Biodiversity and Conservation Science

Seagrass indicators of estuary health 2021-22

Department of Biodiversity, Conservation and Attractions

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Cover photograph: Blue swimmer crab (*Portunus armatus*) amongst *Halophila ovalis* foliage (photo credit: Peter Howie).

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Executive Summary

Introduction

The seagrass monitoring program commenced in 2011, as a collaborative project between the Department of the Biodiversity, Conservation and Attractions (DBCA) and the Department of Water and Environmental Regulation (DWER). DWER led sampling and reporting on this project through to 2017, with DBCA taking custodianship of the program and commencing sampling in 2018-19. The project aims to record and report on seagrass health and pressures, assisting in conservation management with the intent to ensure continually viable and resilient seagrass communities within the Swan Canning Estuary (hereafter known as ‘the Estuary’). The outcomes of seagrass monitoring supports reporting on overall Estuary health through the objectives outlined in the Swan Canning River Protection Strategy.

The seagrass monitoring program targets the peak seagrass growth and reproductive period (late spring to early autumn) and incorporates key performance metrics to assess seagrass health in the Estuary. The four indicators of seagrass performance include: seagrass presence/absence, cover, reproduction, and biomass. Each of these indices are independently scored and averaged into a combined overall performance score for the seagrass season at all sites, providing a useful measure of the current health of the seagrass communities at each location, and a wholistic insight into the health and of the Estuary. A range of environmental and ‘stressor’ metrics are also collected during each sampling season, allowing changes in seagrass performance to be linked to key drivers and providing a basis for any potential management response.

Significant findings

The overall seagrass performance metric for the 2021-22 reporting season was a ‘good’ score for all sites (see Supplementary table 1). Therefore, there are no present concerns for seagrass health in the Estuary and the recommendation generated from this report is to continue the monitoring process. The current overall ‘good’ assessment (Supplementary table 1) at all sites provides a baseline to identify and quantify any future changes in performance metrics and pair these changes with the associated pressure and environmental metrics. This will give management the capacity to understand the multifactorial dynamics that impact seagrass communities in the Estuary.

The site Rocky Bay (RCK) was unique in measuring below the ‘good’ score for two of the performance metrics within this reporting period, recording a ‘fair’ score for both seagrass presence/absence and cover measurements in the 2021-22 period. These metrics also scored ‘fair’ at RCK the previous reporting year. Future monitoring of RCK will ascertain if this fair condition is a persisting issue for this site.

Recommendations

The ongoing recommendations following this yearly report are:

- Continue monitoring seagrass health following the 5-year reporting cycle, at the 6 specified sites, over the summer/spring seasons.
- Maintain the current performance and pressure metrics and persist in validating and refining these indices to ensure optimum monitoring outcomes.
- As improved technology becomes available, update, incorporate, and expand the environmental factors within the current suit of metrics to better understand the factors influencing seagrass community dynamics.

Background

The Department of Biodiversity, Conservation and Attractions (DBCA) has committed to augmenting ongoing weekly physico-chemical water quality monitoring with biotic indexes of fish and seagrass health (Action 6.4, River Protection Strategy[1]). Biological indicators can integrate pressures both over time and across multiple ecological compartments and can be highly sensitive indicators of ecological health[2].

Seagrass meadows play a significant role in aquatic ecosystem functioning. As vastly productive habitats, seagrasses contribute to many ecosystem services, are recognised as bioengineers, and have a substantial economic value. Worldwide, seagrass communities are a food source and nursery for a large range of fauna, including dugongs, swans, fish species, are a habitat for invertebrate species while also playing host to functionally diverse microbial communities. Seagrass meadows increase habitat complexity, reduce the impact of wave action and water flow, stabilise sediment and contribute to blue carbon sequestration. conserving and maintaining seagrass populations, particularly in highly socially impacted areas such as the Swan Canning Estuary, is essential to maintain a healthy environment[3].

Seagrass habitats can be impacted by direct or indirect stressors, resulting in population loss when the stressor increases beyond the seagrass tolerance levels. Direct impacts on seagrass include: Physical disturbance by physical trampling, removal due to excavation or dredging, and propeller and anchor scarring from recreational and commercial vessels. Seagrass loss via indirect causes can often impact a wider area of seagrass population than direct causes. These stressors include light limitations, alterations in salinity levels, temperature changes and anthropogenic pressures such as eutrophication and toxicants (from agriculture, urbanisation and industry) and introduced species. Many indirect stressors respond to natural variation in climatic conditions, which varies seasonally and with changes in long term climate changes. These can impact seagrass productivity and distribution and in extreme cases, result in population range reduction.

Historically, the Swan River was subjected to numerous anthropological pressures from early settlement (1829-1910s) to current times. This includes land modification, dredging[4], discharge from sewage outlets[5], twelve landfill sites, agricultural effluents, and industrial practices (for example, the Swan Brewery, numerous abattoirs, pulp mill[6] , a zinc plating

[1] Swan River Trust, 2022, Swan Canning River Protection Strategy Five Year Review, Department of Biodiversity, Conservation and Attractions, Perth.
[2] Oliva, S., Mascaró, O., *et al.* (2012). Selection of metrics based on the seagrass *Cymodocea nodosa* and development of a biotic index (CYMOX) for assessing ecological status of coastal and transitional waters. *Estuarine, Coastal and Shelf Science*, 114, 7-17.
[3] United Nations Environment Programme. (2020). *Out of the blue: The value of seagrasses to the environment and to people*. UNEP, Nairobi.
[4] William, T., (2003). Rivers too cross: River beautification and settlement in Perth, Western Australia. *National Identities*, 5:1, 25-38. DOI: 10.1080/14608940307118
[5] Riggert, T. L., (1978). The Swan River Estuary: Development, management and preservation. Swan River Conservation Board, Perth, Western Australia.
[6] Spencer, R. S., (1956). Studies in Australian estuarine hydrology. II. The Swan River. *Marine and Freshwater Research*, *7*(2), 193-253

manufacturer, and a wool scouring plant[7]). There was a potential for seagrass populations in the Swan and Canning estuaries to be impacted by all these activities at particular points in time. For the most part, the remnant impacts of these activities are unknown. However, measurements of seagrass communities within the Alfred Cove marine park area have shown long-term reduced seagrass cover, biomass, and shoot density. It has been speculated that this reduction in seagrass health is due to nitrogen enrichment stemming from potential groundwater sources, a phosphorus imbalance in seagrass tissues, and heavy metal toxicity, potentially originating from previous landfill sites[8]. Ongoing monitoring of seagrass populations is warranted to ensure that past, present and future anthropological pressures are managed and mitigated in the Swan River.

This data report presents data for the 2021-22 sampling season against the context of the previous season 2020-21. The 2021-22 season is the 2^{nd} year in the 5-year reporting cycle, (Table 1), and reports on the yearly performance and pressure measurements using core and quadrat data, including the seagrass reproduction measurements.

Table 1 The indicator metric suite and timing across the 5-year reporting cycle.

Metrics	Year 1	**Year 2**	Year 3	Year 4	Year 5
Seagrass performance metrics					
Intensive quadrat survey					
System-wide distribution map					
Seagrass pressure metrics					
Seagrass chemistry					
Environmental metrics					
Sediment and water chemistry					

[7] Cameron, I., & Ho, G. E. (1985, December 2-6). *Disposal of wool scouring effluent in an estuarine environment. Institution of Engineers, Australia* [Conference Paper]. 1985 Australasian Conference on Coastal and Ocean Engineering, Christchurch, New Zealand. 183-192.
[8] Vogwill, R., & Oldmeadow, D., (2017). IF14 Groundwater Sampling and Analysis Report (unpublished report), Department of Biodiversity, Conservation and Attractions, Kensington, Western Australia

Sampling methodology

Site locations

Seagrass monitoring occurs yearly at six sites within the Swan-Canning estuary (Figure 1). These sites were selected to cover a large spatial scope of representative *Halophila ovalis* habitats in the Estuary, with varying exposure to a range of environmental conditions and anthropogenic pressures. The site zones were selected to contour the 1.5-1.6 m bathymetry depths to capture areas where seagrass should flourish, and allow for sampling to be conducted by wading or snorkelling, no freediving or SCUBA is undertaken to collect monthly quadrat/core data. In addition to the regular annual sampling, q5-yearly mapping and deep seagrass edge transects capture and identify the growth and persistence of seagrass communities in the deeper zones to give a wholistic assessment of seagrass distribution in the Estuary.

Within the Estuary's marine parks, the monitoring design inherited by DBCA had sampling sites in the Pelican Point (PPT) and Lucky Bay (LUB) areas, but no site within the Milyu Marine Reserve. A site was required in this area for an all-inclusive reporting approach on marine park conditions, hence, the Milyu site (MIL) was added in 2018-19 and reporting on this site commenced in 2020-21. These three sites represent areas less impacted by direct human activity. The Rocky Bay (RCK) site is furthest downstream and is affected by marine influences (higher salinity and marine biota). The Canning (CAN) and Heathcote (HEA) sampling areas were modified in the 2019-20 reporting period, increasing in area to be depictive of the seagrass conditions at these sites, and to be relatively comparable in size to the other monitoring sites. Canning is the most upstream site, seagrass persists at this site within turbid, tannin-stained waters[9]. The Heathcote site is adjacent to the mouth of the Canning River and the entry point of the fresh/brackish waters from the Canning tributaries into the Estuary.

DBCA-funded research delivered in May 2019 by the University of Western Australia, investigated the reported poor condition of seagrass along the Attadale foreshore (including the LUB site[10,11,12]. It was found that the reported seagrass degradation was spatially restricted and that there was some risk in generalising seagrass health condition across local scales[12]. This information was considered during DBCA's review of the monitoring program, resulting of expansion of all sites to the more extensive (meadow scale) sampling zones from the 2020-21 seagrass sampling season. Further, a key intent of the expansion of sampling zones was to ensure sampling at those sites with extensive shallows was not limited to seagrass within the environmental extreme of the shallow fringe.

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[9] Kilminster & Forbes (2014), Seagrass as an indicator of estuary condition in the Swan-Canning estuary, Water Science Technical Series, report no. 62, Department of Water, Western Australia.
[10] Cahill, K., Rutherford, J., Farmer, D. & Munday, T., (2017) Ground-based geophysics: Results from an investigation near Lucky Bay, Perth, WA. CSIRO, Report EP174246.
[11] Kilminster, K., Forbes, V., & Sanchez Alarcon, M., (unpublished report). Seagrass indicators of estuary health – data report 2015-16 Swan-Canning estuary. Department of Water, Western Australia.
[12] Martin, B. C., Fraser M. W., Middleton J. A. & Kendrick, G. A. (2019). Alfred Cove Eutrophication (ACE) Investigation; assessing eutrophication impacts on seagrass degradation at Alfred Cove. School of Biological Sciences & Oceans Institute, The University of Western Australia

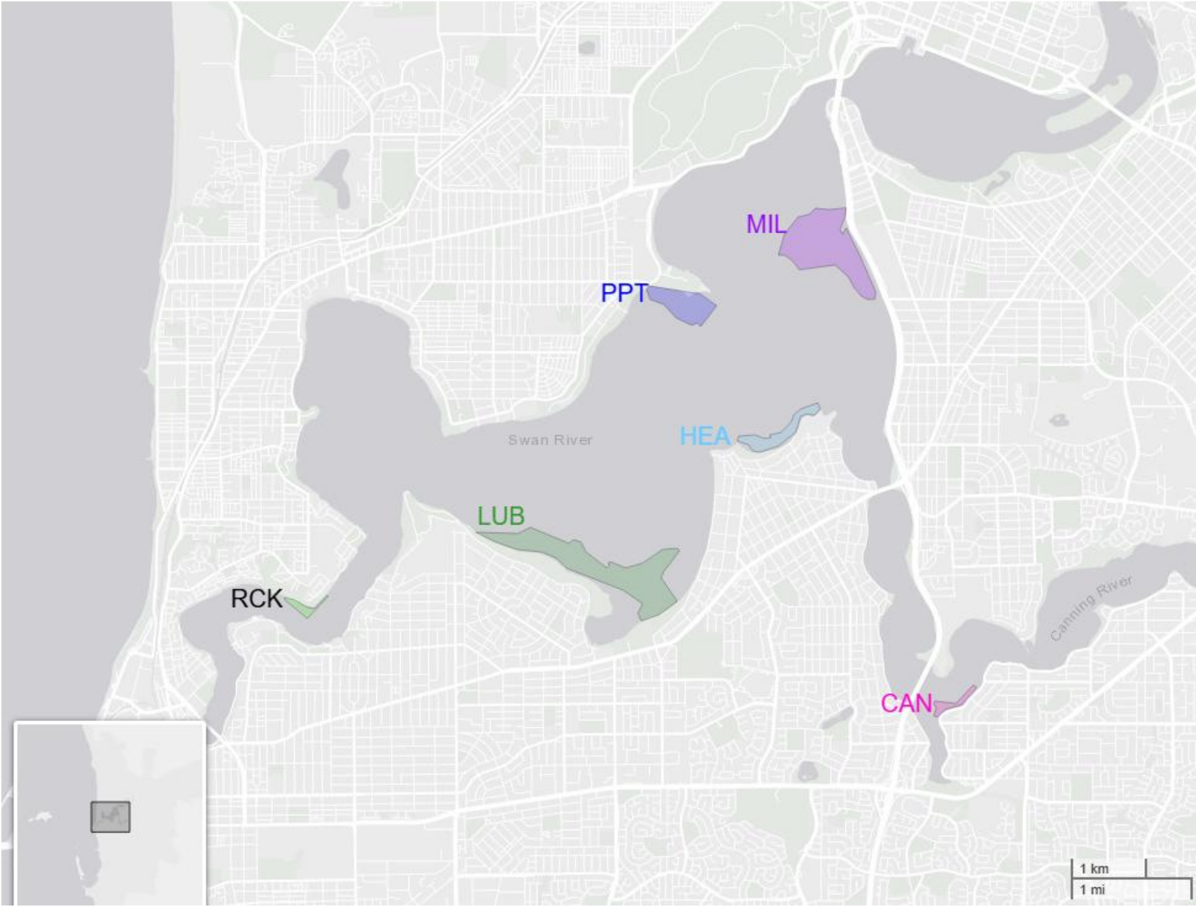


Figure 1: Seagrass sites within the Swan-Canning Estuary. Rocky Bay (RCK), Lucky Bay (LUB), Pelican Point (PPT), Heathcote (HEA), Milyu (MIL) and Canning (CAN).

Sampling dates

Seagrass and environmental data sampling were conducted during selected periods between October 2021 and March 2022. This included:

- Quadrat sampling was completed between November and March.
- Core samples were analysed from December to March.
- In-situ light and temperature loggers were installed in mid-October and full monthly data was recorded between November and March.
- Data retrieved from external government departments and organisations (for example, Department of Transport and Bureau of Meteorology) is collected over a yearly basis; and
- Additional data collected as part of the Rivers and Estuaries Science water quality monitoring can be included and correlated with seagrass data when appropriate.

Measured parameters

Indicators for measuring seagrass health and pressures

The seagrass monitoring indicators were developed over the two reporting periods between 2011-12 and 2013-14. Since then, they have undergone several validation, refinements, and updates. The most recent addition to the DBCA reporting is total biomass (as gram per meter squared of dry seagrass weight; see Table 2), this metric is a replacement for previously recorded productivity indices due to concerns around the accuracy of tagging, measuring and recording the delicate *H. ovalis* new growth.

This report details the outcomes for all performance metrics listed in Table 2. Four of the performance indices (presence/absence, percent cover, reproduction, and total biomass) contribute to the overall performance index, which assists in providing a health status for the Estuary. The pressure metrics include annual measurements of *Batillaria australis* densities and macroalgal cover (

Table 3) and the nutrient analysis, which occurs in the 4th year of the 5-year reporting cycle (Table 1). Therefore, the overall pressure index is not included in this report.

Table 2: Metrics calculated to inform on seagrass PERFORMANCE in the Swan Canning Riverpark. Those indices with grey background are used in the calculation of the final performance index.

Metric	Timing / Freq.	Detail	Performance classification or interpretation (where applicable)
Presence/ absence	Dec – Feb Yearly quadrat survey	% of quadrats with seagrass present	Poor < 0.2 Low 0.2 to < 0.5 Fair 0.5 to < 0.8 Good > 0.8
% Cover	Dec – Feb Yearly quadrat survey	Average % cover of seagrass	Poor < 5% Low 5% to < 25% Fair 25% to < 50% Good > 50%

***H. ovalis* reproduction**	Dec – Mar Yearly core analysis	Average density of flowers and fruit (per sqm)	Poor < 50 flowers m^{-2} and 0 fruit m^{-2} Low > 50 flowers m^{-2} and 0 fruit m^{-2} Fair 1-20 fruit m^{-2} Good >300 flowers m^{-2} or >20 fruit m^{-2}
Total biomass	Dec – Feb Yearly core analysis	Average dry-weight biomass of seagrass (grams per dry weight per m^2)	Poor < 60 g/m^2 dry weight Low 60 to < 90 g/m^2 dry weight Fair 90 to < 120 g/m^2 dry weight Good ≥ 120 g/m2 dry weight
Above/below ground biomass ratio*	Dec – Feb Yearly core analysis	Average ratio of the above ground to below ground biomass	Higher ratio indicates greater above ground growth which may suggest high investment in photosynthetic tissue. Lower ratio indicates greater below ground growth, where the seagrass has invested in below ground carbohydrate storage.
Leaf density*	Dec – Feb Yearly core analysis	Average density of leaves (per sqm)	Higher leaf densities suggest higher productivity, are considered indicative of better seagrass health

Table 3: Pressure metrics for seagrass in the Swan Canning Riverpark. Those indices with grey background are used in the calculation of the final pressure index.

Metric	Timing / Freq.	Detail	Pressure classification or interpretation (where applicable)
% Macroalgae cover	Nov – Mar Yearly quadrat survey	Average % cover of macroalgae	High stress > 80% Moderate-high stress 50 to < 80% Moderate-low stress 20 to < 50% Minimal stress < 20%
δ15N in leaves	Feb 5-Yearly core analysis	Ratio of 15N radio-isotope in leaves compared to local inorganic standard.	High stress >9 Moderate-high stress >7 to 9 Moderate-low stress 5 to 7 Minimal stress <5
δ13C in leaves	Feb 5-yearlycore analysis	Ratio of 13C radio-isotope in leaves compared to local inorganic standard.	High stress <-0.75% Moderate-high stress <0 to -0.75% Moderate-low stress 0 to +0.75% Minimal stress >+0.75%
C:N	Feb 5-yearlycore analysis	Average ratio of carbon to nitrogen in leaves	High stress <17 Moderate-high stress 17 to <19 Moderate-low stress 19 to 21 Minimal stress >21
Batillaria australis* density	Dec – Feb Yearly core analysis	Average density of *B. australis* (per sqm)	*B. australis* provide a hard substrate for algal growth, adding to the habitat complexity by potentially providing additional canopy, restricting light penetration to the seagrass below. Additional, snail induced bioturbation can displace seagrass rhizomes, roots and sediment, influence light, sediment oxygen and nutrients.

* These metrics assist in the understanding and interpretation of seagrass health, but lack performance and pressure criteria and are not included in the overall health indices.

Environmental variables

A range of environmental variables are measured each season to contribute to functional interpretation of any observed changes in seagrass condition. Seagrass, like all plants, are reliant on light to drive photosynthesis and growth. For this reason, 4 of the 7 environmental variables measured are related to light (tide, solar exposure, benthic light and H_{sat}).

Table 4: Measured environmental variables with functional impact on seagrass.

Variable	Timing / Freq.	Detail	Interpretation
Tide	Nov – Feb Yearly Barrack Street Jetty and Fremantle Jetty, data collated from Department of Transport	Average tide height (cm) at each location	Tide influences the depth of water above the seagrass meadow. Higher tidal heights suggest that less light reaches the seagrass meadow, while lower tidal heights mean potential temperature increases for seagrass growing in the shallows. Also, increased risk of seagrass exposure if intertidal zones occur.
Solar exposure	Oct – Feb Yearly data from Bureau of Meteorology's daily global solar exposure model	Average daily global solar exposure (MJ m^{-2})	Higher daily solar exposure means more light is available for photosynthesis and growth. *This is an atmospheric measurement and does not take water conditions into account.
Benthic light	Oct – Feb Yearly *in-situ* logger measurements	Average daily irradiance (mol quanta m^{-2} day^{-1})	Two sensors at each site measure Photosynthetically Active Radiation (PAR) within proximity to the seagrass canopy. Increased benthic light yields suggests increased seagrass growth and carbohydrate storage potential.
H_{sat}	Oct – Feb Yearly *in-situ* logger measurements	Average hours of saturating light at the seagrass canopy	Seagrass generally require a daily minimum of 4-6 hours where light levels are above their light saturation point[†].
Water temperature	Nov – Feb Yearly *in-situ* logger measurements	Average water temperature measured at the seagrass canopy (°C)	Moderate temperatures are most favourable. Low temperatures reduce metabolic rates and growth, while high temperatures can result in physiological damage. Water temperatures

[†] Collier, C. J., Waycott, M. & McKenzie, L. J. (2012). Light thresholds derived from seagrass loss in the coastal zone of the northern Great Barrier Reef, Australia. Ecological Indicators, 23, 211-219. https://doi.org/10.1016/j.ecolind.2012.04.005.

			can be influenced by tides, depth, particulates in water and turbidity.
Air Temperature	Sept – Feb Yearly data from Bureau of Meteorology's daily global solar exposure model	Average daily air temperatures in Perth (°C)	Recorded air temperature at Perth Metro Station 009225. Prolonged hot air temperatures have a direct relationship with water temperatures, as does low air temperatures with colder water temperatures.
Spring rainfall	Sept – Nov Yearly data from Perth Metropolitan meter	Average monthly rainfall (mm)	Rainfall in spring brings nutrients into the system at a time when water clarity and temperatures are favourable for macroalgal growth. Macroalgae compete with seagrass for light and nutrients and may cause 'death zones' where large accumulations of wrack decompose.
Summer rainfall	Dec – Feb Yearly data from Perth Metropolitan meter	Average monthly rainfall (mm)	Significant summer rainfall events are considered a substantial stressor for seagrass. Sudden decreases in salinity can result in significant die-off. Tannin rich riverine flows, or sediment displacement may severely impact water clarity.

