Marine and Coastal

National Environmental Science Program

FINAL REPORT

Project 2.1

May 2024

Improving seabed habitat predictions for southern Australia

Jacquomo Monk[1]*, Tim Langlois[2*], Claude Spencer[2], Skipton Woolley[3], Emma Flukes [1], Brooke Gibbons[2], Ashlee Bastiaansen[1], Justin Hulls[1], Gretchen Grammer[4], Keith Hayes[3], Piers Dunstan[3], Shawn Colbung[5], Ronald 'Doc' Reynolds[6], David Guilfoyle[6], Jennifer Lavers[6], Iszaac Waalitj Webb[7,8], Wayne Webb[8], Neville Barrett[1,] Vanessa Lucieer[1]

** Joint lead authors*

1 Institute for Marine and Antarctic Studies, University of Tasmania
2 The UWA Oceans Institute, The University of Western Australia
3 CSIRO
4 SARDI
5 Binalup Aboriginal Corporation
6 Esperance Tjaltjraak Native Title Aboriginal Corporation
7 Undalup Association Inc
8 Karri Karrak Aboriginal Corporation

Milestone number: 8
Research Plan: 2022
Please address inquiries to: Jacquomo Monk - jacquomo.monk@utas.edu.au
Tim Langlois - tim.langlois@uwa.edu.au

Preferred citation

Monk, J, Langlois, T, Spencer, C, Woolley, S, Flukes, E, Gibbons, B, Bastiaansen, A, Hulls, J, Grammer, G, Hayes, K, Dunstan, P, Colbung, S, Reynolds, R, Guilfoyle, D, Lavers, J, Webb, I W, Webb, W, Barrett, N, Lucieer, V (2024) Improving seabed habitat predictions for southern Australia. Report to the National Environmental Science Program. University of Tasmania

Copyright

Acknowledgement

This work was undertaken for the Marine and Coastal Hub, a collaborative partnership supported through funding from the Australian Government's National Environmental Science Program (NESP). Existing data sets were contributed through Parks Australia's Our Marine Parks grant funded programs and specific collaborations with Traditional Owners from Wadandi, Menang, and Wudjari Countries. We would like to thank Daniel Ierodiaconou and Jamie Hicks for additional datasets from Apollo, Murat and Western Eyre AMPs. The crew of MRV Ngerin, Keshi Mer II, Big Dreams, Maverick and Kamikaze are thanked for their assistance in collection of new imagery datasets. The MRV Ngerin was provided under the Southern Coastal Research Vessel Fleet. Imagery annotation data are stored on GlobalArchive which is supported by Australian Research Data Commons (ARDC). Imagery is stored in the Understanding Marine Imagery Facility (SQUIDLE+) which is supported by Australia's Integrated Marine Observing System (IMOS). IMOS and ARDC are enabled by the National Collaborative Research Infrastructure Strategy (NCRIS).

NESP Marine and Coastal Hub partners

The Australian Institute of Marine Science, Bioplatforms Australia, Bureau of Meteorology, Charles Darwin University, Central Queensland University, CSIRO, Deakin University, Edith Cowan University, Flinders University, Geoscience Australia, Griffith University, Integrated Marine Observing System, James Cook University, Macquarie University, Murdoch University, Museums Victoria, NSW Department of Planning and Environment (Environment, Energy and Science Group), NSW Department of Primary Industries, South Australian Research and Development Institute, The University of Adelaide, University of Melbourne, The University of Queensland, University of New South Wales, University of Technology Sydney, The University of Sydney, University of Western Australia, The University of Wollongong

Disclaimer

Cover images: UWA, UTAS

This report is available on the NESP Marine and Coastal Hub website:

www.nespmarinecoastal.edu.au

Contents

List of figures

List of tables

Executive summary and recommendations for decision makers

Mapping the extent and composition of benthic habitats can help to inform sustainable development of the oceans and maintain key ecosystem services through ecosystem-based fisheries, conservation and infrastructure management, and can provide the baseline information from which to assess cumulative anthropogenic and environmental impacts.

Whilst bathymetric data layers are continually evolving, with extents increasing as more mapping is completed both globally and locally, converting this data into robust maps of the distribution of habitat assemblages relies on adequate spatially balanced ground truthing information and validation. The cost of obtaining this information can be prohibitive across deeper continental shelf waters. Across southern Australia there has been extensive historical and contemporary collections of benthic imagery over the continental shelf (e.g. Harvey et al. 2021).

The outputs from this project represent a major advancement in our ability to predict the location of “functional reef” across southern Australia. The term “functional reef” goes beyond the traditional rocky reef definition used in nearshore continental shelf mapping projects and is defined here as any seabed area functioning as a reef, which may include dense beds of sessile invertebrates growing on sediment or a shellfish reef (such as those found in the Beagle Australian Marine Park (AMP)). This means that these functional reefs can support a diverse range of marine life, provide structure and complexity and provide essential services such as biodiversity support, habitat provision, ecosystem services and have potential cultural or economic value. Knowing where functional reef is will allow a significant improvement in the ability to avoid impacts from many activities, better designing monitoring programs and offers the potential for targeting ecosystem repair.

Project 2.1 collated 2037 drops and collected 652 additional imagery samples to create a synthesised open-access annotation dataset across southern Australia. We demonstrated the utility of sessile benthic assemblage information from both Baited Remote Underwater stereo-Video (stereo-BRUV) and Benthic Observation Survey System (BOSS) samples to model and predict the probability of occurrence and associated uncertainty of functional reefs and key benthic ecosystem components. These components were captured within the horizontally facing fields of view of the imagery, covering the continental shelf from Shark Bay to the Victoria-New South Wales border.

The sampling design for collecting new imagery was enhanced through the development of collaborations with Traditional Owners from Wadandi, Menang, and Wudjari Countries. These collaborations were crucial for identifying potential biodiversity hotspots associated with now submerged "Ancient Cultural Corridors," particularly in regions where scientific knowledge was previously lacking.

Using this synthesised ground-truthing dataset, we found that we can predict the probability of “functional reef” with moderate accuracy (~75% overall accuracy) at the southern Australia scale. Additionally, we also generated moderately accurate (~73% overall accuracy) predictions for the ecosystem components such as macroalgae, seagrass, mixed invertebrates, bare reef, and unvegetated sediments. These prediction accuracies are reasonable, given the large biogeographic scale and coarse resolution of the models.

The mapping of functional reef and ecosystem components revealed distinctive patterns across the continental shelf. Paleo-shoreline features, generally at depths of around 70 and 110 metres, emerged as unique elements in the model predictions. Formed during sea level changes before and during the last ice age, these features now influence the distribution of marine biodiversity and ecosystem components across the modern continental shelf, particularly in the southwest regions. Furthermore, in the flatter, sediment-dominated regions of the Great Australian Bight and extending eastward into western Bass Strait, stabilised “mega-rippled” sediments formed functional reefs, supporting diverse sessile invertebrate communities. Throughout much of Bass Strait and down the eastern side to Tasmania, bryozoan thickets and rubble, along with occasional scallop beds, formed the basis of the functional reef ecosystems. While these unconsolidated substrata were the dominant foundation for functional reefs, extensive regions of consolidated reef substrata were encountered in mesophotic and rariphotic depths within AMPs along the southern and western sides of Tasmania, as well as throughout the Commonwealth waters in southwest Australia (see Appendix 1 for AMP breakdown down).

The modelling approach allowed for a novel presentation of spatial uncertainty associated with model predictions, which has been presented in two alternative ways (e.g. probability of functional reef: https://seamapaustralia.org/map/#0c150f76-64ed-4da3-a28a-abfda8c5eb04 , bivariate probability of functional reef: https://seamapaustralia.org/map/#c98e4f4c-2172-4a3e-b8b7-a6a07cd1fee7). This is important because uncertainty in model predictions can affect the confidence of management decisions and conservation planning based on such data. We observed a general increase in uncertainty further from ground sampling locations, with moderately elevated levels of uncertainty around Shark Bay, eastern Bass Strait, Northern Tasmania, along the continental shelf break and throughout the Great Australian Bight. We recommend that further sampling in these regions may improve model predictions.

It is important to note that our model predictions were limited to the 10-200m depth range, reflecting our continental shelf sampling focus. This limitation clearly led to an underprediction of shallow-water seagrasses and macroalgae, especially in the southeast. Therefore, we recommend using the model predictions from this project as an initial, broad-scale inventory of an area. If validated fine-scale mapping data is available (e.g. Seamap Australia National Benthic Habitat Layer), it should be preferred over our modelled products. Our data product is envisioned to serve as one of the base layers in the process to update the National Values Ecosystems layer used by Parks Australia in their management effectiveness framework. This update is expected to occur in late 2024 or early 2025, pending decisions by Parks Australia.

In addition to direct usage by Parks Australia in their Management Effectiveness Framework, our model predictions could support the Australian government's Nature Repair Market, Sustainable Ocean Plan and Environmental-Economic Accounting efforts. For the Nature Repair Market, our models would enhance the ability to identify and prioritise marine areas for conservation and restoration. In the context of Environmental-Economic Accounting, our predictions, especially with uncertainty estimates, would help refine Ocean Accounting estimates for key marine habitats. Furthermore, our model predictions could assist the offshore renewables sector to understand the likelihood of functional reefs within declaration areas, information important for site selection and impact assessment. However, in most cases validated fine-scale mapping is still required. Our modelled products only identify broad areas of significant ecological value or sensitivity, developers and regulators should ensure the finescale mapping is completed and used to make more informed decisions to better target environmental impact assessments and ensure compliance with regulatory requirements.

