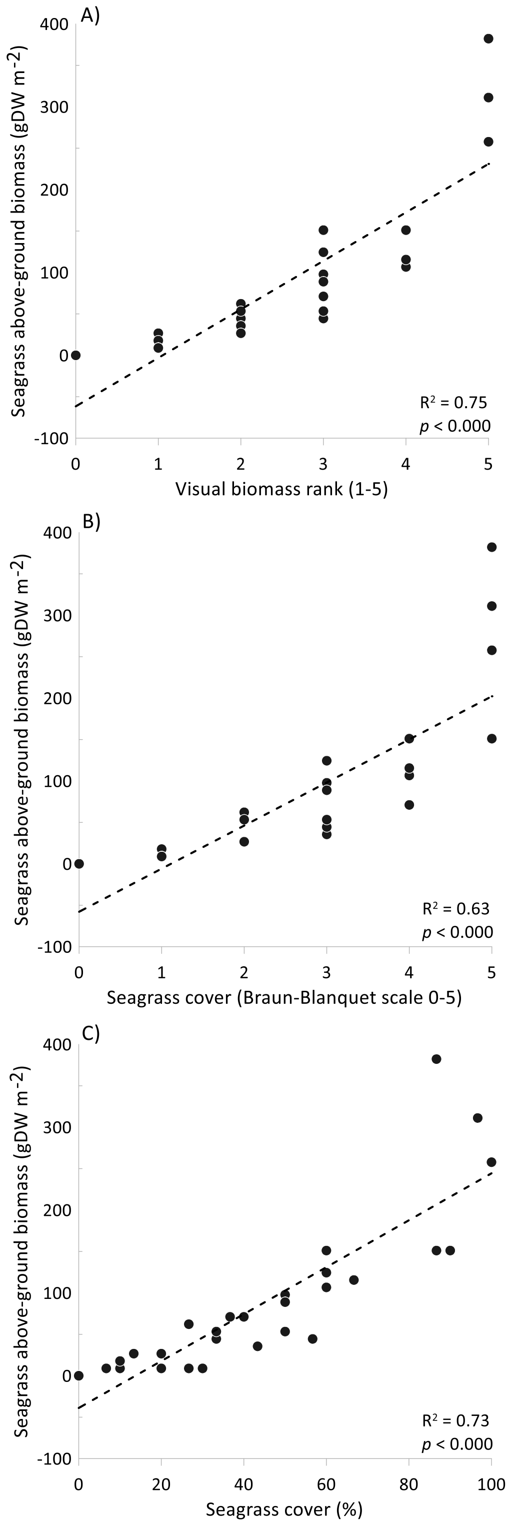


Figure 9. Quantitatively harvested above-ground biomass (gDW m^{-2}) compared with A) visual biomass rank (0-5 scale) and B) seagrass cover estimated using the Braun-Blanquet scale (0-5) and C) seagrass cover estimated using dots on rock method (%), *n* = 28. Linear models have been fitted to the data (A: y = 58.523x – 61.598, and B: y = 53.705x – 74.144, C: y = 2.8323x – 38.901), with p values indicating that relationships were significant.

Table 1. Predicted average above-ground biomass (gDW m^{-2} ± 95% confidence intervals) across seagrass meadows at Slipper and Great Mercury islands estimated using four different techniques: 1) harvested biomass, 2) a visual estimate of biomass, 3) seagrass cover estimated using the Braun-Blanquet method, 4) seagrass cover estimated using the dots-on-rocks (DOR) method.

	n	Slipper	Great Mercury
Harvested biomass	28	108 (± 58)*	50 (± 20)
Visual biomass rank	28	110 (± 41)	66 (± 33)
Seagrass cover Braun-Blanquet scale	28	124 (± 35)	62 (± 22)
Seagrass cover DOR	28	114 (± 42)	57 (± 27)
Seagrass cover Braun-Blanquet extrapolated	125	110 (± 12)	58 (± 8)

* Differs from average value of 118 gDW m^{-2}, reported elsewhere in the report, because a zero value was included to account for seagrass meadow patchiness.

3.2.4. Other observations

Areas of disturbance were present within both seagrass meadows, particularly around swing moorings within South Bay (Figure 10). Anchor damage was difficult to differentiate from other disturbance effects, but as both South Bay and Huruhi Harbour are popular anchorages many of the bare patches in the meadows may be attributable to anchoring.

Figure 10. Photographs showing scouring of seagrass surrounding swing moorings in South Bay, Slipper Island.

Fauna incidentally observed at Slipper Island included hermit crabs (*Pagurus* sp.), comb sea stars (*Astropecten polyacanthus*), purple fanworms (*Branchiomma* sp.), scallops (*Pecten novaezelandiae*), bivalves (*Zemysina* sp.), a rose petal bubble shell (*Hydatina physis*), a sea slug (*Philinopsis taronga*), pipefish (*Stigmatopora* sp.) and eagle rays (*Myliobatis tenuicaudatus*). Eagle rays and stingrays (*Dasyatis* sp.) were common at Great Mercury Island and comb sea stars, purple fanworms, hermit crabs and scallops were also observed here along with a solitary ascidian, an octopus and a hairy triton (*Monoplex parthenopeus*).

4. DISCUSSION

4.1. Seagrass extent

The current survey found the seagrass meadow at South Bay (Slipper Island) to be more than six times larger than estimated in 2004 and more than double the area estimated in 1973. Discrepancies between surveys are likely a result of differences in survey techniques, although temporal fluctuations may have also contributed to changes in extent. Grace and Whitten (1974) reported that seagrass extent was clearly visible from the dinghy and aerial photographs during the 1973 survey. However, maps from this survey are unlikely to have high accuracy as this was before GPS and GIS mapping were readily available. In the 2004 survey, Schwarz et al. (2006) acknowledged that seagrass extent could only be estimated owing to limited time and weather constraints. They recommended that aerial photography with appropriate ground-truthing be undertaken in the future to develop an accurate base map of seagrass extent. The current survey digitised seagrass extent using recent (2017) aerial photographs and these boundaries were ground-truthed in the field from the vessel and by a snorkeller. Good field conditions with minimal wind and excellent water clarity gave us confidence in the accuracy of our results, although there was some subjectivity in deeper areas (> 6 m depth) when a wide-angle view of the extent of seagrass patches was harder to obtain. A snorkeller was essential for estimating seagrass extent in these deeper areas, possibly explaining why this area was not included in the 1973 survey.

At Huruhi Harbour (Great Mercury), the current survey found the seagrass meadow to be only 17% of the of the area estimated in 1975 but almost 30% larger than that estimated in 2004. Unlike Slipper Island, no mention was made by Grace and Grace (1976) of being able to see the seagrass bed from the boat during the 1975 survey. The current[13] and 2004 surveys found water clarity to be poorer at this site, and the presence of muddy sand sediments in 1975 indicate this may have also been the case historically. Therefore, it is possible that seagrass extent was primarily interpolated from five dredge samples collected within the harbour, with three of these stations located within the seagrass extent mapped in 2019. In 2019, we observed no seagrass in the upper reaches of the harbour, despite it being recorded as present here during the 1975 and 2004 surveys, suggesting the upper extent of the seagrass meadow has reduced. However, whether the seagrass meadow encompassed all the intertidal flats, as indicated by the 1975 map, is not certain as this area appears to have been extrapolated from a single sampling station.

The lower extent of the seagrass meadow may have also reduced since 1975, with the outermost sampling station 60 m beyond the edge of the 2019 extent. However, as at Slipper Island, some subjectively was involved in mapping the deeper seagrass

[13] Based on visual observations from divers

boundary, as the patchy nature of seagrass meadow edges is more difficult to map without a good wide-angle view. Overall, seagrass extent was harder to map at Great Mercury compared with Slipper Island, due to reduced water clarity and the absence of a recent aerial photograph for ground-truthing. Seagrass within Parapara Bay was found in a similar location and covering a similar area as observed in 1975.

Although seagrass meadows are usually remain present on a multi-year scale, they are dynamic and can expand and contract over relatively short timeframes (Olesen & Sand-Jensen 1994; Ismail 2001; Spalding et al. 2003; Turner & Schwarz 2006a). Unfortunately, few studies have quantified temporal changes in the distribution, spatial extent or condition of New Zealand seagrass beds, making it difficult to differentiate between natural variation and more serious impacts (Turner & Schwarz 2006a). Seagrass beds in Otago Harbour were found to change by up to 10% in a 6-month period (Ismail 2001) but the magnitude of this value could vary with location or time scale. A local, who has visited Huruhi Harbour for more than 60 years, said the seagrass beds come and go, particularly on the western side of the harbour where seagrass was not observed in 2019. He suggested that seagrass is ripped out during severe storms. Mechanical damage, from activities such as channel dredging in the upper part of the harbour and anchoring, may also contribute to localised seagrass loss.