Seagrass Performance

Overall seagrass performance health indicator

The four metrics of seagrass performance (presence/absence, cover, reproduction, and biomass) score between 1 and 4 based on the individual performance classification for each metric (Table 2) with 1 being the lowest (poor) and 4 being the highest (good). For each site these scores were averaged across all metrics to give the overall indicator of seagrass health performance for the 2021-22 season at each site (Supplementary table 1). Note, reproduction was not recoded in the 2020-21 season and not included in the equation for this reporting period.

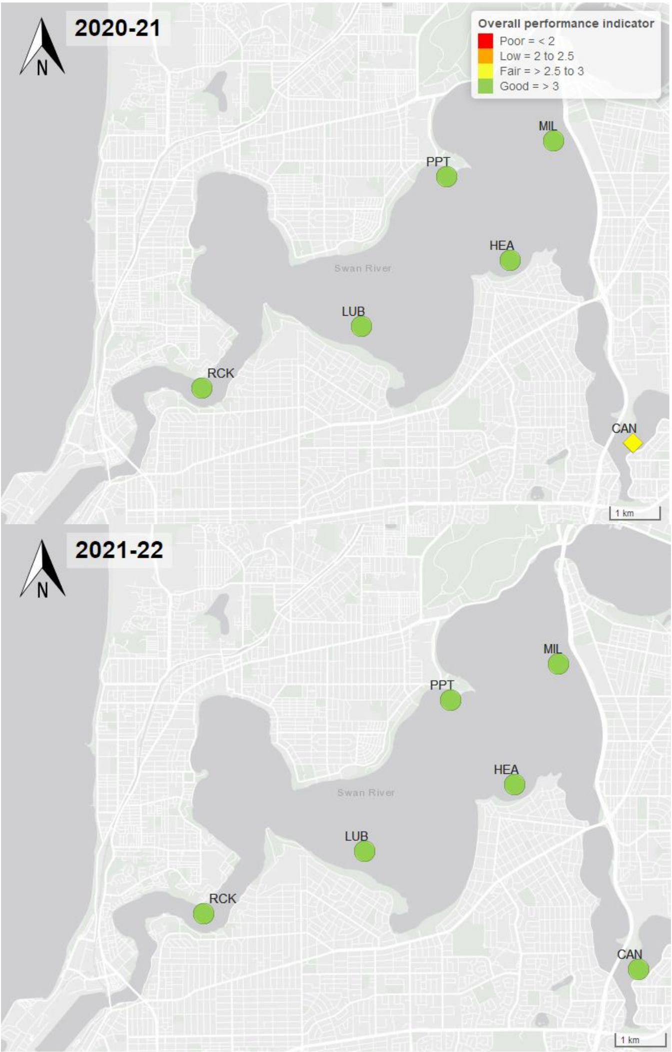


Figure 2: Map of overall seagrass performance indicators for the survey in the 2020-21 (above) and 2021-22 (below) seagrass seasons.

Seagrass performance was considered ‘good’ at all sites for the 2021-22 reporting seasons (Supplementary table 1). Indicating that seagrass communities are currently in good health within the Swan-Canning Estuary. These scores are an improvement on the 2020-21 season and on previous years (2012, 2014, 2015 and 2016)[11] where overall performance scored ≤ 3, for at least one of the six sites.

Seagrass performance metrics

Seagrass presence/absence

Seagrass presence is a measurement of the ratio of quadrats within each site that either has seagrass present, or, was absent of seagrass. A higher value is indicative of consistent growth in the meadow. A score of 1 indicates seagrass was present in 100% of all quadrats, while a score of 0 indicates no quadrats contained seagrass.

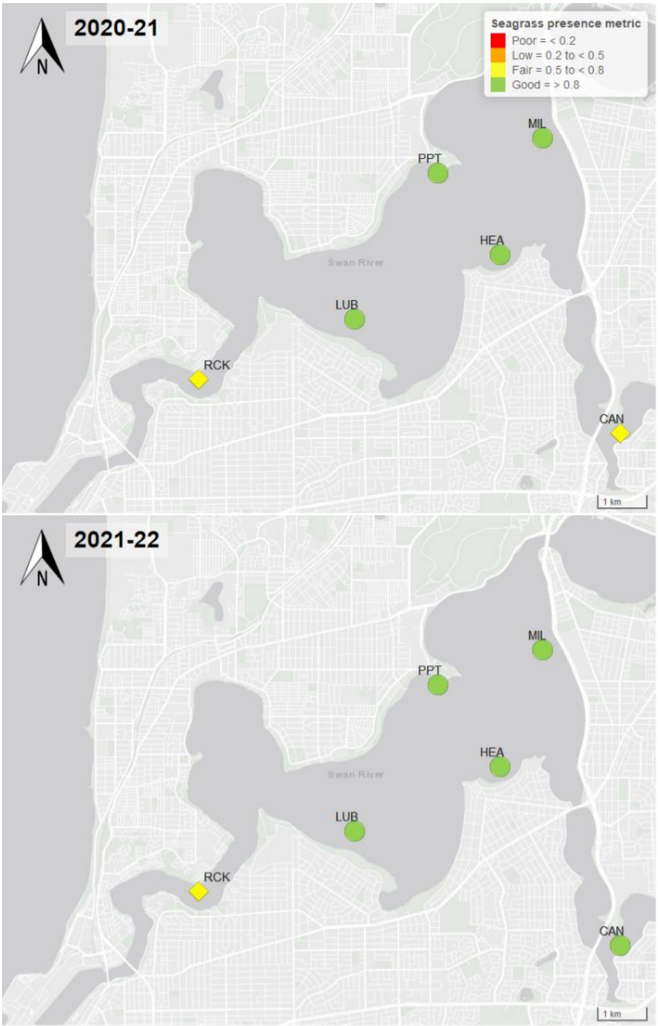


Figure 3: Map of seagrass presence classification for the survey in the 2020-21 (above) and 2021-22 (below) seagrass seasons.

RCK scored ‘fair’ in the seagrass presence performance metric for both seasons (2020-21 and 2021-22) though this slightly improved between seasons (0.55 ± 0.06 SE in 2020-21 vs 0.67 ± 0.06 SE in 2021-22). Macroalgal densities were high in RCK during in November and December, potentially impeding early growth at this site. Seagrass presence at CAN increased more substantially (0.68 ± 0.06 SE in 2020-21 vs 0.87 ± 0.04 SE in 2021-22), resulting in the metric score being promoted from ‘fair’ to ‘good’ in 2021-22 (Figure 3). CAN received higher quantities of benthic light in 2021-22 (25.67 ± 0.91 SE mol quanta m^{-2} day^{-1}; see Benthic light) compared to the previous season 2020-21 (18.96 ± 0.55 mol quanta m^{-2}

day^{-1}) and H^{sat} (8.67 ± 0.18 SE 2020-21; 9.59 ± 0.17 SE 2021-22; see H_{sat}). This additional light may have contributed to the increase of seagrass present at the CAN site.

Overall, seagrass presence was significantly different across sites, times, and seasons (PERMANOVA $p < 0.05$, Supplementary table 2). An increase in annual average seagrass presence was observed between the 2020-21 (0.80 ± 0.02 SE) and the 2021-22 season (0.88 ± 0.02 SE; Figure 4). There were large differences between RCK or CAN and other sites and within RCK or CAN between months in both seasons (PERMANOVA post-hoc, $p < 0.05$, Supplementary table 2).

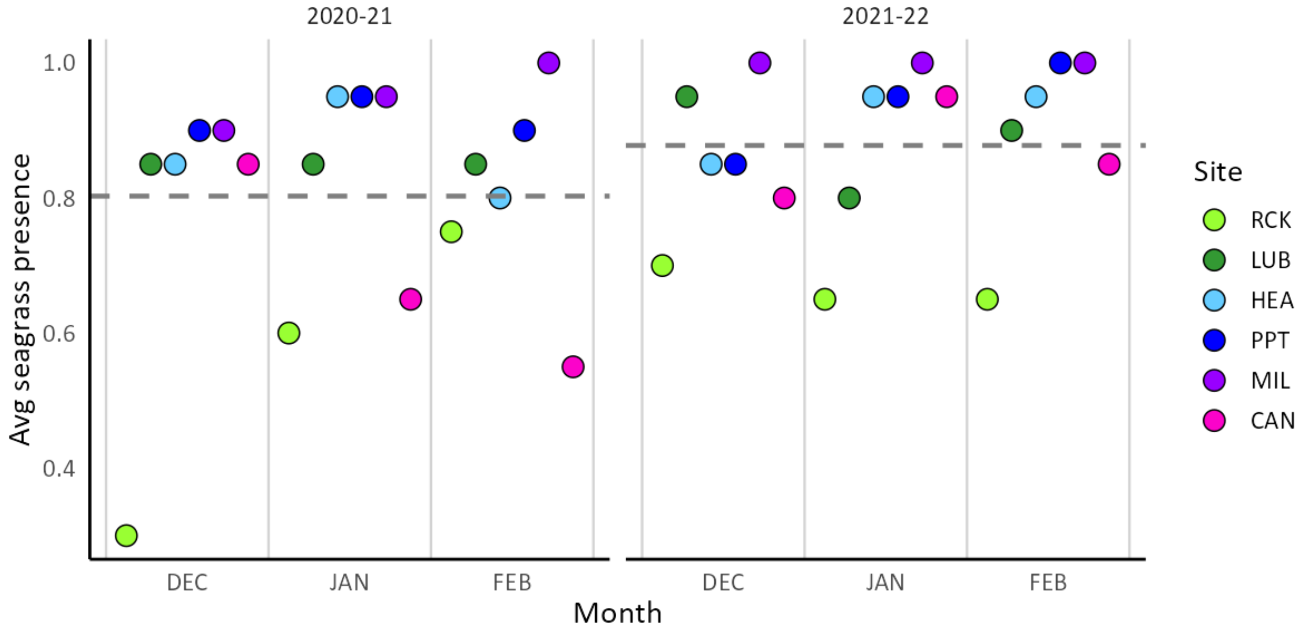


Figure 4: Average seagrass presence, across each site and month, for each of the 2020-21 and 2021-22 seasons. The annual average for each seagrass sampling season (December – February) is shown as dashed a line.

Seagrass cover

Seagrass cover is a useful metric to indicate the complexity (sparse vs dense) of a particular meadow. All sites except RCK scored 'good' with respect to seagrass percent cover in 2021-22. Seagrass cover differed significantly between sites, times, and seasons (PERMANOVA p = 0.007, Supplementary table 5). The annual average increased between 2020-21 (39.05 ± 1.69 SE) and 2021-22 (60.09 ± 1.76 SE) (

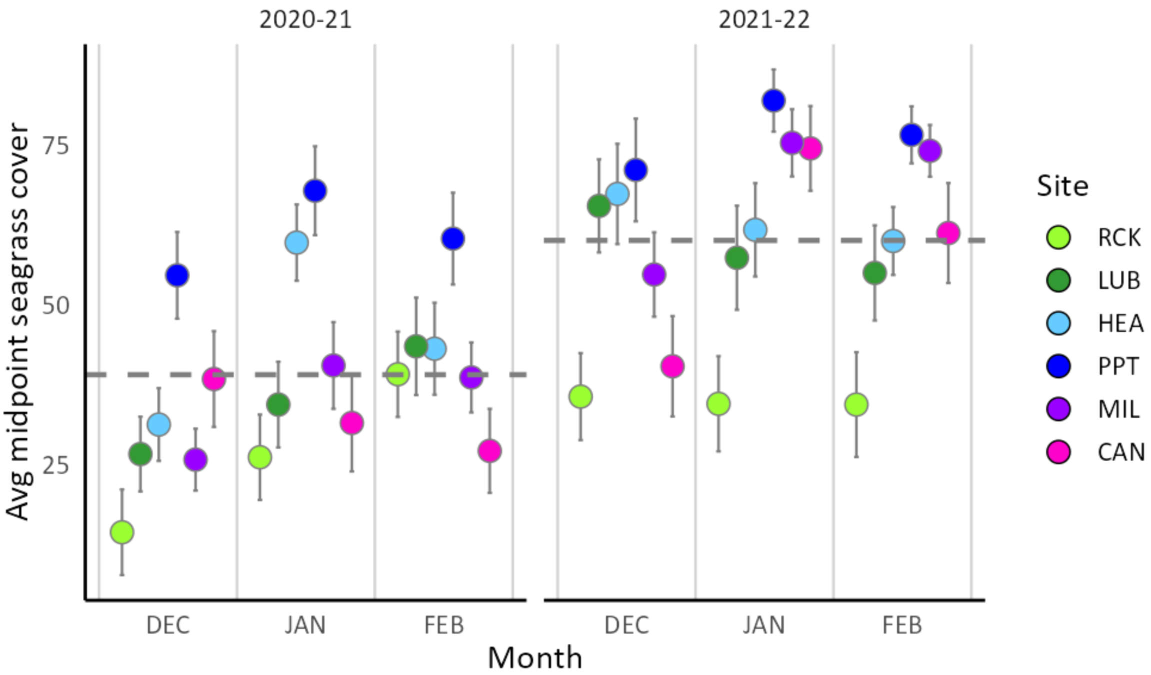
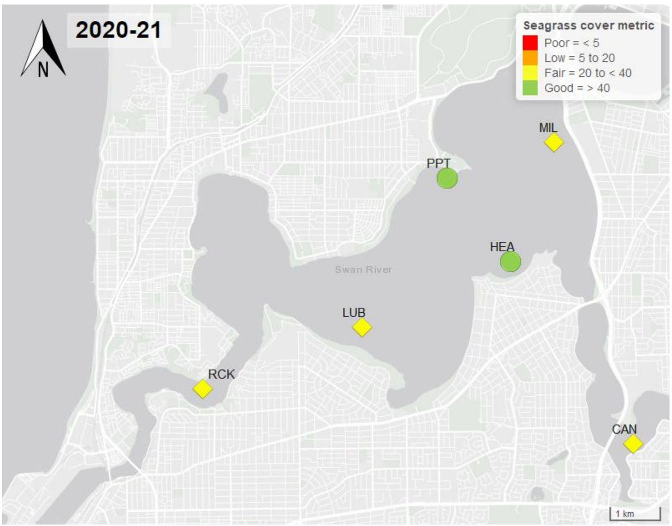


Figure 6), with the metric score at 3 sites (LUB, MIL and CAN) increasing from 'fair' to 'good' (Figure 5).



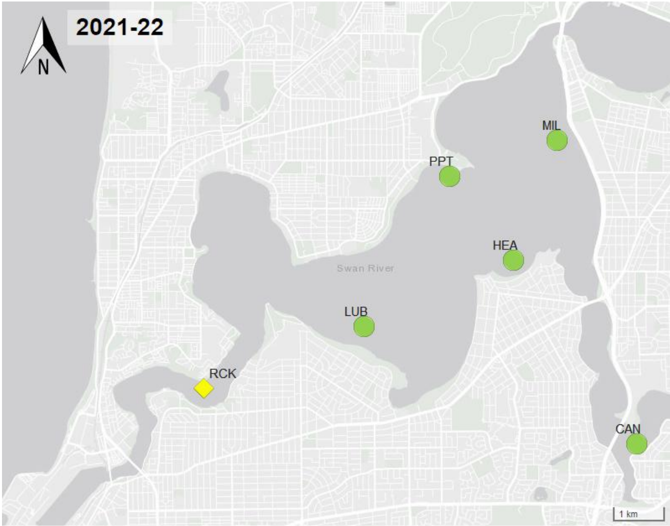


Figure 5: Map of seagrass % cover classification for the survey in the 2020-21 (above) and 2021-22 (below) seagrass seasons.

Seagrass cover at Milyu showed consistent improvement between seasons, where cover was significantly higher every recorded month in comparison to the previous year (e.g. MIL December percent cover was 25.75 ± 4.8 SE, p = 0.011 in 2020-21 compared to 54.75 ± 6.6 SE in 2021-22;

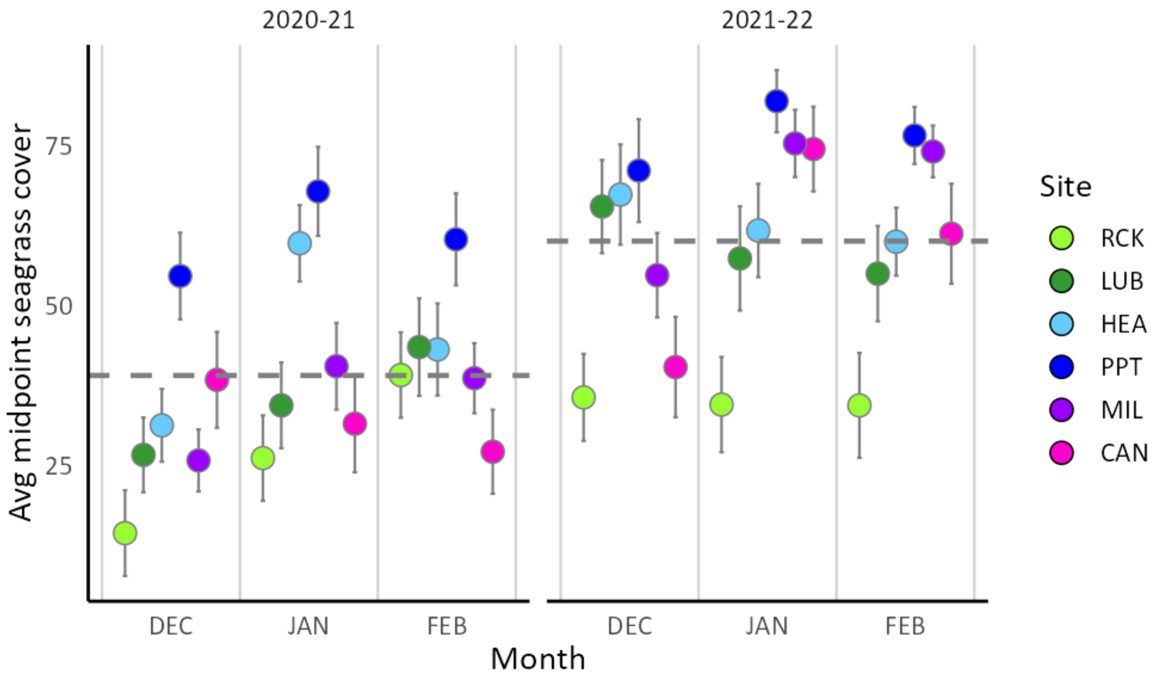


Figure 6).The RCK site, on the other hand, did not experience a significant increase between seasons (2020-21, 26.54 ± 4.02 SE; 2021-22, 34.83 ± 4.26 SE), resulting in no change to the 'fair' score in the performance metric.

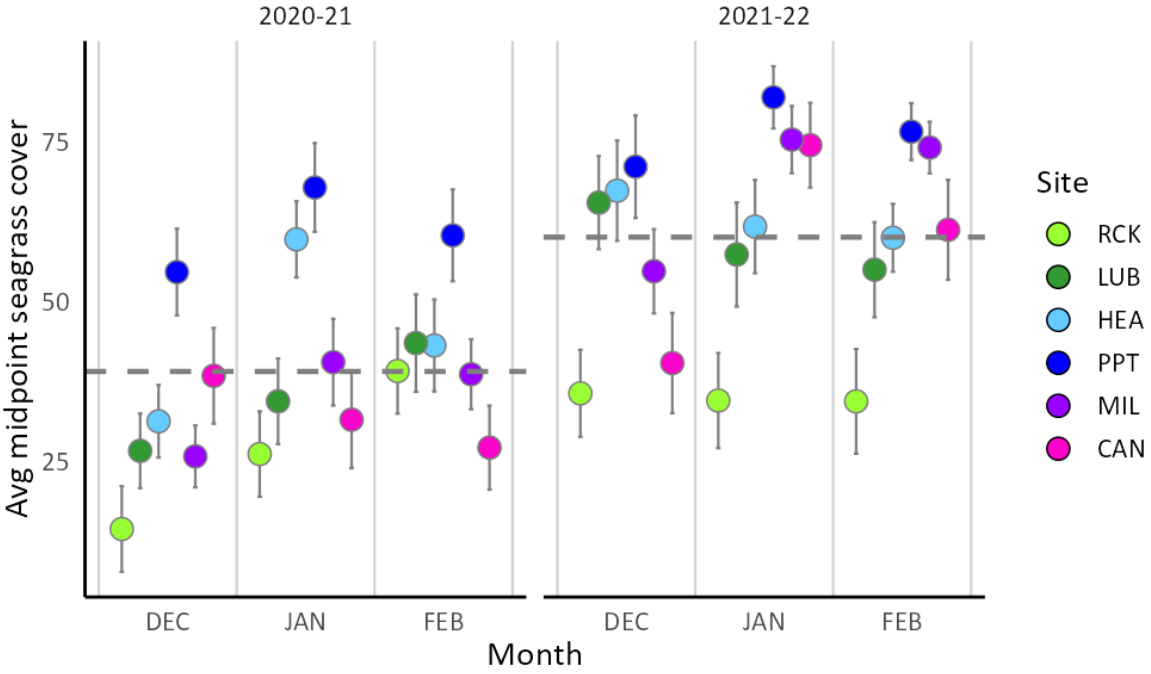


Figure 6: Average midpoint percent seagrass cover (± SE), across each site and month, for each of the 2020-21 and 2021-22 seasons. Annual average for each seagrass sampling season (December to February) shown as dashed grey line.

