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Two decades of seagrass monitoring data show drivers include ENSO, climate warming and local stressors

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.

OWNERSHIP OF INTELLECTURAL PROPERTY RIGHTS

FUNDING SOURCES

The $13.5 million WAMSI Westport Marine Science Program was funded by the Western Australian Government, Department of Transport. WAMSI partners provided significant in-kind funding to the program to increase the value to >$22 million.

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).

LEGAL NOTICE

YEAR OF PUBLICATION

July 2024

This report is part of the project: Pressure-response relationships, building resilience and future proofing seagrass meadows.

CITATION

Webster, C., McMahon, K., Ross, C., Afrifa-Yamoah, E., Said, N., Hovey, R., Martin, B., Strydom, S. (2024). Two decades of seagrass monitoring data show drivers include ENSO, climate warming and local stressors. Prepared for the WAMSI Westport Marine Science Program. Western Australian Marine Science Institution, Perth, Western Australia. 31 pp.

FRONT COVER IMAGE

Theme: Benthic habitats and communities
Front cover image: Seagrass (Posidonia australis) in Cockburn Sound. Photo courtesy of Rachel Austin (The University of Western Australia).

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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.

1 Two decades of seagrass monitoring data show drivers include ENSO, climate warming and local stressors

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Project
Theme 2, Project 2.2: Pressure-response relationships, building resilience and future proofing seagrass meadows

Date
30 November 2023

Executive Summary

The drivers contributing to the trajectories of seagrass ecosystems is a key knowledge gap which limits our effectiveness in preventing their decline. Here, we present the key findings from the regional assessment of seagrass condition (shoot density) over time, which was undertaken to inform environmental impact assessment and monitoring as well as mitigation for the Westport program. To assess regional trends and drivers of these trends, data was collated from five regional seagrass monitoring programs, including the Cockburn Sound State Environmental Policy Seagrass Monitoring Program and marine park monitoring programs conducted by the Department of Biodiversity, Conservation and Attractions. These monitoring programs are located in the temperate waters of Western Australia (WA) along a latitudinal gradient (30-33°S, covering ~365 kms) and focus on the dominant habitat forming species, *Posidonia sinuosa*. WA has been designated as a hotspot for climate pressures, influenced by ocean warming and extreme climatic events and there are localised anthropogenic pressures that seagrasses are susceptible to. Hence, this regional approach enables an assessment of the relative importance of global (e.g. warming) and local (e.g. coastal development) pressures for seagrasses.

The five regions assessed included the highly industrialised marine embayment of Cockburn Sound and four non-industrialised marine parks: Jurien Bay, Marmion, Shoalwater Islands and Geographe Bay within Ngari Capes (hereafter, Ngari Capes). Environmental predictors were selected based on an understanding of the major factors that affect seagrass condition, which included: depth, turbidity, sea surface temperature anomaly, mean sea surface summer temperature and habitat type. Hierarchical Generalised Additive Models (HGAMs) were run to examine the spatiotemporal trends in seagrass condition and to identify significant drivers as identified above, with the addition of region, site and geographic position.

The key findings were:

- Across regions *Posidonia sinuosa* condition varied over time with a downward trend until 2017, after which there was a reversal in abundance. The variations aligned partly with El Niño Southern Oscillation.
- Spatial and temporal shifts in *Posidonia sinuosa* shoot density were reasonably explained by region, year, water depth, turbidity, mean sea surface temperature in summer (mean_summer) and maximum sea surface temperature anomaly (max_over).
- In some cases, there were differences in the effects of predictor variables on seagrass condition within each region (i.e. localised marginal effects). For example, mean_summer led to seagrass declines in Cockburn Sound but had very little effect in Jurien Bay.
- Seagrass condition differed among regions, with shoot densities in Ngari Capes significantly higher than Cockburn Sound. Increased mean_summer temperatures were a strong driver of the observed declines in *Posidonia sinuosa* condition, especially in Cockburn Sound and Marmion.
- Cooler sea surface temperature regime associated with higher latitude (Ngari Capes) appears to be 'buffering' *Posidonia sinuosa* condition from climate change effects.
- Oscillations in *Posidonia sinuosa* abundance were most strongly linked to the El Niño Southern Oscillation cycle in Jurien Bay and to a lesser extent, Cockburn Sound.

Our results suggest that condition of *Posidonia sinuosa* across WA has declined in response to ocean warming and this was most pronounced in mid-latitude regions (31-32°S). Overall, it appears that in response to future climate change there will be variation in *Posidonia sinuosa* condition within regions and safeguarding healthy meadows as potential climate refuge sites is important to consider. Dredging and other coastal development activities that increase turbidity levels are likely to worsen *Posidonia sinuosa* condition given that low light impact seagrasses, and Cockburn Sound is quite susceptible to this. The variation in relationships between predictors and seagrass condition within regions highlights the importance of tailoring management actions to specific stressors and locations. Importantly, this work emphasises the value of long-term seagrass monitoring programs to evaluate ecosystem status in an era of rapid global change.

2 Introduction

Greek philosopher Heraclitus said, “The only constant in life is change”. Studies to investigate how phenomena change and the causes therein are common across research disciplines e.g. public health, political science and ecology (Bennett et al., 2022; Gordon et al., 2017; Machault et al., 2011). A high degree of uncertainty still exists regarding the drivers of marine ecosystem trajectories, making the anticipation of the impacts of disturbances challenging (Fisher et al., 2018). This uncertainty has been attributed to mismatches in the temporal and spatial resolution of data and inconsistencies in sampling methods (Ebrahimi et al., 2017). Decisions on conservation and management actions are often based on our understanding of system drivers, and if studies lack adequate statistical rigour this can reduce the likelihood of gaining stakeholder support for appropriate actions (Schmidt et al., 2014). Long term ecological monitoring data combined with remotely sensed environmental data can alleviate the challenges associated with statistical rigour. For example, Hobday et al. (2016) defined and developed environmental metrics that characterised marine heatwaves using remotely sensed sea surface temperature data (SST), which could then be applied for impact assessment on marine ecosystems. Multiple environmental metrics are useful for improving understanding of biological response since different species, or populations within species, respond differently so that the metrics that predict the response for one species (or population within species) may not necessarily apply to another (Fordyce et al., 2019; Strydom et al., 2020). Generating verifiable scientific evidence such as understanding what environmental drivers explain the trajectory of marine ecosystems can vastly improve conservation outcomes in an era of global change (Grech et al., 2011).

2.1 Potential drivers of seagrass condition

Seagrasses are exemplar habitat-forming species that support the structure and function of marine ecosystems via their influential role on biogeochemical cycles, water quality, food webs and community composition (Marsh et al., 2018; Mcglathery et al., 2004; Moore et al., 2014). Yet seagrasses rank among the most threatened ecosystems on Earth; a demise related to natural and anthropogenic disturbances that directly remove seagrasses (e.g. dredging, storms) or cause indirect losses via unfavourable modifications to the environment (e.g. eutrophication that modifies the amount of light available to seagrasses) (Waycott et al., 2009; Duarte et al., 2009; Erftemeijer and Robin Lewis, 2006). Seagrasses are also perceived as the ‘ugly duckling’ of the ocean resulting in less resources being directed towards research and conservation (Unsworth et al., 2019). Nevertheless, the appreciation for the goods and services seagrasses provide is increasingly demonstrated by their inclusion in monitoring programs to assess coastal ecosystem status (Kilminster et al., 2015), identify important blue-carbon habitats (Hernawan et al., 2021) and studies to investigate global seagrass trends and drivers (Strydom et al., 2023; Turschwell et al., 2021). Whilst there are some consistencies in the trajectories of seagrasses worldwide, variation at local scales do not always reflect global scale trends, which suggests a greater emphasis on identifying local drivers of seagrass condition is needed (O’Brien et al., 2018).

Assessments of seagrass condition at global and local scales indicate that trajectories can be highly variable and likely linked to shifts in environmental conditions as well as the resistance capacity of seagrasses (Dunic et al., 2021; González-Correa et al., 2007; Shelton et al., 2017). Seagrass photosynthesis is influenced by a suite of environmental drivers with light, temperature and nutrients regarded as the most important (Lee et al., 2007). Seagrasses are known to have high light requirements relative to other plants (2-37% of surface irradiance) therefore water depth is often a limiting factor controlling seagrass distribution (Duarte, 1991). Dredging has also contributed to seagrass decline through reduced light, resultant from increased turbidity in the water column during operations (Erftemeijer and Robin Lewis, 2006). Eutrophication, leading to phytoplankton and algal blooms, also reduces light reaching seagrass meadows, and is another cause of seagrass decline (Silberstein et al., 1986). Temperature plays an influential role on photosynthesis; optimum photosynthetic rates generally occur between 15-33 °C, with species from temperate regions typically having lower thermal optima compared to species from tropical regions (Marbà et al., 2022). Modifications to temperature from climate change have caused substantial impacts to seagrass communities (Diaz-Almela et al., 2007). With rising water temperatures, respiration rates increase at a faster rate than photosynthesis resulting in a negative carbon balance, and under extreme temperatures, chronic photosystem damage can occur which leads to reduced seagrass growth and eventual mortality (Collier and Waycott, 2014). The different life history strategies among seagrass species influence the response to environmental variability. For example, the condition of small fast-growing species generally varies as they have limited capacity to resist unfavourable conditions. Contrastingly, larger seagrass species are typically slow-growing and more resistant to disturbances and commonly form persistent meadows in stable habitats (Kilminster et al., 2015). Whilst longer-term (years to decades) data is beneficial for examining trends of all seagrass species, it is particularly important for examining trends of larger, slow-growing species that are slow to respond to stress (Blanco-Murillo et al., 2022).

2.2 Western Australia as a case study for assessing drivers of seagrass condition

The West Australian coastal ecosystem is a biodiversity hotspot, with 26 of 72 global seagrass species, largest meadows globally, representative marine parks and a history of seagrass loss due to local anthropogenic activities and global warming (Carruthers et al., 2007; Edgeloe et al., 2022). Discharge of waste, nutrients and pollutants into marine embayments have resulted in major losses of seagrasses and especially between the 1960-2000s as industrialisation intensified e.g. Cockburn Sound where 22 km^2 was lost (Kendrick et al., 2002) and Princess Royal Harbour where 19 km^2 was lost (Bastyan, 1986). Dredging operations have also directly and indirectly contributed to large seagrass losses in WA (Lavery et al., 2009). Standalone examples of climate change impacts to seagrass have also been documented in WA, including an unprecedented loss of 1,310 km^2 of seagrass from Shark Bay following extreme water temperatures induced by a marine heatwave in 2010/11 (Strydom et al., 2020). Into the future there is the potential for these pressures to continue as the human population growth rate of WA is the highest in Australia (Davies, 2023), therefore consistent development of coastal areas represents a persistent threat to seagrasses. Marine heatwave hotspots like WA are also expected to have more rapid rates of ocean warming from climate change (Hobday and Pecl, 2014). In this context, WA is a useful case study location to examine patterns in the trajectories of seagrasses and identify key environmental drivers of these patterns.