4.2. Seagrass health and condition

The seagrass bed at Slipper Island was double the size of the meadow at Great Mercury and extended into waters almost twice as deep. As observed during the 2004 survey, the seagrass at Slipper Island appeared to be in better condition, with higher cover, leaf length and above-ground biomass than Great Mercury. These differences in seagrass characteristics may reflect the sandier sediments and higher water clarity observed at Slipper Island. Epiphyte cover was low at both sites (1% cover) and where macroalgae was present it did not appear to have a significant shading effect on seagrass plants. The prevalence (35-38%) and severity (< 1% cover) of the fungal wasting disease *Labyrinthula* was also similar between sites.

Although fungal wasting disease has been recorded in other seagrass meadows around New Zealand (Armiger 1965; Woods & Schiel 1997; Ramage & Schiel 1999; Gillespie et al. 2012b, 2012c, 2012d; Berthelsen et al. 2016; Šunde et al. 2017), accurate estimates of the prevalence and severity of the disease are few. Nonetheless, comparison of available survey photographs (Gillespie et al. 2012c, 2012d; Berthelsen et al. 2016; Šunde et al. 2017) suggest fungal wasting disease was less common at Slipper and Great Mercury islands than observed in intertidal meadows in the South Island. Although fungal wasting disease severity averaged less than 1% cover in our study, research has demonstrated that *Labyrinthula* also affects green areas of 'healthy-looking' tissue, compromising their photosynthetic activity

(Muehlstein et al. 1991; Ralph & Short 2002). No net photosynthetic production is likely once *Labyrinthula* lesions affect more than 25% of leaf tissue (Durako & Kuss 1994) and plants with leaves having greater than 50% cover often drop their most infected leaves (Ralph & Short 2002). Therefore, even apparently healthy seagrass beds with minor disease symptoms could be exposed to considerable photosynthetic stress by low levels of *Labyrinthula* infection (Ralph & Short 2002). In our survey, 10% of inspected blades had ≥ 20% cover of wasting disease, and of those only 4% had ≥ 40% cover. Further study is required to understand the epidemiology of fungal wasting disease (Inglis 2003), and whether adverse environmental conditions or anthropogenic stresses increase the susceptibility of seagrass meadows to the disease.

Seagrass cover, leaf length, epiphyte cover and the prevalence and severity of fungal wasting disease all declined with depth at Slipper Island. At Great Mercury, a relationship with depth was only observed for seagrass cover and epiphytes; however, the lack of relationship for other variables may have arisen because the seagrass meadow did not extend as deep as at Slipper Island. Had the seagrass meadow extended deeper, we might have started to see a similar decline in leaf length and the prevalence and severity of fungal wasting disease. In addition, water clarity at Great Mercury was observed to improve with depth, most likely reflecting resuspension of fine sediments by tidal currents in shallower areas. The turbid water may have negated the higher light penetration expected in shallow areas and consequently shallow plants may have been exposed to similar light levels as those growing deeper. Water clarity at Slipper Island on the other hand, was very good in shallow areas, probably due to the coarser sand sediments and absence of large intertidal mudflats nearby.

The relationship between epiphyte cover and depth differed between islands likely reflected the difference in dominant epiphytes between sites. At Slipper Island, encrusting coralline and red filamentous algae declined with depth, while at Great Mercury Island, cyanobacteria and sediment cover increased with depth. Sediments on seagrass in shallower areas at Great Mercury were likely resuspended by tidal currents and settled on seagrass in deeper areas.

At Slipper Island, average above-ground biomass and leaf length were lower in 2019 than observed during the 2004 survey. However, given leaf length has been found to decrease with depth, transect placement may affect this value. Restricting the comparison to transects within the 2004 mapped area indicates that average biomass in this shallow portion of the seagrass meadow was higher in 2019 and average leaf length only 21 mm less (Table 2). It also demonstrates the need to survey the same transects between years in order to make appropriate comparisons. At Great Mercury Island, both biomass and leaf length were greater in 2019 than observed in 2004, even when comparison was restricted to the two shallowest transects (Table 2). Given natural variability in seagrass characteristics (Ramage & Schiel 1999; Ismail 2001;

Turner & Schwarz 2006b), we conclude that the condition of the Slipper Island seagrass meadow is comparable to that observed in 2004 but may have improved at Great Mercury. However, the improvement in seagrass condition at Great Mercury could be an artefact of survey design because subtidal portions of the meadow, which are not subjected to the stress of exposure at low tide, were more represented in the 2019 survey.

Comparison of above-ground biomass with other seagrass meadows around New Zealand (Table 2) shows that biomass at Slipper Island is consistently higher than observed in other seagrass meadows over winter, but higher summer biomass has been recorded in a couple of other estuaries. Leaf length was at the upper end of subtidal seagrass values and 1.5–3.8 times greater than leaf length observed in intertidal meadows. In comparison, biomass at Great Mercury Island in 2019 was at the lower end of average values observed elsewhere in New Zealand in both winter and summer. Leaf length was at the lower end of the range observed in subtidal meadows but greater than most intertidal meadows.

Seagrass characteristics can fluctuate seasonally, with lower above-ground biomass in winter (Ramage & Schiel 1999; Ismail 2001; Turner & Schwarz 2006b) and longer leaf length observed in late summer/autumn or winter (Ismail 2001; Turner & Schwarz 2006b). These patterns have been attributed to variations in photosynthetically available radiation, temperature and available nutrients (Turner & Schwarz 2006a) and the formation of new shoots in spring (Ismail 2001). There is insufficient long-term data on New Zealand seagrass to determine the relative importance of inter-annual versus seasonal variations in biomass (Schwarz et al. 2006), but there is evidence that year-year differences can be greater than those observed between seasons in some cases (Turner & Schwarz 2006b).

Table 2. Average above-ground biomass (gDW m^{-2}) and leaf length (mm) of seagrass at Slipper and Great Mercury islands surveyed in 2019 (shaded grey) and 2004, and other meadows around New Zealand. Results are split temporally to account for seasonal differences in biomass and leaf length. For the 2019 surveys at Slipper and Great Mercury islands, biomass and leaf length are also shown as averages across the two shallowest transects (T1-T2) to be more comparable with 2004 sampling locations.

Location	Date	Zone	Biomass	Leaf length
Winter (May-Jul)				
Slipper (T1&T2)[a]	May 2019	Subtidal	202	269
Slipper[b]	May/Jun 2004	Subtidal	155	290
Slipper[a]	May 2019	Subtidal	108-118	215
Wharekawa[c]	Jul 2000/01	Intertidal	49-164	-
Whangapoua[c]	Jul 2000/01	Intertidal	47-123	-
Whangamata[c]	Jul 2000/01	Intertidal	48-54	-
Great Mercury [a]	May 2019	Subtidal	50	139
Otago Harbour[d]	Jul 1997	Intertidal	45	-
Great Mercury (T1 & T2)[a]	May 2019	Subtidal	40	107
Great Mercury[b]	May 2004	Subtidal	36	78
Summer (Dec-Mar)				
Wharekawa[e]	Jan 2002	Intertidal	522	-
Whangapoua lower[e]	Jan 2002	Intertidal	391	-
Whangapoua upper[e]	Jan 2002	Intertidal	270	-
Whangapoua[f]	Dec-Feb 2002/03	Intertidal	140	-
Otago Harbour[d]	Mar 1997/98	Intertidal	93-97	-
Whangamata[e]	Jan 2002	Intertidal	87	-
Whangapoua lower[b]	Jan 2001	Intertidal	81	71
Whangapoua upper[b]	Jan 2001	Intertidal	75	70
Nelson Haven[g]		Intertidal	72	-
Wharekawa[b]	Jan 2001	Intertidal	69	62
Whangamata[b]	Jan 2001	Intertidal	50	56
Raglan[f]	Dec-Feb 2002/03	Intertidal	42	-
Shakespeare Bay[h]	Feb 2016	Intertidal	42	-
Tauranga[f]	Dec-Feb 2002/03	Intertidal	41	-
Ten central North Island harbours[i]	Jan 2002	Intertidal	19-50	-
Timing unknown				
Urapukapuka Island[j]	NA	Subtidal	-	263
Kaipara[j]	NA	Subtidal	-	259
Waikawa[j]	NA	Subtidal	-	198
Tairua[j]	NA	Subtidal	-	140
Rangaunu[j]	NA	Subtidal	-	170-218
Bluff[j]	NA	Subtidal	-	108-162
Farewell Spit[j]	NA	Intertidal	-	96-150
Kaipara[j]	NA	Intertidal	-	95-129
Rangaunu[j]	NA	Intertidal	-	94-110
Kawhia[j]	NA	Intertidal	-	95
Whanganui Inlet[j]	NA	Intertidal	-	86

[a] Current study, [b] Schwarz et al. (2006), [c] Turner & Schwarz (2006b), [d] Ismail (2001), [e] van Houte-Howes et al. (2004), [f] Matheson & Schwarz (2007), [g] Gillespie et al. (2012c), [h] Berthelsen et al. (2016), [i] Turner & Schwarz (2006a), [j] Morrison et al. (2014b).