***Halophila ovalis* reproduction**

Seagrass reproduction is influenced by temperature, disturbances, nutrient levels, light wavelengths and salinity. For clonal species such as *H. ovalis* these environmental factors can influence trade-offs between the seagrass investing resources in vegetative growth and/or reproductive growth[15]. Overall, in 'healthy' meadows, seagrasses with dense and numerous leaf coverage will produce a larger quantity of flowers than sparse meadows. Seagrass reproduction (flowering/fruiting) was scored as 'fair' at PPT (197.41 flowers/m^2) and MIL (252.13 flowers/m^2) in 2021-22 (Figure 7). Measuring and reporting processes are continuously reviewed and reassessed. As part of this, a trial removing seagrass reproduction from the laboratory analysis was conducted in 2020-21 to assess the impact of this metric on laboratory effort. Therefore, for only this year seagrass reproduction was not measured.

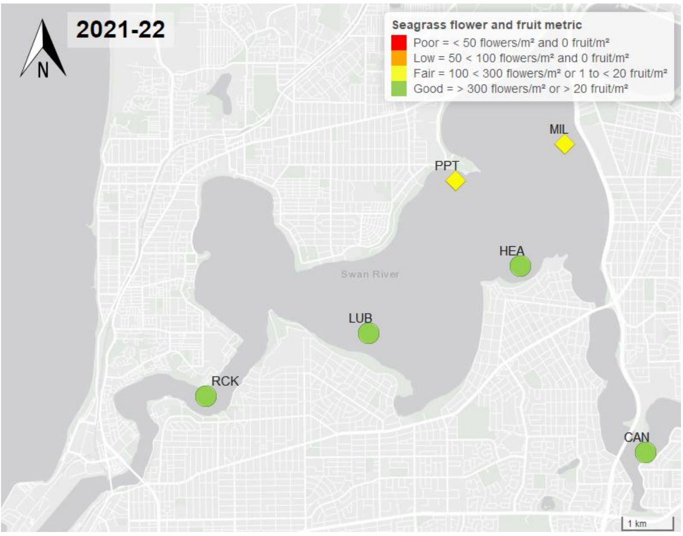


Figure 7: Map of seagrass flower and fruit classification for the survey in the 2021-22 seagrass season.

[15] van Katwijk, M. M. & van Tussenbroek, B. I. (2023) Facultative annual life cycles in seagrasses. *Plants*, *12*(10), 2002. https://doi.org/10.3390/plants12102002.

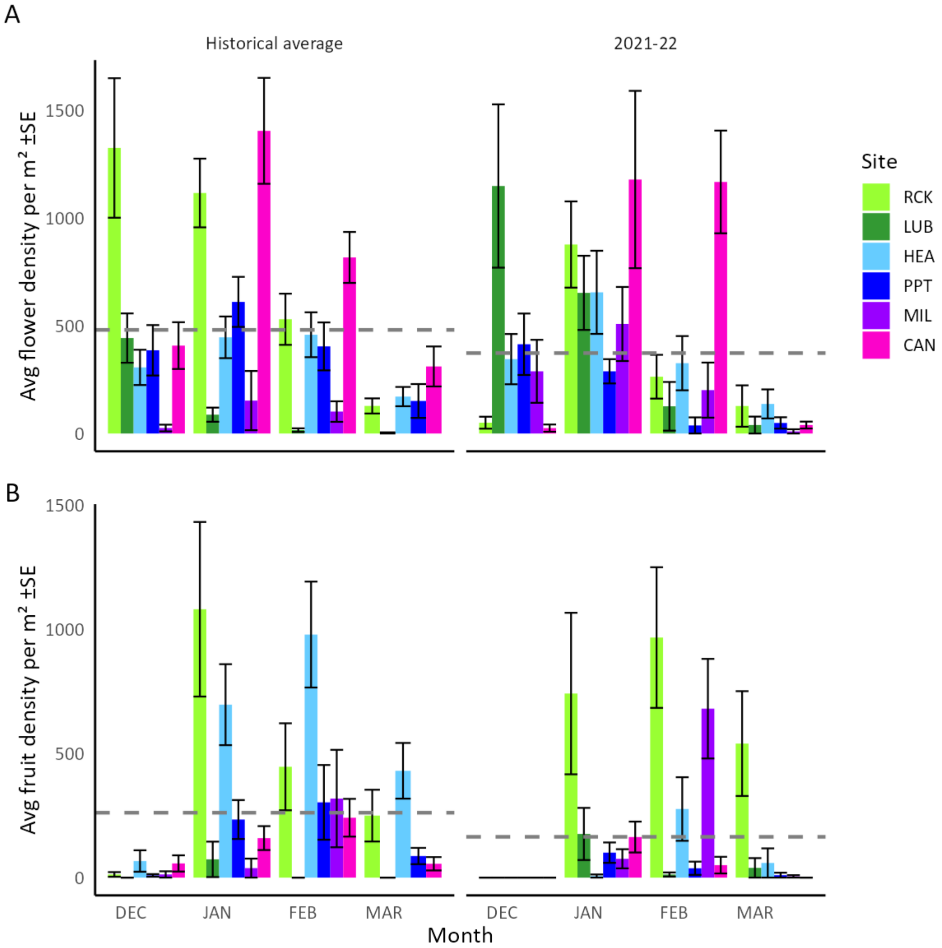


Figure 8: Average seagrass: A) flower density (no. flowers per m2) and; B) fruit density (no. fruit per m2) within each site for the overall historical data (between 2011-2020) and the 2021-22 seagrass season. Annual average for each seagrass sampling season (December – March) shown as dashed line. * No data was available for the 2012-13, 2017-18, 2018-19 and 2020-21 seasons, March data in 2019-20 was not collected and, reproductive data in Milyu commenced in 2019-20.*

Significant differences were observed in flower and also in fruit densities between sites and times in 2021-22 (PERMANOVA p = < 0.01 and 0.01, respectively, Supplementary table 7 and Supplementary table 9). The onset of *H. ovalis* germination in the Swan-Canning River is correlated with temperature, with colder waters driving dormancy in seeds and spring/summer temperatures above 20°C stimulating germination[16]. Temperatures in November 2021-22 were colder than the previous year (see In-situ water temperature), with the RCK site achieving an average of 20°C in mid-November 2021 (Supplementary figure 2).This reduced temperature has contributed to the absence of fruit in Dec 2021 comparative to the low densities observed in the previous season (Figure 8B). Additionally, the initial

[16] Statton, J., Sellers, R., Dixon, K. W., Kilminster, K., Merritt, D. J. & Kendrick, G. A. (2017). Seed dormancy and germination of *Halophila ovalis* mediated by simulated seasonal temperature changes. *Estuarine, Coastal and Shelf Science,* 198A, 156-162. https://doi.org/10.1016/j.ecss.2017.08.045

onset of flowering was delayed in both CAN and RCK (Figure 8A). However, the CAN site progressed to be the most flower dense site recorded for the season, with an average of 603 flowers/ m^2 (± 146 SE). This trend (late flowering/high with subsequent high abundances) was also observed in CAN during the 2011-12 season and was at the time, attributed to low salinity levels (<10 psu) [17]. Lower salinity (as measured at nearby Salter Point, 17 psu in October) was also observed in the 2021-22 season (Supplementary figure 3). PPT produced the least number of flowers (197 flowers/ m^2 ± 46 SE) and subsequently the least number of fruits (36.96 flowers/ m^2 ± 66.9 SE) over the season (Figure 8). Additionally, RCK produced slightly less flowers (329 flowers/ m^2 ± 79) than the yearly average. Despite high flowering at CAN, fruit production was low. Interestingly, RCK produced low numbers of flowers compared to other sites yet produced the highest numbers of fruit for the season (561.99 fruits/ m^2 ± 128.8 SE, Figure 8), there is little information in the literature on the dynamics of this relationship and further investigation is required.

[17] Kilminster K. & Forbes, V. (2014). Seagrass as an indicator of estuary condition in the Swan-Canning estuary, Water Science Technical Series, report no. 62, Department of Water, Western Australia.

Seagrass biomass

Seagrass biomass can be influenced by changes in environmental conditions, including light availability, competitive pressures from algae, and desiccation.

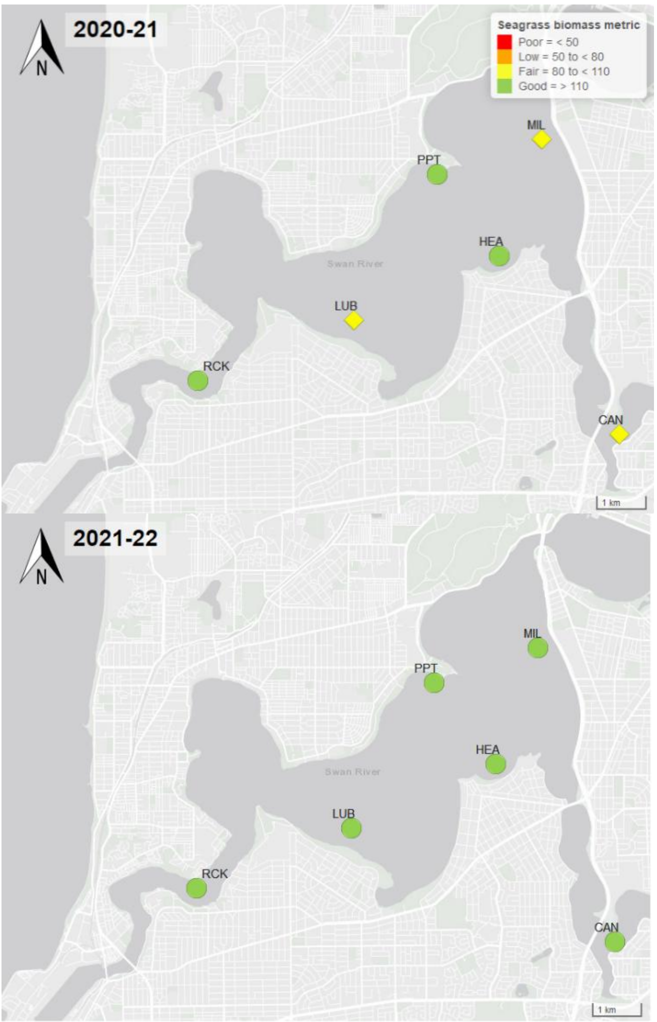


Figure 9: Map of seagrass total biomass classification for the survey in the 2020-21 (above) and 2021-22 (below) seagrass seasons.

Biomass was scored as 'good' at all sites in 2021-22 (Figure 9). Each site was observed to have increased biomass in 2021-22 (176.8 ± 10.47 SE), compared to 2020-21 (123.92 ± 16.33 SE), and this was particularly significant at LUB (Figure 10). During December, the MIL biomass was slightly reduced comparative to other sites, potentially due to the high spring rains increasing turbidity at this upstream site (Supplementary figure 4; Figure 10).

As a perennial species, investment in below ground rhizome carbohydrate storage is vital to ensure persistence over the winter period and to ensure regeneration and high above ground growth in spring. High total biomass suggests higher productivity, effective photosynthetic capabilities and high-performance indicative of overall healthier seagrass. This, combined with low above/below ground ratio, is optimal as it suggests an investment in carbohydrate storage. In spring, an investment in above ground biomass (slightly higher above/below ground ratio) is expected, over the season the below ground ratio will increase (lower above/below ground ratio) as the plant invests in carbohydrate storage for the winter season. Significantly differences were observed between sites, times, and seasons for total biomass (PERMANOVA $p = 0.005$, Supplementary table 13) and significant differences were observed between sites, times, and seasons for above/below ground biomass ratio (PERMANOVA $p = 0.03$, Supplementary table 11).

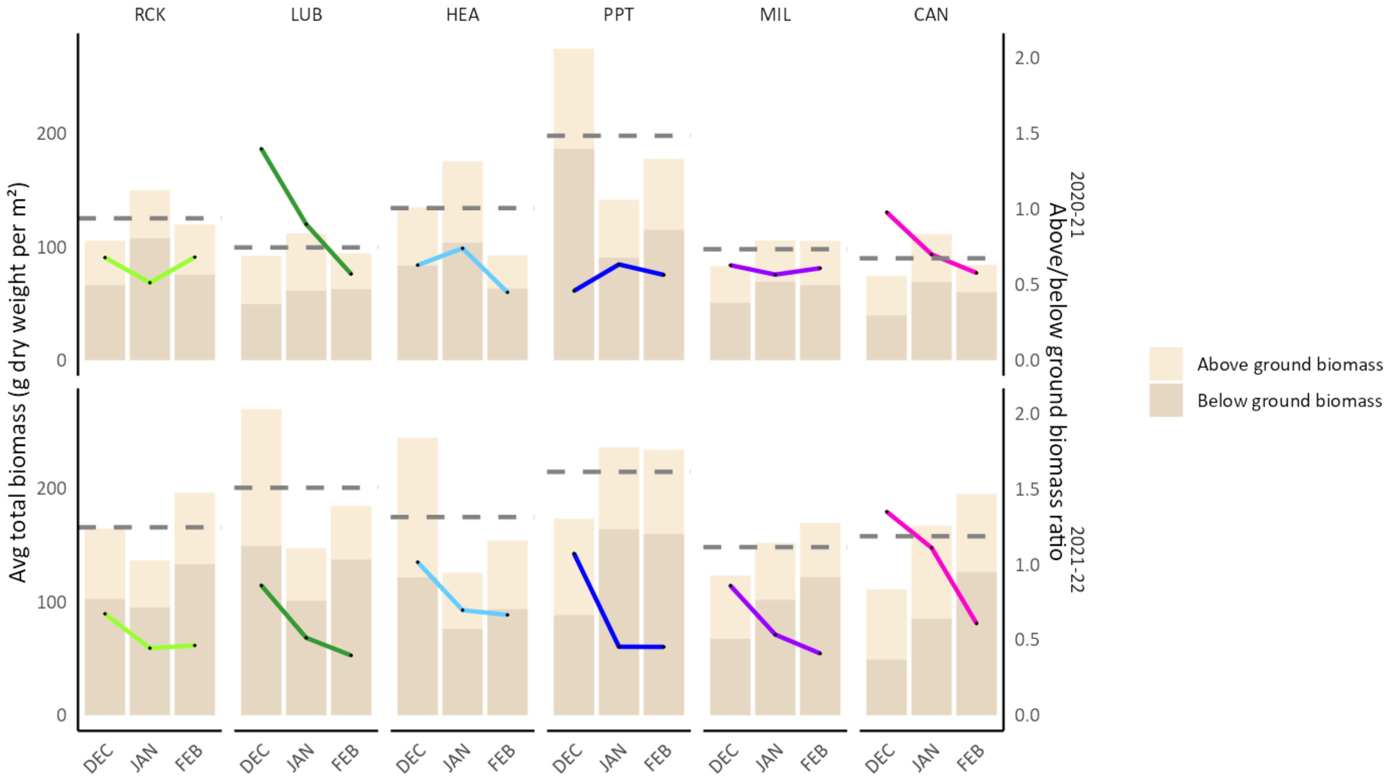


Figure 10: Seagrass above and below ground biomass combined to present total biomass within each site, for each month measured across 2 years of observation. The average total biomass for each seagrass site is shown in dark grey, refer to left y-axis. The coloured line graphs indicate the above/below ground ratio within each site, refer to right y-axis.

Ancillary performance measurements

Seagrass leaf density

As with other metrics analysed above, leaf density within a seagrass meadow may be applied as an indicator of overall health. Where greater leaf densities would suggest higher photosynthetic capabilities, a robust rhizome network, and greater overall performance[18]. Significant differences were observed between sites, times, and seasons for leaf density (PERMANOVA p = 0.01, Supplementary table 15). Overall, the yearly average increased from 6497.76 leaves/ m^2 (± 262.5 SE) in the 2020-21 season to 9568.59 leaves/ m^2 (± 405.3 SE) in the 2021-22 seagrass season (Figure 11). Leaf density in both years peaked in December and gradually reduced in numbers in subsequent months, though this peak was greater in 2021-22. Solar exposure was greater in 2021-22 than the previous year and may have contributed to the increased leaf density observed.

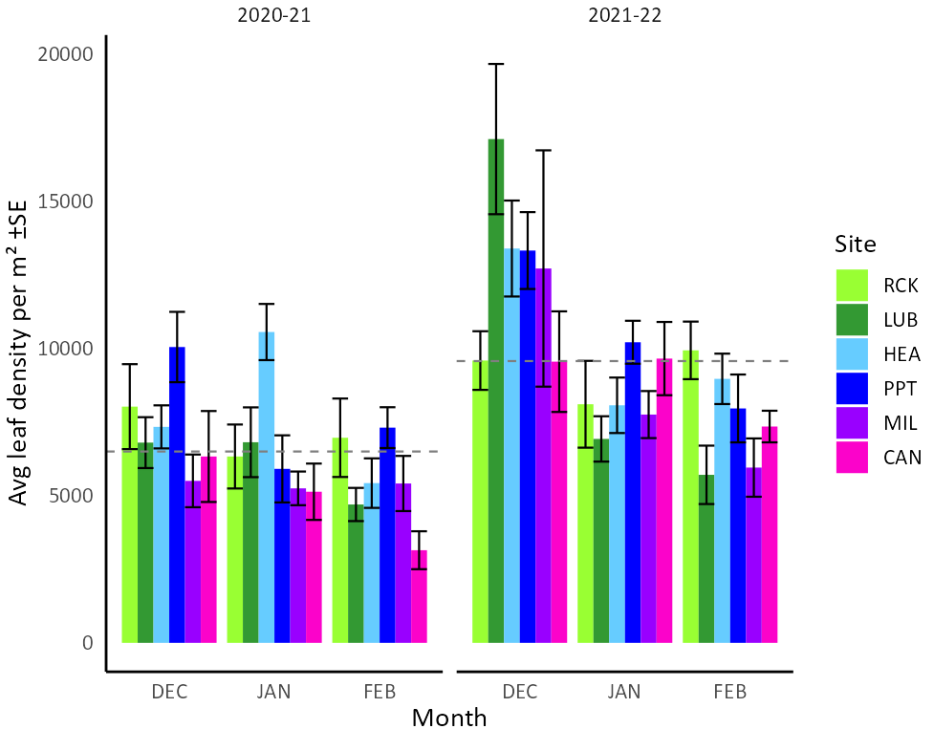


Figure 11: Average seagrass leaf density within each site taken across 2 years of observation. Annual average for each seagrass sampling season (December – February) shown as dashed grey lines.

[18] McMahon, K., Collier, C., & Lavery, P., (2013). Identifying robust bioindicators of light stress in seagrasses: A meta-analysis. *Ecological Indicators, 30,* 7-15. http://dx.doi.org/10.1016/j.ecolind.2013.01.030

Environmental conditions

Noteworthy environmental conditions

The 2020-21 season:

- Spring rainfall was above average; Greater Perth receiving 110-190 mm and Perth Hills, 310-350 mm.
    - Perth Metro experienced a total 182.0 mm of rainfall this spring, the sixth-wettest spring on record.
- Above average temperatures during the 2020-21 summer season
    - December was the second warmest on record in Perth, with 3 consecutive days above 40 °C
    - Only 4 days in total with temperatures over 40 °C for the summer season in Perth
- Summer rainfall was above average, with Perth metro experiencing 43.2 mm, and the greater metro area receiving between 30-80 mm.

The 2021-22 season:

- The Spring 2021 season recorded Perth Metro's wettest spring rainfall on record, with a seasonal total of 233.0 mm.
    - Perth Hills received 250-280 mm of rain.
- Summer 2021-22 was the hottest season since 2012-13 for Perth.
    - Overall, 13 days in summer experienced air temperatures over 40 °C.
    - December 26th had Perth's second highest December temperature on record (43.5 °C), and
    - January 2022 experienced a prolonged heat wave, with 6 consecutive days > 40 °C (18th- 23rd Jan).
- In Perth Metro, only 5.2 mm of rainfall fell through summer, the lowest since 2013-14 (the long-term average is 41.4 mm).

Rainfall

Rainfall can influence estuarine seagrass communities considerably. Substantial rainfall events may act as a stressor for seagrasses by reducing salinity levels, increasing light attenuation through sedimentation and turbidity, and increased nutrient input supporting opportunistic algal growth[19]. Alternatively, low rainfall can result in conditions of high salinity and reduced nutrients inputs.

