Western Australian Marine Science Institution

Westport

Better science Better decisions

Drivers of seagrass decline in Perth waters and actions to halt decline

Theme: Benthic Habitats and Communities

WAMSI Westport Marine Science Program

WAMSI WESTPORT MARINE SCIENCE PROGRAM

ABOUT THE MARINE SCIENCE PROGRAM

The WAMSI Westport Marine Science Program (WWMSP) is a $13.5 million body of marine research funded by the WA Government. The aims of the WWMSP are to increase knowledge of Cockburn Sound in areas that will inform the environmental impact assessment of the proposed Westport development and help to manage this important and heavily used marine area into the future. Westport is the State Government's program to move container trade from Fremantle to Kwinana, and includes a new container port and associated freight, road and rail, and logistics. The WWMSP comprises more than 30 research projects in the biological, physical and social sciences that are focused on the Cockburn Sound area. They are being delivered by more than 100 scientists from the WAMSI partnership and other organisations.

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DATA
Finalised datasets will be released as open data, and data and/or metadata will be discoverable through Data WA and the Shared Land Information Platform (SLIP).

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Front cover image: Seagrass (Posidonia australis) in CockburnSound. Photo courtesy of Rachel Austin (The University of Western Australia).

Contents

The WAMSI Westport Marine Science Program is a $13.5 million body of research that is designed to fill knowledge gaps relating to the Cockburn Sound region. It was developed with the objectives of improving the capacity to avoid, mitigate and offset environmental impacts of the proposed Westport container port development and increase the WA Government's ability to manage other pressures acting on Cockburn Sound into the future. Funding for the program has been provided by Westport (through the Department of Transport) and the science projects are being delivered by the Western Australian Marine Science Institution.

Drivers of seagrass decline in Perth waters and actions to halt decline

Kathryn McMahon[1,2], Simone Strydom[1,3], Natasha Dunham [1], John Whale [1], Chanelle Webster [1], Nicole Said [1]

[1] Centre for Marine Ecosystem Research, Edith Cowan University, Joondalup, Western Australia
[2] Centre for People, Place and Planet, Edith Cowan University, Joondalup, Western Australia
[3] Department of Biodiversity, Conservation and Attractions, Kensington, Western Australia

Pressure-response relationships, building resilience and future proofing seagrass meadows.

1 Executive Summary

- Experts from consulting, government and research including individuals with up to 50 years' experience in Perth coastal waters discussed potential drivers of seagrass decline based on trends from the long-term seagrass monitoring program in Cockburn and Warnbro Sound and Owen Anchorage (27 sites from 2003-2020) and their personal knowledge and expertise.
- The collation of seagrass monitoring data demonstrated that of the 27 sites monitored, only six had a significant decline over time, and these sites were both within and outside of Cockburn Sound (Warnbro Sound, Southern Flats, Jervoise Bay, Garden Island and Woodman Point).
- For the sites that were declining, consistent drivers of decline across these sites were not identified based on expert opinion, indicating the importance of local conditions for influencing seagrass condition.
- Seagrass sites where there was high confidence in the drivers that were impacting condition included Woodman Point, Mangles Bay, Jervoise Bay, Warnbro Sound 2.0 m and Warnbro Sound 3.2 m.
- The drivers of decline that had the most confidence based on expert opinion were erosion and sediment burial in shallow sites, anchor damage at Mangles Bay and sediment plumes from sand mining wash plants at Woodman Point. Other drivers of decline or poor condition were increased temperature, storms and altered hydrodynamics.
- Actions to halt decline and build resilience in seagrass meadows were brainstormed based on the drivers of decline and considering future dredging pressure. Participants were asked to think outside of the box to collate a list that contained innovative and untried actions as well as more well-known or tried and tested actions.
- The drivers from which relevant actions were identified included dredging, shipping and boating, fishing, coastal infrastructure, pollution, biological interaction including grazing and climate change.
- The actions were categorised into the themes of management, nature-based solutions, engineering solutions, industry, knowledge and education.
- Seventy-five different actions linked to the specific drivers were identified that could be implemented to improve seagrass condition and/or build resilience in seagrass ecosystems within Perth coastal waters but also be applied more widely. Before these actions are implemented, an extensive risk benefit analysis should be conducted.

2 Background

The WAMSI Westport Marine Science Program (WWMSP) is a partnership between Westport and WAMSI to deliver a collaborative science program that will ensure the environmental impact assessment for Western Australia's future container port is based on current, relevant and independent science. There are nine research themes, with the largest, Theme 2 Benthic Habitats and Communities co-led by Professor Kathryn McMahon and Professor Gary Kendrick. The goals of this theme are to 1: Address knowledge gaps for the benthic habitats to improve environmental impact assessment and management, and 2: Test innovative restoration and rehabilitation methods for seagrass meadows with the aim of improving ecosystem resilience in Cockburn Sound, and to investigate how seagrass may be strengthened to better cope with climate change. The work presented in this report forms part of the WWMSP project *Pressure-response relationships, building resilience and future-proofing seagrass meadows*, led by Professor Kathryn McMahon and Dr Simone Strydom. Through compiling historical seagrass monitoring data, with input from experts obtained during a workshop, the aim of this report was to develop a consensus on the drivers of seagrass condition in Cockburn Sound, Warnbro Sound and Owen Anchorage. From this consensus, we aimed to identify potential resilience building opportunities for seagrass habitats in the region that could then be explored through a cost-benefit and risk analysis.

In the Perth metropolitan area, the shallow coastal basin of Cockburn Sound supports significant seagrass communities, although this key habitat is under threat from multiple pressures (Carruthers et al., 2007). Despite their ecological and economic importance, major declines have been reported in association with industrialisation (Cambridge and McComb, 1984). Large-scale decline of seagrass habitat occurred in Cockburn Sound from the 1970's with over 2000 ha of seagrass lost (Kendrick et al., 2002), mostly attributed to eutrophication from industrial discharges (Cambridge and McComb 1984). Recent mapping illustrated that over the last two decades, there have been some modest gains (~200 ha) in seagrass extent (Hovey and Fraser 2018). However, decline in seagrass condition continues in some meadows based on temporal monitoring of shoot density, despite improvements in the water quality of Cockburn Sound (Mohring and Rule 2013, Fraser et al., 2019). Other potential drivers proposed for these declines include low water flows at particular times of the year, which leads to reduced oxygen, sulphide intrusion into the shoots, and shoot loss (Olsen et al., 2018, Fraser and Kendrick 2017, Fraser et al., 2023). Gradual seawater temperature increases, and the threat of increased frequency and intensity of marine heatwaves, are additional potential drivers of seagrass decline for Cockburn Sound. For example, during the summer of 2010/2011 central Cockburn Sound waters reached 27.6°C (Rose et al., 2012), 5.4°C higher than the historic average summer water temperatures (22°C). Indeed, warming has been associated with significant seagrass loss in other regions in WA (Strydom et al., 2020) and is known to interact with sulphide intrusion to exacerbate shoot loss (Fraser et al., 2023).

To identify resilience building opportunities, it is important to first understand the existing condition of seagrass. Specifically, identifying areas that are stable and those that are declining, as well as the environmental drivers influencing meadow condition. If the driver is understood, then a course of action to halt the decline could be implemented to directly address the cause (e.g. reduce nutrient loads). However, this is not always possible, particularly in capital dredging scenarios. Therefore, another option is to actively build resilience within the seagrass populations experiencing the decline. For example, if a driver of decline is identified as ocean warming or heatwaves (i.e. thermal thresholds exceeded that lead to mortality), then efforts to build resilience within meadows could include translocation of seagrasses with higher thermal maxima thresholds from other populations within the species' biogeographical range (i.e. Jurien Bay to Cockburn Sound).

2.1 Workshop participants

Thirty-seven experts were invited to participate in the Workshop. Invitees were selected based on a set of criteria including their expertise in seagrass ecosystems of Perth coastal waters and/or potential drivers of decline, as well as experience or interest in monitoring and/or managing seagrass ecosystems in Perth. Participants represented consultancy, government agencies, and universities and their experience working across the Perth coastal waters ranged from 1-50 years (Table 1).

2.2 Workshop format

The Workshop was conducted in person on the 12 October 2022 (10:00-16:00) at the Department of Primary Industries and Regional Development (DPIRD; Marine Operations Centre, Fremantle, Western Australia). Prior to the Workshop, participants were provided with a work pack which provided briefing material, including the aims of the Workshop. Follow-up sessions were also carried out with seven participants who could not attend on the day but wanted to provide input.

2.3 Information summary for the Workshop

The work pack provided to participants comprised a summary of data across seagrass monitoring sites in Cockburn Sound, Owen Anchorage and Warnbro Sound from the Cockburn Sound Management Council (CSMC) monitoring program (from 2003-2022, 21 sites) and the Department of Biodiversity and Conservation and Attractions (DBCA) Shoalwater Islands Marine Park (SIMP) monitoring program (2012-2022, 6 sites) for a total of 27 sites (Appendix 1, Figure 3). Furthermore, a list of potential drivers of seagrass decline in Cockburn Sound were amalgamated from a literature search conducted by the Project Leads before the Workshop (Appendix 2). The twenty drivers of seagrass decline identified were: low light from epiphytic algal blooms, low light from phytoplankton blooms, low light from resuspended fine sediments, change in light quality, erosion &/or deposition of sediment/burial, physical disturbance from anchoring/mooring, invasive species, increased temperature/heatwaves, storms, increased anoxia in sediments and sulphide intrusion, altered hydrodynamics/reduced flushing, organic carbon increases in the sediment, increased grazing, change in salinity, disease, pollutants and toxins, fishing traps, dredging, poor water quality, and depth.

Seagrass monitoring and other data included in the work pack

Each monitoring program collected shoot density data of the dominant seagrass *Posidonia sinuosa* during the austral summer period (January-February; Table 2). Each site had 6 permanent quadrats (20 x 20 cm) sampled across 4 transects (n=24), except for 3 SIMP sites (Penguin Island, Becher Point SZ, and Point Kennedy) that had 8 quadrats sampled over 3 transects (n=24). For each sampling time, and at each site, the number of shoots were counted in each quadrat, and the relative amount and type of algal epiphyte cover noted. For some periods *P. australis* shoot density was also counted but this was not conducted consistently so no temporal assessments were made. The CSMC monitoring program occurred annually - except for 2021 - and seagrass monitoring within SIMP occurred every 2 years. Site depth varied ranging from 2.0 m to 7.0 m. For detailed methodology refer to *Report No. 2007-10 A survey of selected seagrass meadows in Cockburn Sound, Owen Anchorage and Warnbro Sound: Health and status* (CSMC 2007). Data from these monitoring programs were provided by DBCA and CSMC, and quality checked.

The sample size of shoot density data differed among sites and years; therefore, the following edits were made to the dataset to improve spatial and temporal consistency. For CSMC and SIMP sites, the dataset sample size was reduced to between 24-31 by taking the first 24-31 samples. Any sites that were only sampled once were removed. For each site, a Mann-Kendall trend analysis was conducted to assess changes in *P. sinuosa* shoot density over time. This trend analyses quantified differences between later measured shoot densities with the earlier shoot densities and determined whether values were increasing or decreasing over time. The test determines whether the change is statistically significant but cannot assess the magnitude of change (Kendall, 1970). The maximum time period was from 2003 – 2022, sites had between 8 – 19 monitored years, and these were denoted by points on line graphs. Years of missing data, where no shoot density data was collected, were removed and patterns within the data visualised using the *geom_smooth* condition under a generalised linear model. Average shoot density was plotted over time using the *ggplot* function within the Tidyverse package (version 1.3.2, Wickham et al., 2019) in R Language for Statistical Computing (R; version 4.2.1, R Core Team, 2022).

Epiphyte type was allocated a code number as follows, where increasing categories indicate a higher potential to negatively impact seagrass: Encrusting or Corticated were allocated 1, Filamentous and encrusting or Filamentous and Corticated were allocated 2, and Filamentous was allocated 3. Epiphyte cover was recorded differently across time within and between monitoring program, i.e. sites were either reported as a numerical category [percentage] or as a descriptive term [low, moderate or high]. Therefore, the descriptive terms were placed into numerical categories; low <25%, moderate 25-75% and high >75%. Note though that the algal type and cover data were not consistently recorded across all programs, nor in the annual reports, so those data were inconsistent. The available algal cover time-series data were presented as a heatmap (see example handout sheet, Figure 1).

Daily night-time sea surface temperature was extracted from the NOAA Coral Reef Watch Operational Daily Near-Real-Time Global 5 km Satellite Coral Bleaching Monitoring Products dataset at a 5 km resolution. The temperature data for each seagrass meadow (site) was determined by the proximity of each NOAA 5 km pixel, whereby those closest and not impacted by land were selected. Average summer temperatures were calculated from the daily NOAA sea surface temperature data from the start of December 2002 to the end March 2022. This data was plotted as a heatmap (Figure 1, average summer temperature bar).

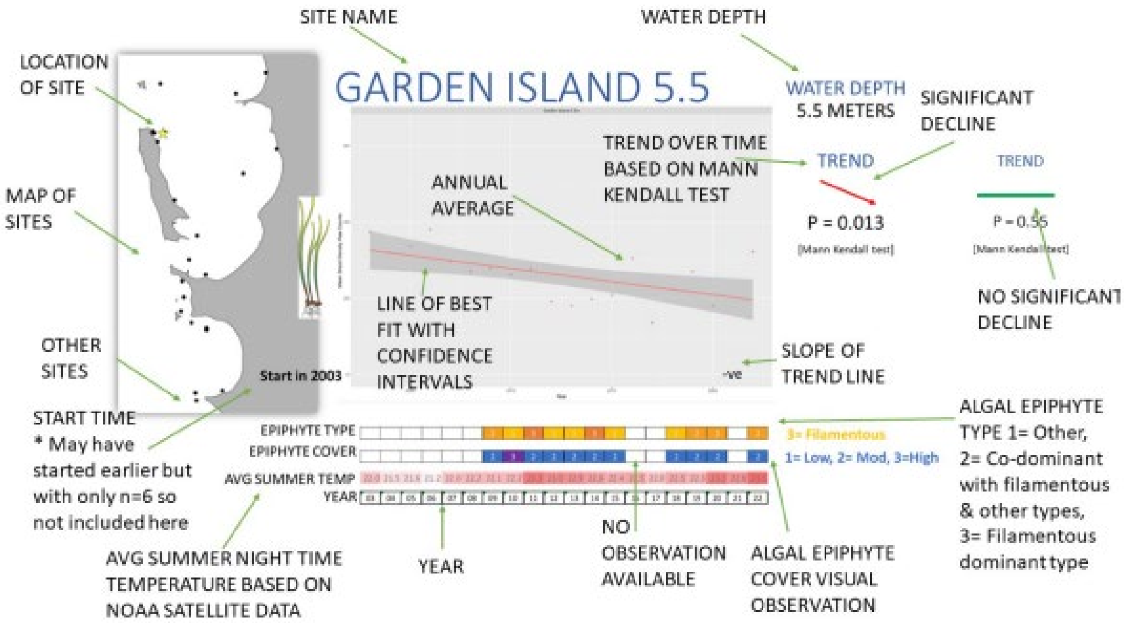

Figure 1: An example handout sheet for seagrass monitoring site Garden Island 5.5. Handout sheets per site were provided at the Workshop to aid in proposing site-specific drivers of decline among participants.

Table 1. Name, organisation, attendance, and post-Workshop consultation of the twenty-nine experts who contributed to the Workshop activities. Yes: confirming in-person Workshop attendance and/or participation in post-Workshop consultation. No: invited experts were unable to attend the Workshop. Blank cells in the consultation post Workshop column represent experts were not consulted.

Name	Organisation	Attended in person	Consultation post Workshop
Adam Gartner	O2 Marine	Yes	
Sarah Scott	BMT	Yes	
Scott Evans	DPIRD	Yes	
Gary Jackson	DPIRD	No	Yes
Peter Mitchell	DPIRD	Yes	
Kieryn Kilminster	DWER	Yes	
Tina Runnion	DWER/ CSMC	Yes	
Paul Lavery	ECU	No	Yes
Glenn Hyndes	ECU	No	Yes
Kathryn McMahon	ECU	Yes	Yes
Simone Strydom	DBCA	Yes	Yes
Natasha Dunham	ECU	No	Yes
Nicole Said	ECU	Yes	Yes
John Whale	ECU	Yes	Yes
Jeremey Fitzpatrick	RPS Consulting	Yes	
Belinda Martin	UWA	Yes	
Matt Hipsey	UWA	Yes	
Matt Fraser	UWA	Yes	
Elizabeth Sinclair	UWA	Yes	
Marion Cambridge	UWA	Yes	
Gary Kendrick	UWA	No	Yes
Giulia Ferretto	UWA	Yes	
Julia Phillips	Water Corporation	Yes	
Hans Kemp	Westport	No	Yes
Paul Erftemeijer	Westport	Yes	
Ray Masini	Westport	No	Yes
Fiona Webster	DWER	Yes	
Rachel Austin	UWA	Yes	
Mike van Kuelen	Murdoch	Yes	

BMT, DBCA (Department of Biodiversity, Conservation and Attractions), DPIRD (Department of Primary Industries & Regional Development), DWER (Department of Water & Environmental Regulation), ECU (Edith Cowan University), UWA (University of Western Australia), WAMSI (Western Australian Marine Science Institution), CSMC (Cockburn Sound Management Council).

Table 2. Spatial (decimal degrees; DD) and temporal summary of the 27 sites over which *P. sinuosa* condition data was collected. Mean summer temperature, minimum (min) and maximum (max) data were calculated from the daily NOAA sea surface temperature data from December 2002 to March 2022 and recorded in degrees Celsius (°C).

Region code	Site code	Latitude (DD)	Longitude (DD)	Data collection years	Mean °C	Min °C	Max °C
CSMC	CAIS	-32.12077	115.69471	2006-2015,2016-2020	20.42	15.94	25.94
SIMP	CSWY	-32.26048	115.70012	2012-2014,2016-2018, 2020	20.39	15.89	25.96
CSMC	COOG	-32.11173	115.76136	2007-2020	20.42	15.94	25.94
CSMC	GRDN_2.0	-32.15816	115.67134	2003-2020	20.43	16.02	25.92
CSMC	GRDN_2.5	-32.15985	115.67160	2003-2020	20.43	16.02	25.92
CSMC	GRDN_3.2	-32.15979	115.67257	2003-2020	20.43	16.02	25.92
CSMC	GRDN_5.5	-32.16018	115.67949	2003-2020	20.43	16.02	25.92
CSMC	GRDN_7.0	-32.15908	115.68062	2003-2020	20.43	16.02	25.92
CSMC	GDNS	-32.21313	115.68872	2005-2011, 2013-2020	20.43	16.02	25.92
CSMC	JERV	-32.17230	115.77004	2005-2020	20.43	16.02	25.92
CSMC	KWIN	-32.19181	115.74355	2005-2020	20.43	16.02	25.92
CSMC	LUBA	-32.16672	115.67521	2005-2020	20.43	16.02	25.92
CSMC	MANG	-32.27244	115.71357	2005-2020	20.39	15.89	25.96
CSMC	MERS	-32.31039	115.70226	2003-2020	20.35	15.78	25.88
CSMC	SOFL	-32.24142	115.70671	2003-2020	20.39	15.89	25.96
CSMC	WOOD	-32.12859	115.73774	2006-2020	20.42	15.94	25.94
SIMP	BEPO	-32.72323	115.70608	2012-2014,2016-2018, 2020	20.32	15.71	25.82
SIMP	Becher SZ	-32.36626	115.70530	2012-2014,2016-2018, 2020	20.32	15.71	25.82
SIMP	BRDI	-32.27733	115.69471	2012-2014,2016-2018, 2020	20.38	15.84	25.93
SIMP	PNGI	-32.30145	115.69378	2012-2014,2016-2018, 2020	20.35	15.78	25.88
SIMP	POKE	-32.36452	115.72680	2012-2014,2016-2018, 2020	20.32	15.71	25.82
SIMP	SEIL	-32.29040	115.69598	2012-2014,2016-2018, 2020	20.38	15.84	25.93
SIMP	WNBR_2.0	-32.31440	115.71409	2012-2014,2016-2018, 2020	20.35	15.78	25.88
SIMP	WNBR_2.5	-32.31476	115.71415	2012-2014,2016-2018, 2020	20.35	15.78	25.88
SIMP	WNBR_3.2	-32.31490	115.71425	2012-2014,2016-2018, 2020	20.35	15.78	25.88
SIMP	WNBR_5.2	-32.31620	115.71393	2012-2014,2016-2018, 2020	20.35	15.78	25.88
SIMP	WNBR_7.0	-32.31639	115.71428	2012-2014,2016-2018, 2020	20.35	15.78	25.88

Summary of seagrass condition in Perth Waters

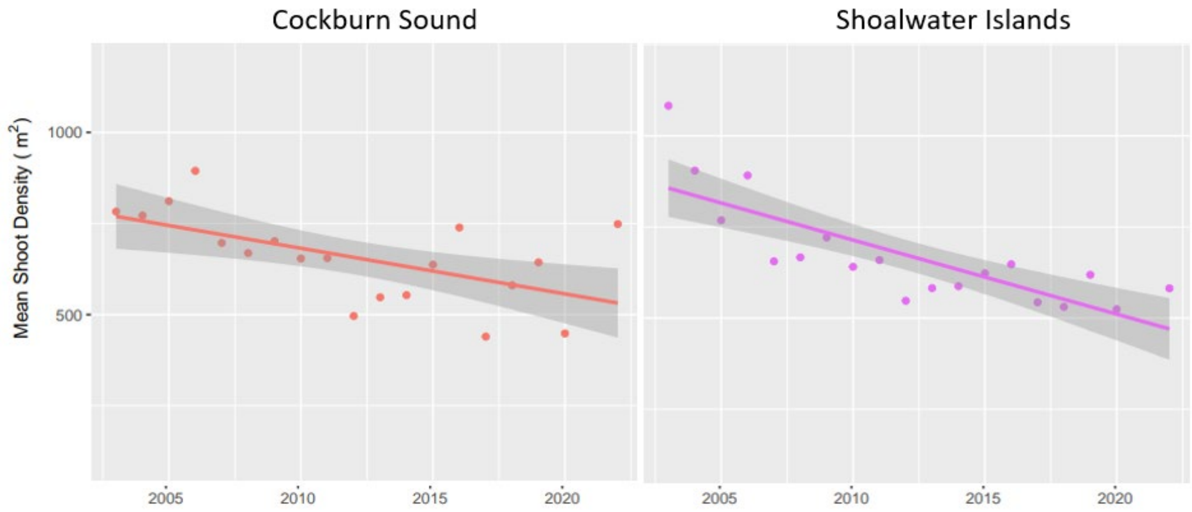

Figure 2: Mean shoot density (m^2) over time for all *Posidonia sinuosa* monitoring sites within Cockburn Sound (CSMC) and Shoalwater Islands Marine Park (SIMP).

Table 3. Results from Mann-Kendall tests for each seagrass site showing slope trend and significance (significant trends, p<0.05 in bold).

Region	Site name	Trend	Significance (p<0.05)	Overall slope	R2	R2 (%)	n=	Year range
SIMP	Becher Point	no trend	0.4	slightly negative	0.1882	19%	9	2012-2022
SIMP	Becher Point SZ	no trend	0.54	slightly negative	0.1027	10%	8	2012-2022
SIMP	Bird Island	no trend	0.32	slightly negative	0.1419	14%	15	2006-2022
SIMP	Mersey Point	no trend	0.62	slightly positive	0.0848	8%	16	2006-2022
SIMP	Penguin Island	no trend	1	slightly positive	0.0199	2%	9	2012-2022
SIMP	Port Kennedy	no trend	0.54	slightly negative	0.0532	5%	8	2012-2022
SIMP	Seal Island	no trend	0.75	slightly negative	0.0026	0%	9	2012-2022
SIMP	Warnbro Sound 2	**significant**	9.35E-06	**negative**	0.8231	82%	18	2003-2020
SIMP	Warnbro Sound 2.5	no trend	0.1	negative	0.1389	14%	18	2003-2020
SIMP	Warnbro Sound 3.2	**significant**	0.0006	**negative**	0.6965	70%	18	2003-2020
SIMP	Warnbro Sound 5.2	no trend	0.53	slightly negative	0.0241	2%	19	2003-2020
SIMP	Warnbro Sound 7	no trend	0.93	positive	0.0915	9%	16	2006-2020
CSMC	Carnac Island	no trend	0.55	slightly negative	0.044	4%	15	2006-2022
CSMC	Coogee	no trend	0.43	negative	0.0883	8%	15	2007-2022
CSMC	Causeway	no trend	1	slightly positive	0.0237	2%	8	2012-2022
CSMC	Garden Island 2.0	no trend	0.82	slightly positive	0.0534	5%	18	2003-2022
CSMC	Garden Island 2.5	no trend	0.44	slightly negative	0.0534	5%	19	2003-2022
CSMC	Garden Island 3.2	no trend	0.16	slightly negative	0.092	9%	19	2003-2022
CSMC	Garden Island 5.5	**significant**	0.007	**negative**	0.398	40%	19	2003-2022
CSMC	Garden Island 7	no trend	0.29	slightly negative	0.0671	7%	19	2003-2022
CSMC	Garden Island Settlement	no trend	0.08	negative	0.1082	11%	16	2005-2022
CSMC	Jervoise Bay	**significant**	1.52E-05	**negative**	0.7963	80%	17	2005-2022
CSMC	Kwinana	no trend	0.9	stable	5.00E-05	0%	17	2005-2022
CSMC	Luscombe Bay	no trend	0.69	slightly positive	0.0162	5%	16	2005-2022
CSMC	Mangles Bay	no trend	0.07	negative	0.1954	19%	17	2005-2022
CSMC	Southern Flats	**significant**	0.04	**negative**	0.2771	28%	19	2003-2022
CSMC	Woodman Point	**significant**	6.15E-05	**negative**	0.7844	78%	16	2006-2022

2.4 Activities at the Workshop

During the Workshop there were two main activities. Firstly, Workshop participants were separated into three groups and each group was allocated a set of sites to assess using the information described above. For each site, the group was asked to identify which drivers from a set provided were associated with decline of seagrass overtime at each site, or if there had been no decline overtime, the drivers associated with seagrass condition at the site. Additional drivers were added if required. Then, participants provided the level of confidence they had in this prediction as Low, Moderate, or High and if there was any site-specific information to support this confidence rating (see blank datasheet in Appendix 2). Data from all sites and groups were then collected and summarised into an excel workbook.