Posidonia spp. are widespread throughout subtropical and temperate WA with traits consistent with a persistent life history strategy i.e. slow-growing, high biomass enduring meadows and in some regions producing abundant fruits and seeds that directly develop (i.e. no dormancy or seed bank) (Paling and McComb, 2000). These traits manifest as a greater capacity for resistance and so avoiding complete loss is critical as recovery can take decades (Meehan and West, 2000). Due to the recognised values these large seagrasses provide, and their ability to indicate ecosystem health, *Posidonia sinuosa* monitoring has been conducted over 19 years at multiple locations along a latitudinal gradient in WA that includes marine parks and the highly industrialised embayment of Cockburn Sound (Table 1). The focus of investigations of seagrass trends and drivers of conditions has generally been limited to a local (within-region) scale and to specific stressors (Fraser et al., 2015). It is therefore possible that these assessments do not capture the global scale influence of climate change in terms of gradual ocean warming; for instance, mean sea surface temperature is more likely to vary with latitude rather than over small distances of separation (Baumann and Doherty, 2013). Comparisons over global and local scales can delineate the relative importance of global and local drivers acting on seagrass communities and provide understanding to improve their conservation under environmental change (Turschwell et al., 2021).

The aim of this study was to investigate the spatiotemporal patterns in abundance of the dominant seagrass species, *Posidonia sinuosa*, along a latitudinal gradient and how this is influenced by relevant environmental conditions over time including major El Niño Southern Oscillation (ENSO) marine heatwave events that have significantly impacted marine ecosystems (e.g. 2010/11 marine heatwave, Pearce and Feng, 2013).

3 Materials and Methods

3.1 General approach

Annual *Posidonia sinuosa* abundance data from 5 regions (7 - 17 sites per region) were collated with a set of potential environmental drivers of meadow condition sourced from remotely sensed data to assess spatial and temporal patterns and the drivers of these patterns. This spanned 3° of latitude (30 - 33°) between regions and distances of approximately 40 km between sites within a region (Figure 1).

3.2 Site description

The climate of WA, like other Mediterranean-climate regions, exhibits variation within and among seasons and interannually (Philip and Yu, 2020; Yu and Neil, 1993). Summer (December-February) is generally characterised by higher water temperatures, low rainfall and winds that are predominantly offshore (Bureau of Meteorology, 2017). Prevailing conditions during winter (June-August) include lower water temperatures, higher rainfall and more frequent storms that can result in extreme wave heights (significant wave height or Hs > 4 m) (Lemm et al., 1999). Designated a marine heatwave hotspot, ocean warming rates in WA are projected to be much faster than other regions (Hobday and Pecl, 2014). Diverse habitats occur along the coastline with broken offshore islands and submerged limestone reefs lining the coast which reduce the impact of ocean swells and allow sand deposition in the lee of islands. Moving south, granite headlands and islands also attenuate ocean swells. These characteristics create sheltered and exposed habitats that a suite a range of seagrass species, although *P. sinuosa* is generally dominant (Kirkman and Kuo, 1990).

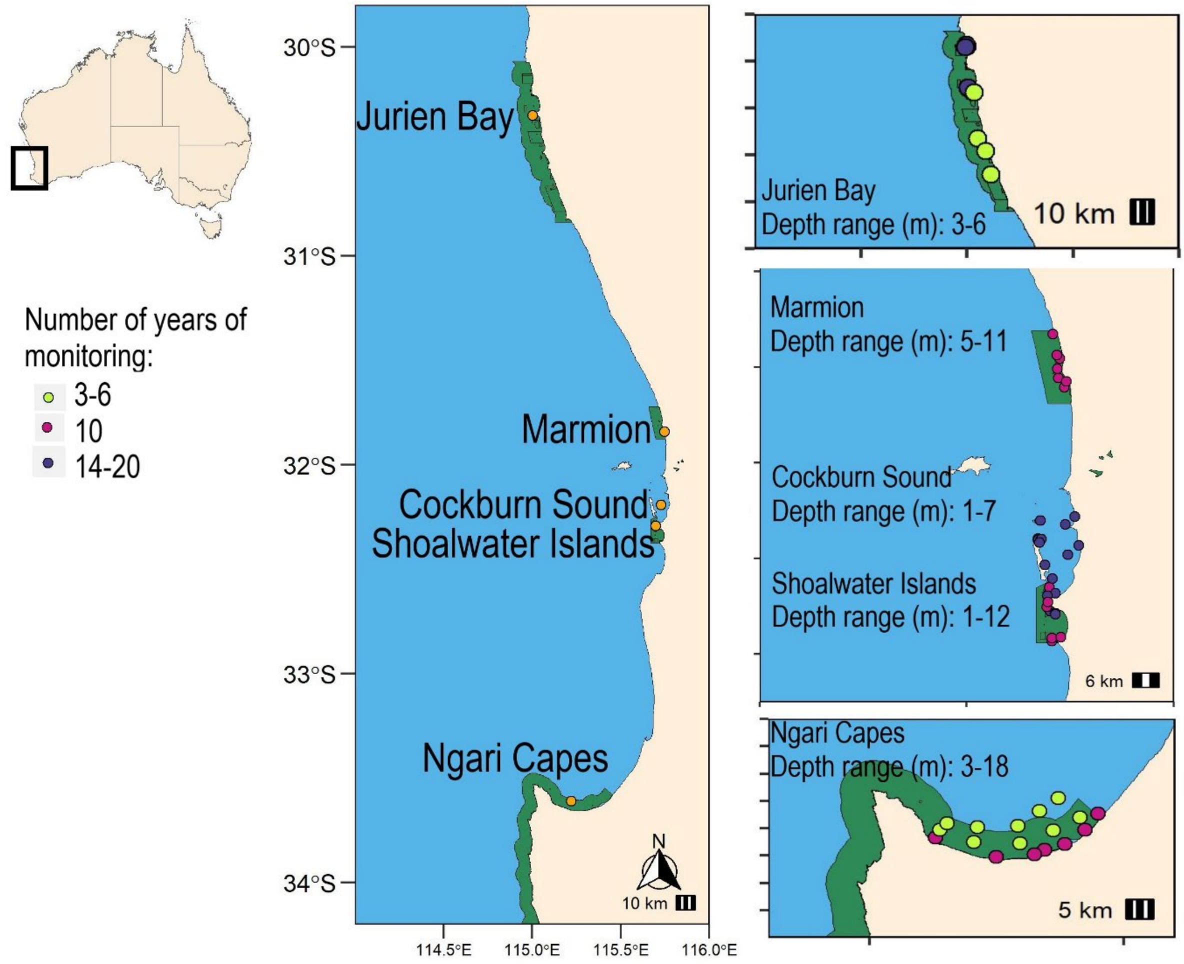


Figure 1. Map of south-west Australia where monitoring of seagrass *Posidonia sinuosa* occurs across a latitudinal gradient (orange dots represent the five regions, left) and the three insets illustrate sites within each region grouped by number of years of monitored (coloured dots). Green shaded areas denote marine park boundaries.

3.3 Monitoring programs

Seagrass monitoring commenced in each region in different years and for different purposes resulting in difference in the methods used to monitor seagrass that evolved over time (Table 1, please refer to Appendix Section 8.1 for more details). In Cockburn Sound, for instance, the Environmental Protection Authority established a State Environmental Policy to assess the environmental quality of this heavily industrialised system (Environmental Protection Authority, 2005). Seagrass, specifically the dominant species *P. sinuosa,* was identified as the key indicator for gauging environmental impact of nutrient enrichment which was the dominant historic stressor for Cockburn Sound. Seagrass monitoring commenced in 2003 in Cockburn Sound with reference sites in Shoalwater Islands and Warnbro Sound. Initially Jurien Bay and Ngari Capes were set-up to monitor seagrass condition in relation to threats from coastal development and eutrophication, then when marine parks were established in these locations, additional sites were added to capture temporal change across different management zones. The seagrass monitoring program in Marmion was established in 2011 by DBCA.

Across the five regions, the number of sites and depth range varied, as well as the timing of monitoring, although monitoring was generally conducted in summer during peak seagrass growth (December to April) and on an annual or bi-annual basis (Figure 1, Table 1). Programs included a suite of indicators, however, this study focussed exclusively on analysing shoot density, which is a widespread indicator of seagrass condition globally, and was most consistently measured throughout all programs. Shoot density reflects consistent changes in meadow condition in response to stress e.g. declining under increasing levels of light reduction (Collier et al., 2009). In all programs the shoot counts were undertaken within 0.04 m^2 quadrats and then scaled to shoot density m^{-2}.

3.4 Description of dataset and QA/QC procedures

Each monitoring program included a quality assurance and control process (QA/QC) to reduce observer error and ensure that shoot counts were consistent among scuba divers collecting data in each Region. For example, in Ngari Capes, observers were asked to count shoots in three different quadrats twice. This process was repeated until there was less than 5 % of error with counting (i.e. difference of 1-3 shoots) and then subsequent counts were recorded. Similarly in other seagrass monitoring programs, at the start of each field program, the leading seagrass scientist who had collected data in previous years would demonstrate how to count *P. sinuosa* shoots underwater within the 0.04 m^2 quadrat, then this count would be compared those counts conducted by the new diver. This process would be repeated until counts among divers were within 5 %. Once the new divers' counts were checked, they could proceed to conduct shoot counts for subsequent programs.

A dataset was compiled by combining data from monitoring programs described above, and to ensure comparability, quality assurance was carried out on this dataset. In this combined dataset we noticed higher variability among counts for one year (2022) in Cockburn Sound. Therefore, counts that resulted in increases or decreases of 20 % in the average shoot density per site were checked and these specific observations removed as we would not expect to see changes in shoot densities of this magnitude given *P. sinuosa* is a slow growing species. Blank cells in the shoot density column of the dataset were verified by checking with the data custodians as to whether these represented true zeros or missing data. If true zeros were confirmed, then the cell was amended to a zero, and if the data was missing, then the entire row was deleted. The average shoot densities were also plotted by year for each site (Appendix Section 8.2). The final shoot density dataset comprised 16,490 observations from 61 sites monitored between 2003 and 2022.

Table 1. Summary of spatial and temporal characteristics of seagrass monitoring programs across five regions within Western Australia. Note depths are stated relative to the Mean Sea Surface then reduced to Australian Height Datum (AHD) to account for tides.