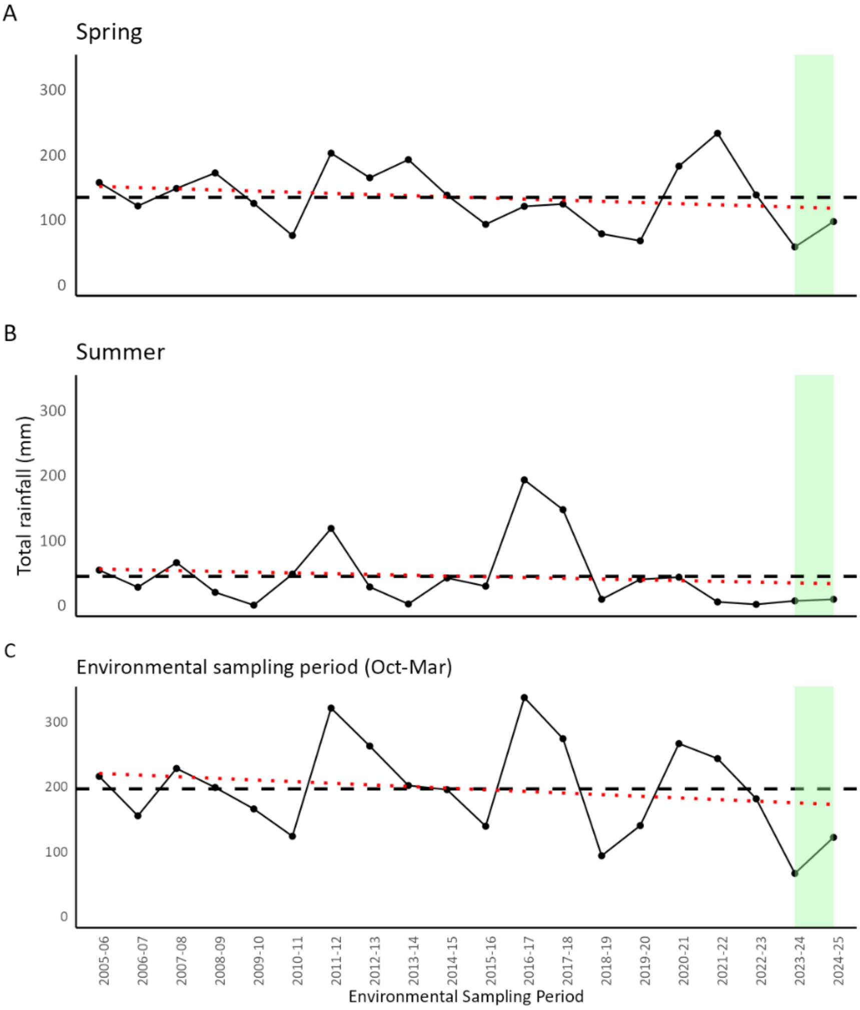


Figure 12: Average total rainfall for: A) Spring period (September to November); B) Summer period (December to February); and C) October-March. Environmental sampling period was selected to reflect the seagrass season, and the total rainfall encompassed within each season recorded at Perth Metro from 2002-03 through to 2021-22, current reporting period highlighted in green. Red line represents the trend line within the data period. Data from Bureau of Meteorology.

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[19] Webster, C. L., Kilminster, K. L., Sanchez Alarcon, M., Bennett, K., Strydom, S., McNamara, S., Lavery, P. S., & McMahon, K. M. (2021). Population-specific resilience of *Halophila ovalis* seagrass habitat to unseasonal rainfall, an extreme climate event in estuaries. *Journal of Ecology*, *109*(9), 3260-3279. https://doi.org/10.1111/1365-2745.13648.

There was elevated rainfall in both 2020-21 and 2021-22 (Figure 12C). With the Perth metropolitan area experiencing the wettest spring rainfall on record during 2021. Although, higher than average rainfall fell in the spring of both reporting seasons (Figure 12A), in particular October and November 2021 experienced several occasions of between 26.4 - 40.4 mm of daily rainfall. Despite the high spring rainfall, lower than average rainfall was observed in the Summer of 2021-22 (Figure 13).

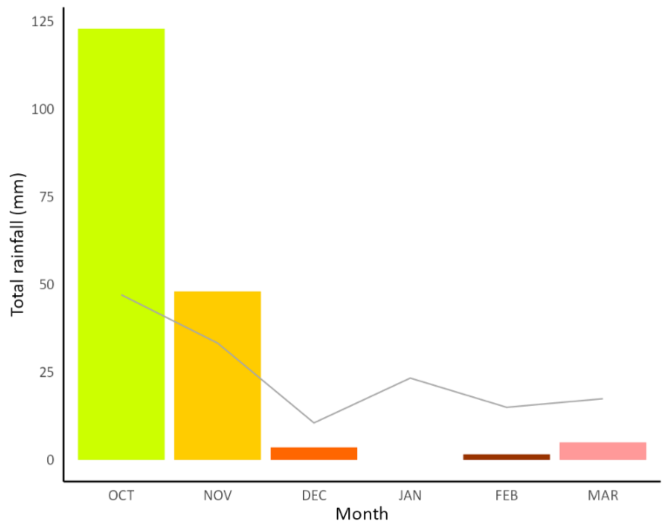


Figure 13: Total rainfall (mm) for each month (October to March) recorded at Perth Metro in 2021-22. The monthly total rainfall averaged over 5 years (2016-17 – 2021-22) shown as black line. Data from Bureau of Meteorology.

In-situ water temperature

The normal physiological thermal limits for *H. ovalis* are between 5 - 35°C, with *H. ovalis* grown at 10°C displaying no growth[20,21]. In aquaria conditions, productivity of local *H. ovalis* was highest when exposed to temperatures between 25-28 °C[22]. When seagrasses reach a critical temperature threshold there can be a large impact on photosynthetic capabilities, growth and shoot mortality.

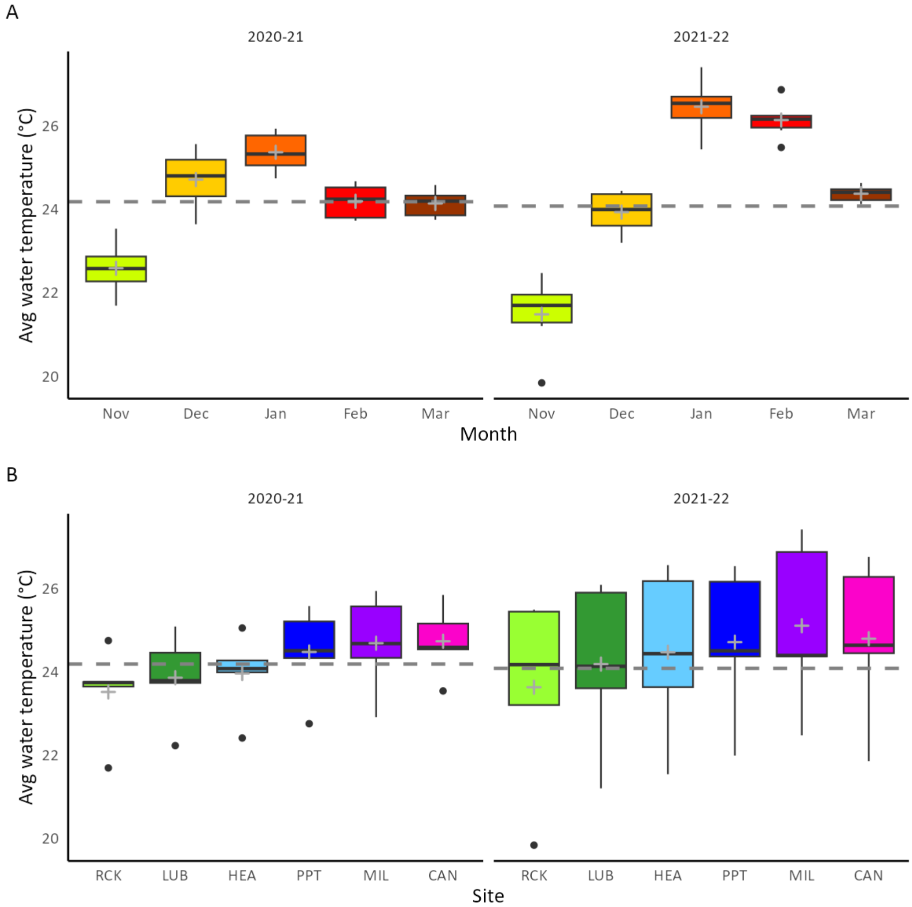


Figure 14: Average water temperature in the shallow regions of each site, recorded over 2 years (2020-21 and 2021-22), from November to March. A) month; and B) site measurements. Readings from MX, Tidbit and Odyssey loggers were combined, temperature variations between the loggers during calibration were incorporated into final measurements. Annual average for each seagrass sampling season (November – March) shown as dashed grey lines.

[20] Hillman K., Walker D. I., Larkum A. W. D., & McComb A. J. (1989) Productivity and nutrient limitation. In: A. W. D. Larkum, A. J. McComb, S. A. Shepherd (eds.) *Biology of seagrasses. a treatise on the biology of seagrasses with special reference to the Australian region* (p. 635). Elsevier, Amsterdam.

[21] Hillman, K., McComb, A. J., & Walker, D. I. (1995). The distribution, biomass and primary production of the seagrass *Halophila ovalis* in the Swan/Canning Estuary, Western Australia. *Aquatic Botany, 51*(1-2)*, 1-54.* *https://doi.org/10.1016/0304-3770(95)00466-D*

[22] Said, N. E., McMahon, K., & Lavery, P. S. (2021). Accounting for the influence of temperature and location when predicting seagrass (*Halophila ovalis*) photosynthetic performance. *Estuarine, Coastal and Shelf Science*, *257*, Article 107414. https://doi.org/10.1016/j.ecss.2021.107414.

On average water temperatures were higher in 2020-21 compared to 2021-22 (Figure 14a), however, this was due to high variability over the season. Specifically in the 2021-22 season, there was considerable variation throughout the season (Figure 14a). Two sites experienced the warmest waters were MIL and LUB in Jan 2022, where temperatures exceeded 35 °C on 3 days at LUB and 2 days in MIL. Conversely, MIL experienced only 1 day over 35 °C in Jan 2021, and LUB did not reach that temperature threshold that year.

Air temperatures

Climatic conditions such as air temperatures can form part of the interpretation but are not a direct indicator in seagrass health. This measurement allows for an overall understanding of climatic changes in the Perth region, which will directly influence changes water temperature and indirectly impact seagrass condition. However, in situations of low tide, seagrass populations can experience full exposure to terrestrial conditions where sunlight and air temperature can directly impact these intertidal seagrass communities. While spring temperatures were slightly above and below average in 2020-21 and 2021-22, respectively, summer temperatures were high. In Perth, the 2021-22 summer months were the hottest observed since 2012-13 with 13 days of the period experiencing air temperatures over 40 °C, resulting in a summer season where the average was 33.3 °C.

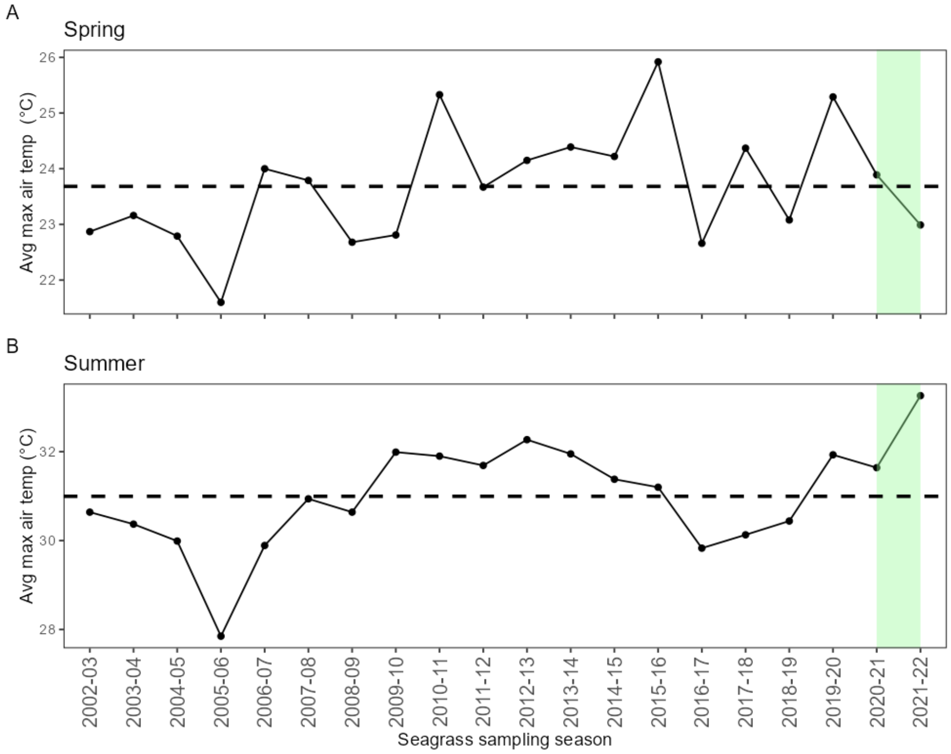


Figure 15: Average yearly temperature for: A) Spring period (September to November); B) Summer period (December to February). Data recorded at Perth Metro from 2002-03 through to 2021-22, current reporting period highlighted in green. Data from Bureau of Meteorology.

Tidal variation

Tide height can have varying impacts on seagrass performance, influence community distribution and in potentially cause ecosystem stress[23]. Low tides may lead to shallow meadow exposure and subsequently, direct sunlight can elevate temperatures, potentially exposing, heating, and desiccating the seagrass communities. Whereas, high tides can alter the light available to deeper meadows, substantially decreasing the photosynthetic capacities of seagrass communities, particular those persisting at the edge of the deep habitat distribution range.

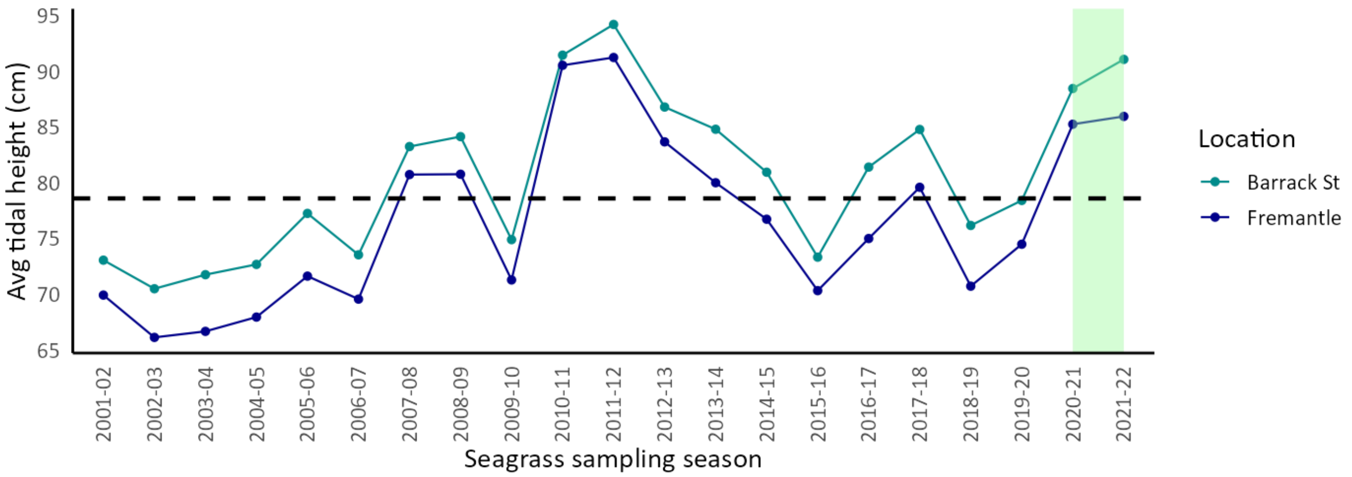


Figure 16: Average tidal height (cm) recorded at two locations: Barrack Street Jetty and Fremantle, within each sampling season (September to March). The current reporting period is highlighted in green. Black dashed line is the total average of all years across both locations. Data compiled from the Department of Transport.

Tide height yearly averages were similar between seasons (86.8 cm, 2020-21 and 88.5 cm, 2021-22). This is considerably high compared to the 20-year (2001-2022) average of 78.6 cm (Figure 16). Higher variation was observed in 2020-21 both between month and within month for Dec, Jan and Feb, alternatively for the 2021-22 season, tides were considerably more stable across months (Figure 17).

[23] Collier, C. J., & Waycott, M., (2014). Temperature extremes reduce seagrass growth and induce mortality. *Marine Pollution Bulletin*, *83*(2), 483-490. https://doi.org/10.1016/j.marpolbul.2014.03.050

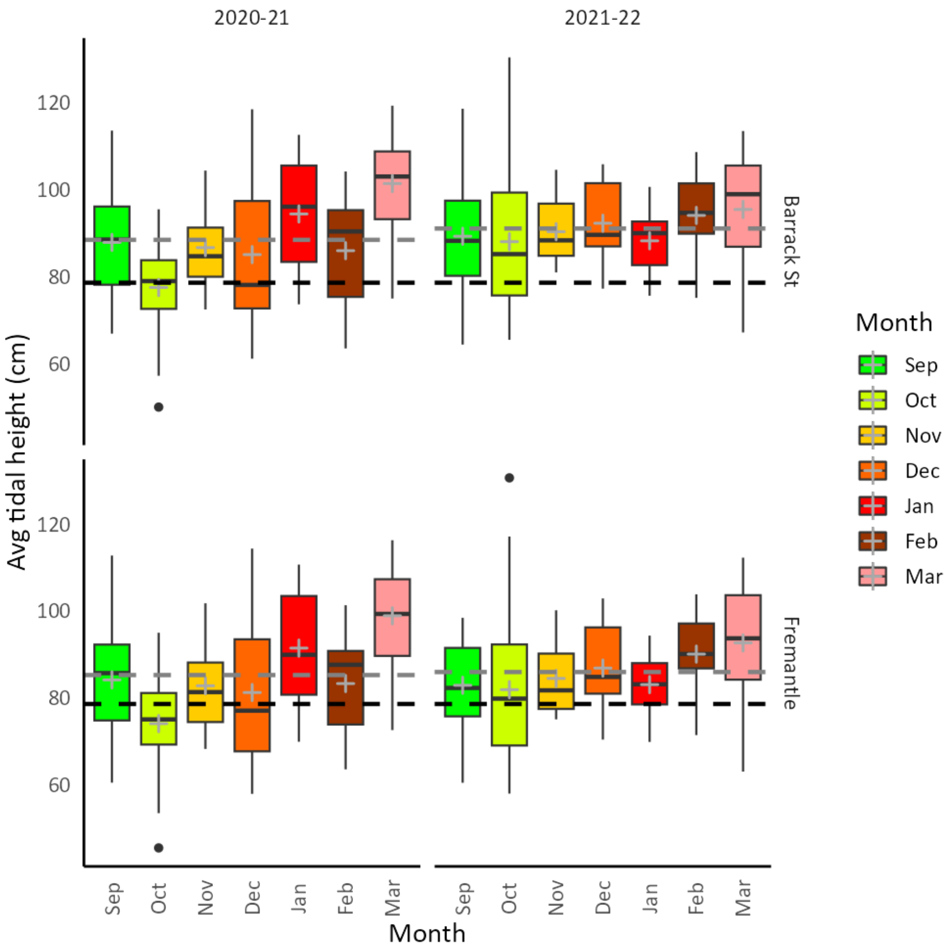


Figure 17: Average tidal height (cm) recorded at two locations: Barrack Street Jetty and Fremantle, from September to March, across 2 years (2020-21 and 2021-22). Grey dashed line is the average tide height within each year at each location, black dashed line is the 20-year average across both locations. Represented within the boxplot; median value shown in black line, the mean value for each time data point represented as '+'. Data obtained from Department of Transport.

Global solar exposure

The global solar exposure is the total solar energy that falls on a horizontal surface, this is influenced by the position of the sun and the extent of cloud cover (http://www.bom.gov.au). Photosynthesis is influenced by the amount of light available to the photoautotroph. Inter-annual differences in solar exposure during the seagrass growing season may influence growth and performance. Solar exposure was slightly higher in the 2021-22 sampling period compared to the lower levels of exposure observed in the 2020-21, overall, both years are very similar to the 20-year average (Figure 18).

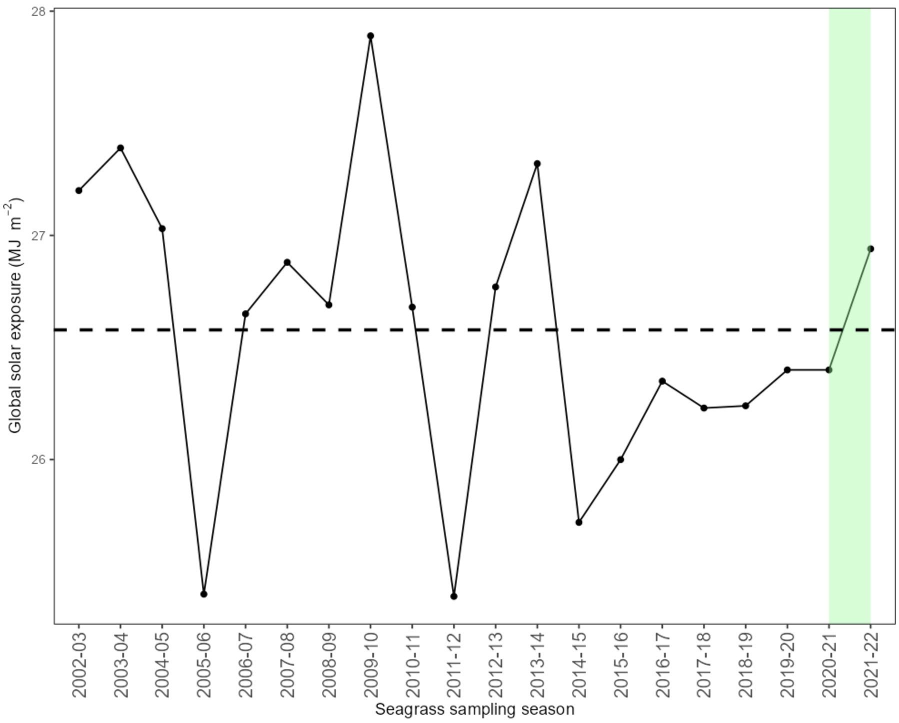


Figure 18: Average daily global solar exposure over Australia, recorded within each sampling season (October to February), recorded across 20 years 2001-02 to 2021-22, reporting period highlighted in green. Dashed line is the total average of all years across both locations. Data from Bureau of Meteorology's daily global solar exposure model.

