Maintenance dredging

MID WEST PORTS

Seagrass Health Survey Report - Seagrass Communities in Champion Bay and Surroundings

Prepared by BMT

Purpose

BMT Commercial Australia was contracted by Mid West Ports Authority to complete a seagrass survey in Champion Bay and surrounding areas to measure seagrass health (shoot density, shoot height, biomass, and percent cover) at potential impact and control sites.

The 2021 study focused on seagrass meadows dominated by the species *Amphibolis antarctica, A. griffithii and Posidonia sinuosa*. Sampling was conducted in five regions: Point Moore to Chapman River, North of Chapman River, Greenough, Port Denison, and Jurien.

Importance

- This study compares characteristics and health indicators of seagrasses regionally over time;
- Outlines spatial trends and species shifts between 2007 and 2021;
- Provides a baseline assessment of seagrass communities prior to the 2021 Maintenance Dredging;
- Informed Environmental Impact Assessments and the Dredge Environmental Management Plan;
- Informs the development of a long-term seagrass health monitoring programme.

MONITOR & MANAGE

Marine fauna observers on board vessel

Aerial surveillance to monitor turbidity

Nearshore placement site hydrographic surveys

✓ Regular monitoring of water quality and light levels

Beach profiles

✓ Seagrass health surveys

Wind, waves, currents

Outcomes

This study found that despite the persistent influence of natural climatic drivers and anthropogenic influences, it appears in general that seagrasses that occur in the region, including Champion Bay, remained in good condition and have recovered since the capital dredging programme in 2002–2003.

Seagrass Communities in Champion Bay and Surroundings

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Synopsis: **Seagrass survey to better understand the long-term trends in resilience of seagrass communities in recognition of Mid West Ports Authority upcoming maintenance dredging and long-term strategic dredging and development requirements.**

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Executive Summary

In January 2021, BMT Commercial Australia was contracted by Mid West Ports Authority (MWPA) to complete a seagrass survey in Champion Bay and surrounding areas to measure seagrass health (shoot density, shoot height, biomass, and percent cover) at potential impact and control sites. This survey was the eleventh in a series of campaigns undertaken by MWPA over the past two decades that have documented long term trends in seagrass health in the region.

The 2021 study focused on seagrass meadows dominated by the species *Amphibolis antarctica*, *A. griffithii* and *Posidonia sinuosa*. Sampling was conducted in five regions: Point Moore to Chapman River, North of Chapman River, Greenough, Port Denison, and Jurien. A subset of sites previously examined by Westera & Babcock (2007) were surveyed. At each site, a team of divers collected seagrass and photographs to assess shoot density and height, aboveground biomass, seagrass leaves per shoot/cluster, presence of epiphyte and epifauna, presence of dead rhizome mat, presence of coloniser species, and benthic cover. Water column profiles were also collected at each site which measured conductivity, temperature, depth, dissolved oxygen, pH, and turbidity. In preparation for the field campaign, study sites were examined using satellite imagery to verify the presence of seagrass at each site, noting natural disturbance events in the past have led to losses of seagrasses in some locations. From the satellite imagery it was determined that 11 of 22 sites either had no seagrass present (only bare sand), the original site was on a small patch of seagrass meadow, or the site was over sparsely vegetated rocky reef and not over seagrass meadow. To avoid the loss of numerous study sites in 2021, new sites were established at the closest nearby meadow (typically sites were moved within a hundred metres of the original location).

In summary, the following spatial trends in seagrass characteristics and distribution were observed in 2021[1]:

- species shifts had occurred at some sites since the previous sampling campaigns in 2007 and 2012, with sites D68 and PD2 now dominated by *Thalassodendron pachyrhizum* (previously by *A. antarctica*), sites D61 and GF1 now dominated by *A. antarctica* (previously dominated by *A. griffithii*), and sites D100 and D4 now dominated by *Posidonia sinuosa* (previously dominated by *A. griffithii*)
- seagrass characteristics (shoot density and height, aboveground biomass, seagrass leaves per cluster) at *A. antarctica* sites varied among all sites, with Greenough and Port Denison sites reporting higher shoot densities and aboveground biomass than at sites in other regions
- *A. griffithii* was only prevalent at sites within the Jurien region; shoot height and leaves per cluster were similar across the three sites in the Jurien region, whereas shoot density and aboveground biomass varied among sites
- *P. sinuosa* was only found in Point Moore to Chapman River region; one site (D100) reported higher shoot density and aboveground biomass than the remaining sites
- *T. pachyrhizum* in site PD2 in Port Denison reported greater shoot density, leaves per shoot, shoot height and aboveground biomass than site D68 in North of Chapman River
- up to 40% cover of calcareous and filamentous epiphytic algae was observed on seagrass at all sites

[1] Results are reported by species to enable equitable comparisons between sites / regions

- up to three coloniser seagrass species were found within and surrounding *A. antarctica, A. griffithii, P. sinuosa* and *T. pachyrhizum* seagrass meadows, and while dead rhizomes were not observed at any sites, bare (possibly dead) *Amphibolis* stems were observed at site PD2
- the ratio of benthic cover at all site was generally dominated by its corresponding seagrass species (*A. antarctica, A. griffithii, P. sinuosa* and *T. pachyrhizum*) followed by macroalgae and coloniser seagrass species.

When comparing the seagrass characteristics temporally, it was determined that:

- all sites within each region (North of Chapman River, Point Moore to Chapman River, Greenough, Port Denison and Jurien) showed a high degree of site variability
- *A. antarctica*: shoot density has increased over time at sites within North of Chapman River and Point Moore to Chapman River. The number of leaves per cluster was greater in the period 2004 – 2021 compared to April and September 2003, when capital dredging activities were occurring. Aboveground biomass varied over time and shoots on average were taller in 2021 compared to previous years. Percent cover of persistent seagrass species increased in 2021 while the area of bare sand at most sites decreased
- *P. sinuosa*: shoot density varied over the years, site Pages reported longer shoots, and a higher aboveground biomass was reported in 2021, relative to previous years. Similar to *A. antarctica* sites, persistent species have gradually increased in cover, coloniser species have fluctuated in cover, while the presence of bare sand significantly reduced.

Trends described above conform with generally understood patterns in seagrasses that occur in high energy environments with mobile sand supply; that both species dominance at the meadow scale and morphological characteristics at the plant scale are heterogeneous in space and time, which can be caused by natural and anthropogenic disturbances. The coastal region of Geraldton is subjected to strong local winds, nearshore currents and swells of up to 3 m that drive the northward transport of sediment. Due to the Port's infrastructure and rocky groynes, the shipping channel has trapped large quantities of sand over the years and Champion Bay is likely suffering from a deficit of sand supply. The study sites have also been exposed to three ocean warming/marine heatwave events since 2007 and one short-term maintenance dredging campaign in 2012. No other anthropogenic pressures have occurred in the area since 2012. This study found that despite the persistent influence of natural climatic drivers and anthropogenic influences on small scale variability, it appears in general that seagrasses that occur in region, including Champion Bay, remain in good condition and have recovered since the capital dredging programme in 2002–2003.

However, it was also apparent that the seagrass system in Champion Bay is highly dynamic and there are multiple drivers which may influence seagrass health, and as such, future studies may need to consider including additional lines of evidence to help single out effects of any particular driver of interest.

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Acronyms

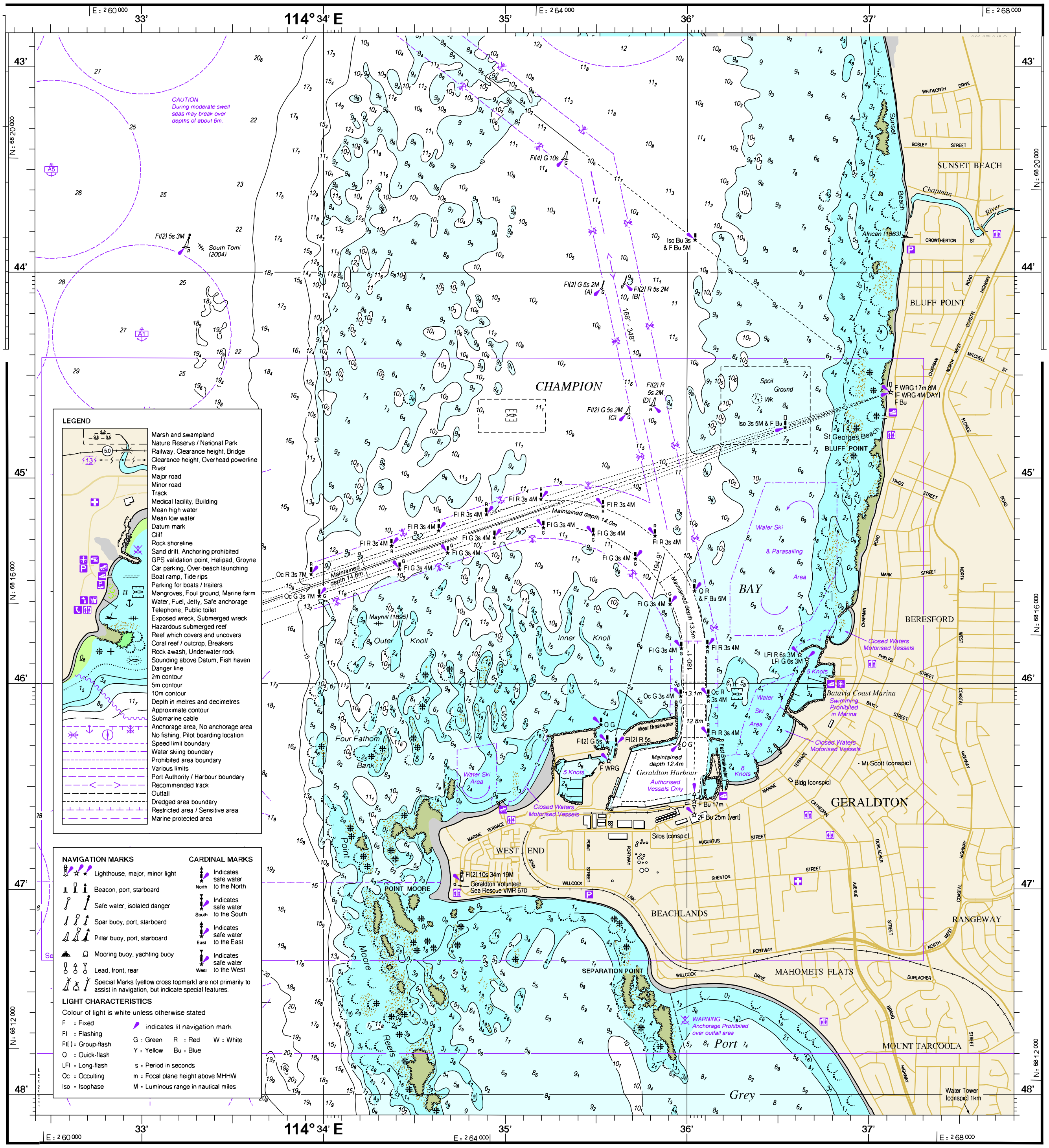
A. antarctica	*Amphibolis antarctica*
A. griffithii	*Amphibolis griffithii*
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ECU	Edith Cowan University
MWPA	Mid West Ports Authority
nMDS	Non-metric multidimensional scaling
QA/QC	Quality assurance and quality control
P. sinuosa	*Posidonia sinuosa*
PERMANOVA	Permutational multivariate analysis of variance
SAP	Sampling and Analysis Plan
SE	Standard error
SST	Sea surface temperature

1 Introduction

1.1 Background

Mid West Ports Authority (MWPA; previously Geraldton Port Authority) is the managing authority of Geraldton Port (hereafter; the Port), located ~420 km north of Perth, in the Mid West region of Western Australia. The Port is the largest commercial harbour of the region and facilitates trade in numerous industry sectors such as iron ore, mineral sands, agricultural products, rock lobster and finfish (Mid West Ports 2020). The Port comprises of seven berths in the main harbour, a fishing boat harbour, tugboats, and other infrastructure and is widely used by commercial vessels. The Port is located on the north side of Point Moore in the southern end of Champion Bay (Figure 1-1) and is surrounded by large areas of seagrass meadow and other significant benthic primary producer habitat. MWPA is presently[2] undertaking maintenance dredging, which has the potential to impact seagrass and MWPA are therefore concerned to track trends in seagrass health to ensure seagrasses in the region have not been disturbed as a result of the dredging activities.

[2] At the time this seagrass health assessment was commissioned and implemented, the maintenance dredging program had not yet commenced.

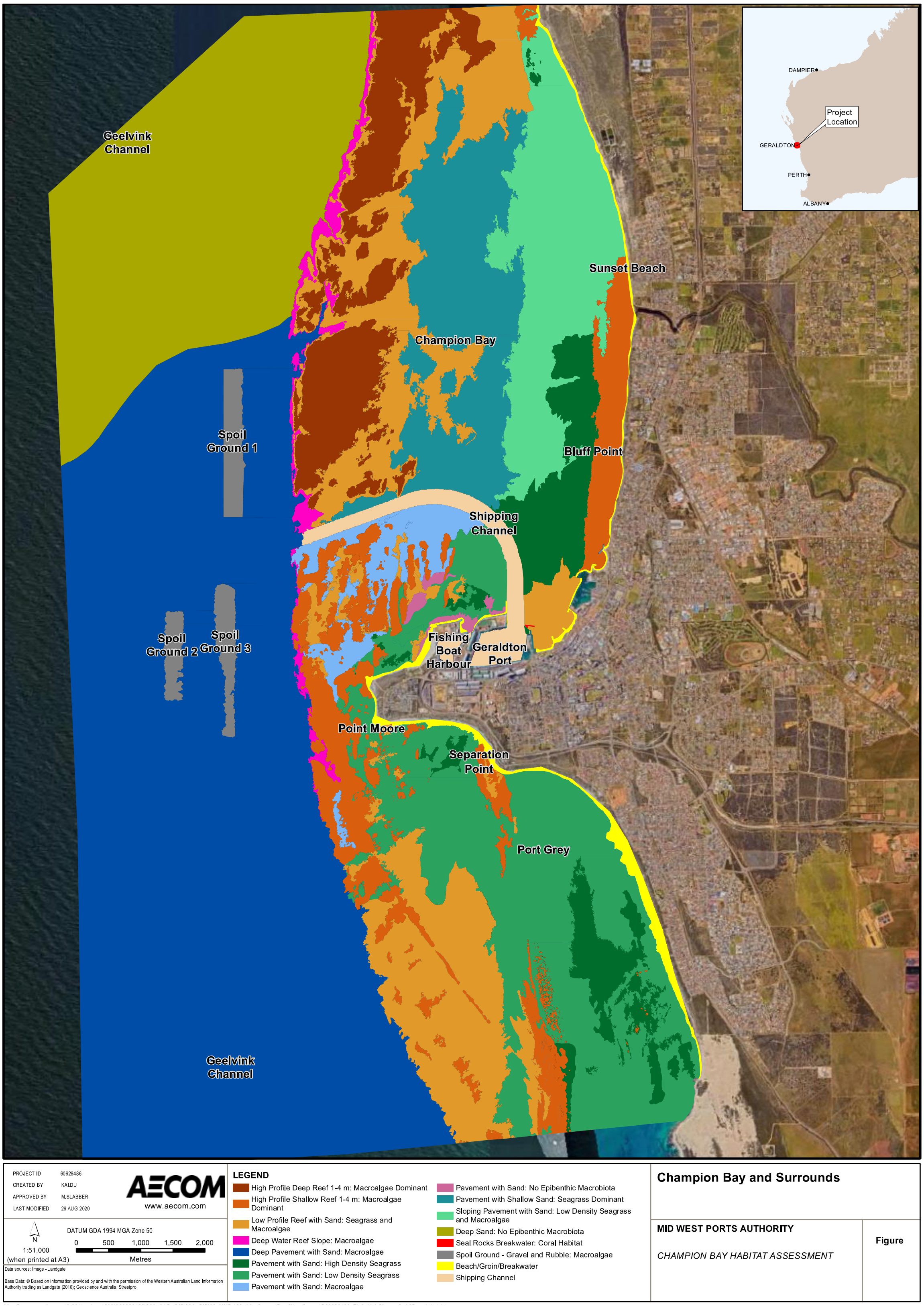


Source: Department of Planning and Infrastructure (2005)

Figure 1-1 Location of the Geraldton Port and the bathymetry of Champion Bay and surrounding areas

In the past two decades, there have been a number of significant disturbance events that have influenced the extent and health of seagrasses in the region. During 2002 and 2003, MWPA undertook a major capital dredging programme and port expansion project that involved the removal of ~4.5 million m^3 of limestone rock to deepen the harbour basin and deepen and widen the shipping channel. The dredging activities created turbid plumes in Champion Bay and surroundings that stressed seagrasses in the region. In response to the turbid plumes, URS Australia Pty Ltd completed two environmental impact assessments post-dredging (April and September 2003) of the seafloor of Champion Bay to assess the recovery of seagrasses in the Geraldton region (URS 2003). These surveys showed that an area approximately 10 km^2 in size located in deeper waters of the Bay had suffered about 40–50% deterioration in seagrass vigour. Additional post-dredging monitoring surveys were completed by Commonwealth Scientific and Industrial Research Organisation (CSIRO) between 2004 and 2007 to assess how turbid plumes, such as those produced by dredging operations, reduce light penetration in the water column and potentially influence long-term trends in seagrass health and distribution (Westera & Babcock 2005, CSIRO 2005, Westera & Babcock 2007). More recently, in April–May 2012, MWPA completed maintenance dredging of the Port's harbour and shipping channel, removing ~130 000 tonnes of sediment. Dredged material was disposed to designated areas within the port. A pre- and post-dredging seagrass monitoring program was conducted by GHD to assess the health of local seagrass habitats, although results showed that the dredging works had no direct impact to seagrasses at sites within Champion Bay (GHD 2012a,b). Since the maintenance dredging in 2012, no other large-scale anthropogenic activities have occurred in the study areas.

In the event of future maintenance and/or capital dredging, ongoing monitoring will continue to be required to track seagrass changes over time (Westera & Babcock 2007; GHD 2012b). Learnings from previous surveys (GHD 2012b) have recommended increasing the number of samples collected at each site to assist in the detection of statistical change. It was also recommended by Westera & Babcock (2007) to undertake regular mapping to track trends in extent and type of key benthic primary producer habitats over time to better inform management responses. In pursuant of these recommendations, MWPA engaged AECOM in 2020 to undertake mapping of the benthic habitats in Champion Bay and surrounding areas to help inform the environmental impact assessment and dredge plume modelling by identifying marine environments that could be susceptible to potential impacts from dredging activities (AECOM 2020). A total of 14 different habitat types were found within Champion Bay, which included reefs, sand, limestone pavement, seagrass, macroalgae and coral communities (Figure 1-2).



Source: AECOM (2020)

Figure 1-2 Classification of benthic habitat extent and distribution in Champion Bay and surrounding areas

Over recent years, sediment accretion has occurred in the Port's commercial harbour and shipping channel. MWPA are therefore proposing to undertake maintenance dredging of these areas in 2021 to return harbour and shipping channel depths to design to maintain safe navigational access. MWPA recognises that a pre-dredging assessment of the seagrass condition in Champion Bay and surrounding areas is required to meet their environmental management responsibilities and ensure that the dredging program has not led to loss of seagrasses in the area. Furthermore, MWPA is developing a long-term dredge strategy outlining future options for capital and maintenance dredging works that align with the Port's Master Plan (Mid West Ports 2020), ensuring the Port continues to operate safely to meet current and future growth opportunities.

In light of the above, BMT Commercial Australia Pty Ltd (BMT) was contracted by MWPA to complete a seagrass survey in Champion Bay and surrounding areas to measure seagrass health (shoot density, shoot height, biomass, and percent cover) at potential impact and control sites. The purpose of this document is to present the current seagrass condition of Champion Bay and surroundings and compare it to historical data to better understand long term trends in seagrass coverage of the region and assess for potential recovery in seagrasses following capital dredging in 2002–2003 and maintenance dredging activities in April–May 2012. The outcomes of this report will support environmental approval processes, and inform environmental monitoring and management plans for future dredging projects.

1.2 Regional setting

Along the mid-west coast of Western Australia, a series of shallow subtidal limestone reef systems located 1 to ~15 km offshore, run parallel to the coastline with many emergent rocks and islands (Sanderson & Eliot 1996). This region (Jurien Bay to the Geraldton) experiences moderate to high north-west offshore swells and seasonal wind patterns ranging from moderate to strong easterly and south-westerly winds (BoM 2021). Sediment is moved northward by south-westerly swell wave and wind-induced longshore transport (Tecchiato et al. 2012). The transport of sediment at times, causes particularly high levels of erosion Grannies Beach at Port Denison and Sunset Beach in Champion Bay (Department of Transport 2019). Recent modelling has shown that sediments entering Champion Bay are slow to leave the system (GEMMS 2021).

Champion Bay is a semi-sheltered embayment adjacent to a heavily developed coastline. Chapman River, located ~5 km north of Point Moore, seasonally discharges into coastal waters near Sunset Beach following significant rain falls in the catchment. The control sites south of Geraldton are located adjacent to small town sites along the coastline. Greenough River which is ~10 km south of Point Moore, meanders through extensive farm lands. Irvine River runs through the town of Dongara and discharges into Arurine Bay ~1.5 km north of Port Denison. Hill River Estuary is a closed estuarine system approximately 9 km south of Jurien Bay. All these rivers are typically closed at the river mouth by a sandbar and only open up in periods of high river flow. Much of this discharge is likely to contain a mixture of water and sediments from urban, intensive market gardening and broad acre farming.

Jurien Bay, Port Denison and Geraldton boat harbours provide an important facility for recreational fisheries and other recreational activities including windsurfing, kitesurfing, SCUBA diving, jet skiing and swimming.

In the summer months of 2020–2021, the waters off the south-west coast of Western Australia experienced a marine heatwave, reporting higher sea surface temperatures (SST) than the expected average (Schlegel 2020). Following the completion of the 2021 seagrass survey, Tropical Cyclone Seroja passed through the Geraldton region on 11 April 2021 that brought wind gusts of up to 170 km/hr and heavy rainfall (BOM 2021).

1.3 Scope of works

The scope of work is based on the Proposal (BMT 2020a) and subsequent communications with MWPA. The scope of works was to deliver:

- a Sampling and Analysis Plan (SAP; BMT 2020b) detailing instructions for implementing all aspects of the seagrass survey design and methods, including a preliminary review of available satellite imagery to confirm seagrass presence
- seagrass sampling program
- laboratory processing and quality assurance and quality control (QA/QC)
- Seagrass Communities in Champion Bay and Surroundings Report (this document)
- a data package.

In addition to the above scope of works, water quality profiles were also collected during the seagrass sampling program to better understand the physical conditions at the study sites before maintenance dredging commences.

1.4 Previous reporting

MWPA has previously engaged universities and environmental consultants to conduct pre- and post-dredging assessments on the recovery of seagrasses in the Geraldton region and reference locations for previous capital and maintenance dredging programs. This report compares the findings of several historical studies to better understand the long-term trends in resilience of seagrass communities in Champion Bay and surroundings. Previous historical studies include:

- URS Australia Pty Ltd September 2002: seagrass survey of 20 sites within Champion Bay conducted pre-dredging activities. At each site, video footage was captured along one 10 m-long transect at ~1 m from the seabed. Seagrasses were surveyed throughout Champion Bay, one transect at each site TL1, TL3, TL4, TL11, TL28, D75, D98 and D101 (eight transects), had seagrass species present, remaining 12 had bare sand or no seagrass present. Reported shoot densities and general health.
- URS Australia Pty Ltd April 2003: seagrass survey completed during capital dredging activities. *Amphibolis antarctica* and *A. griffithii* conditions were assessed based on reduction in leaf numbers compared to reference sites, and *Posidonia sinuosa* based on reduction of leaf number and leaf length compared to other locations. A reduction in leaf numbers and length were recorded in all seagrass species adjacent to dredging areas. Visual observations on coloniser species reported as generally healthy, and no areas of dead seagrass were observed (finding reported in URS 2003).

- URS Australia Pty Ltd 17–18 September 2003: seagrass survey conducted nearing the completion of capital dredging works. Sampling was concentrated in the eastern part of Champion Bay that was previously impacted from dredging operations. Poor underwater visibility prevented a complete quantitative survey and video analysis, instead seagrass was collected to visually record leaf number in *A. antarctica* and *A. griffithii* and leaf length in *P. sinuosa.* A reduction in leaf numbers and length was reported in all seagrass species (URS 2003).
- Geraldton Port Authority 23–25 February 2004: seagrass samples for *A. antarctica*, *A. griffithii* and *P. sinuosa* were collected from 5 replicate 0.4 x 0.4 m quadrats (totalling 0.16 m^2) in the Geraldton region to measure shoot density, aboveground biomass, number of leaves per cluster, canopy height, and percent cover. *A. antarctica* recovered substantially since previous surveys, while *A. griffithii* and *P. sinuosa* showed slight improvements in shoot density but still showed signs of stress at a few sites near the shipping channel and in Town Beach (GPA 2004).
- CSIRO Marine Research 22–26 October 2004: post-dredging survey to assess the condition and recovery of seagrasses in the Geraldton region. The survey established reference sites (Greenough, Port Denison, and Jurien) for comparison with Geraldton sites, re-surveyed seagrass sites selected by GPA (GPA 2004) and determined a subset of sites for ongoing monitoring. Seagrass measurements included shoot density, shoot height, above ground biomass, leaf and stem biomass, leaf area, leaves per cluster, percent cover of the meadow, epiphyte and epifaunal biomass, the presence of dead rhizome mat, and the presence of coloniser species. Seagrass measurements were taken from five replicate quadrats of 0.5 x 0.5 m, and qualitative benthic cover was captured from one video using a circular transect at a radius of 10 m and ~1 m above the seafloor (Westera & Babcock 2005).
- CSIRO Marine Research 20–24 February 2005: ongoing seagrass monitoring following post-dredging activities ceasing in 2003. The same sites and sampling methodology were used as per Westera & Babcock (2005); however, seagrass measurements were taken from six replicate quadrats of 0.5 x 0.5 m instead of five replicate quadrats, and quantitative benthic cover was captured using five replicate 10 m transects instead of one replicate transect. A temporal comparison of seagrass data collected in February 2004 and February 2005 was presented, and videography collected in September 2004 was used for visual purposes (CSIRO 2005).
- CSIRO Marine Research 2006: this report was not available for review; however, it is the ongoing seagrass monitoring that follows the same sampling methodologies as CSIRO (2005). The only difference being that site TL1 was sampled for *A. antarctica* in 2005 but *A. griffithii* was sampled in 2006.
- CSIRO Marine Research 18–21 February 2007: ongoing seagrass monitoring following the same sampling methodologies as CSIRO (2005) (Westera & Babcock 2007).
- GHD 26 April 2012: pre-maintenance dredging seagrass baseline assessment at six potential impact and two reference sites in the Geraldton region. A 0.5 x 0.5 m quadrat (totalling 0.25 m^2) was placed at 10 m and 20 m along six replicate 20 m-long transect to measure shoot density, percentage cover, seafloor type and seagrass species (GHD 2012a).
- GHD 26 May 2012: post-maintenance dredging evaluation of the seagrass habitat health using the same sampling methodologies as pre-dredging seagrass assessment (GHD 2012b).