4.3. Visual biomass assessment

In this study, we trialled visual biomass assessment techniques as a non-destructive and rapid method for future sampling. Evaluation of the visual biomass rank technique (Mellors 1991), by regressing quantitatively harvested above-ground biomass against the visual ranking, resulted in a coefficient of determination (R^2 = 0.75) within the range (R^2 = 0.65–0.96) recorded by other observers using this approach (Mellors 1991) and a correlation coefficient (r = 0.87) greater than the 0.80 recommended by Duarte and Kirkman (2001). If this approach is to be used in the future, calibration with a range of observers is suggested to further improve biomass estimates and decrease the variance.

Seagrass cover, estimated using the DOR method, was also found to be a suitable proxy for biomass (R^2 = 0.73, r = 0.87) and slightly better than seagrass cover estimated using the Braun-Blanquet scale (R^2 = 0.63, r = 0.80). Using seagrass cover to estimate above-ground biomass would result in greater time efficiency because only one variable would need to be approximated. Additionally, observers tend to be better at visually estimating seagrass cover than biomass, which may result in less variation between observers.

The large confidence intervals surrounding average values suggest that none of the estimates of above-ground biomass are sufficiently robust to provide a point-in-time estimate of seagrass biomass when only 12 replicate samples are considered. Only seagrass cover estimated using the Braun-Blanquet scale was available to test how extrapolation across a greater number of samples would affect biomass estimates. Using the Braun-Blanquet seagrass cover method with 125 samples gave similar average above-ground biomass values to that estimated using harvested biomass, but with considerably better precision. Although, quantitative harvesting of above-ground biomass remains the most accurate method of measuring biomass in a given location, using seagrass cover as a proxy for biomass may be more representative of overall biomass and allow smaller changes to be detected. Seagrass cover estimated using the DOR method gave a slightly higher correlation coefficient than cover estimated using the Braun-Blanquet scale, speeds up data collection in the field and removes diver bias. However, the DOR method requires post-processing effort unlike the Braun-Blanquet method, which requires no additional data processing.

During this survey we used scissors and a mesh bag to harvest above-ground biomass from 0.0225 m^2 quadrats (*n* = 28). We found the biomass samples quick and easy to collect and the small quadrat size meant that only 0.3–0.35 m^2 was harvested from each meadow in total. Given that bare patches in above-ground biomass can be recolonised within a few months (Duarte & Kirkman 2001), and the total impacted area is less than the damage from one anchor, a limited number of above-ground biomass samples could be collected in future surveys without significantly damaging the habitat.

4.4. Recommendations for future monitoring

Accurate information on seagrass distribution is essential for managing seagrass habitats (McKenzie et al. 2001) and can be used to identify 'healthy' areas that may deserve special protection efforts (e.g. Slipper Island) as well as areas that are potentially under stress and may require management action to improve health (e.g. Great Mercury Island; Turner & Schwarz 2006a). For future surveys of seagrass extent at these islands, we recommend obtaining good quality aerial photographs taken within 12 months of the ground-truthing surveys. The use of recent photographs would allow greater reliance to be placed on boundaries estimated from photographs, although ground-truthing deeper boundaries is still advised, particularly at Great Mercury Island where water clarity is poorer.

Monitoring allows early detection of change, enabling managers to act before impacts become too severe. Given the unique nature of these offshore subtidal seagrass beds, we recommend continuing to monitor key parameters that indicate the health and condition of seagrass (seagrass cover, leaf length, above-ground biomass) as well as indicators of stress (cover of macroalgae and epiphytes and the severity and prevalence of fungal wasting disease). Ideally, future monitoring programmes would also collect information on physical parameters that are important for seagrass growth and survival (e.g. light, turbidity, depth, sediment characteristics, nutrient levels, temperature, storm events) so that changes in seagrass condition can be interpreted (Turner & Schwarz 2006a). To enable comparison of results across years, surveys should be carried out in May/June and transect locations should be kept the same between surveys. Some consideration should be given to moving Transects 3 and 4 at Slipper Island to somewhere slightly shallower to provide a more even representation of that meadow as well as more information at comparable depths to the Great Mercury meadow. The fungal wasting disease *Labyrinthula* was detected at both islands and should be continued to be monitored in view of its potential to cause widespread seagrass die-offs and the lack of knowledge about its distribution and epidemiology.

For future surveys, we suggest using seagrass cover, estimated using the DOR or Braun-Blanquet method, as a proxy for above-ground biomass because these approaches are more time efficient and likely to be less affected by observer variation than the visual biomass assessment technique. Compared to the Braun-Blanquet method, the DOR method is slightly more accurate, speeds up data collection in the field and removes diver bias but requires post-processing effort. We also recommend continuing to collect a limited number (e.g. 12 per meadow) of above-ground biomass samples (0.0225 m^2) in future surveys. These data can be added to the 2019 survey results, increasing the number of replicates in the seagrass cover-biomass regression and allowing differences between years or observers to be evaluated.

Observations of aerial photographs indicate that subtidal seagrass meadows may be found in other bays around these islands, and potentially other islands in the area. For example, a 2017 dive survey noted the presence of sporadic pockets of healthy seagrass on the western side of Slipper Island and in Coralie Bay, on the eastern side of Great Mercury Island. Given the rarity of subtidal seagrass meadows in New Zealand, it is important to identify and map their distribution so these unique habitats can be protected. Habitat suitability could be evaluated using substrate (mud or sand), depth (< 12 m) and exposure (sheltered from wave action and strong currents) information, with potential locations assessed using aerial imagery and *in situ* ground-truthing.

Once seagrass meadows are lost, the locations that once supported them may become unsuitable as seagrass habitat because feedback mechanisms mean the specific suite of environmental conditions necessary for seagrass growth are no longer maintained (Turner & Schwarz 2006a). Seagrass restoration is expensive and laborious and has had limited success. Emphasis should be on protecting and conserving remaining seagrass meadows, with regular monitoring (every 3–5 years) to quantify trends in distribution, extent and condition (Turner & Schwarz 2006a; Morrison et al. 2014b). The Slipper and Great Mercury islands seagrass meadows represent some of the only subtidal seagrass meadows documented in New Zealand and have been shown to be important for supporting biodiversity and fish populations (Schwarz et al. 2006). Consideration should be given to further protection for these areas, including limiting the damage resulting from anchoring, swing moorings, propellers and dredging.

5. ACKNOWLEDGMENTS

The authors of this study would like to acknowledge Ross Sneddon (Cawthron) and Thomas Maxwell (Mad Max Sportfishing Ltd) for their help in the field; Fiona Gower and Bill Nikkel (Cawthron) for quantifying seagrass biomass; Kyle and Ollie Shutt for hosting us on the Coromandel; Jess Trott (Cawthron) for arranging the health and safety prequalification necessary for this work; Lisa Floerl (Cawthron) for GIS technical assistance; Paula Casanovas (Cawthron) for carrying out statistical analyses; Steve Webb (Cawthron) for providing expertise on fungal wasting disease; and Paul Gillespie (Cawthron) for report review.

6. REFERENCES

Armiger LC 1964. An occurrence of *Labyrinthula* in New Zealand *Zostera*. New Zealand Journal of Botany 2(1): 3-9.

Armiger LC 1965. A contribution to the autecology of *Zostera*. Unpublished MSc thesis, University of Auckland. Auckland, New Zealand.

Berthelsen A, Clement D, Gillespie P 2016. Shakespeare Bay estuary monitoring 2016. Prepared for Marlborough District Council. Cawthron Report No. 2833. 40 p. plus appendices.

Braun-Blanquet J 1932. Plant sociology: the study of plant communities. Translated and edited by Conard HS, Fuller GD. London, McGraw-Hill.

Burdick DM, Short FT, Wolf J 1993. An index to assess and monitor the progression of wasting disease in eelgrass *Zostera marina*. Marine Ecology Progress Series 94: 83-90.

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van der Belt M 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253-260.

Duarte CM, Chiscano CL 1999. Seagrass biomass and production: a reassessment. Aquatic Botany 65: 159-174.

Duarte CM, Kirkman H 2001. Methods for the measurement of seagrass abundance and depth distribution. Chapter 7 in: Short FT, Coles RG eds. Global seagrass research methods. Elsevier Science.