Benthic light

Sufficient light availability is a limiting factor in overall productivity and health of seagrass. Benthic light is the amount of light that reaches the seagrass bed, and is influenced by hours, intensity (global solar exposure) and direction of sunlight, water depth, water clarity (turbidity and phytoplankton accumulations) and macroalgal cover. Benthic light is measured as photosynthetically active radiation (PAR) recorded as moles m^{-2} d^{-1} and can be interpreted as the total light received per day.

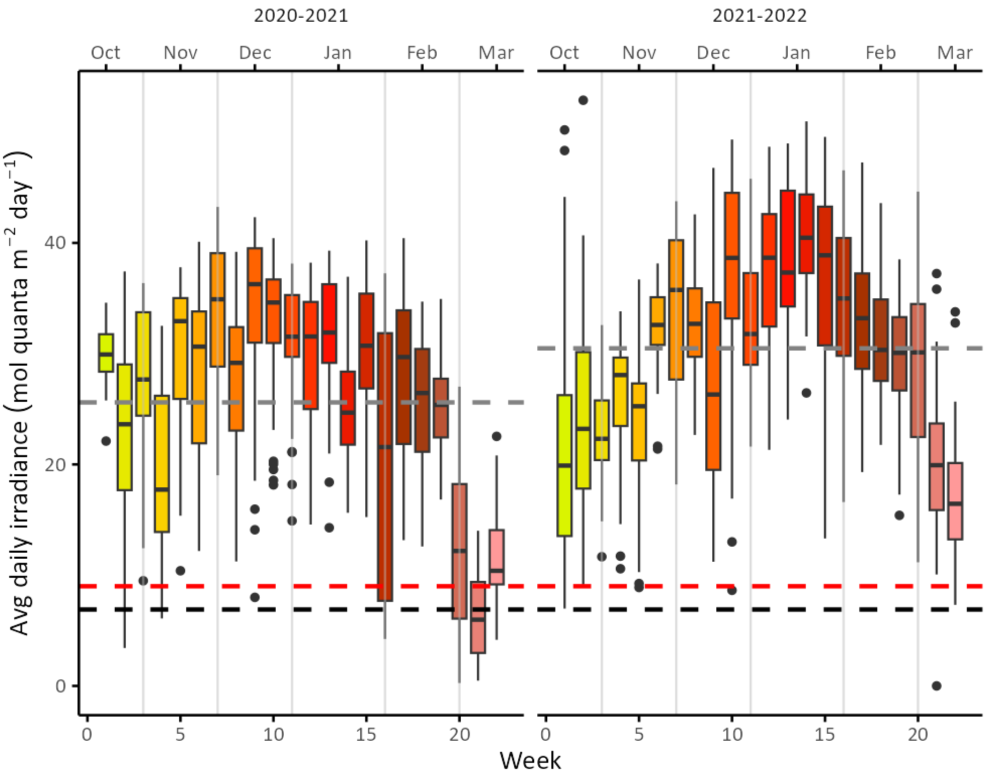


*Figure 19: Daily average benthic light recorded per week, over 2 seasons. Weeks are inclusive of the 3rd Monday in October to 3rd Sunday in March. Dashed grey line is the average daily irradiance for each season. Displayed on the plot are the potential light levels necessary to ensure H. ovalis is 80% protected against reductions in shoot density (red dashed line) or growth rate (black dashed line)[24]**

[24] Collier, C. J., Adams, M. P., Langlois, L., Waycott, M., O'Brien, K. R., Maxwell, P. S., McKenzie, L. (2016). Thresholds for morphological response to light reduction for four tropical seagrass species. *Ecological Indicators*. *67*. 358-366. https://doi.org/10.1016/j.ecolind.2016.02.050

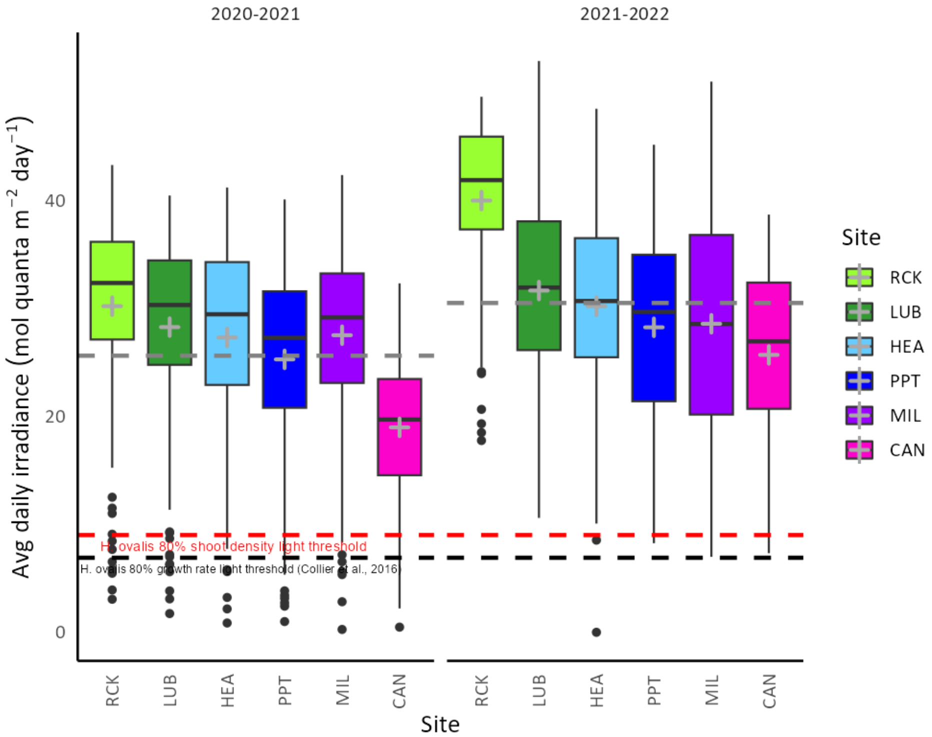


Figure 20: Site-based average daily benthic light, recorded over 2 seasons (3rd Monday in October to 3rd Sunday in March). Dashed grey line is the average daily irradiance across all sites for each year. Represented by the boxplot is the median value shown as the black crossbar and the mean value for each site as '+'. Displayed on the plot are the light thresholds necessary to ensure H. ovalis is 80% protected against reductions in shoot density (red dashed line) or growth rate (black dashed line) at cool temperatures (~23°C)[24].

On average, light received by the seagrass was 25.60 moles m^{-2} d^{-1} (2020-21) and 30.48 moles m^{-2} d^{-1} (2021-22) over between the October to March period (Figure 19). *Halophila ovalis* biomass reduces rapidly during incidences of light reduction and therefore this species has limited tolerance to severe light reduction. The difference in light conditions between seasons may be influenced by a combination of accumulative pressures including the varying solar expose received in each year, increased tannins from late spring, macroalgal cover, cloud cover and tidal exposure.

H_{sat}

Plants require a minimum level of photosynthetically active light to be productive. For *H. ovalis* in the Swan River, this compensating irradiance (I_c) has been estimated as 40 μmol photons m^{-2} s^{-1} (Figure 21)[26]. Conversely, I_k pinpoints the level where light is saturating for photosynthesis (200 μmol photons m^{-2} s^{-1} for *H. ovalis*), above this point primary production is at maximum capacity, and increased light does not lead to greater productivity (Figure 21)[26]. Therefore, the measure of time (hours) that seagrass is exposed to light above the saturation point (I_k) is a useful measure for maximum productivity (H_{sat}). It is generally accepted that H_{sat} need to be greater than 4-6 hrs for good growth to occur, where less than 4 hrs has been associated with seagrass loss[†]. H_{comp} refers to the net number of hours positive net production is occurring (Figure 21). It should be noted the above values are only indicative of potential minimum and maximum thresholds and that localised variation of light tolerances will occur within seagrasses of the Swan-Canning Estuary[25,26].

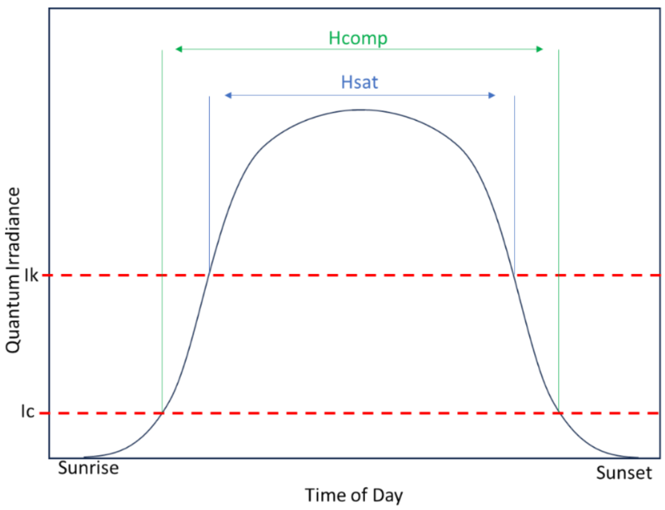


Figure 21: Generalised diurnal light curve, representing any given day with no cloud cover. Light compensation point (I_c) and light saturation point (I_k) are used to determine hours of compensating irradiance (H_{comp}) and hours of saturating irradiance (H_{sat}; Image adapted from Dennison 1987).

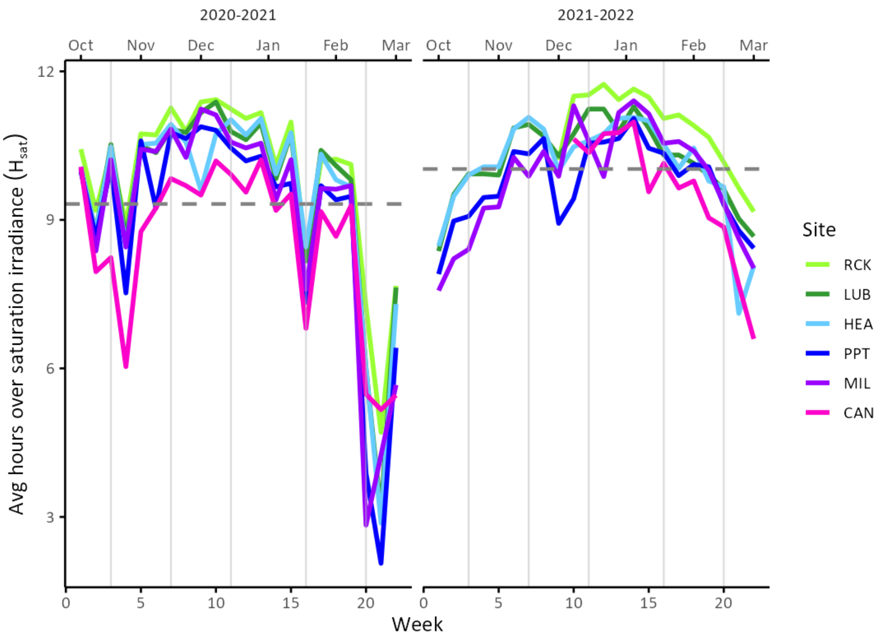


Figure 22: Weekly average daily hours that light levels exceeded 200 mmol m-2 s-1 (H_{sat}, the level assumed to saturate photosynthesis), recorded over 2 years (2020-21 and 2021-22), at each site from 3rd Monday in October to 3rd Sunday in March. Note: Loggers in the 2021-22 season were not placed in RCK and CAN until mid-December.

[25] Said, N. (2017) *Effects of temperature and location on the photosynthesis-irradiance relationship of the seagrass* Halophila ovalis [Master's thesis, Edith Cowan University]. Retrieved from http://ro.ecu.edu.au/theses/2028.

[26] Dennison, W. C. (1987). Effects of light on seagrass photosynthesis, growth and depth distribution. *Aquatic Botany*, *27*(1), 15-26, https://doi.org/10.1016/0304-3770(87)90083-0.

For both seasons reported, seagrass received similar total hours (9.32 hrs, 2020-21; 10.0 hrs, 2021-22) of light greater than the saturating threshold (H_{sat}). In March 2021 the H_{sat} values significantly reduce, which corresponds to the reduced daily irradiance observed in the benthic light measurements (Figure 22). This may be attributed to the combination of increased turbidity (Supplementary figure 4) near the Narrows Bridge, and increased cloud cover in early March (Supplementary figure 5) and increased swell as a result of the wind and rainfall (total 34 mm) experienced between 1-5th March. Therefore, seagrass in MIL, PPT, HEA experienced less than 4 hours of light above the saturating threshold during this period potentially resulting in seagrass loss.

Seagrass pressures

Macroalgal cover

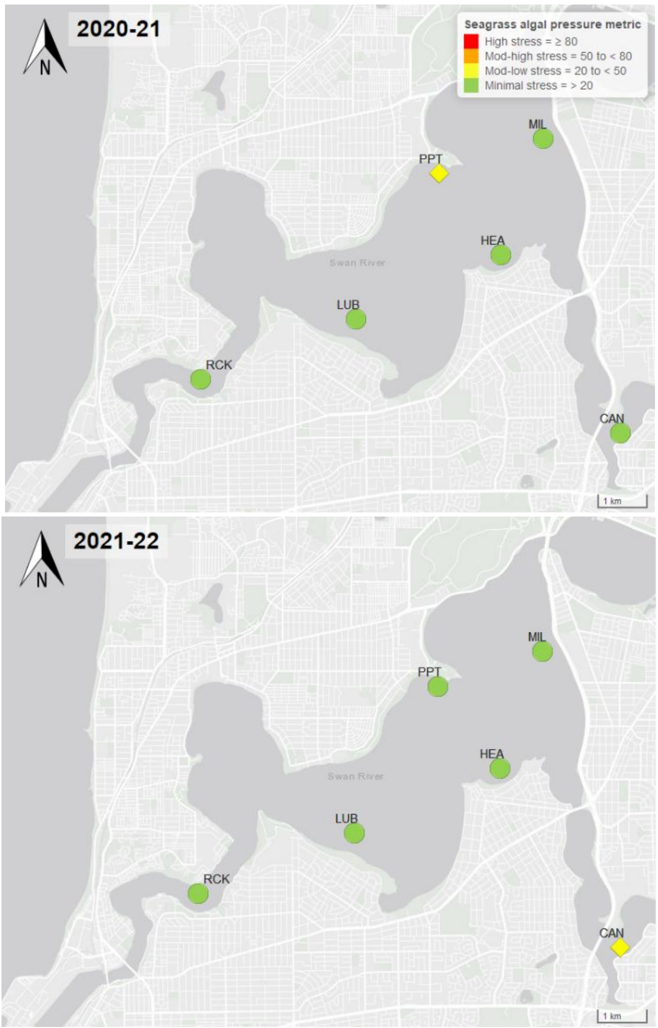


Figure 23: Map of seagrass macroalgae pressure metric for the survey in the 2020-21 (above) and 2021-22 (below) seagrass seasons.

Macroalgae is ubiquitously found in the Swan-Canning Estuary with 36 unique species recorded in 1995[27]. For some of these species, for example, *Chaetomorpha* and *Cladophora*, excess nutrients, and high temperatures can lead to increased abundances and proliferation throughout the system. This can impact seagrass communities by limiting light penetration to the benthos and competing with available nutrients. The presence of drift algae can also raise the sulphide horizon in the sediment within seagrass meadows, and at night, the oxygen concentration in the water column reduces, increasing risk of hypoxia. In aquaria conditions, *H. ovalis* exposed to the opportunistic alga *Gracilaria comosa* in combination with increased temperatures (30 °C) lead to reductions in the growth of

[27] Astill, H. L., & Lavery, P. S. (2004). Distribution and abundance of benthic macroalgae in the Swan-Canning Estuary, South-Western Australia. *Journal of the Royal Society of Western Australia*, *87*, 9.

seagrass leaves, roots and rhizomes and displayed high levels of plant mortality[28]. In the Swan-Canning Estuary rainfall in spring transports nutrients from catchment runoff into the estuary. This increased nutrient supply, combined with increasing light and temperature availability in the spring months, provides optimum growth for macroalgal species.

While the macroalgae pressure metric improved in PPT from 2020-21 to 2021-22, an increased the quantity of algae was observed at CAN, increasing pressure on seagrass at this site (Figure 23). Macroalgae percent cover was observed with monthly quadrats between November and March at each site (Figure 24). Species present within a quadrat was identified and recorded (Figure 25). Overall, macroalgal cover increased in the 2021-22 season compared to 2020-21. Spring rainfall was high in both years, but higher in the 2021-22 season, benthic light and solar exposure was higher in the 2021-22 season which may have contributed to the high cover observed in this season (Figure 24). The sites, RCK, LUB and CAN experienced the highest cover in November, the dominate species with the highest proportion being *Gracilaria sp.* (RCK, CAN), and *Chaetomorpha linium* (LUB; Figure 25).

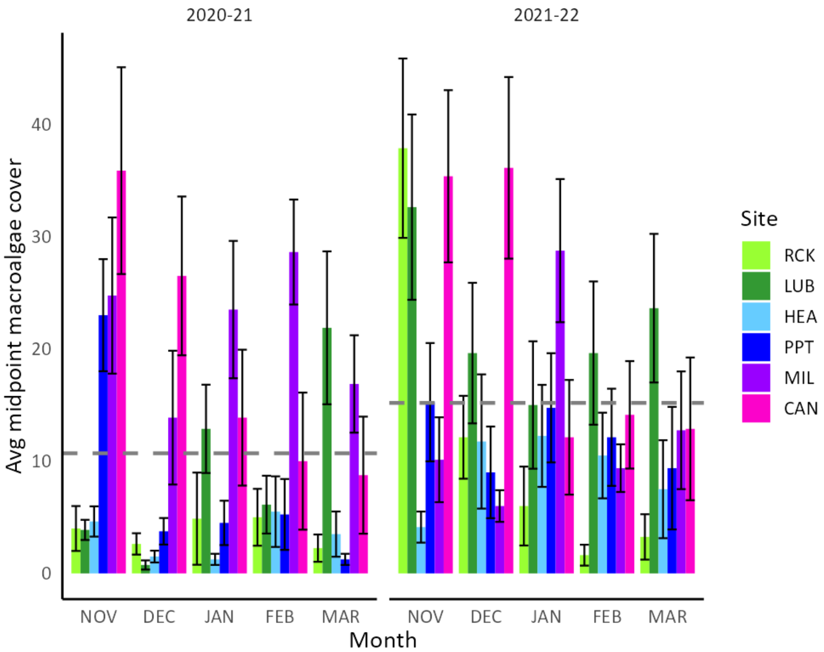


Figure 24: Average midpoint percent macroalgae cover, across each site and month, for each of the 2020-21 and 2021-22 seasons. Annual average for each seagrass sampling season (November – March) shown as dashed grey lines.

[28] Holmer, M., Wirachwong, P., & Thomsen, M. S. (2011). Negative effects of stress-resistant drift algae and high temperature on a small ephemeral seagrass species. *Marine Biology*, *158*, 297-309. https://doi.org/10.1007/s00227-010-1559-5.