The second activity was also conducted in break-out groups and based on the list of key drivers of decline or condition identified in the first activity, groups were asked to brainstorm and record for each driver, actions that could reduce the severity, frequency or impact of the driver to seagrass or actions that could make seagrass more resilient to the driver. For example, if the driver was physical disturbance from anchoring, the action could be to reduce anchoring in particular areas, or if the driver was warming or heatwaves, the action could be to introduce temperature resilient individuals into the site. At the end of the brainstorming activity, all actions were translated into an excel workbook. The drivers were grouped into similar categories and the actions categorised. See Appendix 5 for a summary of the categories.

2.5 Post-Workshop data analysis

Following the Workshop, information provided by the seven additional participants who did not attend the in-person Workshop were collated into the excel workbook containing drivers of change and confidence by site. Note that drivers that had zero values across all sites were removed (e.g. changes in salinity, depth and disease), thus, 17 final drivers remained for analysis. For each driver across all sites, the count for each site where the driver was identified was tallied to understand which drivers were more commonly associated with seagrass condition. Then, for each site, the count of the number of drivers identified was tallied, as well as the average confidence of these drivers and the total confidence based on the sum of the confidence levels assigned. The average confidence was converted to a level of High, Medium, or Low confidence based on 50th, 75th and 90th percentiles. Then, all sites were plotted on a map categorised by confidence level and condition based on previous Mann-Kendall tests and coloured as "decline" or "stable" (Table 4). Using the heatmap function in R, the eight declining sites were mapped against 12 potential drivers of decline (Figure 3). Data wrangling was performed using Tidyverse packages, site maps using rgdal (version 1.62, Bivand et al 2022), raster (version 3.6), sp (version 1.5, Pebesma et al 2013) and ggsn (version 0.5, Baquero 2019) in R.

3 Spatial variation and confidence in drivers of decline

3.1 Patterns in seagrass decline

After examining the long-term condition of *P. sinuosa,* based on shoot density in Cockburn Sound (CSMC), Warnbro Sound and Shoalwater Islands Marine Park (SIMP) from all monitored sites, it was evident that there was a global decline in seagrass condition over the 19 years of data analysed (Figure 2) but with high variability among sites. Assessing each site independently, decline was not restricted to Cockburn Sound but occurred in all regions (e.g. Warnbro Sound, Cockburn Sound, Owen Anchorage). Only one site had a significant positive trend in shoot density (Warnbro Sound 7.0; the deepest site) and one site was stable (Kwinana). There were 6 sites that had a significant ($p<0.05$) negative trend: Warnbro Sound 2.0, Warnbro Sound 3.2, Garden Island 5.5, Jervoise Bay, Southern Flats and Woodman Point and two others with a negative trend that was not significant at $p<0.05$ but was at $p<0.09$, Mangles Bay and Garden Island Settlement (Table 3, Figure 3). The magnitude of the decline varied with the Warnbro Sound sites as well as Jervoise Bay and Mangles Bay declining to near zero. Notably, the sites with a declining tended to be shallower, with 7 of the 8 sites in ≤3 m water depth. There did not appear to be any correlation with algal cover or type as the sites that declined did not have more algal cover or filamentous types, although this data was not collected consistently over time.

3.2 Drivers of decline

Seventeen drivers were identified as linked to seagrass condition across the 27 sites assessed (Table 4). Only three drivers were rated with high confidence, erosion or deposition of sediment (at 4 sites), physical disturbance from anchoring (at 1 site) and sand mining and plumes (at 1 site). An additional 8 drivers were rated with moderate confidence (Table 4), and of these, increased temperature (at 6 sites), storms (at 6 sites) and altered hydrodynamics (at 4 sites) were most commonly cited. Then, there were another 5 drivers which were only rated with low confidence (Table 4). When summing the confidence across all sites, the 7 most common drivers identified as impacting seagrass condition, from most to least common were: storms, pollutants and toxicants, increased temperature, erosion and/or sediment deposition, altered hydrodynamics, physical disturbance from anchoring and low light (Table 4, see brown, orange and beige colours).

Table 4: Confidence matrix illustrating drivers of decline for each site across the Perth coastal waters. The 7 most common drivers of decline across multiple sites are highlighted in brown, orange and beige. Confidence allocation in the drivers impacting the site were based on the site average confidence.

SITES	Low light from epiphytic algal blooms	Low light from phytoplankton blooms	Low light from resuspended fine sediments	Change in light quality	Erosion &/or deposition of sediment / Burial	Physical disturbance from anchoring	Invasive Species	Increased temperature/ heat waves	Storms	Increased anoxia in sediments & sulfide intrusion	Altered hydrodynamics/ reduced flushing	Organic carbon increases in sediment	Increased grazing	Pollutants & Toxins	Fishing traps	Sand mining / plumes	Poor Water Quality	Count of drivers	Site average confdence for drivers >0	Confidence Allocation
Warnbro Sound 2.0	0	0	0	0	3	0	0	0	2	0	2	0	0	0	0	0	0	3	2.33	High
Woodman Point	0	0	2	1	3	0	0	2	2	0	0	0	0	0	2	3	2	8	2.13	High
Warnbro Sound 3.2	0	0	0	0	3	0	0	0	2	0	2	1	0	0	0	0	0	4	2	High
Mangles Bay	2	1	0	0	0	3	0	1	0	2	2	2	0	1	0	0	0	8	1.75	High
Jervoise Bay	0	0	0	0	3	0	0	1	0	0	2	0	0	1	0	0	1	5	1.6	High
Warnbro Sound 2.5	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	2	1.5	High
Garden Is. 3.2	1	0	0	0	0	1	0	2	2	0	0	0	1	1	0	0	0	6	1.33	Medium
Garden Is. 2.0	1	0	1	0	0	1	0	2	2	0	0	0	1	1	0	0	0	7	1.29	Medium
Garden Is. 2.5	1	0	1	0	0	1	0	2	2	0	0	0	1	1	0	0	0	7	1.29	Medium
Garden Island 7.0	1	0	0	0	0	1	0	2	1	0	0	0	1	1	0	0	0	6	1.17	Medium
Garden Is. 5.5	0	0	1	0	0	1	1	2	1	0	0	1	1	1	0	0	0	8	1.13	Medium
Garden Is. Settlement	1	0	0	0	1	1	0	1	1	2	1	0	0	1	0	0	0	8	1.13	Medium
Causeway	0	0	0	0	0	1	0	0	0	1	1	1	0	1	0	0	0	5	1	Low
Coogee	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	2	1	Low
Carnac Is.	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	2	1	Low
Kwinana	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	1	Low
Southern Flats	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2	1	Low
Luscombe Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	Low
Mersey Point	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	Low
Becher Point SZ	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	Low
Becher Point	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	Low
Bird Is.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
Seal Is.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
Penguin Is.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
Warnbro Sound 5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
Warnbro Sound 7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
Port Kennedy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	None
TOTAL	7	1	4	1	8	8	1	9	15	3	8	4	5	12	1	1	2			

3.3 Evidence for drivers of decline

During the Workshop, participants were asked to provide evidence to justify drivers of decline across individual sites. Most participants relied upon their experience working in the area, some mentioned grey literature (i.e., unpublished reports), while others referred to peer-reviewed scientific publications to link shoot density declines with specific drivers. For example, experts suggested that shoot density decline at the Garden Island Settlement site could be impacted by sediment stressors attributed to high sulphur concentrations (Fraser & Kendrick 2017). Similarly, for Woodman Point where sand mining operations leads to periods of low light availability, which subsequently makes meadows more vulnerable to sulphide intrusion. Indeed, sulphide intrusion measured in *P. sinuosa* leaves was identified as an indicator of stress associated with high environmental pressure (i.e. multiple drivers of decline; Holmer and Kendrick 2013).

Periods of seawater warming were also proposed as drivers of decline across multiple sites. For example, in 2011 Cockburn Sound experienced seawater temperature anomalies of 3–4◦C above the 2002-2010 mean which persisted for > 8 weeks (Rose and Botting 2011). The associated low dissolved oxygen levels in March 2011 were most likely a consequence of increased stratification (i.e. minimal surface mixing), together with increased biological activity during the warming period (Rose et al., 2012). There were also reports of high invertebrate mortality (e.g. *Archaster angulatus*) and it was supposed that algal blooms were likely associated with these exceedingly warm conditions (Rose et al., 2012). Elsewhere along the WA coast, high levels of fish and invertebrate mortalities, coral bleaching and extensive algal blooms were attributed to the same 2011 warming event (Pearce et al., 2011; Wernberg et al., 2012). Seawater temperature has been recognised as a significant pressure on seagrass in the Cockburn Sound and Owen Anchorage region - often alongside pressures from reduced light, turbidity and phytoplankton blooms - at sites including Woodman Point and Mangles Bay (Table 21 in Mohring & Rule 2013). This was captured in the Workshop where these multiple drivers were indicated as causes of decline with a high level of confidence (Table 4 above). Some drivers of decline that were identified were not necessarily accompanied by supporting documentation but have been established from observations of the participants and a review of historical and contemporary satellite imagery such as Mangles Bay being impacted by anchoring due to the concentrated boating activity in the area.

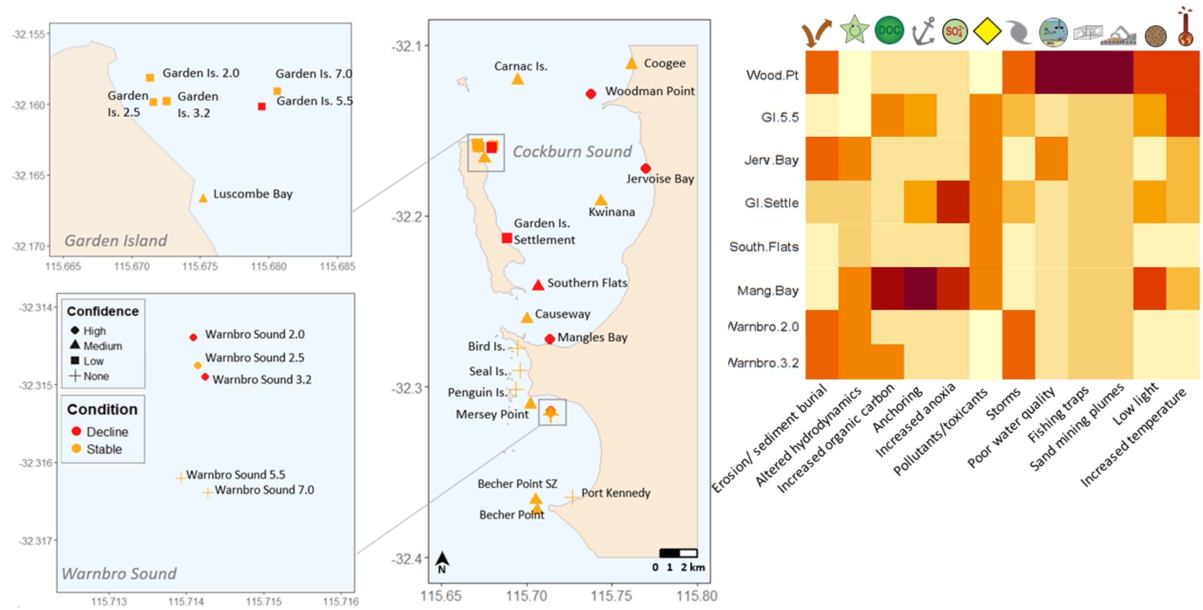

Figure 3: A summary of confidence in drivers of decline based on expert opinion for explaining the decline or condition of seagrass in the CSMC and SIMP monitoring data. The left map indicates which sites were stable (orange) or declining (red) and the associated confidence (none, low, medium and high). The heatmap matrix on the right displays the potential drivers of poor condition for the 8 declining sites.

3.4 Spatial variation in drivers of decline

Confidence in the drivers identified varied, with were no clear spatial patterns in the identified drivers. For example, confidence varied from, Low at Garden Island 5.5 m, to Medium at Southern Flats and High at Woodman Point, Jervoise Bay, Mangles Bay and Warnbro Sound 2.0 and 3.2 m (Figure 3, left). This suggests that there is not one location where decline is occurring and not one specific area where the confidence in the driver of decline is higher, therefore, to actively improve conditions a site-specific approach is required. Such a localised approach could be more directed at sites where the confidence in the driver is higher. For the sites that did not show a decline, but were stable over time, there were no individual drivers influencing condition with high confidence. However, there were some influencing conditions identified with moderate confidence, such as heatwaves and storms at some Garden Island sites, as well as altered hydrodynamics at Warnbro Sound 2.5 m.

3.5 Occurrence of multiple drivers

Generally, there were 3-7 potential drivers identified to explain the decline, based on expert opinion. The highest number of drivers occurred at Woodman Point, Mangles Bay, Garden Island 5.5 m and Garden Island Settlement (count of drivers column, Table 4). For the 8 sites that declined over time, there were multiple drivers of decline, and the suite of drivers varied amongst sites (Figure 3). For example, at the Woodman Point site, which is in close proximity to the long-term shell-sand dredging works (by Cockburn Cement Ltd), the drivers of decline with the greatest confidence were sand mining plumes, disturbance from fish traps and poor water quality; whereas at Mangles Bay the drivers of decline with the greatest confidence were anoxia, increased organic carbon in the sediments and disturbance from anchoring. The multiple drivers, which vary by site, indicate there is not one solution to improve conditions and halt seagrass decline across all sites and therefore multiple actions specific to locations should be implemented.

4 Actions for halting decline and building resilience

4.1 Types of actions identified

The broad drivers that were considered to develop actions for included the following:

- dredging,
- shipping and recreational boating,
- fishing,
- coastal infrastructure,
- pollution,
- biological interactions (including grazing by echinoderms)
- climate change (particularly ocean warming and heatwaves).

Some of these broad drivers were considered in a more granular way to provide focus for identifying actions. For example, dredging was considered from a sand mining and processing perspective, as well as new port development, channel construction and on-going maintenance (Appendix 3). Seventy-five unique actions were identified in the brain-storming activity to address potential drivers of change or improve conditions for seagrass (Appendix 5A-5H). These actions were categorised after the Workshop based on broad themes, which included management, nature-based solutions, technology, engineering, as well as knowledge and education (Appendix 4). Within most themes there were sub-themes, for example, management consisted of policy, regulation and enforcement; best practise guidelines; modify processes or timing to minimise impact; and monitor. Nature-based solutions included restoration and/or rehabilitation; climate proofing and nature-positive actions, engineering included engineering solutions; infrastructure or design to minimise impact and nature-positive infrastructure or actions, and knowledge and education included improve understanding to inform decisions; new studies; and education (Appendix 4).

4.2 Prioritising actions

All the actions identified in this report were the result of a brain-storming activity within the Workshop. Participants were asked to think outside of the box and consider new innovative actions. Therefore, before any of these actions are considered a rigorous feasibility assessment, including a cost-benefit and risk analysis, should be conducted.

A range of management actions linked to policy, regulation and enforcement were identified for dredging, shipping, recreational boating and fishing (Figure 4a, Appendix 5). Actions to manage anchoring, wake disturbance from large ships and regulated fishing zones were identified as important. Development of best practise guidelines for these drivers such as shipping speed restrictions, an anchoring code of conduct, and development of a guideline for fish trap deployment and retrieval were suggested. In addition, best practise guidelines for the design of coastal infrastructure and pollution reduction were also identified (Figure 4a). Management of activities through selecting specific periods to carry out activities (e.g. dredging) and stopping or reducing some activities (e.g. fishing) were also identified, with ongoing monitoring also considered important for assessing seagrass condition as well as shipping channel depths to understand the potential for sediment resuspension and wake disturbance from shipping movement on seagrass. It was suggested that actions to reduce pollution pressures would be valuable for building seagrass resilience (Figure 4a).

Nature-based solutions were identified across most drivers except for fishing (Figure 4a, Appendix 5). Restoration and rehabilitation were identified as actions relevant to consider in relation to the pressures from dredging and boating (e.g. mooring or anchor scars), increasing sediment stability and to include in the development of coastal infrastructure. Furthermore, the selection of resilient seagrass species or co-planting of different species for rehabilitation efforts could be part of the decisions around these actions. Climate-proofing was considered highly relevant for addressing climate change and although not directly relevant to climate, understanding species or populations more tolerant of low light is also of benefit. A range of additional nature-positive actions were identified such as planting seagrass in channels to reduce sediment resuspension, designing coastal infrastructure to promote ecosystem functions, using biofilters such as oyster reefs or seaweed farms to reduce nutrient pollution and developing an urchin industry that may reduce top-down grazing pressure on seagrass (Figure 4a).

Engineering actions were identified across all drivers, particularly for dredging, shipping and boating, coastal infrastructure and pollution (Figure 4b, Appendix 5). These engineering actions were considered to minimise the impacts of activities such as dredging (e.g. silk curtains), boating and shipping (e.g. booms to reduce wake, seagrass friendly moorings) or for coastal infrastructure to address changes in water flow and sediment movement and generate positive outcomes from existing infrastructure or activities (e.g. re-use of dredged sediment or enhancing water flow for exchange and temperature regulation (Figure 4b, Appendix 5).

A range of actions were identified that align with knowledge and education across most drivers, with the exception of fishing (Figure 4b, Appendix 5). Most of the actions to improve the understanding of managing drivers, incorporated a combination of field measurements and modelling (e.g. modelling plumes, sediment resuspension and movement and pollution; scenario testing; and habitat vulnerability or suitability assessment). New studies were recommended to assess the cumulative impacts of sand mining (i.e. associated multiple stressors include low light and sedimentation) on seagrass condition, as well as how future conditions will impact the condition and functioning of seagrass systems (e.g. climate change and changing ecological thresholds). Finally, education activities were recommended for improving community understanding and practises in relation to anchoring damage (Figure 4b, Appendix 5).

			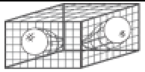	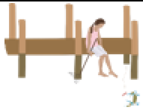	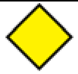	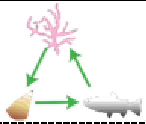	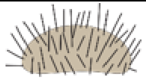	
	Dredging & sand mining	**Shipping & Boating**	**Fishing**	**Coastal infrastructure**	**Pollution**	**Biotic Interactions**	**Grazing**	**Climate change**
Management								
Regulate	Sand mining	Wake disturbance & Anchoring	Exclusion zones & licence number					
Policy		Anchoring						
Enforcement			Police zones & activities					
Best practise	Dredging & Sand mining	Shipping code of conduct & anchoring	Fish trap deployment & retrieval	Design	Pollution reduction			
Minimise impact					Manage pressures to build resilience			
Timing	Environmental windows		Seasonal management					
Monitor	Seagrass condition	Channel depth						
Nature-based solutions								
Restore / Rehabilitate	Impacted areas or as part of EIA	In anchor /mooring scars		Increase sediment stability or add sediments		Species selection, co-planting, increase density		
Climate proofing	Low-light tolerant species/individual							Priming or thermal tolerant species/individual
Nature-positive		Plant seagrass in channels		Design to promote ecosystem functions	Biofiltration & Bioturbation		Urchin industry	

Figure 4a: Summary of key actions categorised by action type (management and nature-based solutions) and linked to particular drivers of seagrass condition. See detailed actions in Appendix 5.

	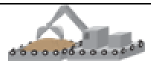		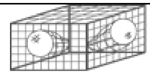	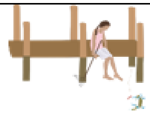	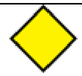	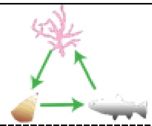	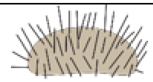	
Technology							Urchin fishery	
Engineering actions								
Solutions	Diffusers or silk curtains	Booms to reduce wake		Active sediment delivery, remove physical structures		Design to promote natural systems		Pump cool water into Cockburn Sound
Design to minimise impact		Turning basins to reduce wake	Design gear	Pumps to circulate water, designs consider bathymetry, design with modelling	Desing to enhance environmental conditions			
Nature-positive infrastructure		Seagrass friendly moorings			Increase water exchange through porosity			
Nature-positive actions	Sediment capping with dredged sediment			Desalination water extraction to increase flow	Remove fine sediments with dredging & add iron to bind sulfides			
Knowledge & Education								
Improve understanding	Measure & model plume	Measure & model sediment resuspension		Model scenarios for mitigation	Model and manage pollutants			Habitat vulnerability analysis
New studies	Sand mining cumulative impacts					Historical state, seagrass species interactions, tropicalisation, ecosystem functions, thresholds, desired states	Urchin population management & impact to seagrass	
Education		Anchoring						

Figure 4b: Summary of key actions categorised by action type (Industry, Engineering and Knowledge and Education) and linked to particular drivers of seagrass condition. See Appendix 5 for more detail.

5 Conclusion

The information for this report was gathered from a Workshop with experts from the consulting, government and research sectors, including individuals with up to 50 years' experience in Perth coastal waters. The Workshop identified drivers of seagrass decline based on long-term monitoring data and generated ideas for potential actions to halt the decline in seagrass condition and increase resilience in existing seagrass meadows. Trends in seagrass condition from long-term seagrass monitoring programs in Cockburn and Warnbro Sound, Shoalwater Bay and Owen Anchorage (27 sites from 2003-2020) were collated to help inform the Workshop activities. The outcomes were informed based on this data as well as the participants knowledge and expertise.

Although it was determined that there is a general decline in seagrass condition within the 27 monitoring sites over the monitoring period (2003-2022), only 6 had significant declines, with an additional 2 sites showing a downward trend, though not statistically significant. The sites that demonstrated declines were both within and outside of the highly industrialised areas of Cockburn Sound and included Warnbro Sound 2.0m and 3.2m, Mangles Bay, Southern Flats, Garden Island Settlement, Jervoise Bay, Garden Island 5.5m and Woodman Point. The drivers attributed to the decline across these sites were not consistent. This highlights that there is not likely to be a singular approach to halt declines and improve the condition of seagrass in this region and therefore actions should consider the local context, specific conditions at sites and specific drivers. A broader regional analysis of drivers in seagrass condition over time also identified the importance of the local context for managing seagrass condition (Webster et al. 2024). Importantly, this work emphasises the value of long-term monitoring programs consistently collecting seagrass condition data to inform appropriate management decisions and evaluate ecosystem status.

The confidence of experts in the determining the drivers impacting seagrass condition varied. The drivers of decline that reflected the highest confidence were erosion and sediment burial at shallow sites, anchor damage at Mangles Bay and sediment plumes from sand mining operations at Woodman Point. Other drivers of decline or poor seagrass condition that were commonly cited but reflected lower confidence from the experts, included increased temperature, storms and altered hydrodynamics. This assessment highlights that there is a need to improve the understanding of the key drivers impacting seagrass condition in this region. For example, outputs from the WAMSI Westport Science Program have identified increased warming and marine heatwaves as a likely future driver of further seagrass decline (Webster et al. 2024), especially in this region, with some species more at risk (Said et al. 2024). There are some drivers that can be directly managed such as anchor damage or sediment plumes from sand mining; however, other drivers such as increased temperatures and storm activity resulting in erosion and burial, are more challenging to directly manage and require broader resilience building considerations, that could buffer these meadows against these stressors.

Seventy-five different actions linked to the specific drivers that could be implemented to improve seagrass condition and/or build resilience in seagrass ecosystems within Perth Coastal waters as well as applied more widely were identified. These included a range of innovative and untested actions, as well as more established actions. The actions were categorised into the themes of management, nature-based solutions, engineering solutions, industry, knowledge and education. This study has highlighted the breadth of local knowledge within the Perth coastal area that can be leveraged to support such research and determine appropriate solutions to reduce impacts on, and build resilience for seagrass communities within Cockburn Sound.