Region	Latitude	Marine Park (Year of designation)	Year monitoring started	Years (n) sampling*	n of sites	Method	n of quadrat observations	Depth range (m)	Habitat types	Data custodians
Jurien Bay	30	Yes (2003)	2003	14	10	Fixed transect Semi-random	24	3 - 5.6	Exposed reef, sheltered reef	DBCA
Marmion	31.6	Yes (1987)	2011	6	7	Semi-random	24	5.7 - 10.7	Exposed reef	DBCA
Cockburn	32	No	2003	19	15	Fixed transect	24	1.2 - 6.8	Semi-enclosed embayment	CSMC
Shoalwater Islands	32.5	Yes (1990)	2003	19	12	Fixed transect Semi-random	24	1.6 - 11.8	Exposed reef, open embayment, semi-enclosed embayment	DBCA
Ngari Capes	33.5	Yes (2012)	2012	10	17	Random	30	3.6 -18	Open embayment	DBCA, ECU

*Years of sampling is not the same across all sites

Data custodians: DBCA- Department of Biodiversity, Conservations and Attractions; CSMC- Cockburn Sound Management Council; ECU- Edith Cowan University

3.5 Environmental predictors of seagrass condition

Shoot density was used as the response variable as it reflects changes at the meadow-scale. Generally, shoot density changes take time (months to years) to manifest in response to the effects of past environmental conditions (McMahon et al., 2013). Hence, we selected shoot density of the year of sampling (t) and matched this with the data for all environmental predictors from the year prior to seagrass sampling (t-1). Additionally, the interval of ‘t – 1’ reflects consideration of timescales that are likely to be relevant for adapting management actions. Two temperature metrics were included to assess the effects of gradual, long-term changes in seawater temperature and extreme events such as marine heatwaves on seagrass. The first metric, mean sea surface temperature in summer (mean_summer), was the temperature averaged over the summer months for December, January, February and March of the year prior to when the seagrass was monitored. The second metric was the maximum sea surface temperature difference between the global mean of temperature (long term average over 20 years) and the maximum daily temperature value reached within the year (max_over) prior to when the seagrass was monitored. In relation to light, a MODIS Kd490 product called “KD2” was used and refers to the rate at which light at 490 nm attenuates with depth (i.e. diffuse attenuation coefficient), therefore the higher the coefficient value the lower the water clarity and less light reaching the seafloor (Wang et al 2009); this predictor is hereafter referred to as turbidity. Depth data was extracted for each site from the Two Rocks to Cape Naturaliste LiDAR survey which acquired accurate bathymetry data using Airborne Laser Bathymetry techniques with the final bathymetry grid adjusted to the Mean Sea Surface then, reduced to Australian Height Datum (AHD) to account for tides (Fugro, 2009). A product of the survey was a geo-referenced surface image of the bathymetry data (10 m resolution) which was sampled at each site using the Sample tool in ArcGIS (version 10.7). The extracted depth value for each site was the same for that site across time. Daily Kd490 and sea surface temperature (SST) were extracted from NOAA’s ERRDAP data server (Kd490: Institution: NOAA NESDIS CoastWatch; Dataset ID: noaacwNPPVIIRSSQkd490Daily across 4km grid cells (pixels); SST: Dataset ID: NOAA_DHW across 5 km grid cells). The proximity of seagrass sites meant that in some cases two sites were contained with the same NOAA 5 km grid and in these cases, the same value was used for both sites. To avoid the NOAA land mask, the NOAA grid cell closest to each seagrass site was selected manually. Habitat type was included as a categorical predictor based on the synthesis of Carruthers et al. (2007) which proposed that composition of seagrass communities varies among habitat types that represent key features of the southwest Australian coastline: exposed reef, open embayment, semi-enclosed embayment and sheltered reefs.

3.6 Statistical analyses

Hierarchical Generalised Additive Models (HGAM) were used to assess the relative global and local scales of importance of scale predictor variables, including habitat type, depth, turbidity, max_over, mean summer temperature, region, sites within region and year on seagrass condition (shoots m^{-2}) (Table 2). The HGAM approach was used due to its capability of modelling nonlinear functional relationships between covariates, and to outcomes and adequately capture between and within variations of different grouping levels. Thus, HGAM generates a global (overall) estimates of the relationships, as well as, group-specific relationships that were penalised to be close to mean function (Pedersen et al., 2019). All variables were included as fixed factors, except for site (because the levels of site were not exhaustive of the regions of interest). One of the objectives was to understand how drivers may differ between the most industrialised region of Cockburn Sound and the non-industrialised marine parks. Thus, Cockburn Sound was treated as the reference level for the factor Region and the mean value of shoot densities for the other regions was compared against the mean value for Cockburn Sound. Site was included as a random effect. The formula fitted to the model was as follows:

$$E(count\ per\ square\ meter) = \ \beta_{\mathbf{1}_i} Region_i + \beta_{2_i} Habitat_i + f_1(Year)$$
$$+ f_2(Depth) + f_3(Site) + f_4(kd490) + f_5(\max over) + f_6(\mathrm{mean}\, summer)$$
$$count\ per\ square\ meter \sim Gaussian(\mu, \Sigma)$$
where f_i are smooth functions.

Mixed effects were estimated given the repeated sampling across years. An unbalanced design was used given the number of sites, the number of years of sampling and the timing of sampling, were not consistent among regions. The Horvitz-Thompson type estimator was used to adjust for any sampling biases. The relationships between the continuous independent variables (depth, turbidity, and temperature) and the response variable were nonlinear and therefore, they were estimated via smoothing functions (i.e., splines) in the HGAM framework. A Gaussian distribution was used to model seagrass condition because of the large counts which would imply a large mean value (Theory – Poisson approximation to the Normal distribution). Spatial autocorrelation was corrected by including the latitude and longitude coordinates as a smooth term in the model. There were 12 continuous predictor variables but only 8 variables were included to avoid issues with collinearity ($R \geq 0.7$) (Table 2). Five predictor variables that were highly correlated ($R > 0.7$) were excluded to avoid issues with collinearity (Appendix 8.2, Table 5). A predictor was considered to be statistically significant if the p-value was ≤ 0.05. Statistical analysis for identifying predictors of seagrass condition were conducted in the R language for statistical computing (version 4.3.1) and utilising packages such as mgcv (Wood, 2017), mgcViz (Fasiolo et al., 2020) and gratia (Simpson, 2023).

Table 2. Large and local-scale predictor variables that were modelled against seagrass condition (shoot m^{-2}) at each site. Note that the seagrass shoot density in the year of sampling (t) is matched with the value for the environmental predictor variables (turbidity, mean_summer, max_over) calculated in the year prior to when the seagrass was sampled (t - 1).

Predictor	Description
Region	Refers to the general area of the coast that has common features (e.g. latitude) where *Posidonia sinuosa* has been monitored along the Western Australian coast (see Table 1)
Year	Year that seagrass monitoring took place
Site (Region)	Sites are unique to each region (i.e. the site Kangaroo Island can only be found in the region of Jurien Bay) and not all regions have the same number of sites. Thus, site has been treated as a nested factor within region which allows us to control for the variation coming from sites
Habitat type	Classification of seagrass habitat type which is influenced by swell exposure and based on Carruthers et al. (2007) (exposed reef, open embayment, semi-enclosed embayment and sheltered reefs)
Depth	Depth of site measured in metres relative to mean sea surface
Turbidity	Indicated by the diffuse attenuation coefficient (Kd490) which represents the rate at which light at 490 nm is attenuated with depth.
Mean_summer	Sea surface temperature averaged over the summer months of December, January, February and March of year prior to when the seagrass was monitored to create a value representing the mean sea surface temperature in summer
Max_over	The maximum sea surface temperature difference between the global mean of temperature (long term average over 20 years) and the maximum daily temperature value reached within a year

4 Results

4.1 General shoot density trends

Across all regions and years seagrass shoot density ranged between 180 (± 22) to 1262 (± 36) m^{-2} (Figure 2). Shoot density fluctuated over time, but these temporal patterns were not consistent across regions (Figure 2). There were similarities in the shoot density patterns in Jurien Bay, Cockburn Sound and Shoalwater Islands where seagrass was monitored over the longest timeframe. Specifically, densities were highest in the first 3-5 years then generally declined over time, although from year to year there was considerable variation, increasing or decreasing by 100 – 200 shoots m^{-2} on average (Figure 2). Shoot densities in Ngari Capes tended to be higher and the values were more consistent compared to the other regions, ranging from 827 (± 27) to 1262 (± 36) shoots m^{-2} (Figure 2). Overall, shoot densities were generally lower in Marmion, ranging from 180 (± 22) to 431 (± 24) m^{-2} (Figure 2).

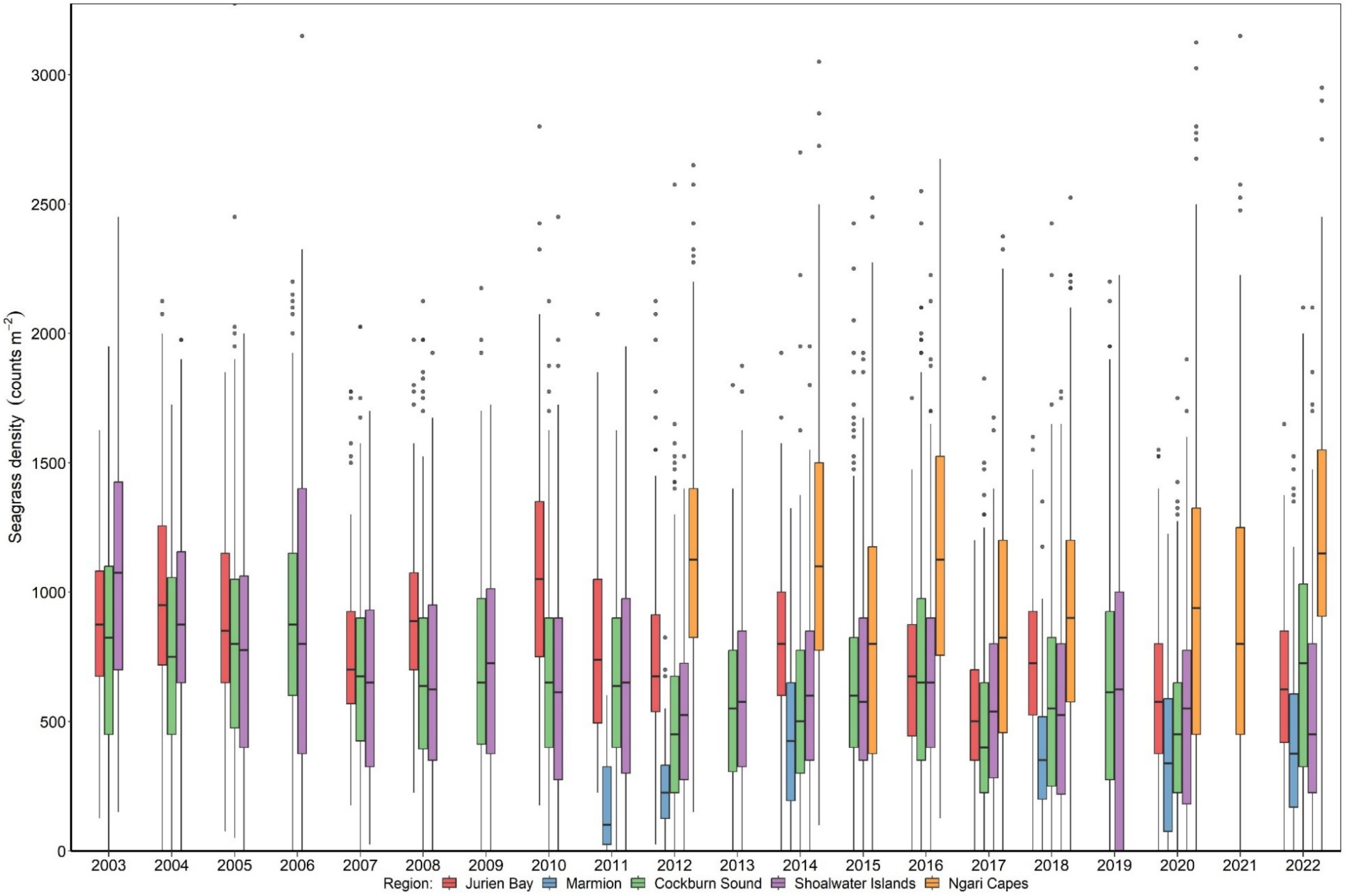


Figure 2. Mean (± SE) shoot density (m^{-2}) of seagrass *Posidonia sinuosa* across five regions in Western Australia monitored between 2003 to 2022. Note y-axis ranges are different according to region.