2 Methods

2.1 Survey locations and timing

The MWPA series of seagrass health studies have included long-term / repeated monitoring over a number of selected seagrass meadows dominated by *Amphibolis antarctica*, *A. griffithii* and *Posidonia sinuosa* which are prevalent in the study area and in the mid-west region.

For this survey, a subset of sites surveyed by Westera and Babcock (2007) were re-sampled between the dates 15–28 January 2021 (Figure 2-1). The selected sites were representative of previously impacted and control sites, located across five regions. Impact sites were disturbed by sediment plumes resulting from capital dredging works in 2002–2003 in the regions Point Moore to Chapman River and North of Chapman River. Control sites to the north and south of Geraldton were established in October 2004 that were outside any potential influence of the dredge plume and had significant seagrass meadows and were located at Greenough, Port Denison, and Jurien (Westera & Babcock 2005).

To assist with field planning and survey design, a preliminary review of available current satellite imagery (as outlined in BMT 2020b) was completed to confirm seagrass presence at the sites identified in the CSIRO seagrass monitoring program (Westera & Babcock 2007).

Satellite imagery revealed that seven of the ten sites in Point Moore to Chapman River (D90, D114, TL11, D4, D100, D75 and D84), three of the five sites in North of Chapman River (D57, D68 and TL1), and one of three sites in Jurien (GPAR3) either had no seagrass present (only bare sand), the original site was on a small patch (<10 m) of seagrass meadow, or the site was over sparsely vegetated rocky reef and not over seagrass meadow (Table 2-1, Figure 2-2). Since monitoring commenced, several sites have been abandoned as the site was no longer comparable with the other study sites (Westera & Babcock 2005, Westera & Babcock 2007). If the same methods of removing sites were used for this survey, the study design and the number of impact sites would be significantly reduced. As such and to retain adequate spatial representation, sites were moved within a hundred metres of the original location to the nearest seagrass patch (Table 2-1, Figure 2-1).

Similar to previous studies, seagrass were sampled in the austral summer before any major leaf senescence periods (~April for *P. sinuosa*), before any major winter storm activity, and during relatively high light and temperature. Table 2-1 details the final site location, seagrass species collected, depth of the survey site and years of available data.

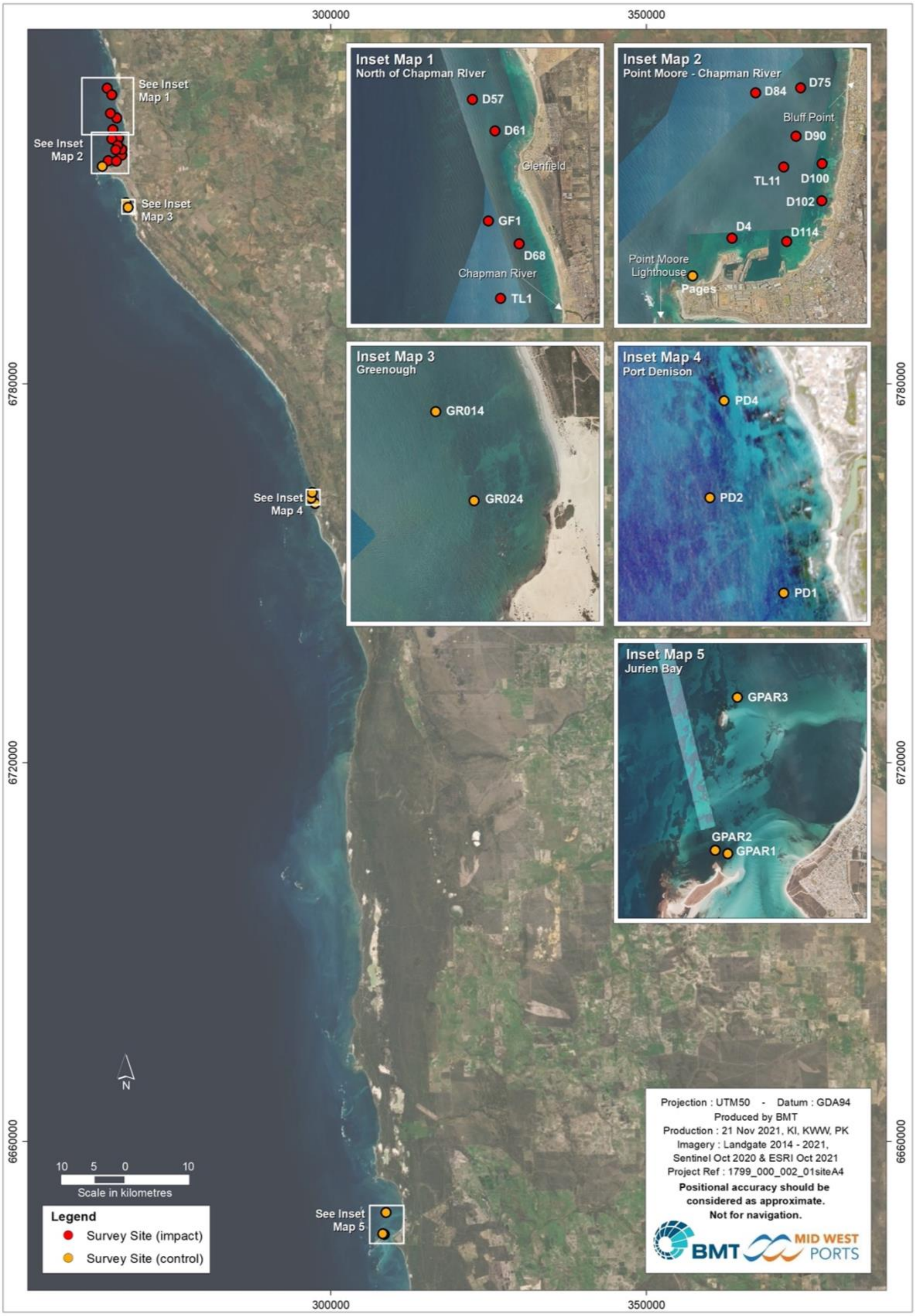


Figure 2-1 Locations of impact and control seagrass sampling sites within regions

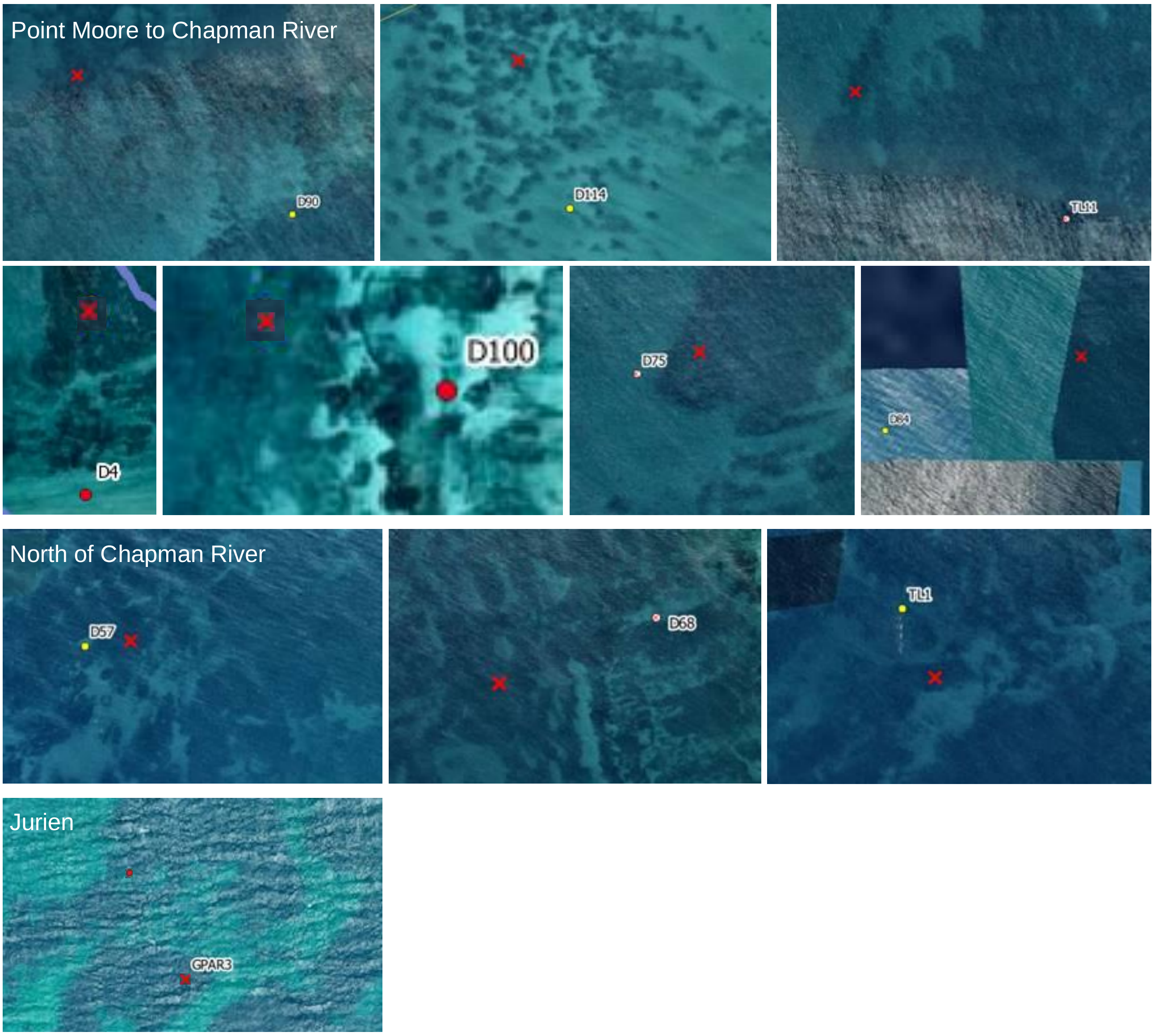


Figure 2-2 Screenshots of study sites that were moved based on habitat type visible on available satellite imagery, with 'X' marking the new site location

Table 2-1 Seagrass sampling locations, dominant seagrass species in 2007 and whether the site was shifted based on satellite imagery

Region	Site name	Treatment	Dominant seagrass species in 2007	Shifted based on satellite imagery?	Habitat type visible on satellite imagery?	Easting	Northing	Depth (m)	Years of data[1]
Point Moore to Chapman River	D90	Impact	*P. sinuosa*	Yes	Sparsely vegetated reef	266257	6817825	8.0	4
	D114	Impact	*P. sinuosa*	Yes	Small patches of seagrass	266033	6815331	4.4	5
	TL11	Impact	*P. sinuosa*	Yes	Densely vegetated reef (macroalgae)	265962	6817095	9.4	5
	Pages	Control	*P. sinuosa*	No	n/a	263814	6814517	5.0	4
	D4	Impact	*A. griffithii*	Yes	Bare sand	264742	6815405	5.0	5
	D100	Impact	*A. griffithii*	Yes	Shallow reef	266874	6817169	10.0	5
	D75	Impact	*A. antarctica*	Yes	Bare sand	266367	6818968	8.9	5
	D84	Impact	*A. antarctica*	Yes	Insufficient satellite visibility	265300	6818845	10.4	5
	D102	Impact	*A. antarctica*	No	n/a	266866	6816290	5.0	5
North of Chapman River	D61	Impact	*A. griffithii*	No	n/a	265301	6825847	7.0	5
	GF1	Impact	*A. griffithii*	No	n/a	265086	6822887	10.1	4
	D57	Impact	*A. antarctica*	Yes	Sand patch	264558	6826877	9.0	5
	D68	Impact	*A. antarctica*	Yes	Bare sand, habitat in direct vicinity of reef	266098	6822134	8.0	4
	TL1	Impact	*A. antarctica*	Yes	Bare sand	265490	6820334	9.0	4
Greenough	GR014	Control	*A. antarctica*	No	n/a	267569	6808704	6.7	4
	GR024	Control	*A. antarctica*	No	n/a	267887	6807970	5.4	4
Port Denison	PD1	Control	*A. antarctica*	No	n/a	297552	6761114	7.4	4
	PD2	Control	*A. antarctica*	No	n/a	296904	6761948	9.6	4
	PD4	Control	*A. antarctica*	No	n/a	297031	6762799	5.7	4
Jurien	GPAR1	Control	*A. griffithii*	No	n/a	308517	6645274	5.1	4
	GPAR2	Control	*A. griffithii*	No	n/a	308247	6645350	6.1	4
	GPAR3	Control	*A. griffithii*	Yes	Small patches of seagrass	308729	6648700	7.0	4

Notes:
(1) 4 years of data indicates 2005, 2006, 2007 and 2021; 5 years of data indicates 2004, 2005, 2006, 2007 and 2021
(2) Magenta text indicates the site was shifted from the original location as per Westera & Babcock (2007)
(3) *A. antarctica = Amphibolis antarctica, A. griffithii = Amphibolis griffithii, P. sinuosa = Posidonia sinuosa*

2.2 Seagrass measurements

Seagrass health measurements were collected via scuba as per Westera & Babcock (2007) and included:

- seagrass shoot density and height
- seagrass aboveground biomass
- seagrass leaves per shoot/cluster
- the presence of epiphyte and epifauna
- the presence of dead rhizome mat
- the presence of coloniser species, and
- benthic cover.

Specific seagrass health measurements were selected based on expert reviews determining robust bioindicators of health and stressors in seagrasses (Kirkman 1996, Wood & Lavery 2000, McMahon et al. 2013, Kilminster et al. 2015, Roca et al. 2016), as well as to provide continuity for the prior CSIRO study (Westera & Babcock 2007).

Shoot density, which measures of the number of seagrass shoots per m^2, is considered a fundamental indicator of seagrass health by regulators as density responds to changes in light climate along a sub-lethal to lethal response continuum and therefore any changes in health can be detected (and responded to) prior to permanent loss. Shoot height (also referred to as canopy height) can be used as an indicator of stress associated with hydrodynamic erosion / or burial and also shading effects (due to reduced photosynthetic activity). Aboveground biomass is a measure of the amount of organic matter that can be converted to secondary production or detrital matter. For example, if the seagrass meadows are stressed, the aboveground biomass can reflect underlying changes in net production. When seagrasses are light limited, they shed or senesce leaves, therefore, counting the number of leaves on each shoot/cluster provides a sub-lethal measure of past or current stress (noting that natural leaf shedding patterns of *Amphibolis* species are much more predictable than *Posidonia* species, and therefore, this indicator is typically only applied to *Amphibolis*).

The presence of enhanced biomass of epiphytes on leaves or stems can be a useful indicator of stress. While it is commonly used for understanding impacts associated with eutrophication; (an increased loading of nutrients reduces water clarity and may promote epiphytic growth on seagrass) enhanced epiphytic growth may also come about due to reduced productivity from other mechanisms. The presence of dead rhizome mats would indicate recent death of the seagrass plant associated to a range of direct and/or indirect mechanisms. Coloniser species are seagrasses that mature rapidly, are short-lived and have the ability to recover quickly from a disturbance, and belong to the genera *Halophila*, *Syringodium*, and *Zostera*.

2.2.1 In-situ collection of seagrass

For all seagrass measurements excluding benthic cover, seagrass was collected using a stratified random sampling approach. Within a 20 m radius of each site where seagrass was present, six replicate 0.5 x 0.5 m quadrats, which were subdivided into 25 squares of 0.1 x 0.1 m, were randomly placed over seagrass meadows but stratified on the dominant seagrasses of interest. Prior to harvesting the seagrass, a photograph of the quadrat was taken ~1 m above the seagrass. This provided a qualitative measure on the presence/absence of epiphytes and epifauna. This approach was chosen as it was less time consuming than Westera & Babcock (2007) method of scraping epiphytes and epifauna from seagrass leaves and stems.

Using scissors, seagrass was randomly harvested from 5 of the 25 squares within each 0.5 x 0.5 m quadrat (totalling 0.25 m^2) and placed in one labelled calico bag to form a single composite sample. All aboveground material including stems, leaves and leaf sheathes but not rhizome or roots, were collected. A total of six samples were collected per site.

After harvesting the seagrass, sandy areas within or surrounding the sampled seagrass meadow were inspected to a depth of ~10 cm for the presence of dead rhizomes and photographed. The presence of dead rhizomes may indicate previous stress of seagrass that resulted in death. The presence of coloniser seagrass species (e.g., *Halophila* spp., *Syringodium* spp., and *Zostera* spp. [formally *Heterozostera*]) within and surrounding the seagrass meadow were also photographed and recorded. All seagrass samples were submitted to Edith Cowan University (ECU) for processing in their laboratory.

Sampling of benthic cover (%) was completed using underwater videography. Five 10 m-long transects were randomly placed within ~30 m radius of each site. The diver slowly swam along the transect (~10 m/min) maintaining ~1 m above the seabed. The camera faced downwards to capture footage of the benthic habitat. All videos were time stamped and backed up at the completion of survey sets.

2.2.2 Laboratory analyses

Seagrass shoot density and height, aboveground biomass, and seagrass leaves per shoot/cluster were determined in the ECU laboratory. To measure seagrass shoot density, for *Amphibolis* spp., only the primary shoots were counted. The primary shoot for *Amphibolis* spp. is generally the longest shoot that is connected to the rhizome. For *P. sinuosa* samples, only the shoots were counted and not the leaves.

To measure shoot height, which is defined as the height above the sediment of 80% of the seagrass shoots (Duarte & Kirkman 2001), seagrass leaves were extended to their maximum length, ignoring the longest 20% of leaves, and measured from the sediment to the height of the top of the remaining 4/5 of this bundle (80% of the leaves).

The number of seagrass leaves in each cluster of leaves for *Amphibolis* spp. were counted to estimate cluster and leaf density (m^2). A cluster was defined as a group of leaves on the stem separate from the next cluster. A leaf was counted if the leaf was emerged from the sheath. For *P. sinuosa* samples, the number of leaves per shoot were counted.

To determine seagrass aboveground biomass, seagrass samples were dried at 90°C for 24 hours (or until constant weight), placed in a desiccator to cool to ambient temperature (~2 hours), and then weighed.

2.2.2.1 *Laboratory quality assurance and quality control*

As part of ECU's procedures, only one laboratory technician processed the samples to minimise errors during analyses. ECU's QA/QC measures consisted of processing one duplicate sample every 10 samples by a second laboratory technician to test reproducibility. Reproducibility between the primary laboratory technician and second laboratory technician was 100%.

2.2.3 Video analysis and habitat classification

Video footage of the benthic cover was analysed using TransectMeasure (SeaGIS 2021). For each video, ten random points were overlaid on ten random frames for a total of 100 identification points per transect and 500 points per site. The benthic habitat types within each frame of the video were determined by an experienced marine scientific analyst according to pre-determined habitat categories that were used in the previous analyses of the Geraldton region (Westera & Babcock 2007), listed in Table 2-2.

Table 2-2 Benthic habitat classifications

Category	Subcategory
Seagrass	*Amphibolis antarctica*
	Amphibolis griffithii
	Posidonia sinuosa
	Posidonia australis
	Posidonia coriacea
	Thalassodendron pachyrhizum
	Halophila australis
	Halophila spinulosa
	Zostera tasmanica (formerly known as *Heterozostera tasmanica* or *Heterozostera nigricaulis*)
	Syringodium isoetifolium
Coral	Hard
	Soft
Macroalgae	*Ecklonia* spp.
	Sargassum spp.
	Green algae
	Red algae
	Other brown algae
Rock/reef	
Rubble	
Dead stem or rhizome	

Category	Subcategory
Wrack	
Sand	

2.2.3.1 *Video quality assurance and quality control*

Prior to analysis of the benthic cover videos, three random frames were classified by both the analyst and a trained scientist with expertise in marine benthic ecology to ensure calibration was at an acceptable level (within 10%). Calibration between classification by the analyst and expert was 100%.

2.3 Water quality profiles

Profiles of depth, temperature, pH, salinity, specific conductivity, turbidity, and dissolved oxygen (oxygen demand) profiles were collected concurrently using a YSI EXO2 water quality profiler at all seagrass sampling sites from the sea surface to a depth of 0.5 m above the seabed. The sensors recorded data at 4 Hz, with triplicate recordings collected at each site to ensure high quality data and to understand within site variability.

Water quality profiles for temperature captured at each seagrass site were compared to the Copernicus marine data service sea surface temperature (SST) (https://marine.copernicus.eu/) to understand how a single measurement of temperature in time (January 2021) compares to historical trends, and identify any peaks or drops in temperature that may assist with interpreting seagrass data. Daily average SST at 20 cm depth from surface were obtained from 1 January 2000 to 28 February 2021 from an area covering Jurien Bay to Geraldton. The annual average SST were calculated for each year and presented in a graph.

2.4 Statistical analyses

2.4.1 Availability and comparability of historical seagrass data

During previous capital and maintenance dredging programs, MWPA have collected a large amount of data to understand the condition of seagrasses of the Geraldton region and surrounding areas (see Section 1.4). However, due to differences in sampling methodologies, changes in sampling sites over the years, and collection of different seagrass measurements, not all available historical data could be used for comparison in this report (see Section 1.4 for more information). The below tables (Table 2-3, Table 2-4, Table 2-5, Table 2-6) outlines the available historical data and data used for comparison in this report.

Where applicable, single data points (mean and standard errors (S.E.)) from any previous years have been included as bar charts to provide descriptive analyses of potential changes in seagrass communities prior to capital and/or maintenance dredging operations.

Table 2-3 Available historical data for sites dominated by *Amphibolis antarctica*

Region	Site name	Shoot density						Shoot height					Leaves per cluster							Seagrass aboveground biomass					Epiphyte biomass				
Year of data		Sep-03	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Apr-03	Sep-03	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07
Point Moore to Chapman River	D75	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	D84		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	D102		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
North of Chapman River	D57		Y		Y	Y	Y	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y			Y	Y	Y			Y	Y	Y
	D61		Y		Y	Y	Y			Y	Y	Y	Y	Y	Y		Y	Y	Y			Y	Y	Y			Y	Y	Y
	TL1		Y		Y	Y	*			Y	Y	*			Y		Y	Y	*			Y	Y	*			Y	Y	*
Greenough	GR014			Y	Y	Y	Y		Y	Y	Y	Y				Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	GR024			Y	Y	Y	Y		Y	Y	Y	Y				Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
Port Denison	PD1			Y	Y	Y	Y		Y	Y	Y	Y				Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	PD2			Y	Y	Y	Y		Y	Y	Y	Y				Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y
	PD4			Y	Y	Y	Y		Y	Y	Y	Y				Y	Y	Y	Y		Y	Y	Y	Y		Y	Y	Y	Y
Data used for this report		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes:
(1) * = Asterisks indicates that when sampling TL1 in February 2007, it was only sampled for benthic cover as different species were harvested in past years due to poor visibility

Table 2-4 Available historical data for sites dominated by *Amphibolis griffithii*

Region	Site name	Shoot density							Shoot height					Leaves per cluster							Seagrass aboveground biomass					Epiphyte biomass			
Years of data		Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Apr-12	May-12	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Apr-03	Sep-03	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Oct-04	Feb-05	Feb-06	Feb-07
Point Moore to Chapman River	D4	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	D100	Y		Y	Y	Y	Y	Y	Y		Y	Y	Y		Y	Y		Y	Y	Y			Y	Y	Y		Y	Y	Y
North of Chapman River	D61	Y		Y	Y	Y			Y		Y	Y	Y	Y	Y	Y		Y	Y	Y			Y	Y	Y		Y	Y	Y
	GF1			Y	Y	Y					Y	Y	Y					Y	Y	Y			Y	Y	Y		Y	Y	Y
Jurien	GPAR1	Y*							Y*														Y	Y					
	GPAR2			Y	Y	Y					Y	Y	Y					Y	Y	Y			Y	Y	Y		Y	Y	Y
	GPAR3			Y	Y	Y					Y	Y	Y					Y	Y	Y			Y	Y	Y		Y	Y	Y
Data used for this report		Yes	No	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes

Notes:
(1) * = Asterisks indicates Jurien Bay control site GPAR1 in February 2004 is ~250 m north-east of Boullanger Island
(2) Jurien Bay control site GPAR1 in February 2005, 2006 and 2007, videography only was taken at it was in close proximity to control site GPAR2

Table 2-5 Available historical data for sites dominated by *Posidonia sinuosa*

Region	Site name	Shoot density								Shoot height						Leaves per shoot		Seagrass aboveground biomass					Epiphyte biomass			
Years of data		Sep-02	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Apr-12	May-12	Apr-03	Sep-03	Oct-04	Feb-05	Feb-06	Feb-07	Apr-03	Sep-03	Feb-04	Oct-04	Feb-05	Feb-06	Feb-07	Oct-04	Feb-05	Feb-06	Feb-07
Point Moore to Chapman River	D90				Y	Y	Y			Y	Y		Y	Y	Y	Y				Y	Y	Y		Y	Y	Y
	D114		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	TL11	Y	Y		Y	Y	Y						Y	Y	Y					Y	Y	Y		Y	Y	Y
	Pages				Y	Y	Y	Y	Y				Y	Y	Y					Y	Y	Y		Y	Y	Y
Data used for this report		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2-6 Available historical data for benthic cover

Region	Site name	Years of data							
		Sep-02	Jun-03	Oct-04	Feb-05	Feb-06	Feb-07	Apr-12	May-12
Point Moore to Chapman River	D90				Y	Y	Y		
	D114				Y	Y	Y	Y	Y
	TL11	Y	Y	*	Y	Y	Y		
	Pages				Y	Y	Y	Y	Y
	D4				Y	Y	Y	Y	Y
	D100				Y	Y	Y	Y	Y
	D75	Y		Y	Y	Y	Y		
	D84				Y	Y	Y		
	D102				Y	Y	Y		
North of Chapman River	D61				Y	Y	Y		
	GF1				Y	Y	Y		
	D57				Y	Y	Y		
	D68				Y	Y	Y		
	TL1	Y	Y	*	Y	Y	Y		
Greenough	GR014		Y^	Y	Y	Y	Y		
	GR024				Y	Y	Y		
Port Denison	PD1				Y	Y	Y		
	PD2				Y	Y	Y		
	PD4				Y	Y	Y		
Jurien	GPAR1				Y	Y	Y		
	GPAR2				Y	Y	Y		
	GPRA3				Y	Y	Y		
Data used in this report		No	No	No	Yes	Yes	Yes	Yes	Yes

Notes:
(1) ^ = Data collected at TL28 was 200 m north-east of the GR014 site near Greenough
(2) * = Asterisks indicate no data available
(3) Blank cells indicate no data was collected for the site

2.4.2 Pre-treatment of historical and 2021 seagrass data

Prior to the analysis of historical and 2021 seagrass data, data were pre-treated to ensure a valid and robust statistical comparison could be made. The following pre-treatment were completed prior to analyses:

- Seagrass data collected in February and October 2004 had five replicate quadrats while all subsequent sampling in 2005, 2006, 2007 and 2021 used six replicate quadrats. To balance the replication level for an appropriate statistical analysis, the average of the five replicate quadrats was used as the sixth replicate sample for the February and October 2004 data (Underwood 1997).