Durako M, Kuss KM 1994. Effects of *Labyrinthula* infection on the photosynthetic capacity of *Thalassia testudinum*. 727-732 p.

Fonseca MS 1996. The role of seagrasses in nearshore sedimentary processes: a review. Nordstrom KF, Roman CT ed. New York, John Wiley.

Gillespie P, Clement D, Asher R 2012a. Baseline mapping of selected intertidal habitats within Grove Arm, Queen Charlotte Sound. Prepared for Marlborough District Council. Cawthron Report No. 2133. 30 p. plus appendices.

Gillespie P, Forrest R, Clark DE, Asher R 2012b. Coastal effects of the Nelson (Bell Island) regional sewerage discharge: benthic monitoring survey 2011. Prepared for Nelson Regional Sewerage Business Unit. Cawthron Report No. 2068. 24 p.

Gillespie P, Clement D, Clark DE, Asher R 2012c. Nelson Haven fine-scale benthic baseline 2012. Prepared for Nelson City Council. Cawthron Report No. 2209. 22 p. plus appendices.

Gillespie P, Clement D, Asher R, Tiernan F 2012d. Baseline mapping of selected intertidal habitats within Grove Arm, Queen Charlotte Sound. Prepared for Marlborough District Council Cawthron Report No. 2133. 30 p. plus appendices.

Grace RV, Whitten RF 1974. Benthic communities west of Slipper Island, north-eastern New Zealand. Tane 20: 5-20.

Grace RV, Grace AB 1976. Benthic communities west of Great Mercury Island, north-eastern New Zealand. Tane 22: 85-101.

Hailes SF 2006. Contribution of seagrass (*Zostera muelleri*) to estuarine food webs revealed by carbon and nitrogen stable isotope analysis. Unpublished MSc. thesis, University of Waikato.

Heiss WM, Smith AM, Probert PK 2000. Influence of the small intertidal seagrass Zostera novazelandica on linear water flow and sediment texture. New Zealand Journal of Marine and Freshwater Research 34(4): 689-694.

Henriques PR 1980. Faunal community structure of eight soft shore, intertidal habitats in the Manukau harbour. New Zealand Journal of Ecology 3: 97-103.

Hughes RG, Potouroglou M, Ziauddin Z, Nicholls JC 2018. Seagrass wasting disease: Nitrate enrichment and exposure to a herbicide (Diuron) increases susceptibility of *Zostera marina* to infection. Marine Pollution Bulletin 134: 94-98.

Inglis GJ 2003. The seagrasses of New Zealand. In: Green EP, Short FT ed. World atlas of seagrasses. Berkley, California, University of California Press. Pp. 148-157.

Ismail N 2001. Ecology of eelgrass, *Zostera novazelandica* Setchell, in Otago Harbour, Dunedin, New Zealand. Unpublished PhD thesis, University of Otago, Dunedin.

Jacobs SWL, Les D, Moody M 2006. New combinations in Australasian *Zostera* (Zosteraceae). 127-128 p.

Kirkman H 1996. Baseline and monitoring methods for seagrass meadows. Journal of Environmental Management 47: 191-201.

Matheson F, Dos Santos V, Inglis G, Pilditch C, Reed J, Morrison M, Lundquist C, Van Houte-Howes K, Hailes S, Hewitt J 2009. New Zealand seagrass general information guide. NIWA Information Series No. 72.

Matheson FE, Schwarz A-M 2007. Growth responses of *Zostera capricorni* to estuarine sediment conditions. Aquatic Botany 87(4): 299-306.

McKenzie LJ, Finkbeiner MA, Kirkamn H 2001. Methods for mapping seagrass distribution. Chapter 5 in: Short FT, Coles RG eds. Global seagrass research methods. Elsevier Science

Meese RJ, Tomich PA 1992. Dots on rocks: a comparison of percentage cover methods. Journal of Experimental Marine Biology and Ecology 165: 59-73.

Mellors JE 1991. An evaluation of a rapid visual technique for estimating seagrass biomass. Aquatic Botany 42(1): 67-73.

Morrison M, Francis M 2001. In search of small snapper. Seafood New Zealand 21-22.

Morrison MA, Jones EG, Consalvey M, Berkenbusch K 2014a. Linking marine fisheries species to biogenic habitats in New Zealand: a review and synthesis of knowledge. Wellington, Ministry for Primary Industries.

Morrison MA, Lowe ML, Grant CM, Smith PJ, Carbines GD, Reed J, Bury SJ, Brown J 2014b. Seagrass meadows as biodiversity and productivity hotspots Ministry for Primary Industries New Zealand Aquatic Environment and Biodiversity Report No. 137. 122 p. plus appendices.

Muehlstein LK, Porter D, Short FT 1991. *Labyrinthula zosterae* sp. nov., the Causative Agent of Wasting Disease of Eelgrass, *Zostera marina*. Mycologia 83(2): 180-191.

NIWA 2019. NIWA Tide Forecaster. Retrieved June 2019 2019, from https://www.niwa.co.nz/node/26820/results

Olesen B, Sand-Jensen K 1994. Patch dynamics of eelgrass *Zostera marina.* Marine Ecology Progress Series 106: 147-156.

Park SG 1999. Changes in abundance of seagrass (*Zostera* spp.) in Tauranga Harbour from 1959–1996. Whakatane, Environment Bay of Plenty Environmental Report 99/30. Pp. 19.

Pellikaan GC, Nienhuis PH 1988. Nutrient uptake and release during growth and decomposition of eelgrass, *Zostera marina* L., and its effects on the nutrient dynamics of Lake Grevelingen. Aquatic Botany 30(3): 189-214.

R Core Team 2019. R: A language and environment for statistical computing. Vienna, Austria, R Foundation for Statistical Computing.

Ralph PJ, Short FT 2002. Impact of the wasting disease pathogen, *Labyrinthula zosterae*, on the photobiology of eelgrass *Zostera marina*. Marine Ecology Progress Series 226: 265–271.

Ramage DL, Schiel DR 1999. Patch dynamics and response to disturbance of the seagrass *Zostera novazelandica* on intertidal platforms in southern New Zealand. Marine Ecology Progress Series 189: 275-288.

Schwarz A-M, Morrison M, Hawes I, Halliday J 2006. Physical and biological characteristics of a rare marine habitat: sub-tidal seagrass beds of offshore islands. Department of Conservation Science for Conservation 269.

Short FT 1987. Effects of sediment nutrients on seagrasses: Literature review and mesocosm experiment. Aquatic Botany 27(1): 41-57.

Short FT, Wyllie-Echeverria S 1996. Natural and human-induced disturbance of seagrasses. Environmental Conservation 23(1): 17-27.

Spalding M, Taylor M, Ravilious C, Short FT, Green E 2003. The distribution and status of seagrasses. In: Green EP, Short FT ed. World atlas of seagrasses. Berkley, California, University of California Press. Pp. 5-26.

Šunde C, Berthelsen A, Sinner J, Gillespie PA, Stringer K, Floerl L 2017. Impacts of vehicle access at Delaware (Wakapuaka) Inlet. Prepared for Nelson City Council. Cawthron Report No. 3015. 65 p. plus appendices

Turner SJ, Schwarz A-M 2006a. Management and conservation of seagrass in New Zealand: an introduction. Department of Conservation Science for Conservation 264.

Turner SJ, Schwarz A-M 2006b. Biomass development and photosynthetic potential of intertidal *Zostera capricorni* in New Zealand estuaries. Aquatic Botany 85(1): 53-64.

Turner SJ, Hewitt JE, Wilkinson MR, Morrisey DJ, Thrush SF, Cummings VJ, Funnell G 1999. Seagrass patches and landscapes: The influence of wind-wave dynamics and hierarchical arrangements of spatial structure on macrofaunal seagrass communities. Estuaries 22(4): 1016-1032.

van Houte-Howes KSS, Turner SJ, Pilditch CA 2004. Spatial differences in macroinvertebrate communities in intertidal seagrass habitats and unvegetated sediment in three New Zealand estuaries. Estuaries 27(6): 945-957.

Woods CMC, Schiel DR 1997. Use of seagrass *Zostera novazelandica* (Setchell, 1933) as habitat and food by the crab *Macrophthalmus hirtipes* (Heller, 1862) (Brachyura: Ocypodidae) on rocky intertidal platforms in southern New Zealand Journal of Experimental Marine Biology and Ecology 214: 49-65.