4.2 Global marginal effect of predictors on seagrass condition across regions

Region, Site, Year, Turbidity, Depth, max_over and mean_summer significantly influenced the shoot density of *P. sinuosa* (Table 3). Habitat type was non-significant and there was no spatial autocorrelation (Table 3). Shoot densities were significantly higher in Ngari Capes (p=0.003) compared to Cockburn Sound (reference region); no differences were observed among the other regions (p>0.05, Table 3, Figure 3a). Globally, over time shoot densities oscillated for approximate periods of 2 to 3 years either increasing or decreasing with oscillative downward pattern until 2017. However, after 2017 the trajectory was upwards (Figure 3b). Higher shoot densities were associated with shallower depths (Figure 3c) and lower turbidity (Figure 3d). Shoot densities declined with mean summer temperatures between 23.5 to 26 °C with the influence of temperature in the upper range (27-28 °C) less certain (Figure 3f), likely due to less temperature values present in the upper range. Although, max_over was identified as a significant predictor of shoot density the nature of the relationship was not clear, and there was high uncertainty above 6 °C (Figure 3e). Most sites followed the global patterns, except for some individual sites showing distinct patterns of variation depicted at the upper and lower extremities (Figure 3g).

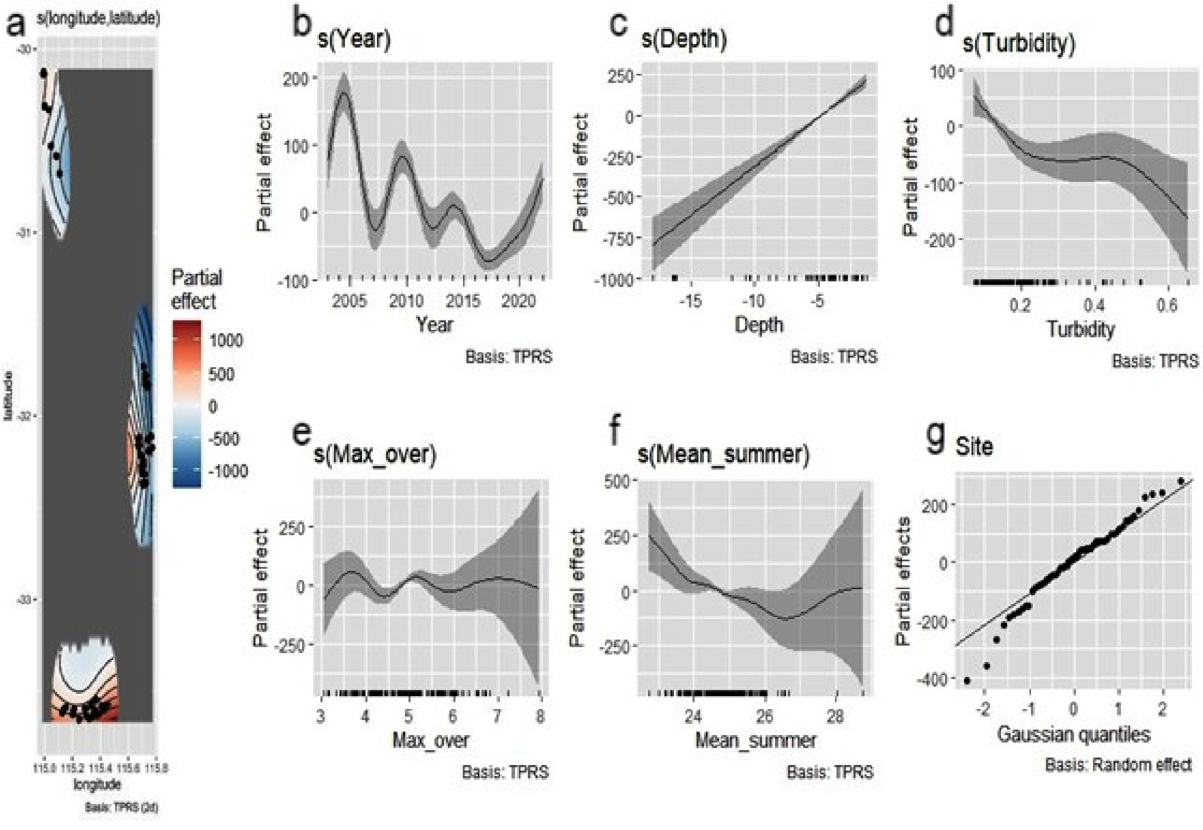


Figure 3. Global marginal effects of predictors on *Posidonia sinuosa* abundance from a hierarchical generalised additive model. Values on the x-axis are raw values of the predictor, while values on the y-axis represent the predicted fit from the smoothed residuals accounting for the influence of the other predictors in the model (i.e. the independent relationship of the predictor to *P. sinuosa* abundance).

Table 3. Outputs of Hierarchical Generalised Additive Model analyses for the Global marginal effects with standard error and p-values of factors indicated. Factor deemed statistically significant if p<0.05.

Variables	Estimate (Std error)	p-value
Region		
Cockburn Sound	(Reference)	
Jurien Bay	-1109.11 (631.760)	0.079
Marmion	-305.60 (199.810)	0.126
Ngari Capes	**1470.04 (493.470)**	**0.003**
Shoalwater Islands	75.61 (88.800)	0.395
Habitat type		
Exposed reef	(Reference)	
Open embayment	-15.320 (130.250)	0.906
Semi-enclosed embayment	-84.390 (130.270)	0.517
Sheltered reef	107.350 (128.430)	0.403
Smooth terms	edf (Ref df)	
Year of sampling	**8.744 (8.970)**	**<0.001**
Depth	**1.001 (1.001)**	**<0.001**
Site	**48.433 (50.000)**	**<0.001**
Turbidity	**3.830 (4.719)**	**<0.001**
Max over	**7.638 (8.411)**	**<0.001**
Mean summer SST	**6.177 (7.173)**	**<0.001**
s(longitude, latitude)	2.035 (2.037)	0.125

4.3 Localised marginal effects – influence of environmental predictors within regions

The strength and nature of the relationship between shoot density and the predictors at times varied among regions (Figure 4). Jurien Bay reflected the global pattern with shoot densities oscillating up and down across years but with an overall decline (Figure 4). Cockburn Sound was similar, but the variation associated with the oscillations was lower and there was an increase in shoot density after 2019 (Figure 4). In contrast, densities in Marmion trended upwards and then plateaued; Ngari Capes consistently increased whereas Shoalwater Islands consistently decreased (Figure 4). The relationship of higher shoot densities in shallower depths was observed in all regions except for Marmion, where the greatest densities were observed at 9 m and then declined at shallower depths, although there was less certainty with this prediction (Figure 4). Within Marmion and Ngari Capes, and to a lesser extent in Cockburn Sound, there was a clear trend of declining shoot densities with higher turbidity, whereas, the opposite relationship was observed at Shoalwater Islands and there was no association with turbidity in Jurien Bay (Figure 4). In Cockburn Sound and Marmion, shoot densities declined with higher mean_summer values, however, in Shoalwater, shoot densities increased with summer average temperatures up to ~24.5 °C, but then the effects were minimal thereafter (Figure 4). Higher max_over values tended to be associated with lower shoot densities in Shoalwater whereas the opposite pattern was observed in Marmion. There was no clear pattern with max_over in Cockburn (Figure 4). For Jurien and Ngari Capes, there was no strong relationship between shoot density and average summer temperature nor max_over, with considerable uncertainty in these predictions (Figure 4).