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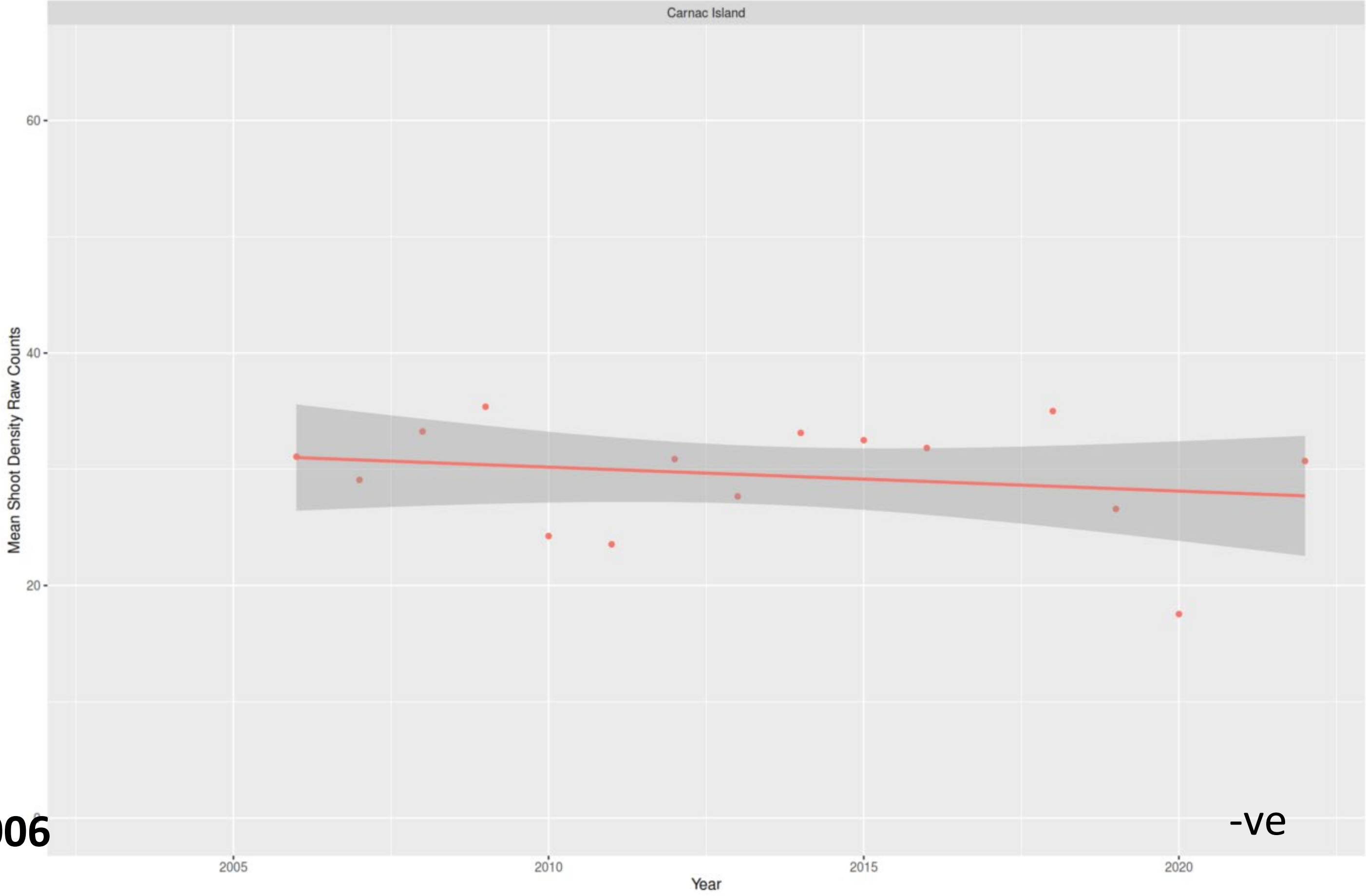
7 Appendices

7.1 Appendix 1

The figures and site descriptions display trends in *Posidonia sinuosa* seagrass condition by site presented in order of sites from north to south orientation. Each figure includes a map with the site location indicated with a yellow star, water depth, mean annual raw shoot density counts with line of best fit and confidence intervals, slope of trend, overall trend over time based on Mann Kendall test, algal epiphyte coverage and type, and mean nighttime summer sea surface temperature per year (where data is available) from 2003 to 2022. Algal epiphyte type was coded 1 (other), 2 (co-dominant with filamentous and other types), or 3 (filamentous dominant). Algal epiphyte cover was coded 1 (low), 2 (moderate), or 3 (high). Average night-time sea surface temperatures are in degrees Celsius (°C) and downloaded from NOAA at a 5 km pixel resolution.

This Appendix contains data for sites Carnac Island, Coogee, Woodman Point, Garden Island 2.0, Garden Island 2.5, Garden Island 3.2, Garden Island 5.5, Garden Island 7.0, Luscombe Bay, Jervoise Bay, Kwinana, Garden Island Settlement, Southern Flats, Causeway, Mangles Bay, Bird Island, Seal Island, Penguin Island, Mersey Point, Warnbro Sound 2.0, Warnbro Sound 2.5, Warnbro Sound 3.2, Warnbro Sound 5.2, Warnbro Sound 7.0, Port Kennedy, Becher Point SZ, and Becher Point. Note: numbers in site name denotes meadow depth.

CARNAC ISLAND



Start in 2006

-ve

WATER DEPTH

4 Meters

TREND

P = 0.55

[Mann Kendall test]

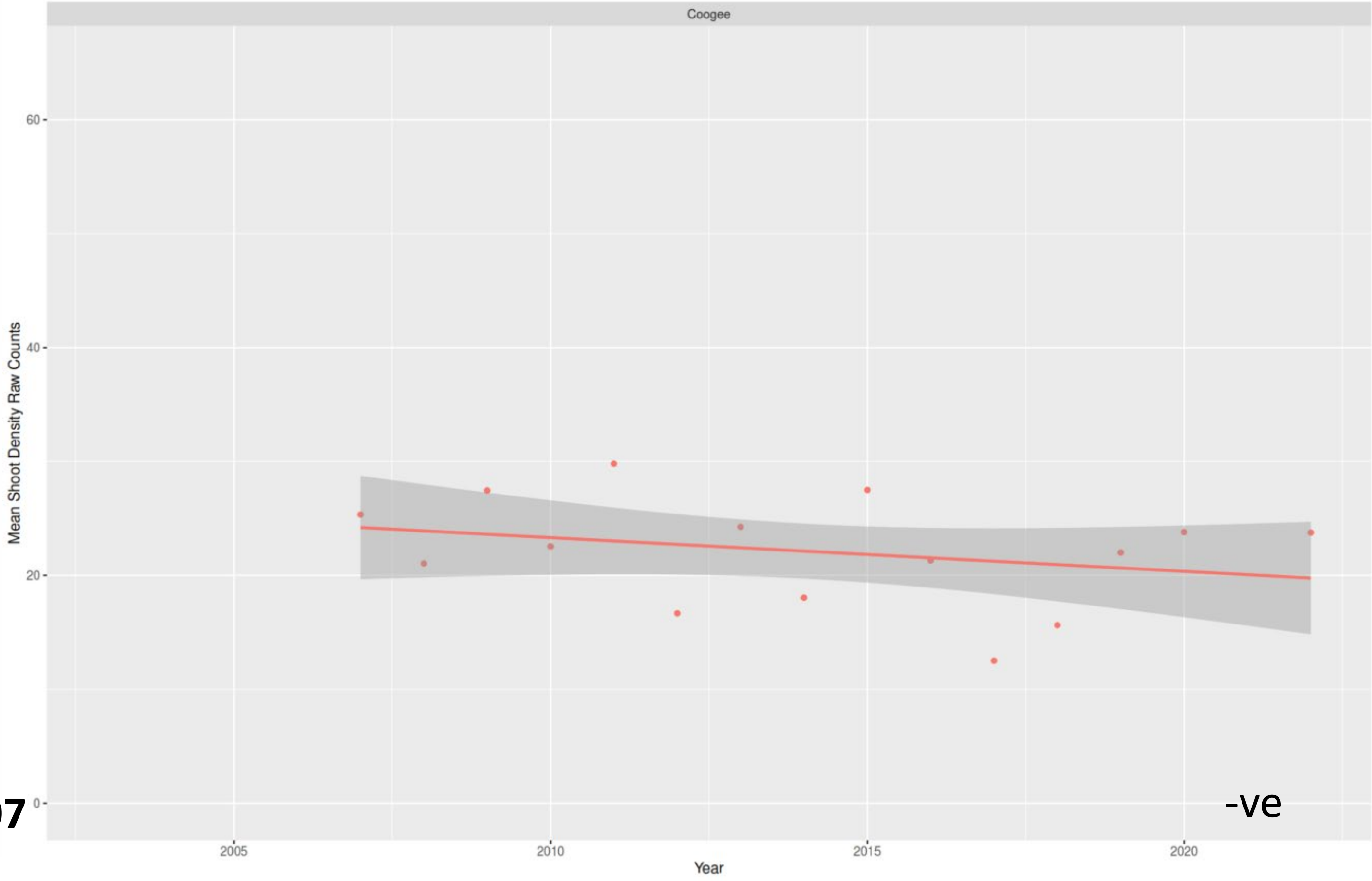
EPIPHYTE TYPE	1	1	1	1	1	1	1	1	1	1	1	1					2	1		1
EPIPHYTE COVER	1	1					1	2	2	2	1	1					2	1		2
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

COOGEE

Start in 2007



-ve

WATER DEPTH
5 Meters

TREND

P = 0.55

[Mann Kendall test]

EPIPHYTE TYPE							3	3	1	1	1	1	1			1	1	2		2
EPIPHYTE COVER							2	3	2	2	2	2	2			2	2	2		2
AVG SUMMER TEMP	22.0	21.5	21.5	21.2	21.9	22.1	22.1	22.1	23.2	22.9	22.8	22.5	22.3	22.4	21.9	22.3	22.0	23.0	22.7	23.3
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

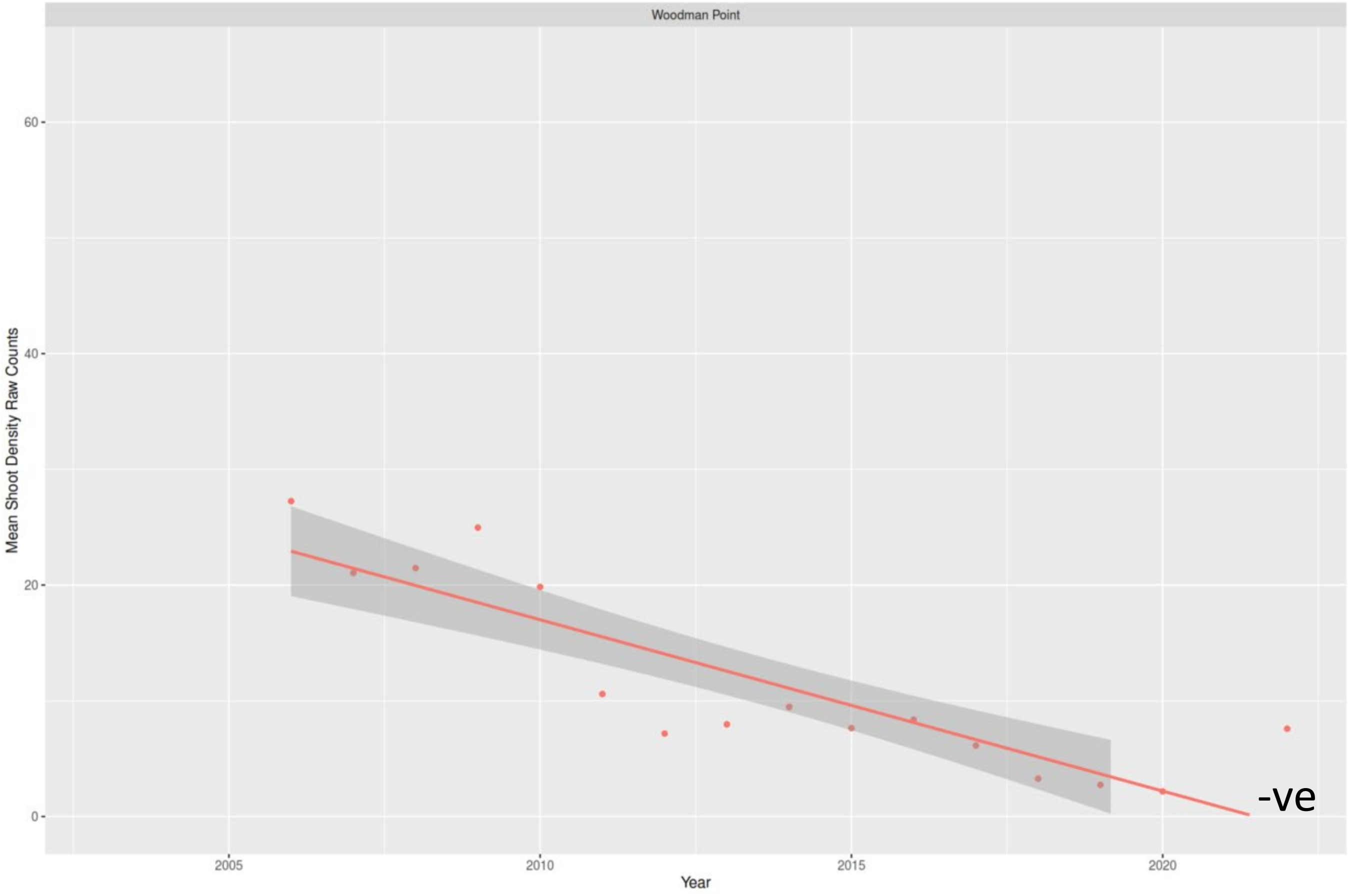
WOODMAN POINT

WATER DEPTH
3 METERS

TREND

P = 0.0002

[Mann Kendall test]

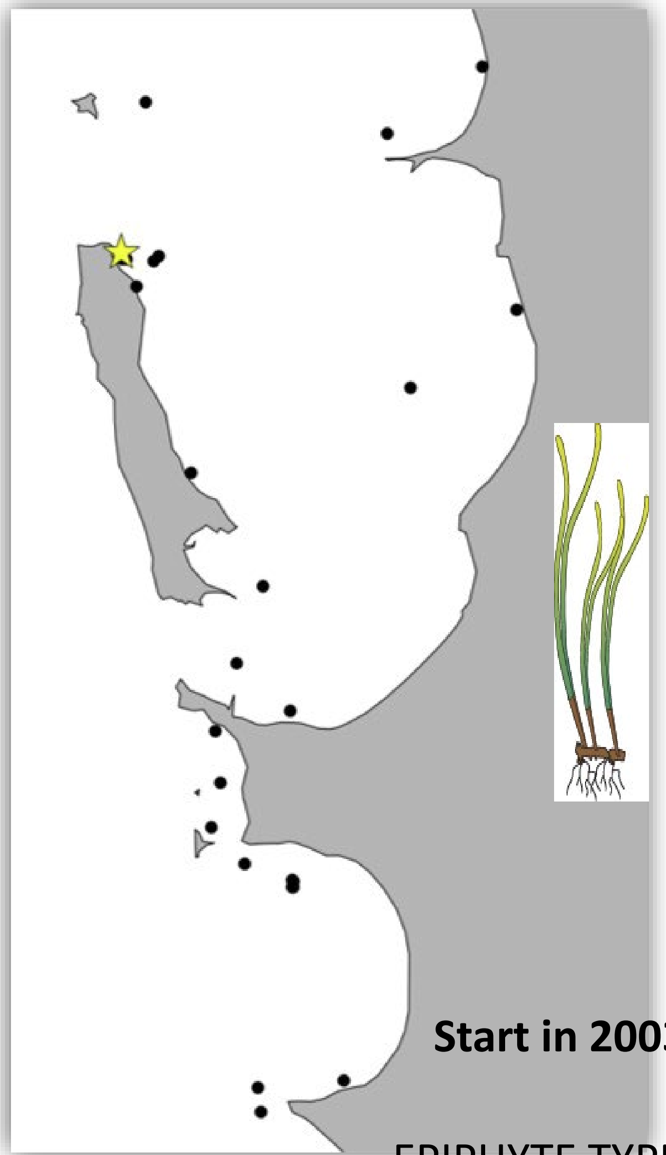


Start in 2006

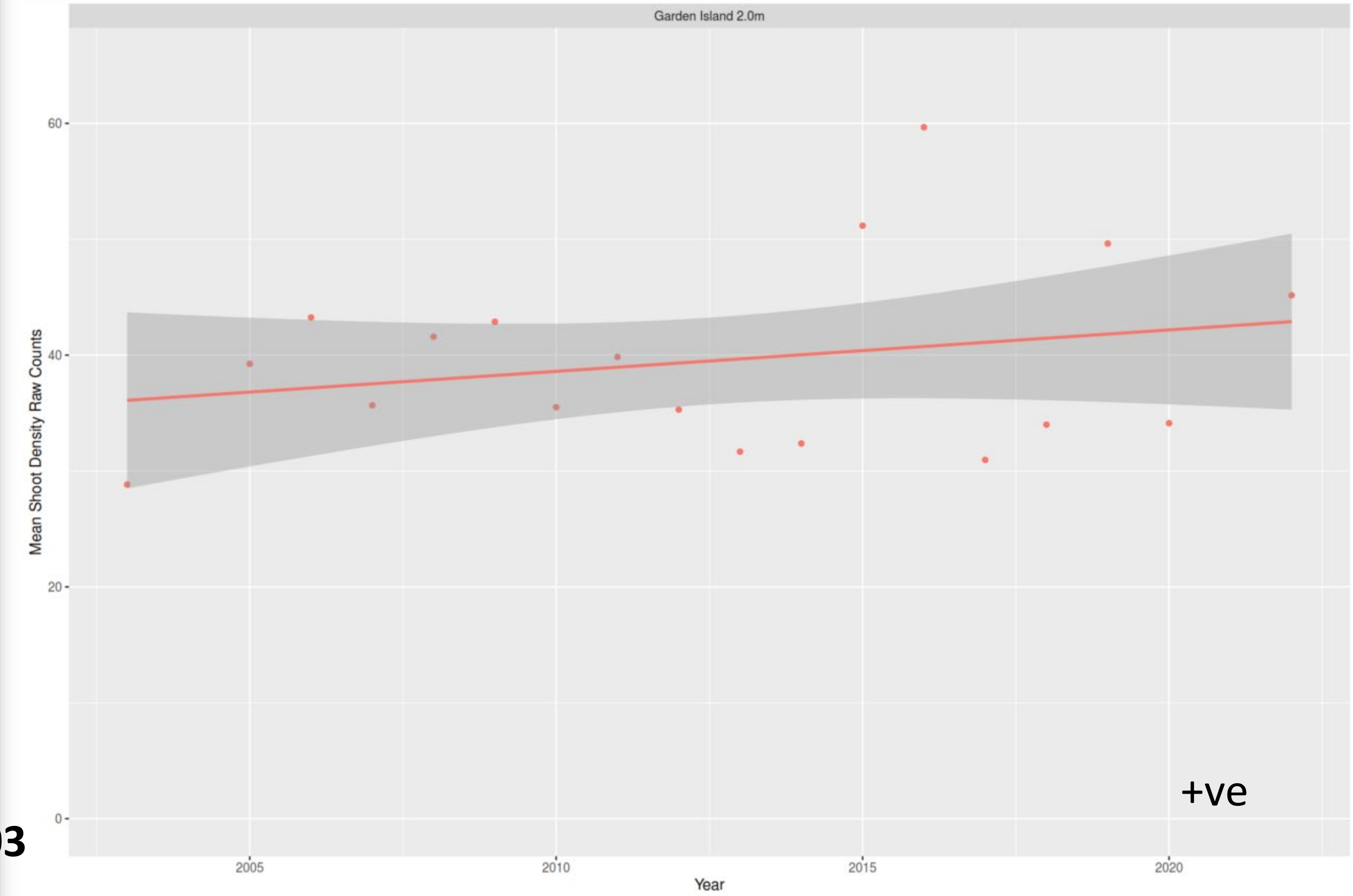
EPIPHYTE TYPE	3	3	1	3	2	2	2	2	1	1										
EPIPHYTE COVER	2	2	2	3	3	3	2	3	2	3										
AVG SUMMER TEMP	22.0	21.5	21.5	21.2	21.9	22.1	22.1	22.1	23.2	22.9	22.8	22.5	22.3	22.4	21.9	22.3	22.0	23.0	22.7	23.3
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High



GARDEN ISLAND 2.0



WATER DEPTH
2 Meters

TREND

P = 0.82

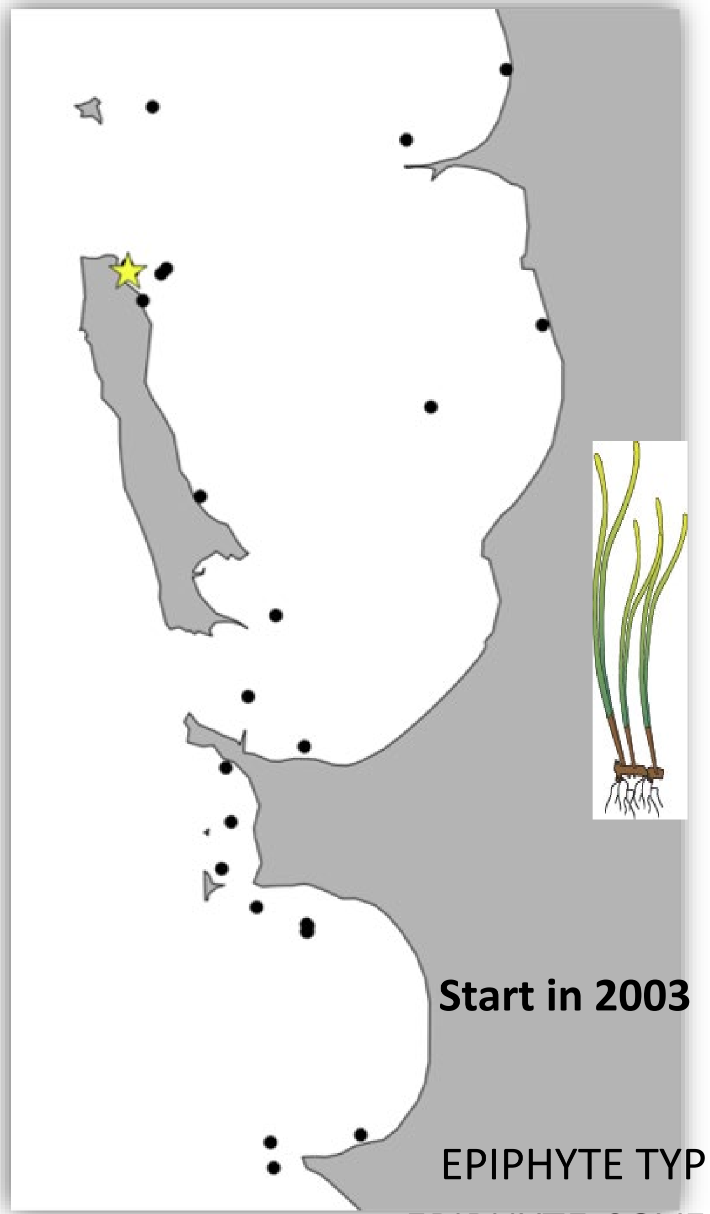
[Mann Kendall test]

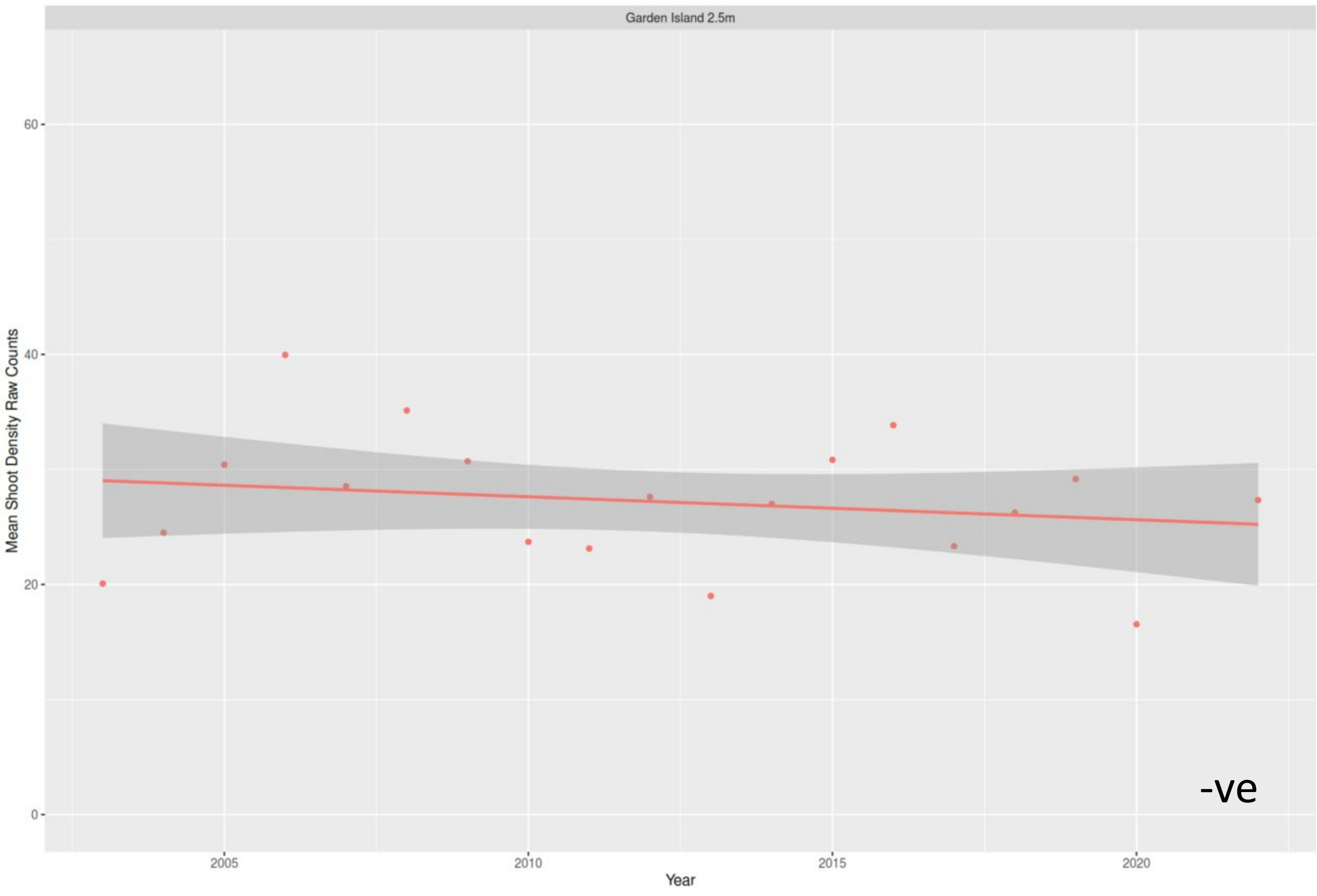
EPIPHYTE TYPE							2	1	1	1	1	1	1			1	1	2		2
EPIPHYTE COVER							2	3	2	2	2	2	2			2	1	2		2
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