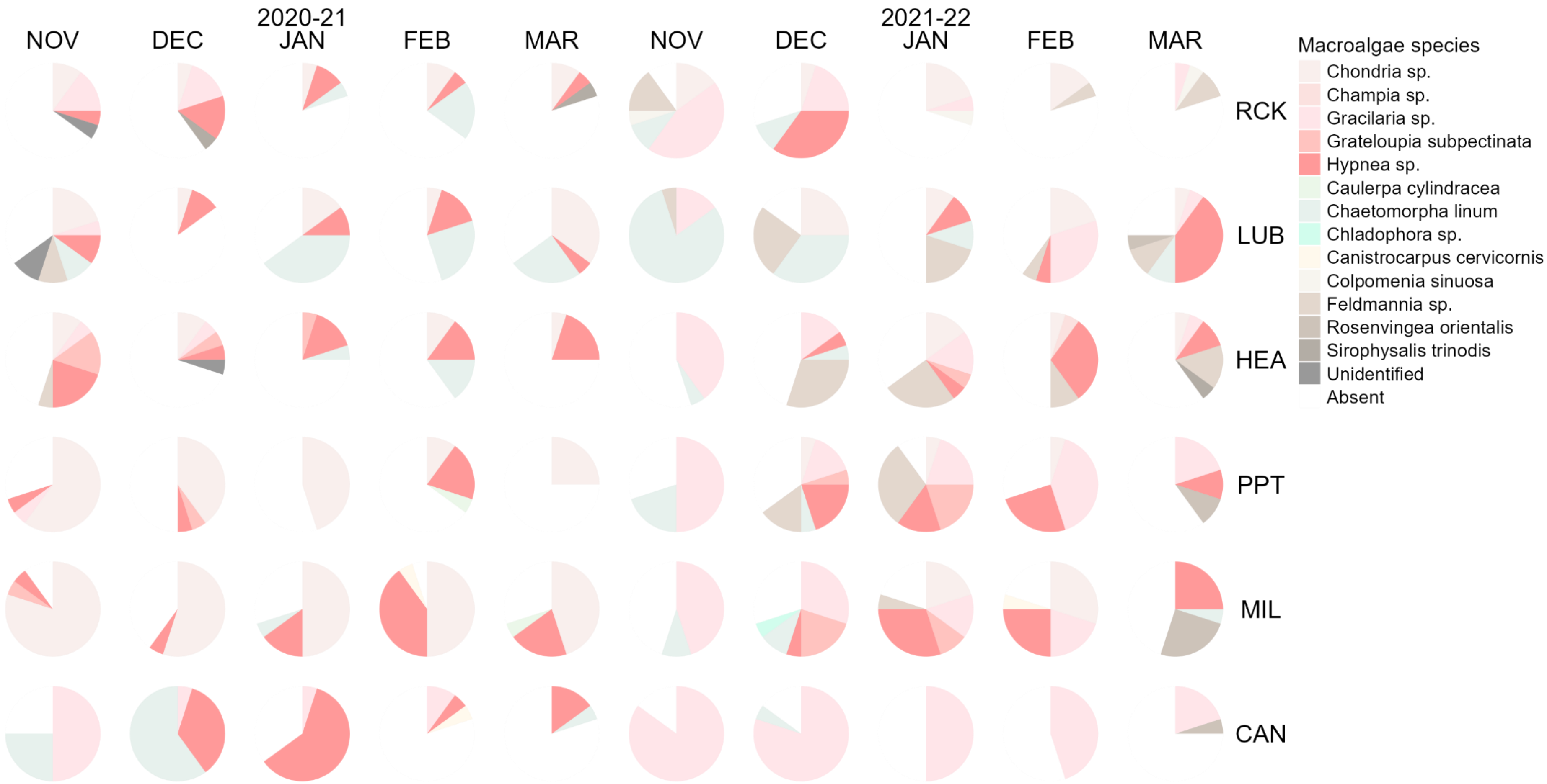


Figure 25: Pie graph representing the one macroalgal species that was recorded in highest abundance within each quadrat. Recorded over 2 years (2020-21 and 2021-22), at each site from November to March. Each taxa is colour coded to represent the applicable grouping (Rhodophyta = Red, Chlorophyta = Green, Phaeophyceae =Brown)

Ancillary pressure measurements

***Batillaria australis* density**

The invasive mud snail *B. australis* is widely distributed in the Swan-Canning. A survey conducted in 2007 assessed that within the Swan Estuary there was an estimated 424 individuals per square meter living in seagrass beds, from this it was predicted a total 3.6 billion invasive snails persisted in the Estuary[29]. Forbes & Kilminster (2016) indicate that *B. australis* population in seagrass communities are increasing with approximately 5 billion individuals in 2012 to ~7 billion in 2016-17 based on individuals per square meter, with the total area of the Swan-Canning estuary comprising 403 ha[29,30].

Within the seagrass beds, the snail impacts *H. ovalis* by reducing biomass in both leaves and roots observed in aquaria studies potentially through its burying behaviour causing bioturbation and uprooting[31]. Additionally, their shells provide a substrate for the attachment of algae such as *Gracilaria spp*. which when in high abundances can create shade seagrass and reduce photosynthesis.

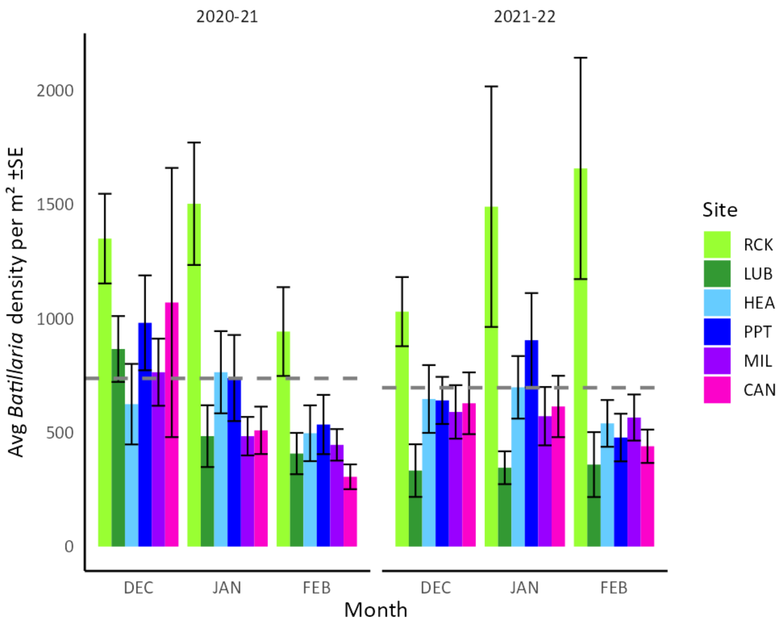


Figure 26: Average seagrass Batillaria australis *within each site taken across 2 years of observation. Annual average for each seagrass sampling season (December – February) shown as dashed grey lines.*

Significant differences were observed between sites, times, and seasons for *B. australis* density (PERMANOVA $p = 0.01$, Supplementary table 17). The yearly average slightly deceased from 737.1 individuals/ m^2 (± 52.1 SE) in the 2020-21 season to 696 individuals/

[29] Forbes, V.R. and Kilminster, K. (2016). Monitoring seagrass extent and distribution in the Swan-Canning estuary. Water Science Technical Series, Report no. 70, Western Australia Department of Water, Perth.
[30] Thomsen, M. S., Wernberg, T., Tuya, F., & Silliman, B. R. (2010). Ecological performance and possible origin of a ubiquitous but under-studied gastropod. *Estuarine, Coastal and Shelf Science*, *87*(4), 501-509. https://doi.org/10.1016/j.ecss.2010.02.014.
[31] Hoffle, M., Wernberg, T., Thomsen, M. S., & Holmer, M. (2012). Drift algae, an invasive snail and elevated temperature reduce ecological performance of a warm-temperate seagrass, through additive effects. *Marine Ecology Progress Series. 450.* 67-80. https://doi.org/10.3354/meps09552.

m^2 (± 53.5 SE) in the 2021-22 seagrass season (Figure 26). Therefore, approximately 2.8 to 3 billion *B. australis* were present in the Swan Estuary during these seasons. These numbers have been decreasing since the peak in the 2015-16 period (Figure 27). This may be attributed to the change in core processing methodology which occurred in the 2019-20 season, prior to this year, all *B. australis* shells within the core sample were counted and recorded in the final density measurement. However, from 2019-20 onwards, *B. australis* shells were physically opened to determine if a living snail was present. Henceforth, only organisms deemed 'alive' in the core sample were included in the density count. Alive is defined as, having moist, colour appropriate (yellow or grey, blue) flesh within the shell. This change in methodology would see an expected decrease in density numbers, as all 'dead' organisms were omitted from the count data. Potentially co-contributing to this reduction in *B. australis* abundances, include the summer flood event in 2017, the influx of low salinity waters, turbidity, and sediment displacement, may have impacted snail numbers, directly, or indirectly through a reduction of reproductive success.

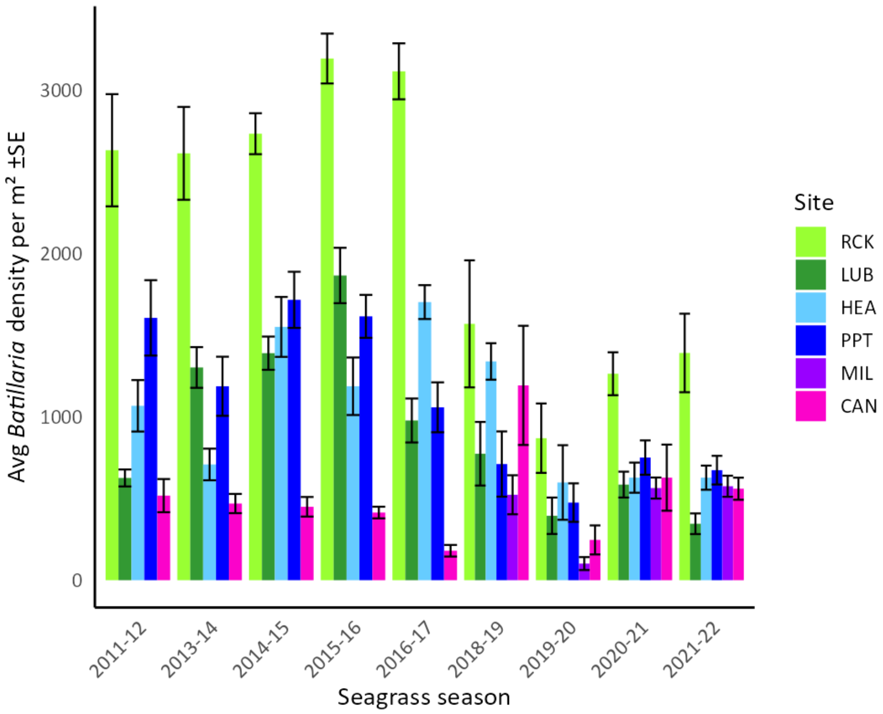


Figure 27: Average B. australis *density within each site taken at each seagrass season between 2011-2022. Milyu site added in 2018-19, no* B. australis *data was recorded in the 2012-13 and 2017-18 seasons. Commencing the 2019-20 season, only individuals deemed 'alive' were included.*

Conclusion

The Swan Canning River Protection Strategy emphasises the importance of protecting, managing, and enhancing biodiversity. For seagrass communities within the Swan Canning Riverpark, this objective can be evaluated through regular monitoring and reporting. The overall summary index for seagrass performance in the 2021-22 season was ‘good’ for all monitored sites.

Despite the higher spring rainfall, extreme summer temperatures and average benthic light, there was a ‘good’ outcome observed in this report period. The spring rainfall potentially transported nitrogen and phosphorous from the Swan-Canning catchment, promoting seagrass and macroalgal growth and productivity. However, with the increased nutrient load, high macroalgae cover was recorded this year compared to last, particularly early in the season at Rocky Bay (RCK). The high rainfall also increased turbidity in the upstream sites early in the 2021-22 season. Finally, comparative to previous years, *B. australis* numbers were low during the 2021-22 reporting period.

The RCK site was the only site to not improve performance metric scores for presence/ absence and percent cover, these metrics retained a ‘fair’ score for both seasons. Macroalgae was high at this site in November and December and would have impacted select areas of seagrass beds. This site is also impacted by human activities including, fishing, boating activities and dog walking. It is also feasible that the ‘fair’ score was influenced by *B. australis* densities that remained high in RCK consistently over both seasons. Further monitoring at this site will gain awareness and understanding of the site’s unique environmental dynamics and pressures influencing seagrass presence and cover.

The CAN site achieved only a ‘low’ biomass performance metric during 2020-21 however conditions where more favourable in 2021-22 a ‘good’ score for this metric was attained. The lower score in 2020-21 was potentially due to high temperatures and low light observed at CAN during that season.

Regardless of the good seagrass states reported here, continued monitoring is essential to report of changing conditions and the environmental factors influencing perceived variations in seagrass health. As specified by the Swan Canning River Protection Strategy, ensuring healthy, sustainable, and resilient seagrass communities is an important aspect of estuary management and will ensure maintained or enhanced benefits for future generations. Data from this monitoring also feeds into annual marine park reporting for the Swan Canning Estuary Marine Park areas.

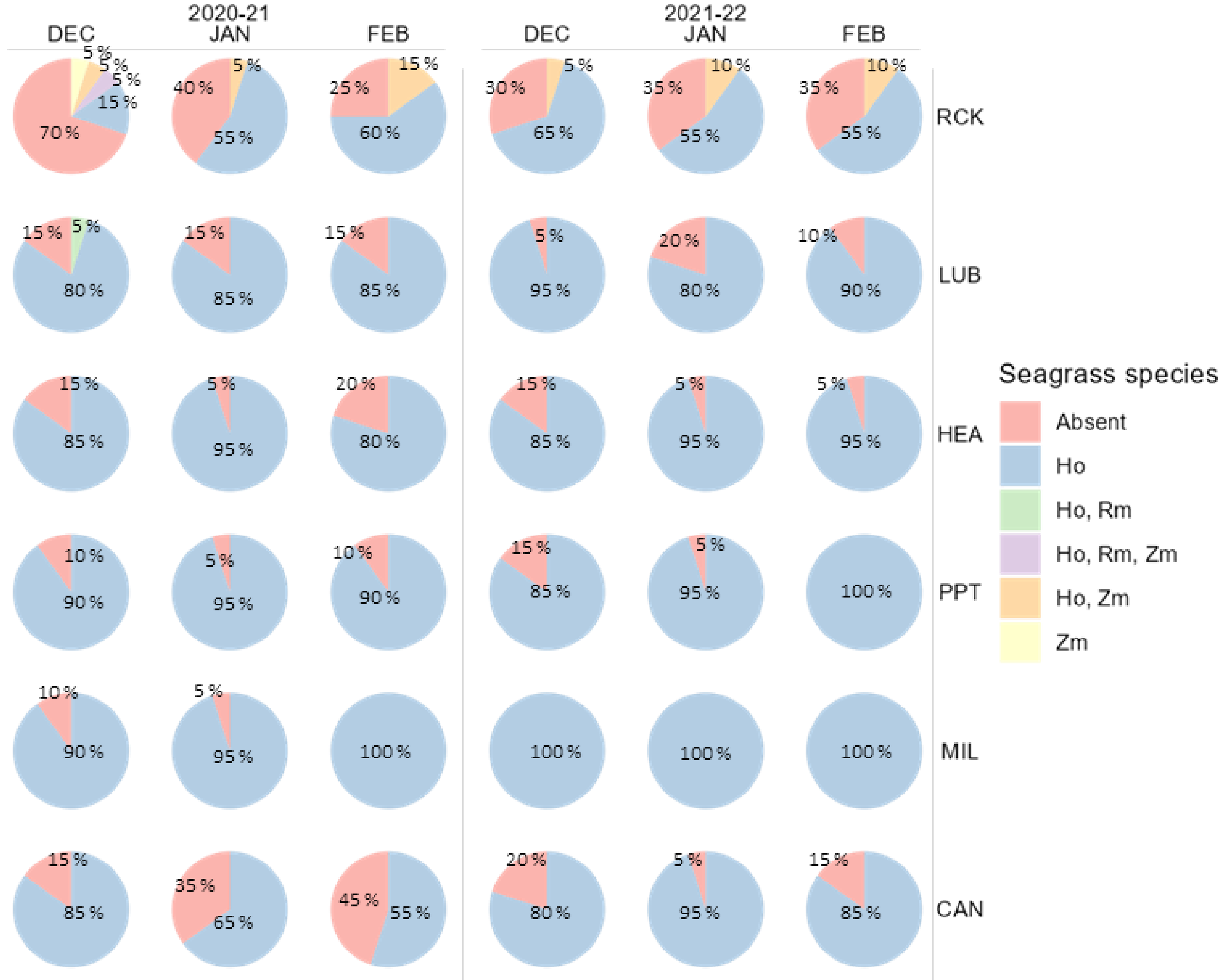
Appendices

Overall seagrass performance health indicator score

Supplementary table 1: Overall seagrass performance health indicator score in the seasons 2020-21 and 2021-22 at each site.

	RCK	LUB	PPT	HEA	MIL	CAN
2020/21	3.33	3.33	4.00	4.00	3.33	3.00
2021/22	3.50	4.00	3.75	4.00	3.75	4.00

Seagrass species composition



Supplementary figure 1: *Average seagrass species composition (%) at each site across 2 years of observation (2020-21 and 2021-22). Species recorded:* Halophila ovalis *(Ho),* Ruppia megacarpa *(Rm) or* Zostera muelleri *(Zm). Where species composition was mixed the combination of species is assigned an individual category. Absent indicates no seagrass present.*

Three species of seagrass (*Halophila ovalis*, *Ruppia megacarpa* and *Zostera muelleri*) were observed in the Swan-Canning estuary during the 2020-21 and 2021-22 surveys (Supplementary figure 1). There were no significant differences ($p > 0.05$, Supplementary table 2) in seagrass composition between sites, times, and seasons. The dominant species in all sites and times is *H. ovalis*. RCK was the only site to record *Z. mulleri* present in both seasons, whereas both RCK and LUB recorded the presence of *R. megacarpa* in the 2020-21 season, both species are found at the sites situated towards the marine end of the estuary. Interestingly, *R. megacarpa* was not identified at any site in the 2021-22 season. *Posidonia australis* was observed at the RCK site in 2015-16 but has not been recorded in the estuary to date, potentially due to the reduced salinity waters and the shift in salinity stability experienced following the summer flood event in 2017.

Statistical data

Supplementary table 2: Univariate three-way PERMANOVA. Outputs based on Euclidian distance resemblance matrix for seagrass species composition, performed with season, site and time as fixed factors (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	0.56	0.56	1.82	9761	0.181
Time	2	0.21	0.10	0.34	9951	0.719
Site	5	2.67	0.53	1.75	9952	0.127
Season x Time	2	0.10	0.05	0.17	9951	0.842
Season x Site	5	0.63	0.13	0.41	9941	0.841
Time x Site	10	2.48	0.25	0.81	9931	0.614
Season x Time x Site	10	2.21	0.22	0.73	9943	0.709

Supplementary table 3: Univariate three-way PERMANOVA on seagrass presence/absence. Outputs based on zero-adjusted Bray-Curtis similarity, performed with season, site and time as fixed factors. Significant values indicated in bold (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	1125.0	1125.0	8.6	9622	**0.0025**
Time	2	225.3	112.7	0.9	9948	0.432
Site	5	11563.0	2312.7	17.7	9951	**< 0.001**
Season x Time	2	27.8	13.9	0.1	9953	0.900
Season x Site	5	662.0	132.4	1.0	9951	0.407
Time x Site	10	1663.6	166.4	1.3	9936	0.245
Season x Time x Site	10	2824.1	282.4	2.2	9944	**0.019**

Supplementary table 4: PERMANOVA pairwise interactions on seagrass presence, showing only the significant interactions. Monte Carlo (MC) permutation test performed when an interaction uses <100 unique permutations.

Factor	Groups	t	Unique perms	*p* (MC)

Time (December) x Site (RCK)	2020-21 x 2021-22	2.69	8	0.0113
Time (February) x Site (CAN)	2020-21 x 2021-22	2.14	6	0.0394
Time (January) x Site (CAN)	2020-21 x 2021-22	2.49	5	0.0168
Season (2020-21) x Site (CAN)	December x February	2.14	6	0.0418
Season (2020-21) x Site (RCK)	December x February	3.11	6	0.0035
Season (2020-21) x Time (December)	CAN x RCK	4.13	6	0.0005
Season (2020-21) x Time (December)	HEA x RCK	4.13	6	0.0002
Season (2020-21) x Time (December)	LUB x RCK	4.13	7	0.0004
Season (2020-21) x Time (December)	MIL x RCK	4.77	7	0.0001
Season (2020-21) x Time (December)	PPT x RCK	4.77	7	0.0001
Season (2020-21) x Time (January)	CAN x HEA	2.49	5	0.0161
Season (2020-21) x Time (January)	CAN x MIL	2.49	5	0.0193
Season (2020-21) x Time (January)	CAN x PPT	2.49	5	0.0188
Season (2020-21) x Time (January)	HEA x RCK	2.85	5	0.0075
Season (2020-21) x Time (January)	MIL x RCK	2.85	5	0.0076
Season (2020-21) x Time (January)	PPT x RCK	2.85	5	0.0079
Season (2020-21) x Time (February)	CAN x LUB	2.14	6	0.0413
Season (2020-21) x Time (February)	CAN x MIL	3.94	5	0.0001
Season (2020-21) x Time (February)	CAN x PPT	2.63	5	0.0125
Season (2020-21) x Time (February)	HEA x MIL	2.18	3	0.0383
Season (2020-21) x Time (February)	MIL x RCK	2.52	3	0.0154
Season (2021-22) x Time (December)	CAN x MIL	2.18	3	0.0367
Season (2021-22) x Time (December)	LUB x RCK	2.15	4	0.0430
Season (2021-22) x Time (December)	MIL x RCK	2.85	4	0.0067
Season (2021-22) x Time (January)	CAN x RCK	2.49	5	0.0151
Season (2021-22) x Time (January)	HEA x RCK	2.49	5	0.0160
Season (2021-22) x Time (January)	LUB x MIL	2.18	3	0.0389
Season (2021-22) x Time (January)	MIL x RCK	3.20	4	0.0024
Season (2021-22) x Time (January)	PPT x RCK	2.49	5	0.0170
Season (2021-22) x Time (February)	HEA x RCK	2.49	5	0.0153
Season (2021-22) x Time (February)	MIL x RCK	3.20	4	0.0033
Season (2021-22) x Time (February)	PPT x RCK	3.20	4	0.0023

Supplementary table 5: Univariate three-way PERMANOVA on seagrass cover. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with season, site and time as fixed factors. Significant values indicated in bold (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	26075	26075	31.512	9840	**< 0.001**
Time	2	5592.6	2796.3	3.3794	9948	**0.026**
Site	5	72907	14581	17.622	9941	**< 0.001**
Season x Time	2	460.39	230.19	0.2782	9958	0.833
Season x Site	5	5535.4	1107.1	1.3379	9952	0.232
Time x Site	10	8269.7	826.97	0.99942	9922	0.443
Season x Time x Site	10	18723	1872.3	2.2627	9931	**0.007**

Supplementary table 6: PERMANOVA pairwise interactions on seagrass cover, showing only the significant interactions.