7. APPENDICES

Appendix 1. Transect locations

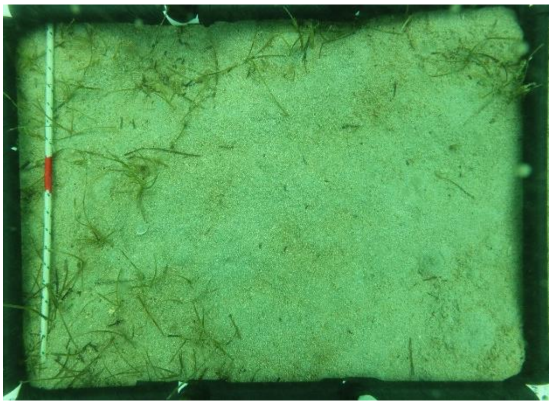
Transect	Depth range (m, MSL)	Start NZTME	Start NZTMN	End NZTME	End NZTMN
Slipper T1	2.9-3.5	1861255	5894592	1861214	5894721
Slipper T2	2.2-3.1	1861201	5894747	1861143	5894843
Slipper T3	4.9-5.3	1861074	5894652	1861033	5894773
Slipper T4	5.5-5.8	1861018	5894711	1860976	5894835
Slipper T5	6.0-7.2	1860907	5894781	1860943	5894656
Slipper T6	6.5-7.6	1860873	5894920	1860901	5894801
Great Mercury T1	1.2-2.7	1848055	5945990	1847949	5945945
Great Mercury T2	1.3-2.7	1848101	5945953	1847993	5945913
Great Mercury T3	1.9-3.0	1848169	5945885	1848071	5945853
Great Mercury T4	2.1-4.8	1848251	5945845	1848128	5945805
Great Mercury T5	2.7-5.3	1848291	5945798	1848186	5945771
Great Mercury T6	3.4-4.8	1848338	5945748	1848210	5945712

Appendix 2. Seagrass cover classes

Photographs representing the Braun-Blanquet seagrass cover classes used in this survey.

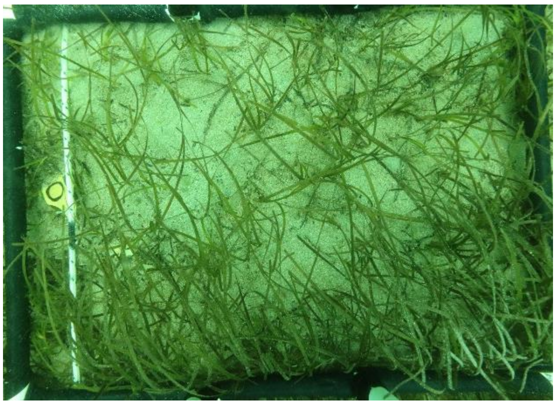
Cover class 0 (0%)

Cover class 1 (1-5%)



Cover class 2 (6-25%)

Cover class 3 (26-50%)



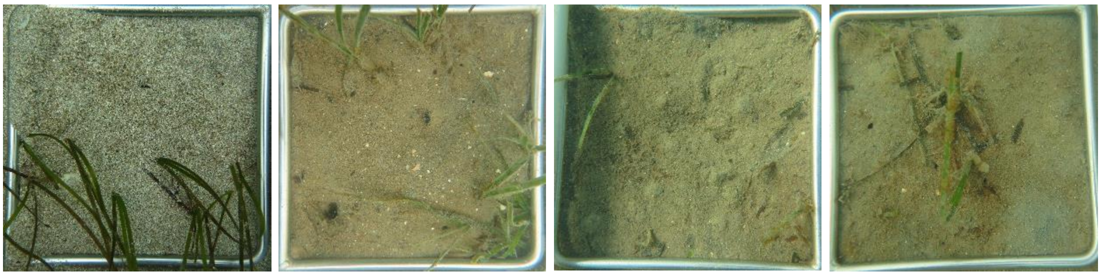
Cover class 4 (51-71%)

Cover class 5 (> 75%)

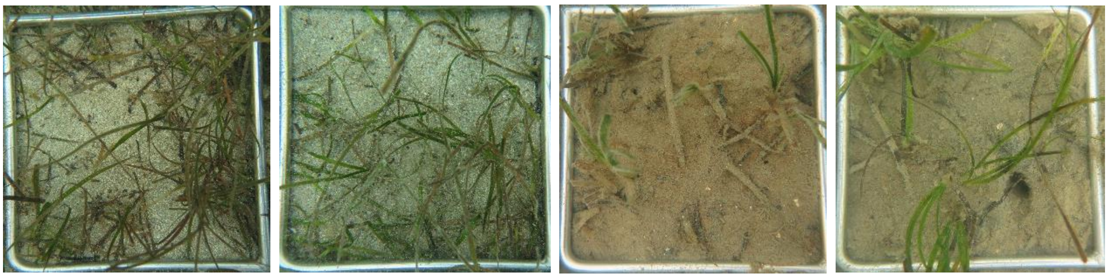
Appendix 3. Reference scale for visual biomass estimates

Photographs representing the range of visual biomass ranks used to estimate seagrass biomass in this survey.

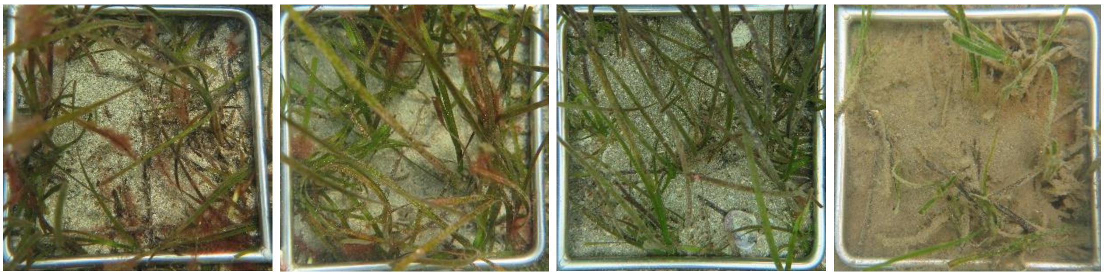
Rank 1



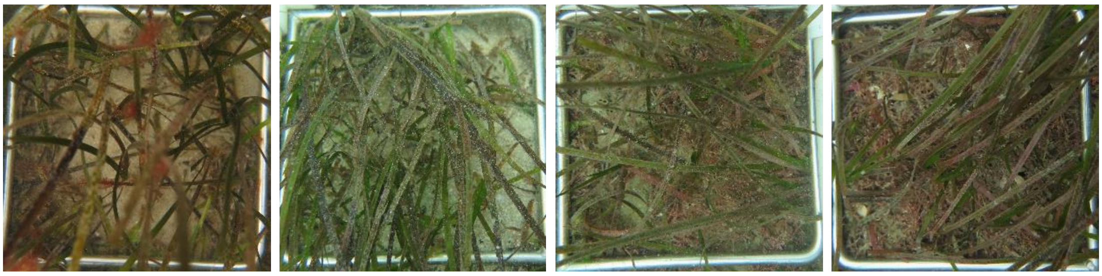
Rank 2



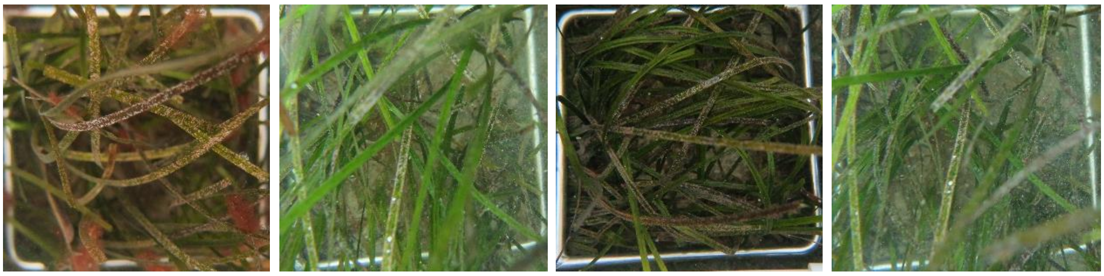
Rank 3



Rank 4



Rank 5



Appendix 4. Semi-quantitative scale for estimating epiphyte cover and severity of fungal wasting disease

The Wasting Index Method was developed by Burdick et al. (1993) as a rapid visual determination of the amount of necrotic tissue on seagrass shoots infected with fungal wasting disease (*Labyrinthula*). We used a semi-quantitative ranking system, corresponding to the percentage of disease cover in each class of the Wasting Index Key (Figure A4.1), to estimate percentage cover of both fungal wasting disease and epiphyte cover.