- Quadrats used to sample seagrass in February 2004 (GPA 2004) were 0.4 x 0.4 m, while studies from October 2004 (Westera & Babcock 2005) onwards used 0.5 x 0.5 m quadrats. To compare the data collected using two different quadrats sizes, the data were normalised to 1 m^2.
- Studies between February 2004 and February 2007 measured epiphyte and epifaunal biomass by scraping all epiphytic and epifaunal growth from leaves and stems and then dried. For this study, epiphytes were not quantitatively measured, instead, photographs of the 0.5 x 0.5 m^2 quadrats were taken to provide a qualitative measure on the presence/absence of epiphytes and epifauna. Epiphytic load on seagrass is more a response to changes in available nutrients, generally nitrogen and phosphorus (Frankovich et al 2009), rather than a response to dredging and changes in light climate. Therefore, results from February 2004 to February 2007 will be presented differently to the January 2021 results.
- The January 2021 field campaign identified that some study sites were dominated by a different seagrass species compared to previous studies (see Section 3.1). To ensure seagrass data from the same species can be compared with historical data, some sites were removed from temporal statistical analyses. All January 2021 data are presented in Sections 3.2 and 3.3.

2.4.3 Statistical design

The overarching objective of this study was to assess the condition and potential recovery of seagrass in Champion Bay and surrounding areas following capital dredging in 2002–2003 and maintenance dredging activities in April–May 2012. Due to differences in sampling protocols and collection of a different suite of seagrass measurements in previous monitoring programs (see Sections 1.4, 2.4.1 and 2.4.2), statistical analyses of the data were confined to the available replicated data.

To determine whether seagrass communities have changed over time (years of pre- and post-dredging monitoring, and ongoing monitoring) and spatially (among regions), the data was analysed using three different statistical designs, depending on data availability:

Time versus Regions, with the following factors:

- Time (fixed factor, orthogonal with up to six levels: summer periods of February 2004, October 2004, 2005, 2006, 2007, 2021)
- Region (random factor, orthogonal with up to five levels: North of Chapman River, Point Moore to Chapman River, Greenough, Port Denison, Jurien)
- Site (random factor, nested within Region)

Treatment versus Time, with the following factors:

- Time (fixed factor, orthogonal with up to six levels: summer periods of February 2004, October 2004, 2005, 2006, 2007, 2021)
- Treatment (fixed factor, orthogonal with two levels: control, impact)
- Site (random factor, nested within Treatment).

Impact sites versus Time, with the following factors:

- Time (fixed factor, orthogonal with up to six levels: summer periods of February 2004, October 2004, 2005, 2006, 2007, 2021)
- Site (impact sites only, fixed factor).

Data on shoot density, shoot height, seagrass aboveground biomass, leaves per shoot/cluster, and percent cover of climax seagrass species were compared using univariate analyses. Data on the percent cover and benthic assemblages were compared using multivariate analyses. Qualitative observations of the presence/absence of dead rhizomes, coloniser species and epiphyte and epifauna are also presented.

All statistical analyses, including post-hoc tests on significant factors, were undertaken using PERMANOVA (permutational multivariate analysis of variance, Version 1.0.1, Primer-E Ltd; Anderson 2001a,b). This method enabled analysis of univariate and multivariate datasets, without explicitly requiring normalised data, homogeneous variances or balanced designs. All analyses were run using permutations of residuals under a reduced model (n = 9999 permutations) as suggested by Anderson (2001b). Monte Carlo sampling was used where there were less than 100 unique permutations possible in PERMANOVA as recommended by Anderson et al. (2008). This involves the use of random number simulation techniques to mimic a statistical population and is commonly used in practical statistics. Results of Monte Carlo sampling are only presented if they change the interpretation of the results (e.g., from significant to non-significant or vice versa).

2.4.4 Univariate analyses

2.4.4.1 Spatial comparisons

Spatial comparisons were made between the regions and/or sites with the respective dominant seagrass species (*A. antarctica*, *A. griffithii*, and *P. sinuosa*) for year 2021 alone. Data were square-root transformed prior to analyses of shoot density, shoot height, seagrass aboveground biomass, leaves per shoot/cluster, and percent cover of climax seagrass species. This transformation allowed all sites to contribute to the analysis by down-weighting the contribution of sites reporting higher seagrass measurements and allowed sites with lower measurements to play a part in the analyses (Clarke 1993). Euclidean distance was used as a dissimilarity measure for univariate analyses. By using the Euclidean measure, PERMANOVA returns an equivalent test statistic to a standard analysis of variance (Anderson et al. 2008). Univariate analyses were completed using one of two statistical designs: Region and Site (Region) when multiple regions were assessed, or Site alone. Analyses on two factors were completed using permutation of residuals under a reduced model. Analyses with only one factor was done using unrestricted permutation of raw data. If Region was significant, it was interpreted using post-hoc, pair-wise comparisons to test for differences among levels within Region. Results from the univariate analyses were presented using bar graphs of means and standard errors for region and site.

2.4.4.2 Temporal comparisons

Comparisons of shoot density, shoot height, seagrass aboveground biomass, leaves per shoot/cluster, and percent cover of climax seagrass species were made over temporal scales (years of survey) using univariate analyses. Data were square-root transformed and used Euclidean distance as the dissimilarity measure. Univariate analyses were completed on three statistical designs: Time versus Region, Control versus Impact, and Impact sites versus Time (see Section 2.4.3). Analyses were completed using permutation of residuals under a reduced model. If either Time, Region and/or Treatment or interaction term between any of the three factors were significant, it was interpreted using post-hoc, pair-wise comparisons to test for differences among levels within each factor. Results from the univariate analyses were presented using bar graphs of means and standard errors.

2.4.5 Multivariate analyses

For multivariate analysis of percent cover and benthic assemblages, data were fourth-root transformed prior to analysis to down-weigh the contribution of the dominant biota and to allow intermediate or rarer groups to play a part in the analyses (Clarke & Green 1988). Prior to analysis with PERMANOVA, the Bray-Curtis dissimilarity measure was used (Clarke & Gorley 2006). Any significant results were interpreted using post-hoc tests to test for differences among levels within each factor.

Results of multivariate analysis were presented graphically using a non-metric multidimensional scaling plot (nMDS). The nMDS preserves relationships among samples in two-dimensional space; sites with similar data are grouped close together, whereas dissimilar sites appear farther apart (Clarke & Warwick 2001). Upon detection of a significant difference among levels within a factor, vector overlays were plotted on the nMDS. This enabled the top benthic groups that have the strongest correlations (Spearman correlation >0.4) with the patterns in the multivariate data (i.e., along a spatial gradient) to be determined.

3 Results

3.1 Change in seagrass species: January 2021

Although this study focused on seagrass meadows dominated by *Amphibolis antarctica*, *A. griffithii* and *Posidonia sinuosa,* species shifts had occurred at some sites since the previous sampling campaigns in 2007 (Westera & Babcock 2007) and 2012 (GHD 2012a,b). Specifically, sites D68 and PD2 were now dominated by *Thalassodendron pachyrhizum* (previously by *A. antarctica*), sites D61 and GF1 now dominated by *A. antarctica* (previously dominated by *A. griffithii*), and sites D100 and D4 now dominated by *Posidonia sinuosa* (previously dominated by *A. griffithii*; Figure 3-1, Table 3-1).

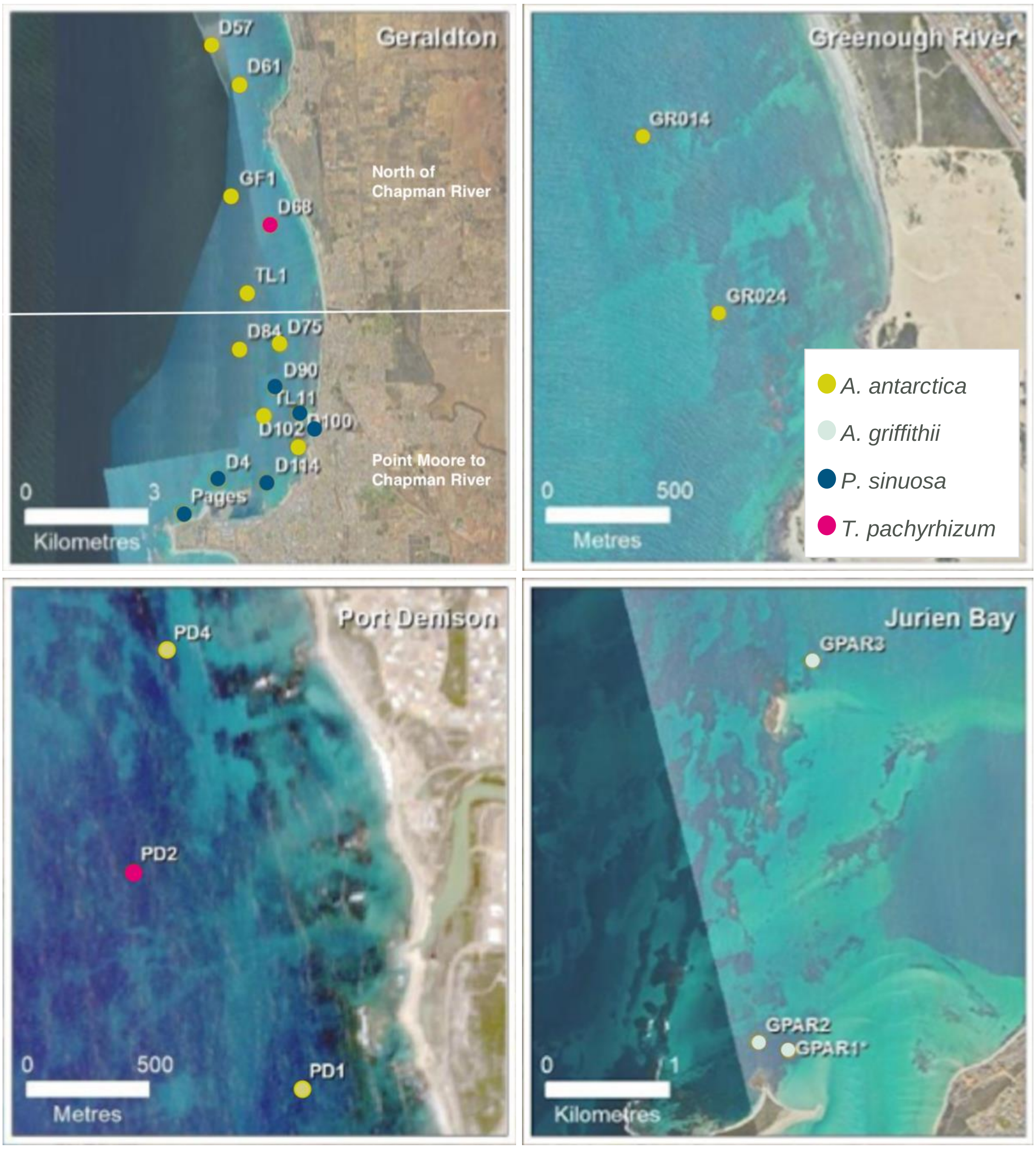


Figure 3-1 Dominant seagrass species at each sampling site in January 2021

Two of the original sites (D4 and D74; as per Westera & Babcock 2007) were visited by the field team to confirm if the benthic habitat corresponded to what was observed in the satellite imagery (Section 2.1). It was confirmed that both sites were dominated by bare sand as identified in the satellite imagery (Table 3-1). Field validation of remaining sites was not performed due to time constraints in the sampling programme.

Table 3-1 Change in dominant seagrass species from 2007 to 2021

Region	Site name	Treatment	Dominant seagrass species in 2007	Shifted based on satellite imagery?	Dominant seagrass species in 2021
Point Moore to Chapman River	D90	Impact	*P. sinuosa*	Yes	*P. sinuosa*
	D114	Impact	*P. sinuosa*	Yes	*P. sinuosa*
	TL11	Impact	*P. sinuosa*	Yes	*P. sinuosa*
	Pages	Control	*P. sinuosa*	No	*P. sinuosa*
	D4	Impact	*A. griffithii*	Yes	*P. sinuosa*
	D100	Impact	*A. griffithii*	Yes	*P. sinuosa*
	D75	Impact	*A. antarctica*	Yes	*A. antarctica*
	D84	Impact	*A. antarctica*	Yes	*A. antarctica*
	D102	Impact	*A. antarctica*	No	*A. antarctica*
North of Chapman River	D61	Impact	*A. griffithii*	No	*A. antarctica*
	GF1	Impact	*A. griffithii*	No	*A. antarctica*
	D57	Impact	*A. antarctica*	Yes	*A. antarctica*
	D68	Impact	*A. antarctica*	Yes	*T. pachyrhizum*
	TL1	Impact	*A. antarctica*	Yes	*A. antarctica*
Greenough	GR014	Control	*A. antarctica*	No	*A. antarctica*
	GR024	Control	*A. antarctica*	No	*A. antarctica*
Port Denison	PD1	Control	*A. antarctica*	No	*A. antarctica*
	PD2	Control	*A. antarctica*	No	*T. pachyrhizum*
	PD4	Control	*A. antarctica*	No	*A. antarctica*
Jurien	GPAR1	Control	*A. griffithii*	No	*A. griffithii*
	GPAR2	Control	*A. griffithii*	No	*A. griffithii*
	GPAR3	Control	*A. griffithii*	Yes	*A. griffithii*

Notes:
(1) Magenta text indicates the site was shifted from the original location as per Westera & Babcock (2007), and the new dominant seagrass species present at that site in January 2021
(2) *A. antarctica = Amphibolis antarctica, A. griffithii = Amphibolis griffithii, P. sinuosa = Posidonia sinuosa, T. pachyrhizum = Thalassodendron pachyrhizum*

3.2 Spatial comparison of seagrass characteristics: January 2021

3.2.1 *Amphibolis antarctica* sites

Mean shoot density at the *A. antarctica* sites ranged from 200 to 700 shoots/m^2 (Figure 3-2). Site D84 in Point Moore to Chapman River reported the lowest shoot density (200 shoots/m^2) compared to 700 shoots/m^2 at PD1 in Port Denison, displayed high variability among sites within each region (Table 3-2). The mean number of *A. antarctica* leaves per cluster was not significantly different between regions (Table 3-2) but varied across sites, ranging from 9.60 to 14.23 leaves per cluster (Figure 3-2). Significant regional differences were detected for *A. antarctica* shoot height, with post-hoc pair-wise comparisons showing that Greenough sites (GR014 and GR024) were significantly different to North of Chapman River, Point Moore to Chapman River and Port Denison ($p<0.05$), as

Greenough recorded the greatest mean shoot height (GR014: 61.17 cm, GR024: 70.00 cm, respectively; Figure 3-2). Mean shoots for *A. antarctica* shoots ranged from 27.08 to 70 cm (Figure 3-2).

For aboveground biomass (leaves, sheaths and stems combined), post-hoc tests revealed that Greenough was statistically different to North of Chapman River and Point Moore to Chapman River, as aboveground biomass was greatest at both Greenough sites (GR014 and GR024), weighing an average 903.57 and 975.83 g dry weight/m^2, respectively (Figure 3-2). Both sites in Port Denison (PD1 and PD4) were also significantly different to North of Chapman River and Point Moore to Chapman River, reporting higher mean aboveground seagrass biomass (PD1: 622.13 g dry weight/m^2, PD4: 755.04 g dry weight/m^2, respectively) than sites in North of Chapman River and Point Moore to Chapman River, which ranged from 149.90 and 494.30 g dry weight/m^2 (Figure 3-2).

A full list of the statistical results is provided in Appendix A.

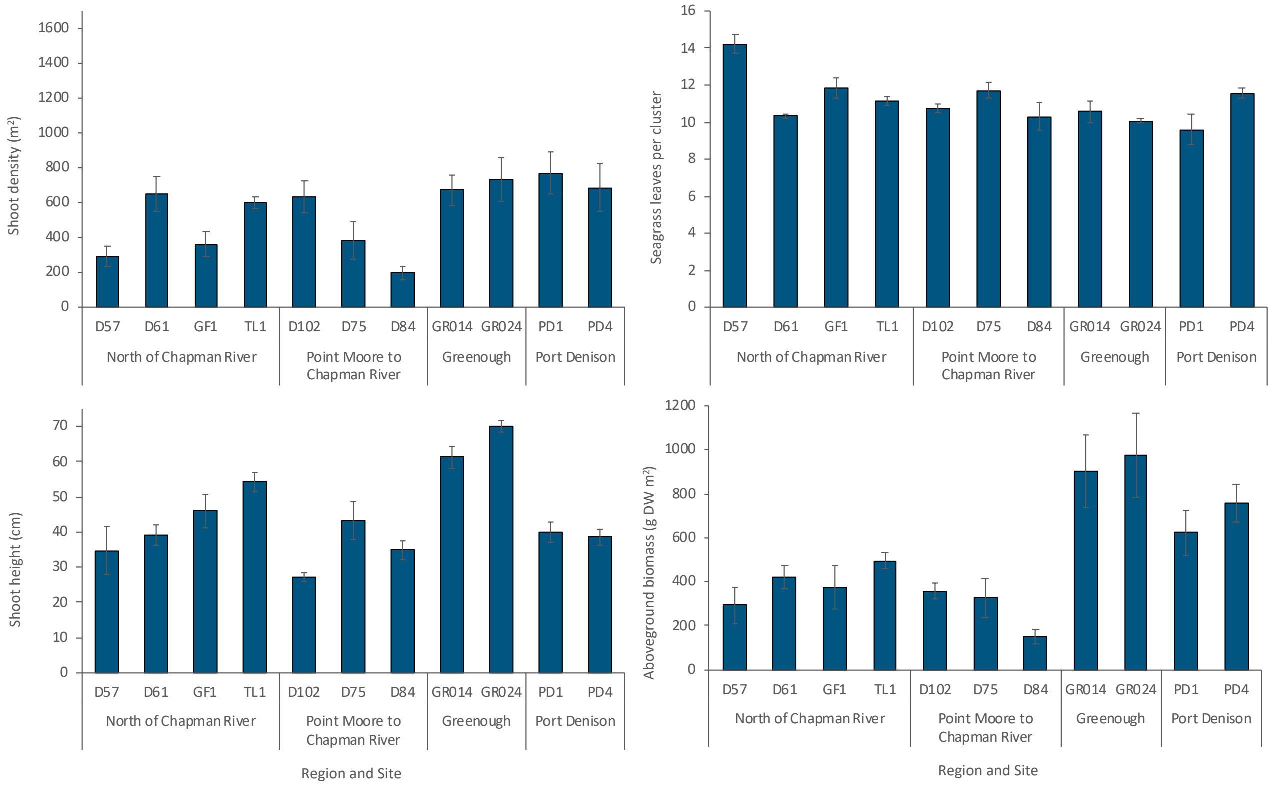


Figure 3-2 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for each *Amphibolis antarctica* dominated site nested within region in January 2021

Table 3-2 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Amphibolis antarctica* across regions and sites

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Region	3	613.65	204.55	2.0146	0.2134	38.02	12.673	6.1288	**0.0302**
Site(Region)	7	710.72	101.53	4.1520	**0.0010**	14.475	2.0678	4.1389	**0.0009**
Residual	55	1345.0	24.454			27.478	0.4996		
Total	65	2669.3				79.973			

		Aboveground biomass				Leaves per cluster			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Region	3	1807.9	602.64	13.867	**0.0022**	25.864	8.6212	0.8708	0.5120
Site(Region)	7	304.21	43.458	1.6303	0.1409	69.306	9.9008	6.8444	**0.0001**
Residual	55	1466.1	26.657			79.561	1.4466		
Total	65	3578.3				174.73			

Note:
(1) Values in bold in P(perm) column denote a significant difference

Calcareous and filamentous epiphytic algae was evident in all photographs taken of the 0.5 x 0.5 m quadrat at all *A. antarctica* sites, with the exception of two quadrats at site GF1 in North of Chapman River (Table 3-3, Figure 3-3). Mean percent cover of calcareous epiphytic algae growth on *A. antarctica* leaves ranged from <5 to >40%, while filamentous algae occupied <10% cover on *A. antarctica* leaves (Figure 3-3). The sampled collected further verified th e large quantities of encrusting epiphytic algal growth on leaves. A gastropod was observed in one quadrat photograph at site PD1 in Port Denison and another in two photographs in site D102 in Point Moore to Chapman River (Table 3-3).

Table 3-3 Presence/absence of epiphytes and epifauna from photographs of six replicate quadrats

Region	Site name	Presence of calcareous epiphytic algae?	Presence of filamentous epiphytic algae?	Percent cover of epiphytic algae	Presence of epifauna?	If epifauna present, fauna type?
		From six (6) quadrats			From six (6) quadrats	
North of Chapman River	D57	Yes – 5/5[1]	Yes – 5/5[1]	<20% total cover	No	n/a
	D61	Yes – 6/6	Yes – 6/6	<40% calcareous, <10% filamentous	No	n/a
	GF1	Yes – 6/6	Yes – 4/6	<20% calcareous, <10% filamentous	No	n/a
	TL1	Yes – 5/5[1]	Yes – 5/5[1]	<5% calcareous, <10% filamentous	No	n/a
Point Moore to Chapman River	D102	Yes – 6/6	Yes – 6/6	<5% calcareous, <10% filamentous	Yes – 2/6	Gastropod
	D75	Yes – 6/6	Yes – 6/6	<20% total cover	No	n/a
	D84	Yes – 6/6	Yes – 6/6	<20% total cover	No	n/a

Region	Site name	Presence of calcareous epiphytic algae?	Presence of filamentous epiphytic algae?	Percent cover of epiphytic algae	Presence of epifauna?	If epifauna present, fauna type?
		From six (6) quadrats			From six (6) quadrats	
Greenough	GR014	Yes – 6/6	Yes – 6/6	<20% calcareous, <10% filamentous	No	n/a
	GR024	Yes – 6/6	Yes – 6/6	<5–10% calcareous, <10% filamentous	No	n/a
Port Denison	PD1	Yes – 6/6	Yes – 6/6	>40% calcareous, <10% filamentous	Yes – 1/6	Gastropod
	PD4	Yes – 6/6	Yes – 6/6	>30% calcareous, <10% filamentous	No	n/a

Notes:
(1) Only five (5) photographs were taken of the quadrat instead of six (6) photographs
(2) n/a = not applicable

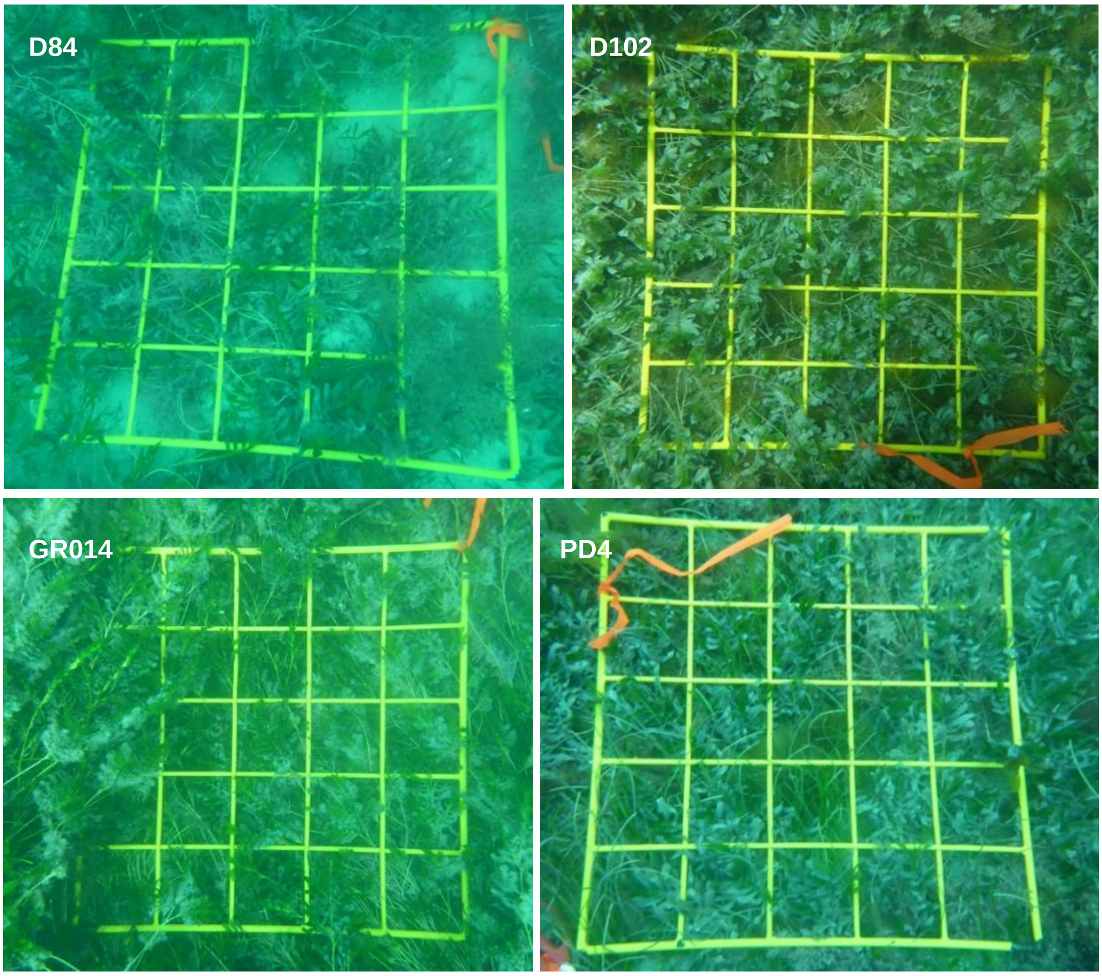


Figure 3-3 Example of photographs taken at *Amphibolis antarctica* dominated sites D84, D102, GR014 and PD4 to show the presence/absence of epiphytes and epifauna in January 2021

Dead rhizomes were not observed at any of the *A. antarctica* dominated sites during the 2021 field campaign, indicating that there has been no recent loss of *A. antarctica* in the area. Coloniser seagrass species *Halophila ovalis* and *Syringodium isoetifolium* were observed within and surrounding the *A. antarctica* meadows, and were subsequently collected during harvesting of the seagrass. In five of the quadrat images used to provide a presence/absence of epiphytes and epifauna, *Zostera tasmanica* was observed: four images at D75 and one image at D84, both in the Point Moore to Chapman River region.