Some collated data products need annotation corrections, highlighting the importance of platforms like SQUIDLE+ for easy 'third-party' verification against underlying imagery without commercial specialised software. We recommend using QA/QC pipelines in tools like SQUIDLE+ for future projects to check and enhance imagery-based ground-truthing data quality before modelling.

Currently, the production of these models relies on coarse geographical surrogates to account for bioregional variance. We recommend that future updates of these models may consider limiting their spatial extent to within smaller biogeographic boundaries, for example, by considering the relatively distinctive south-west and south-east bioregions (e.g. IMCRA) separately.

To facilitate future updates to the predictions as new data is collected, we have created an R-based workflow. This workflow sources imagery-based ground-truthing annotations hosted on GlobalArchive and SQUIDLE+ using controlled annotation schema, annotated according to the National Field Manuals for Marine Sampling, and replicates the modelling approach. It is stored in an open-access Git repository (https://github.com/UWA-Marine-Ecology-Group-projects/nesp-2.1), enabling easy updates using the same methods.

Final mapping products are hosted by Seamap Australia which enables the dynamic exploration of model predictions, composition of ground-truthing observations represented as spatially-referenced pie charts, and links to habitat images hosted through SQUIDLE+. Visit https://seamapaustralia.org/map/#704ac727-4a63-4789-a06d-b07fed6b4294 to access these features.

1 Background

Mapping the extent and composition of benthic habitats has been recognised as a key challenge in the United Nations Decade of Ocean Science for Sustainable Development. Understanding the extent of benthic habitats can help inform the sustainable development of the oceans and maintain key ecosystem services through ecosystem-based fisheries, conservation and infrastructure management, and provides the basis for the assessment of cumulative anthropogenic and environmental impacts.

Globally, despite our coastal waters and deeper continental shelves (30-200 m) being recognised to support the majority of ocean productivity and ecosystem services, spatially continuous predictions of biological patterns across these habitats are extremely rare (LaFrance et al. 2014). Whilst there are increasing extents of detailed bathymetric information, both globally and locally, converting these into robust maps of the distribution of habitat assemblages relies on adequate spatially balanced ground truthing information and validation (Mastrantonis et al. 2023), but the cost of obtaining this information can be prohibitive across deeper continental shelf waters.

Across southern Australia there has been extensive historical and modern collections of imagery over the continental shelf (Harvey et al. 2021). This data typically comes from towed cameras, autonomous underwater vehicles, Baited Remote Underwater stereo-Video systems (stereo-BRUVs), but also recently from spatially balanced sampling using a novel four-camera platform, the Benthic Observation Survey System (BOSS), using a wide combined field of view (~270°, see NESP MaC Project 1.4; Langlois et al. 2022). Stereo-BRUVs have been primarily used to collect information on the size distribution and composition of fish assemblages but increasingly to simultaneously characterise the benthic habitats captured by their imagery within their horizontally facing field of view (Langlois et al. 2021), whereas BOSS have been demonstrated to be an efficient sampling method for benthic assemblages, collecting a wide field of view of horizontally-facing habitat imagery (Langlois et al. *in review*). Where these sampling platforms have been used to collect data across spatially balanced sampling designs, the benthic annotation collected from their horizontal fields of view can be suitable for spatial modelling and prediction.

The Management Effectiveness Framework for Australian Marine Parks (AMPs) identifies seabed habitats as critical factors in determining the location of key natural values (Hayes et al. 2021). A recent collaboration between Parks Australia and the NESP Marine Hubs (Hayes et al. 2021; Dunstan et al. 2023) highlighted that the extent of seabed habitats, including reefs, is a key unknown for many AMPs. Addressing this knowledge gap is crucial for enhancing our ability to assess management effectiveness in marine parks. As first demonstrated in NESP Marine Biodiversity Hub Project SS2 and NESP MaC Project 1.4 (Langlois et al. 2022), the horizontally facing imagery from stereo-BRUV and BOSS are both suited to constructing broad-scale habitat maps at resolutions of 5 m^2 to 250 m^2. In addition to the use of this broader horizontally facing imagery, these projects demonstrated that coarser scale bathymetry, such as the national 250 m resolution grid (https://ecat.ga.gov.au/geonetwork/srv/api/records/00648206-505c-4858-8b9d-c2324cc2c7ba) can be suitable for creating representative habitat maps to inform management at the scale of marine parks zones in the AMP network.

This project aimed to construct bioregional benthic habitat maps by completing three activities: 1) collating and analysing existing data that can be used to validate the presence/absence of seabed habitats on the continental shelf in temperate Australia; 2) collecting and analysing new data to validate the presence/absence of habitats (Figure 1), 3) developing new predictive models of seabed habitats to advance our understanding of extent and distribution of seabed habitats on the continental shelf in temperate Australia and guidance to ensure this knowledge can be updated using the repeatable methodologies.

2 Survey design and methods

2.1 Existing natural values ecosystems layer

There are ongoing concerns regarding the accuracy and presentation of the natural values ecosystem layers without a detailed explanation of their derivation (Figure 1). For example, the current layer represents a merged dataset of validated fine-scale data derived from multibeam, LiDAR, and aerial photos that were combined with broad-scale predictions detailed in Hayes et al. (2021). This merged product appears to obscure the validated data resulting in a perceived overestimate the extent of some of the natural values, such as mesophotic rocky reefs.

2.2 Collection of existing data to validate presence/absence of seabed habitats on the continental shelf

The project team collected and collated 12 datasets that can be used to validate presence/absence of seabed habitats (Figure 1). These datasets covered areas around south-western Australia, southern Australia, Tasmania and the Bass Strait (Figure 1; Table 1). Based on learnings from previous mapping work undertaken by the Hub (e.g. Hayes et al. 2021), which found that the inclusion of biased (e.g. actively targeting reef) datasets in such a habitat model resulted in unrealistic predictions. As such the collation of existing data was limited to spatially-balanced datasets that follow the national standards for sampling design (e.g. Foster et al. 2024).

2.2.1 Spatially-balanced design for southern Australia

Sampling locations were chosen using a ‘spatially balanced’ sampling design, which spreads samples throughout space and across key variables of interest, thereby reducing spatial autocorrelation and optimising modelling outcomes. A Balanced Accepted Sampling algorithm was implemented using the MBHdesign package in R (Foster et al. 2017). This package allows for unequal inclusion probabilities, which can bias a greater number of samples in areas of high heterogeneity. For this study, a ‘master’ sampling design was created for the entirety of shelf waters (<250m depth) in southern Australia, spanning from the Tropic of Capricorn south (https://github.com/UWA-Marine-Ecology-Group-projects/nesp-

2.1/blob/main/data/mbh-design/National_Sampling_Master.csv). Depth, derived from the Geoscience Australia 250 m resolution Bathymetry and Topography Grid (2023), was categorised into a ‘shallow’ (0 - 125m) and a ‘deep’ (126 - 250m) strata. These strata were informed by previous NESP reports and studies, which indicated higher habitat heterogeneity in waters inshore of the 125m contour line, and relatively homogenous habitats dominated by soft unconsolidated sediments in shelf waters deeper than 125m (Langlois et al. 2022). A total of 2,000,000 samples were allocated across the study area, with unequal inclusion probabilities created, biasing ~95% of samples in the shallow strata and ~5% in the deep strata. Due to logistical constraints, the density of sampling locations within some campaigns was reduced by selecting samples within a polygon in the order assigned by MBHdesign (this approach maintains the spatial balance of the design).