GARDEN ISLAND 2.5





WATER DEPTH
2.5 Meters

TREND

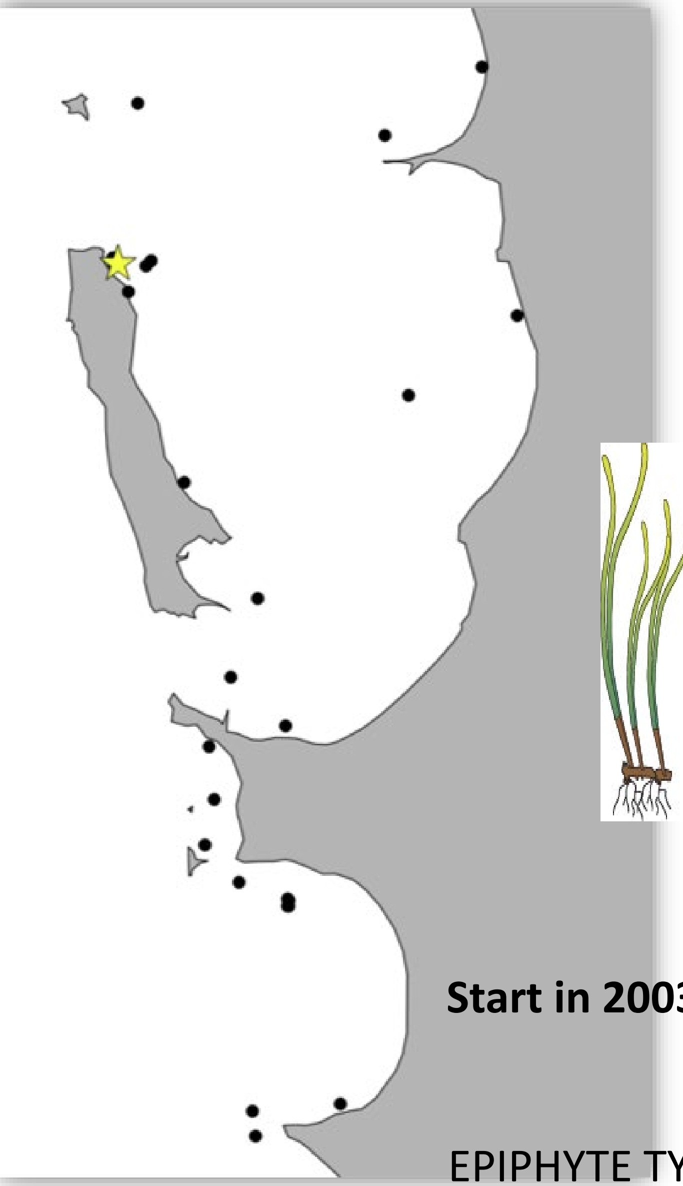
P = 0.53

[Mann Kendall test]

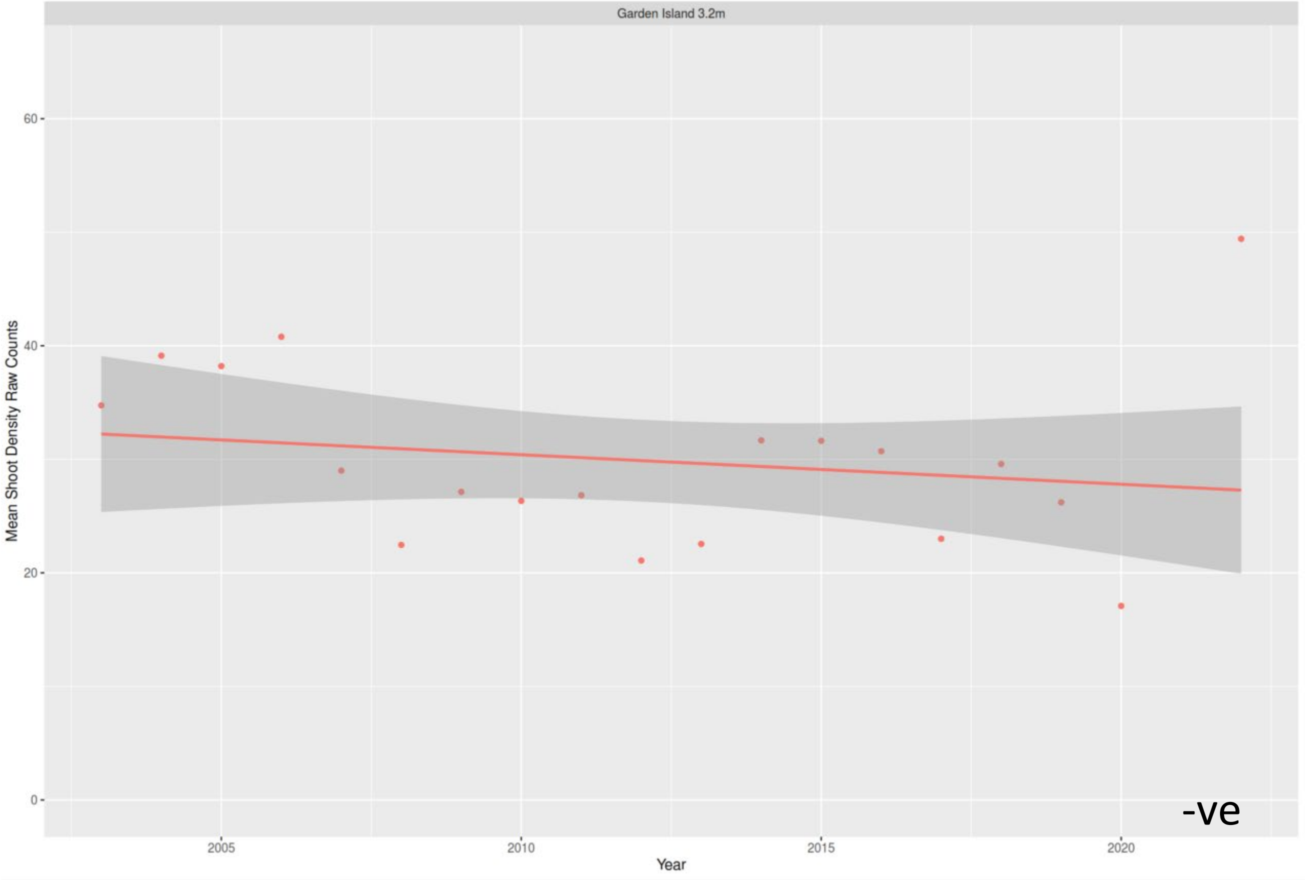
EPIPHYTE TYPE							1	1	2	1	1		1			1	1	1		1
EPIPHYTE COVER							1	2	2	2	1		2			2	1	2		3
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High



GARDEN ISLAND 3.2



WATER DEPTH
3.2 METERS

TREND

P = 0.16

[Mann Kendall test]

Start in 2003

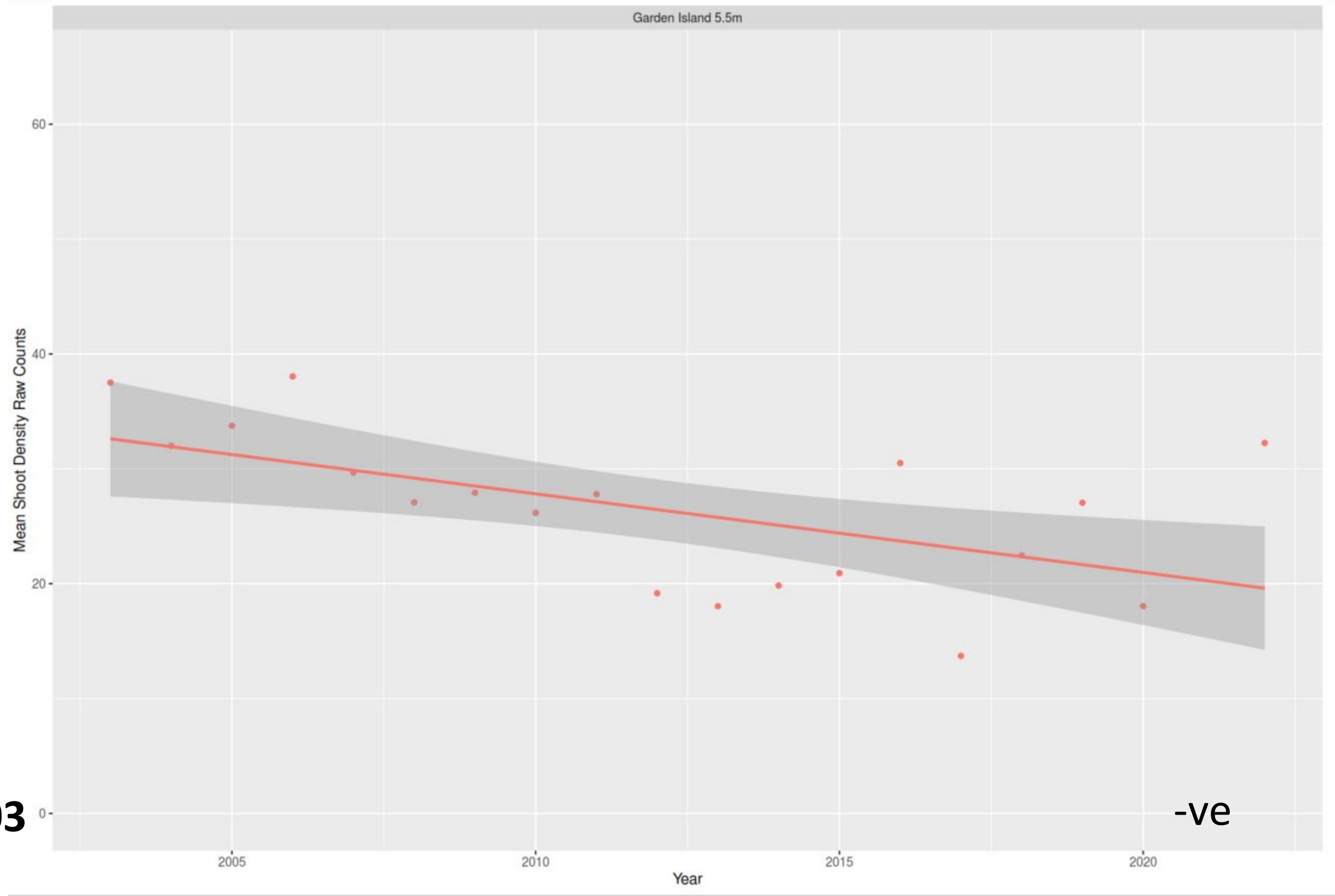
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE							1	1	3	1	2	1	3			3	1	1		2
EPIPHYTE COVER							1	1	2	2	2	2	2			2	1	2		1
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5

3= Filamentous

1= Low, 2= Mod, 3=High

GARDEN ISLAND 5.5

Start in 2003



WATER DEPTH
5.5 METERS

TREND

P = 0.013

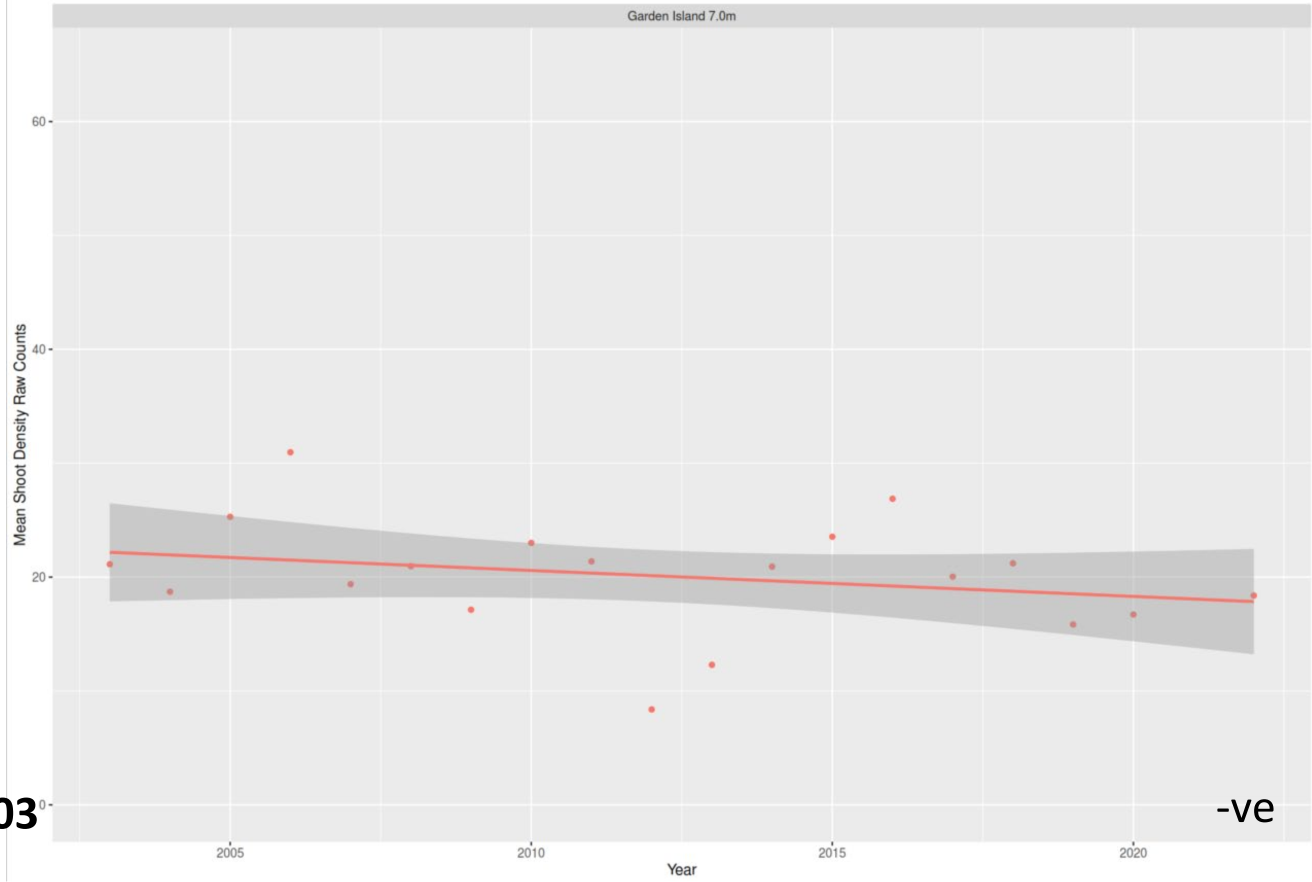
[Mann Kendall test]

YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE							2	1	3	1	1	3	1			1	2	2		2
EPIPHYTE COVER							2	3	2	2	2	2	2			2	2	2		2
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5

3= Filamentous

1= Low, 2= Mod, 3=High

GARDEN ISLAND 7.0



Start in 2003

WATER DEPTH
7 METERS

TREND

P = 0.29

[Mann Kendall test]

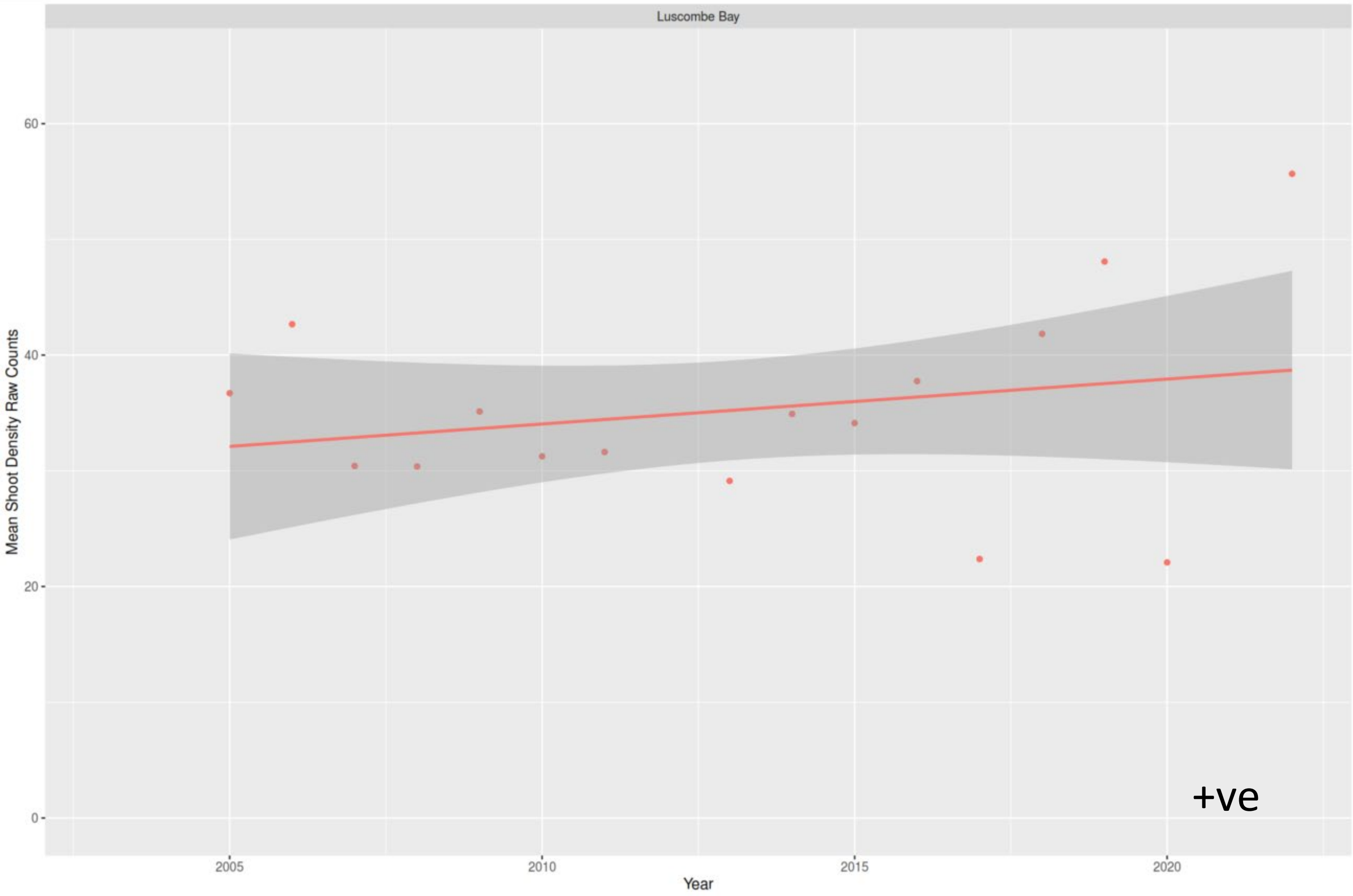
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE	3	3	3	3	3	3	2	1	2	1	1	3	1			1	3	2		2
EPIPHYTE COVER	3	3	3	3	3	3	2	3	3	2	2	2	1			1	1	2		3
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5

3= Filamentous

1= Low, 2= Mod, 3=High

Start in 2005

LUSCOMBE BAY



+ve

WATER DEPTH
2 METERS

TREND

P = 0.62

[Mann Kendall test]

EPIPHYTE TYPE	3	1	2	1	3	2					2	1					3	2		2
EPIPHYTE COVER	1	2	2								2	2					2	2		2
AVG SUMMER TEMP	22.0	21.5	21.5	21.2	21.9	22.1	22.1	22.1	23.2	22.9	22.8	22.5	22.3	22.4	21.9	22.3	22.0	23.0	22.7	23.3
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

JERVOISE BAY

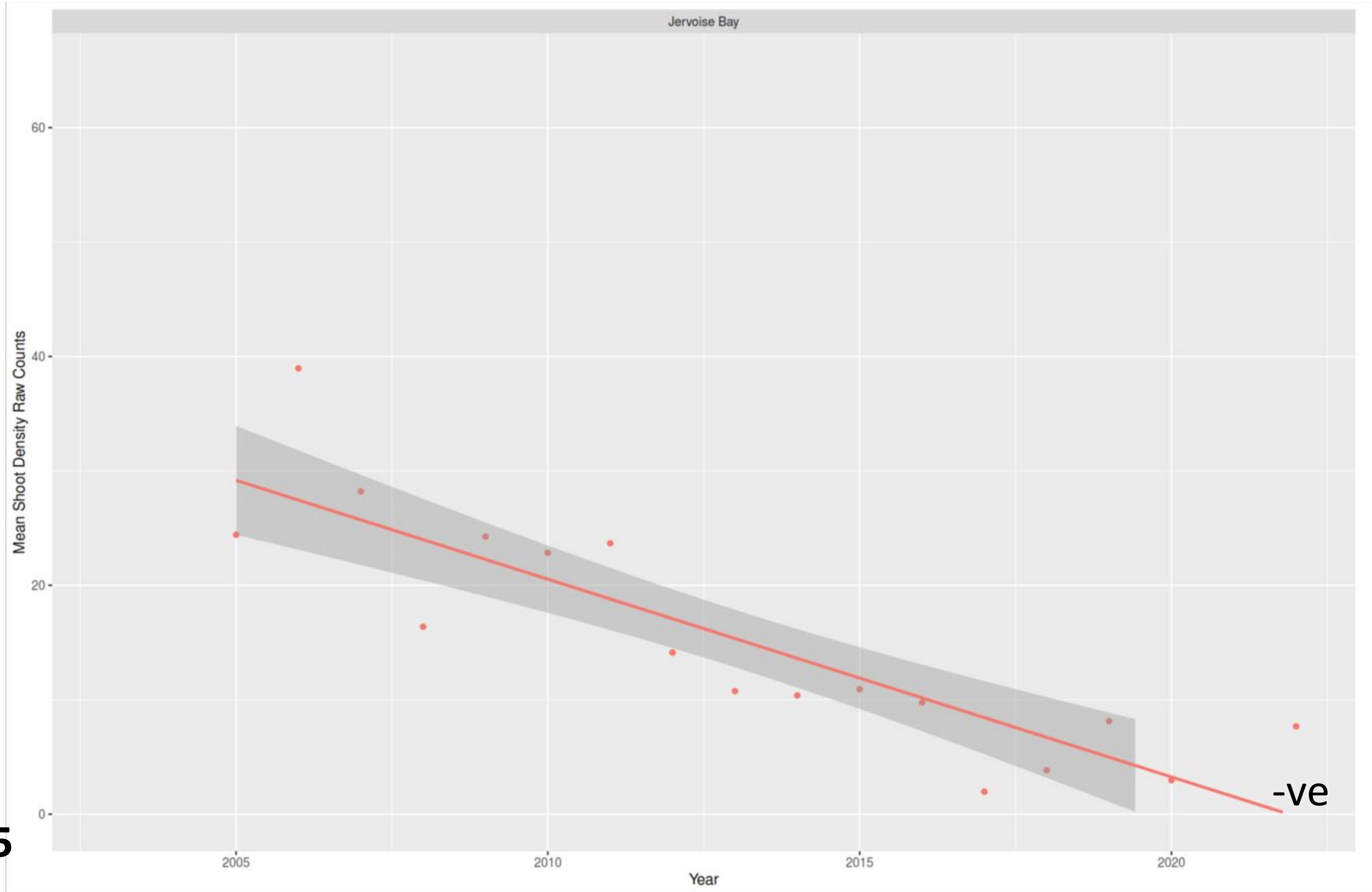
WATER DEPTH
2.5 METERS

TREND

P = <0.01

[Mann Kendall test]

Start in 2005



EPIPHYTE TYPE	1	3	2	3	3	2	1	1	1	1	1	1					1	2		2
EPIPHYTE COVER	2	2	2	3	3	3	2	2	3	3	1	2					2	2		2
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