Factor	Groups	t	Unique perms	*p*
Time (December) x Site (LUB)	2020-21 x 2021-22	2.73	2101	**0.003**
Time (December) x Site (MIL)	2020-21 x 2021-22	2.37	2405	**0.011**
Time (December) x Site (RCK)	2020-21 x 2021-22	2.83	893	**0.007**
Time (January) x Site (CAN)	2020-21 x 2021-22	3.11	1814	**0.003**
Time (January) x Site (MIL)	2020-21 x 2021-22	3.04	2213	**< 0.001**
Time (February) x Site (CAN)	2020-21 x 2021-22	2.26	1778	**0.027**
Time (February) x Site (MIL)	2020-21 x 2021-22	4.76	987	**< 0.001**
Time (February) x Site (PPT)	2020-21 x 2021-22	1.72	425	**0.036**
Season (2020-21) x Site (HEA)	December x January	2.07	1386	**0.029**
Season (2020-21) x Site (MIL)	December x February	1.82	996	**0.044**
Season (2020-21) x Site (RCK)	December x February	3.35	1159	**0.002**
Season (2021-22) x Site (CAN)	December x January	2.18	2678	**0.026**
Season (2021-22) x Site (MIL)	December x February	2.05	775	**0.011**
Season (2021-22) x Site (MIL)	December x January	2.40	1039	**0.039**
Season (2020-21) x Time (December)	CAN x RCK	3.70	1623	**< 0.001**
Season (2020-21) x Time (December)	HEA x RCK	3.79	1446	**< 0.001**
Season (2020-21) x Time (December)	LUB x RCK	3.67	1476	**< 0.001**
Season (2020-21) x Time (December)	MIL x PPT	1.87	2657	**0.049**
Season (2020-21) x Time (December)	MIL x RCK	4.15	1345	**< 0.001**
Season (2020-21) x Time (December)	PPT x RCK	4.96	1626	**< 0.001**
Season (2020-21) x Time (January)	CAN x HEA	2.83	984	**0.005**
Season (2020-21) x Time (January)	CAN x MIL	2.02	2222	**0.040**
Season (2020-21) x Time (January)	CAN x PPT	3.04	2716	**0.003**
Season (2020-21) x Time (January)	HEA x LUB	1.95	1241	**0.042**
Season (2020-21) x Time (January)	HEA x RCK	3.23	907	**< 0.001**
Season (2020-21) x Time (January)	LUB x PPT	2.25	2713	**0.017**
Season (2020-21) x Time (January)	MIL x PPT	1.89	2551	**0.041**
Season (2020-21) x Time (January)	MIL x RCK	2.38	1900	**0.018**
Season (2020-21) x Time (January)	PPT x RCK	3.43	2592	**< 0.001**
Season (2020-21) x Time (February)	CAN x MIL	3.21	870	**0.002**
Season (2020-21) x Time (February)	CAN x PPT	2.78	850	**0.005**
Season (2021-22) x Time (December)	CAN x LUB	1.97	2713	**0.041**
Season (2021-22) x Time (December)	LUB x RCK	2.34	1969	**0.017**
Season (2021-22) x Time (December)	MIL x RCK	2.26	2221	**0.020**
Season (2021-22) x Time (January)	CAN x RCK	2.71	1920	**0.007**
Season (2021-22) x Time (January)	HEA x RCK	2.28	2350	**0.022**
Season (2021-22) x Time (January)	LUB x MIL	2.05	971	**0.048**
Season (2021-22) x Time (January)	LUB x PPT	1.74	650	**0.047**
Season (2021-22) x Time (January)	MIL x RCK	3.46	1569	**0.000**
Season (2021-22) x Time (January)	PPT x RCK	3.13	1128	**0.002**
Season (2021-22) x Time (February)	HEA x PPT	1.56	483	**0.036**

Season (2021-22) x Time (February)	HEA x RCK	2.78	1378	**0.006**
Season (2021-22) x Time (February)	LUB x MIL	2.06	1459	**0.014**
Season (2021-22) x Time (February)	LUB x PPT	2.11	1433	**0.011**
Season (2021-22) x Time (February)	MIL x RCK	3.78	1461	**< 0.001**
Season (2021-22) x Time (February)	PPT x RCK	3.80	1386	**< 0.001**

Supplementary table 7: Univariate two-way PERMANOVA on flower density. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with site and time as fixed factors. Significant values indicated in bold (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Time	3	92046	30682	19.165	9953	**< 0.0001**
Site	5	16356	3271.2	2.0433	9945	**0.0543**
Time x Site	15	68054	4537	2.8339	9889	**< 0.0001**

Supplementary table 8: PERMANOVA pairwise interactions on seagrass flower densities, showing only the significant interactions. Monte Carlo (MC) permutation test performed when an interaction uses <100 unique permutations.

Factor	Groups	t	Unique perms	*p* (MC)
Site (CAN)	December x February	4.66	417	**0.001**
Site (CAN)	December x January	3.20	285	**0.002**
Site (CAN)	February x March	3.53	603	**0.001**
Site (HEA)	January x March	2.54	2494	**0.014**
Site (LUB)	December x February	2.43	255	**0.018**
Site (LUB)	December x March	3.11	128	**0.004**
Site (LUB)	February x January	2.53	191	**0.017**
Site (LUB)	January x March	3.26	96	**0.004**
Site (MIL)	December x March	2.05	24	**0.044**
Site (MIL)	January x March	4.00	143	**0.001**
Site (PPT)	December x February	3.07	96	**0.004**
Site (PPT)	February x January	7.72	171	**< 0.001**
Site (PPT)	January x March	4.43	452	**< 0.001**
Site (RCK)	December x January	4.57	1435	**< 0.001**
Site (RCK)	February x January	2.37	5197	**0.016**
Site (RCK)	January x March	3.80	1649	**< 0.001**
Time (December)	CAN x HEA	3.12	78	**0.004**
Time (December)	CAN x LUB	2.62	127	**0.012**
Time (December)	CAN x PPT	2.49	80	**0.019**
Time (December)	HEA x RCK	2.43	152	**0.019**
Time (December)	LUB x RCK	2.10	255	**0.036**
Time (January)	CAN x PPT	2.00	4375	**0.027**
Time (January)	LUB x PPT	2.08	1847	**0.034**
Time (January)	PPT x RCK	2.73	4365	**0.009**

Time (February)	CAN x LUB	4.32	554	**< 0.0001**
Time (February)	CAN x MIL	2.92	1439	**0.006**
Time (February)	CAN x PPT	5.62	285	**< 0.0001**
Time (February)	CAN x RCK	2.01	2140	**0.043**
Time (February)	HEA x PPT	2.53	32	**0.015**
Time (February)	PPT x RCK	2.52	48	**0.020**

Supplementary table 9: Univariate two-way PERMANOVA on seagrass fruit density. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with site and time as fixed factors (p < 0.05). Significant values indicated in bold (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Time	3	31929	10643	15.811	9959	**< 0.0001**
Site	5	12494	2498.8	3.7121	9943	**0.0029**
Time x Site	15	21474	1431.6	2.1267	9924	**0.0116**

Supplementary table 10: PERMANOVA pairwise interactions on seagrass fruit densities, showing only the significant interactions. Monte Carlo (MC) permutation test performed when an interaction uses <100 unique permutations.

Factor	Groups	t	Unique perms	*p* (MC)
Site (CAN)	December x January	3.28	12	**0.004**
Site (CAN)	January x March	3.28	12	**0.004**
Site (HEA)	December x February	2.72	12	**0.015**
Site (HEA)	February x January	2.48	24	**0.023**
Site (MIL)	December x February	3.57	24	**0.002**
Site (MIL)	December x January	2.31	4	**0.034**
Site (MIL)	February x January	2.43	94	**0.024**
Site (MIL)	February x March	3.42	48	**0.003**
Site (PPT)	December x January	2.84	8	**0.011**
Site (PPT)	January x March	2.25	16	**0.036**
Site (RCK)	December x February	3.60	24	**0.003**
Site (RCK)	December x January	2.70	16	**0.015**
Site (RCK)	December x March	3.24	32	**0.005**
Month (January)	CAN x HEA	2.90	24	**0.011**
Month (January)	HEA x PPT	2.39	16	**0.029**
Month (January)	HEA x RCK	2.57	32	**0.020**
Month (February)	CAN x MIL	2.81	72	**0.011**
Month (February)	CAN x RCK	2.98	48	**0.007**
Month (February)	HEA x LUB	2.26	36	**0.040**
Month (February)	LUB x MIL	3.22	72	**0.004**
Month (February)	LUB x RCK	3.32	72	**0.004**
Month (February)	MIL x PPT	2.94	80	**0.010**
Month (February)	PPT x RCK	3.08	96	**0.006**
Month (March)	CAN x RCK	3.24	32	**0.005**

Month (March)	HEA x RCK	2.52	64	**0.019**
Month (March)	LUB x RCK	2.68	48	**0.015**
Month (March)	MIL x RCK	3.08	64	**0.006**
Month (March)	PPT x RCK	3.00	64	**0.008**

Supplementary table 11: Univariate three-way PERMANOVA on seagrass above-ground to below-ground biomass ratio. Outputs based on Euclidean distance resemblance matrix, performed with season, site and time as fixed factors (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	0.021544	0.021544	0.1625	9821	0.6908
Time	2	7.4732	3.7366	28.185	9951	**< 0.0001**
Site	5	4.4283	0.88567	6.6805	9930	**< 0.0001**
Season x Time	2	1.1472	0.57362	4.3268	9944	**0.0134**
Season x Site	5	3.9126	0.78251	5.9025	9951	**< 0.0001**
Time x Site	10	2.6075	0.26075	1.9668	9933	**0.0340**
Season x Time x Site	10	2.6097	0.26097	1.9685	9930	**0.0308**

Supplementary table 12: PERMANOVA pairwise interactions on biomass above/below ground ratio, showing only the significant interactions.

Factors	Groups	t	Unique perms	*p*
Season (2020-21) x Site (LUB)	December x February	1.9152	9430	**0.0161**
Season (2020-21) x Site (LUB)	January x February	2.5438	9330	**0.0235**
Season (2021-22) x Site (CAN)	December x February	4.1467	9350	**0.0002**
Season (2021-22) x Site (CAN)	January x February	3.1997	9334	**0.0036**
Season (2021-22) x Site (HEA)	December x January	2.866	9331	**0.0106**
Season (2021-22) x Site (HEA)	December x February	3.0843	9347	**0.0071**
Season (2021-22) x Site (LUB)	December x January	3.2656	9314	**0.0040**
Season (2021-22) x Site (LUB)	December x February	4.6245	9276	**0.0003**
Season (2021-22) x Site (MIL)	December x January	2.7194	9247	**0.0098**
Season (2021-22) x Site (MIL)	December x February	4.018	9316	**0.0004**
Season (2021-22) x Site (PPT)	December x January	4.2888	9358	**0.0004**
Season (2021-22) x Site (PPT)	December x February	4.1709	9304	**0.0005**
Season (2020-21) x Time (December)	CAN x HEA	2.7611	9387	**0.0065**
Season (2020-21) x Time (December)	CAN x MIL	2.7108	9356	**0.0051**
Season (2020-21) x Time (December)	CAN x PPT	4.0188	9311	**0.0002**
Season (2020-21) x Time (December)	HEA x LUB	1.8173	9446	**0.0134**
Season (2020-21) x Time (December)	HEA x PPT	2.4329	9297	**0.0271**
Season (2020-21) x Time (December)	LUB x MIL	1.815	9442	**0.0163**
Season (2020-21) x Time (December)	LUB x PPT	2.2154	9498	**0.0014**
Season (2020-21) x Time (December)	MIL x PPT	2.2832	9342	**0.0372**
Season (2020-21) x Time (January)	LUB x MIL	3.1932	9349	**0.0065**
Season (2020-21) x Time (January)	LUB x PPT	2.5326	9366	**0.0204**

Season (2020-21) x Time (January)	LUB x RCK	3.5459	9323	**0.0025**
Season (2021-22) x Time (December)	CAN x LUB	2.7606	9345	**0.0058**
Season (2021-22) x Time (December)	CAN x MIL	2.5427	9364	**0.0169**
Season (2021-22) x Time (December)	CAN x RCK	3.6489	9329	**0.0005**
Season (2021-22) x Time (December)	HEA x RCK	2.7845	9402	**0.0138**
Season (2021-22) x Time (December)	PPT x RCK	2.5356	9314	**0.0195**
Season (2021-22) x Time (January)	CAN x HEA	2.6532	9329	**0.0121**
Season (2021-22) x Time (January)	CAN x LUB	3.6143	9309	**0.0014**
Season (2021-22) x Time (January)	CAN x MIL	3.6791	9304	**0.0006**
Season (2021-22) x Time (January)	CAN x PPT	4.3304	9338	**0.0001**
Season (2021-22) x Time (January)	CAN x RCK	3.8231	9346	**0.0018**
Season (2021-22) x Time (January)	HEA x PPT	2.8423	9321	**0.0111**
Season (2021-22) x Time (February)	CAN x MIL	2.3068	9330	**0.0345**
Season (2021-22) x Time (February)	HEA x LUB	2.5723	9337	**0.0197**
Season (2021-22) x Time (February)	HEA x MIL	2.9299	9294	**0.0103**
Season (2021-22) x Time (February)	HEA x PPT	2.2234	9334	**0.0409**
Time (December) x Site (HEA)	2020-21 x 2021-22	3.8216	9392	**0.0005**
Time (December) x Site (MIL)	2020-21 x 2021-22	2.0529	9338	**0.0478**
Time (December) x Site (PPT)	2020-21 x 2021-22	4.269	9312	**0.0007**
Time (January) x Site (LUB)	2020-21 x 2021-22	3.2626	9361	**0.0051**
Time (January) x Site (PPT)	2020-21 x 2021-22	2.1278	9341	**0.0470**
Time (February) x Site (MIL)	2020-21 x 2021-22	2.1833	9365	**0.0403**
Time (February) x Site (RCK)	2020-21 x 2021-22	2.1357	9344	**0.0474**

Supplementary table 13: Univariate three-way ANOVA using PERMANOVA on total seagrass biomass. Outputs based on Euclidian distance resemblance matrix, performed with site and time as fixed factors (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	10.441	10.441	58.22	9839	**< 0.0001**
Time	2	0.16046	0.08023	0.44739	9942	0.639
Site	5	9.5827	1.9165	10.687	9954	**< 0.0001**
Season x Time	2	1.3536	0.67682	3.7741	9959	**0.0232**
Season x Site	5	2.1591	0.43183	2.408	9934	**0.0373**
Time x Site	10	4.5742	0.45742	2.5507	9925	**0.0059**
Season x Time x Site	10	5.7094	0.57094	3.1837	9948	**0.0005**

Supplementary table 14: PERMANOVA pairwise interactions on total biomass, showing only the significant interactions.

Factors	Groups	t	Unique perms	*p*
Season (2020-21) x Site (HEA)	December x February	2.5997	9319	0.0131
Season (2020-21) x Site (HEA)	January x February	3.4193	9358	0.0037
Season (2020-21) x Site (PPT)	December x January	2.8575	9351	0.0121

Season (2020-21) x Site (PPT)	December x February	2.2561	9292	0.0357
Season (2021-22) x Site (CAN)	December x February	3.5979	9314	0.0027
Season (2021-22) x Site (HEA)	December x January	3.1124	9342	0.0076
Season (2021-22) x Site (HEA)	December x February	2.1732	9330	0.0467
Season (2021-22) x Site (PPT)	December x January	2.2097	9350	0.0414
Season (2021-22) x Site (RCK)	January x February	2.2758	9335	0.0333
Season (2020-21) x Time (December)	CAN x HEA	3.4482	9361	0.0030
Season (2020-21) x Time (December)	CAN x PPT	5.6469	9332	0.0005
Season (2020-21) x Time (December)	HEA x LUB	2.3507	9331	0.0332
Season (2020-21) x Time (December)	HEA x MIL	2.5460	9299	0.0223
Season (2020-21) x Time (December)	HEA x PPT	3.7114	9310	0.0025
Season (2020-21) x Time (December)	LUB x PPT	4.7536	9274	0.0004
Season (2020-21) x Time (December)	MIL x PPT	4.6277	9284	0.0002
Season (2020-21) x Time (December)	PPT x RCK	4.0113	9096	0.0012
Season (2020-21) x Time (January)	CAN x HEA	2.3837	9306	0.0297
Season (2020-21) x Time (January)	HEA x LUB	2.3656	9307	0.0310
Season (2020-21) x Time (January)	HEA x MIL	2.9449	9341	0.0094
Season (2020-21) x Time (February)	CAN x PPT	4.5112	9378	0.0002
Season (2020-21) x Time (February)	HEA x PPT	4.8170	9344	0.0003
Season (2020-21) x Time (February)	LUB x PPT	5.0757	9339	0.0003
Season (2020-21) x Time (February)	MIL x PPT	3.8460	9328	0.0004
Season (2020-21) x Time (February)	PPT x RCK	2.6380	9325	0.0135
Season (2021-22) x Time (December)	CAN x HEA	3.6046	9333	0.0034
Season (2021-22) x Time (December)	CAN x LUB	3.0907	9349	0.0099
Season (2021-22) x Time (December)	CAN x PPT	2.2845	9343	0.0357
Season (2021-22) x Time (December)	HEA x MIL	3.2886	9348	0.0054
Season (2021-22) x Time (December)	LUB x MIL	2.7603	9329	0.0144
Season (2021-22) x Time (January)	CAN x PPT	2.1878	9323	0.0421
Season (2021-22) x Time (January)	HEA x PPT	4.2352	9319	0.0012
Season (2021-22) x Time (January)	LUB x PPT	3.8223	9299	0.0028
Season (2021-22) x Time (January)	MIL x PPT	2.7874	9303	0.0108
Season (2021-22) x Time (January)	PPT v RCK	3.4209	9347	0.0031
Season (2021-22) x Time (February)	HEA x PPT	2.3486	9353	0.0334
Time (December) x Site (HEA)	2020-21 x 2021-22	2.9996	9298	0.0078
Time (December) x Site (LUB)	2020-21 x 2021-22	3.6372	9295	0.0026
Time (December) x Site (PPT)	2020-21 x 2021-22	2.2156	9348	0.0409
Time (January) x Site (PPT)	2020-21 x 2021-22	2.8569	9338	0.0078
Time (February) x Site (CAN)	2020-21 x 2021-22	4.7279	9350	0.0004
Time (February) x Site (HEA)	2020-21 x 2021-22	2.6365	9382	0.0175
Time (February) x Site (LUB)	2020-21 x 2021-22	3.3151	9297	0.0045
Time (February) x Site (MIL)	2020-21 x 2021-22	2.8657	9320	0.0095
Time (February) x Site (RCK)	2020-21 x 2021-22	2.8867	9290	0.0088

Supplementary table 15: Univariate three-way ANOVA using PERMANOVA on leaf density. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with site and time as fixed factors ($p < 0.05$).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	2488.4	2488.4	57.103	9925	**< 0.0001**
Time	2	1280.1	640.06	14.688	9951	**< 0.0001**
Site	5	1201.6	240.33	5.5149	9948	**< 0.0001**
Season x Time	2	152.04	76.022	1.7445	9945	0.1713
Season x Site	5	396.79	79.358	1.8211	9945	0.0977
Time x Site	10	719.97	71.997	1.6522	9924	0.0781
Season x Time x Site	10	983.76	98.376	2.2575	9927	**< 0.0122**

Supplementary table 16: PERMANOVA pairwise interactions on leaf density, showing only the significant interactions.

Factor	Groups	t	Unique perms	*p*
Month (December) x Site (HEA)	2020-21 x 2021-22	3.23	8793	**0.005**
Month (December) x Site (LUB)	2020-21 x 2021-22	4.12	8793	**0.001**
Month (December) x Site (MIL)	2020-21 x 2021-22	2.11	9175	**0.038**
Month (January) x Site (CAN)	2020-21 x 2021-22	2.88	9374	**0.012**
Month (January) x Site (MIL)	2020-21 x 2021-22	2.69	9142	**0.016**
Month (January) x Site (PPT)	2020-21 x 2021-22	2.74	9141	**0.004**
Month (February) x Site (CAN)	2020-21 x 2021-22	4.45	9156	**0.001**
Month (February) x Site (HEA)	2020-21 x 2021-22	3.14	9391	**0.007**
Season (2020-21) x Site (HEA)	December x January	2.67	9073	**0.015**
Season (2020-21) x Site (HEA)	January x February	4.17	9137	**0.001**
Season (2020-21) x Site (PPT)	December x January	2.32	8291	**0.021**
Season (2021-22) x Site (HEA)	December x January	2.63	9102	**0.017**
Season (2021-22) x Site (HEA)	December x February	2.12	8786	**0.047**
Season (2021-22) x Site (LUB)	December x January	4.17	9366	**0.001**
Season (2021-22) x Site (LUB)	December x February	4.46	9130	**0.000**
Season (2021-22) x Site (MIL)	December x February	2.04	9375	**0.049**
Season (2021-22) x Site (PPT)	December x February	3.07	9394	**0.009**
Season (2020-21) x Month (December)	CAN x PPT	2.11	8786	**0.037**
Season (2020-21) x Month (December)	MIL x PPT	2.51	8240	**0.010**
Season (2020-21) x Month (January)	CAN x HEA	3.82	9134	**0.001**
Season (2020-21) x Month (January)	HEA x LUB	2.52	7455	**0.015**
Season (2020-21) x Month (January)	HEA x MIL	5.27	8751	**0.000**
Season (2020-21) x Month (January)	HEA x PPT	2.75	8767	**0.004**
Season (2020-21) x Month (January)	HEA x RCK	2.44	9181	**0.008**
Season (2020-21) x Month (February)	CAN x HEA	2.45	8795	**0.024**
Season (2020-21) x Month (February)	CAN x LUB	2.09	7639	**0.048**
Season (2020-21) x Month (February)	CAN x MIL	2.25	8825	**0.038**
Season (2020-21) x Month (February)	CAN x PPT	4.31	9128	**0.001**
Season (2020-21) x Month (February)	CAN x RCK	2.37	8766	**0.029**
Season (2020-21) x Month (February)	LUB x PPT	2.97	8097	**0.008**
Season (2021-22) x Time (December)	CAN x LUB	2.55	9210	**0.021**
Season (2021-22) x Time (December)	CAN x PPT	2.17	9404	**0.047**
Season (2021-22) x Time (December)	LUB x RCK	2.60	9402	**0.021**
Season (2021-22) x Time (December)	PPT x RCK	2.27	9127	**0.037**
Season (2021-22) x Time (January)	LUB x PPT	3.20	8779	**0.006**
Season (2021-22) x Time (January)	MIL x PPT	2.33	9408	**0.033**
Season (2021-22) x Time (February)	CAN x RCK	2.14	9130	**0.046**
Season (2021-22) x Time (February)	HEA x LUB	2.66	9160	**0.015**
Season (2021-22) x Time (February)	HEA x MIL	2.53	9390	**0.019**
Season (2021-22) x Time (February)	LUB x RCK	3.09	9149	**0.007**
Season (2021-22) x Time (February)	MIL x RCK	3.00	9418	**0.009**

Supplementary table 17: Univariate three-way ANOVA using PERMANOVA on B. australis density. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with site and time as fixed factors (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	63.58	63.58	0.58	9925	**< 0.0001**
Time	2	1057.00	528.52	4.79	9951	**< 0.0001**
Site	5	8341.20	1668.20	15.13	9948	**< 0.0001**
Season x Time	2	883.30	441.65	4.01	9945	0.1713
Season x Site	5	570.36	114.07	1.03	9945	0.0977
Time x Site	10	591.14	59.11	0.54	9924	0.0781
Season x Time x Site	10	575.48	57.55	0.52	9927	**< 0.0122**

Supplementary table 18: PERMANOVA pairwise interactions on B. australis densities, showing only the significant interactions.