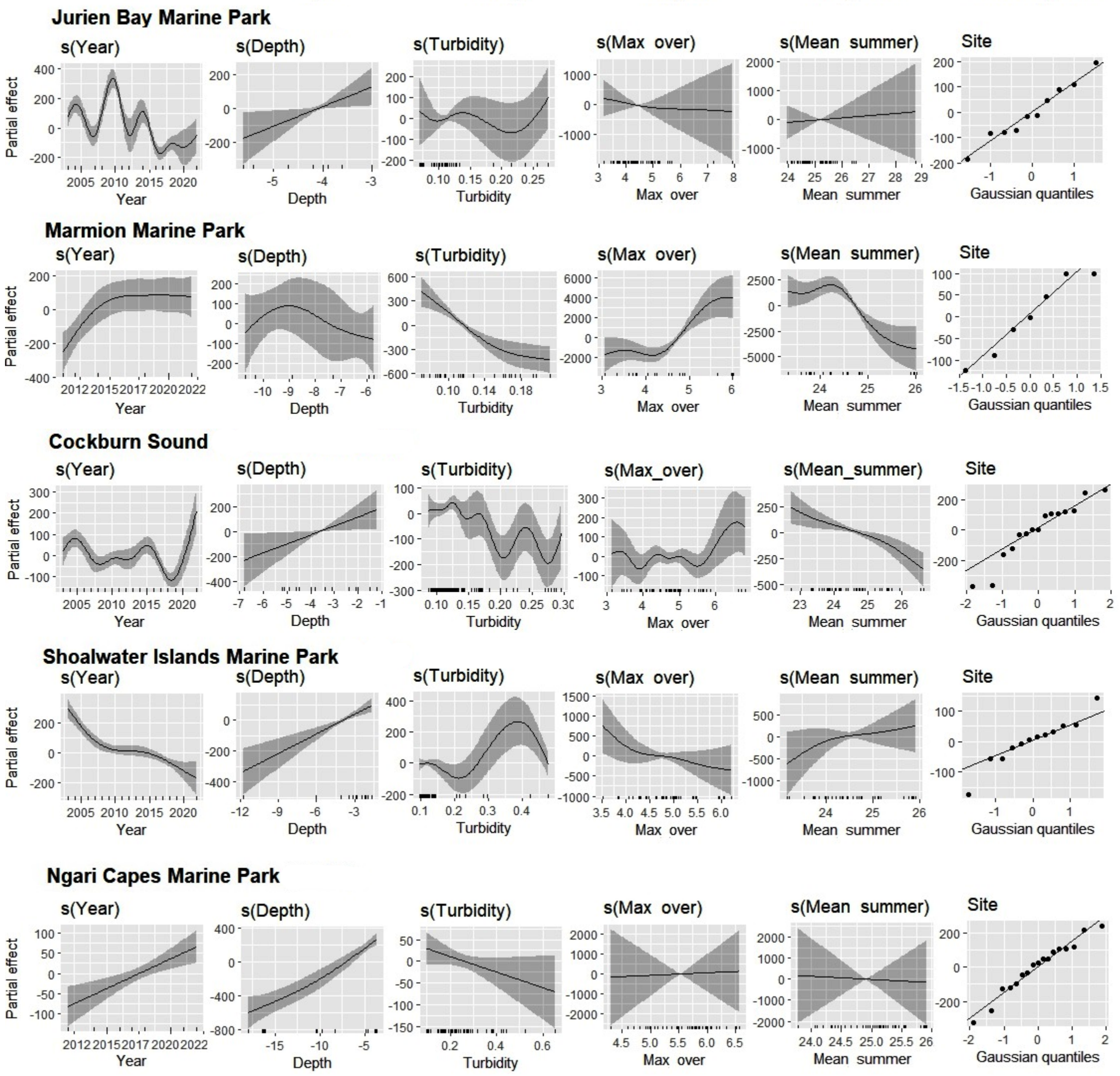


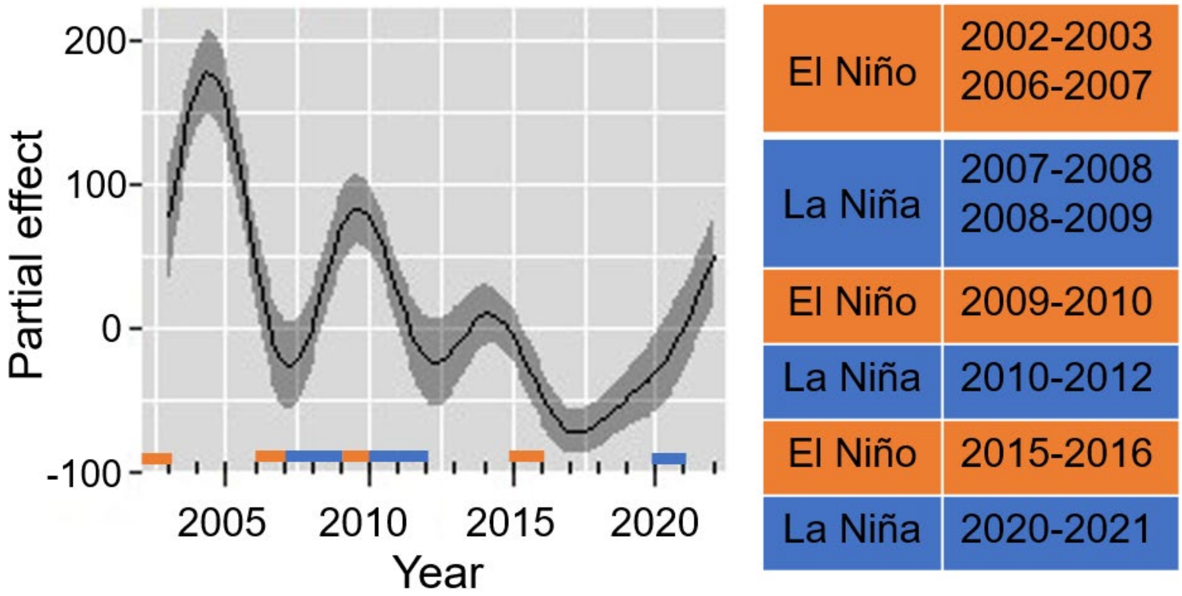
Figure 4. Localised marginal effects with respect to region of *Posidonia sinuosa* abundance from a hierarchical generalised additive model. Values on the x-axis are raw values of the predictor, while values on the y-axis represent the predicted fit from the smoothed residuals accounting for the influence of the other predictors in the model (i.e. the independent relationship of the predictor to *P. sinuosa* abundance).

5 Discussion

Long-term datasets are highly valuable for identifying key processes influencing the distribution of habitat-forming species, especially in times of rapid global change (Firth et al., 2015; Gorman et al., 2020). Examination of 20 years of seagrass shoot density data covering a ~365 km latitudinal gradient across regions with different management strategies, and levels of industrialisation, revealed a striking temporal trend of decline in seagrass condition from 2005 to 2017. This temporal trend was observed in highly industrialised regions as well as marine protected areas and was best reflected in the lower and mid-latitude *Posidonia sinuosa* meadows of Jurien Bay, Cockburn Sound and Shoalwater Islands. The highest latitude meadows of Ngari Capes did not follow this trend, with significantly higher shoot densities than all other regions that increased over time. At the broad scale across WA, drivers of decline in seagrass condition were higher temperatures, increased water depth and higher turbidity. However, these trends were not present in all regions e.g. in Cockburn Sound there was a decline with mean_summer but not in Jurien Bay. This study highlighted that significant change in *P. sinuosa* condition over time is linked with global climatic cycles and changing seawater temperature linked to climate change, and due to the variability in drivers within regions, there is a need to tailor region-specific actions for seagrass management.

5.1 Temporal oscillations in *Posidonia sinuosa* reflects influence of global climatic cycles

The striking feature of the global trend in *P. sinuosa* shoot density was oscillations over 20 years. This pattern may in part be related to ENSO cycles as shoot density declines coincided with the earlier La Niña events (2007-08, 2008-09, 2010-12) (Figure 5). The exception was following the 2020-21 La Niña period where there were no shoot density declines and this may have been due to other environmental factors buffering the decline. By comparison, the 2010-12 La Niña event was extreme and influenced seagrass communities across WA. On the west coast of Australia, warmer waters are associated with La Niña conditions and it is well documented that the 2010/11 marine heatwave was triggered by extreme La Niña conditions and a near record Leeuwin current flow (Pearce and Feng, 2013). Seagrass loss was quantified by Strydom et al. (2020) in Shark Bay (1,310 km^2) that ensued from the 2010/11 event and confirmed that heat stress metrics were the best predictors of seagrass decline. Similarly, interannual changes in shoot mortality in *P. oceanica* have also been linked to warming variability (Marbà and Duarte, 2010). Temperatures that exceed thresholds are known to cause reductions in photosynthesis and induce mortality (Collier and Waycott, 2014). The optimal range for net photosynthesis of *P. sinuosa* is between 18 - 23 °C (Masini et al., 1995), although this could be higher as these were the only temperatures that have been tested. Thus, it is likely that one of the mechanisms driving 'poor seagrass years' (i.e. lower shoot densities) that we observed at the latitudinal scale could be above average water temperatures associated with ENSO cycles, namely La Niña events. This mechanism is supported by the negative relationship observed between higher mean summer water temperatures and shoot density identified in the global trend of the hierarchical generalised linear models. However, the effects of La Niña conditions on seagrass density did not appear uniform across WA, suggesting other factors (and their interactions) may also account for region-specific trends. The temporal oscillations observed in the global trend were most evident in Jurien Bay which is likely because the Leeuwin Current is stronger at lower latitudes (Feng et al., 2005). The oscillations in the global trend were partially reflected in Cockburn Sound indicating that this region is also affected by ENSO cycles but to a lesser degree than Jurien Bay, which is quite exposed and is likely related to the weaker influence of the Leeuwin Current as it moves south. Shoot densities in Ngari Capes did not oscillate but increased consistently over time. This is likely because the warm Leeuwin Current turns eastward at Cape Leeuwin (22°S) and bypasses the Ngari Capes seagrass sites and the stronger Capes Current brings cooler waters from the south (Cresswell and Golding, 1980). These latitudinal patterns indicate that the effects of future climate change, and particularly marine heatwaves, on seagrass condition could manifest differently and need to be considered in determining outcomes at the ecosystem-level.



El Niño	2002-2003 2006-2007
La Niña	2007-2008 2008-2009
El Niño	2009-2010
La Niña	2010-2012
El Niño	2015-2016
La Niña	2020-2021

Figure 5**.** Relationship between shoot density of *Posidonia sinuosa* and year derived from Hierarchical Generalised Additive Mixed Model with occurrence of El Niño and La Niña events across Australia (http://www.bom.gov.au/climate/history/enso/).

5.2 Differences in the trajectory of seagrass condition in relation to local stressors, temperature and latitude

Interestingly, increasing mean_summer resulted in declines in shoot density in Cockburn Sound but not in Jurien Bay. This could be due to differences in the thermal optima: populations in Cockburn Sound had lower thermal optima compared to those in Jurien Bay (Said et. al, 2024). On this basis, it is possible that the impact of intensifying temperature stressors from climate change could be worse in Cockburn Sound in the future compared to Jurien Bay. The negative impacts of warmer temperatures in Cockburn Sound may be exacerbated by other stressors. For instance, increased temperature exacerbates sulphide intrusion in seagrasses (Koch et al., 2007) which is a known pathway for seagrass shoot mortality and has been demonstrated at some sites in Cockburn Sound where there was a trajectory of seagrass decline (Fraser et al., 2015). High levels of sulphide intrusion were detected in Warnbro Sound and believed to be due to the low light conditions in this area which would constrain oxygen production via photosynthesis (Fraser et al., 2015). Warmer average water temperatures also led to declines in seagrass condition in Marmion where most sites are deeper receiving less light and may be more susceptible to warming as seagrasses have been shown to have lower thermal tolerance under light limiting conditions (Collier et al., 2011). In Cockburn Sound and Marmion, the initial relationship between max_over values less than 5 °C and seagrass condition was uncertain and the effects were positive between 5-6 °C. Contrastingly, max_over resulted in declines in seagrass in Shoalwater Islands. The variation in these may be due to acclimation. The meadows in Shoalwater Islands are generally shallower than Cockburn Sound and Marmion so the rate of change in temperature anomalies might be faster limiting the amount of time plants have to acclimate resulting in a negative effect. We would expect that, in general, average summer temperatures are possibly below the thermal optimum, therefore increased temperature towards the optimum manifests as a benefit for overall growth and condition of meadows. Additionally, seagrasses can acclimate and become more tolerant of environmental variables if the changes are slow enough for acclimation to occur (Staehr and Borum, 2011). Hence, in Shoalwater Islands, acclimation to slower changes in average summer temperatures may explain the positive trend we observed whilst the limited ability to acclimate might account for the negative effect of max_over. Overall, it appears that variation in the role of temperature on seagrass condition in the mid-latitude regions could be due to smaller scale processes, as well as interactions among dominant drivers.

Temperature metrics were weak predictors of seagrass condition in the most northern region of Jurien Bay and the most southern region of Ngari Capes. Given the temperature regime is typically warmer in Jurien Bay, it is probable that these plants have higher upper thermal limits and so the overall importance of temperature is lower compared to elsewhere. Temperature may be having limited effects on the meadows in Ngari Capes as temperatures are frequently within the thermal optimum range for net photosynthesis of *P. sinuosa* (18-23 °C) (Masini and Manning, 1997) (Figure 12, Appendix). Overall, the patterns we observed may be explained by latitudinal differences in the annual temperature regimes which can generate variation in the thermal safety margins of populations i.e. the difference between an organism's upper limit and its upper environmental temperatures. Bennett et al. (2022) recently demonstrated this in *P. oceanica* and found central populations had narrower thermal safety margins compared to cool and warm-edge populations. Recent work has documented variation in thermal optimum and maximums among populations of *P. sinuosa* sampled from the same regions in this study providing further support for this explanation (Said et al., 2024, in prep). Therefore, differences in the temperature regime driven by latitudinal separation likely explain the varied role in temperature between the low-, mid- and high-latitude regions.