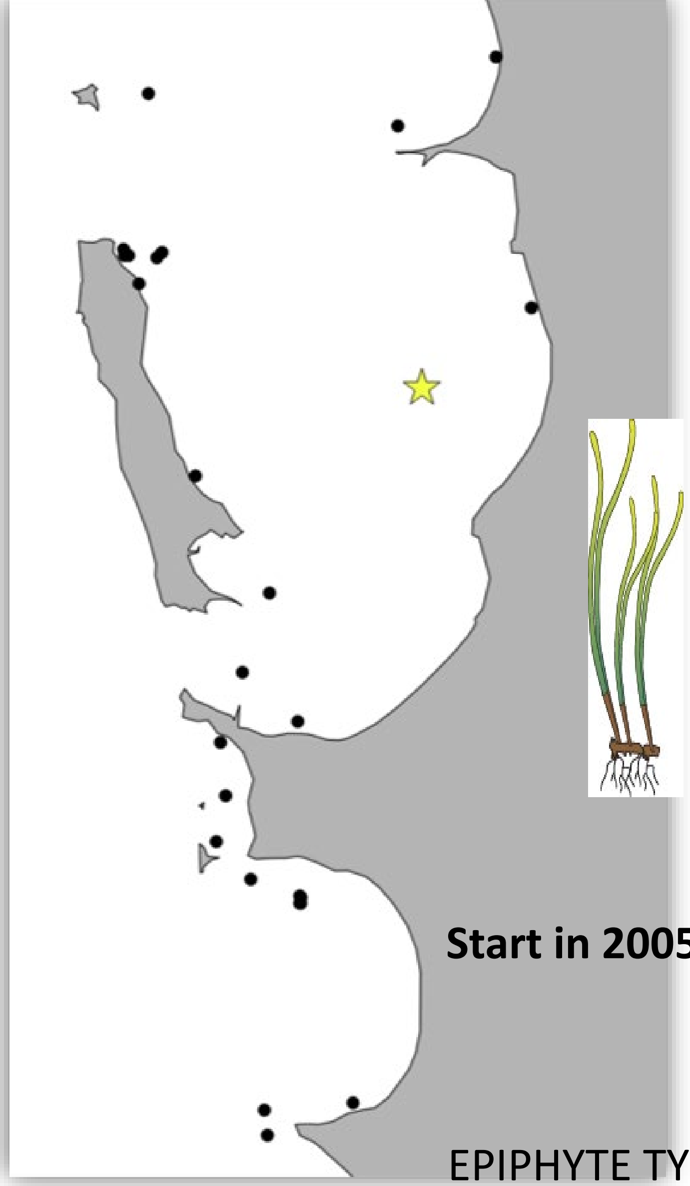
KWINANA

WATER DEPTH
5.2 METERS

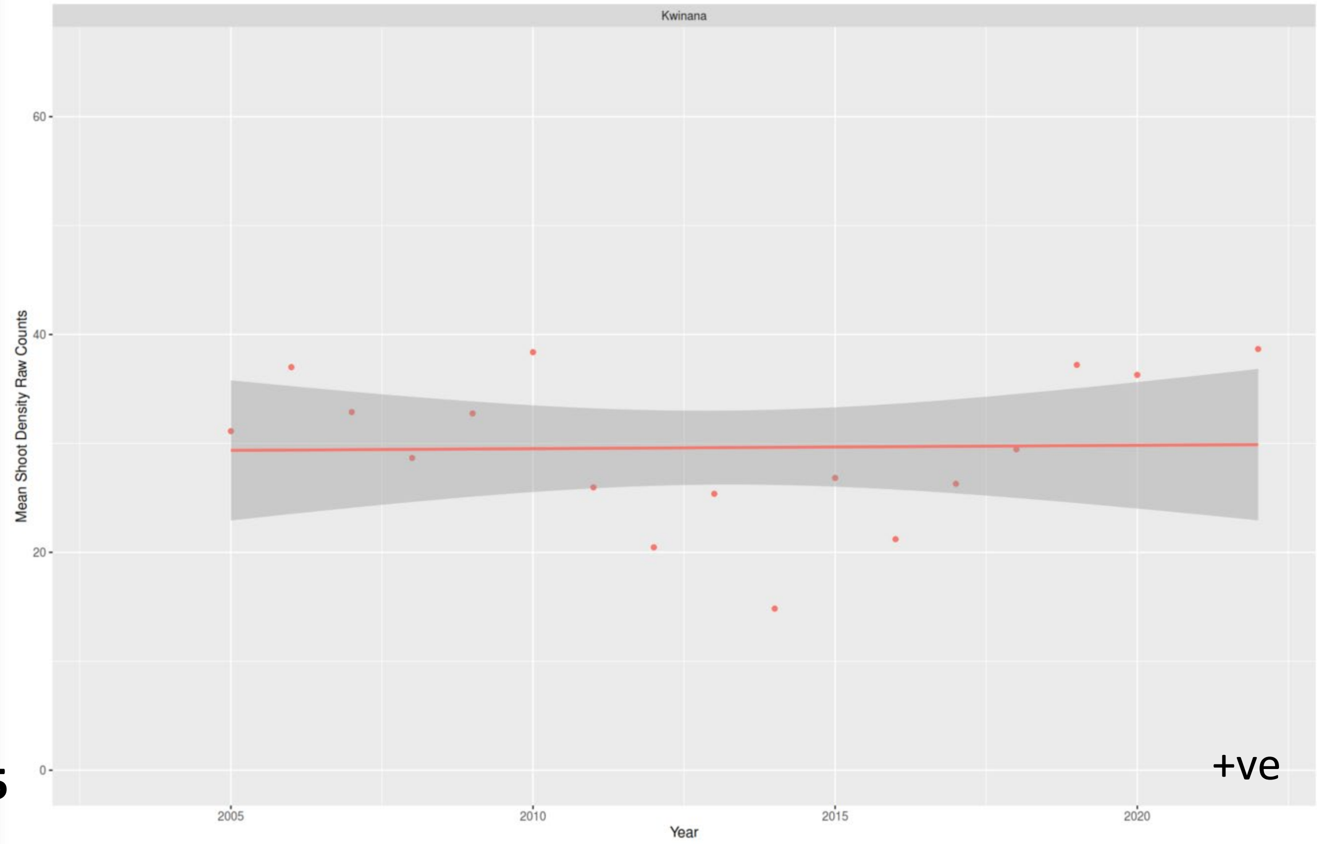
TREND

P = 0.9

[Mann Kendall test]



Start in 2005



YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE	1	1	1	1	3	2	2	2	2	1	3	3	3			3	2	2		2
EPIPHYTE COVER	2	2	3	1		1	1	2	2	2	2	2	2			2	2	2		3
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.3	23.0	22.9	22.6	22.4	22.5	22.0	22.5	22.3	23.2	22.8	23.5

3= Filamentous

1= Low, 2= Mod, 3=High

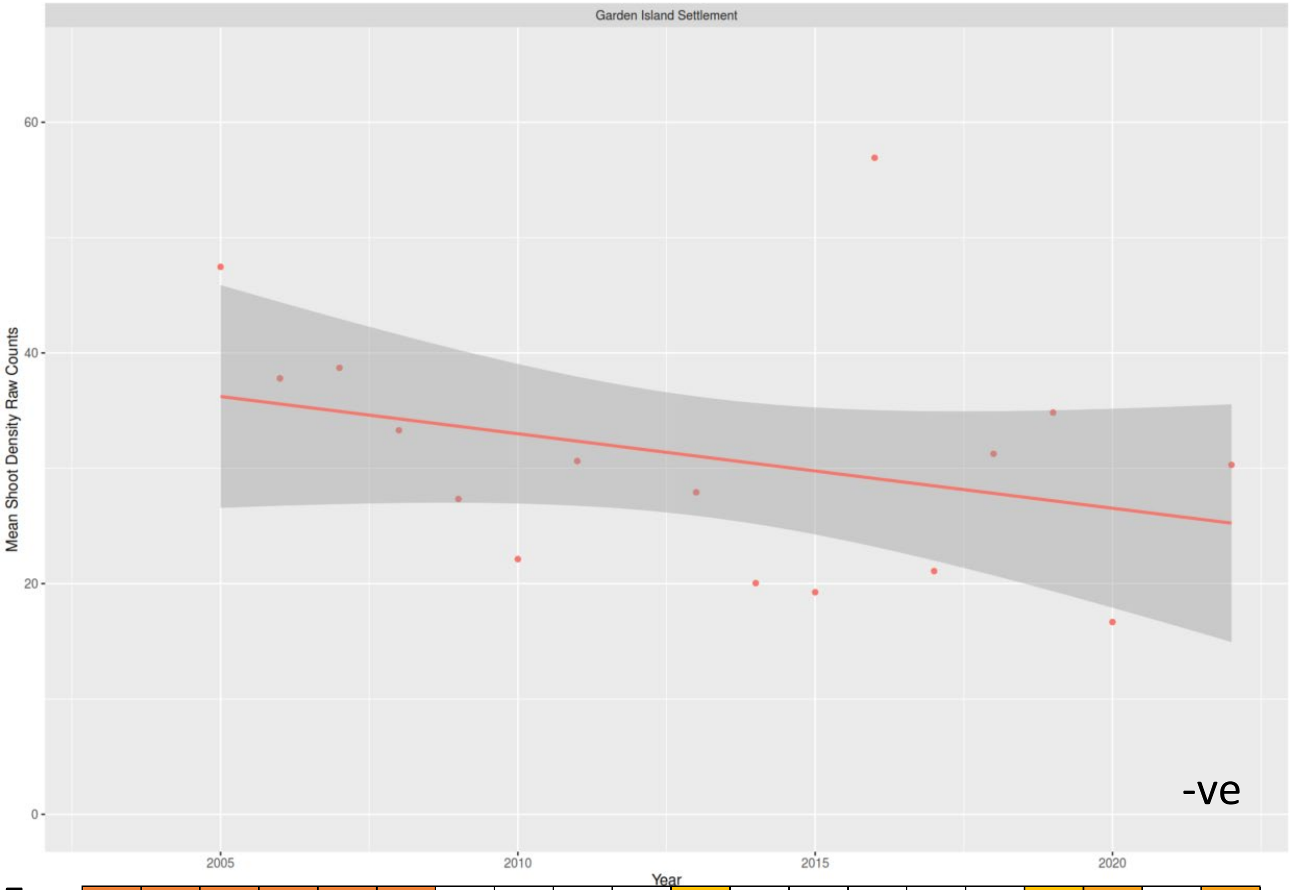
GARDEN ISLAND SETTLEMENT

WATER DEPTH
2 METERS

TREND

P = 0.08

[Mann Kendall test]



Start in 2005

EPIPHYTE TYPE	3	3	3	3	3	3					1						1	2		2
EPIPHYTE COVER	2	3	3	3							2						1	2		3
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.2	22.9	22.8	22.5	22.3	22.4	22.0	22.4	22.1	23.1	22.7	23.4
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

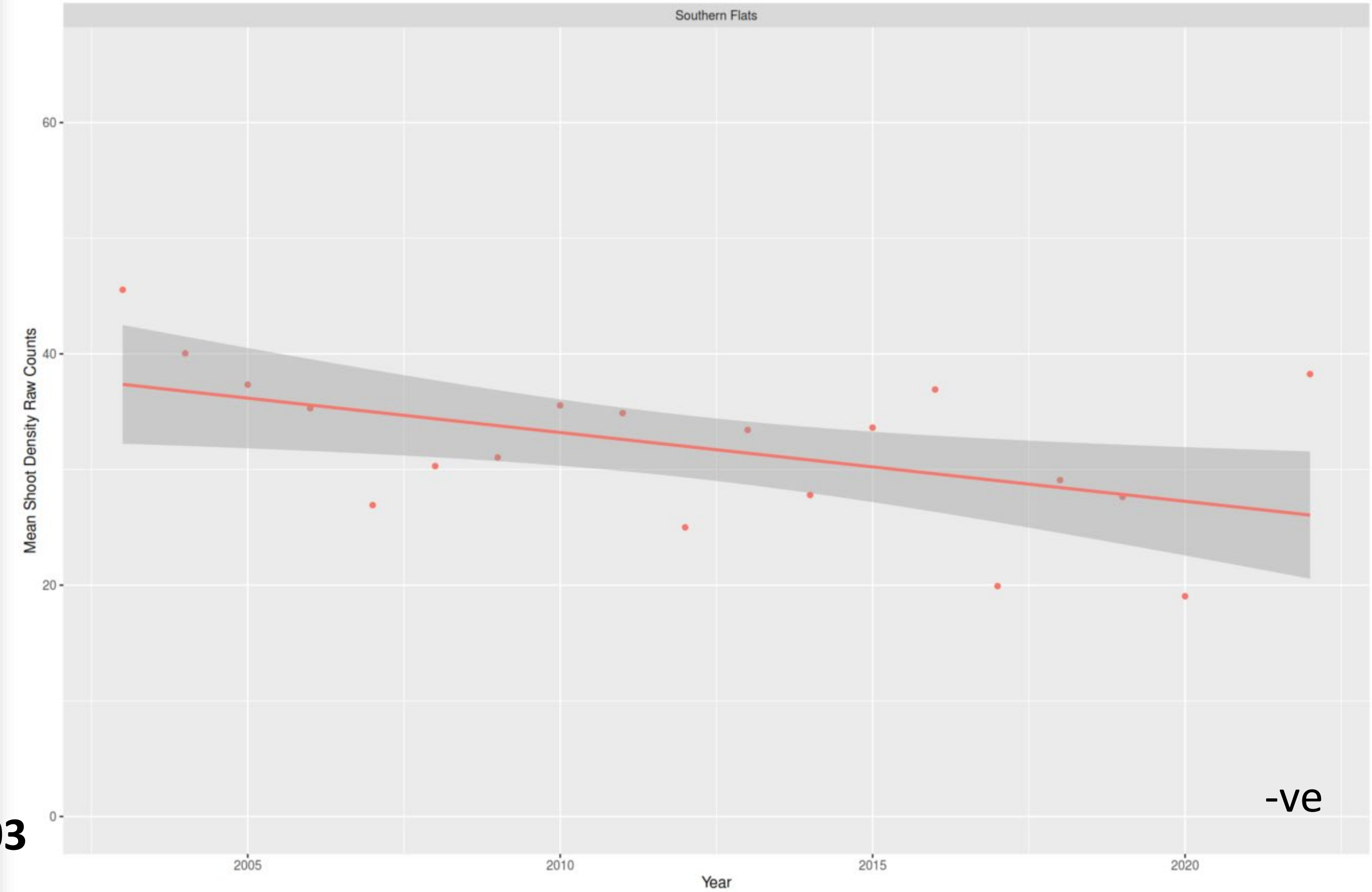
3= Filamentous

1= Low, 2= Mod, 3=High

SOUTHERN FLATS

WATER DEPTH
2 METERS

Start in 2003



TREND

P = 0.04

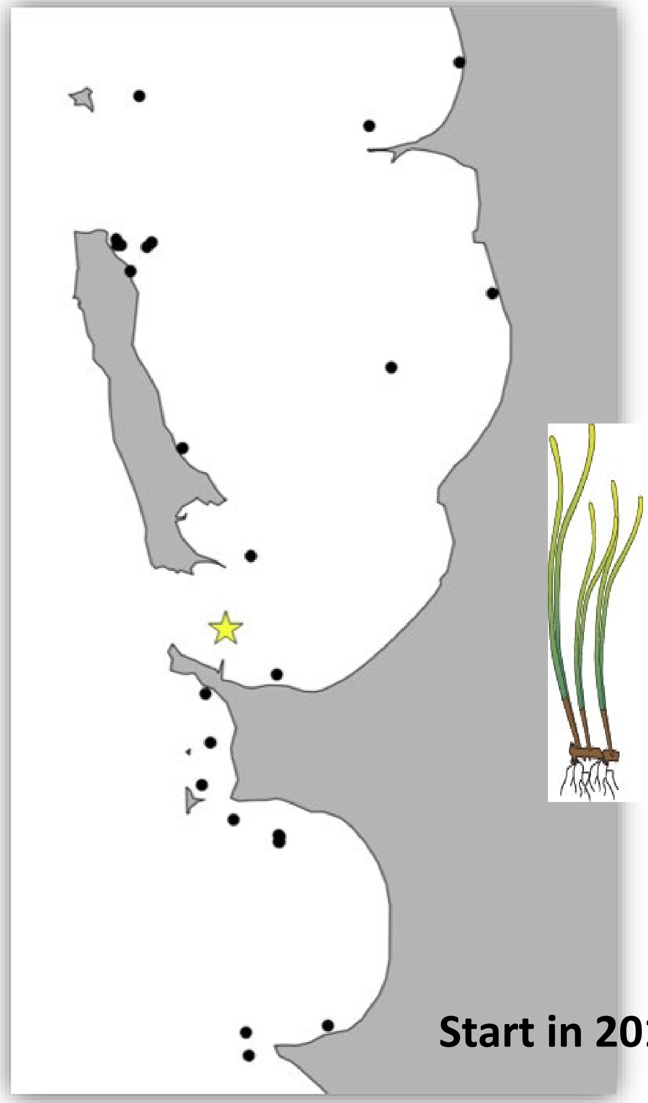
[Mann Kendall test]

YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE	1	1	1	1	2	1	2	1	1	1	3	3	1				1	2		2
EPIPHYTE COVER	1	1	2		1	1	2	2	2	1	2	2	2				2	2		2
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.2	22.9	22.8	22.5	22.3	22.4	22.0	22.4	22.1	23.1	22.7	23.4

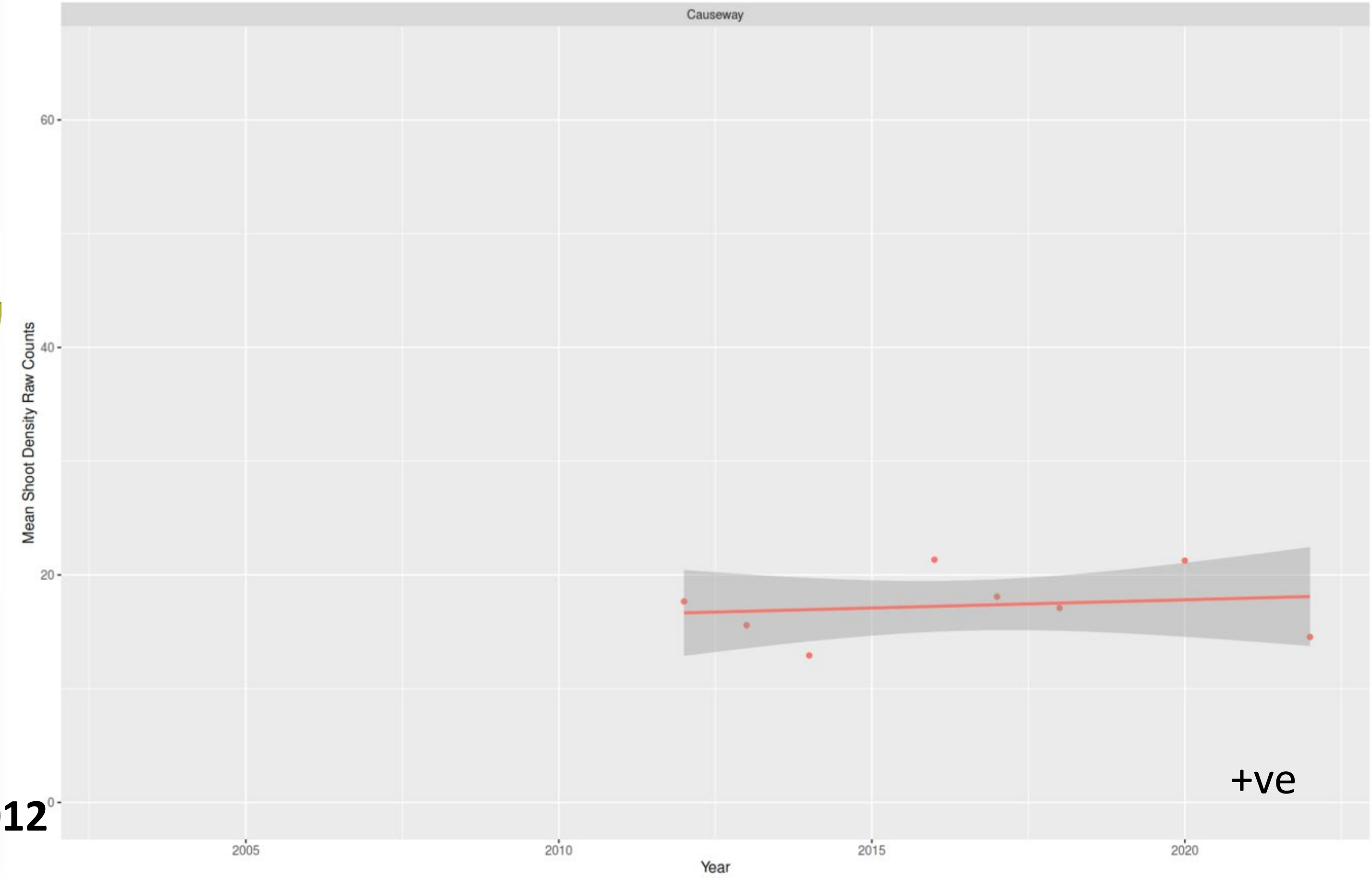
3= Filamentous

1= Low, 2= Mod, 3=High

CAUSEWAY



Start in 2012



WATER DEPTH
5.5 METERS

TREND

P = 1

[Mann Kendall test]

EPIPHYTE TYPE

EPIPHYTE COVER

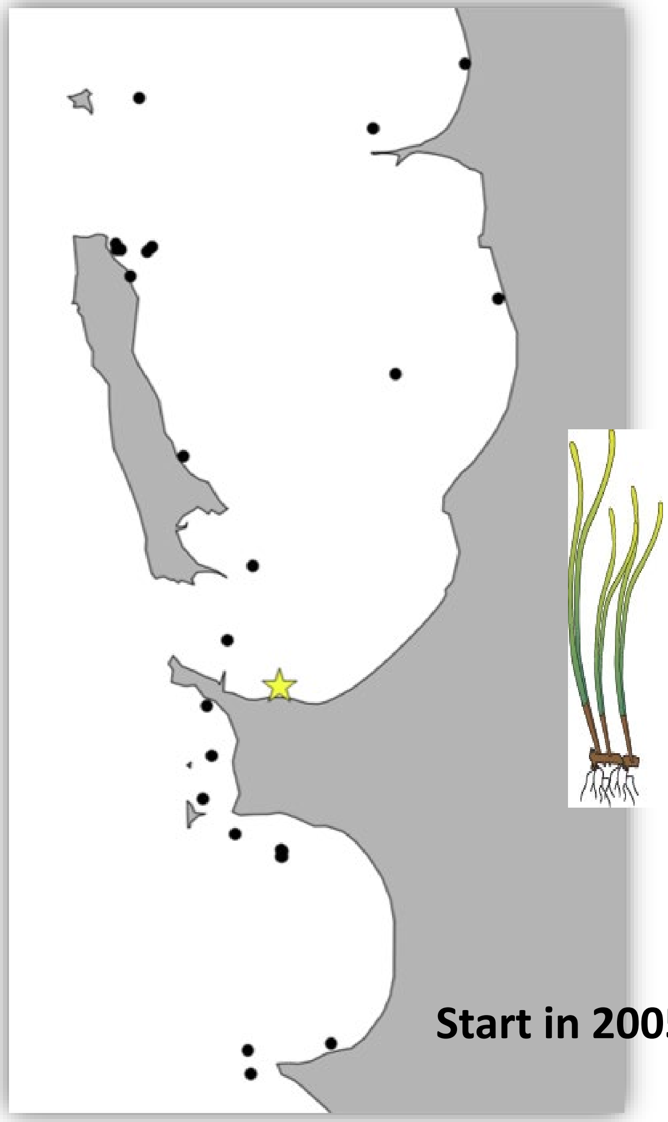
AVG SUMMER TEMP

3= Filamentous

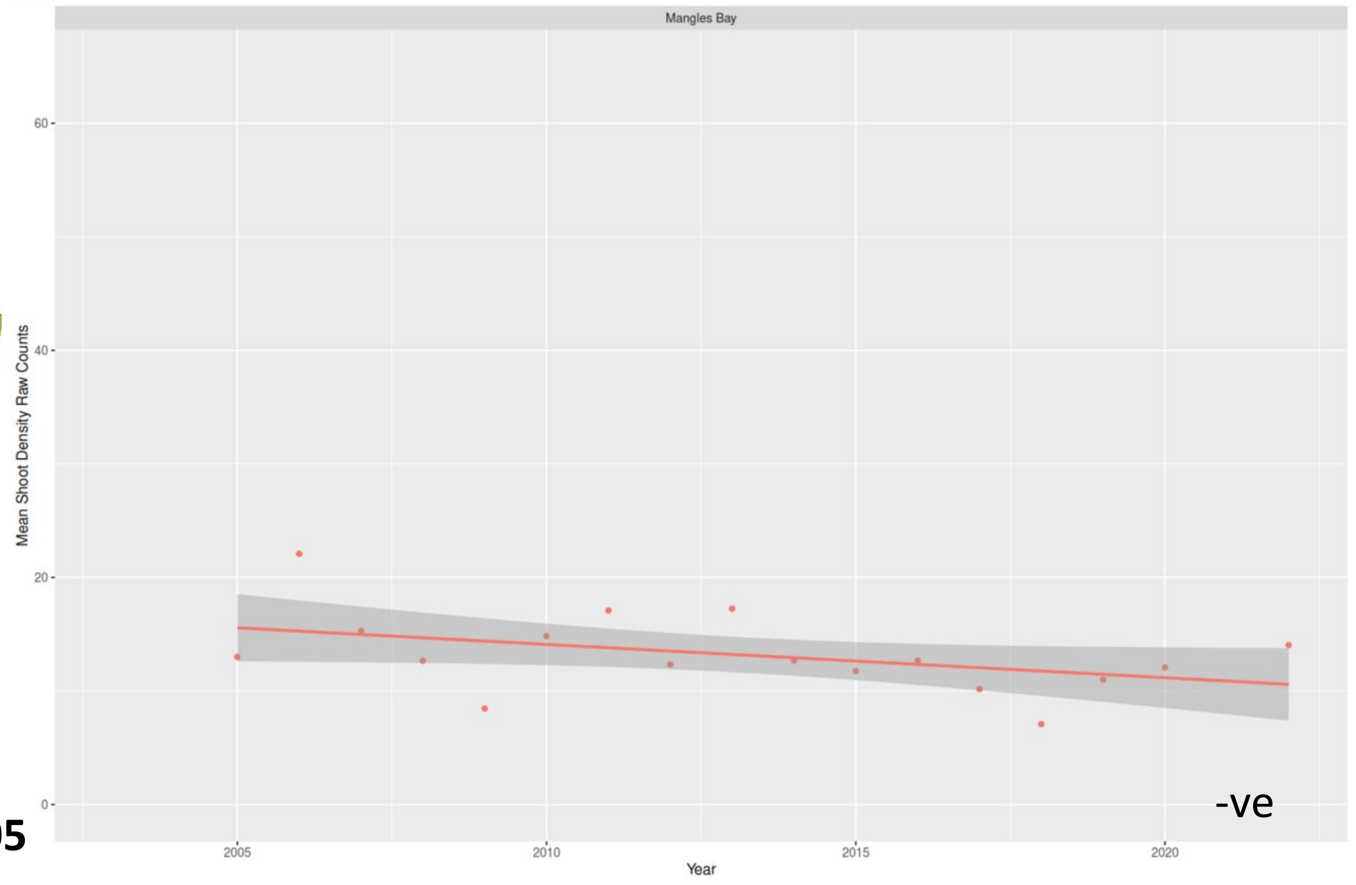
1= Low, 2= Mod, 3=High

YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

MANGLES BAY



Start in 2005



WATER DEPTH
3.2 METERS

TREND

P = 0.07

[Mann Kendall test]