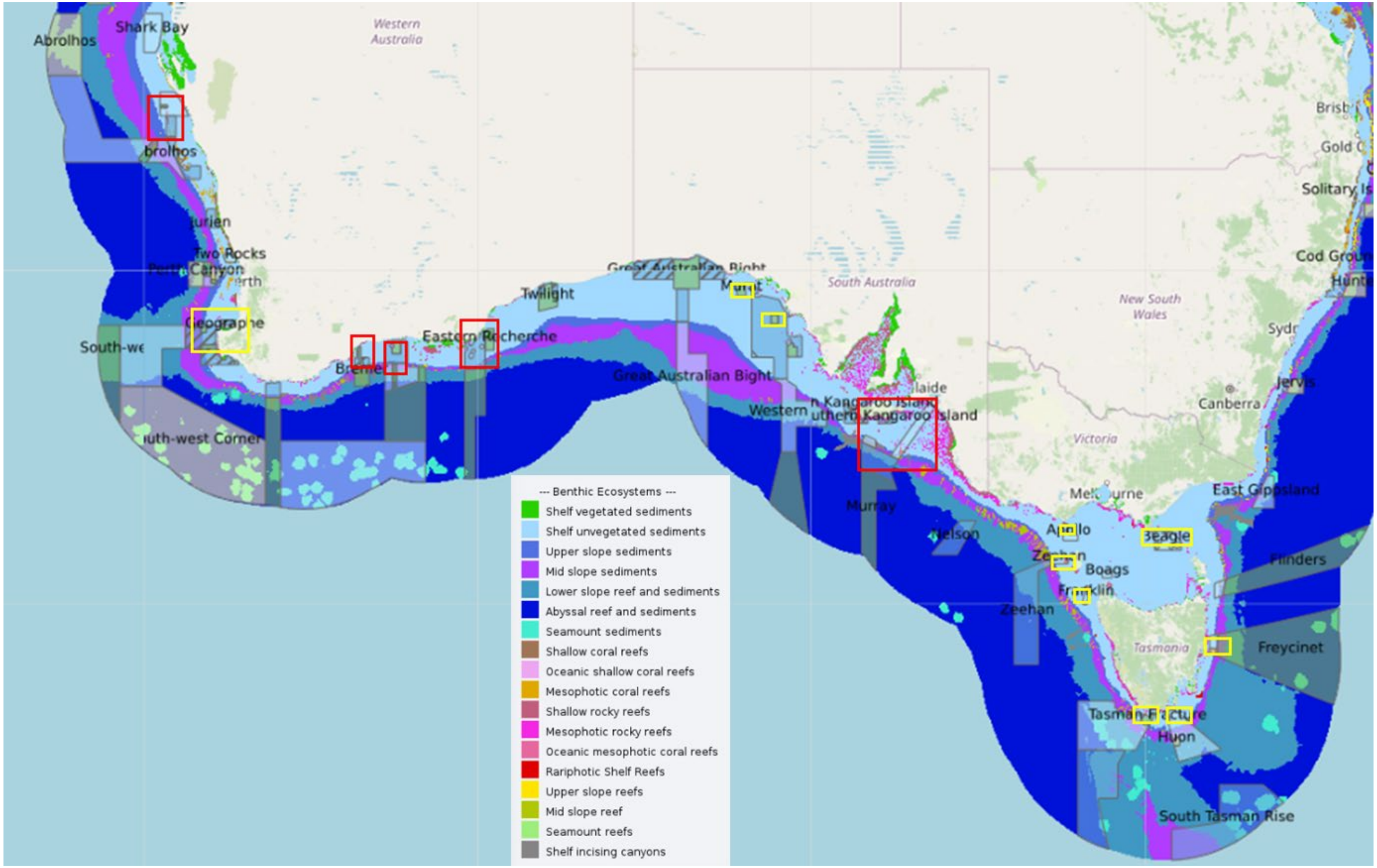

Figure 1. Map showing existing Ecosystems layer sampling domain showing the priority areas within this domain where field sampling was completed (red boxes) and assimilated (yellow boxes). Dynamic view: https://seamapaustralia.org/map/#7f749233-8e79-48cd-8faa-8fbfc310a4f3

Table 1. Summary of imagery campaigns used in this project. Assimilated data is accessible https://github.com/UWA-Marine-Ecology-Group-projects/nesp-2.1

Campaign	Number of samples	Inclusion probability variables	Platform
Bremer	130	Depth	BOSS
Investigator Island	160	Depth	BOSS & stereo-BRUV
Daw & Salisbury Islands	197	Depth	BOSS & stereo-BRUV
Murray	165	Depth	BOSS
South-west Corner	346	Depth & Slope	BOSS & stereo-BRUV
Beagle	127	Zone	stereo-BRUV
Geographe	198	Depth & Slope	BOSS
Abrolhos	122	Depth & Slope	BOSS & stereo-BRUV
Apollo	50	NA	BRUV
Zeehan	300	Depth & Slope	BOSS
Franklin	281	Depth & Slope	BOSS
Tasman Fracture	111	Zone & Reef	stereo-BRUV
Huon	167	Depth & Slope	stereo-BRUV
Freycinet	284	Depth & Slope	stereo-BRUV
Murat	18	NA	stereo-BRUV
Western Eyre	18	NA	BRUV
Western Kangaroo Island	15	NA	stereo-BRUV

2.2.2 Ground-truthing

2.2.2.1 Platforms

Two stereo-video platforms were used to ground-truth habitat data for this study: Baited Remote Underwater stereo-Video systems (stereo-BRUVs) and the Benthic Observation Sampling System (BOSS; Figure 2). Stereo-BRUVs are a globally accepted method, predominately used to survey benthic fish communities, which consist of a stereo-pair of horizontally-facing cameras mounted inside a trapezoid frame (Langlois et al. 2020). This frame is deployed to the seafloor, where cameras record benthic communities and their associated fish communities for an hour. In some stereo-BRUV systems, an additional backwards facing camera is added to increase the information on benthic habitat provided by each deployment. The BOSS is a novel method developed to rapidly survey benthic communities and consists of four horizontally-facing single or stereo-pairs of cameras mounted at 90-degree intervals inside an upright metal frame (Langlois et al. in review). The BOSS is deployed to the seafloor for three to five minutes and collects a ~270° view of the seafloor. For each method, metadata, including the exact deployment location, water depth, date and time were recorded, and all methods were deployed following standard operating procedures which are detailed in the national field manuals for marine sampling (marine-sampling-field-manual.github.io/). All imagery is publicly available through https://squidle.org/.

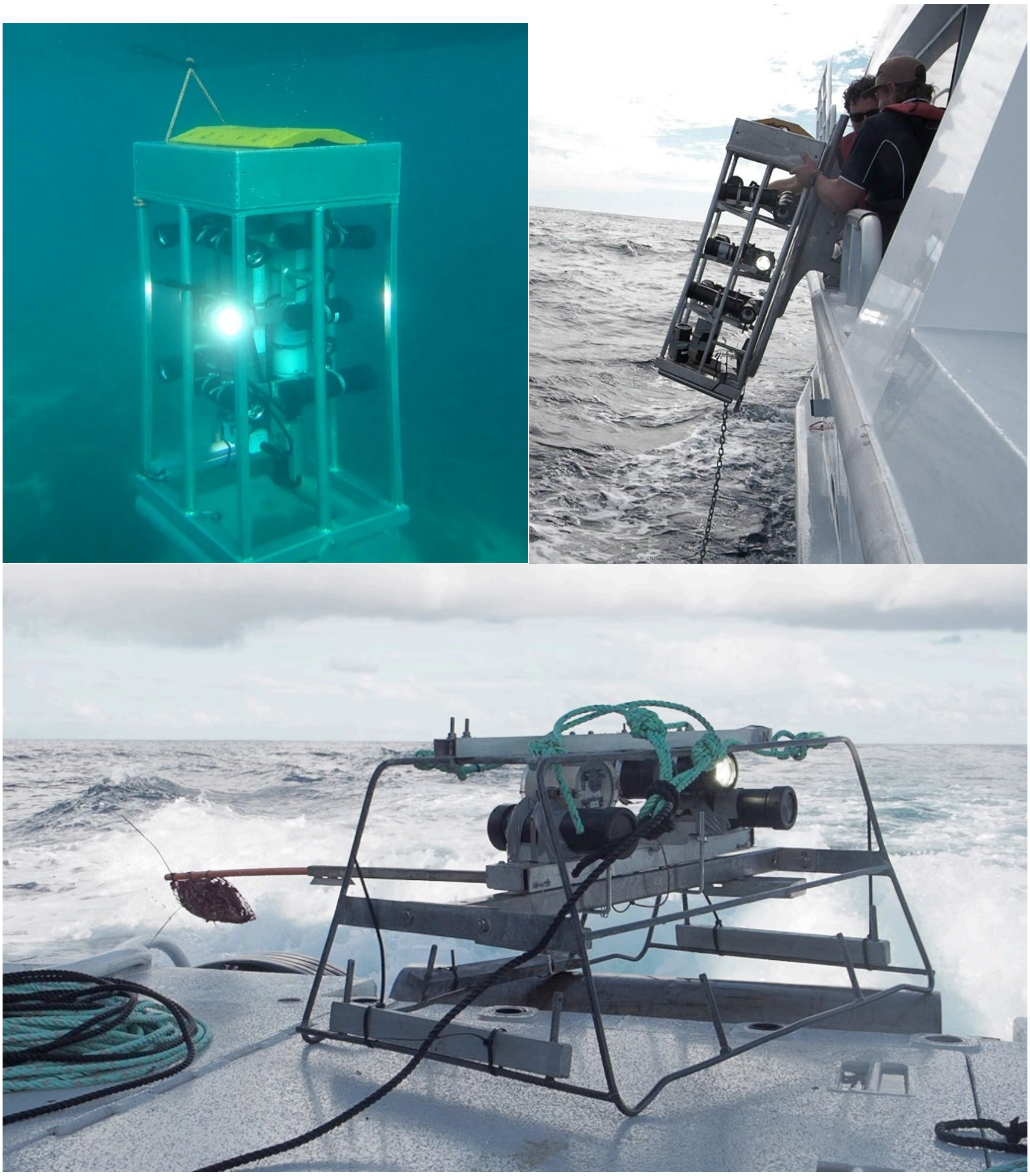

Figure 2. Example camera systems used in the project. Top left: a drop camera system in action as it descends after deployment, top right: deploying a drop camera system from charter vessel Adrianus (left), bottom: a stereo-BRUV ready for deployment.

2.2.2.2 Video annotation

Still images were extracted from video footage from each stereo-BRUV or BOSS deployment on the seafloor. The annotation of benthic habitat in each still image was carried out in TransectMeasure (www.seagis.com.au/transect.html), and followed standard operating procedures (globalarchivemanual.github.io/CheckEM). For each image, 20 randomly positioned points were allocated across the lower 50% of each image, and the benthic composition was identified under each point. A variety of different habitat annotation schemas were used, however all consisted of modified versions of the CATAMI Classification Scheme (e.g. Australian Morphospecies Catalogue).