In the samples collected, a total of 43 flowers were identified at four *A. antarctica* sites: TL1, PD1, GR024 and GR024.

3.2.2 *Amphibolis griffithii* sites

Results show that site GPAR2 had a significantly lower mean shoot density (290 shoots/m^2) compared to GPAR1 and a significantly lower mean aboveground biomass (310.60 g dry weight/m^2) than sites GPAR1 and GPAR3 (Figure 3-4; Table 3-4). Site GPAR2 reported a shorter average shoot height (44 cm) than the other Jurien sites, however was not statistically significant (Table 3-4). Site GPAR1 had a slightly higher mean shoot density (480 shoots/m^2), taller mean shoots (57.67 cm) and greater mean aboveground biomass (827.77 g dry weight/m^2) compared to site GPAR2 (Figure 3-4). All three sites reported approximately 3.2 leaves per cluster (Figure 3-4).

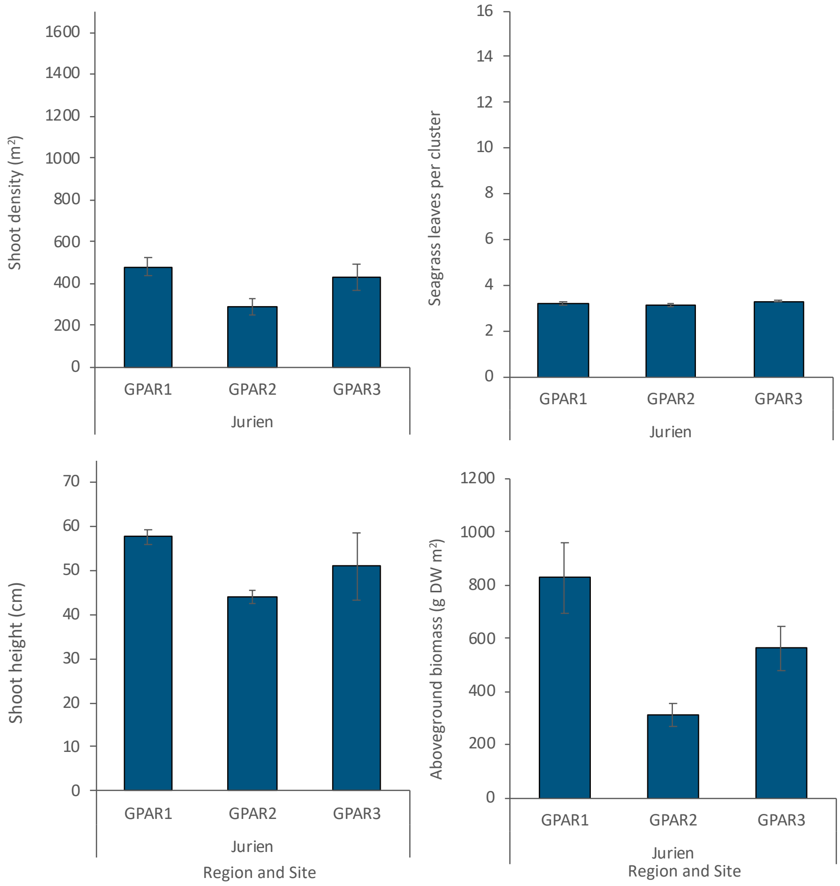


Figure 3-4 Mean shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for each *Amphibolis griffithii* dominated site nested within region in January 2021

Table 3-4 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Amphibolis griffithii* across sites

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	2	78.438	39.219	4.2556	**0.0405**	2.8245	1.4123	1.6539	0.2130
Residual	15	138.24	9.2157			12.808	0.8539		
Total	17	216.67				15.633			

		Aboveground biomass				Leaves per cluster			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	2	355.51	177.76	8.3985	**0.0048**	0.0717	0.0358	2.3507	0.1281
Residual	15	317.48	21.165			0.2287	0.0152		
Total	17	672.99				0.3004			

Note:
(1) Values in bold in P(perm) column denote a significant difference

Filamentous epiphytic algae were evident in all quadrat photos in all *A. griffithii* sites (Table 3-5, Figure 3-5). Growth of filamentous algae on *A. griffithii* leaves were typically less that 20%. Four of the six images at site GPAR3 showed no calcareous epiphytic growth on *A. griffithii* leaves and stems, whereas calcareous epiphytic algae were present in all other images with up to <30% cover (Table 3-5, Figure 3-5). Only one image at GPAR3 showed the presence of a sponge growing on a *A. griffithii* stem (Table 3-5, Figure 3-5).

Table 3-5 Presence/absence of epiphytes and epifauna from photographs of six replicate quadrats

Region	Site name	Presence of calcareous epiphytic algae?	Presence of filamentous epiphytic algae?	Percent cover of epiphytic algae	Presence of epifauna?	If epifauna present, fauna type?
		From six (6) quadrats			From six (6) quadrats	
Jurien	GPAR1	Yes – 6/6	Yes – 6/6	<10% calcareous, <5% filamentous	No	n/a
	GPAR2	Yes – 6/6	Yes – 6/6	<30% calcareous, <20% filamentous	No	n/a
	GPAR3	Yes – 2/6	Yes – 6/6	<1% calcareous, <5% filamentous	Yes – 1/6	Sponge

Note:
(1) n/a = not applicable

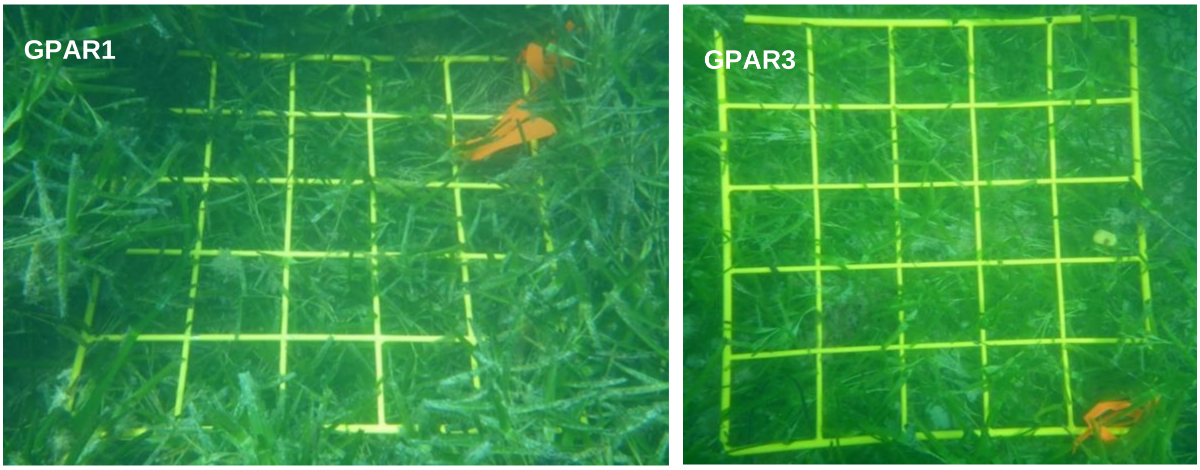


Figure 3-5 Example of photographs taken at *Amphibolis griffithii* dominated sites GPAR1 and GPAR3 to show the presence and absence of epiphytes and epifauna in January 2021

Dead rhizomes were not observed at any of the three *A. griffithii* sites, indicating no recent loss of *A. griffithii* in the study area. Coloniser species *S. isoetifolium* was found at all three sites within Jurien (GPAR1, GPAR2 and GPAR3), while *H. ovalis* was only observed within and surrounding *A. griffithii* meadow at site GPAR3. Across two sites (GPAR1 and GPAR3), six individual flowers were identified in the seagrass samples.

3.2.3 *Posidonia sinuosa* sites

In January 2021, mean shoot density was greatest at site D100 (1480 shoots/m^2), while the average shoot density at the remaining sites (D114, D4, D90, TL11 and Pages) ranged from 620 to 920 shoots/m^2 (Figure 3-6). The number of leaves per shoot at all *P. sinuosa* sites ranged from 1.9 and 2.4 (Figure 3-6). *P. sinuosa* meadows at site D114 reported an average shoot height of 31.8 cm, which was slightly shorter than the remaining sites that varied from an average height of 43.9 to 52.3 cm (Figure 3-6). The aboveground biomass was greatest at site D100 reporting 819.5 g dry weight/m^2 which coincides with the greatest average shoot density. The remaining sites reported an average aboveground biomass from 249.8 to 539.1 g dry weight/m^2 (Figure 3-6). Overall, a significant difference among sites was recorded for all seagrass measures, showing a high degree of variability among sites (Table 3-6).

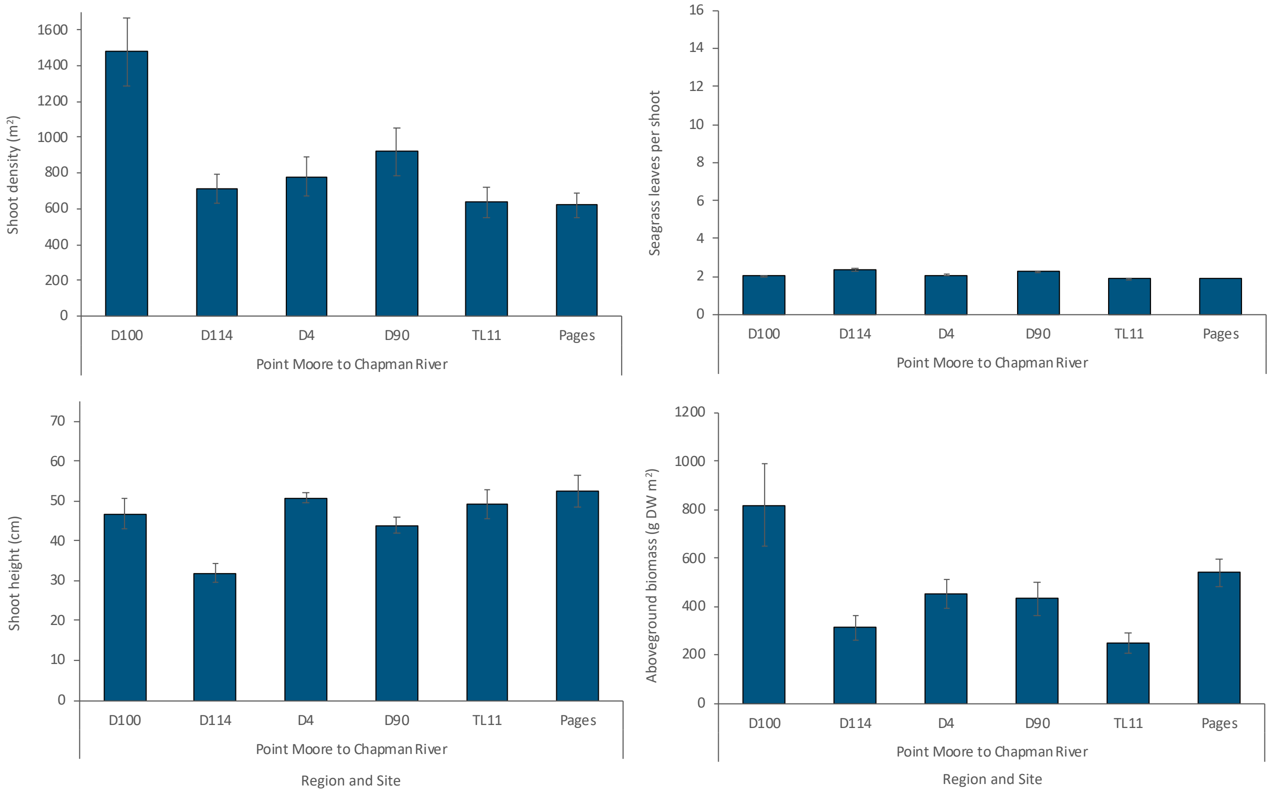


Figure 3-6 Shoot density, seagrass leaves per shoot, shoot height and aboveground biomass (mean ± S.E.) for each *Posidonia sinuosa* dominated site nested within region in January 2021

Table 3-6 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Posidonia sinuosa* across sites

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	5	673.15	134.63	6.6223	**0.0005**	10.187	2.0375	7.1257	**0.0002**
Residual	29	589.57	20.33			8.2921	0.2859		
Total	34	1262.7				18.479			

		Aboveground biomass				Leaves per cluster			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	5	533.9	106.78	6.8435	**0.0002**	1.1204	0.2241	16.551	**0.0001**
Residual	29	452.49	15.603			0.3926	0.0135		
Total	34	986.4				1.5131			

Note:
(1) Values in bold in P(perm) column denote a significant difference

Filamentous and calcareous epiphytic algal growth on *P. sinuosa* meadows was observed in all quadrat photos at all *P. sinuosa* sites, with the exception of two images at site D90 that did not report calcareous epiphytic algae (Table 3-7, Figure 3-7). Percent cover of calcareous epiphytic algae growth on *P. sinuosa* leaves ranged from <5 to less than 40%, and filamentous algae growth occupied between less than 5 to 20% (Table 3-7, Figure 3-7). One gastropod was observed in one quadrat image at site D100 (Table 3-7, Figure 3-7).

Table 3-7 Presence/absence of epiphytes and epifauna from photographs of six replicate quadrats

Region	Site name	Presence of calcareous epiphytic algae?	Presence of filamentous epiphytic algae?	Percent cover of epiphytic algae	Presence of epifauna?	If epifauna present, fauna type?
		From six (6) quadrats			From six (6) quadrats	
Point Moore to Chapman River	D100	Yes – 5/5[1]	Yes – 5/5[1]	<10% calcareous, <5% filamentous	Yes – 1/6	Gastropod
	D114	Yes – 6/6	Yes – 6/6	<40% calcareous, <5% filamentous	No	n/a
	D4	Yes – 5/5[1]	Yes – 5/5[1]	<20% calcareous, <10% filamentous	No	n/a
	D90	Yes – 4/6	Yes – 6/6	<5% calcareous, <20% filamentous	No	n/a
	TL11	Yes – 6/6	Yes – 6/6	<10% calcareous, <20% filamentous	No	n/a
	Pages	Yes – 6/6	Yes – 6/6	<40% calcareous, <20% filamentous	No	n/a

Notes:
(1) Only five (5) photographs were taken of the quadrat instead of six (6) photographs
(2) n/a = not applicable

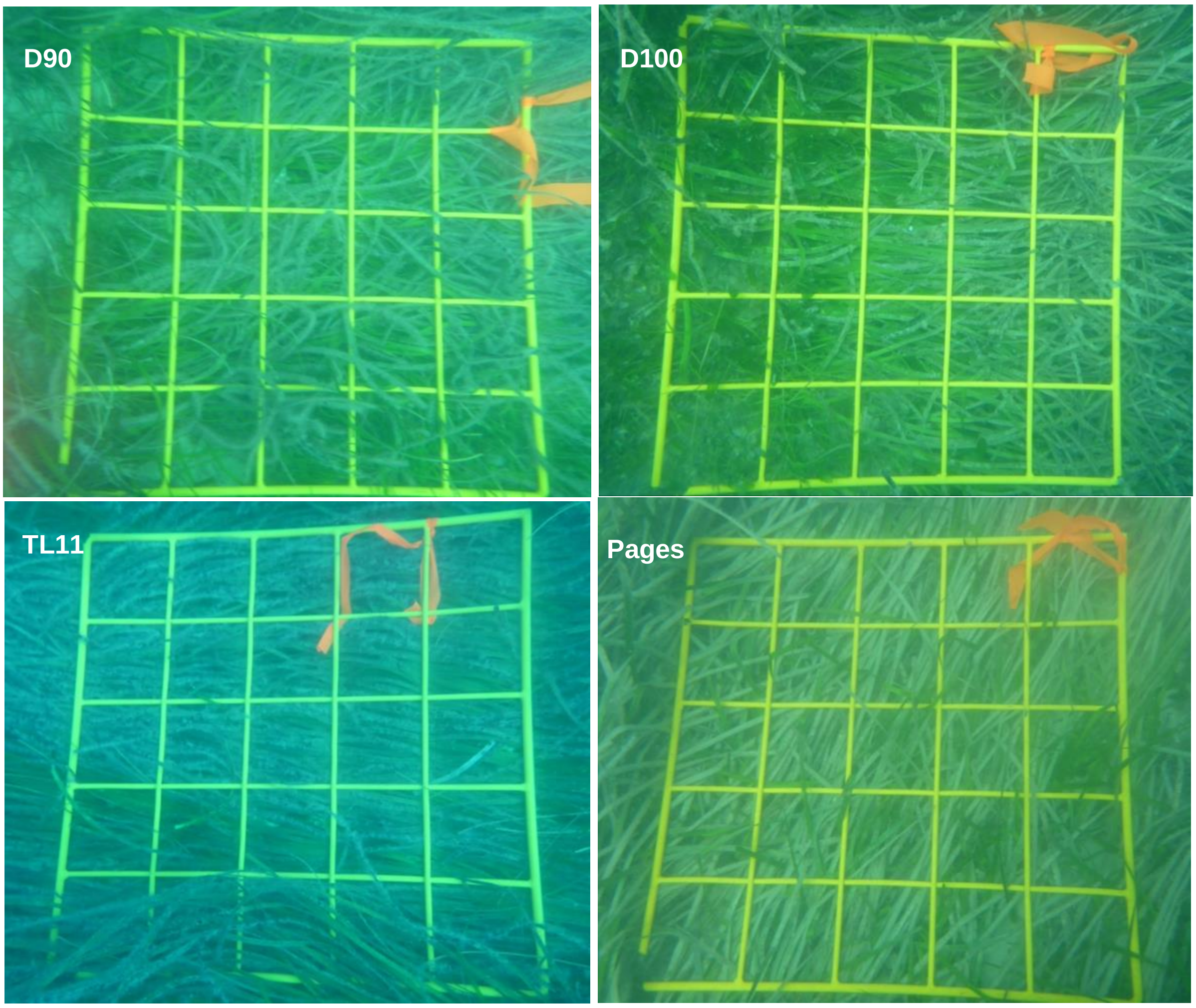


Figure 3-7 Example of photographs taken at *Posidonia sinuosa* dominated sites D90, D100, TL11 and Pages to show the presence/absence of epiphytes and epifauna in January 2021

Dead rhizomes were not observed at any of the six *P. sinuosa* seagrass sites, indicating that there has been no recent loss of *P. sinuosa* in the study area. Both coloniser seagrass species *H. ovalis* and *S. isoetifolium* were recorded at five sites within Point Moore to Chapman River (D100, D4, D90, Pages and TL11), while only *H. ovalis* was observed at site D114. *Zostera tasmanica* was only observed at site D100. Ten samples had flowers across three sites (D90, D100 and D114).

3.2.4 *Thalassodendron pachyrhizum* sites

Site PD2 in Port Denison had a significantly higher mean shoot density (490 shoots/m^2), shoot height (38.48 cm) and aboveground biomass (334.8 g dry weight/m^2) than site D68 in North of Chapman River (193.3 shoots/m^2, 29.98 cm, 109.07 g dry weight/m^2, respectively; Figure 3-8; Table 3-8). On average, site D68 reported 2.86 leaves per shoot, while site PD2 had 3.32 leaves per shoot (Figure 3-8).

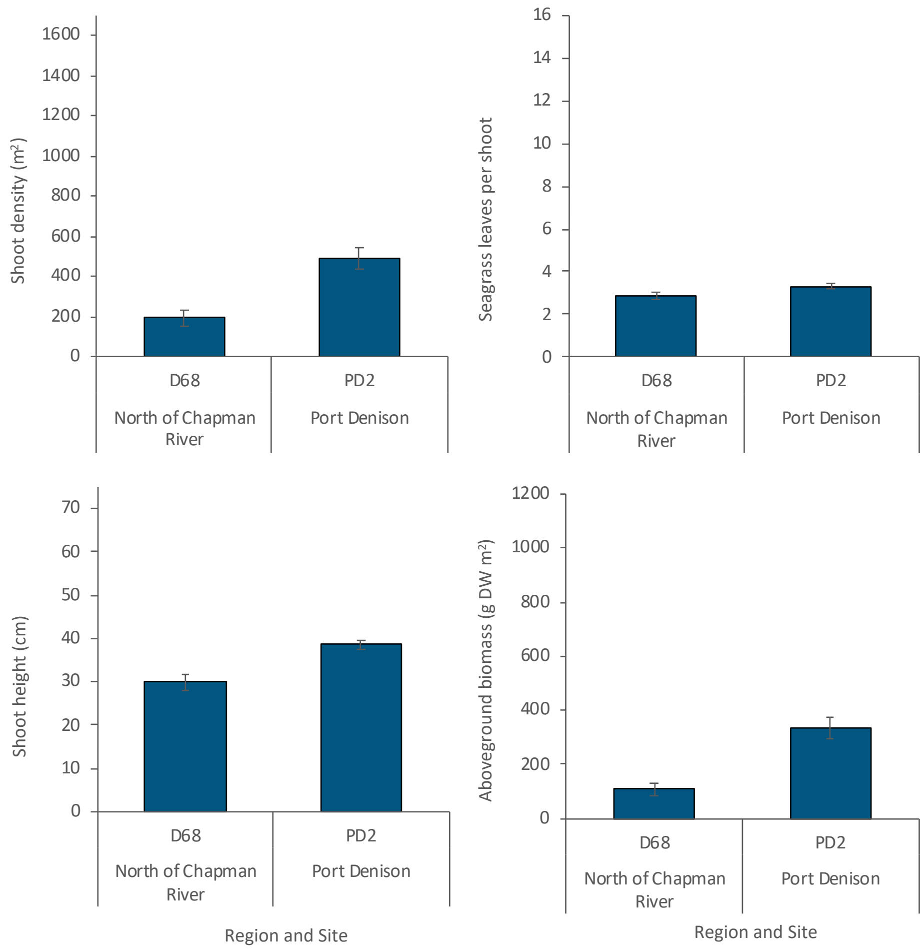


Figure 3-8 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for each *Thalassodendron pachyrhizum* dominated site nested within region in January 2021

Table 3-8 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Thalassodendron pachyrhizum* across sites

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	1	215.07	215.07	17.93	**0.0082**	6342	1.6342	15.561	**0.0055**
Residual	10	119.95	11.995			1.0502	0.1050		
Total	11	335.02				2.6844			

		Aboveground biomass				Leaves per cluster			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Site	1	194.57	194.57	23.441	**0.0028**	0.6362	0.6362	4.8071	0.0568
Residual	10	83.007	8.3007			1.3234	0.1323		
Total	11	277.58				1.9596			

Note:
(1) Values in bold in P(perm) column denote a significant difference

Calcareous and filamentous epiphytic algae on *T. pachyrhizum* meadows was observed in all quadrat photographs at sites D68 and PD2 (Table 3-9, Figure 3-9). The percent cover of calcareous and filamentous epiphytic algae growth on *T. pachyrhizum* leaves varied from 30 to 40% (Table 3-9, Figure 3-9). No epifauna were observed in the quadrat images (Table 3-9, Figure 3-9).