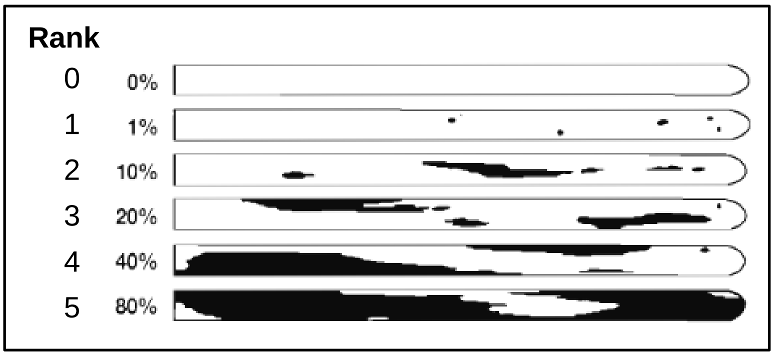


Figure A4.1. Ranks corresponding to the Wasting Index Key developed by Burdick et al. (1993).

Appendix 5. Statistical results

A5.1. Results from GAMs testing for differences between sites with depth as a covariate

Seagrass cover

```
## Family: Ordered Categorical(-1,-0.01,1.06,2.74,4.4)
## Link function: identity
##
## Formula:
## value + 1 ~ Depth * Island
##
## Parametric coefficients:
##                  Estimate Std. Error z value Pr(>|z|)
## (Intercept)        2.2460     0.4966   4.523 6.10e-06 ***
## Depth             -0.4156     0.1645  -2.527  0.01151 *
## IslandSlipp        5.2859     0.7783   6.792 1.11e-11 ***
## Depth:IslandSlipp  -0.5342     0.1999  -2.672  0.00755 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## Deviance explained =   15%
## -REML = 378.57  Scale est. = 1         n = 251
```

Leaf length

```
## Family: gaussian
## Link function: identity
##
## Formula:
## value ~ Depth * Island
##
## Parametric coefficients:
##                  Estimate Std. Error t value Pr(>|t|)
## (Intercept)       144.489     26.809   5.389 3.91e-07 ***
## Depth              -1.737      8.819  -0.197   0.8442
## IslandSlipp       186.702     36.211   5.156 1.09e-06 ***
## Depth:IslandSlipp  -21.519      9.966  -2.159   0.0329 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.392   Deviance explained = 40.8%
## GCV =   3267  Scale est. = 3155.3    n = 117
```

Biomass

```
## Family: gaussian
## Link function: identity
##
```

```
## Formula:
## Biomass ~ Depth * Island
##
## Parametric coefficients:
##                   Estimate Std. Error t value Pr(>|t|)
## (Intercept)          87.81      74.20   1.183   0.2512
## Depth               -10.80      24.71  -0.437   0.6671
## IslandSlipp         251.80     102.44   2.458   0.0237 *
## Depth:IslandSlipp   -30.65      28.15  -1.089   0.2898
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.374   Deviance explained = 45.9%
## GCV = 6180.9  Scale est. = 5106      n = 23
```

Epiphyte cover

```
## Family: Beta regression(0.14)
## Link function: logit
##
## Formula:
## value ~ Depth * Island
##
## Parametric coefficients:
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)        -3.8686     0.5800  -6.669 2.57e-11 ***
## Depth               1.1682     0.1907   6.126 9.01e-10 ***
## IslandSlipp         5.6307     0.7993   7.044 1.86e-12 ***
## Depth:IslandSlipp  -1.3564     0.2188  -6.199 5.68e-10 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.405   Deviance explained = -2.09%
## -REML = -2066.5  Scale est. = 1         n = 117
```

Fungal wasting disease severity

```
## Family: Beta regression(0.207)
## Link function: logit
##
## Formula:
## value ~ Depth * Island
##
## Parametric coefficients:
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)        0.66372    0.61647   1.077  0.28164
## Depth              0.08505    0.20155   0.422  0.67304
## IslandSlipp        2.64137    0.80944   3.263  0.00110 **
```

```
## Depth:IslandSlipp -0.67961    0.22628  -3.003  0.00267 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.239   Deviance explained = -2.04%
## -REML = -1254.2  Scale est. = 1         n = 117
```

Fungal wasting disease prevalence

```
## Family: Beta regression(0.891)
## Link function: logit
##
## Formula:
## value/100 ~ Depth * Island
##
## Parametric coefficients:
##                   Estimate Std. Error z value Pr(>|z|)
## (Intercept)        -0.5795     0.5501  -1.053   0.2922
## Depth              -0.2167     0.1773  -1.222   0.2215
## IslandSlipp         3.3655     0.7608   4.424  9.7e-06 ***
## Depth:IslandSlipp  -0.4989     0.2019  -2.471   0.0135 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.137   Deviance explained = -24.2%
## -REML = -293.85  Scale est. = 1         n = 120
```

A5.2. Results from Kruskal-Wallis rank sum tests testing for differences between sites without considering the effect of depth

Seagrass cover: chi-squared = 32.889, df = 1, p-value = 9.758e-09
Leaf length: chi-squared = 28.805, df = 1, p-value = 8.005e-08
Epiphyte cover: chi-squared = 8.2006, df = 1, p-value = 0.004188
Fungal wasting disease severity: chi-squared = 2.7749, df = 1, p-value = 0.09576
Fungal wasting disease prevalence: chi-squared = 0.38914, df = 1, p-value = 0.5328

A5.3. Results from GAMs testing for an effect of depth at each site

Seagrass cover Slipper

```
## Family: Ordered Categorical(-1,-0.21,0.12,1.39,2.87)
## Link function: identity
##
## Formula:
## value + 1 ~ Depth
##
## Parametric coefficients:
```

```
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   5.4497     0.5721   9.527  < 2e-16 ***
## Depth        -0.7649     0.1056  -7.242 4.43e-13 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## Deviance explained = 13.2%
## -REML = 183.86  Scale est. = 1         n = 125
```

Seagrass cover Great Mercury

```
## Family: Ordered Categorical(-1,0.32,1.92,4.09,17.42)
## Link function: identity
##
## Formula:
## value + 1 ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   3.4452     0.5379   6.405  1.5e-10 ***
## Depth        -0.5616     0.1782  -3.151  0.00163 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## Deviance explained = 2.74%
## -REML = 173.97  Scale est. = 1         n = 126
```

Leaf length Slipper

```
## Family: gaussian
## Link function: identity
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  331.191     25.761  12.856  < 2e-16 ***
## Depth        -23.256      4.913  -4.734  1.5e-05 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =   0.27   Deviance explained = 28.2%
## GCV = 3658.4  Scale est. = 3534.4    n = 59
```

Leaf length Great Mercury

```
## Family: gaussian
```

```
## Link function: identity
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  144.489     25.117   5.753 3.83e-07 ***
## Depth         -1.737      8.262  -0.210    0.834
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  -0.0171   Deviance explained = 0.0789%
## GCV = 2868.4  Scale est. = 2769.5    n = 58
```

Epiphyte cover Slipper

```
## Family: Beta regression(0.095)
## Link function: logit
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  2.58854    0.50629   5.113 3.17e-07 ***
## Depth       -0.24309    0.09933  -2.447   0.0144 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =   0.11   Deviance explained = -1.62%
## -REML = -688.5  Scale est. = 1         n = 59
```

Epiphyte cover Great Mercury

```
## Family: Beta regression(0.095)
## Link function: logit
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -2.9621     0.6066  -4.883 1.05e-06 ***
## Depth         0.8970     0.1993   4.501 6.78e-06 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
```

```
## R-sq.(adj) =  0.346   Deviance explained = -0.892%
## -REML = -1388.9  Scale est. = 1         n = 58
```

Fungal wasting disease severity Slipper

```
## Family: Beta regression(0.317)
## Link function: logit
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  4.22695    0.50065   8.443  < 2e-16 ***
## Depth       -0.77119    0.09833  -7.843  4.4e-15 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.484   Deviance explained = -8.55%
## -REML = -555.26  Scale est. = 1         n = 59
```

Fungal wasting disease severity Great Mercury

```
## Family: Beta regression(0.156)
## Link function: logit
##
## Formula:
## value ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)   0.5144     0.6340   0.811    0.417
## Depth         0.0727     0.2075   0.350    0.726
##
##
## R-sq.(adj) =  -0.0145   Deviance explained = -0.0489%
## -REML = -703.87  Scale est. = 1         n = 58
```

Fungal wasting disease prevalence Slipper

```
## Family: Beta regression(1.122)
## Link function: logit
##
## Formula:
## value/100 ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  3.13114    0.51000   6.139 8.28e-10 ***
## Depth       -0.80012    0.09403  -8.509  < 2e-16 ***
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.481   Deviance explained = -61.2%
## -REML = -166.48  Scale est. = 1         n = 60
```