2.2.2.3 Data processing

Raw annotation data were processed in R using the 'tidyverse' suite of packages (Wickham et al. 2019). Point annotation data were grouped into five classes per deployment, with habitat classes matching with Parks Australia's ecosystem components. Classes included were "sessile invertebrates", "bare rocky reef", "shelf unvegetated sediments", "macroalgae" and "seagrass" (Figure 3). Any annotations that did not fit into these five classes (e.g. mobile invertebrates) were excluded from the final dataset.

These five habitat classes were further combined to produce a binomial functional reef/shelf sediments dataset (Figure 4). For this we combined "sessile invertebrates", "bare rocky reef", "macroalgae", *Amphibolis* spp and *Thalassodendron* spp as 'functional reef' and *Posidonia* spp, *Halophila* spp, *Rupia* spp, and *Zostera* spp as "shelf sediments" (Figure 4; Figure 5).

It is crucial to highlight that we are mapping "functional reef," which extends beyond the rocky reef terminology typically used in nearshore continental shelf mapping projects. Generally, such mapping projects have used fine-scale bathymetric data (from multibeam sonar or LiDAR) to identify areas with higher seafloor relief, often in combination with interpreting higher backscatter. Alternatively, areas of rocky reef are mapped from aerial imagery based on the contrast with adjacent unconsolidated sediments, which appear lighter. Neither of these workflows identify the middle three functional reef types in Figure 5 as reef.

Accordingly, we define any area of seabed that is functioning as a reef, including beds of sessile invertebrates or habitat forming molluscs (such as scallops) on unconsolidated sediments (Figure 4; Figure 5). We chose this term because much of the continental shelf is dominated by sediment, yet it is stable enough to support emergent sessile biota that provide habitat structure and resources for "reef-affiliated" species, such as Bight Redfish in the southwest and Jackass Morwong in the southeast. Importantly, this term is mappable to Parks Australia's Natural Value Common Language (NVCL). Figure 4 shows the relevant Ecosystems and Ecosystem Components that need to be combined to form the functional reef class. A depth threshold can be applied to the prediction if required to separate shallow, mesophotic and rariphotic depths should this be required to confirm to the NVCL.

Reproducible code for synthesising these benthic annotations is available publicly on GitHub (https://github.com/UWA-Marine-Ecology-Group-projects/nesp-2.1), along with the final dataset.

Descriptions of key spatial and depth patterns from each dataset is provided in Section 4.1, including a breakdown within each AMP, where appropriate.

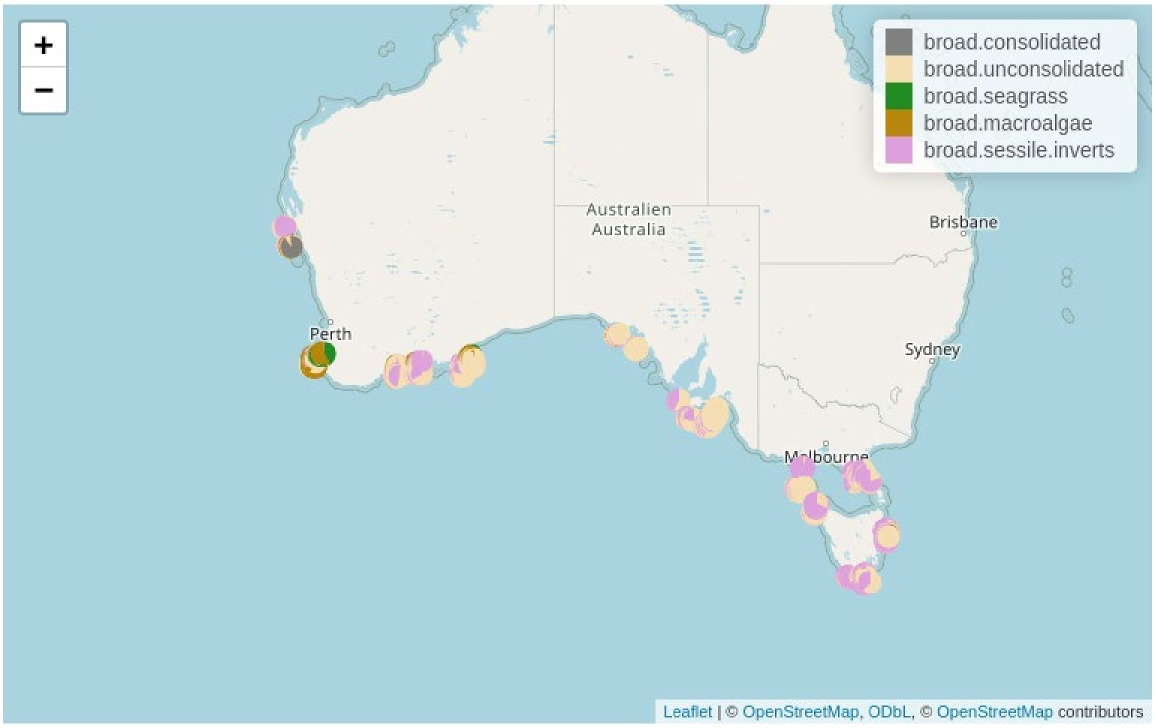

Figure 3. Spatial distribution of sampling for stereo-BRUV and BOSS surveys done across temperate shelf habitats of Australia. Pie charts represent the proportion of each ecosystem component per site.

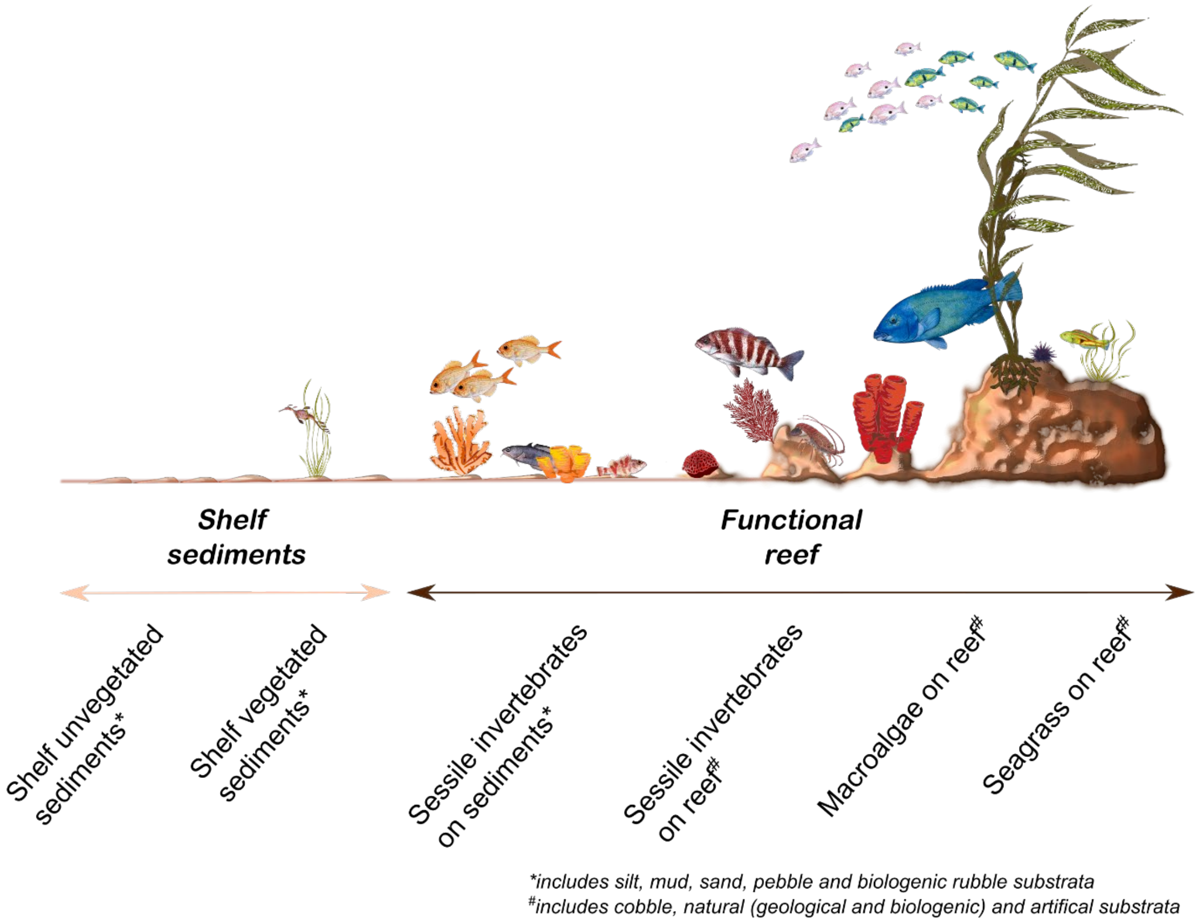

Figure 4. Illustration of the ‘functional reef’ concept which combines relevant Ecosystems and Ecosystem Components from Parks Australia’s Natural Value Common Language for form Functional reef.