Table 3-9 Presence/absence of epiphytes and epifauna from photographs of six replicate quadrats

Region	Site name	Presence of calcareous epiphytic algae?	Presence of filamentous epiphytic algae?	Percent cover of epiphytic algae	Presence of epifauna?	If epifauna present, fauna type?
		From six (6) quadrats			From six (6) quadrats	
North of Chapman River	D68	Yes – 6/6	Yes – 6/6	<40% calcareous, <30% filamentous	No	n/a
Port Denison	PD2	Yes – 6/6	Yes – 6/6	<40% calcareous, <40% filamentous	No	n/a

Note:
(1) n/a = not applicable

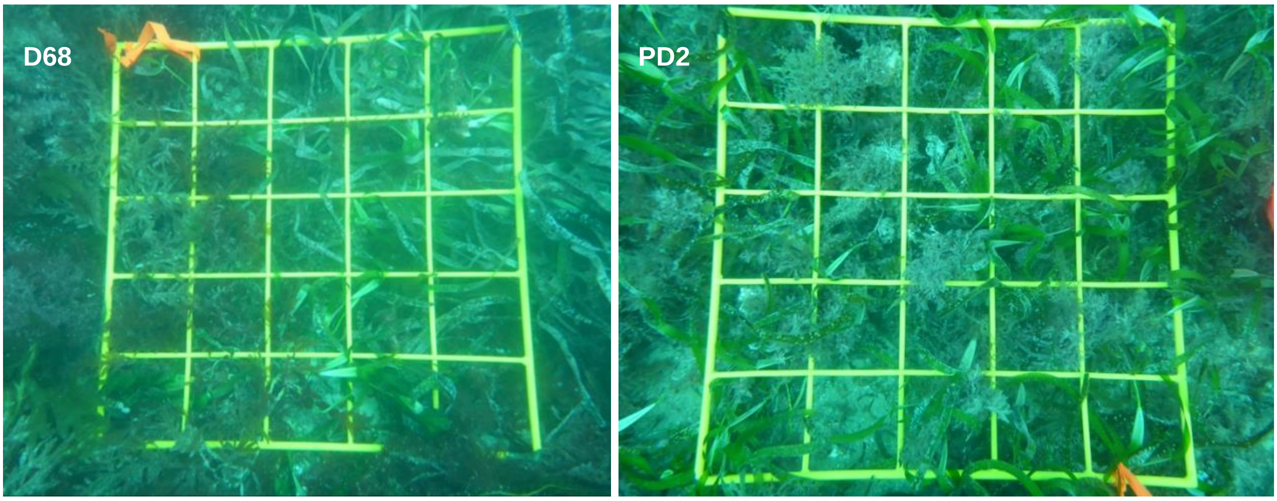


Figure 3-9 Example of photographs taken at *Thalassodendron pachyrhizum* dominated sites D68 and PD2 to show the presence/absence of epiphytes and epifauna in January 2021

While no dead rhizomes were observed at any of the *T. pachyrhizum* sites, dead *Amphibolis* stems were observed at site PD2. The presence of dead *Amphibolis* stems suggests that *Amphibolis* was previously prevalent in the area and may have been exposed to a disturbance(s), causing the seagrass to die-off. Both coloniser seagrass species *H. ovalis* and *S. isoetifolium* were recorded at five sites within Point Moore to Chapman River (D100, D4, D90, Pages and TL11), while only *H. ovalis* was observed at site D114. *Z. tasmanica* was only observed at site D100.

3.3 Spatial comparison of percent and benthic cover: January 2021

3.3.1 *Amphibolis antarctica* sites

While *A. antarctica* was the dominant species in terms of cover, there were no sites that were purely mono-specific and all sites supported a blend of *A. antarctica, A. griffithii,* macroalgae and coloniser seagrass species but in varying proportions (Figure 3-10). Site GR024 had the greatest representation of *A. antarctica* (88% cover), while PD4 had the lowest (2.2% cover; Figure 3-10). Macroalgal cover, primarily red algae and other brown algae, was also typically high at most sites (Figure 3-10). Colonising species, which were reported at all sites except for site GR024, predominantly comprised of *H. ovalis* and *S. isoetifolium* (Figure 3-10).

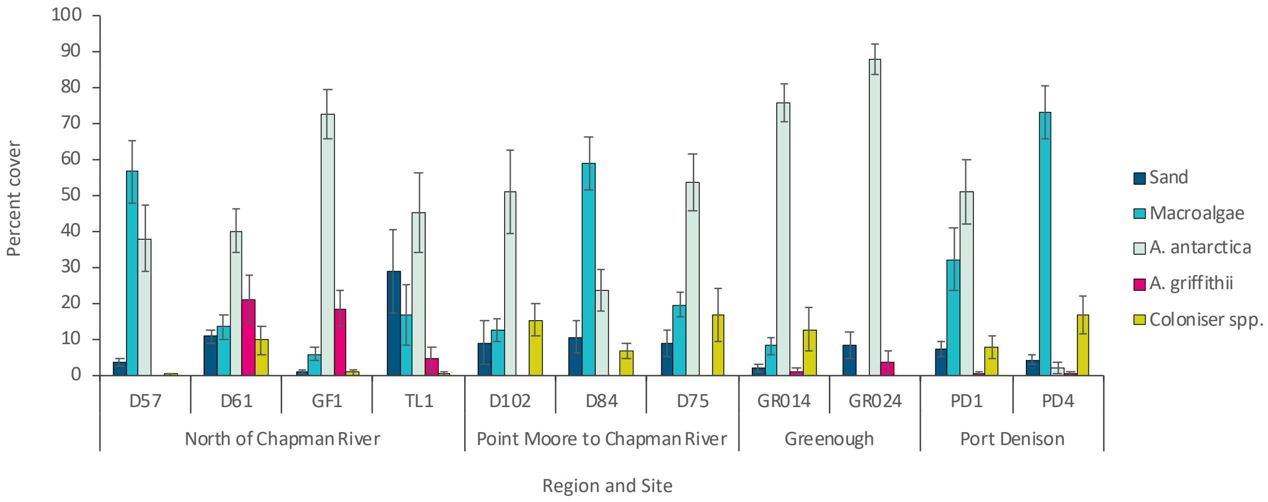


Figure 3-10 Percent cover (mean ± S.E.) of dominant benthic habitat types at *Amphibolis antarctica* dominated sites

PERMANOVA results at *A. antarctica* dominated sites showed a significant difference in benthic cover across regions and sites (Table 3-10), indicating a high degree of variability in benthic cover at site and regional level. Post-hoc tests further showed high variability of benthic cover between sites within each region, with the exception of sites D102 and D75 in Point Moore to Chapman River, whereby both sites had a relatively similar benthic cover. The nMDS plot shows a reasonable separation of benthic cover between regions with some overlap (Figure 3-11). Port Denison is separated from the other regions, Point Moore to Chapman River is centred and there is some overlap of North of Chapman River with Point Moore to Chapman River which is expected as they are adjacent regions (Figure 3-11). The benthic cover at sites on the top left of the plot (Figure 3-11; excluding sites GR024 and GF1) were dominated by other brown algae, *A. antarctica* was the primary driver of the benthic cover at sites to the bottom right of the nMDS plot (excluding site PD4; Figure 3-11).

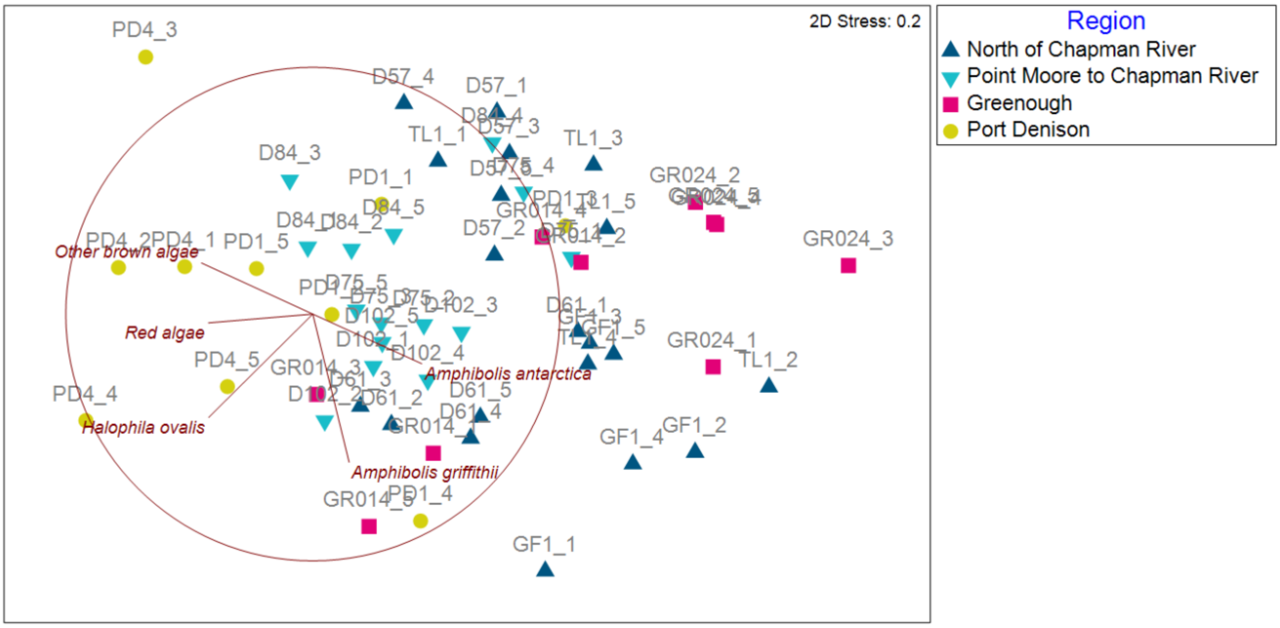


Figure 3-11 nMDS plot of benthic cover at *Amphibolis antarctica* dominated sites

Table 3-10 PERMANOVA results to test for differences in benthic cover for *Amphibolis antarctica* dominated sites

Source	df	SS	MS	Pseudo-F	P(perm)
Region	3	19357	6452.4	2.3920	**0.0066**
Site(Region)	7	18882	2697.5	6.0957	**0.0001**
Residual	44	19471	442.52		
Total	54	57711			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.3.2 *Amphibolis griffithii sites*

Similar to *A. antarctica* sites, *A. griffithii* sites comprised of multiple species including macroalgae, *A. antarctica, A. griffithii, P. sinuosa* and coloniser seagrass species in varying proportions (Figure 3-12). *A. griffithii* was the dominant benthic category recorded at each of the three sites in Jurien (Figure 3-12). Only two transects within GPAR3 (transects 1 and 5) recorded less than 5% cover of *A. griffithii*, therefore, bringing the average percent cover of *A. griffithii* lower than GPAR1 and GPAR2 (Figure 3-12). Site GPAR3 had a greater percent cover of other benthic habitat types compared to GPAR1 and GPAR2 (Figure 3-12). *P. sinuosa* was recorded in four of the five transects at GPAR1, with a percent cover ranging from 10–58% at individual transect level (Figure 3-12).

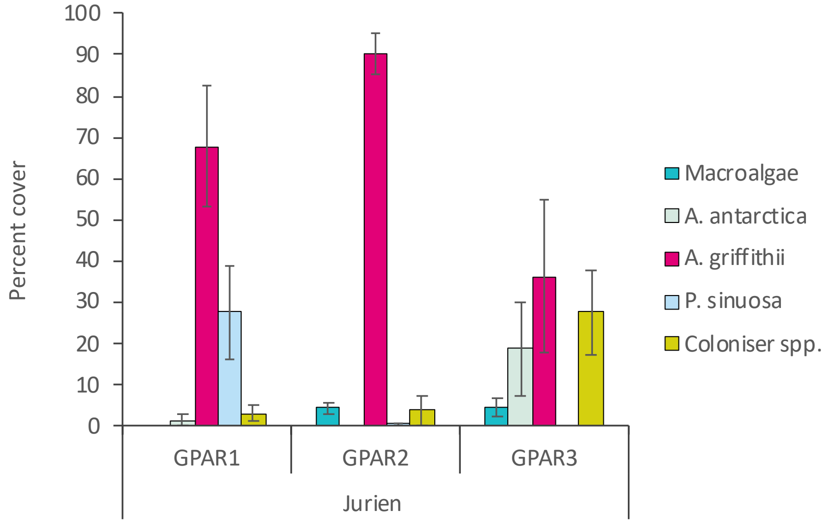


Figure 3-12 Percent cover (mean ± S.E.) of dominant benthic habitat types at *Amphibolis griffithii* dominated sites

Statistical analyses on benthic cover at *A. griffithii* dominated sites showed a significant difference among sites (Table 3-11). Post-hoc pair-wise comparisons showed that the benthic cover was significantly different between all three sites, however, GPAR2 and GPAR3 showed similarities in benthic cover. The nMDS plot shows minor clustering of sites, except for one transect at each site that was comprised of identical benthic cover (Figure 3-13). *A. griffithii* was the dominant species found at sites GPAR1 and GPAR3 (Figure 3-13). The benthic cover at site GPAR3 had a greater cover of *A. antarctica*, sand, coloniser species *H. ovalis* and other brown algae than the other sites (Figure 3-13).

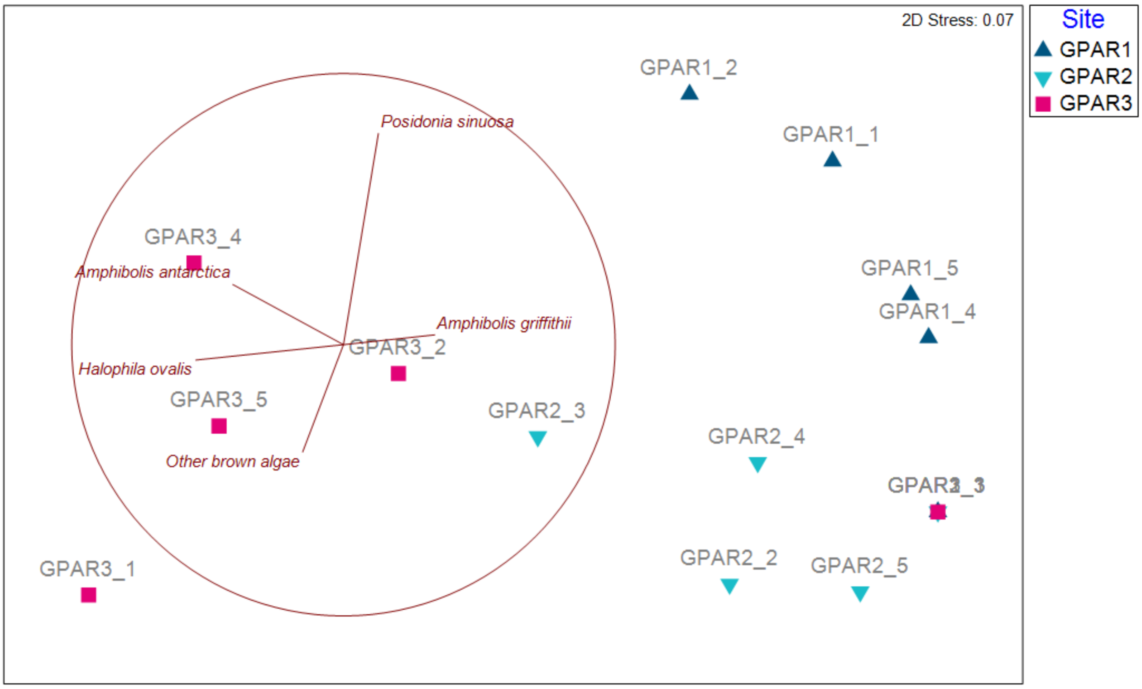


Figure 3-13 nMDS plot of benthic cover at *Amphibolis griffithii* dominated sites

Table 3-11 PERMANOVA results to test for differences in benthic cover for *Amphibolis griffithii* dominated sites

Source	df	SS	MS	Pseudo-F	P(perm)
Site	2	9984.6	4992.3	5.1054	**0.0034**
Residual	12	11734	977.84		
Total	14	21719			

Note:
(1) Value in bold in P(perm) column denote a significant difference

3.3.3 *Posidonia sinuosa* sites

While *P. sinuosa* was the dominant species in terms of cover, all sites showed multiple species and comprised a blend of macroalgae, *A. antarctica, P. australis, P. sinuosa* and coloniser seagrass species in varying proportions (Figure 3-14). *P. sinuosa* was the dominant benthic category recorded at four sites in Point Moore to Chapman River (40.2–89.6% cover) whereas *P. sinuosa* was absent at site D114 (Figure 3-14). Colonising species (comprising primarily of *H. ovalis* and *S. isoetifolium*) was also typically high at most sites, but were absent at site Pages (Figure 3-14). Coloniser species *Z. tasmanica* was also present in sites D100, D114 and TL11 covering <20%. *P. australis* was also observed at four of the five transects at site Pages, covering between 9 and 18% cover (Figure 3-14).

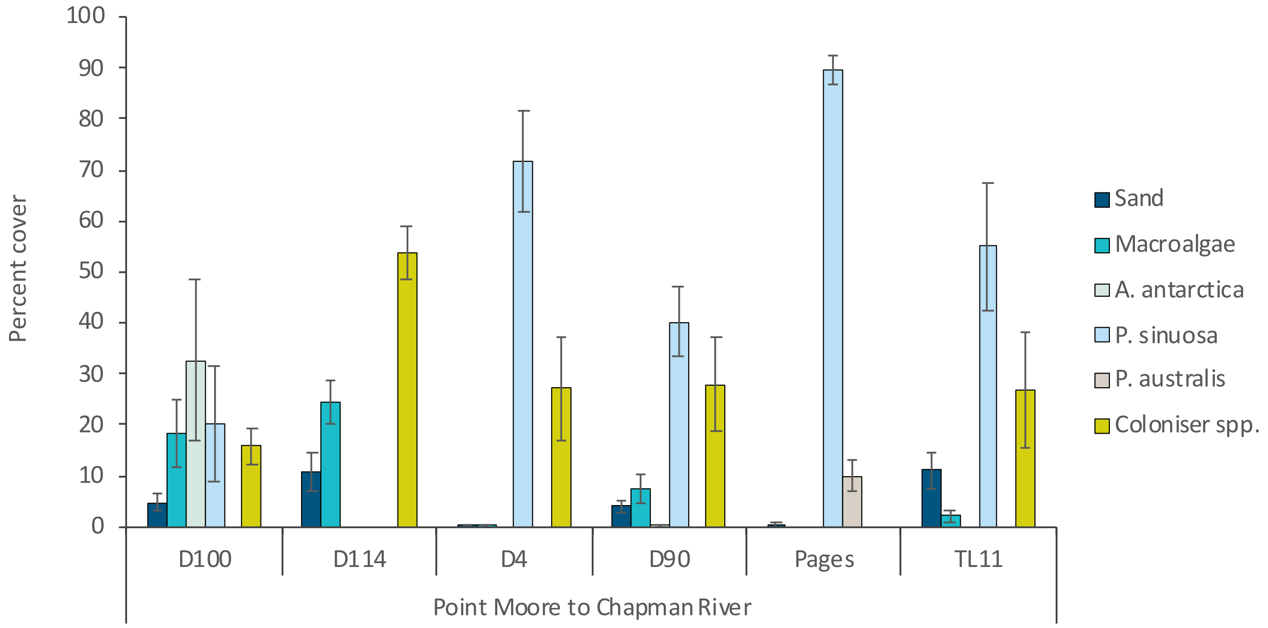


Figure 3-14 Average percent cover of dominant benthic habitat types at *Posidonia sinuosa* dominated sites

Statistical analyses on benthic cover at *P. sinuosa* dominated sites showed a significant difference in the main effect (Site; Table 3-12), indicating that there were differences in benthic cover across sites. Post-hoc tests showed that all sites were significantly different to each other, except for D4 and TL11, which had a similar benthic cover. The nMDS plot does not show a clear grouping of sites primarily due to differences in benthic cover across transects (Figure 3-15). Rock/reefs were a dominant benthic characteristic observed in sites D100 and D114 and hence a higher percent cover of macroalgae were recorded at these sites, whereas *P. sinuosa* was the main driver of benthic cover at all sites except for site D114 (Figure 3-15).

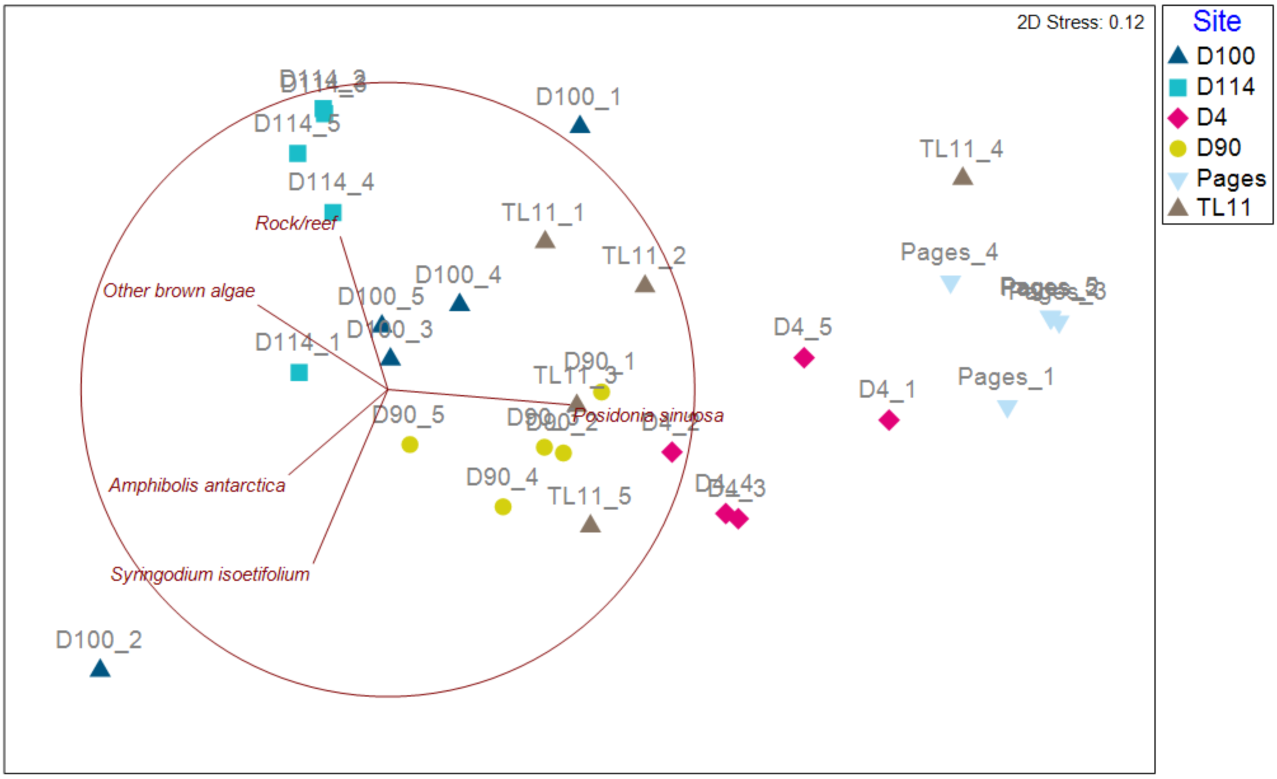


Figure 3-15 nMDS plot of benthic cover at *Posidonia sinuosa* dominated sites

Table 3-12 PERMANOVA results to test for differences in benthic cover for *Posidonia sinuosa* dominated sites

Source	df	SS	MS	Pseudo-F	P(perm)
Site	5	35934	7186.9	13.846	**0.0001**
Residual	24	12457	519.06		
Total	29	48392			

Note:
(1) Value in bold in P(perm) column denote a significant difference

3.3.4 *Thalassodendron pachyrhizum* sites

Similar to all previous sites, there were no sites that were purely mono-specific and both sites support a blend of macroalgae, *A. griffithii, T. pachyrhizum* and coloniser seagrass species but in varying proportions (Figure 3-16). Site D68 was the only site to contain *T. pachyrhizum* (3.6% cover) and was absent in site PD2 (Figure 3-16). Macroalgal cover, primarily red and other brown algae (besides *Ecklonia* spp. and *Sargassum* spp.), was high at both sites (81.6–88.6% cover; Figure 3-16).

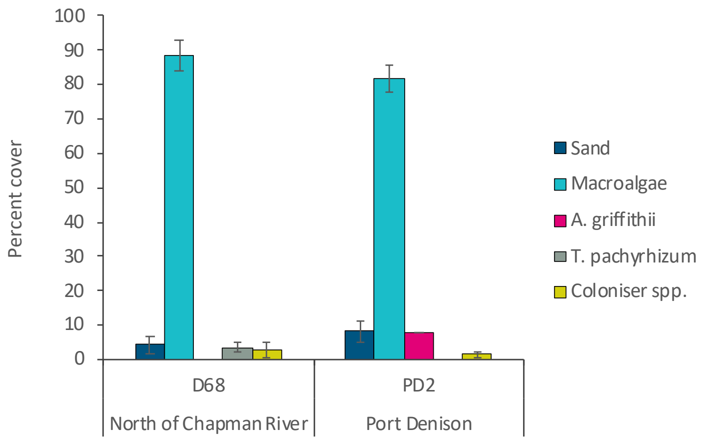


Figure 3-16 Percent cover of dominant benthic habitat types at *Thalassodendron pachyrhizum* dominated sites

PERMANOVA analyses showed a significant difference between the two sites ($p<0.05$; Table 3-13) which was evident in the nMDS ordination plot (Figure 3-17). Sites PD2 and D68 were separated on the nMDS plot, as *T. pachyrhizum* was only observed in transects 2 to 5 at site D68, and green algae was the dominant habitat type at site PD2 (Figure 3-17).