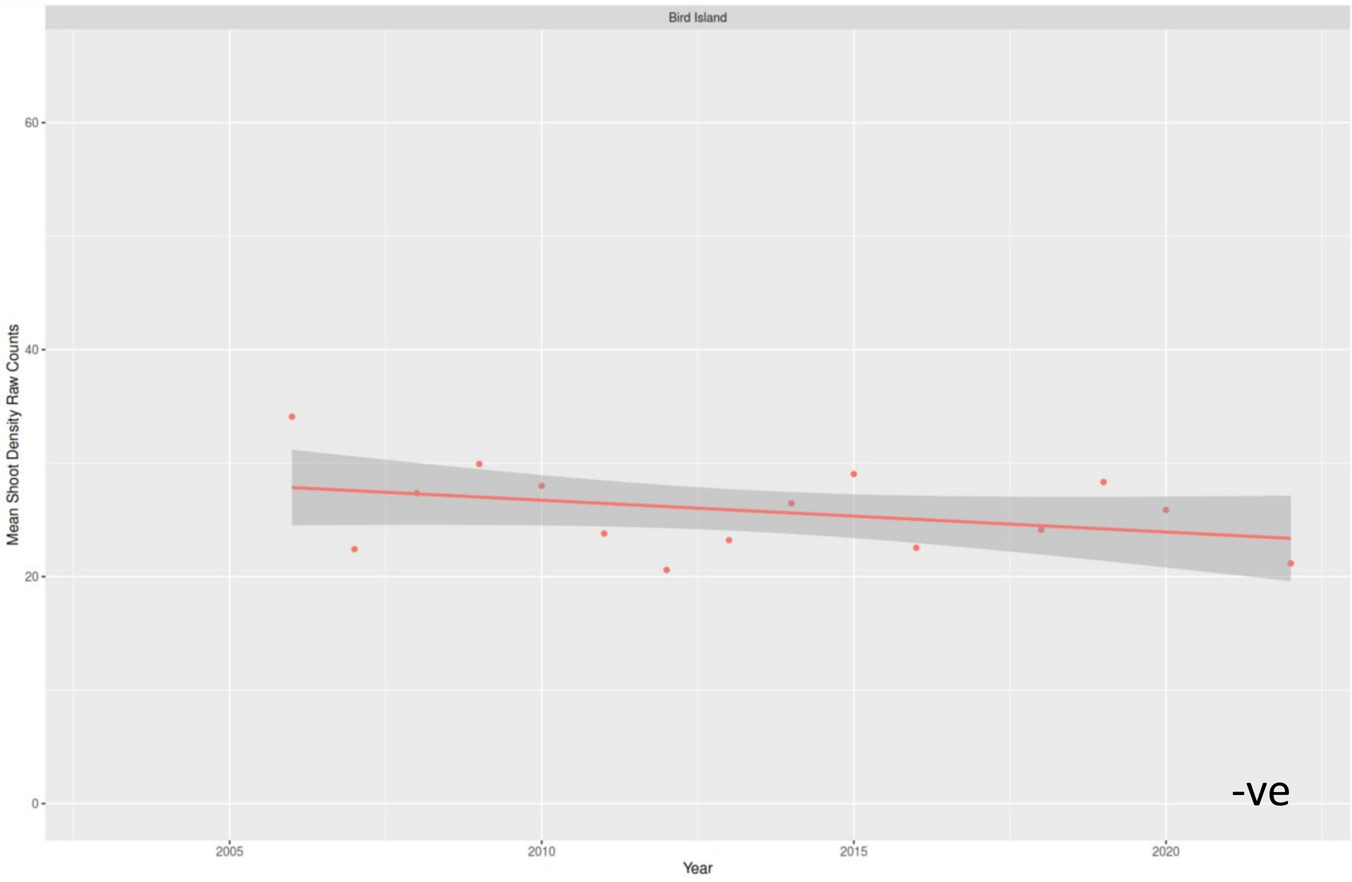
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE	3	3	3	3	3	3	3	3	3	2	3	3					3	2		3
EPIPHYTE COVER	3	3	3	3	3	3	3	3	3	3	3	3					3	2		3
AVG SUMMER TEMP	22.0	21.5	21.6	21.2	22.0	22.2	22.1	22.2	23.2	22.9	22.8	22.5	22.3	22.4	22.0	22.4	22.1	23.1	22.7	23.4

3= Filamentous

1= Low, 2= Mod, 3=High

BIRD ISLAND

Start in 2006



WATER DEPTH
2 METERS

TREND

P = 0.32
[Mann Kendall test]

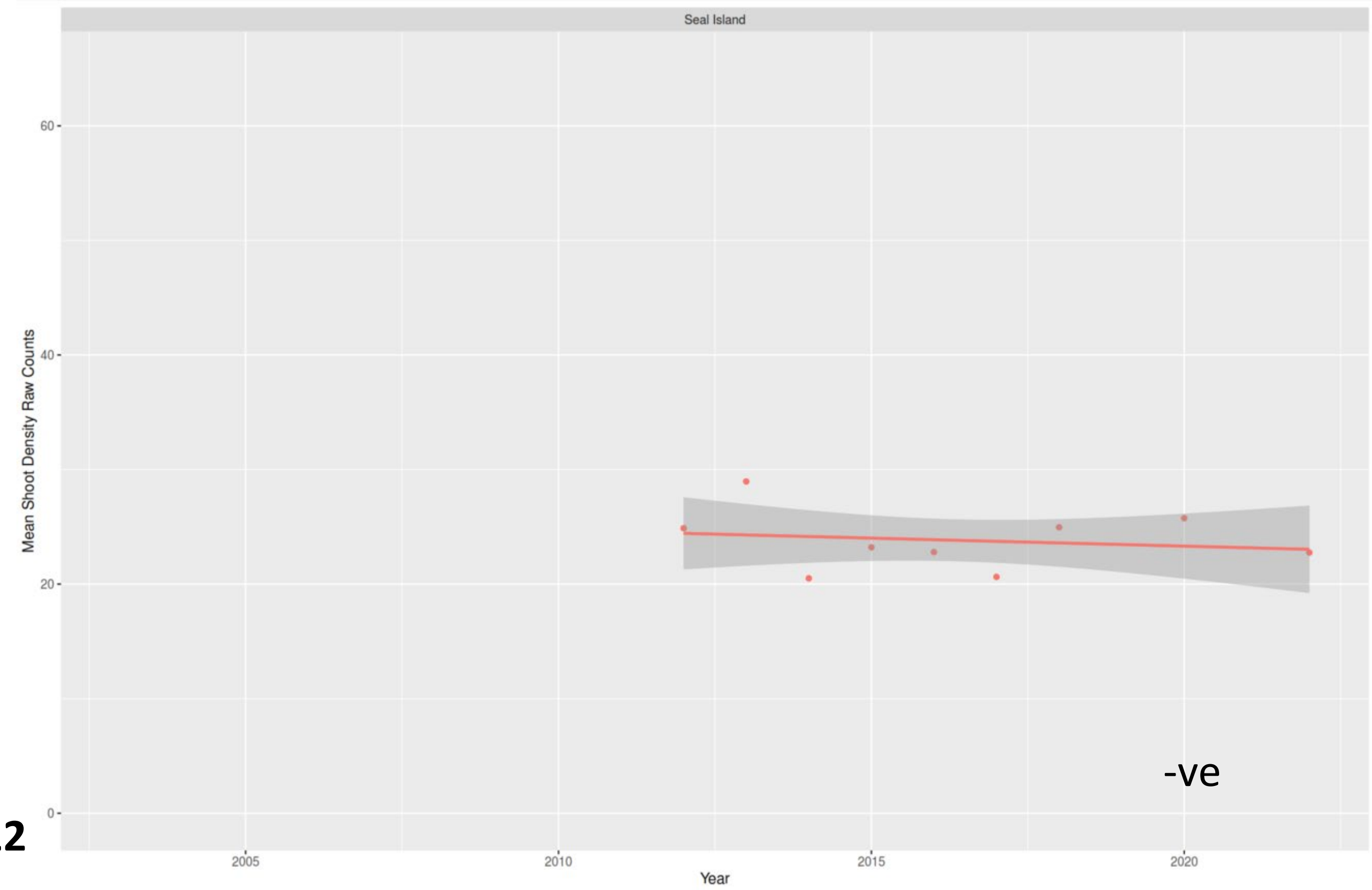
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE	3	3	3	2	3	1	1	1	1	1	1	3					3	2		
EPIPHYTE COVER	2	3	3		2	2	2	2	2	2	2	2					2	3		
AVG SUMMER TEMP	22.0	21.5	21.6	21.1	22.0	22.1	22.0	22.1	23.2	22.9	22.8	22.5	22.3	22.4	21.9	22.3	22.0	23.1	22.6	23.3

3= Filamentous

1= Low, 2= Mod, 3=High

SEAL ISLAND

Start in 2012



WATER DEPTH
5.1 METERS

TREND

P = 0.92

[Mann Kendall test]

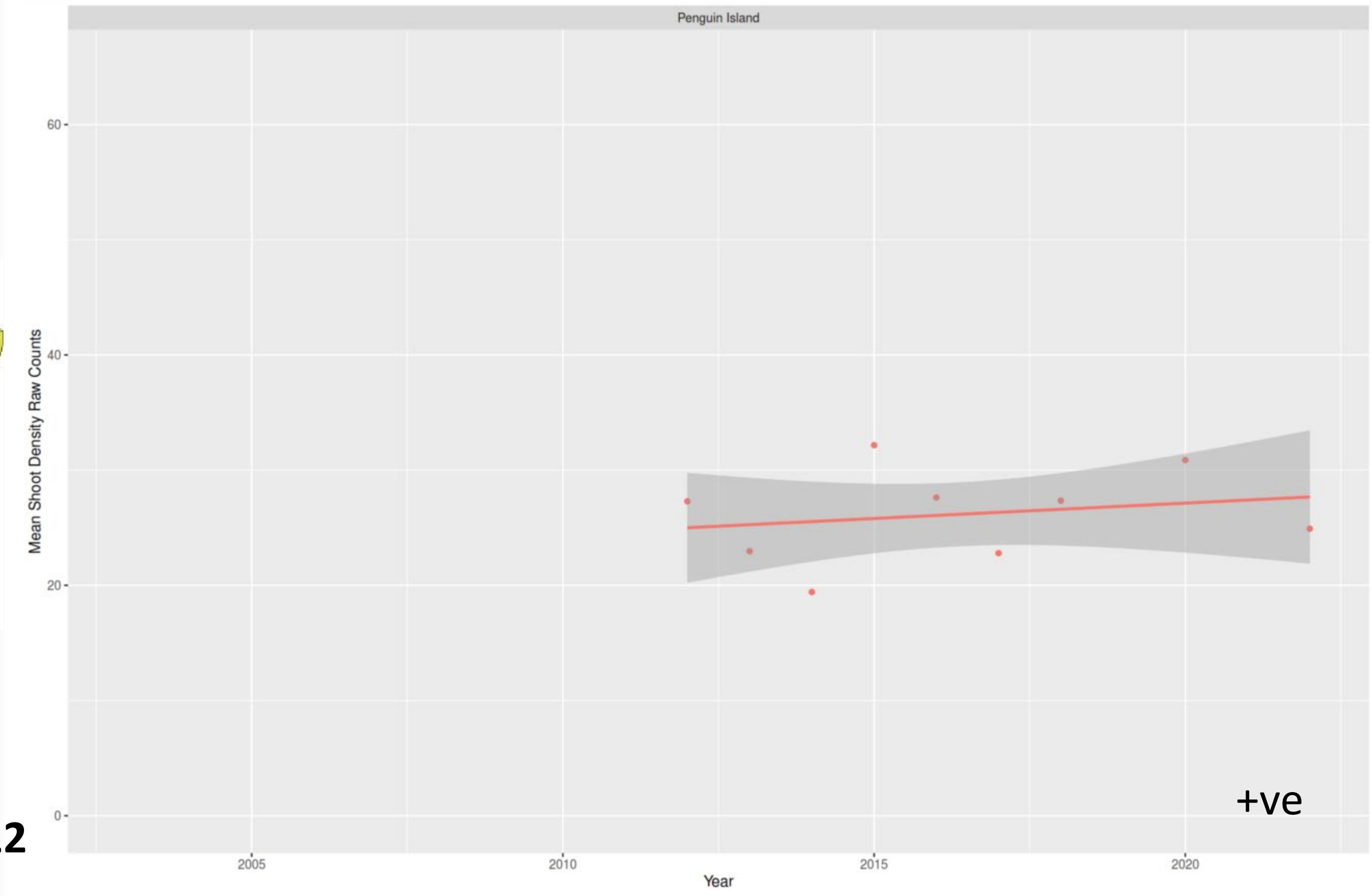
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE										1	1	1		3						
EPIPHYTE COVER										2	2	2		1						
AVG SUMMER TEMP	22.0	21.5	21.6	21.1	22.0	22.1	22.0	22.1	23.2	22.9	22.8	22.5	22.3	22.4	21.9	22.3	22.0	23.1	22.6	23.3

3= Filamentous

1= Low, 2= Mod, 3=High

PENGUIN ISLAND

Start in 2012



WATER DEPTH
3.6 METERS

TREND

P = 0.75

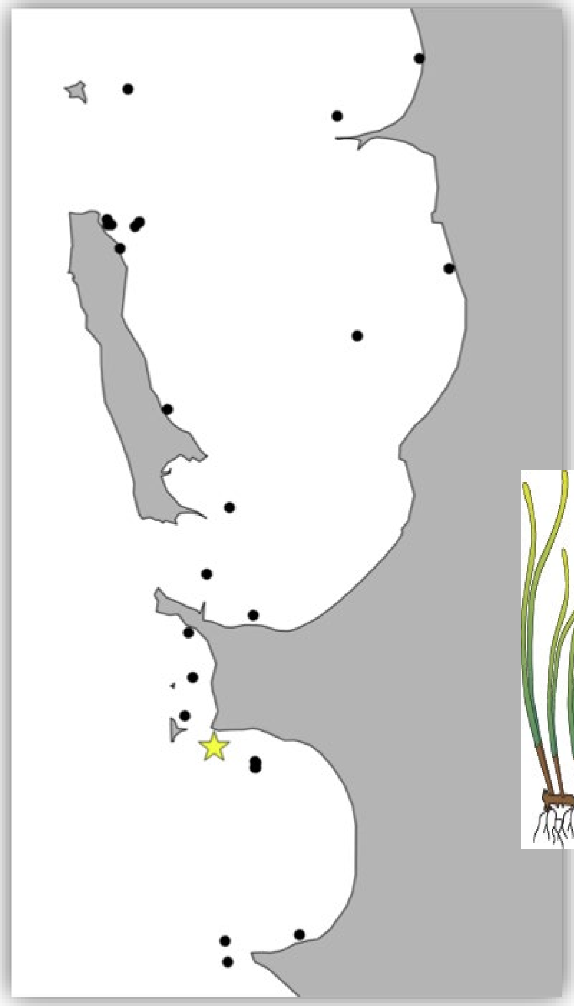
[Mann Kendall test]

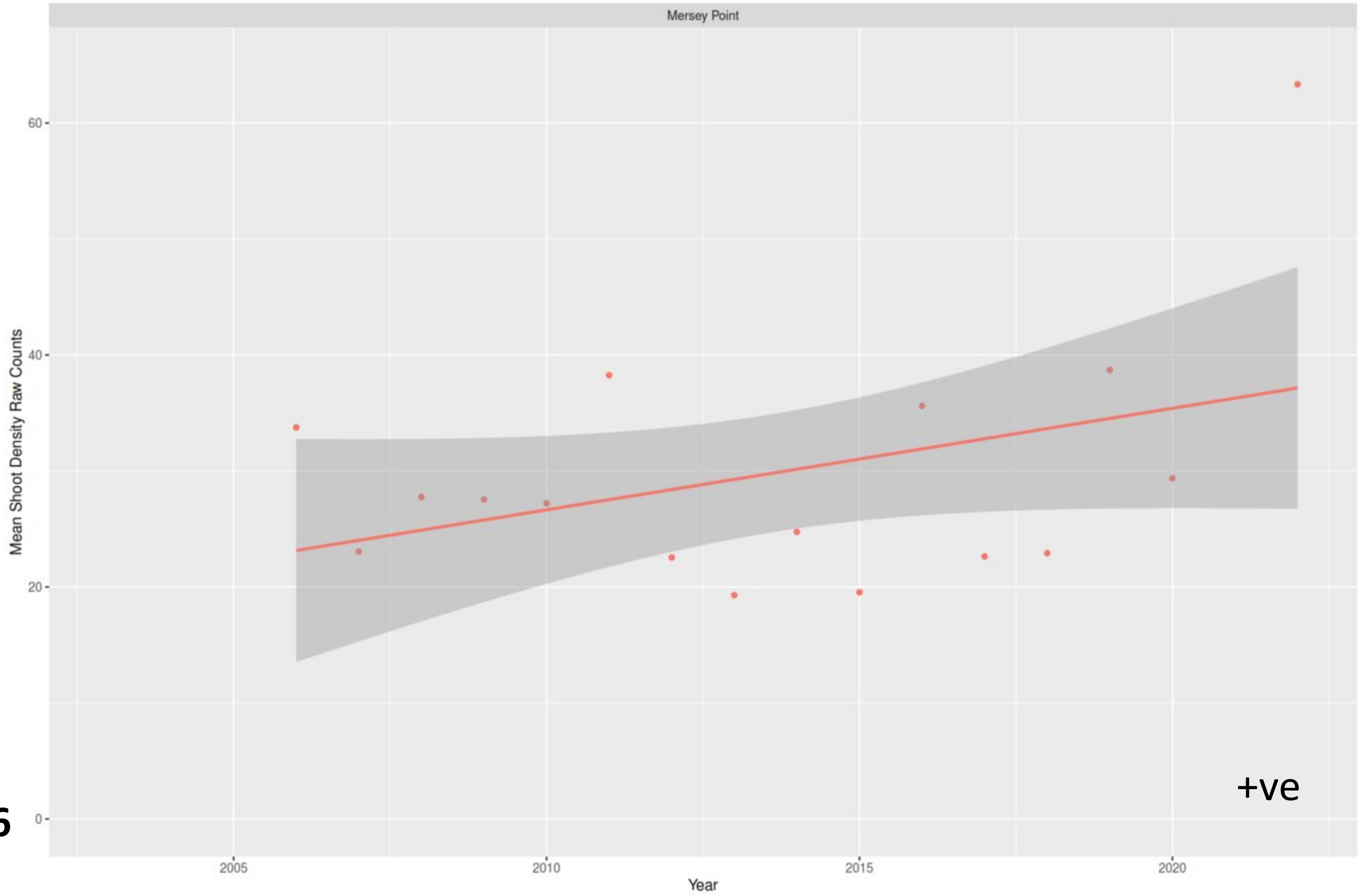
EPIPHYTE TYPE										1	1	3	1	1						
EPIPHYTE COVER										2	3	3	2	2						
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

MERSEY POINT





WATER DEPTH
3 METERS

TREND

P = 0.62
[Mann Kendall test]

Start in 2006

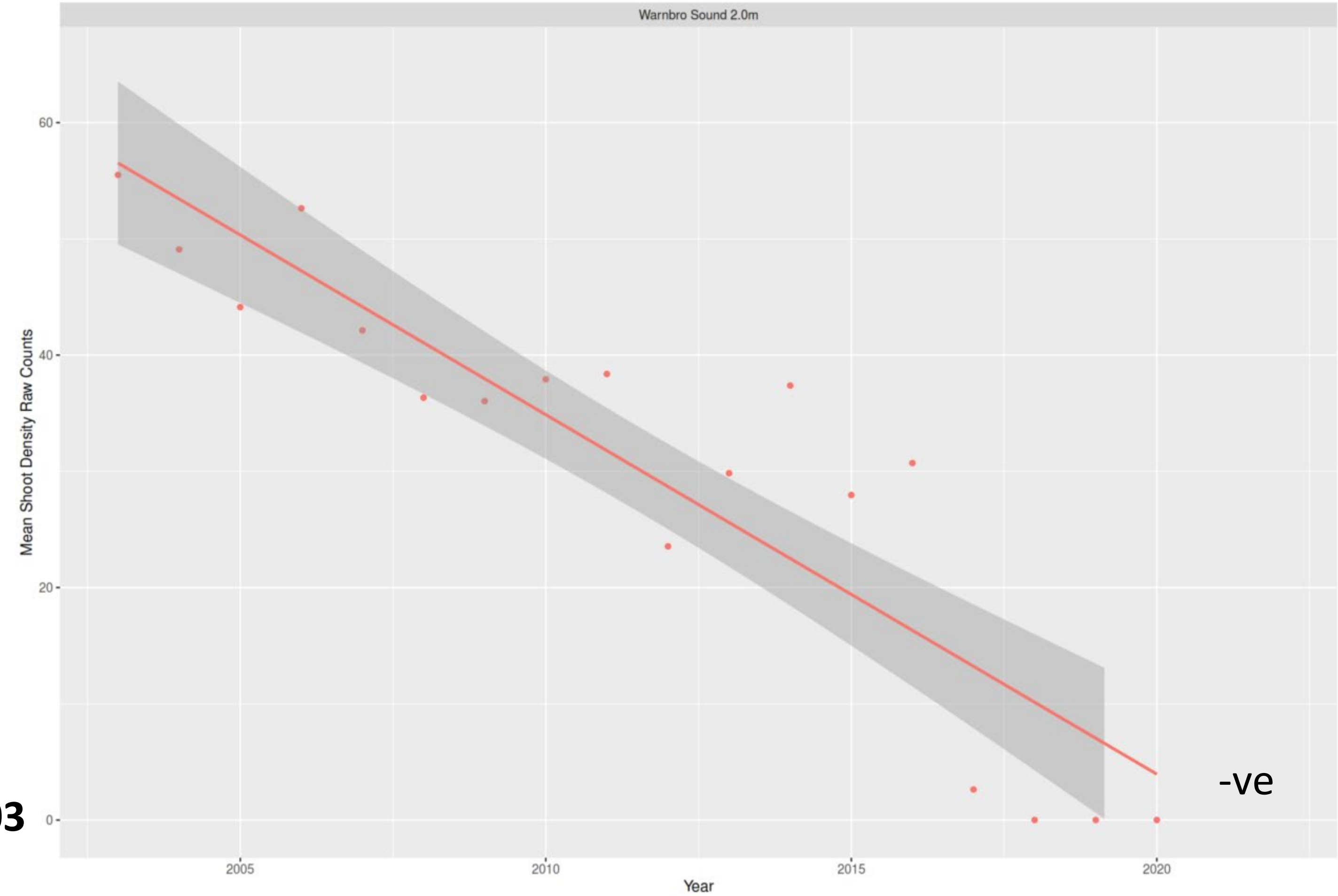
EPIPHYTE TYPE	1	2	1	1	2		1	1	1	1	2	1					1	1		1
EPIPHYTE COVER	1	1	1	1	2	2	2	2	2	2	2	2					2	2		2
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