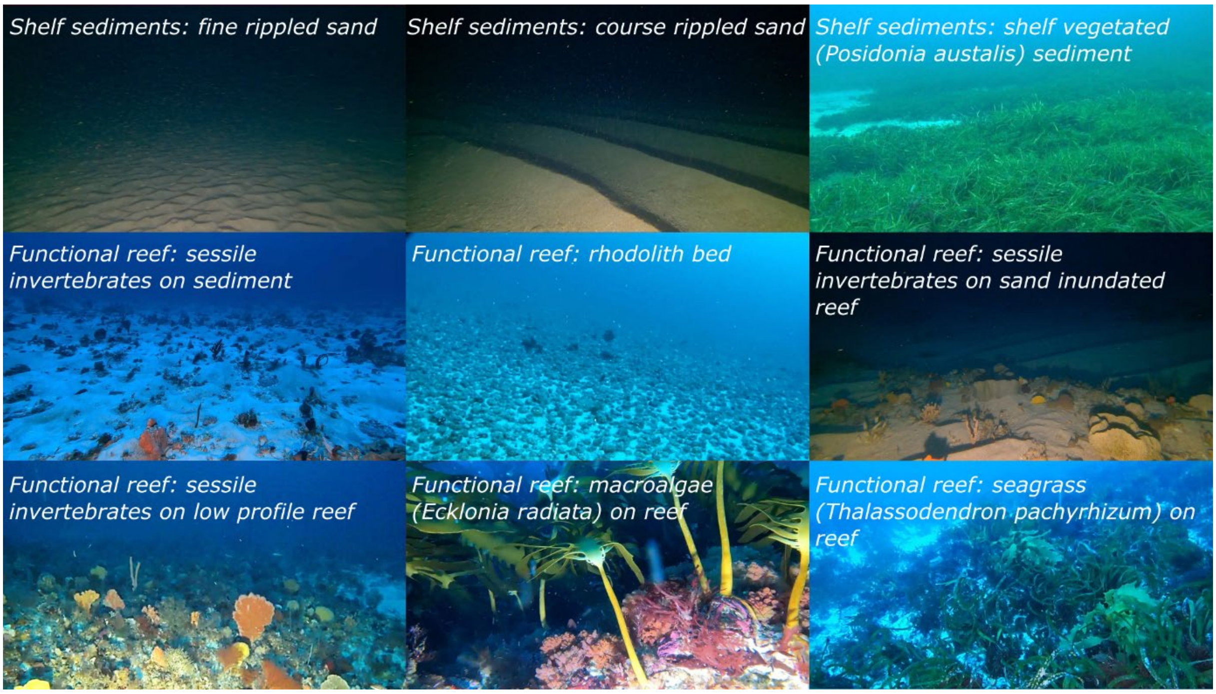

Figure 5. Example images of how various the organisms and substrata map into the ‘functional reef’ concept.

2.3 Physical data

Several physical datasets were used as covariates to describe the spatial distribution of ecosystem classes as part of model development (see Table 1). All oceanographic variables were smoothed to 250-metre resolution to match the Geosciences Australia bathymetric product (https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/148758). If near-shore physical variables were missing, then these areas were spatially interpolated based on the nearest known physical variables. The inclusion of depth resulted in the model being unidentifiable due to the full or partial separation of the ecosystem classes with depth as a covariate. Also, several of the environmental covariates were particularly coarse across this extent and did not provide any meaningful contribution to the models (Table 1), and the development of high-resolution (statistically downscaled) or regionalised oceanographic variables would be useful for future modelling exercises.

Table 2. Available physical covariates used for describing the distribution of ecosystem class distributions.

Variable	Method	Data Source	Basis expansion in model	Retained in final model Reef model	Retained in final Ecosystem type model
Longitude		Longitude of central point of GA 250m raster pixel	Quadratic	1	1
Latitude		Latitude of central point of GA 250m raster pixel	Quadratic	1	1
Depth		Geosciences Australia 250m bathymetry and topography grid	Quadratic	1	1
Roughness		Derived from GA 250m bathymetry and topography grid	Quadratic	0	0
Detrended bathymetry		Derived from GA 250m bathymetry and topography grid	Quadratic	0	0
Bathymetric Slope	As per Horn 1981 – neighbours = 8	Derived from GA 250m bathymetry and topography grid	Quadratic	1	1
Bathymetric Aspect	As per Horn 1981 – neighbours = 8	Derived from GA 250m bathymetry and topography grid	Quadratic	1	0
Topographic position index (TPI)	As per Wilson et al. 2007 – neighbours = 8	Derived from GA 250m bathymetry and topography grid	Quadratic	1	1
Terrain Ruggedness Index (TRI)	As per Wilson et al. 2007 – neighbours = 8	Derived from GA 250m bathymetry and topography grid	Quadratic	1	1
Sea surface temperature		IMOS 1 monthly day and night average made into a 10 year average	Quadratic	0	0
Sea level anomaly		IMOS DM02 dataset made into a 10 year average	Quadratic	0	0
Southerly current velocity		IMOS DM02 dataset made into a 10 year average	Quadratic	0	0

Easterly current velocity		IMOS DM02 dataset made into a 10 year average	Quadratic	0	0
Primary productivity		IMOS Net Primary Productivity (GSM & Eppley-VGPM algorithm)	Quadratic	0	0
Openness		Euclidian distance from shore	Quadratic	0	0
Annual Mean Bottom Stress (proxy for current speed)		BlueLinks ReAnalysis (BRAN2020) - Years 1993 to 2022	Quadratic	1	1
Annual Variance of Bottom Stress (proxy for variability in current speed)		BlueLinks ReAnalysis (BRAN2020) - Years 1993 to 2022	Quadratic	0	0
Linear trend through time for Bottom Stress		BlueLinks ReAnalysis (BRAN2020)- Years 1993 to 2022	Quadratic	0	0

3 Model descriptions

We used two different Bayesian models. First, we developed a 'functional reef' model, which tried to discriminate 'functional reef' from unconsolidated sediment (no-reef) ecosystem types. Secondly, we modelled the distribution of ecosystem components where we maintained the same class structure used in the NESP project 2.3 case study (Hayes et al., 2024).

3.1 Bayesian Binomial Functional Reef Model

Here we used a Bayesian representation of a binomial generalised linear model. A similar Bayesian implementation was used as documented in NESP project 2.3 (Hayes et al., 2024). This approached appropriately captured uncertainties in the form of a posterior distribution. The binomial generalised linear model (GLM) has a bounded count N , where our outcomes (successes) for a given observation y_i at site i are the total number of functional reef habitat observations. At each site, N_i is the total number of points scored as benthic habitat per stereo-BRUV in the model. The probability of observing will be distributed as binomial:

$$y_i \sim Binomial(N_i, \pi)$$

The parameter $\pi \in (0,1)$ is typically modelled via with an appropriate link function $g(.)$ to map the linear predictor to probabilistic space. For the binomial model we use logit link function:

$$\pi_i = g(x_i\beta) = \frac{1}{1+\exp(-x_i\beta)}$$

where β is a vector of length *p*, and *p* represents the total number of covariates in x_i (including any transformation of data to polynomials or other functional forms) and an intercept. x_i is a vector of observed covariates at site *i*. For each parameter β_j, we assumed it was drawn from a Gaussian distribution, with a known mean (μ_j) and variance (σ_j):

$$\beta_j \sim N(\mu_j, \sigma_j)$$

For the purposes of this work, we used uninformative priors, with a zero ($\mu_j = 0$) mean and standard deviation of 10 ($\sigma_j = 10$) for all β_j. It is worth noting, that informative priors derived through probabilistic expert elicitation could replace these priors and would provide insightful information for understanding the distribution of reef in data poor regions.

3.2 Bayesian Multinomial Ecosystem Types Model

Here we define a Bayesian implementation of multinomial family for a GLM. The Bayesian implementation enables a few useful extensions. Firstly, it enables us to sample the full posterior distribution of model parameters, and in turn generate uncertainty metrics for the predictive distribution of ecosystem types. Secondly, it also enables the formal inclusion of expert opinion via prior elicitation. The prior elicitation step is beyond the scope of this project, but it should be noted that it provides a powerful option to inform model-based inference on the distribution of ecosystem classes, where empirical data are lacking, or extra gains can be made up consulting with experts from the field of marine ecosystems (or related disciplines).

The multinomial GLM can be described as follows: if we have n vectors of dimension K nominal categories. The observations of each ecosystem type are defined as $\{y_1\}, \ldots, \{y_k\}$, where each site observation y_i contains the count of each ecosystem type. Working with the total count of ecosystem types, enables the total number of points scored as an ecosystem type to vary cross sites. However, $\sum_k^K y_{ik} = m_i$, and m_i is fixed per site. Thus, for each site *i*, y_i will be distributed with a multinomial distribution:

To define the log-likelihood we consider k probability vectors $\{\pi_1\}, \ldots, \{\pi_k\}$. We can express the probability vectors in terms of parameters in the model, where regression coefficients are estimated against the observed covariates, the ecosystem class membership probabilities depend on covariates via a link-linear model:

$$\pi_{ik} = g(x_i; \beta_k) = \frac{\exp\left(\beta_k X_i^{\top}\right)}{\sum_{k=1}^{K} \exp\left(\beta_l x_i^{\top}\right)}$$

where β_k is a vector from the K^{th} row of B a $K \times p$ matrix of parameters. x_i is a vector of covariates observed at site i , π_{ik} is the probability of each ecosystem class (k) at observed site (i). The link $g(.)$ is the Softmax link function (Gibbs 1902), which maintains the constraint that the elements of π_i sum to one, the K^{th} row of covariates is held at zero which enables identifiability of the parameters in B . The reference class is set as the last class ($k = K$) in Y . The implication here is that these coefficients B represent the effects of X on the log-odds between categories $1 \leq k \leq K - 1$ and the reference class.