5.3 Region-specific trajectories highlights the importance of local context

Light limiting factors such as water depth and turbidity, are renowned drivers of seagrass decline (Duarte, 1991). As such, it was not surprising that both predictors were significant drivers of decline in this assessment. However, there were inconsistencies in the region-specific trends in relation to these two variables. For instance, depth was a much stronger predictor in Ngari Capes, where sites spanned the broadest depth range (2-18 m) but was a much weaker predictor in Marmion which had the narrowest depth range (5-10 m). In most regions, poorer seagrass condition was generally associated with greater turbidity, apart from Shoalwater Islands, where shoot density declined at several shallow sites (2-3.5 m) over time and were eventually completely lost (e.g. Warnbro Sound 2.0, Figure 10). These sites are exposed to prevailing winds and swell during storm events (Hollings, 2004) and swell exposure is known to induce seagrass decline through erosion (Han et al., 2012), reductions in light and sediment deposition that lead to intrusion of sulphides (Fraser et al., 2015). Therefore, the relationship between high turbidity and low seagrass density may be confounded here where low density is caused by the local erosion occurring in the shallow sites.

5.4 Management and research of seagrass condition and drivers into the future

This study represents the first assessment of the current state of the southwest WA seagrass ecosystem. Overall, the variation in seagrass trends within each region highlights a need to tailor and develop region-specific management priorities. Based on this key finding, we have devised a range of recommended management-focused investigation points and directions for future research in the points below and Figure 6.

1. The continuation of long-term monitoring should be a high priority for each Region. Alongside this, we propose that analyses of seagrass trends and drivers be iterative given that resilience is a dynamic property of ecosystems and there is clear evidence for rapid change in the oceans and especially in climate change hotspots like WA.
2. Despite industrialization in Cockburn Sound, seagrass condition was poorer in comparison to only one out of the four other regions. This indicates that in general, local scale management is proving effective and should be continued.
3. Interestingly, the regions were not equally susceptible to warming from climate change. We recommend Cockburn Sound and Marmion marine park as priority locations for investigating future proofing of seagrasses. Indeed, because of the cooler temperature

regime within the highest latitude region of Ngari Capes, these meadows may become refuge populations for WA. Therefore, managers could benefit from adopting a conservative approach with decisions that could significantly impact these meadows of high conservation value (e.g. proposals that lead to turbidity plumes). The effects of temperature were also less certain in Jurien Bay which may be linked to high thermal optima of plants in this region (Said et al., 2024, in prep). Further research is required to verify the efficacy of these meadows to build resilience against future warming across the other locations.

4. If there is capacity to do so, managers and scientists could leverage collaborative projects to improve understanding of local process and potential drivers of change of seagrass condition. For example, deploying light loggers, investigating sediment biogeochemistry, meadow reproductive outputs, population thermal thresholds, water quality and sand movement.
5. As turbidity was a driver of seagrass decline in Jurien Bay, Marmion, Cockburn Sound and Ngari Capes, so we recommend actions that reduce or avoid excessive turbidity to maintain/ improve seagrass condition in these regions (Figure 6). Such actions are already required under the ministerial conditions and licensing requirements in WA which regulate the duration of dredging activities and nutrient discharge and should foster seagrass recovery.
6. Verification of erosion as a mechanism of seagrass decline is recommended for future research. Meadows in Shoalwater Islands marine park are likely to be most impacted by erosion processes, but it is also relevant for meadows in other regions. In relation to Cockburn Sound, dredging operations for Westport that result in the direct removal of seagrasses or movement of sediment away from existing meadows could expose the remaining plants to erosion and negatively impact inflexible tissues like rhizomes and roots. Rhizomes are the main carbohydrate storage organ for seagrasses, especially large *Posidonia* sp., and imperative for their resilience. Thus, information regarding their tolerance to erosion processes will be useful to ensure their persistence.

In Cockburn Sound and Marmion, higher sea surface temperature was a strong driver of shoot decline which may be exacerbated by local-scale processes within these two regions (e.g. sulphide intrusion) and could make them highly susceptible to cumulative stressors like dredging and warming. Hence, avoiding dredging during a heatwave is recommended for these two regions but should be supported by researching any cumulative effects (e.g. Cockburn Sound, temperature and sulphide intrusion) to empower local management. More broadly, managers and scientists could leverage collaborative projects to improve understanding of local process and potential drivers of change of seagrass condition. For example, deploying light loggers, investigating sediment biogeochemistry, meadow reproductive outputs, population thermal thresholds, water quality and sand movement.

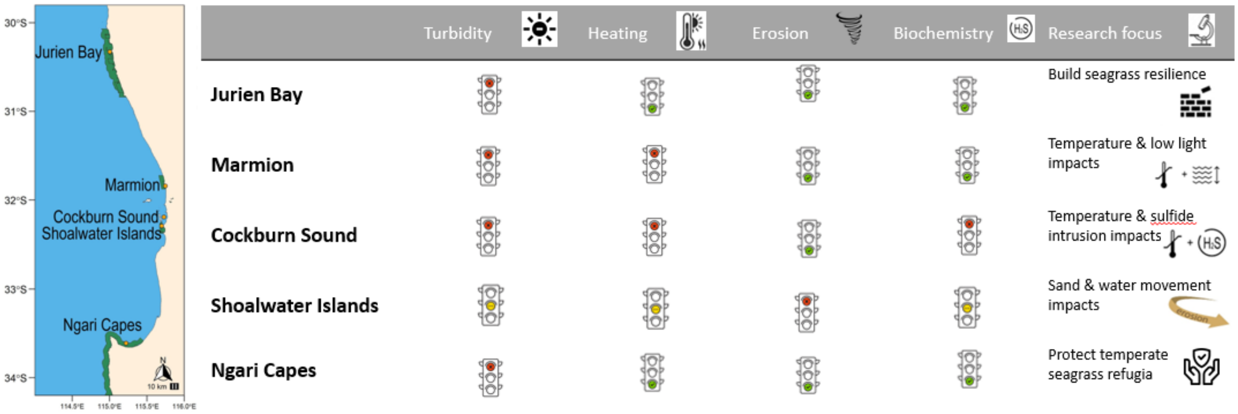


Figure 6. Range of recommended considerations for management and research based on the influence of each driver on seagrass condition within each region. Red lights indicate that the region is vulnerable to a particular environmental factor (based on the localised marginal effects, Figure 4) therefore management actions should aim to avoid activities that contribute to that factor wherever possible. Green lights indicate that seagrass condition in that region was not strongly influenced by the environmental factor; for example, heating in Jurien Bay was not a major driver of condition (green light), but turbidity was (red light) therefore excessive turbidity actions should be avoided there. The yellow light indicates that the influence of that factor is less certain than red or green lights, and therefore not a priority for management interventions but managers should remain cautious, and researchers could use this to investigate gaps.

6 Conclusions

Analyses of twenty years of seagrass monitoring covering 3° of latitude revealed some consistent spatial and temporal variability amongst southwest WA seagrass temperate ecosystems and the drivers of condition. Surprisingly, the condition of meadows in the highly industrialised region of Cockburn Sound were only poorer when compared with one of the four marine parks. This finding highlights that local management interventions, specifically improvement in water quality, can successfully maintain seagrass condition and are worth continuing. Consistent trends of increasing seagrass condition were unique to the highest-latitude region, indicating a cooler temperature regime may have ‘buffered’ these meadows to the effects of climate change. Increasing temperature was linked to seagrass declines in lower latitude regions but the relationship was not significant in all locations. Within mid-latitude regions, the negative impacts of climate driven warming were most evident and likely reflects the presence of local-scale processes that, under increasing temperature, exacerbate the negative impacts on seagrass (e.g. sulphide intrusion). Under further warming, we predict that meadows in the highest latitude region may become refuge populations for WA in the future. Overall, this study highlights the value of collecting long-term data for understanding the implications of regional and local processes on ecosystems. To empower local management, our findings indicate the need to tailor management actions to reflect the unique characteristics within each region. In Cockburn Sound specifically, avoiding excessive levels of turbidity, exploring avenues for future-proofing seagrass against climate change and investigating the nature of interactions between temperature and other stressors on seagrasses is recommended.

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8 Appendices

8.1 Description of methodologies used to monitor seagrass within each region.

For the fixed transect method, a central star picket was deployed. A transect set up comprised a 'start' and 'end' picket spaced 10 m apart. These transects were set up at four different bearings and the 'start' picket was between 2-7 m away from the central picket. The 'end' picket followed the same bearing as the 'start'. There were four transects set up per site with 6 quadrats per transect (n=24 observations). This fixed transect method was used for shoot density counts at some sites in Jurien Bay, Cockburn Sound and Shoalwater Islands (Table 4). For the semi-random method, three transects were swum out on a pre-determined bearing to a length of 15 m and 8 quadrats were placed on a pre-determined distance along the transect. This semi-random method was adopted for shoot density counts at some sites in Jurien Bay and Shoalwater Islands and all Marmion sites (Table 4). A random approach to shoot density counts was applied in Ngari Capes; transects (n=5) were laid out along pre-determined compass bearings and randomly generated quadrat distances (n=5 per transect) (n observations = 30) (Table 4).

Table 4. Monitoring methods for *Posidonia sinuosa* across the regions of Western Australia.

Monitoring method	Region	Sites	Transects	Quadrats	Total observations
Fixed transect	Shoalwater Islands	Becher Point, Penguin Island & Seal Island	4	6	24
Fixed transect	Jurien Bay	Fishermans Islands (x 3) Boullanger Islands (x 3)	4	6	24
Fixed transect	Cockburn Sound	All	4	6	24
Semi-random	Marmion	All	3	8	24
Semi-random	Shoalwater Islands	Becher Point SZ, Causeway & Port Kennedy	3	8	24
Semi-random	Jurien Bay	Kangaroo Point, Cervantes & Green Island	4	6	24
Random	Ngari Capes	All	3	10	30

Table 5. List of excluded predictor variables due to high co-correlation values (R > 0.7)

Predictor name	Description
maxannualmIST	Maximum temperature within a year / annual cycle
minannualmIST	Minimum temperature within a year/ annual cycle
CVannualmIST	Coefficient of variation in temperature within a year/ annual cycle
meansummermIST	Average temperature across summer (Dec to March)
maxsummermIST	Maximum daily temperature in summer (Dec to March)
minsummermIST	Minimum daily temperature in summer (Dec to March)
CVsummermIST	Coefficient of variation in temperature in summer (Dec to March)