WARNBRO SOUND 2.0

Start in 2003



WATER DEPTH

2 METERS

TREND

P = <0.01

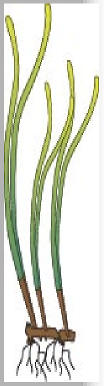
[Mann Kendall test]

EPIPHYTE TYPE							1	1	1	1	1	1	1							
EPIPHYTE COVER							1	1	2	2	2	2	2							
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

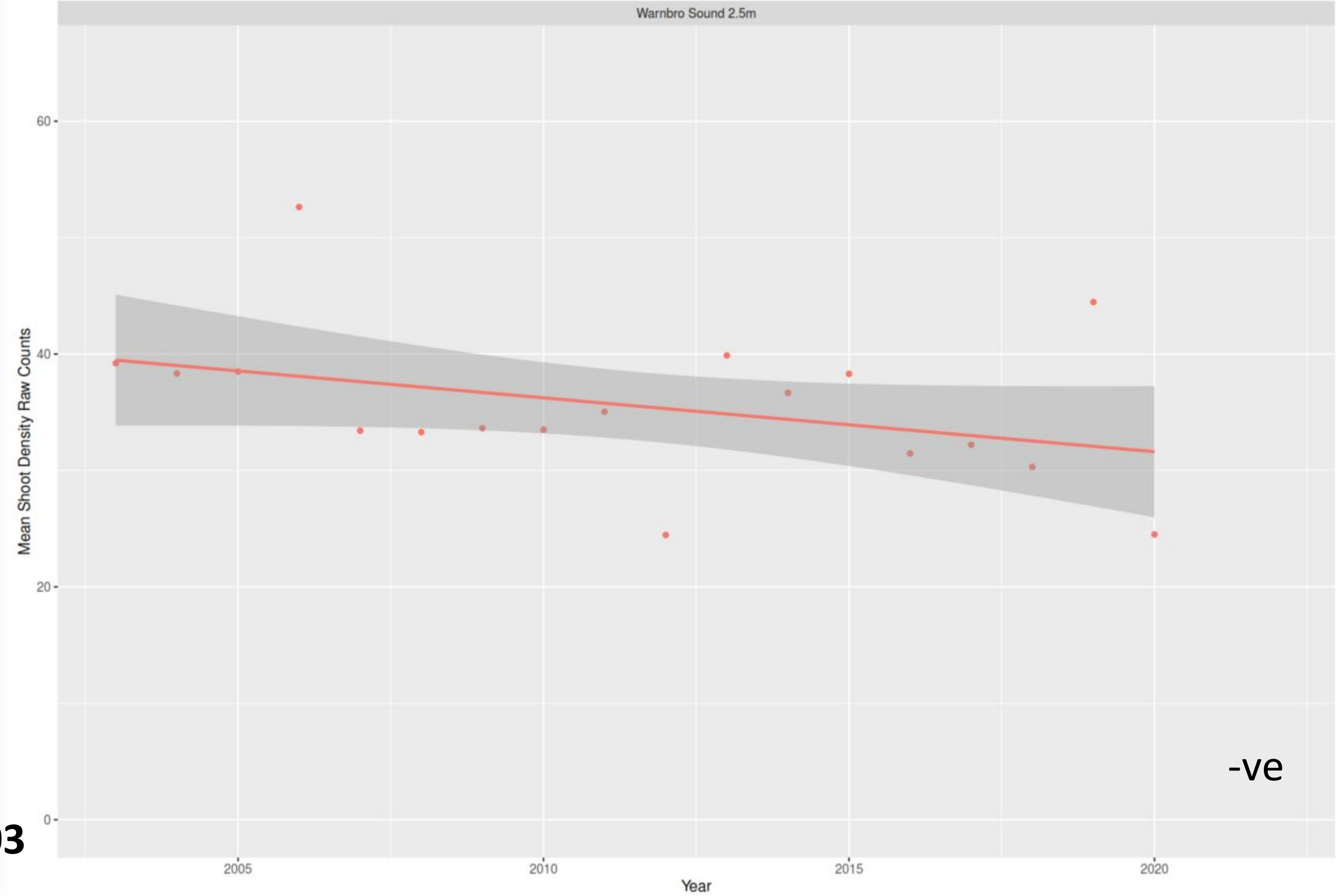
3= Filamentous

1= Low, 2= Mod, 3=High

Start in 2003



WARNBRO SOUND 2.5



WATER DEPTH
2.5 METERS

TREND

P = 0.82

[Mann Kendall test]

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EPIPHYTE COVER							2	1	1	2	2	1	2				2	1		
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1

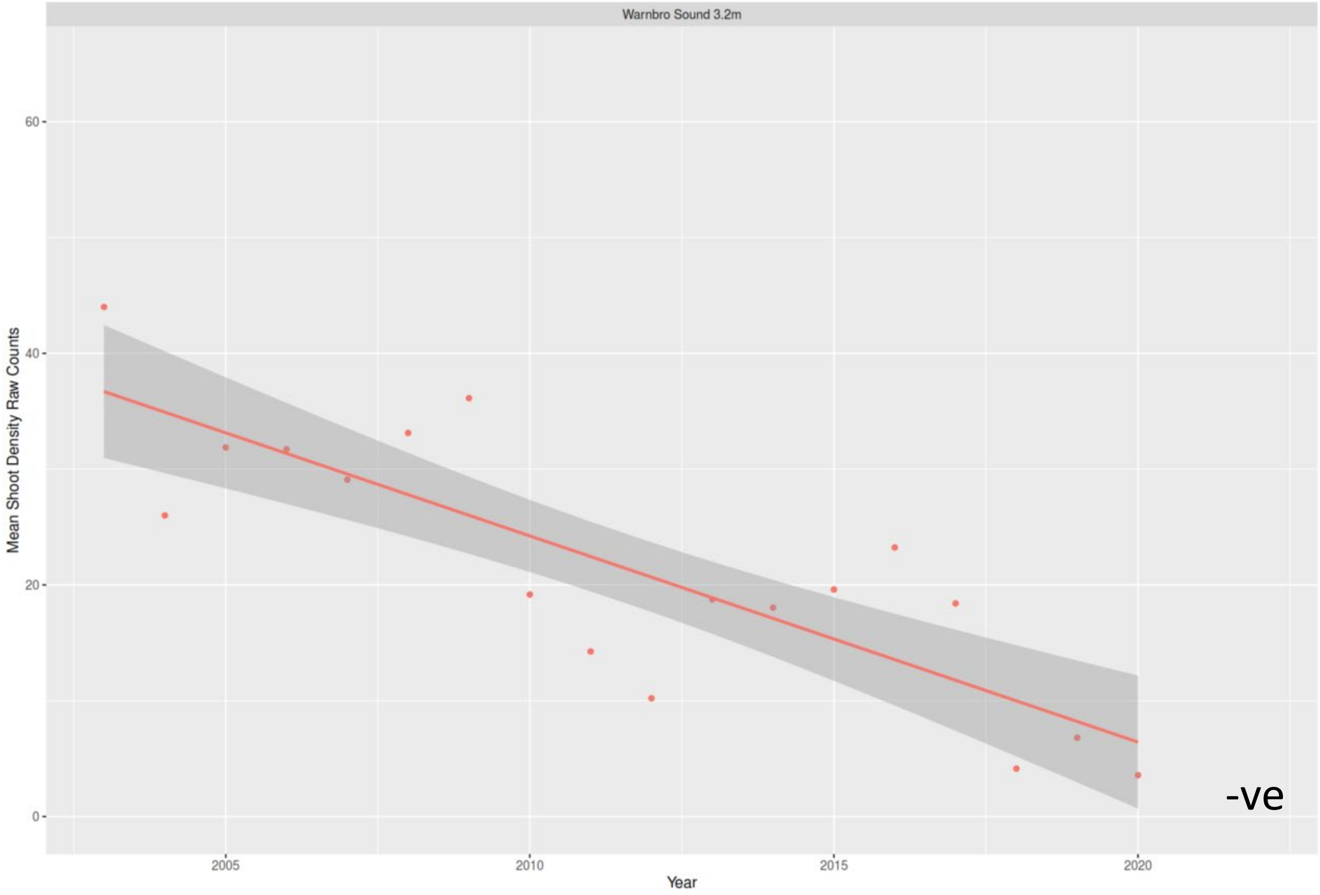
3= Filamentous

1= Low, 2= Mod, 3=High

WARNBRO SOUND 3.2

WATER DEPTH

3.2 METERS



TREND

P = 0.0006

[Mann Kendall test]

Start in 2003

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EPIPHYTE COVER							1	1	2	2	1	1	2				1	1		
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

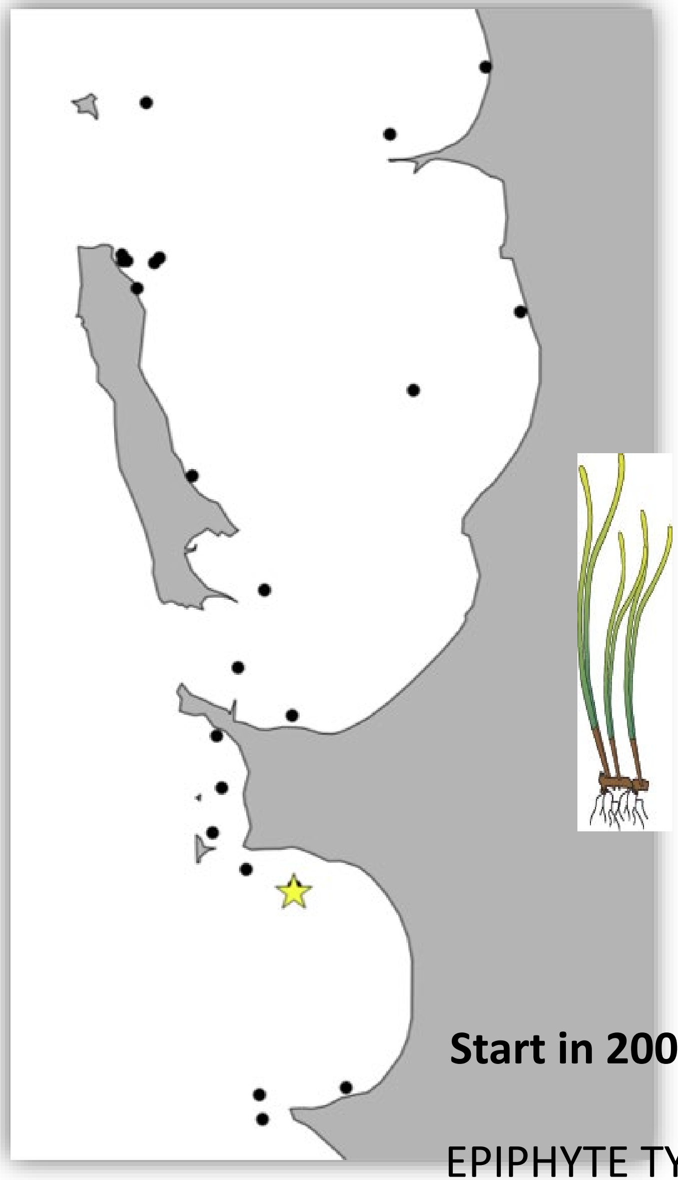
3= Filamentous

1= Low, 2= Mod, 3=High

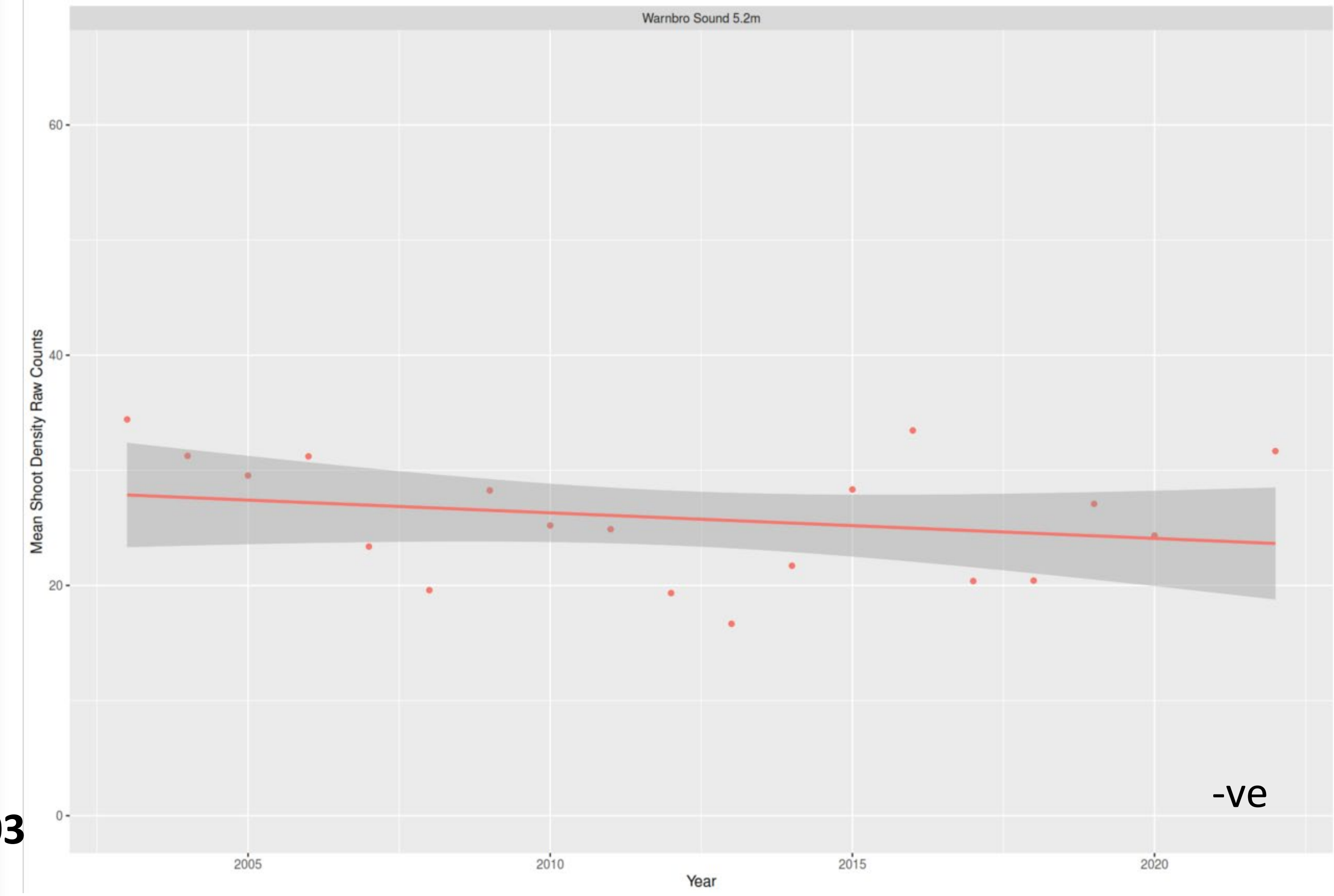
WARNBRO SOUND 5.2

WATER DEPTH

5.5 METERS



Start in 2003



TREND

P = 0.13

[Mann Kendall test]

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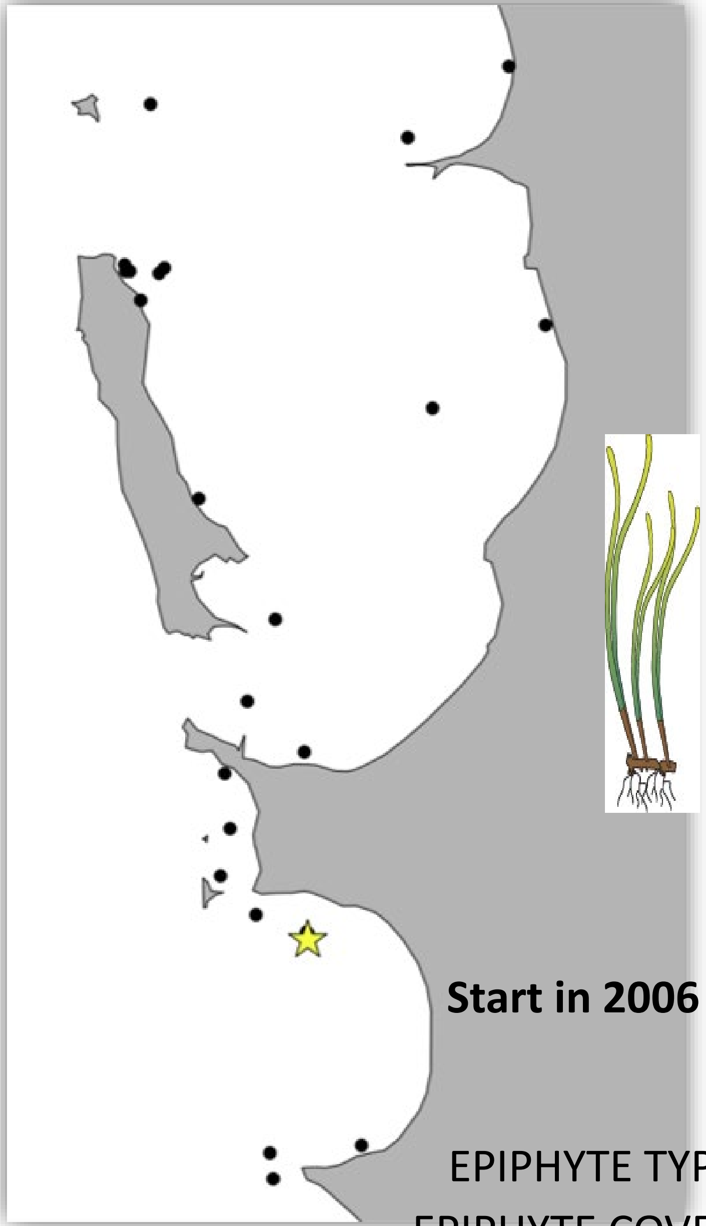
EPIPHYTE COVER							2	2	2	2	1	2	2				2	2		3
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1

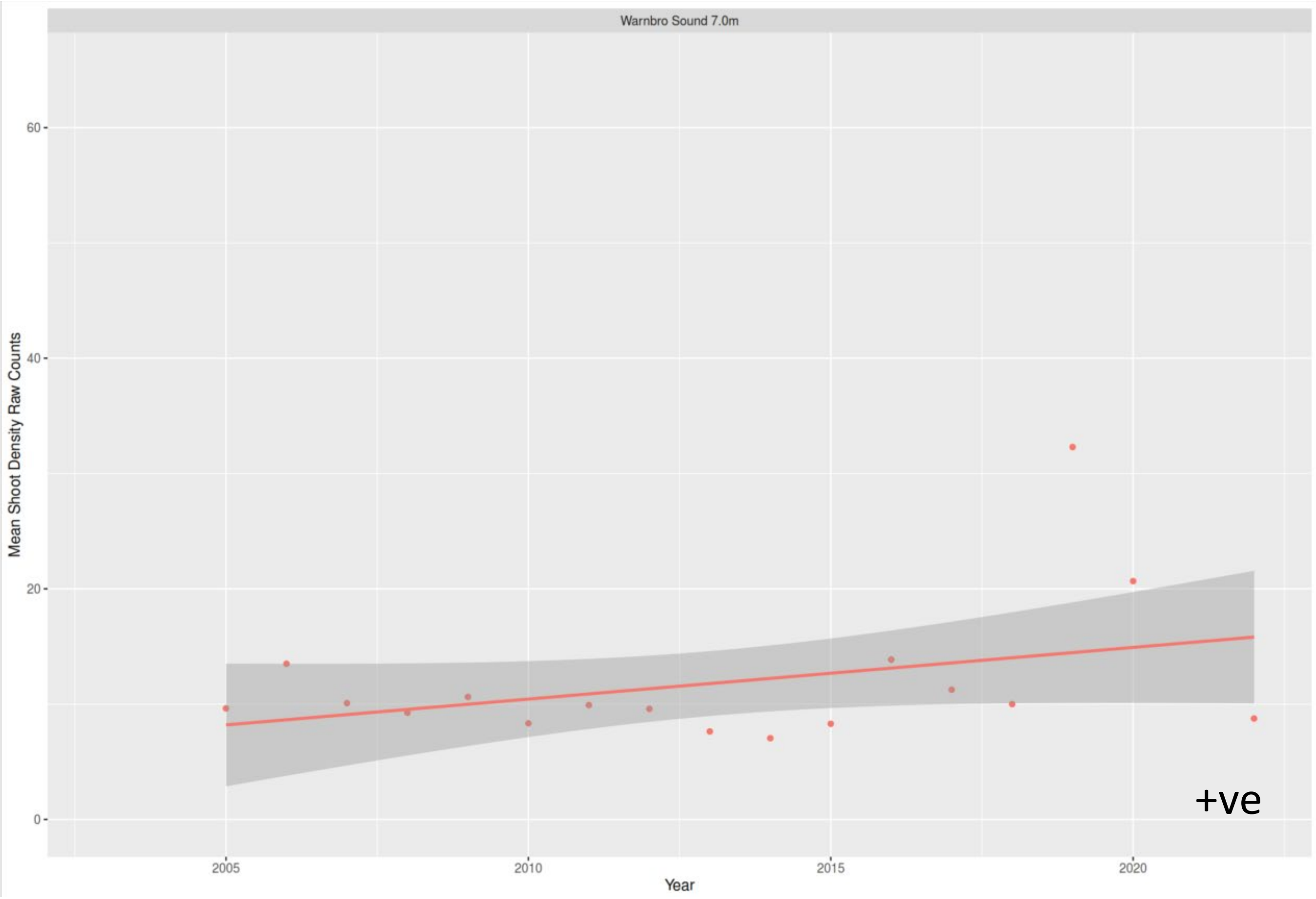
3= Filamentous

1= Low, 2= Mod, 3=High

WARNBRO SOUND 7.0



Start in 2006



WATER DEPTH
7 METERS

TREND

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[Mann Kendall test]

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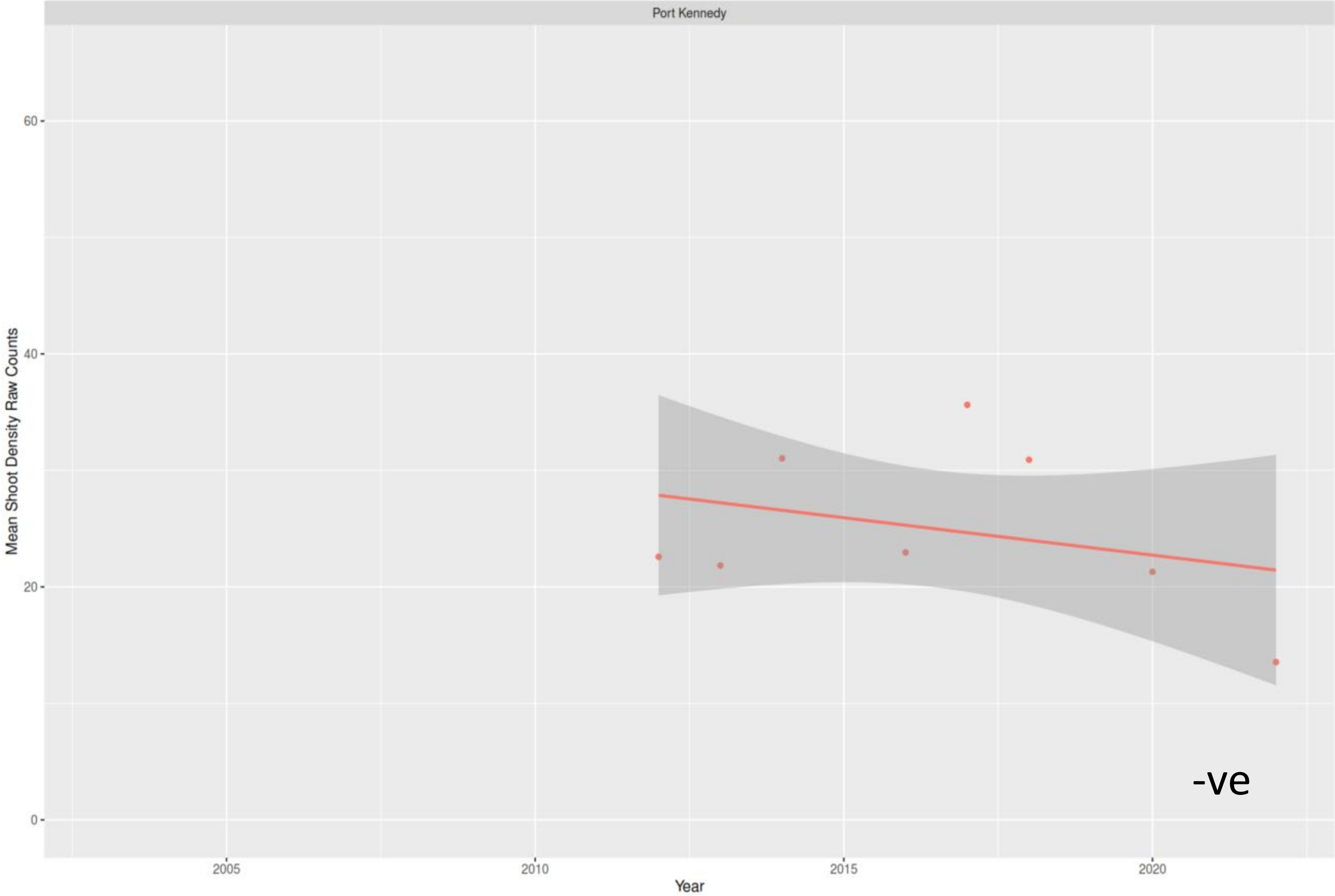
EPIPHYTE COVER							2	2	2	2	2	2	3				2	2		2
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.1	22.0	22.0	23.1	22.8	22.7	22.4	22.2	22.3	21.8	22.2	21.8	22.9	22.5	23.1
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