For each parameter (β_{pk}) in the β_k vectors, we assume is drawn from a Gaussian distribution, with a known mean (μ_{pk}) and variance (σ_{pk}):

$$\beta_{pk} \sim N\left(\mu_{pk}, \sigma_{pk}\right)$$

for the purposes of this report these priors are uninformative, and we set the mean for all $\beta_{pk} = 0$ and $\sigma_{pk} = 10$. Under a weakly informative or expert derived elicitation priors we could provide known values for μ_{pk} and σ_{pk}. It must be noted that the informative priors or the elicitation process would need to frame the questions as the difference between the ecosystem class of interest and the ecosystem type which is set as the reference class for the model (typically the first or last column in Y . Where we generate priors as a series of log-odds ratios. For example, we might ask the question, given the reference class, sessile invertebrates, does the ecosystem class seagrasses tend to inhabit areas that have higher or lower current speeds?

3.3 Model code

The code for the Bayesian binomial and multinomial GLMs were written in rstan (Stan Development Team, 2020) code. Stan is a C++ based library for running gradient-based Markov Chain Monte Carlo algorithms like Hamiltonian Monte Carlo (Neal, 2011) or no-u-turns-sampler (NUTS) (Hoffman & Gelman, 2014). The code provided in the project GitHub repository provides the appropriate stan and R functions to fit, interpret and predict the Bayesian GLMs.

3.4 Model fitting

3.4.1 Sampling the posterior distribution

Sampling the posterior distribution was done using the NUTS in Stan (Hoffman & Gelman, 2014). For each model run, we sampled the posterior distribution of estimated parameters using three independent chains, where each chain was run in parallel, and each chain was sampled using 5000 iterations. For parameter inference and prediction, we discard the first 2500 samples per chain and treat these as a burn-in (referred to as warm up in Stan).

3.4.2 Assessing posterior sampling

We assess the sampling of the posterior distribution by looking at the trace plots for each parameter. Trace plots where the chains are well mixed (i.e. should look like a "fuzzy caterpillar") are a good indicator that the model is identifying the parameters well. We also look at the posterior distribution to make sure there are no problematic distributions that appear too bimodal.

We also assess fits via partial response plots, these plots enable up to assess the marginal effect of a covariate on the response of ecosystem type across a one-dimensional gradient (say bathymetry). This helps us identify any strange behaviour in the model that would no fit well with our ecological understanding of how reef or ecosystem types are expected to respond to environmental and physical covariates.

3.4.3 Cross-validation of model predictions

To demonstrate the capacity of the model to predict new observations (cross-validation), it is desirable to compare counts of observed reef or ecosystem types predicted from the model vs counts of reef or counts of ecosystem types kept aside as a hold-out dataset. Under a cross-validation framework we would call these "train" and "test" dataset. The training dataset is used to estimate the known parameters in the model, while test (hold-out) dataset is then used to see how well the trained model can predict a new data. In Bayesian context we not only have a point prediction for each observation, but rather a predictive posterior distribution. We used a predictive posterior distribution cross-validation approach, as described in Gelfand (1995). The predictive posterior distribution for cross-validation is defined as:

$$p\left(y_j \middle| y_{1:n\backslash j}\right) = \sum p\left(y_j \middle| y_{1:n\backslash j}, \Phi\right) p\left(\Phi \middle| y_{1:n\backslash j}\right)$$

In this approach we assess the predictive posterior distribution where Y_i is the i^{th} of n observations and $Y_{1:n\backslash i}$ is the set of $1{:}\,n \setminus j$ observations excluding Y_j, in this case j is approximately 25% of sites n and is chosen at random. The unknown Φ are unobserved quantities, such as β parameters estimated in both binomial and multinomial models. Samples from each cross-validation predictive density $p\left(y_i \middle| y_{1:n\backslash i}\right)$ may be obtained as part of the MCMC process, where we predict a posterior predictive distributions (binomial or multi-nominal) for each observation of the “test” datasets. We used these predictive posterior distributions to construct central cross-validation predictive intervals. The goal is to accurately predict the median response for reef or ecosystem responses for each site. The proportion of the j observations that fall within their corresponding central cross-validation predictive intervals should then be close to the 50% for the median, 50% for the interquartile range, and 90% for the 90th credible intervals.

Using the hold-out data and predictive posterior probabilities as described above, we calculated a separate cross-validation metric and reported classification accuracy via a confusion matrix. We compared the mean probability of functional reef and each ecosystem class based on the posterior predictive distribution for each site in the hold-out (test) dataset. The more accurate the mean predictions are the higher the classification rate (with 100% being perfect classification). This approach ignores the variance and the full range of values in the posterior predictive distribution, as per Gelfland (1995). Because it is a relatively simpler test (just testing the means), it should perform better than as the Gelfland (1995) approach.

3.5 Interpreting and visualising uncertainty

One of the key objectives of this project was to demonstrate how to report uncertainty in the distribution of functional reef or ecosystem components. Here we present two ways to report uncertainty:

- The first approach was to report a map of uncertainty for the predicted probability of occurrence for functional reef or each ecosystem class as a separate map that can be viewed in parallel to a map of the expected (mean) probability of occurrence. The error is reported as the inter-quartile range (IQR), which is the $|P(y_{ik})_{0.75} - P(y_{ik})_{0.25}|$ and provides a general summary of dispersion and shows the reader how the upper bounds of probability of prediction differ from the lower bounds. From a Bayesian context this most analogous to standard errors, as commonly reported in maximum-likelihood models. This first approach is the classic way to report uncertainty, being two maps, one showing the (mean) probability of occurrence and a second showing the predicted error.
- The second approach was to report a map of expected probability of occurrence combined with a map of uncertainty, we use the same mean probability of occurrence

and the IQR of probability of occurrence as described above, to generate a bivariate map to represent these two axes in a single map. The colours scales are reported on two axes, one for the probability of occurrence and the second axis which represents the error in those predictions (Figure 6). The colour bins are derived based on the quantiles from the set $\{0,0.1,0.2,0.3,\ldots,0.9,1\}$, although this does not evenly space the probabilities into fixed bins, it helps identify areas of low and high probability combined with low and high uncertainty.

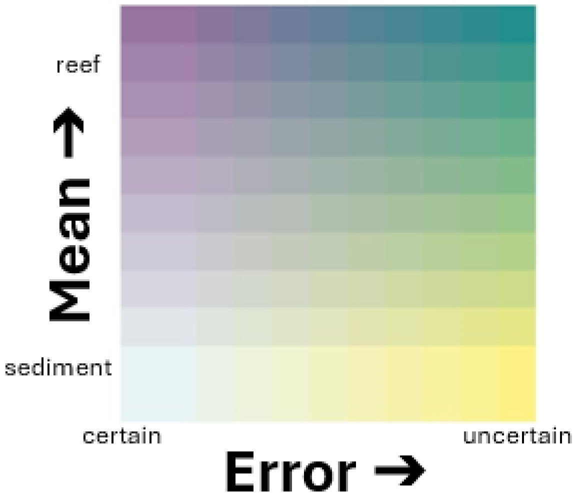

Figure 6. Colour ramp showing a simplified way to interpret the bivariate legends of expected probability of occurrence combined with uncertainty in a single map.

4 Results

4.1 Summary of key observations for ground truthing areas

4.1.1 *Yamatji Sea Country* - Abrolhos Marine Park

A total of 122 BOSS and stereo-BRUV drops were completed across the two National Park Zones (NPZs) and adjacent Special Purpose Zone (SPZ; Figure 7). In the most northern NPZ, these drops revealed an ecosystem primarily dominated by shelf unvegetated sediments, with small, isolated patches of sessile invertebrate reefs (Figure 7).

The southern NPZ and adjacent SPZ exhibited greater ecosystem diversity. Macroalgae dominated the shallow reefs in the eastern regions of this area (Figure 7; Figure 8). Additionally, in mesophotic depths, there were moderate amounts of bare reef, macroalgae, and sessile invertebrates observed (Figure 8). In contrast, the rariphotic depths were characterised by shelf unvegetated sediments and sessile invertebrates (Figure 8). Dense and expansive Rhodolith beds we also recorded in the northern NPZ in 51 m (Figure 12).