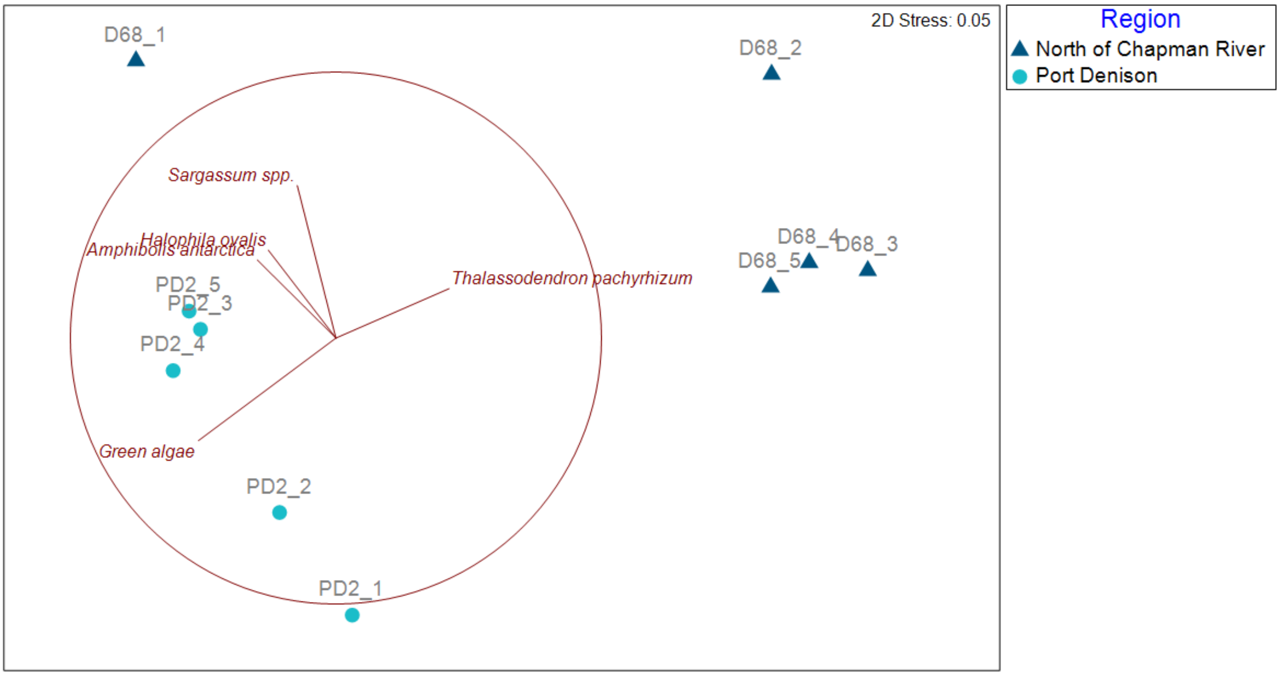


Figure 3-17 nMDS plot of benthic cover at *Thalassodendron pachyrhizum* dominated sites

Table 3-13 PERMANOVA results to test for differences in benthic cover for *Thalassodendron pachyrhizum* dominated sites

Source	df	SS	MS	Pseudo-F	P(perm)
Site	1	2909.9	2909.9	5.7239	**0.0252**
Residual	8	4067.1	508.39		
Total	9	6977			

Note:
(1) Value in bold in P(perm) column denote a significant difference

3.4 Temporal comparison of seagrass characteristics: 2004, 2005, 2006, 2007, and 2021

3.4.1 *Amphibolis antarctica* sites

3.4.1.1 Regional differences over time

There was a high degree of site variability for all seagrass characteristics (shoot density, leaves per cluster, shoot height, and aboveground biomass) across most years at *A. antarctica* sites (Figure 3-18; Table 3-14). Shoot density was significantly greater at Greenough (average of 656 shoots/m^2) compared to Point Moore to Chapman River (221 shoots/m^2) and North of Chapman River regions (272 shoots/m^2; Figure 3-18; Table 3-14). Shoot density was also significantly different across all years, with the exception of shoot density between 2006, 2007 and 2012, in which densities were relatively similar (Figure 3-18; Table 3-14).

For leaves per cluster, a higher count of leaves per cluster were recorded in February 2004 (average of 11.99 leaves per cluster) compared to other years, and post-hoc test showed leaves per cluster were similar between 2005, 2006 and 2021 (Figure 3-18; Table 3-14). There were no statistical differences in leaves per cluster across regions (Table 3-14). Available URS data from April 2003 and September 2003 (URS 2003) collected during and near completion of capital dredging activities were added to Figure 3-18 for contextual purposes only; no statistical analyses were performed as only an average for each site was available. In comparison to the overall results, lower counts of seagrass leaves per cluster were recorded in April 2003 (during capital dredging) and September 2003 (nearing completion of capital dredging). These results however, must be interpreted with caution as poor weather conditions (low water visibility and strong surge) limited a successful collection of seagrasses.

A. antarctica shoot heights did not show any distinct trends and were variable within and between sites (Figure 3-18; Table 3-14). Across all sites, seagrass shoots on average were significantly taller in 2005 (40.04 cm), 2006 (37.13 cm) and 2021 (44.31 cm) compared to other years (Figure 3-18). There were no significant differences in shoot heights across regions (Table 3-14).

Similar to shoot density results, an overall higher aboveground biomass was recorded at Greenough (average of 866.32 g DW m^2) compared to Point Moore to Chapman River (269.15 g DW m^2) and North of Chapman River (292.34 g DW m^2) regions. At each *A. antarctica* site, aboveground biomass varied over time (Figure 3-18).

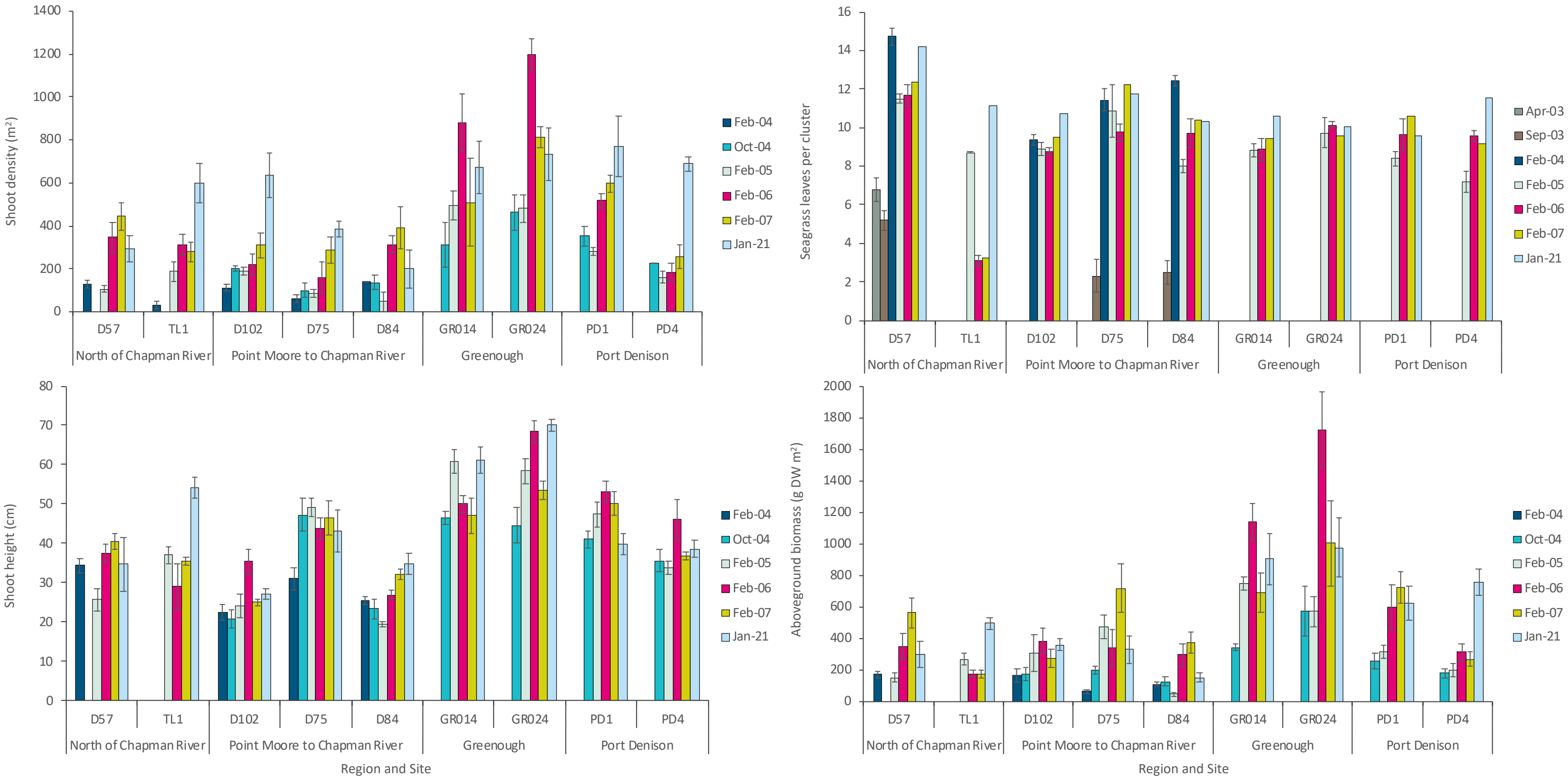


Figure 3-18 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for each *Amphibolis antarctica* dominated site nested within region across time

Table 3-14 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Amphibolis antarctica* across time and regions

		Shoot density				Leaves per cluster			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Time	5	12950	2589.9	48.768	**0.0001**	454.4	90.881	61.782	**0.0001**
Region	3	2887.8	962.62	7.013	**0.0454**	18.775	6.2584	0.91395	0.5494
Site(Region)	5	686.31	137.26	9.1306	**0.0001**	34.238	6.8477	99.775	**0.0001**
Time x Region	15	5358.9	357.26	6.7272	**0.0001**	103.92	6.9279	4.7097	**0.0005**
Time x Site(Region)	25	1327.7	53.107	3.5327	**0.0001**	36.775	1.471	21.433	**0.0001**
Residual	270	4058.9	15.033			18.53	0.0686		
Total	323	26189				661.14			

		Shoot height				Aboveground biomass			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Time	5	873.28	174.66	29.862	**0.0001**	14766	2953.2	30.824	**0.0001**
Region	3	111.29	37.096	2.4213	0.1963	5070.9	1690.3	9.2555	**0.0279**
Site(Region)	5	76.605	15.321	34.227	**0.0001**	913.13	182.63	8.3654	**0.0001**
Time x Region	15	654.51	43.634	7.4603	**0.0001**	5816.8	387.79	4.0475	**0.0015**
Time x Site(Region)	25	146.22	5.8488	13.066	**0.0001**	2395.2	95.809	4.3887	**0.0001**
Residual	270	120.86	0.4476			5894.4	21.831		
Total	323	1845.8				33480			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.4.1.2 Control versus Impact sites over time

A. antarctica sites were classified as Control or Impact sites, which was based on whether the site was impacted by the plume that resulted from the 2003 capital dredging operations. The Impacts sites available for historical comparison were D102, D57, D75, D84 and TL1. The Control sites available for historical comparison include GR014, GR024, PD1 and PD4.

For all four *A. antarctica* bioindicators (shoot density, leaves per cluster, shoot height and aboveground biomass), the interaction term Time x Treatment was statistically significant (Table 3-15). This significant result was primarily driven by the high variability observed at each site, and when combining sites into impact and control groups, the control group report higher measurements than the impact group (Figure 3-19, Table 3-15). Shoot density and aboveground biomass were both consistently higher at control sites but varied across time (Figure 3-19; Table 3-15). Post-hoc tests for Impact sites showed that shoot density was significantly different across all times with the exception of densities reported in 2007 and 2021, which were statistically similar. Shoot density reported at site D102 was significantly different to all other Impact sites (D57, TL1, D75 and D84). A lower average aboveground biomass was recorded in Impact and Control sites in February and October 2004 compared to other times (Figure 3-19). Although shoot were taller in impact sites compared to control sites (Figure 3-19), it was not statistically different due to the high variability across sites and time. Leaves per cluster at impact and control sites were statistically similar however, leaf counts varied significantly between sites across time.

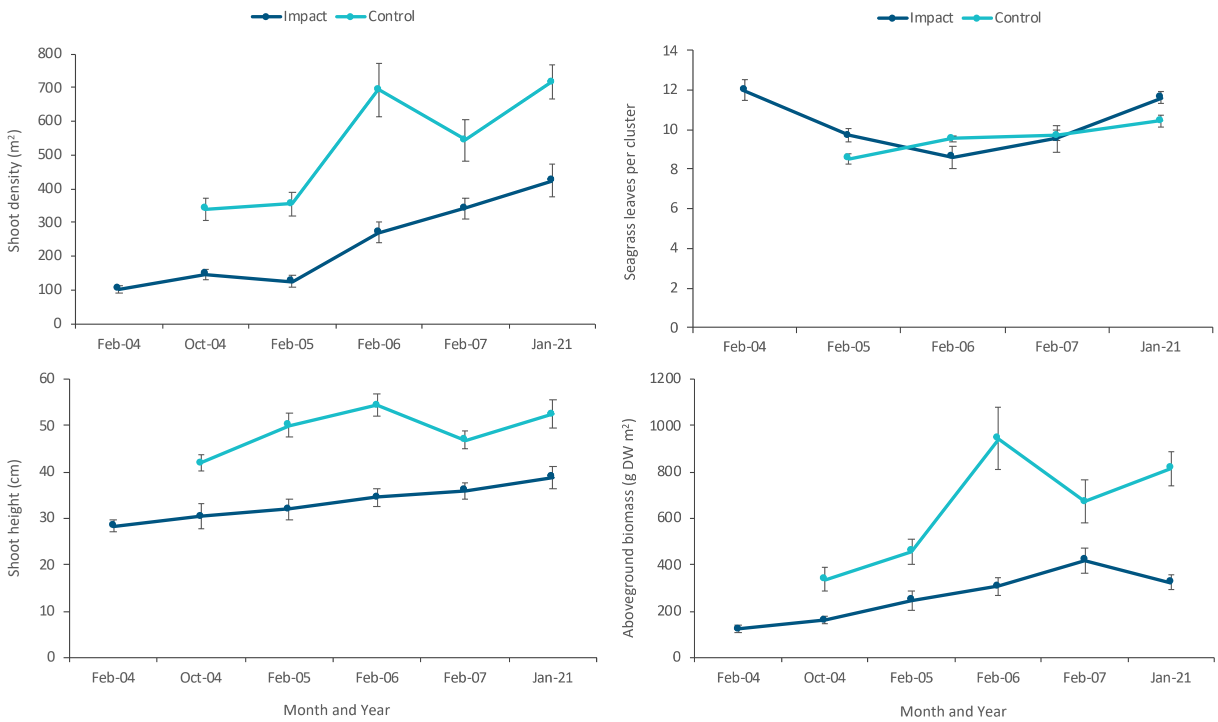


Figure 3-19 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for combined impact and control for sites dominated by *Amphibolis antarctica* across time

Table 3-15 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Amphibolis antarctica* across time and treatment

		Shoot density				Leaves per cluster			
Source	**df**	**SS**	**MS**	**Pseudo-F**	**P(perm)**	**SS**	**MS**	**Pseudo-F**	**P(perm)**
Time	5	12635	2527.1	26.223	**0.0001**	457.22	91.445	59.707	**0.0001**
Treatment	1	2023.7	2023.7	9.1369	**0.0253**	15.057	15.057	2.7769	0.1288
Site(Treatment)	7	1550.4	221.49	14.733	**0.0001**	37.956	5.4223	79.007	**0.0001**
Time x Treatment	5	3313.7	662.74	6.8772	**0.0003**	87.088	17.418	11.372	**0.0001**
Time x Site(Treatment)	35	3372.9	96.368	6.4104	**0.0001**	53.605	1.5316	22.316	**0.0001**
Residual	270	4058.9	15.033			18.53	0.068631		
Total	323	26189				661.14			

		Shoot height				Aboveground biomass			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Time	5	823.41	164.68	15.848	**0.0001**	14504	2900.7	23.121	**0.0001**
Treatment	1	40.478	40.478	1.9221	0.2044	2825.5	2825.5	6.2621	**0.0482**
Site(Treatment)	7	147.42	21.059	47.047	**0.0001**	3158.5	451.21	20.668	**0.0001**
Time x Treatment	5	437.04	87.408	8.4118	**0.0001**	3821	764.2	6.0913	**0.0002**
Time x Site(Treatment)	35	363.69	10.391	23.214	**0.0001**	4391	125.46	5.7467	**0.0001**
Residual	270	120.86	0.44762			5894.4	21.831		
Total	323	1845.8				33480			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.4.2 *Posidonia sinuosa* sites

3.4.2.1 *Regional differences over time*

Posidonia sinuosa was only recorded in one region (Point Moore to Chapman River) therefore comparisons of seagrass characteristics were only made between factors Time and Site. Similar to *A. antarctica* results for temporal comparisons, there was a high degree of variability between sites. For shoot density, a significantly lower shoot density was recorded during February 2004 and October 2004, however, this was primarily due to fewer sites (only D114 and Tl11) sampled during this period (Figure 3-20). Overall, site TL11 recorded a significantly higher shoot density (average of 763 shoots/m^2) compared to the other three *P. sinuosa* sites (D90, D114 and Pages). Available GHD data from pre- (April 2012; GHD 2012a) and post- (May 2012; GHD 2012b) maintenance dredging were included in Figure 3-20 for contextual purposes only (i.e., not statistically analysed) as only an average and S.E. for each site was provided. Compared to existing data, sites D114 and Pages had a lower shoot density, with Pages reporting a slight increase in shoot density from pre- to post-maintenance dredging (pre-dredging: 145 ± 27.5 shoots/m^2, post-dredging: 242 ± 15.5 shoots/m^2), whereas site D114 reported no shoots following post-dredging, a decline from 1.2 ± 1.2 shoots/m^2 prior to dredging activities (Figure 3-20).

For shoot height, the interaction term Time x Site confounded the results, as there were complex interactions among individual sites over time (Table 3-16). Overall, site Pages recorded on average, a significantly higher shoot height (49.58 cm) while site D114 reported significantly shorter shoot heights (30.26 cm; Figure 3-20).

Similar to *P. sinuosa* shoot height results, complex interactions between time and sites were evident for aboveground biomass. In summary, a higher aboveground biomass was recorded in 2021 (average of 383.18 g DW m^2), while site D114 reported the lowest average aboveground biomass across the years (87.09 g DW m^2; Figure 3-20). Interpretation of results should be read with caution as fewer sites were sampled in February and October 2004 (only D114 and TL11).

Leaves per shoot for *P. sinuosa* sites were not measured in previous years (February 2004, 2005, 2006 and 2007) therefore, no statistical temporal comparisons were made for *P. sinuosa* leaves per shoot.

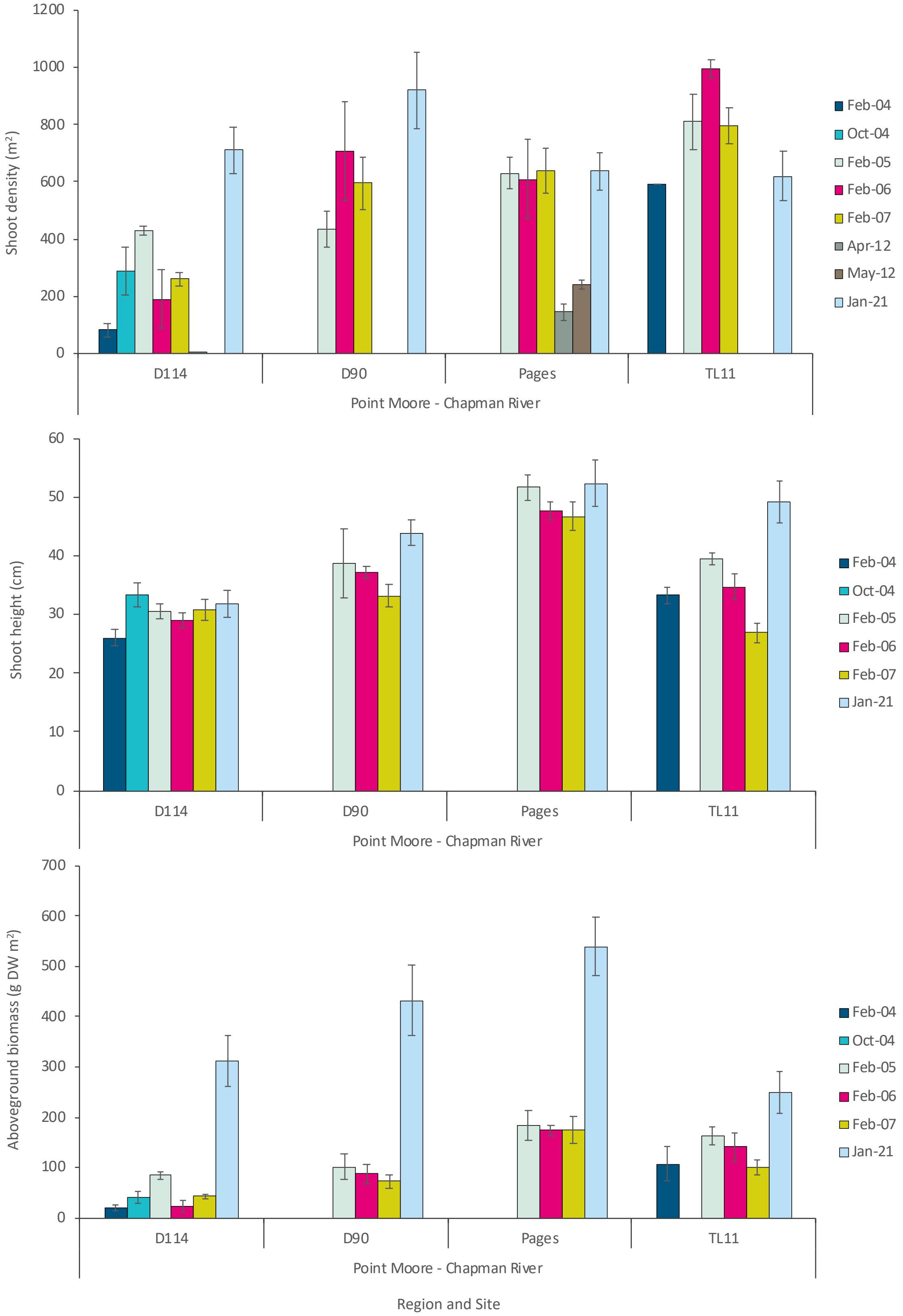


Figure 3-20 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for each *Posidonia sinuosa* dominated site nested within region across time

Table 3-16 PERMANOVA results to test for differences in shoot density, shoot height and aboveground biomass of *Posidonia sinuosa* across sites and time

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Time	5	11001	2200.2	90.691	**0.0001**	609.92	121.980	114.32	**0.0001**
Site	3	974.64	324.88	13.392	**0.0001**	12.578	4.1927	3.9293	**0.0082**
Time x Site	15	4512.7	300.85	12.401	**0.0001**	331.91	22.127	20.737	**0.0001**
Residual	120	2911.2	24.26			128.04	1.0670		
Total	143	19399				1082.4			

		Aboveground biomass			
Source	df	SS	MS	Pseudo-F	P(perm)
Time	5	4702.1	940.43	144.61	**0.0001**
Site	3	199.47	66.491	10.225	**0.0001**
Time x Site	15	1056.1	70.406	10.827	**0.0001**
Residual	120	780.37	6.5031		
Total	143	6739.1			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.4.2.2 *Impact sites over time*

Posidonia sinuosa sites were not statistically analysed as Control versus Impact over the years as there was only one control site (Pages). Instead, plots for shoot densities, shoot height and aboveground biomass comparing impact (TL11, D90, D114) and control (Pages) sites have been presented below for contextual purposes only. Lower shoot densities were reported in February (average of 336.40 ± 137.71 shoots/m^2; Figure 3-21) and October 2004 (288.00 ± 86.04 shoots/m^2; Figure 3-21), however, this is because only one or two sites were sampled (D114 and TL11). From February 2005 to January 2021, shoot densities between impact and control sites were relatively similar (Figure 3-21). *P. sinuosa* shoots were taller at Pages than the impact sites, and similar trends between impact and control sites for aboveground biomass (Figure 3-21).

P. sinuosa sites were statistically compared using Impact sites only (TL11, D90 and D114) over time (Table 3-17). There was a significant interaction between Time and Site for all three *P. sinuosa* measures (shoot density, shoot height and aboveground biomass; Table 3-17). Post-hoc tests for shoot density revealed no significant difference between 2005 and 2006, 2005 and 2007, and between 2006 and 2007, however shoot densities at sites D114 and D90 2021 in 2021 were significantly greater than previous years. Shoot heights were similar between February and October 2004, and between 2006 and 2007, while a significant increase in shoot height was reported for sites D114, D90 and Pages in 2021. Aboveground biomass significantly increased at all *P. sinuosa* impact sites in 2021 (Figure 3-21).

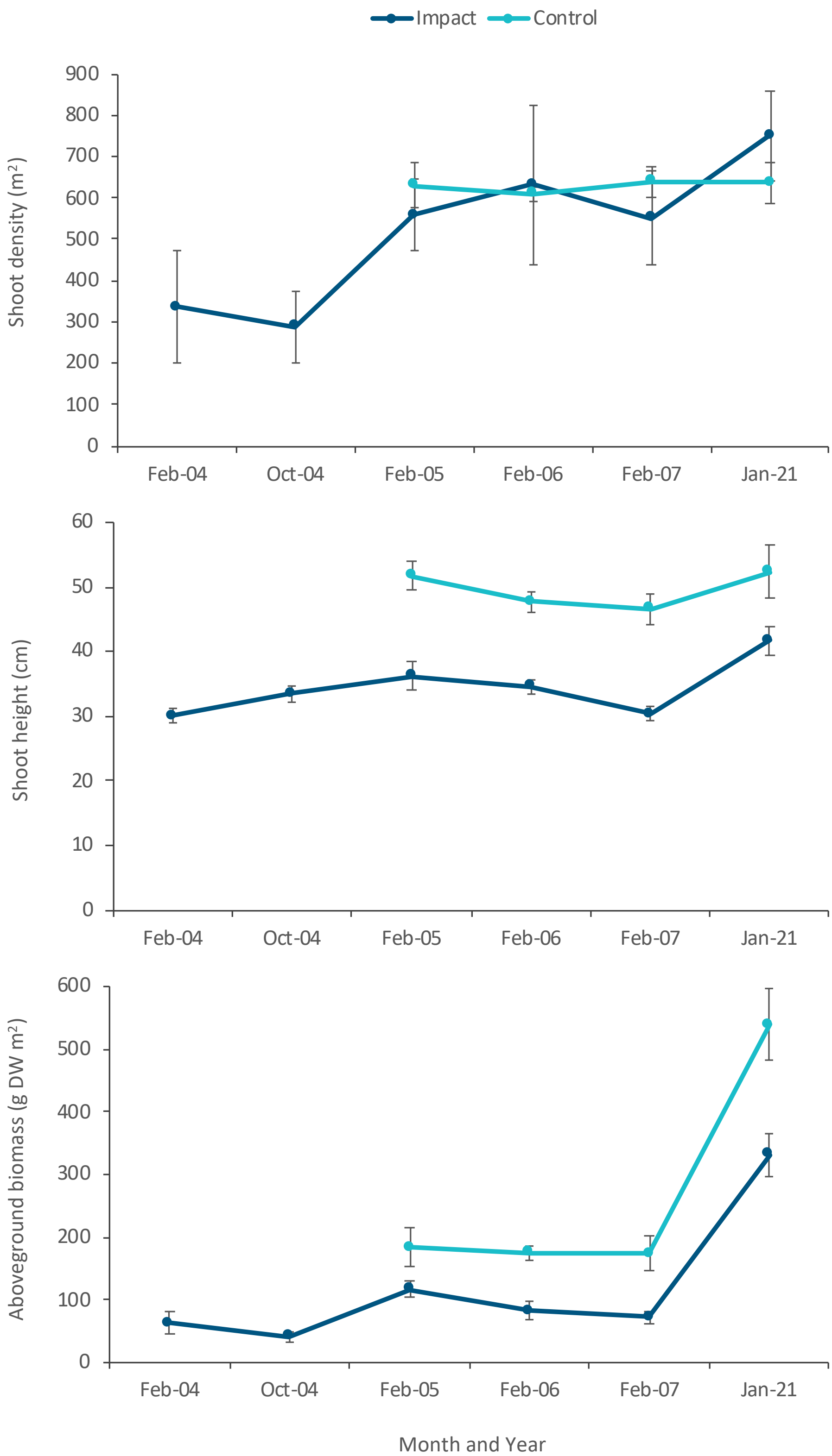


Figure 3-21 Shoot density, seagrass leaves per cluster, shoot height and aboveground biomass (mean ± S.E.) for combined impact and control for sites dominated by *Posidonia sinuosa* over time

Table 3-17 PERMANOVA results to test for differences in shoot density, shoot height, aboveground biomass and leaves per cluster of *Posidonia sinuosa* at impact sites over time

		Shoot density				Shoot height			
Source	df	SS	MS	Pseudo-F	P(perm)	SS	MS	Pseudo-F	P(perm)
Time	5	6640.7	1328.1	45.205	**0.0001**	299.86	59.971	43.667	**0.0001**
Site	2	885.97	442.98	15.078	**0.0001**	12.203	6.1017	4.4428	**0.0110**
Time x Site	10	3927.8	392.78	13.369	**0.0001**	246.32	24.632	17.935	**0.0001**
Residual	90	2644.2	29.38			123.61	1.3734		
Total	107	14099				681.99			

		Aboveground biomass			
Source	df	SS	MS	Pseudo-F	P(perm)
Time	5	2695	539	74.812	**0.0001**
Site	2	97.32	48.660	6.7539	**0.0023**
Time x Site	10	668.63	66.863	9.2804	**0.0001**
Residual	90	648.43	7.2047		
Total	107	4109.4			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.5 Temporal comparison of benthic cover: 2005, 2006, 2007, and 2021

3.5.1 *Amphibolis antarctica* sites

Percent cover of persistent seagrass species generally increased in percent cover over time with the exception of Port Denison, which declined in 2021 (Figure 3-22). Cover of colonising species at Point Moore to Chapman River has gradually increased over time, while no clear trends were seen for macroalgae (Figure 3-22). Percent cover of sand has declined over time, and declined substantially since 2006 in North of Chapman River and Point Moore to Chapman River regions (Figure 3-22).