8.2 Site specific shoot densities over time within each region.

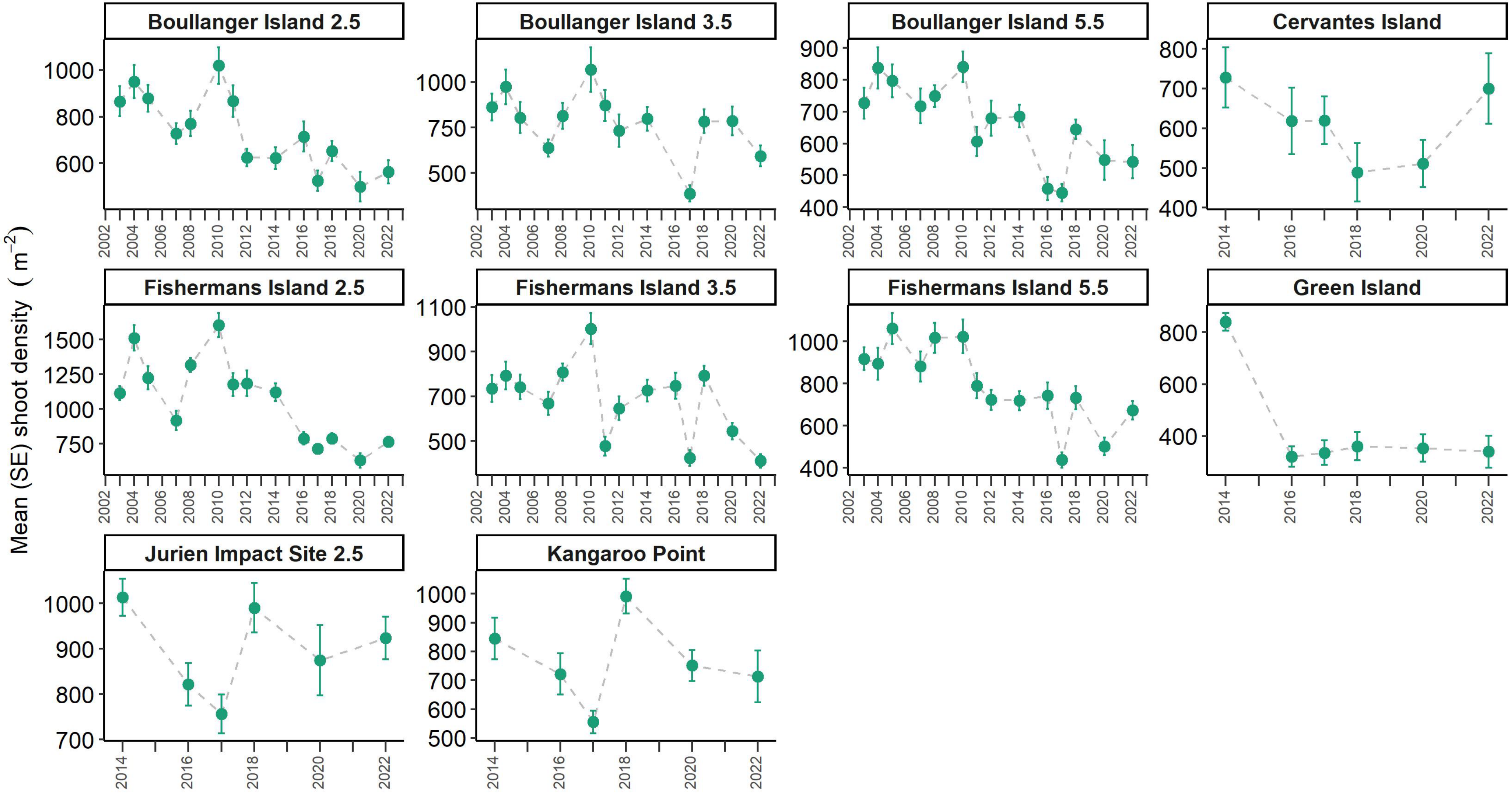

Figure 7. Mean (± SE) shoot density (m^{-2}) of seagrass *Posidonia sinuosa* across sites within Jurien Bay Marine Park in Western Australia (2003 to 2022).

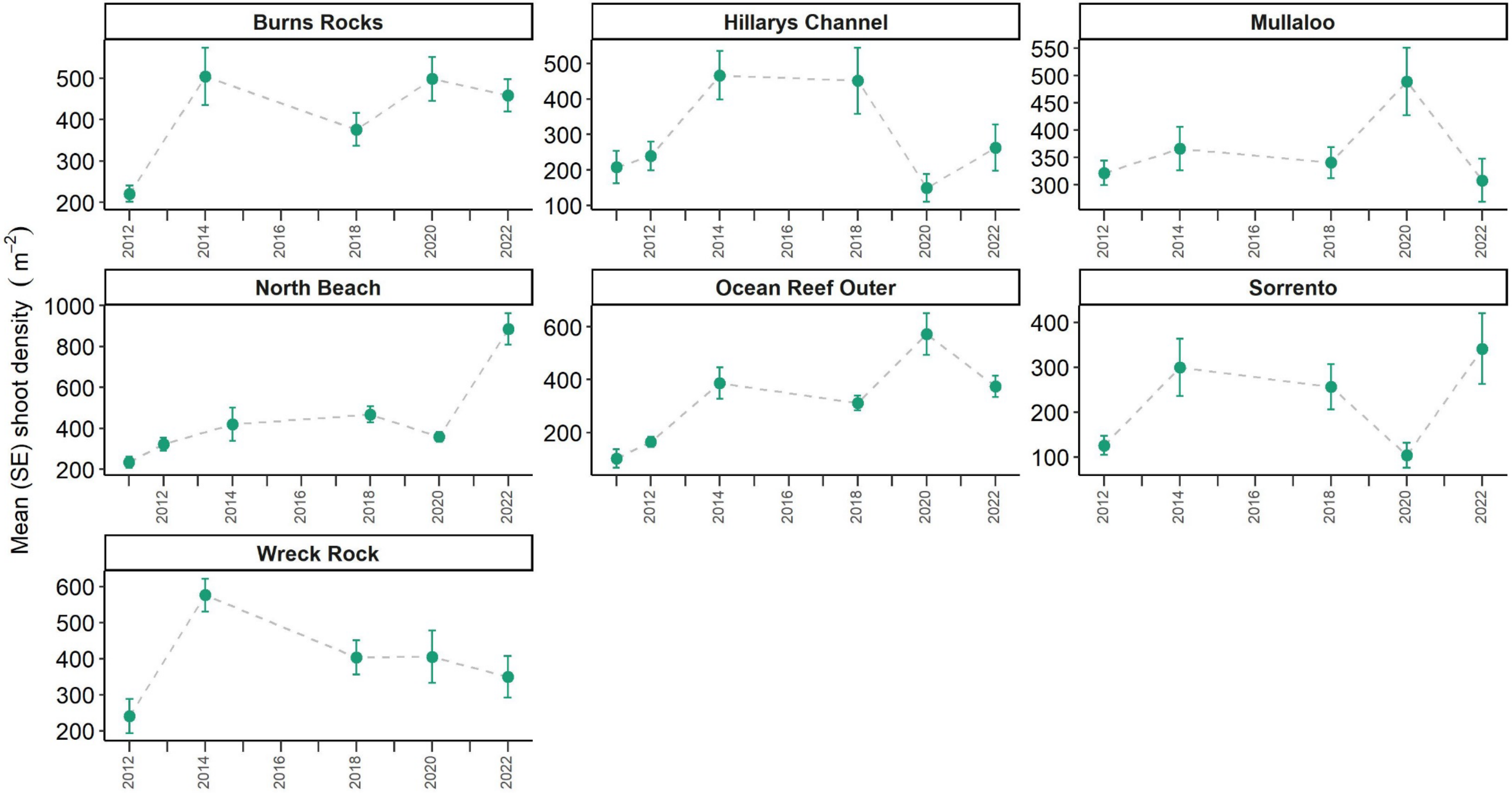

Figure 8. Mean (± SE) shoot density (m^{-2}) of seagrass *Posidonia sinuosa* across sites within Marmion Marine Park in Western Australia (2003 to 2022).

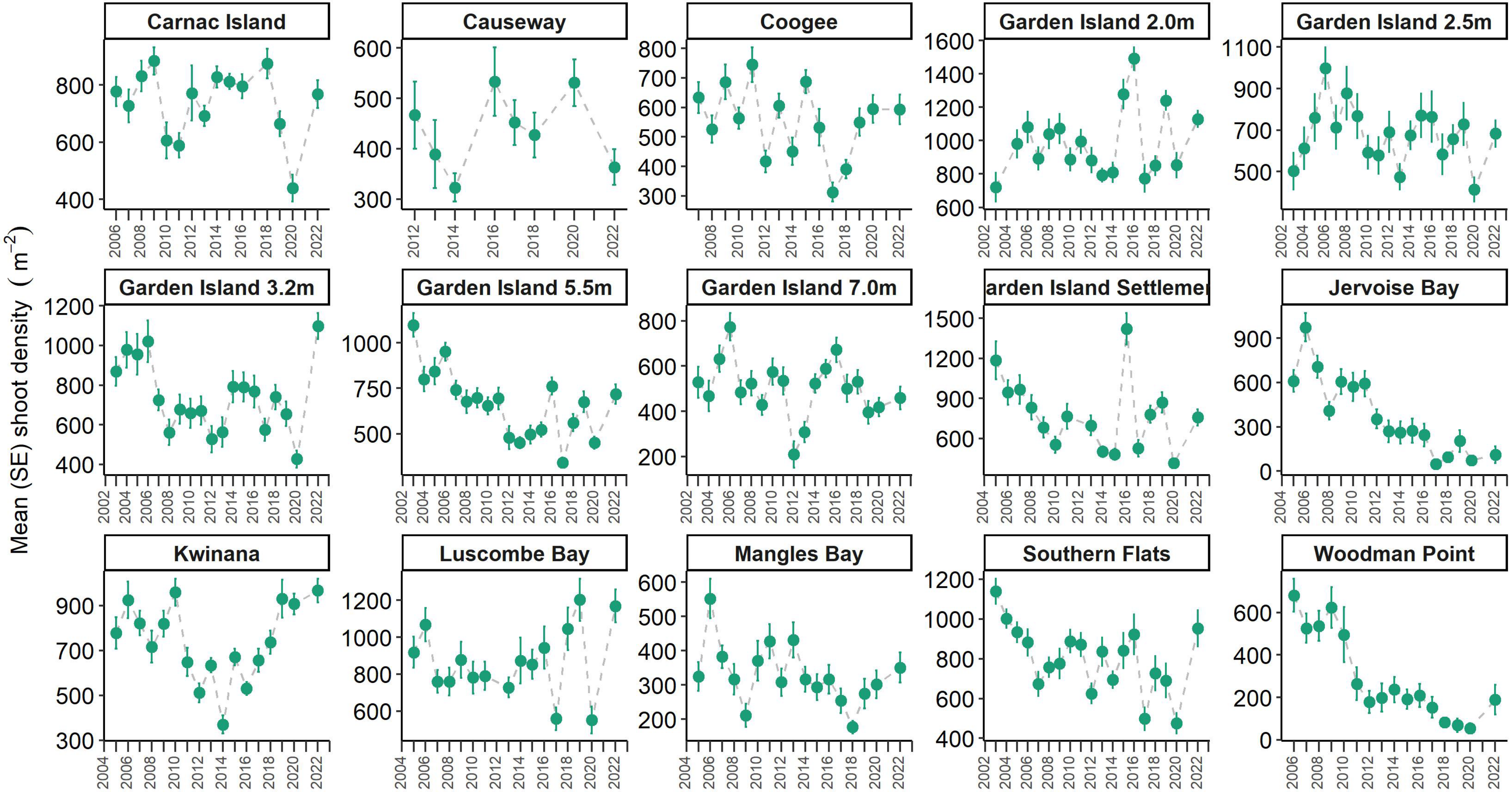

Figure 9. Mean (± SE) shoot density (m^{-2}) of seagrass *Posidonia sinuosa* across sites within Cockburn Sound including sites within Owen Anchorage (Carnac Island, Coogee, Woodman Point) in Western Australia (2003 to 2022).