Example images of these ecosystems are provided in Figure 9 to Figure 12

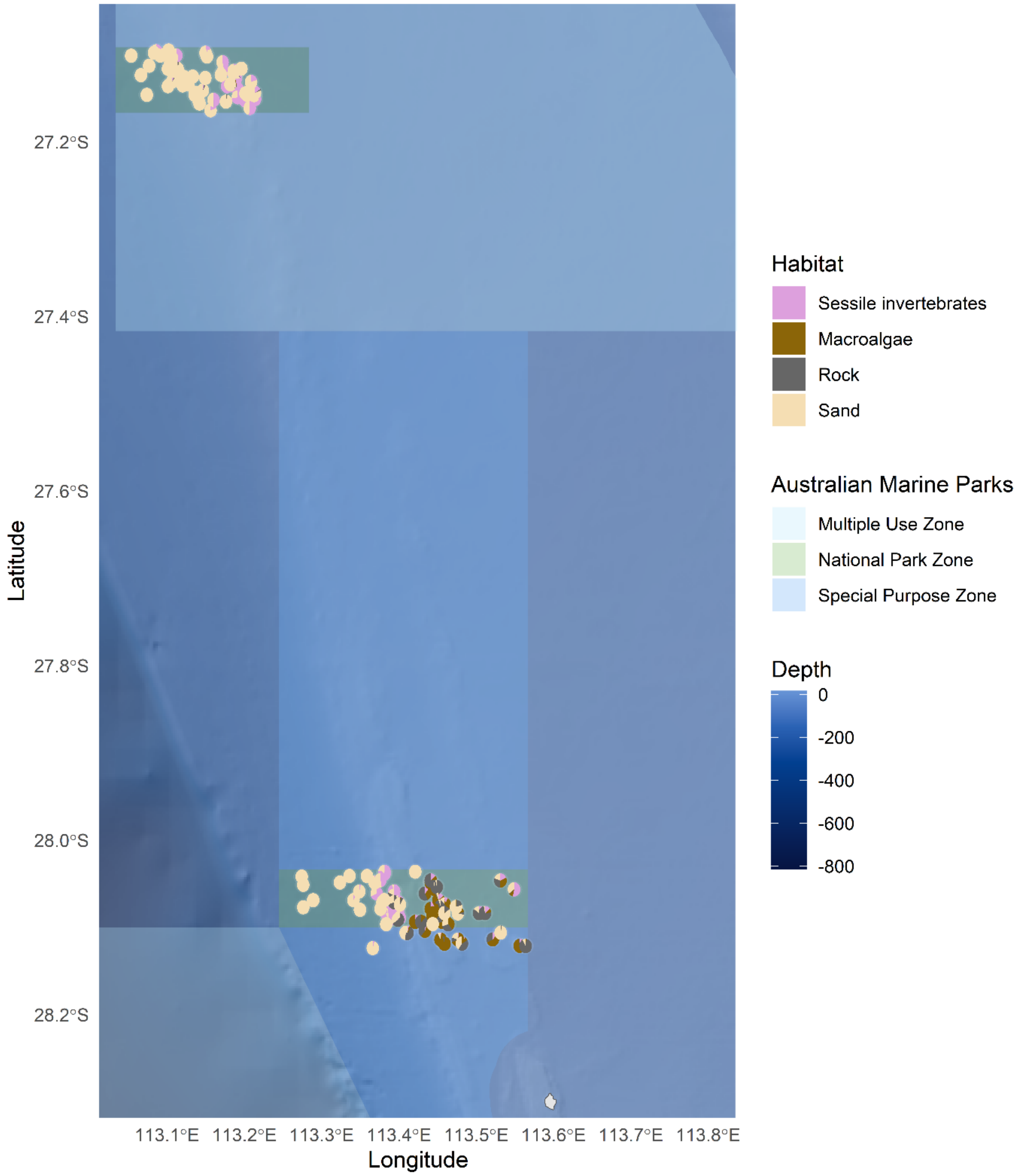

Figure 7. Spatial pie charts of habitat classification for deployments on Yamatji Sea Country (Abrolhos Marine Park). Dynamic link https://seamapaustralia.org/map/#a35c9093-7114-4258-961e-afeb91728c10

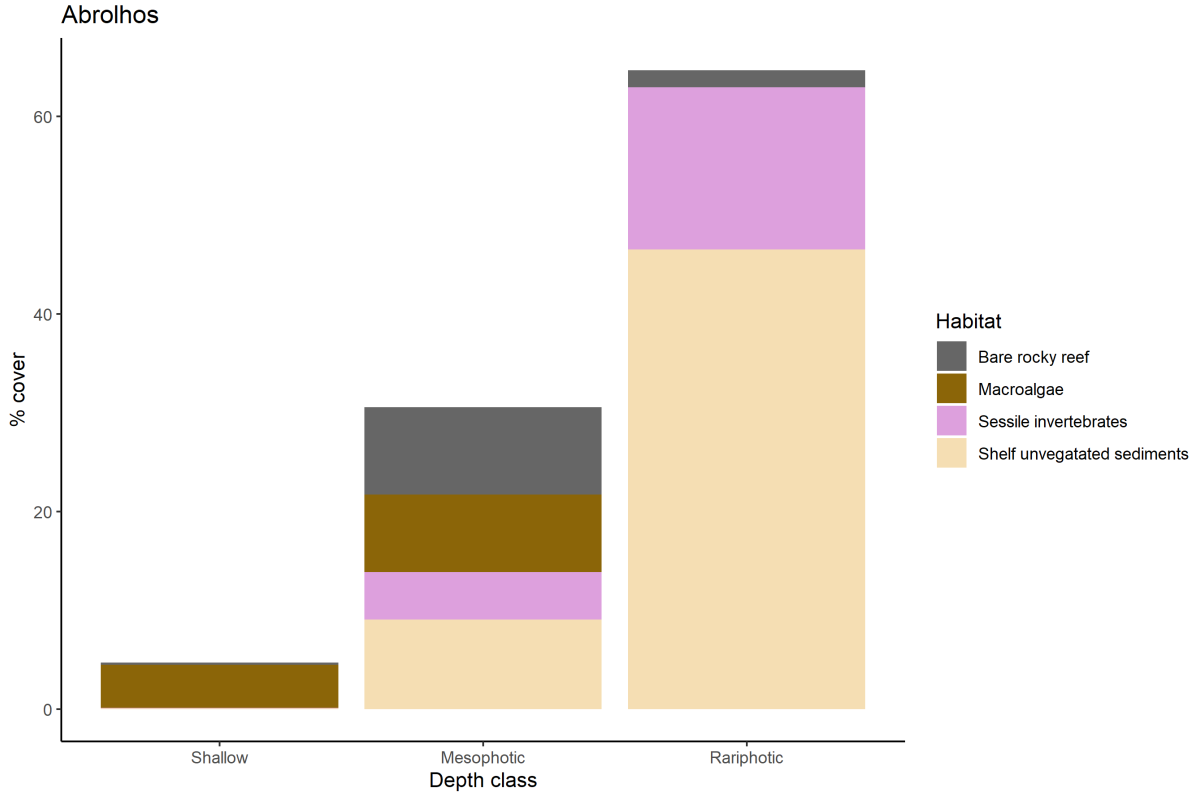

Figure 8. Percent cover of each habitat classification observed within each depth class on Yamatji Sea Country (Abrolhos Marine Park). Depth classes are: Shallow (0-30 m), Mesophotic (30-70 m), Rariphotic (70-200 m).

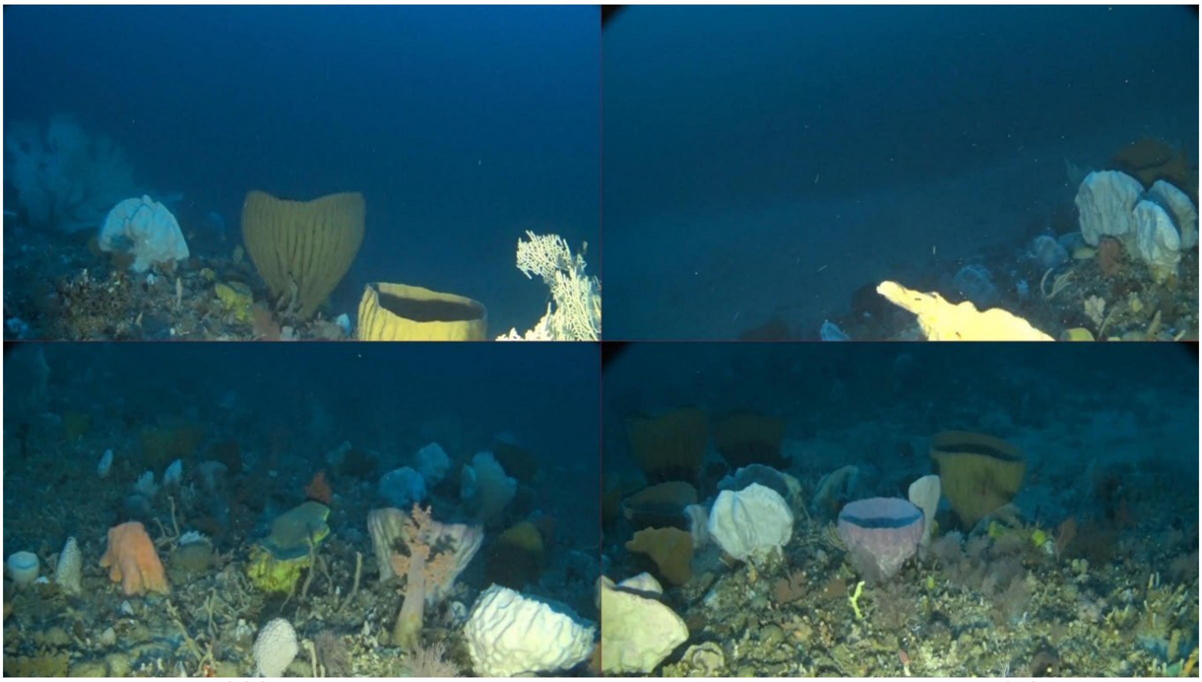

Figure 9. Example BOSS imagery highlighting the diverse sponge and sessile invertebrate reefs found on Yamatji Sea Country (Abrolhos Marine Park) in 92 m depth. These features were observed in the southern National Park Zone.