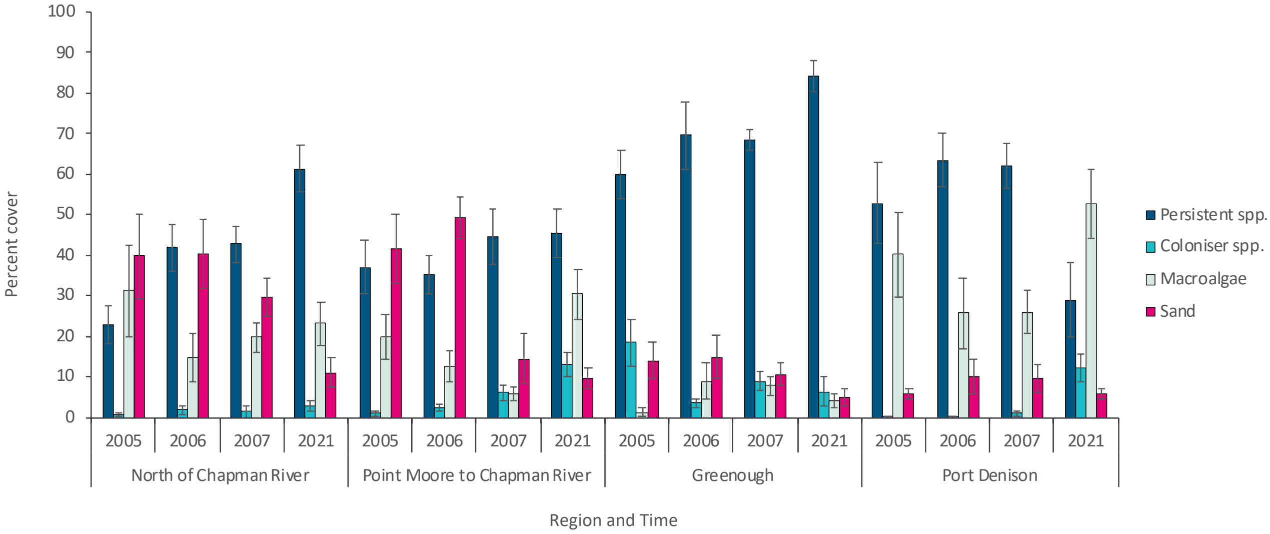


Figure 3-22 Percent cover (mean ± S.E.) of dominant benthic habitat types at *Amphibolis antarctica* dominated site over time

PERMANOVA results show that while there is no significant difference in benthic cover across regions, benthic cover was significantly different over time and sites (Table 3-18). Post-hoc tests showed there are significant differences in benthic cover between 2021 and remaining years (2005, 2006 and 2007), however there is a high degree of variability between sites. The nMDS ordination plot does not show any clear separation between sites within regions nor time (Figure 3-23). Instead, points for sites within regions across the years vary across the plot, further highlighting the high level of site variability.

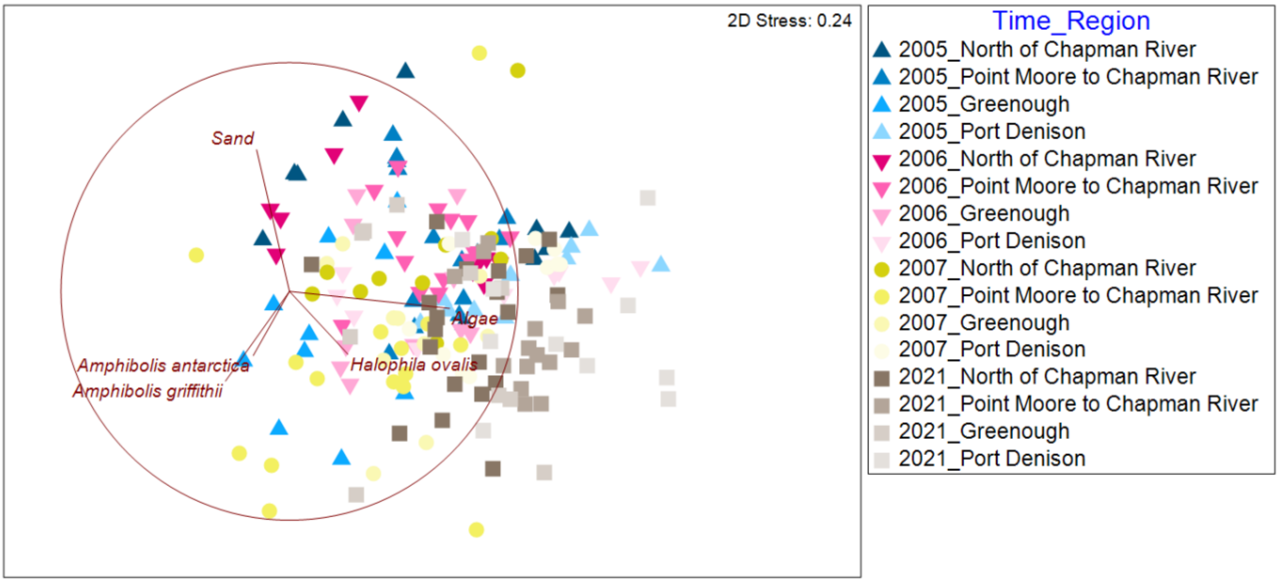


Figure 3-23 nMDS plot of benthic cover at *Amphibolis antarctica* dominated sites over time

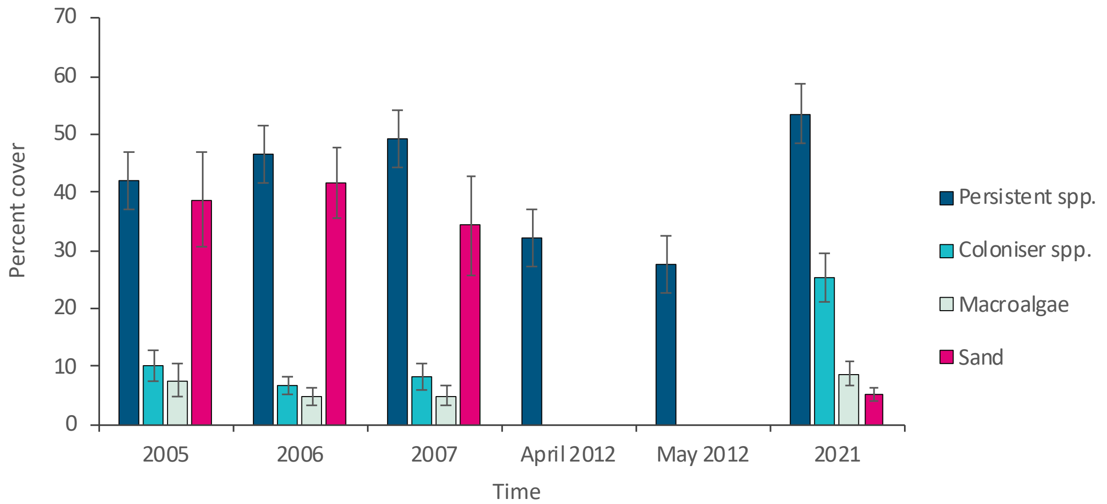
Table 3-18 PERMANOVA results to test for differences in benthic cover for *Amphibolis antarctica* dominated sites over time

Source	df	SS	MS	Pseudo-F	P(perm)
Time	3	18223	6074.4	3.8082	**0.0003**
Region	3	31741	10580	1.5701	0.1054
Site(Region)	7	47425	6775	19.138	**0.0001**
Time x Region	9	21822	2424.6	1.5200	**0.0420**
Time x Site(Region)	15	23926	1595.1	4.5059	**0.0001**
Residual	152	53808	354		
Total	189	204190			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.5.2 *Posidonia sinuosa* sites

Persistent species at *P. sinuosa* dominated sites gradually increased in percent cover over time, while coloniser species have fluctuated in percent cover over time recording a higher percent cover in 2021 (Figure 3-24). Percent cover of macroalgae has remained fairly steady over the years, while sand has reduced over time (Figure 3-24).



Note:
(1) Percent cover data for April 2012 and May 2012 combine a subset of *P. sinuosa* sites studied in 2021, which include D100, D114 and Pages

Figure 3-24 Percent cover (mean ± S.E.) of dominant benthic habitat types found at *Posidonia sinuosa* dominated site over time

Multivariate analyses of benthic cover show a significant difference in benthic cover with time and site, indicating high site variability (Table 3-19). Post-hoc tests showed that benthic cover changed over time however, not at all *P. sinuosa* sites. For instance, benthic cover at site D114 did not change between 2005 and 2006 (p>0.05), however significant changes were reported for all other remaining years. Similar results were observed for site Pages. The nMDS ordination did not show any clear groupings of benthic cover among sites, however there is a slight separation of 2021 benthic cover to the top right compared to previous years (Figure 3-25). This separation was driven by an increase cover of coloniser species (*S. isoetifolium* and *H. ovalis*) across the sites (Figure 3-25).

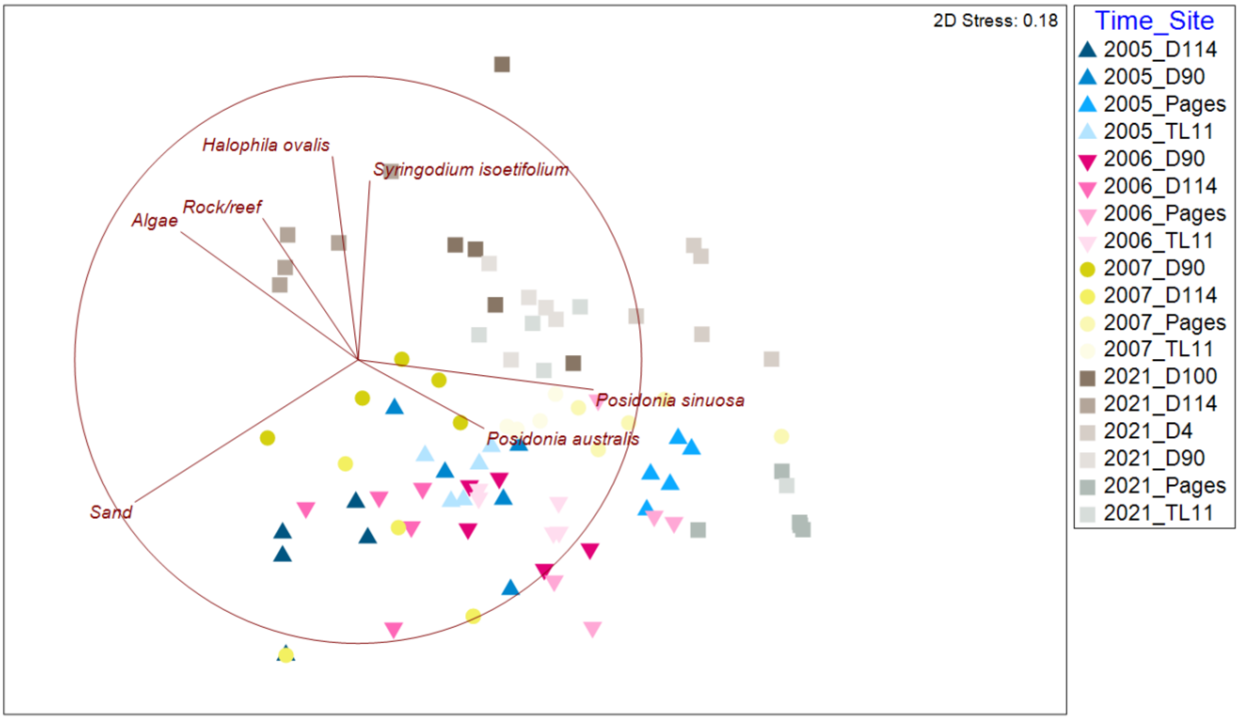


Figure 3-25 nMDS plot of benthic cover at *Posidonia sinuosa* dominated sites over time

Table 3-19 PERMANOVA results to test for differences in benthic cover for *Posidonia sinuosa* dominated sites over time

Source	df	SS	MS	Pseudo-F	P(perm)
Time	3	17719	5906.5	13.846	**0.0001**
Site	5	55741	11148	26.135	**0.0001**
Time x Site	9	22839	2537.6	5.9489	**0.0001**
Residual	72	30713	426.57		
Total	89	135500			

Note:
(1) Values in bold in P(perm) column denote a significant difference

3.6 Water quality profiles

Three water quality profiles were collected at each site during the January 2021 survey to provide a snapshot of the water quality at the time of sampling. In general, water quality measurements were relatively uniform with increasing depth (maximum depth 10.5 m; Figure 3-26). Sites at Jurien, on average, had lower temperatures, pH, salinity and conductivity compared to other sites, potentially due to its higher latitude. Greenough sites (GR014 and GR024) overall reported the highest measures in temperatures, pH, salinity, conductivity and oxygen demand, which may be caused by shallower and warmer waters. Sites in North of Chapman River, Point Moore to Chapman River and

Greenough reported similar water quality profiles which is not uncommon due to their close proximities. pH and salinity were in the normal range of marine waters, and clear waters were observed at all sites (low turbidity levels; Figure 3-26).

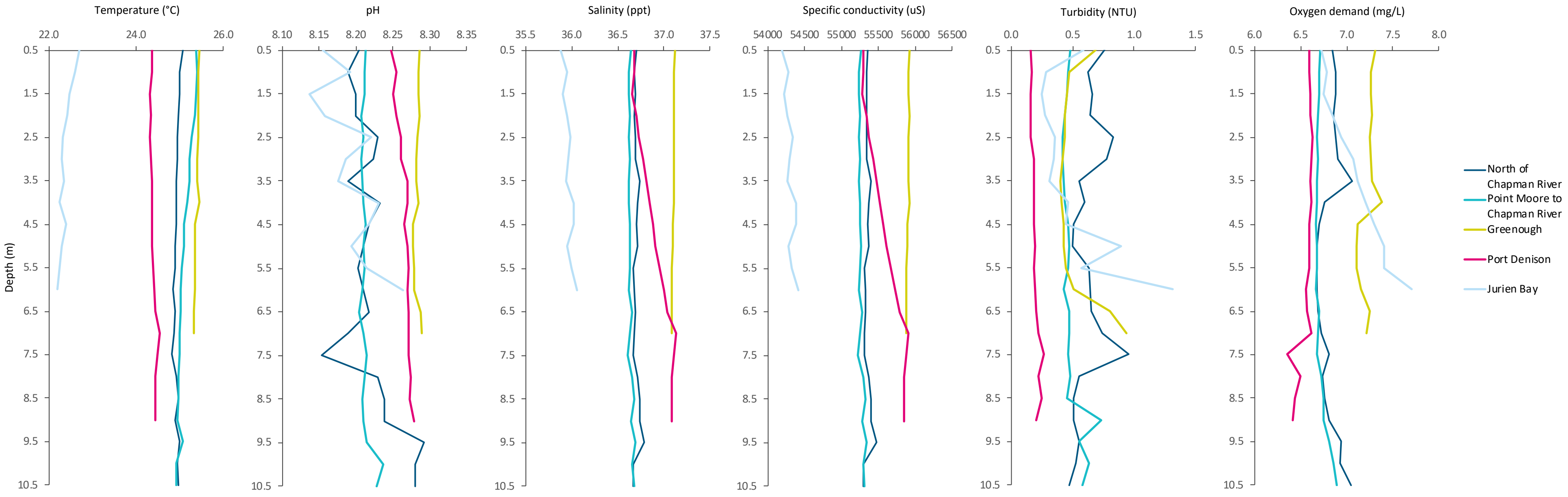


Figure 3-26 Water quality profiles (temperature, pH, salinity, specific conductivity, turbidity and oxygen demand) averaged across regions

Temperatures recorded near the surface (0.5 m below surface) for all five regions in January 2021 were within the range (21.9–25.5°C) of historical SST recordings for January and February 2000 to 2020 (Figure 3-27a). Four discrete peaks in SST were recorded during the summer months (January and February) in the years 2000, 2008, 2011 and 2021 (Figure 3-27a). All four discrete elevations in SST were associated with an unusually strong La Niña conditions that increased the transfer of tropical warm waters down the Leeuwin Current (Pearce et al. 2011, Wernberg et al 2013). The waters off the south-west coast of Western Australia in 2011 experienced elevated water temperatures between 2 and 4°C above long-term averages in the austral summer months of February to March 2011 (Feng et al. 2013, Wernberg et al 2013, Figure 3-27b). In mid-December 2020, SST were higher than the expected average and January 2021 reported temperatures above the marine heatwave threshold (Schlegel 2020).

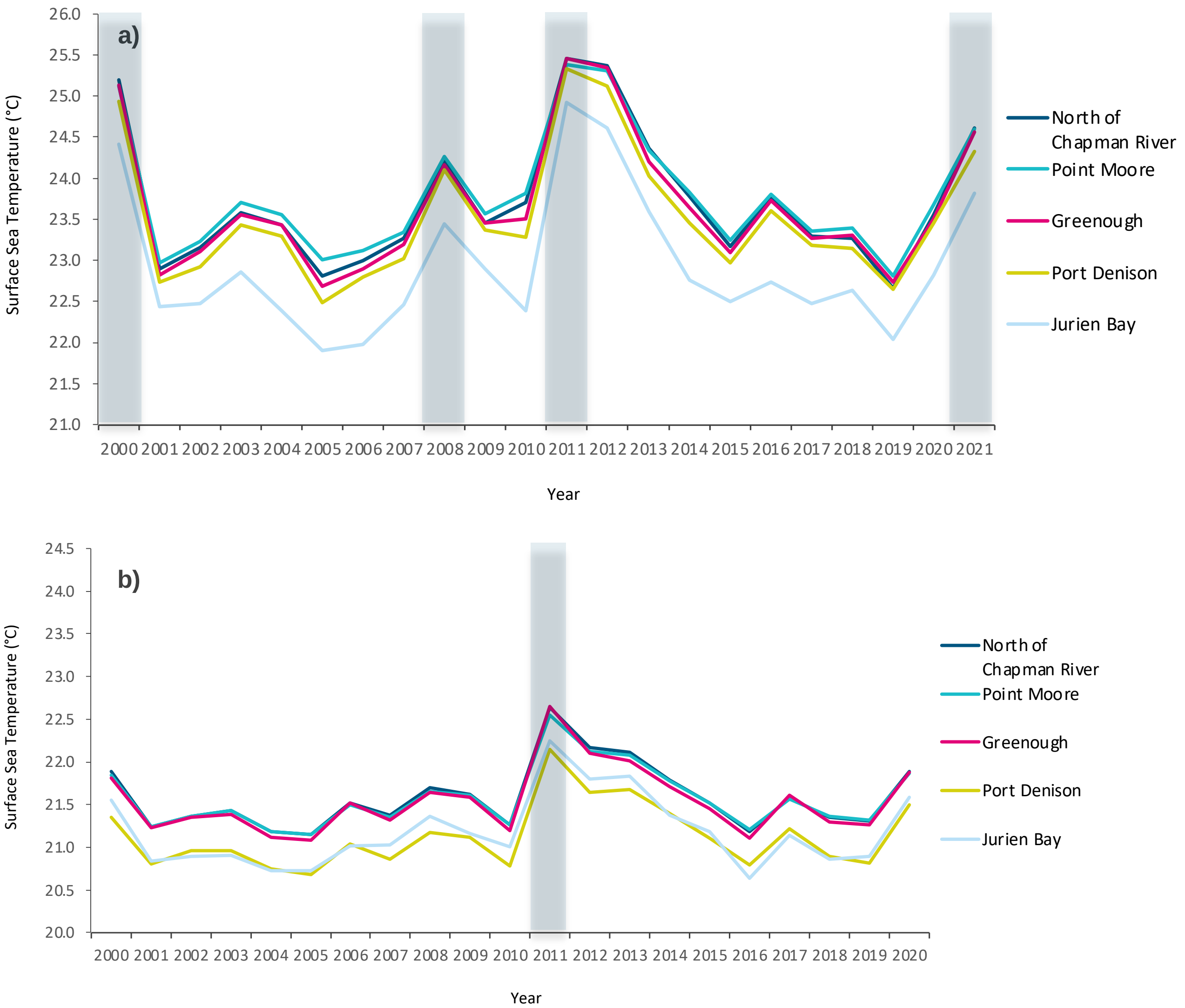


Figure 3-27 Sea surface temperature (°C) at Jurien Bay to North of Chapman River regions a) averaged over two months (January and February from 2000 to 2021), and b) averaged annually from January 2000 to December 2020. Grey lines indicate ocean warming/marine heatwaves experienced along the Western Australian coastline

4 Discussion and Recommendations

4.1 Long term trends in impacts to seagrass and their ability to recover from historical dredging impacts

Bioindicators are commonly used in ecological assessments to understand seagrass health associated with a range of natural disturbances including meteorological events (e.g., heavy or prolonged rains, cyclones), and biological interactions (e.g., grazing, sediment bioturbation), and anthropogenic disturbances such as reduced water clarity (e.g., eutrophication, resuspension, sediment loading), direct mechanical damage (e.g., dredging), and the release of toxic compounds into coastal waters (e.g., industrial discharge). This study examined six seagrass health bioindicators to assess the current condition of seagrass meadows relative to historical trends to determine if the seagrasses had recovered after exposure to turbid plumes produced by dredging operations in 2002–2003 and 2012. These bioindicators included morphological and structural indicators (shoot density, shoot height, leaves per shoot/cluster, aboveground biomass, percent cover and presence/absence of dead rhizomes) and community indicators (epiphyte and epifauna presence/absence, benthic cover, presence/absence of coloniser species). As *A. antarctica* and *P. sinuosa* were the dominant species in Champion Bay, the discussion will focus primarily on sites dominated by these two species.

Most sites in North of Chapman River and Point Moore to Chapman River showed a high degree of site variability for all seagrass bioindicators over time, which is expected as marine habitats are rarely homogenous in structure (Guidetti & Bussotti 2000). Natural and anthropogenic disturbances can cause seagrass habitats to change and result in patchiness, variable cover and fragmentation (Hastings et al. 1995, Short & Wyllie-Echeverria 1996). Given that many of the original sites in these two impact regions had changed since 2007 (i.e., not a dense seagrass meadow) as identified via satellite imagery, it is possible that these sites were impacted by a previous disturbance. Since the 2007 survey, three ocean warming/marine heatwave events struck the WA coast in the summer months of 2008, 2011 and 2021. Climate-driven warming of the waters induces heat stress in seagrass when their thermal optima are exceeded and leads to their death. Several studies reported declines or loss of persistent seagrass following the 2011 heatwave along the WA coastline (Ariane et al. 2018; Strydom et al. 2020). In addition to these heat warming events, a short-term maintenance dredging took place in 2012 and only sites D114 and Pages that were comparable to this study, reported significantly lower shoot densities compared to previous years. No other anthropogenic pressures have occurred in the area following the maintenance dredging campaign. These events may explain the small patches (<10 m) of seagrass meadow and bare sand seen at the original site on the satellite imagery. Due to time constraints in the sampling programme, a large portion of the original sites were not visited by the field team to see if there was any evidence of previous disturbance (i.e., dead rhizome mats). It is therefore suggested that if a field programme is proposed to assess possible changes in seagrass health for a small or large-scale dredging campaign, additional time in the field programme should be considered to allow the field team to visit the original sites in Westera & Babcock 2007.