PORT KENNEDY

Start in 2012



WATER DEPTH
2.6 METERS

TREND

P = 0.54

[Mann Kendall test]

EPIPHYTE TYPE

EPIPHYTE COVER

3= Filamentous

1= Low, 2= Mod, 3=High

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YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

BECHER POINT SZ

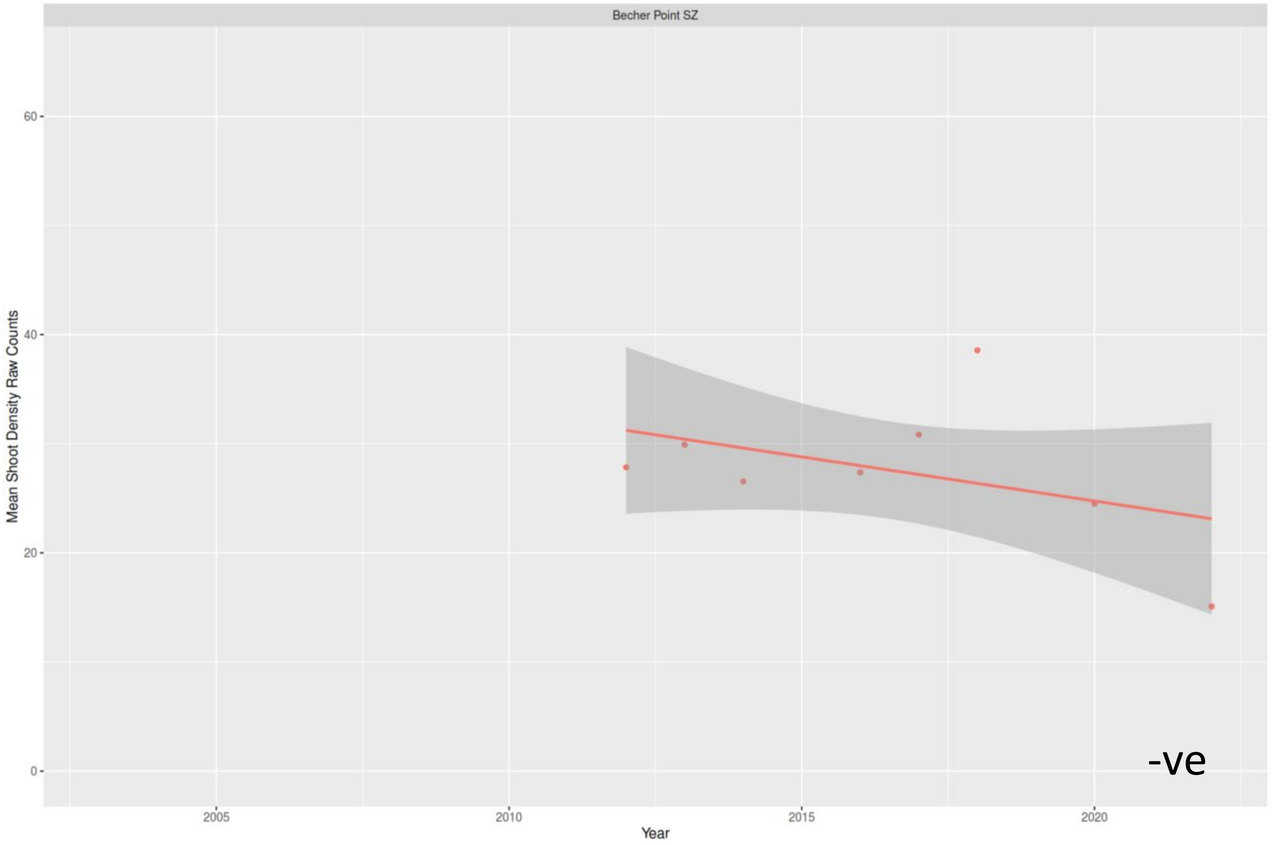
WATER DEPTH
3.2 METERS

TREND

P = 0.53

[Mann Kendall test]

Start in 2012



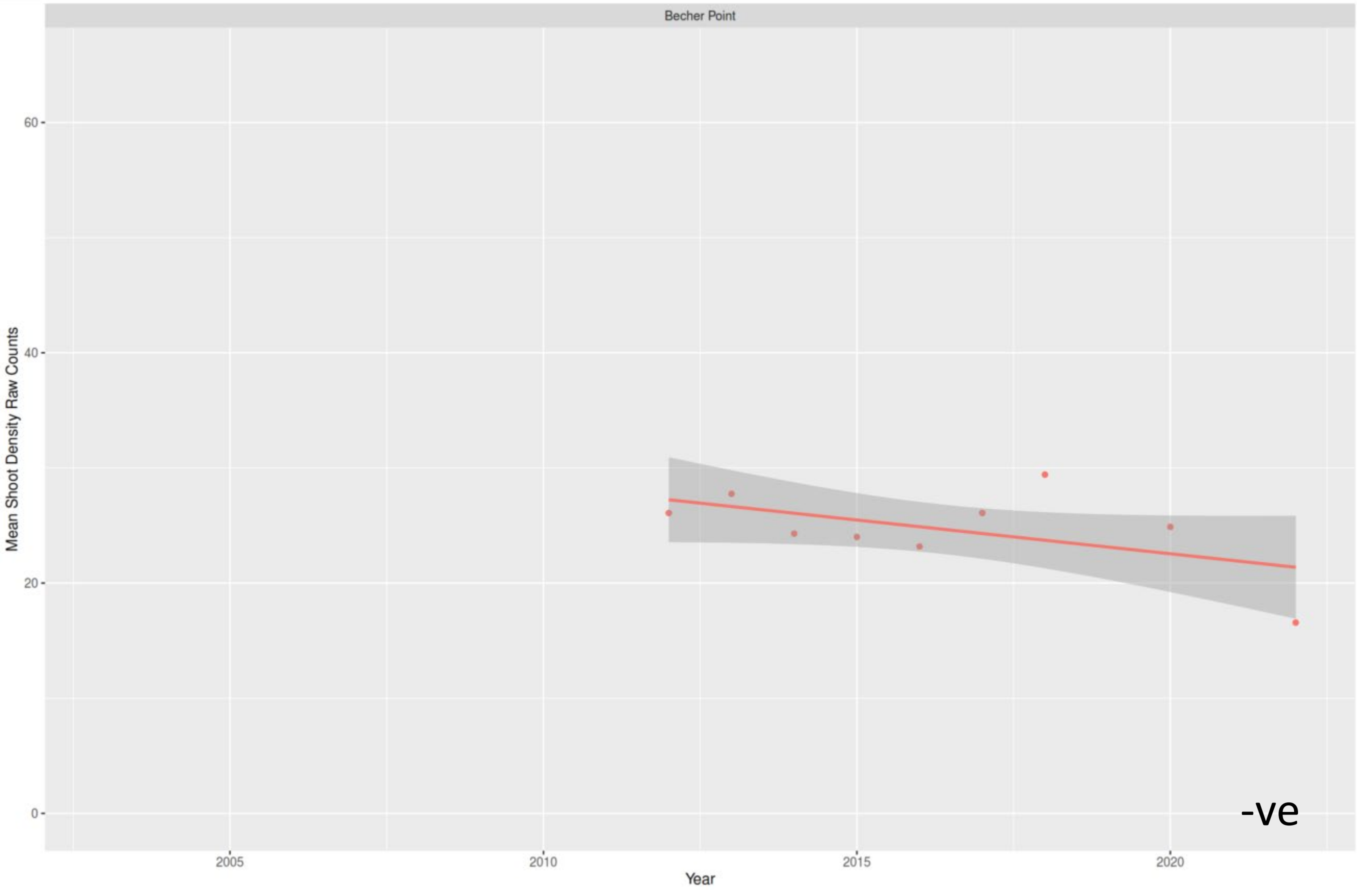
	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
EPIPHYTE TYPE										2	1	1								
EPIPHYTE COVER										2	2	2								
AVG SUMMER TEMP	21.9	21.4	21.5	21.0	21.9	22.0	21.9	22.0	23.1	22.8	22.7	22.3	22.2	22.2	21.7	22.1	21.7	22.8	22.4	23.0
YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

BECHER POINT

Start in 2012



WATER DEPTH
4 METERS

TREND

P = 0.4

[Mann Kendall test]

EPIPHYTE TYPE										2	1	1								
EPIPHYTE COVER										2	2	2								
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YEAR	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22

3= Filamentous

1= Low, 2= Mod, 3=High

7.2 Appendix 2: Data sheet used at the Workshop to capture participants view of the drivers of seagrass decline or condition, the confidence in this prediction, and to identify any relevant supporting information.

SITE NAME			
GROUP NAME			
Drivers of seagrass decline / condition	**Confidence (Low, Moderate, High)**	**Site specific support (Y/N)**	**Supporting Information (List Papers, Reports)**
Low light from epiphytic algal blooms			
Low light from phytoplankton blooms			
Low light from resuspended find sediments			
Change in light quality			
Sediment burial			
Physical disturbance			
Invasive species			
Increased temperature / heat waves			
Storms			
Erosion			
Increased anoxia in the sediments and sulphide intrusion			
Altered hydrodynamics / reduced flushing			
Organic carbon increases in the sediment			
Increased grazing			
Change in salinity			
Disease			
Pollutants & toxins			
Fishing traps			
Dredging			

7.3 Appendix 3: Summary and grouping of drivers of condition from which actions to reduce the impact of the drivers or build resilience in seagrasses to this driver were identified.

General activity	**Detailed activity or consequence of activity**
Dredging	Sand mining & processing, plumes from sand-washing
Dredging	New port developments, channels & on-going maintenance dredging
Shipping	Ship traffic
Recreational boating	Anchoring, mooring & propellor scars in shallow water
Fishing	Fish traps deployment, physical movement & retrieval
Coastal infrastructure & coastal morphology	Coastal Infrastructure/impacts on hydrology/flow
Modification of physical environment	Low flow
Modification of physical environment	Loss of sediment
Nutrient enrichment & other contaminants	Nutrient enrichment & other contaminants
Nutrient enrichment & other contaminants	Sediment quality
Biological interactions	Urchin grazing
Biological interactions	Species changes
Biological interactions	Growth forms/density meadow interactions
Ocean warming and heatwaves	Warming

7.4 Appendix 4: Categories of actions identified

Type of Action	**Detailed Action**
Management	POLICY, REGULATION & ENFORCEMENT
Management	BEST PRACTISE GUIDELINES & MONITORING
Management	MODIFY PROCESSES OR TIMING TO MINIMISE IMPACT
Management	MONITOR
Nature-based solutions	RESTORATION &/OR REHABILITATION
Nature-based solutions	CLIMATE PROOFING
Nature-based solutions	NATURE-POSITIVE ACTIONS
New industry	NEW INDUSTRY
Engineering	ENGINEERING SOLUTIONS
Engineering	INFRASTRUTURE OR DESIGN TO MINIMISE IMPACT
Engineering	NATURE-POSITIVE INFRASTRUCTURE OR ACTIONS
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS
Knowledge and education	NEW STUDIES
Knowledge and education	EDUCATION

7.5 Appendix 5: Complete list of actions for all drivers arranged by category of action

	General driver	**5A: Dredging**
	Detailed driver	**Sand mining and processing particularly plumes generated from washing sands & New port developments including channels and on-going maintenance dredging.**
Action Category	***Detailed category***	***Action***
Management	REGULATION	Regulate activity especially the plumes generated from sand washing and for the restoration of impacted areas.
Management	BEST PRACTISE GUIDELINES	Reassess activities and update to follow best practice.
Management	CONSIDER TIMING TO MINIMISE IMPACT	Identify and implement environmental windows for activities.
Management	CONSIDER TIMING TO MINIMISE IMPACT	Identify and implement environmental windows for activities e.g. minimise plumes during seagrass seedling establishment time.
Management	MONITOR	Identify the optimum density of plants under the plume footprint to set shoot density indicators that can be used in monitoring.
Nature-based solutions	RESTORATION &/ OR REHABILITATION	Restore or rehabilitate areas that are dredged or impacted from the dredge plume footprint e.g. through seed restoration or using particular species or growth forms that facilitate or enhance success of restoration / rehabilitation.
Nature-based solutions	RESTORATION &/ OR REHABILITATION	Identify potential restoration areas in the impact prediction process for the new port development including for seagrass (soft sediments) but also reef (hard substrates).
Nature-based solutions	CLIMATE PROOFING	Recognise that seagrasses growing in the plume footprint may be acclimated to high turbidity and could be used to future proof other meadows that may receive low light / high turbidity events in the future.
Engineering actions	ENGINEERING SOLUTIONS	Use engineering options such as diffusers or silk curtains to minimise impacts from plumes.
Engineering actions	NATURE-POSITIVE ACTIONS	Use dredged sediments for beneficial use e.g. capping poor quality sediment areas or replenishing areas where sediment has been lost and is not being replaced through natural processes
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS	Monitor the spatial footprint of the plume and how it effects the light climate by using loggers and / or modelling.
Knowledge and education	NEW STUDIES	To improve both current and potential future impacts, understand how the combination of reduced light, fine sediment deposition and warming will interact to effect seagrasses in the sand mining and plume footprint.

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

General activity **5B: Shipping & boating**

Detailed activity **Ship traffic & Anchoring, mooring and propellor scars in shallow water.**

Action Category	*Detailed category*	*Action*
Management	REGULATION	Set shipping operations to particular channels and speeds (based on largest vessels) to minimise negative effects of wake and propellor wash on adjacent habitats.
Management	REGULATION	Introduce anchor free zones, potentially rolling exclusion zones over time in sensitive areas and encourage the use of low impact anchoring.
Management	POLICY	Codesign policy with boaters and recreational fishers for solutions that will encourage behaviour change in anchoring including actions such as policy updates, improvements to anchoring approaches and will promote the uptake & implementation.
Management	BEST PRACTISE GUIDELINES	Code of conduct for shipping operations including considerations such as speed, depth of channels, turning basins & timing of activities as well as permanent moorings.
Management	BEST PRACTISE GUIDELINES	Incentivise alternative anchoring systems e.g. dynamic positioning poles rather than anchors.
Management	MONITOR	Monitor deep channels for depth assessment and other relevant characteristics.
Nature-based solutions	RESTORATION &/OR REHABILITATION	Focus restoration inside anchoring / mooring scars where small scale restoration is feasible.
Nature-based solutions	NATURE-POSITIVE ACTIONS	Plant seagrass in shipping channels to minimise resuspension of sediments (recolonisation has been noted along channels of Parmelia Bank)
Engineering actions	ENGINEERING SOLUTIONS	Use engineering options such as booms along shipping channels and berthing areas and turning basins or other engineering options to reduce wake and resuspension of sediments.
Engineering actions	NATURE-POSITIVE INFRASTRUCTURE	New moorings must be "seagrass friendly" moorings & replace old moorings with 'seagrass friendly' designs.
Engineering actions	DESIGN TO AVOID/MINIMISE IMPACT	Design turning basins into berthing area to reduce wake and propellor wash such as appropriate water depths.
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS	Model the potential impacts of sediment resuspension from shipping activities especially for Kwinana Shelf
Knowledge and education	EDUCATION	Provide education messages to the general public regarding the value of seagrass and not to anchor in seagrass meadows.

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

General activity **5C: Fishing**

Detailed activity **Fish traps deployment, physical movement and retrieval.**

Action Category	*Detailed category*	*Action*
Management	REGULATION	Establish exclusion zones and regulate the number of licences for participation.
Management	ENFORCEMENT	Police the zones and fishing activities, especially for recreational activities.
Management	BEST PRACTISE GUIDELINES	Provide best practise management for laying & retrieval of traps.
Management	CONSIDER TIMING TO MINIMISE IMPACT	Consider seasonal fishing ban.
Engineering actions	INFRASTRUCUTRE TO AVOID/ MINIMISE IMPACT	Ensure gear types are used that minimise impacts especially for recreational activities.

General activity **5D: Biological interactions**

Detailed activity **Urchin grazing.**

Action Category	*Detailed category*	*Action*
Nature-based solutions	NATURE-POSITIVE ACTIONS	Manage urchin population through harvesting.
New industry	NEW INDUSTRY	Explore urchins as a food product
Knowledge and education	NEW STUDIES	Research to understand if urchin populations can be managed through harvesting, biological control (predators) or biotechnology (e.g. invoking sterility).
Knowledge and education	NEW STUDIES	Research to assess significance of urchin grazing in reducing seagrass cover, the species involved and if significant, identify the cause-effect pathway.

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

	General activity	**5E: Coastal infrastructure and coastal morphology and modification of physical environment**
	Detailed activity	**Coastal Infrastructure/impacts on hydrology/flow & Low flow, & No sediment.**

Action Category	***Detailed category***	***Action***
Management	BEST PRACTISE GUIDELINES	Inform design of coastal infrastructure from best practise and successful relevant case-studies.
Nature-based solutions	RESTORATION &/OR REHABILITATION	In restoration, consider increasing stability of sediments with biodegradable netting or hessian that seeds or seeds can be attached to.
Nature-based solutions	RESTORATION &/OR REHABILITATION	If areas with lower sediment depths (i.e. the substrate in which seagrass grows) are selected for seagrass restoration, then species adapted to such environments should be chosen (e.g. *Amphibolis* spp. can grow on low sediment substrates such as rocky reefs)..
Nature-based solutions	NATURE-POSITIVE ACTIONS	Consider design of coastal infrastructure that promotes biodiversity and has positive flow-on effects to the food web.
Nature-based solutions	NATURE-POSITIVE ACTIONS	Green infrastructure, promote ecosystem functions e.g. biodiversity, stabilising sediments, filtering water, storing carbon through seagrass restoration, oyster reefs, shore-based dune restoration or rehabilitation
Engineering actions	ENGINEERING SOLUTIONS	Use dredged sediments for nourishment, contamination assessment needed, and grain size considered combined with structures to stabilise e.g. geotextiles
Engineering actions	ENGINEERING SOLUTIONS	Remove structures to improve coastal processes or modify existing structures to have a positive influence on or reduce impacts to coastal processes, e.g. to maximise the survival of seagrass on Southern Flats and enhance water flow, increase the porosity of the causeway to increase flow and water exchange but not increase wave energy.
Engineering actions	INFRASTRUCUTRE TO AVOID/ MINIMISE IMPACT	Use fountain pumps to increase mixing of the water column and reduce the chance of deoxygenation and low oxygen in bottom waters.
Engineering actions	NATURE-POSITIVE ACTIONS	Consider how extraction of seawater for desalination plants can be used to help increase flow and mixing of water for example to reduce low oxygen events.
Engineering actions	DESIGN TO AVOID/MINIMISE IMPACT	For assessment of future developments ensure the impact on bathymetry and benthic water flow is considered and design to minimise reduced flow. Ensure that assessment is made at the local scale and relevant for different habitat types.
Engineering actions	DESIGN TO AVOID/MINIMISE IMPACT	Use conventional modelling to inform design of engineering solutions. For example, for the location of the northern channel through Owen Anchorage to Cockburn Sound, select locations away from seagrass.
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS	Use modelling that incorporates habitats and dynamic processes to make decisions and test scenarios for different mitigation measures and their potential locations. Make sure that future conditions ie changes in sea level are incorporated into these models.

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

	General activity	**5F: Nutrient enrichment & other contaminants**
	Detailed activity	**Nutrient enrichment & other contaminants in water column and sediment**
Action Category	***Detailed category***	***Action***
Management	BEST PRACTISE GUIDELINES	Reduce nutrient loads to coastal environment (surface and groundwater).
Management	MODIFY PROCESSES TO MINIMISE IMPACT	If sediment quality is impacting seagrass condition, then manage other pressures to reduce stress to increase seagrass resilience & condition.
Nature-based solutions	NATURE-POSITIVE ACTIONS	Use natural biofiltration and remediation to improve water quality e.g. oyster reefs or seaweed farms.
Nature-based solutions	NATURE-POSITIVE ACTIONS	Encourage optimal levels of bioturbation potentially through the addition of infauna to improve sediment biogeochemistry.
Engineering actions	NATURE-POSITIVE INFRASTRUCTURE	Increase water exchange in Cockburn Sound by increasing the porosity of the Causeway.
Engineering actions	NATURE-POSITIVE ACTIONS	Remove fine sediments during dredging to minimise accumulation in the sediment and degradation of sediment quality.
Engineering actions	NATURE-POSITIVE ACTIONS	Prior to dredging collect top sediment layer for rehabilitation or restoration activities and if seagrass absent then cap substrate with layer of clean sediment if sediment totally unsuitable for seagrass colonisation or restoration and consider sorting to include the most appropriate grain size.
Engineering actions	NATURE-POSITIVE ACTIONS	Addition of Fe^{2+} to sediments to bind sulphides and change biogeochemistry so that sulphide intrusion into seagrass is reduced.
Engineering actions	DESIGN TO AVOID/MINIMISE IMPACT	Interventions to improve environmental conditions to enhance seagrass condition such as optimal water flow or benthic light.
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS	Use modelling to identify key nutrient and contaminant inputs to Cockburn Sound and Owen Anchorage and then manage key sources to minimise inputs of nutrients into the coastal zone (both surface and groundwater).

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

General activity **5G: Biological interactions**

Detailed activity **Species changes & Growth forms/density meadow interactions.**

Action Category	*Detailed category*	*Action*
Nature-based solutions	RESTORATION &/OR REHABILITATION	Select most appropriate species for restoration programs based on an understanding of habitat suitability.
Nature-based solutions	RESTORATION &/OR REHABILITATION	Use understanding of ecological succession to inform restoration actions e.g. co-planting of colonising and persistent species.
Nature-based solutions	RESTORATION &/OR REHABILITATION	Actions to increase density of meadows to enhance sediment trapping functions.
Engineering actions	ENGINEERING SOLUTIONS	Develop coastal infrastructure that facilitates natural colonisation of seagrass and supports succession to desired species.
Knowledge and education	NEW STUDIES	Understand the historical seagrass and algal species assemblages through paleoecology using a combination of carbon and lead dating, eDNA and isotopes.
Knowledge and education	NEW STUDIES	Understand seagrass species interactions e.g. why is *P. australis* increasing in some areas that were once *P. sinuosa* and is this a problem or can this understanding improve restoration?
Knowledge and education	NEW STUDIES	Understand the threat from tropicalisation of other benthic primary producers such as Caulerpa.
Knowledge and education	NEW STUDIES	Understand if the epiphyte community varies across different seagrass species and if this affects ecosystem functions.
Knowledge and education	NEW STUDIES	Understand how ecosystem function varies with different combinations of seagrass species.
Knowledge and education	NEW STUDIES	As there are differences in seagrass meadow structure across Cockburn Sound and Owen Anchorage, and these can vary over depth gradients or other environmental pressures, use this to indicate where/when intervention should occur e.g. at what is considered a low density select this for a restoration site.
Knowledge and education	NEW STUDIES	Recognise that the meadow condition (species / density) will vary over Cockburn Sound and Owen Anchorage due to environmental conditions therefore the desired state will vary by location.

Appendix 5 (con't): Complete list of actions for all drivers arranged by category of action

General activity **5H: Ocean warming and heatwaves**

Detailed activity **Warming seawater temperatures**

Action Category	***Detailed category***	***Action***
Nature-based solutions	CLIMATE PROOFING	Trial resilience building options such as priming adult plants or seedlings to warmer conditions that could be incorporated into restoration programs or other resilience building activities.
Nature-based solutions	CLIMATE PROOFING	Identify if there are more thermal tolerant seagrass populations within a species geographic distribution to supplement temperate cousins e.g. Jurien to Perth.
Engineering actions	ENGINEERING SOLUTIONS	To reduce localised warming of waters in Cockburn Sound increase the porosity of the Causeway so that cooler water is flushed into Cockburn Sound or pump cooler water into Cockburn Sound or utilise wastewater recycling to introduce cooler water.
Knowledge and education	IMPROVE UNDERSTANDING TO INFORM DECISIONS	Modelling future climate conditions in Cockburn Sound to identify vulnerable areas for seagrass based on environmental thresholds.

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Review completed	15/01/2025
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Approved by WAMSI CEO	11/04/2025
Final report	

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