Factors	Groups	t	Unique perms	*p*
Season (2020-21)	December x February	2.4081	9945	0.008
Season (2020-21)	December x March	3.3853	9942	0.0005
Season (2020-21)	HEA x RCK	2.9381	9923	0.0016
Season (2020-21)	PPT x RCK	3.0054	9938	0.0015
Season (2020-21)	PPT x MIL	1.9155	9936	0.0487
Season (2020-21)	CAN x RCK	3.3108	9953	0.0001
Season (2020-21)	RCK x LUB	3.027	9940	0.0001
Season (2020-21)	RCK x MIL	2.763	9949	0.0005
Season (2021-22)	HEA x RCK	2.6639	9941	0.0018
Season (2021-22)	HEA x LUB	2.0032	9933	0.0386
Season (2021-22)	PPT x RCK	2.2153	9948	0.0082
Season (2021-22)	PPT x LUB	2.2601	9940	0.0186
Season (2021-22)	CAN x RCK	2.5706	9947	0.0027
Season (2021-22)	CAN x LUB	2.1022	9941	0.0294
Season (2021-22)	RCK x LUB	3.6901	9949	0.0001
Season (2021-22)	RCK x MIL	2.5069	9953	0.0013
Time (MAR)	2020-21 x 2021-22	3.0674	9925	0.001
Site (PPT)	2020-21 x 2021-22	1.9439	9937	0.0488

Supplementary table 19: Univariate three-way ANOVA using PERMANOVA on macroalgae percent cover category. Outputs based on zero-adjusted Bray-Curtis similarity resemblance matrix, performed with site and time as fixed factors (p < 0.05).

Factor	df	SS	MS	Pseudo-F	Unique perms	*p*
Season	1	7876.20	7876.20	23.10	9917	**< 0.001**
Month	4	19744.00	4936.00	14.48	9942	**< 0.001**
Site	5	31513.00	6302.70	18.49	9943	**< 0.001**
Season x Month	4	2285.80	571.45	1.68	9946	0.148
Season x Site	5	8842.00	1768.40	5.19	9944	**< 0.001**

Month x Site	20	33534.00	1676.70	4.92	9905	**< 0.001**
Season x Month x Site	20	20494.00	1024.70	3.01	9889	**< 0.001**

Supplementary table 20: PERMANOVA pairwise interactions on macroalgae percent cover category, showing only the significant interactions. Monte Carlo (MC) permutation test performed when an interaction uses <100 unique permutations.

Factor	Groups	t	Unique perms	*p*	*p* (MC)
Month (November) x Site (LUB)	2020-21 x 2021-22	4.28	676	**< 0.001**	
Month (November) x Site (MIL)	2020-21 x 2021-22	2.50	866	**0.016**	
Month (November) x Site (RCK)	2020-21 x 2021-22	5.00	1730	**< 0.001**	
Month (December) x Site (LUB)	2020-21 x 2021-22	6.18	213	**< 0.001**	
Month (December) x Site (RCK)	2020-21 x 2021-22	2.31	160	**0.032**	
Month (January) x Site (HEA)	2020-21 x 2021-22	2.94	47		**0.006**
Month (January) x Site (PPT)	2020-21 x 2021-22	3.40	252	**0.002**	
Month (February) x Site (MIL)	2020-21 x 2021-22	2.63	544	**0.009**	
Month (February) x Site (PPT)	2020-21 x 2021-22	2.28	148	**0.032**	
Season (2020-21) x Site (CAN)	November x February	3.70	761	**0.001**	
Season (2020-21) x Site (CAN)	November x March	3.73	752	**< 0.001**	
Season (2020-21) x Site (CAN)	December x January	3.15	746	**0.002**	
Season (2020-21) x Site (CAN)	December x February	6.48	711	**< 0.001**	
Season (2020-21) x Site (CAN)	December x March	6.56	484	**< 0.001**	
Season (2020-21) x Site (CAN)	January x February	2.51	222	**0.017**	
Season (2020-21) x Site (CAN)	January x March	2.53	198	**0.016**	
Season (2020-21) x Site (HEA)	November x January	2.12	22		**0.041**
Season (2020-21) x Site (LUB)	November x December	3.68	13		**< 0.001**
Season (2020-21) x Site (LUB)	December x January	3.91	138	**0.001**	
Season (2020-21) x Site (LUB)	December x February	2.27	28		**0.026**
Season (2020-21) x Site (LUB)	December x March	4.01	324	**0.000**	
Season (2020-21) x Site (MIL)	November x December	2.17	662	**0.032**	
Season (2020-21) x Site (MIL)	December x February	3.37	1342	**0.001**	
Season (2020-21) x Site (MIL)	February x March	2.25	857	**0.026**	
Season (2020-21) x Site (PPT)	November x December	2.51	448	**0.015**	
Season (2020-21) x Site (PPT)	November x January	2.70	451	**0.012**	
Season (2020-21) x Site (PPT)	November x February	3.20	462	**0.004**	
Season (2020-21) x Site (PPT)	November x March	4.32	366	**0.001**	
Season (2021-22) x Site (CAN)	November x January	2.87	1764	**0.009**	
Season (2021-22) x Site (CAN)	November x February	2.90	2086	**0.008**	
Season (2021-22) x Site (CAN)	November x March	4.24	1442	**< 0.001**	
Season (2021-22) x Site (CAN)	December x January	2.73	1751	**0.010**	
Season (2021-22) x Site (CAN)	December x February	2.77	2164	**0.009**	
Season (2021-22) x Site (CAN)	December x March	4.08	1349	**0.001**	
Season (2021-22) x Site (LUB)	November x January	3.64	1949	**0.001**	
Season (2021-22) x Site (LUB)	November x February	2.78	1991	**0.007**	
Season (2021-22) x Site (LUB)	December x January	2.09	1224	**0.041**	

Season (2021-22) x Site (MIL)	November x January	2.18	1094	**0.034**	
Season (2021-22) x Site (MIL)	January x March	2.06	1560	**0.045**	
Season (2021-22) x Site (PPT)	November x March	2.03	256	**0.047**	
Season (2021-22) x Site (PPT)	January x March	3.39	392	**0.001**	
Season (2021-22) x Site (RCK)	November x December	2.37	2206	**0.019**	
Season (2021-22) x Site (RCK)	November x January	5.15	1897	**< 0.001**	
Season (2021-22) x Site (RCK)	November x February	6.68	1403	**< 0.001**	
Season (2021-22) x Site (RCK)	November x March	6.26	1623	**< 0.001**	
Season (2021-22) x Site (RCK)	December x January	2.62	242	**0.013**	
Season (2021-22) x Site (RCK)	December x February	3.71	148	**0.001**	
Season (2021-22) x Site (RCK)	December x March	3.46	182	**0.003**	
Season (2020-21) x Month (November)	CAN x HEA	2.26	792	**0.026**	
Season (2020-21) x Month (November)	CAN x LUB	2.03	610	**0.045**	
Season (2020-21) x Month (November)	CAN x RCK	3.27	837	**0.003**	
Season (2020-21) x Month (November)	HEA x MIL	3.00	661	**0.003**	
Season (2020-21) x Month (November)	HEA x PPT	2.16	469	**0.030**	
Season (2020-21) x Month (November)	LUB x MIL	2.71	353	**0.009**	
Season (2020-21) x Month (November)	MIL x RCK	4.28	491	**< 0.001**	
Season (2020-21) x Month (November)	PPT x RCK	3.26	440	**0.004**	
Season (2020-21) x Month (December)	CAN x HEA	7.36	345	**< 0.001**	
Season (2020-21) x Month (December)	CAN x LUB	10.10	344	**< 0.001**	
Season (2020-21) x Month (December)	CAN x MIL	3.39	886	**0.001**	
Season (2020-21) x Month (December)	CAN x PPT	4.99	370	**< 0.001**	
Season (2020-21) x Month (December)	CAN x RCK	5.99	356	**< 0.001**	
Season (2020-21) x Month (December)	HEA x MIL	2.25	62		**0.029**
Season (2020-21) x Month (December)	LUB x MIL	3.35	58		**0.001**
Season (2020-21) x Month (December)	LUB x PPT	2.55	16		**0.017**
Season (2020-21) x Month (January)	CAN x HEA	2.92	81		**0.005**
Season (2020-21) x Month (January)	CAN x RCK	2.95	115	**0.006**	
Season (2020-21) x Month (January)	HEA x LUB	3.09	140	**0.005**	
Season (2020-21) x Month (January)	HEA x MIL	3.81	348	**0.001**	
Season (2020-21) x Month (January)	LUB x RCK	3.11	243	**0.005**	
Season (2020-21) x Month (January)	MIL x PPT	2.31	445	**0.281**	
Season (2020-21) x Month (January)	MIL x RCK	3.79	434	**0.001**	
Season (2020-21) x Month (February)	CAN x MIL	6.30	995	**< 0.001**	
Season (2020-21) x Month (February)	HEA x MIL	5.33	699	**< 0.001**	
Season (2020-21) x Month (February)	LUB x MIL	4.78	516	**< 0.001**	
Season (2020-21) x Month (February)	MIL x PPT	5.72	694	**< 0.001**	
Season (2020-21) x Month (February)	MIL x RCK	5.69	474	**< 0.001**	
Season (2020-21) x Month (March)	CAN x LUB	2.86	456	**0.008**	
Season (2020-21) x Month (March)	CAN x MIL	3.24	445	**0.003**	
Season (2020-21) x Month (March)	HEA x LUB	2.94	437	**0.005**	
Season (2020-21) x Month (March)	HEA x MIL	3.34	269	**0.002**	
Season (2020-21) x Month (March)	LUB x PPT	3.27	342	**0.002**	
Season (2020-21) x Month (March)	LUB x RCK	3.34	394	**0.003**	
Season (2020-21) x Month (March)	MIL x PPT	3.71	226	**0.001**	

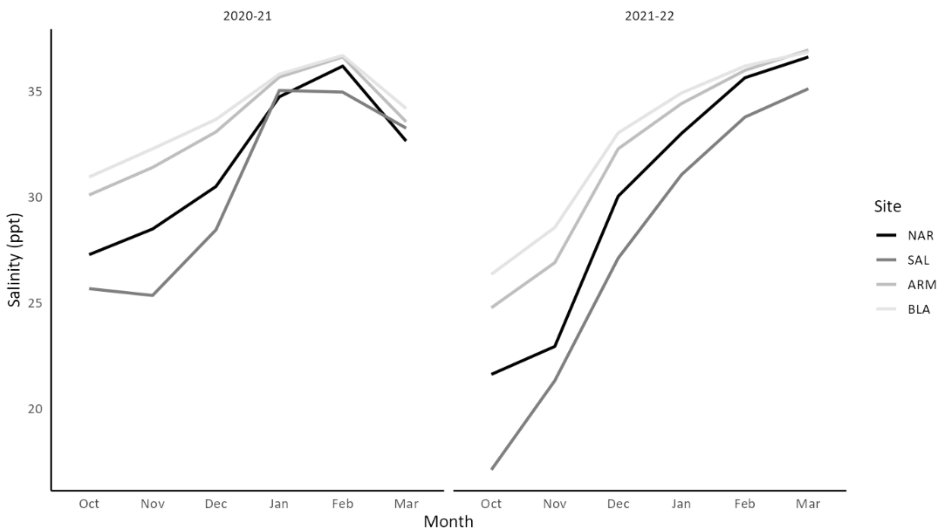
Season (2020-21) x Month (March)	MIL x RCK	3.79	199	**0.001**	
Season (2021-22) x Month (November)	CAN x HEA	3.83	1219	**< 0.001**	
Season (2021-22) x Month (November)	CAN x MIL	2.81	1980	**0.008**	
Season (2021-22) x Month (November)	HEA x LUB	5.11	897	**< 0.001**	
Season (2021-22) x Month (November)	HEA x RCK	4.32	1625	**< 0.001**	
Season (2021-22) x Month (November)	LUB x MIL	3.78	1639	**0.001**	
Season (2021-22) x Month (November)	LUB x PPT	2.54	1252	**0.011**	
Season (2021-22) x Month (November)	MIL x RCK	3.22	2197	**0.003**	
Season (2021-22) x Month (November)	PPT x RCK	2.12	1959	**0.034**	
Season (2021-22) x Month (December)	CAN x HEA	2.76	1561	**0.009**	
Season (2021-22) x Month (December)	CAN x MIL	2.38	1468	**0.019**	
Season (2021-22) x Month (December)	CAN x PPT	2.12	1730	**0.038**	
Season (2021-22) x Month (December)	HEA x LUB	2.20	519	**0.029**	
Season (2021-22) x Month (January)	CAN x MIL	2.26	1632	**0.029**	
Season (2021-22) x Month (January)	CAN x PPT	2.35	674	**0.024**	
Season (2021-22) x Month (January)	HEA x RCK	2.16	79		**0.036**
Season (2021-22) x Month (January)	LUB x MIL	2.15	1277	**0.039**	
Season (2021-22) x Month (January)	LUB x PPT	2.23	649	**0.028**	
Season (2021-22) x Month (January)	MIL x RCK	3.90	831	**0.001**	
Season (2021-22) x Month (January)	PPT x RCK	4.29	309	**< 0.001**	
Season (2021-22) x Month (February)	HEA x RCK	2.25	111	**0.033**	
Season (2021-22) x Month (February)	LUB x RCK	3.06	268	**0.005**	
Season (2021-22) x Month (February)	MIL x RCK	4.67	73		**< 0.001**
Season (2021-22) x Month (February)	PPT x RCK	3.61	112	**0.002**	
Season (2021-22) x Month (March)	CAN x LUB	2.98	1202	**0.005**	
Season (2021-22) x Month (March)	HEA x LUB	2.60	637	**0.136**	
Season (2021-22) x Month (March)	LUB x PPT	2.52	765	**0.014**	
Season (2021-22) x Month (March)	LUB x RCK	4.05	549	**< 0.001**	
Season (2021-22) x Month (March)	MIL x RCK	2.34	114	**0.029**	

Complementary environmental data

In-situ water temperature (November)

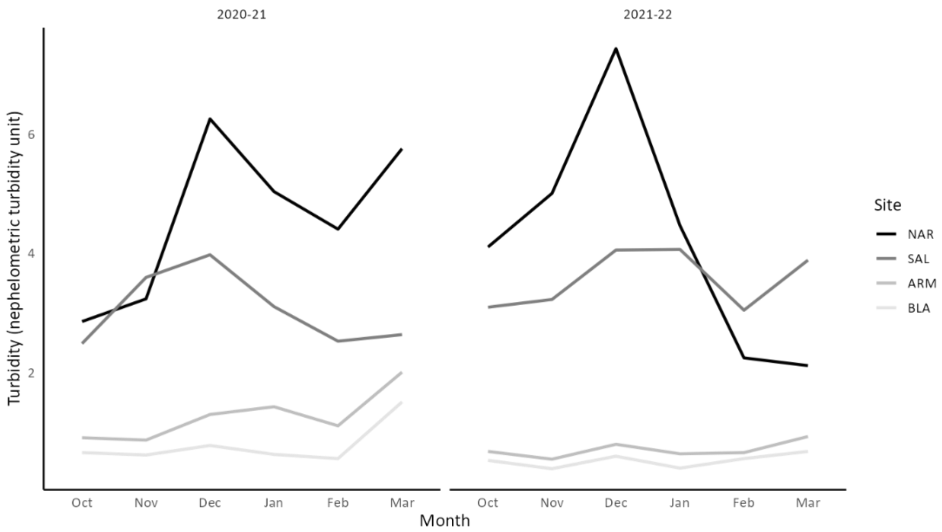
Supplementary figure 2: Average daily in-situ water temperatures (°C) in the shallow regions of each site, recorded over 2 years (2020-21 and 2021-22), recorded in November. Readings from MX and Odyssey loggers were combined, temperature variations between the loggers during calibration were incorporated into final measurements.

Salinity



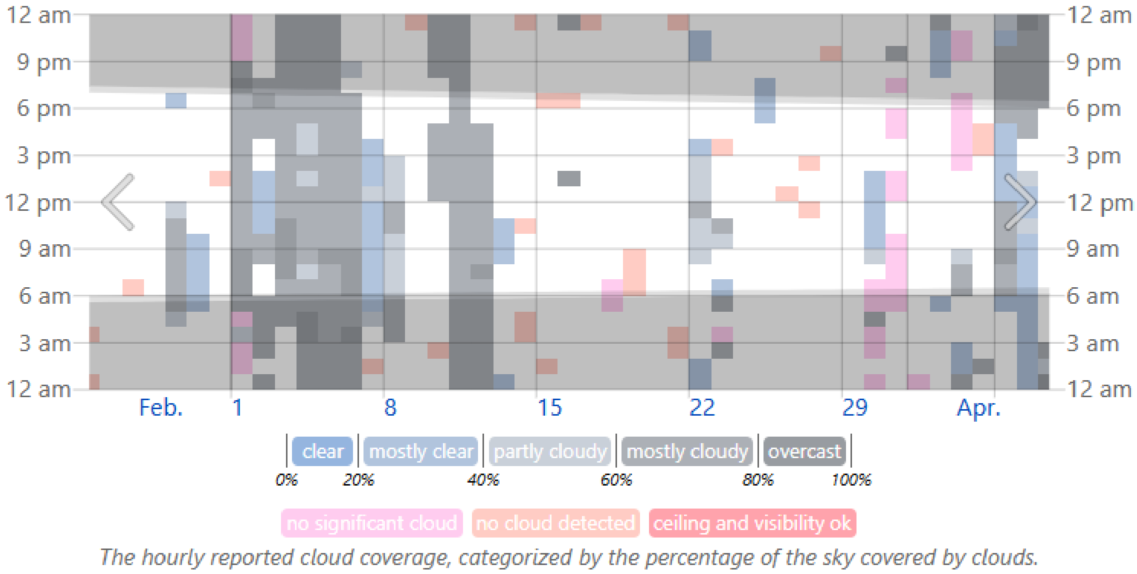
Supplementary figure 3: Average salinity (ppt) for each month (October to March) recorded within the DBCA-RES Water Quality Monitoring Program at sites located within the Swan-Canning Estuary. Narrows Bridge (NAR) is in the vicinity of MIL, Salter Point (SAL) is within the Canning River, ARM is *central to the Estuary, between sites PPT, HEA and LUB. The Blackwall Reach (BLA) site is in the vicinity of RCK.*

Turbidity



Supplementary figure 4: Average turbidity (nephelometric turbidity unit) for each month (October to March) recorded at 4 sites located within the Lower Swan-Canning Estuary within the DBCA-RES Water Quality Monitoring Program.

Cloud cover



Supplementary figure 5: Cloud cover per day in March 2021 recorded over 24 hours [© WeatherSpark.com](WeatherSpark.com)

Glossary

CAN	The site Canning
DBCA	Department of Biodiversity, Conservation and Attractions
DWER	Department of Water and Environmental Regulation
the Estuary	The Swan-Canning Estuary
HEA	The site Heathcote
H_{comp}	Hours above the compensation point
H^{sat}	Hours above saturating irradiance
I_c	Light levels at the compensation point
I^k	Light levels above the saturation point
Isotope	Elements which have the same number of protons and differing numbers of neutrons, therefore have different atomic weights, but almost identical chemical properties.
LUB	The site Lucky Bay
MIL	The site Milyu
MJ	Megajoule/s
nm	Nanometers
PAR	Photosynthetically Active Radiation
P-I	Photosynthesis-irradiance
PPT	The site Pelican Point
psu	Practical salinity units
RCK	The site Rocky Bay
SE	Standard error
Sedimentation	Deposit/accumulation of sediment of benthic surface
Quadrat	A square plot used to quantify seagrass measurements in a standardised manner