Instead of removing these sites from the 2021 monitoring campaign which would have resulted in a significantly reduced design, sites were moved to an area nearby with seagrass present and of similar composition to the original site. For *A. antarctica*, impact sites within North of Chapman River and Point Moore to Chapman River regions showed a gradual increase in shoot density over time, which is indicative of potential recovery of seagrass over time. The number of leaves per cluster in these regions were significantly lower during capital dredging activities in April and September 2003 (2.3–6.8 leaves per cluster) compared to 2004 to 2021 (3.1–14.7 leaves per cluster). Results here conform with the literature which suggests that *Amphibolis* is able to recover following light reduction stress induced by dredging by increasing the number of leaves to maximise their ability to capture light (McMahon et al. 2011). Aboveground biomass varied over time showing great variability at site level, while shoots on average were taller in 2021 compared to previous years. Percent cover of persistent species (*A. antarctica*, *A. griffithii*, *P. sinousa*, *P. australis*, *P. coriacae* and *T. pachyrhizum*) increased in 2021 across all regions except for Port Denison, which shows that persistent seagrasses have recovered following dredging operations and have remained resilient to other natural disturbances. There was a gradual decline in percent cover of sand at most sites within North of Chapman River and Point Moore to Chapman River regions and a slight increase in coloniser species at Point Moore to Chapman River sites over time. Coloniser species have different survival strategies to persistent species, as these species are short-lived and have the ability recolonise more quickly following a disturbance (Erftemeijer & Lewis 2006). These impact sites were however, still largely dominated by persistent or long-living seagrass species.

At *P. sinuosa* sites (all sites in Point Moore to Chapman River region), shoot density varied both among sites and within sites over time. There was less variability in shoot height over the years however, control site Pages reported taller shoots. *Posidonia* may respond to fluctuations in sediment depth by elongating their vertical shoots to relocate their leaf-producing meristems closer to the new sediment level to avoid burial (Marba & Duarte 1994). Shoot height data collected from Pages, which receives a regular supply of sand from around Point Moore, indicates seagrasses at this location are responding in such a manner.

Higher aboveground biomass was reported across all sites and regions in 2021. Aboveground biomass is a robust indicator to numerous stressors including shading, nutrients, burial and organic matter (Roca et al. 2016), therefore, an overall increase in aboveground biomass at these sites suggests seagrasses are responding well to the natural variability in light conditions. Over the years, persistent species have gradually increased in cover, coloniser species have fluctuated in cover, while the presence of bare sand significantly reduced.

Although epiphytic algal growth on seagrass were not scraped (as per Westera & Babcock 2007 methods), a qualitative approach was taken instead by capturing photos of the seagrass canopy. Up to 40% of filamentous and/or calcareous epiphytic algae was visible on leaves and stems at most *A. antarctica* and *P. sinuosa* sites in 2021. Depending on the type of algae (calcareous versus filamentous algae), epiphytic growth of algae on seagrass may indicate possible elevations in water column nutrients that could later lead to a reduction in light available for photosynthesis, reduced rate of diffusion of materials across the seagrass blade surface, and may increase the physical drag of the seagrass. This study did not analyse nutrient levels in the water column, therefore only interpretations can be made. Many of the study sites are situated near rivers, in which nutrients can enter the marine system. The Chapman River catchment consists of cleared agricultural land that is heavily fertilised and flows following heavy rainfall typically in winter (Brearley 2005). Chapman River mouth was last open to the marine environment in mid-August 2020, which may have introduced high concentrations of nitrogen and phosphorus. The epiphytic load on *Amphibolis* may also be a result of the physical structure of *Amphibolis*. As suggested by Borowitzka et al. (1990), *Amphibolis* stems and leaves may provide additional structure and habitat for epiphyte colonisation. Given that epiphytic algae are an indicator for nutrient enrichment rather than an effect of light deprivation, it is suggested that monitoring epiphytic load on seagrasses are not required for future monitoring programmes.

An increase in suspended sediments can be caused by natural factors such as storms, wind-induced wave actions, river discharges and other local perturbations. Seagrass sites in the Geraldton region are exposed to strong seasonal environmental conditions, including southerly and south-westerly winds up to 40 knots and high seas (BoM 2021; MWPA 2021). These high energy areas resuspend and shift sediment, possibly dislodging seagrass and reducing sediment stability for seagrass settlement and growth (Boer 2007), changing the seagrass community structure, resilience and overall health of seagrass over time. These disturbances can also create ripples in sediments such as those mapped in Champion Bay (AECOM 2020), allowing space for other competitive species such as macroalgae and coloniser seagrass species to settle. A shift in benthic community has been previously reported in the north-western Mediterranean Sea, as *P. oceanica* seagrass meadows shifted and were substituted by *Cymodocea nodosa* and one native and two invasive macroalgal species (Montefalcone et al 2007). A shift in seagrass community was apparent in this survey, as sites D68 in North of Chapman River and PD2 in Port Denison that were previously dominated by *A. antarctica* were now colonised by *T. pachyrhizum*. *T. pachyrhizum* has similar life-history traits to that of *Amphibolis* spp., in which it is a persistent seagrass species with a slow ability to recover, high physiological resistance and is long-living (Kilminster et al. 2015). Divers reported dead *Amphibolis* spp. stems aboveground at PD2, indicating a recent and localised disturbance. It is probable that *A. antarctica* died off following the heatwave events and over time, was colonised by *T. pachyrhizum* and macroalgae. The substrate at both sites comprised of low-lying limestone reef platforms and pavements (AECOM 2020, and verified in the field), which is the habitat that both *Amphibolis* spp. and *T. pachyrhizum* occupy (Kirkman & Cook 1987).

The overall health of seagrasses in Champion Bay and corresponding control sites has improved post dredging. As these sites were not quantitively surveyed before the commencement of capital dredging, it is difficult to know whether seagrasses have recovered to their pre-capital dredging state.

4.2 Sediment dynamics of Champion Bay influencing seagrass health

The coastal region of Geraldton is subjected to strong local winds, nearshore currents, waves of up to 3 m and tides of less than 2 m (BoM 2021). These wind-driven oceanic processes drive the dominant northward littoral transport of sediment. Site Pages, which is located on the north side of Point Moore, receives a regular supply of sand that moves northerly around Point Moore into Champion Bay (Tecchiato et al. 2015). Due to the Port's infrastructure and rocky groynes, the shipping channel has trapped large quantities of sand (a total of ~300 000 m^3) since 2003 and Pages Beach has been subjected to significant sediment accretion (Tecchiato et al. 2012, O2 Marine 2021). This accretion has led to the requirement of periodic mechanical bypassing of sand to renourish Geraldton northern beaches (O2 Marine 2021).

In the 2021 survey, Pages reported taller shoots and a reduced presence of bare sand compared to impact sites in North of Chapman River and Point Moore to Chapman River regions. It is reasonable to suggest that the constant supply of northward transported sediments combined with high energy local conditions has made the site difficult for colonisation of coloniser species, and has allowed *Posidonia* leaves to grow taller in response to sediment burial. A study by Marba and Duarte (1993) showed that an increase in sediment depth of ~4 cm (mimicking moderate burial) stimulated vertical growth in *C. nodosa* while burial greater than 7 cm resulted in mortality. Large established *Posidonia* meadows may be able to survive greater burial depth than smaller and thinner leaved seagrasses due to their larger leaf size and aboveground biomass (Cabaço et al. 2008).

This study also showed a lower percent cover of bare sand and a gradual increase in persistent species cover in impact sites within Point Moore to Chapman River. Coastal infrastructure has modified the local sediment dynamics and presently, Champion Bay receives less sediment (Tecchiato et al. 2015). The shipping channel was last dredged in 2012, and since then, sediments have been trapped in the channel via localised northward longshore drift, decreasing the sand supply to Champion Bay (O2 Marine 2021). Although Champion Bay is likely suffering from a sand deficit, seagrasses appear to remain healthy in the region most likely as they are able to trap and stabilise sediment by reducing bed shear stress, and can produce carbonate sediment in situ through the deposits of skeletal bioclasts that live in association with seagrass meadows (Tecchiato et al. 2016).

Champion Bay contained sections of bare sand with ripples up to 100 cm heading in a north-easterly direction (AECOM 2020, BMT 2021), which is indicative of a highly dynamic environment. As these ripples move through the bay, limestone platform basement is sequentially exposed and buried that may result in a dynamic distribution of habitat and associated seagrass and macroalgal communities. However, it is not known if there is a tipping point (theoretical or otherwise) following which seagrasses will either shift in species composition from those that prefer a sedimentary substrate such as *Posidonia* to those that are better adapted to rock / reef such as *Amphibolis*, or, if such changes would also be accompanied by long-term declines. Adding further complexity in system understanding is the highly dynamic nature of the Champion Bay region (i.e., influence of waves, climatic events, etc), which not only effect sediment movements but also likely directly influence the seagrasses themselves as evidenced from the high variability in results from this seagrass monitoring program. As such, tracking long-term trends and interpreting impacts associated with any particular cause-effect pathway will always be difficult, but needs to be accounted for to understand seagrass species-specific response to external stressors and the natural dynamics at Champion Bay.

4.3 Recommendations for future measures of seagrass health and extent

This study examined morphological, structural and community indicators linked to potential stressors such as burial of seagrass and shading caused by dredge plumes to assess seagrasses health over time. These indicators are commonly adopted as the standard approach for measuring seagrass health and should continue to be monitored either periodically, or as required, to track long-term trends in the region. However, it was also apparent at the completion of this survey that the seagrass system is highly dynamic and there are multiple drivers which may influence seagrass health, and as such, future studies may need to consider including additional lines of evidence to help single out effects of any particular driver of interest. Therefore, the following recommendations have been made:

- Conducting seagrass monitoring surveys pre-dredging operations provide crucial information of the baseline conditions (i.e., water quality, seagrass health sub-lethal indicators, seagrass extent) at proposed impact and control sites. Characterising these baseline conditions provide an opportunity to determine background natural variability of impact and control sites with respect to health sub-lethal indicators. It also allows locally relevant thresholds to be determined and applied in impact prediction in line with ANZG (2018) values. The development of thresholds can be applied to define the boundaries of Zone of Influence/Moderate Impact and High Impact to confirm whether an impact(s) has occurred and allows for valid comparisons to baseline studies.
- Depending upon specific cause-effect pathways of interest, it would be useful to review a broader suite of sub-lethal bioindicators that may provide additional lines of evidence of sub-lethal stress to light reduction and burial. Physiological and biochemical responses to light reduction and burial stress include leaf and rhizome nitrogen, rhizome sucrose and carbohydrates, leaf delta 13 carbon ($\delta^{13}C$), electromagnetic radiation, number of necrosis marks, proportion of live leaf tissue to narcotic tissue, and total biomass (Roca et al. 2016, Lavery et al. 2019). These indicators are effective in documenting recovery processes at the cellular level, particularly for larger seagrass species.
- Habitat mapping is an accurate and cost-effective method for mapping the distribution of seagrass meadows and determine changes in overall extent at the meadow scale over time (Hovey & Fraser 2018, Veettil et al. 2020). The application of remote sensing is generally a requirement for any environmental impact assessment for dredging and would help understand the effects of any broad-scale sediment movement in Champion Bay. It is therefore recommended that more regular habitat mapping of seagrasses in Champion Bay and surrounding areas using high-resolution remote sensing are conducted.
- Given that the seagrass system in Champion Bay is exposed to many other influences that are acting on both long-term (e.g., sediment trap of a channel) and short-term scales (e.g., storms and La Niña), these additional influences should be measured during seagrass monitoring programmes to account for potential impacts to seagrasses which are not related to dredging operations.
- Since marine quality monitoring was not undertaken during this seagrass survey, it is not possible to comment on the extent to which water or sediment quality may have contributed to the overall health of seagrasses. As such, it would be useful for any future seagrass monitoring surveys, if practical, to be combined with a water and sediment quality program to ensure data can be related.

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Appendix A PERMANOVA statistical results for shoot density, shoot height, aboveground biomass, leaves per cluster/shoot, percent and benthic cover

PERMANOVA Statistical Results for Seagrass Survey

3.2 Spatial comparison of seagrass characteristics: January 2021

3.2.1 *Amphibolis antarctica* – aboveground biomass

Resemblance worksheet
Name: Resem15
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Region	Fixed	4
Site name	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Region	3	1807.9	602.64	13.867	0.0021	8663	0.0024
Site name(Region)	7	304.21	43.458	1.6303	0.1517	9944	0.1487
Res	55	1466.1	26.657				
Total	65	3578.3					

3.2.1 *A. antarctica* – leaves per cluster

Resemblance worksheet
Name: Resem12
Data type: Distance
Selection: All
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Region	Fixed	4
Site name	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Region	3	25.864	8.6212	0.87076	0.5058	8663	0.5089
Site name(Region)	7	69.306	9.9008	6.8444	0.0001	9942	0.0001
Res	55	79.561	1.4466				
Total	65	174.73					

3.2.1 *A. antarctica* – shoot density

Resemblance worksheet
Name: Resem1
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Region	Fixed	4
Site name	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Region	3	613.65	204.55	2.0146	0.2141	8615	0.1958
Site name(Region)	7	710.72	101.53	4.152	0.0009	9937	0.0009
Res	55	1345	24.454				
Total	65	2669.3					

3.2.1 *A. antarctica* – shoot height

Resemblance worksheet
Name: Resem2
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Region	Fixed	4
Site name	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Region	3	38.02	12.673	6.1288	0.0263	8650	0.0222
Site name(Region)	7	14.475	2.0678	4.1389	0.0014	9944	0.0009
Res	55	27.478	0.49961				
Total	65	79.973					

3.2.2 *A. griffithii* – aboveground biomass

Resemblance worksheet
Name: Resem16
Data type: Distance

Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Site name	2	355.51	177.76	8.3985	0.0041	9931
Res	15	317.48	21.165			
Total	17	672.99				

3.2.2 *A. griffithii* – leaves per cluster

Resemblance worksheet
Name: Resem11
Data type: Distance
Selection: All
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	2	0.071677	0.035839	2.3507	0.1305	9931	0.1298
Res	15	0.22869	0.015246				
Total	17	0.30036					

3.2.2 *A. griffithii* – shoot density

Resemblance worksheet
Name: Resem3
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	2	78.438	39.219	4.2556	0.0403	9807	0.0352
Res	15	138.24	9.2157				
Total	17	216.67					

3.2.2 *A. griffithii* – shoot height

Resemblance worksheet
Name: Resem4
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	2	2.8245	1.4123	1.6539	0.205	9650	0.2252
Res	15	12.808	0.85389				
Total	17	15.633					

3.2.3 *Posidonia sinuosa* – aboveground biomass

Resemblance worksheet
Name: Resem17
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	5	533.9	106.78	6.8435	0.0002	9964	0.0005
Res	29	452.49	15.603				

Total	34	986.4

3.2.3 *P. sinuosa* – leaves per shoot

Resemblance worksheet
Name: Resem13
Data type: Distance
Selection: All
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	5	1.1204	0.22409	16.551	0.0001	9957	0.0001
Res	29	0.39262	0.013539				
Total	34	1.5131					

3.2.3 *P. sinuosa* – shoot density

Resemblance worksheet
Name: Resem5
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	5	673.15	134.63	6.6223	0.0001	9950	0.0007
Res	29	589.57	20.33				
Total	34	1262.7					

3.2.3 *P. sinuosa* – shoot height

Resemblance worksheet
Name: Resem6
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	5	10.187	2.0375	7.1257	0.0004	9959	0.0004
Res	29	8.2921	0.28593				
Total	34	18.479					

3.2.4 *Thalassodendron pachyrhizum* – aboveground biomass

Resemblance worksheet
Name: Resem18
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	2

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	1	194.57	194.57	23.441	0.003	462	0.0011
Res	10	83.007	8.3007				
Total	11	277.58					

3.2.4 *T. pachyrhizum* – leaves per shoot

Resemblance worksheet
Name: Resem14
Data type: Distance
Selection: All
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	2

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	1	0.63618	0.63618	4.8071	0.0564	336	0.0551
Res	10	1.3234	0.13234				
Total	11	1.9596					

3.2.4 *T. pachyrhizum* – shoot density

Resemblance worksheet
Name: Resem7
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	2

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	1	215.07	215.07	17.93	0.0062	244	0.0017
Res	10	119.95	11.995				
Total	11	335.02					

3.2.4 *T. pachyrhizum* – shoot height

Resemblance worksheet
Name: Resem8
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site name	Fixed	2

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site name	1	1.6342	1.6342	15.561	0.0054	462	0.0031
Res	10	1.0502	0.10502				
Total	11	2.6844					

3.3 Spatial comparison of percent and benthic cover: January 2021

3.3.1 *A. antarctica* sites

Resemblance worksheet
Name: Resem4
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Region	Fixed	4
Site	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Region	3	19357	6452.4	2.392	0.0066	8650	0.0306
Site(Region)	7	18882	2697.5	6.0957	0.0001	9888	0.0001
Res	44	19471	442.52				
Total	54	57711					

3.3.2 *A. griffithii* sites

Resemblance worksheet
Name: Resem6
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site	2	9984.6	4992.3	5.1054	0.0034	8626	0.0053
Res	12	11734	977.84				
Total	14	21719					

3.3.3 *P. sinuosa* sites

Resemblance worksheet
Name: Resem5
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site	5	35934	7186.9	13.846	0.0001	9937	0.0001
Res	24	12457	519.06				
Total	29	48392					

3.3.4 *T. pachyrhizum* sites

Resemblance worksheet
Name: Resem2
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Unrestricted permutation of raw data
Number of permutations: 9999

Factors

Name	Type	Levels
Site	Fixed	2

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Site	1	2909.9	2909.9	5.7239	0.0252	126	0.0091
Res	8	4067.1	508.39				
Total	9	6977					

3.4 Temporal comparison of seagrass characteristics: 2004, 2005, 2006, 2007, and 2021

3.4.1.1 *A. antarctica* regional differences over time – aboveground biomass

Resemblance worksheet
Name: Resem3
Data type: Distance
Selection: All
Transform: Square root

Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Region	Fixed	4
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	14766	2953.2	30.824	0.0001	9946	0.0001
Region	3	5070.9	1690.3	9.2555	0.0279	1258	0.0168
Site(Region)	5	913.13	182.63	8.3654	0.0001	9949	0.0001
TimexRegion	15	5816.8	387.79	4.0475	0.0015	9935	0.001
TimexSite(Region)	25	2395.2	95.809	4.3887	0.0001	9899	0.0001
Res	270	5894.4	21.831				
Total	323	33480					

3.4.1.1 *A. antarctica* regional differences over time – leaves per cluster

Resemblance worksheet
Name: Resem4
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Region	Fixed	4
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	454.4	90.881	61.782	0.0001	9954	0.0001
Region	3	18.775	6.2584	0.91395	0.5494	1258	0.4942
Site(Region)	5	34.238	6.8477	99.775	0.0001	9949	0.0001
TimexRegion	15	103.92	6.9279	4.7097	0.0005	9937	0.0006
TimexSite(Region)	25	36.775	1.471	21.433	0.0001	9908	0.0001
Res	270	18.53	0.068631				
Total	323	661.14					

3.4.1.1 *A. antarctica* regional differences over time – shoot density

Resemblance worksheet
Name: Resem1

Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Region	Fixed	4
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	12950	2589.9	48.768	0.0001	9951	0.0001
Region	3	2887.8	962.62	7.013	0.0454	1258	0.0314
Site(Region)	5	686.31	137.26	9.1306	0.0001	9942	0.0001
TimexRegion	15	5358.9	357.26	6.7272	0.0001	9929	0.0001
TimexSite(Region)	25	1327.7	53.107	3.5327	0.0001	9899	0.0001
Res	270	4058.9	15.033				
Total	323	26189					

3.4.1.1 *A. antarctica* regional differences over time – shoot height

Resemblance worksheet
Name: Resem2
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Region	Fixed	4
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	873.28	174.66	29.862	0.0001	9953	0.0001
Region	3	111.29	37.096	2.4213	0.1963	1258	0.1823
Site(Region)	5	76.605	15.321	34.227	0.0001	9950	0.0001
TimexRegion	15	654.51	43.634	7.4603	0.0001	9932	0.0001
TimexSite(Region)	25	146.22	5.8488	13.066	0.0001	9899	0.0001
Res	270	120.86	0.44762				
Total	323	1845.8					

3.4.1.2 *A. antarctica* control versus impact sites over time – aboveground biomass

Resemblance worksheet
Name: Resem3
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
CvI	Fixed	2
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	14504	2900.7	23.121	0.0001	9951	0.0001
CvI	1	2825.5	2825.5	6.2621	0.0482	126	0.0396
Site(CvI)	7	3158.5	451.21	20.668	0.0001	9930	0.0001
TimexCvI	5	3821	764.2	6.0913	0.0002	9959	0.0005
TimexSite(CvI)	35	4391	125.46	5.7467	0.0001	9888	0.0001
Res	270	5894.4	21.831				
Total	323	33480					

3.4.1.2 *A. antarctica* control versus impact sites over time – leaves per cluster

Resemblance worksheet
Name: Resem4
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
CvI	Fixed	2
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	457.22	91.445	59.707	0.0001	9945	0.0001
CvI	1	15.057	15.057	2.7769	0.1288	126	0.143
Site(CvI)	7	37.956	5.4223	79.007	0.0001	9935	0.0001
TimexCvI	5	87.088	17.418	11.372	0.0001	9952	0.0001
TimexSite(CvI)	35	53.605	1.5316	22.316	0.0001	9882	0.0001

Res	270	18.53	0.068631
Total	323	661.14	

3.4.1.2 *A. antarctica* control versus impact sites over time – shoot density

Resemblance worksheet
Name: Resem1
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
CvI	Fixed	2
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	12635	2527.1	26.223	0.0001	9963	0.0001
CvI	1	2023.7	2023.7	9.1369	0.0253	126	0.0207
Site(CvI)	7	1550.4	221.49	14.733	0.0001	9944	0.0001
TimexCvI	5	3313.7	662.74	6.8772	0.0003	9949	0.0001
TimexSite(CvI)	35	3372.9	96.368	6.4104	0.0001	9888	0.0001
Res	270	4058.9	15.033				
Total	323	26189					

3.4.1.2 *A. antarctica* control versus impact sites over time – shoot height

Resemblance worksheet
Name: Resem2
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
CvI	Fixed	2
Site	Random	9

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	823.41	164.68	15.848	0.0001	9936	0.0001
CvI	1	40.478	40.478	1.9221	0.2044	126	0.2117

Site(CvI)	7	147.42	21.059	47.047	0.0001	9938	0.0001
TimexCvI	5	437.04	87.408	8.4118	0.0001	9950	0.0001
TimexSite(CvI)	35	363.69	10.391	23.214	0.0001	9879	0.0001
Res	270	120.86	0.44762				
Total	323	1845.8					

3.4.2.1 *P. sinuosa* regional differences over time – aboveground biomass

Resemblance worksheet
Name: Resem7
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	4

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	4702.1	940.43	144.61	0.0001	9963	0.0001
Site	3	199.47	66.491	10.225	0.0001	9949	0.0001
TimexSite	15	1056.1	70.406	10.827	0.0001	9931	0.0001
Res	120	780.37	6.5031				
Total	143	6738.1					

3.4.2.1 *P. sinuosa* regional differences over time – shoot density

Resemblance worksheet
Name: Resem5
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	4

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	11001	2200.2	90.691	0.0001	9956	0.0001
Site	3	974.64	324.88	13.392	0.0001	9958	0.0001
TimexSite	15	4512.7	300.85	12.401	0.0001	9927	0.0001

Res	120	2911.2	24.26
Total	143	19399	

3.4.2.1 *P. sinuosa* regional differences over time – shoot height

Resemblance worksheet
Name: Resem6
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	4

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	609.92	121.98	114.32	0.0001	9947	0.0001
Site	3	12.578	4.1927	3.9293	0.0082	9941	0.0085
TimexSite	15	331.91	22.127	20.737	0.0001	9930	0.0001
Res	120	128.04	1.067				
Total	143	1082.4					

3.4.2.2 *P. sinuosa* impact sites over time – aboveground biomass

Resemblance worksheet
Name: Resem3
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	2695	539	74.812	0.0001	9951	0.0001
Site	2	97.32	48.66	6.7539	0.0023	9940	0.0018
TimexSite	10	668.63	66.863	9.2804	0.0001	9928	0.0001
Res	90	648.43	7.2047				
Total	107	4109.4					

3.4.2.2 *P. sinuosa* impact sites over time – shoot density

Resemblance worksheet
Name: Resem1
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	6640.7	1328.1	45.205	0.0001	9945	0.0001
Site	2	885.97	442.98	15.078	0.0001	9957	0.0001
TimexSite	10	3927.8	392.78	13.369	0.0001	9927	0.0001
Res	90	2644.2	29.38				
Total	107	14099					

3.4.2.2 *P. sinuosa* impact sites over time – shoot height

Resemblance worksheet
Name: Resem2
Data type: Distance
Selection: All
Transform: Square root
Resemblance: D1 Euclidean distance

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	6
Site	Fixed	3

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	5	299.86	59.971	43.667	0.0001	9940	0.0001
Site	2	12.203	6.1017	4.4428	0.011	9952	0.0148
TimexSite	10	246.32	24.632	17.935	0.0001	9937	0.0001
Res	90	123.61	1.3734				
Total	107	681.99					

3.5 Temporal comparison of benthic cover: 2005, 2006, 2007, and 2021

3.5.1 *A. antarctica* sites

Resemblance worksheet
Name: Resem1
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	4
Region	Fixed	4
Site	Random	11

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	3	18223	6074.4	3.8082	0.0003	9923	0.0004
Region	3	31741	10580	1.5701	0.1054	9682	0.16
Site(Region)	7	47425	6775	19.138	0.0001	9892	0.0001
TimexRegion	9	21822	2424.6	1.52	0.042	9899	0.0822
TimexSite(Region)**	15	23926	1595.1	4.5059	0.0001	9872	0.0001
Res	152	53808	354				
Total	189	2.0419E+05					

3.5.2 *P. sinuosa* sites

Resemblance worksheet
Name: Resem2
Data type: Similarity
Selection: All
Transform: Fourth root
Resemblance: S17 Bray-Curtis similarity

Sums of squares type: Type III (partial)
Fixed effects sum to zero for mixed terms
Permutation method: Permutation of residuals under a reduced model
Number of permutations: 9999

Factors

Name	Type	Levels
Time	Fixed	4
Site	Fixed	6

PERMANOVA table of results

Source	df	SS	MS	Pseudo-F	P(perm)	Unique perms	P(MC)
Time	3	17719	5906.5	13.846	0.0001	9942	0.0001
Site	5	55741	11148	26.135	0.0001	9932	0.0001
TimexSite**	9	22839	2537.6	5.9489	0.0001	9895	0.0001
Res	72	30713	426.57				

Total	89	1.355E+05

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