Fungal wasting disease prevalence Great Mercury

```
## Family: Beta regression(0.748)
## Link function: logit
##
## Formula:
## value/100 ~ Depth
##
## Parametric coefficients:
##             Estimate Std. Error z value Pr(>|z|)
## (Intercept)  -0.4933     0.5626  -0.877    0.381
## Depth        -0.2045     0.1812  -1.128    0.259
##
##
## R-sq.(adj) =  -0.041   Deviance explained = -8.5%
## -REML = -128.65  Scale est. = 1         n = 60
```

A5.4. Results from GAMs testing for a relationship between quantitively assessed biomass and biomass estimated using the visual biomass assessment techniques

Visual biomass rank

```
## Family: gaussian
## Link function: identity
##
## Formula:
## Biomass ~ Biomass_visual
##
## Parametric coefficients:
##                Estimate Std. Error t value Pr(>|t|)
## (Intercept)     -61.598     19.308  -3.190  0.00369 **
## Biomass_visual   58.523      6.623   8.837 2.61e-09 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.741   Deviance explained =   75%
## GCV = 2496.6  Scale est. = 2318.2    n = 28
```

Seagrass cover using Braun-Blanquet scale

```
## Family: gaussian
## Link function: identity
##
```

```
## Formula:
## Biomass ~ Seagrass_cov
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -74.144     26.724  -2.774   0.0101 *
## Seagrass_cov  53.705      8.019   6.698 4.17e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.619   Deviance explained = 63.3%
## GCV = 3667.5  Scale est. = 3405.5    n = 28
```

Seagrass cover using dots-on-rocks

```
## Family: gaussian
## Link function: identity
##
## Formula:
## Biomass ~ Seagrass_DOR
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -38.9014    17.8664  -2.177   0.0387 *
## Seagrass_DOR  2.8323     0.3363   8.421 6.67e-09 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
##
## R-sq.(adj) =  0.721   Deviance explained = 73.2%
## GCV = 2681.4  Scale est. = 2489.9    n = 28
```

Appendix 6. Raw data from the Slipper Island and Great Mercury Island seagrass surveys

Refer to Appendices 2 to 4 for an explanation of the rankings used for seagrass cover, visual biomass, macroalgal cover, epiphyte cover and fungal wasting disease.

Table A5.1. Raw data from the Slipper Island seagrass survey with average values ± SE. Leaf length, epiphyte cover, fungal wasting severity and fungal wasting prevalence are means of 10 blades of seagrass.

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
T1	0									
	5	3.5	5				0			
	10	3.3	5	305			0	0.9	1.3	60%
	15	3.2	4				0			
	20	3.1	5	283			0	0.3	1.4	80%
	25	3.2	4		124.4	3	0			
	30	3.1	4	306			0	1.1	1.4	60%
	35	3.0	5				0			
	40	3.0	4	308			0	1.2	1.0	40%
	45	3.1	4				0			
	50	3.0	3	220			0	1.7	0.5	40%
	55	3.0	4				0			
	60	3.0	5	319			0	0.8	1.3	50%
	65	3.0	4				0			
	70	2.9	5	282			0	1.2	1.4	40%
	75	3.0	5		151.1	3	0			
	80	3.0	4	263			0	1.5	0.8	30%
	85	3.0	4				0			
	90	3.1	5	284			0	1.0	0.9	40%
	95	3.1	5				0			
	100	3.0	5	315			0	0.9	1.8	80%
T2	0	3.1	5				0			
	5	3.1	5				0			
	10	3.1	5	290			0	0.5	0.8	60%

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	15	3.1	4				0			
	20	3.1	5	293			0	1.1	1.1	70%
	25	3.1	5		382.2	5	0			
	30	3.1	5	313			0	1.8	1.8	80%
	35	3.1	5				0			
	40	3.1	5	311			0	1.0	1.5	90%
	45	3.1	4				0			
	50	3.1	3	130			0	1.1	1.0	70%
	55	3.1	2				0			
	60	3.1	3	301			0	1.2	2.3	100%
	65	2.9	5				0			
	70	2.9	5	264			0	0.7	2.3	80%
	75	2.8	5		151.1	4	0			
	80	2.7	5	307			0	1.2	1.6	70%
	85	2.7	2				0			
	90	2.5	4	184			0	2.0	0.7	40%
	95	2.3	4				0			
	100	2.2	3	124			0	1.3	1.1	50%
T3	0	4.9	5				0			
	5	5.0	3	209			0	1.1	0.7	30%
	10	5.1	5				0			
	15	5.1	4				0			
	20	5.2	3	145			0	0.2	0.7	50%
	25	5.3	3		44.4	2	0			
	30	5.2	5	181			0	0.6	0.3	30%
	35	5.1	5				0			
	40	5.1	5	249			0	1.0	0.5	30%
	45	5.2	1				0			
	50	5.2	2	136			0	0.2	0.3	20%
	55	5.1	4				0			
	60	5.1	3	155			0	0.6	0.1	10%

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	65	5.3	0				0			
	70	5.1	4	174			0	0.3	0.1	10%
	75	5.2	3		35.6	2	0			
	80	5.1	4	210			0	1.2	0.2	10%
	85	5.1	3				0			
	90	5.0	5	259			0	1.9	0.8	50%
	95	5.0	4				0			
	100	5.0	3	121			0	0.5	0.0	0%
T4	0	5.8	3				0			
	5	5.7	5				0			
	10	5.7	3	161			0	0.2	0.1	10%
	15	5.6	3				0			
	20	5.6	5	256			0	0.4	0.6	40%
	25	5.6	4		151.1	4	0			
	30	5.7	4	269			0	1.5	0.7	30%
	35	5.6	0				0			
	40	5.6	3	176			0	0.6	0.1	10%
	45	5.6	2				0			
	50	5.6	4	267			0	1.4	1.3	70%
	55	5.7	4				0			
	60	5.6	3	167			0	0.4	0.7	40%
	65	5.7	4				0			
	70	5.7	5	217			0	1.1	0.4	20%
	75	5.8	1		71.1	3	0			
	80	5.6	5	307			0	0.6	0.5	40%
	85	5.7	1				0			
	90	5.6	4	181			0	0.9	0.1	10%
	95	5.5	5				0			
	100	5.5	4	194			0	0.5	0.1	10%
T5	0	6.0	5	171			0	0.5	0.9	50%
	5	6.2	1				0			
	10	6.3	2	175			0	0.5	0.4	30%
	15	6.6	1				0			

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	20	6.6	1	129			0	0.1	0.0	0%
	25	6.5	0		NA	NA	0			
	30	6.6	1	67			0	1.8	0.0	0%
	35	6.6	0				0			
	40	6.7	1	110			0	0.7	0.0	0%
	45	6.7	2				1			
	50	6.7	0	112.5			0	0.25	0.4	20%
	55	6.8	1				0			
	60	6.9	0	85			0	0.4	0.2	20%
	65	6.9	0				0			
	70	7.0	0	103			0	0	0.5	20%
	75	7.0	1		8.9	1	0			
	80	7.1	0	150.5			0	0.7	0.3	30%
	85	7.1	0				0			
	90	7.2	0	NA			0	NA	NA	NA
	95	7.1	0				1			
	100	7.2	3	NA			0	NA	NA	NA
T6	0	7.6	3				0			
	5	7.5	3				2			
	10	7.3	3	238			0	1.2	0.1	10%
	15	7.3	3				2			
	20	7.2	3	224			2	1.1	0.4	20%
	25	7.2	3		71.1	3	2			
	30	7.1	4	258			1	0.4	0.3	20%
	35	7.0	4				1			
	40	7.0	4	215			0	0.2	0.0	0%
	45	7.0	3				2			
	50	6.9	4	249			1	0.7	0.6	30%
	55	6.9	3				0			
	60	6.9	0	165			0	0.2	0.3	20%
	65	6.8	4				1			
	70	6.7	3	194			3	1.3	0.1	10%
	75	6.7	3		106.7	4	3			

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	80	6.6	4	199			1	1.5	0.4	30%
	85	6.8	0				0			
	90	6.5	3	257			2	1.9	0.1	10%
	95	6.5	4				3			
	100	6.5	1	155			0	0.3	0.0	0%
	Average	5.1 (± 0.1)	**3.2 (± 0.1)**	**215 ± (9.1)**	**118 (± 30)**	**3.1 (± 0.3)**	**0.2 (± 0.1)**	**0.9 (± 0.1)**	**0.7 (± 0.1)**	**35 (±3.4)**
	T1	3.1 (± 0.0)	4.5 (± 0.1)	288 (± 9.4)	-	-	0 (± 0.0)	1.1 (± 0.1)	1.2 (± 0.1)	52 (± 5.5)
	T2	2.9 (± 0.1)	4.2 (± 0.2)	252 (± 24)	-	-	0 (± 0.0)	1.2 (± 0.1)	1.4 (± 0.2)	71 (± 5.7)
	T3	5.1 (± 0.0)	3.5 (± 0.3)	184 (± 15)	-	-	0 (± 0.0)	0.8 (±0.1)	0.4 (± 0.1)	24 (± 5.4)
	T4	5.6 (± 0.0)	3.4 (± 0.3)	219 (± 16)	-	-	0 (± 0.0)	0.8 (± 0.1)	0.5 (± 0.1)	28 (± 6.3)
	T5	6.7 (± 0.1)	0.9 (± 0.3)	123 (± 12)	-	-	1.0 (± 0.3)	0.6 (±0.2)	0.3 (± 0.1)	17 (± 5.4)
	T6	7.0 (± 0.1)	3.0 (± 0.3)	215 (±12)	-	-	1.4 (± 0.2)	0.9 (±0.2)	0.2 (± 0.1)	15 (± 3.4)

Table A5.2. Raw data from the Great Mercury Island seagrass survey with average values ± SE. Leaf length, epiphyte cover, fungal wasting severity and fungal wasting prevalence are means of 10 blades of seagrass.