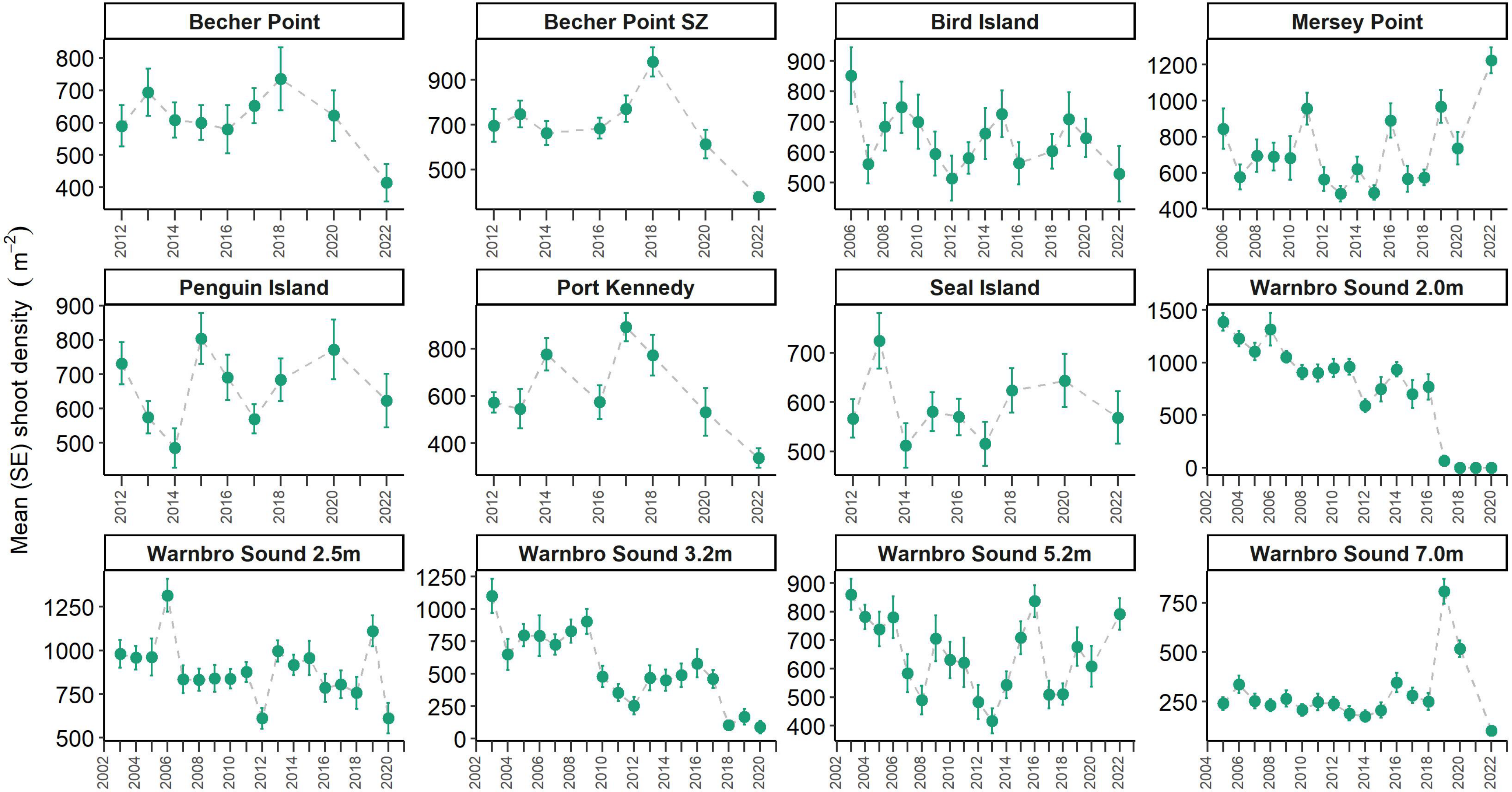

Figure 10. Mean (± SE) shoot density (m^{-2}) of seagrass *Posidonia sinuosa* across sites within Shoalwater Islands Marine Park in Western Australia (2003 to 2022).

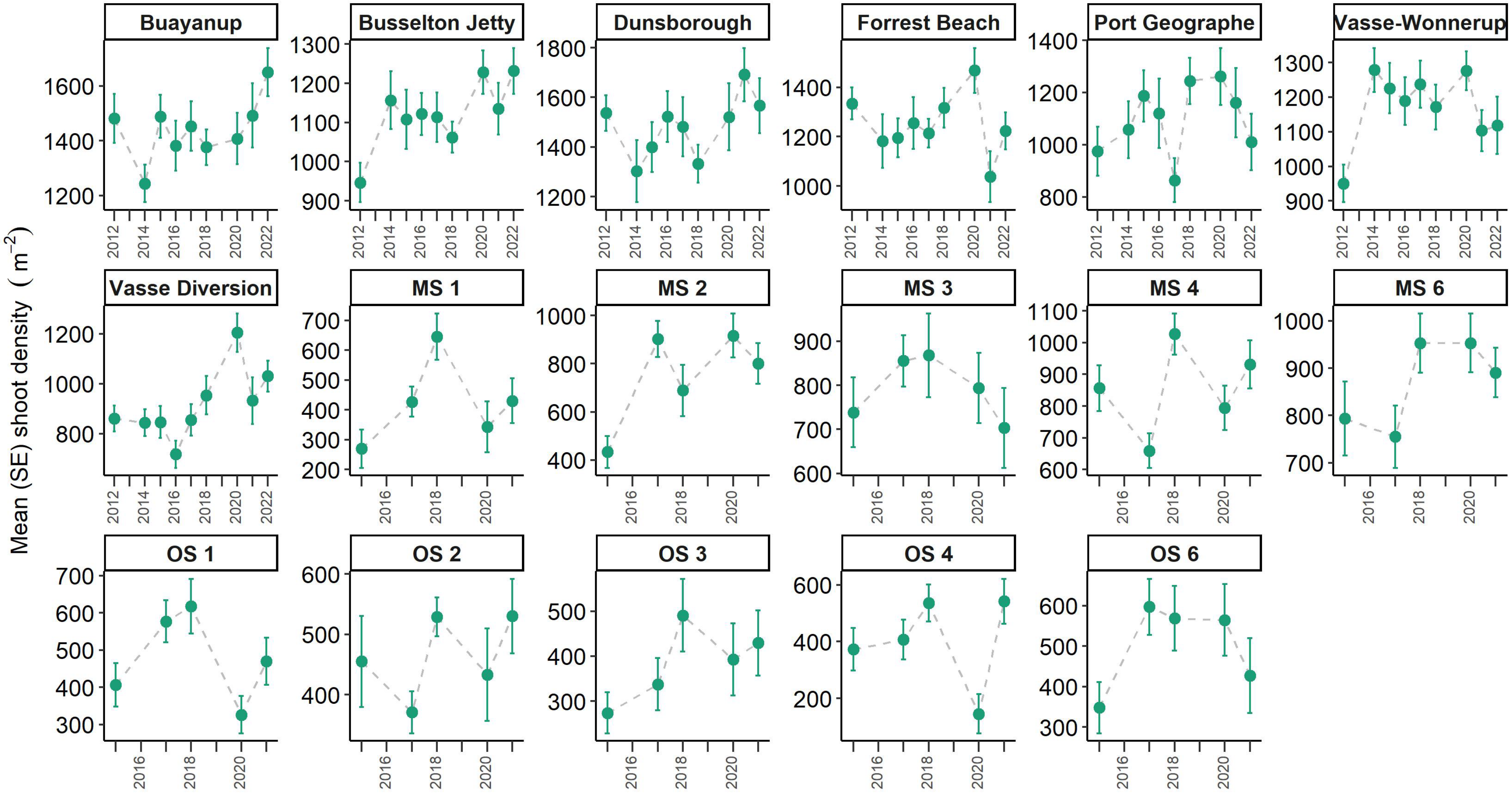

Figure 11. Mean (± SE) shoot density (m^{-2}) of seagrass Posidonia sinuosa across sites within Ngari Capes Marine Park in Western Australia (2003 to 2022)

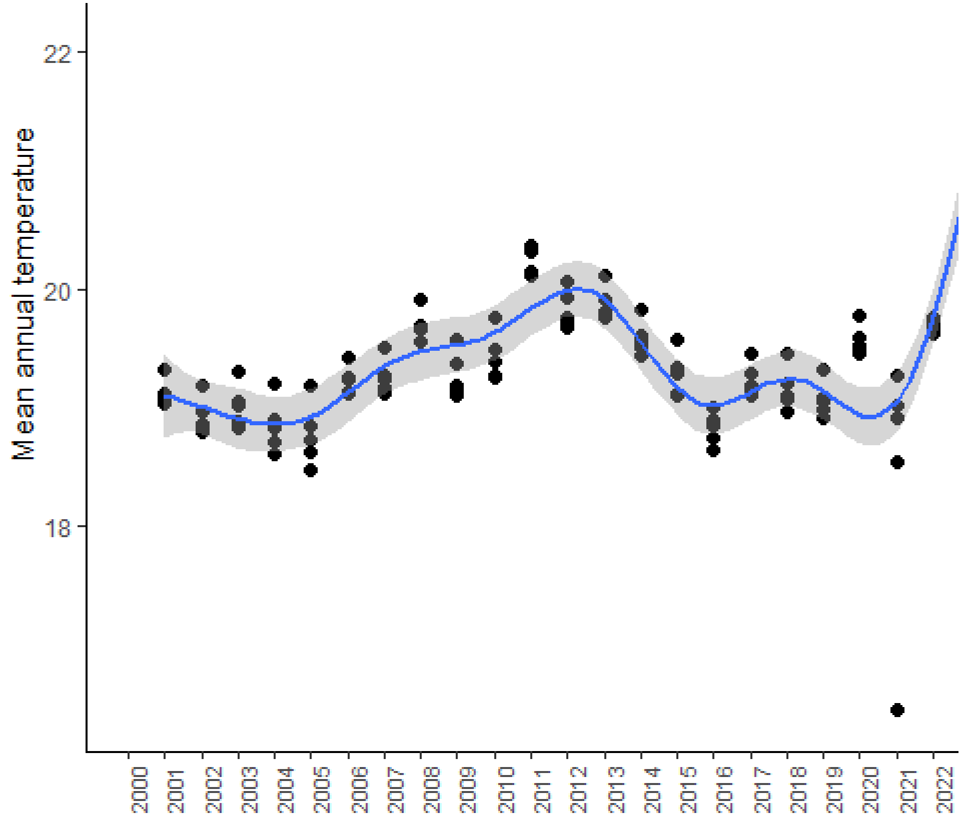

Figure 12. Mean annual sea surface temperature in Ngari Capes Marine Park

Submitted as draft	30/11/2023
Review completed	6/5/2024
Submitted as revised draft	31/5/2024
Approved by Science Program Leadership Team	27/6/2024
Approved by WAMSI CEO	19/7/2024
Final report	30/7/2024

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