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
T1	0	1.2	3				0			
	5	1.4	2				0			
	10	2.4	0	174.3			0	0	0.375	20%
	15	1.8	1				0			
	20	1.8	1	58			0	0.0	0.4	20%
	25	2.1	3		44.4	3	0			
	30	2.5	0	NA			0	NA	NA	NA
	35	2.6	2				0			
	40	2.6	2	165			0	0.0	2.2	70%
	45	2.7	3				0			
	50	2.6	2	82			0	0.0	0.6	40%
	55	2.5	2				0			
	60	2.5	1	75			0	0.0	0.2	10%
	65	2.5	1				0			
	70	2.3	3	95			0	0.0	0.0	0%
	75	2.3	2		26.7	2	0			
	80	2.4	2	90			0	0.0	0.3	20%
	85	2.4	1				0			
	90	2.4	2	58			0	0.0	0.4	20%
	95	2.4	2				0			
	100	2.5	0	45			0	5	0	0%
T2	0	1.3	3				0			
	5	1.4	3				0			
	10	1.5	3	163			0	0.0	1.4	70%
	15	1.7	3				0			
	20	1.9	3	179			0	0.0	1.7	60%
	25	2.0	3		62.2	2	0			
	30	2.0	2	125			0	0.0	1.2	60%
	35	2.1	3				0			

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	40	2.1	3	151			0	0.0	0.2	10%
	45	2.3	2				0			
	50	2.3	3	130			0	0.0	1.0	40%
	55	2.3	2				0			
	60	2.4	1	64			0	0.0	0.2	10%
	65	2.4	2				0			
	70	2.4	2	148			0	0.0	0.4	20%
	75	2.4	2		26.7	1	0			
	80	2.5	2	78			0	0.0	0.4	20%
	85	2.5	2				0			
	90	2.6	1	52			0	0.3	0.0	0%
	95	2.7	2				0			
	100	2.6	2	101			0	0.0	0.9	50%
T3	0	1.9	3				0			
	5	2.0	3				0			
	10	2.0	3	202			0	0.0	0.8	50%
	15	2.1	2				0			
	20	2.2	3	166			0	0.0	0.2	10%
	25	2.2	3		53.3	2	0			
	30	2.2	3	154			0	0.0	0.4	20%
	35	2.3	2				0			
	40	2.4	2	203			0	0.0	0.7	30%
	45	2.3	2				0			
	50	2.3	2	114			0	0.2	0.6	20%
	55	2.3	3				0			
	60	2.4	3	142			0	0.0	0.6	30%
	65	2.6	3				0			
	70	2.5	2	83			0	0.7	0.7	20%
	75	2.6	2		8.9	1	0			
	80	2.8	3	122			0	2.5	0.4	20%
	85	2.8	2				0			
	90	3.0	2	100			0	2.2	0.3	20%

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	95	3.0	3				0			
	100	2.9	2	177			0	2.3	1.5	60%
T4	0	2.1	4				0			
	5	2.1	3				0			
	10	2.1	4	250			0	0.0	1.5	70%
	15	2.2	4				0			
	20	2.3	4	176			0	0.0	0.5	30%
	25	2.3	3		97.8	3	0			
	30	2.4	2	168			0	0.2	1.5	50%
	35	2.5	3				0			
	40	2.6	3	186			0	1.4	0.7	30%
	45	2.8	4				0			
	50	2.8	3	118			0	3.4	1.1	40%
	55	2.9	3				0			
	60	3.1	3	151			0	3.4	0.4	10%
	65	3.4	2				0			
	70	3.7	3	139			0	3.5	0.5	40%
	75	4.0	2		53.3	3	0			
	80	4.2	2	82			0	3.4	0.2	10%
	85	4.5	2				0			
	90	4.7	1	99			0	3.0	0.3	10%
	95	4.8	0				0			
	100	4.8	0	NA			0	NA	NA	NA
T5	0	2.7	3	221			0	0.0	1.7	80%
	5	2.7	3				0			
	10	2.7	4	176			0	0.0	1.6	80%
	15	2.7	4				0			
	20	2.7	4	189			0	0.0	1.9	70%
	25	2.7	4		115.6	4	0			
	30	2.7	4	211			0	0.0	1.4	80%
	35	2.8	3				0			
	40	2.8	4	200			0	0.0	2.0	80%

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	45	2.8	3				0			
	50	3.0	3	187			0	0.0	1.8	80%
	55	3.1	3				0			
	60	3.3	2	131			0	0.7	1.0	50%
	65	3.4	2				0			
	70	3.7	2	156			0	2.3	1.1	60%
	75	4.0	1		17.8	1	0			
	80	4.3	0	56.7			0	4.6	0	0%
	85	4.6	0				0			
	90	4.8	1	131			0	4.3	0.8	40%
	95	5.1	0				0			
	100	5.3	1				0			
T6	0	3.4	1				0			
	5	3.4	1				0			
	10	3.4	1	69			0	2.6	0.0	0%
	15	3.5	1				0			
	20	3.4	1	179			0	0.0	1.9	80%
	25	3.6	3		88.9	3	0			
	30	3.6	4	213			0	0.0	1.9	80%
	35	3.6	3				0			
	40	3.7	4	215			0	0.0	1.5	80%
	45	3.8	3				0			
	50	3.9	3	190			0	0.0	1.2	50%
	55	4.0	3				0			
	60	4.1	3	162			0	1.6	1.3	60%
	65	4.2	3				0			
	70	4.3	3	136			0	2.6	1.9	80%
	75	4.4	2		8.9	1	0			
	80	4.5	2	138			0	4.4	0.9	30%
	85	4.6	2				0			
	90	4.6	2	62			0	3.9	0.2	10%
	95	4.7	3				0			

Transect	Distance (m)	Depth (m)	Seagrass cover (rank 1-5)	Leaf length (mm)	Biomass (gDW m^{-2})	Visual biomass (rank 1-5)	Macroalgal cover (rank 1-5)	Epiphyte cover (rank 1-5)	Fungal wasting severity (rank 1-5)	Fungal wasting prevalence (%)
	100	4.8	3	209			0	4.4	1.8	70%
	Average	2.9 (± 0.1)	2.3 (± 0.1)	139 (± 6.9)	50 (± 10)	2.1 (± 0.3)	0 (± 0.0)	1.1 (± 0.2)	0.9 (± 0.1)	38 (± 3.5)
	T1	2.2 (± 0.1)	1.7 (± 0.2)	93 (± 15)	-	-	0 (± 0.0)	0.6 (± 0.6)	0.5 (± 0.2)	20 (± 6.8)
	T2	2.1 (± 0.1)	2.3 (± 0.1)	119 (± 14)	-	-	0 (± 0.0)	0.0 (± 0.0)	0.7 (± 0.2)	34 (± 7.9)
	T3	2.5 (± 0.1)	2.5 (± 0.1)	146 (± 13)	-	-	0 (± 0.0)	0.8 (± 0.3)	0.6 (± 0.1)	28 (± 4.9)
	T4	3.1 (± 0.2)	2.6 (± 0.3)	152 (± 17)	-	-	0 (± 0.0)	2.0 (± 0.5)	0.7 (± 0.2)	29 (± 6.9)
	T5	3.4 (± 0.2)	2.4 (± 0.3)	166 (± 16)	-	-	0 (± 0.0)	1.2 (± 0.6)	1.3 (± 0.2)	62 (± 8.3)
	T6	4.0 (± 0.1)	2.4 (± 0.2)	157 (± 18)	-	-	0 (± 0.0)	2.0 (± 0.6)	1.3 (± 0.2)	54 (± 9.7)