Figure 10. Example BOSS imagery highlighting the mixed reef assemblage dominated by small red macroalgae, *Ecklonia radiata* (Golden Kelp) and massive sponges in 42 m. These habitats were observed in the southern National Park Zone on Yamatji Sea Country (Abrolhos Marine Park).

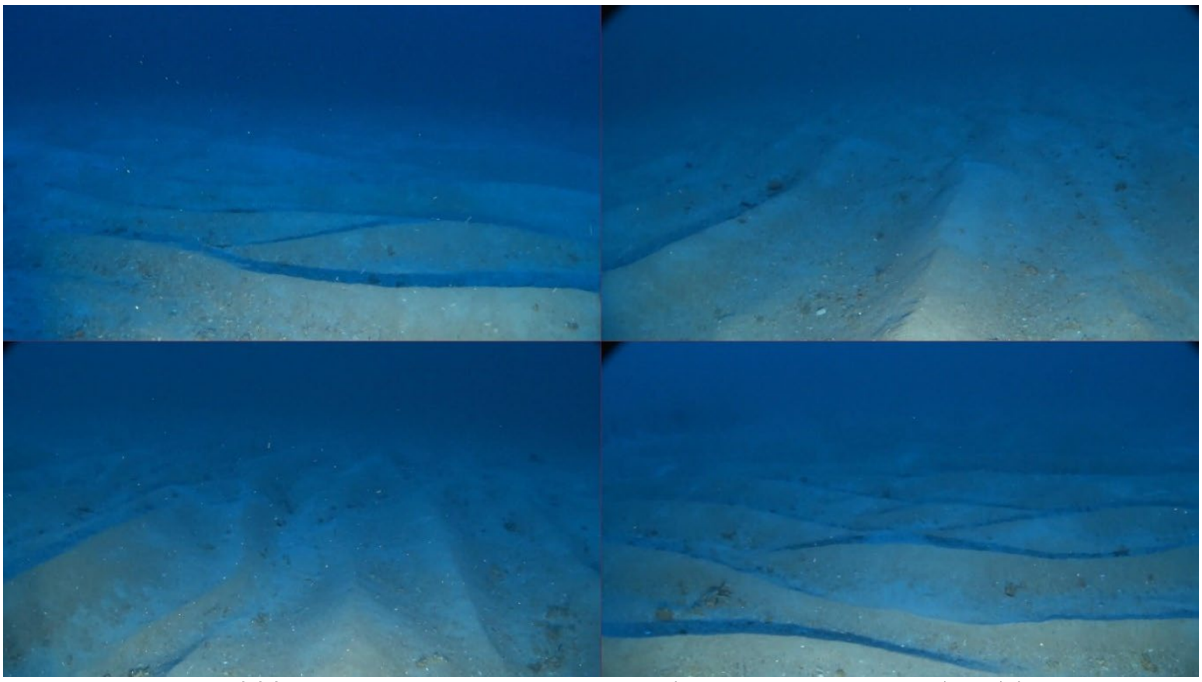

Figure 11. Example BOSS imagery highlighting the typical shelf unvegetated sediments (sand) formed into coarse 2D rippled sand waves in the northern National Park Zone on Yamatji Sea Country (Abrolhos Marine Park) in 103 m. These ripples indicate strong current or wave activity.

Figure 12. Example BOSS imagery highlighting impressive Rhodolith beds and rocky reef features with associated massive sponges and sessile invertebrates in the southern National Park Zone on Yamatji Sea Country (Abrolhos Marine Park) in 51 m.

4.1.2 *Wadandi Sea Country* - Geographe Marine Park

A total of 198 BOSS and stereo-BRUV drops were aggregated across the NPZ, Habitat Protection Zone (HPZ), Multiple Use Zone (MUZ) and SPZ (Figure 13). The imagery revealed that seagrass, unvegetated sediments and macroalgae dominated the shallow regions of the Geographe AMP (Figure 13). Within the NPZ imagery revealed that it is dominated by seagrass mixed with macroalgae with occasional outcrops of bare reef (Figure 14).

The eastern section of the MUZ and adjacent SPZ exhibited similar habitats (Figure 13), while the HPZ and western end of the MUZ consisted of more bare sand dominated habitats which appears to support moderate densities of scallops (Figure 14). Example images of these ecosystems are provided in Figure 15 to Figure 18.

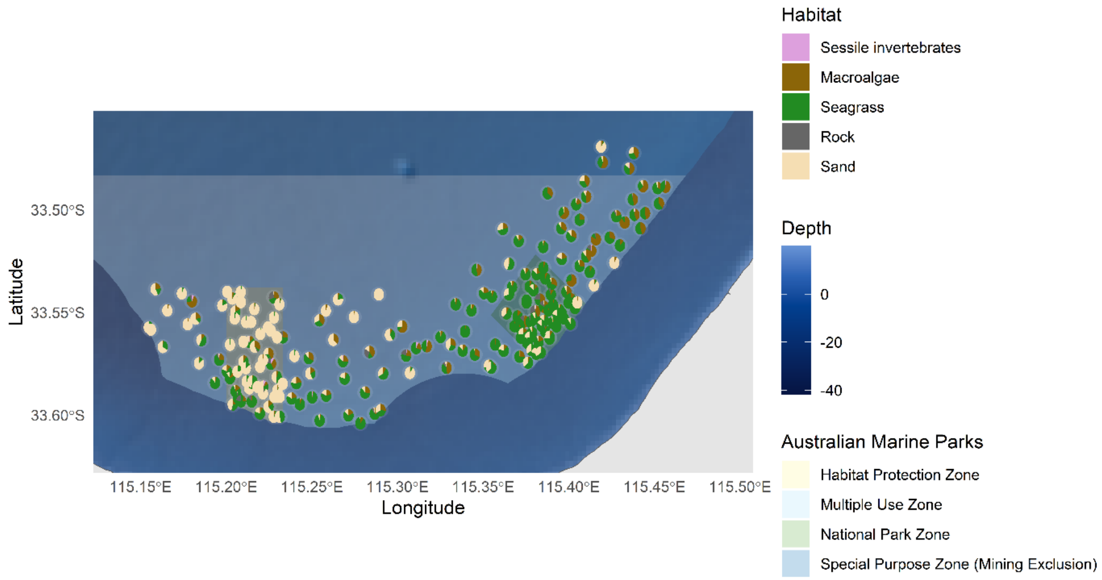

Figure 13. Spatial pie charts of habitat classification for deployments on Wadandi Sea Country (Geographe Marine Park). Dynamic link: https://seamapaustralia.org/map/#48e01960-186d-4999-ba96-3e112617450e.

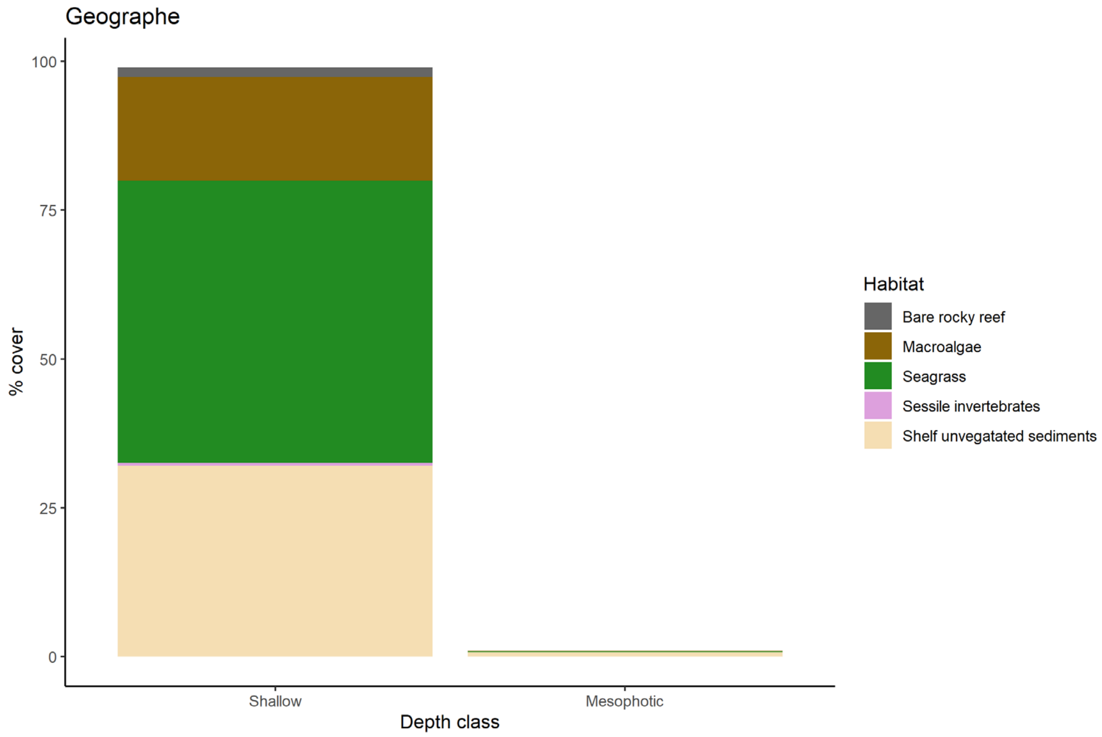

Figure 14. Percent cover of each habitat classification observed within each depth class on Wadandi Sea Country (Geographe Marine Park). Depth classes are: Shallow (0-30 m), Mesophotic (30-70 m).

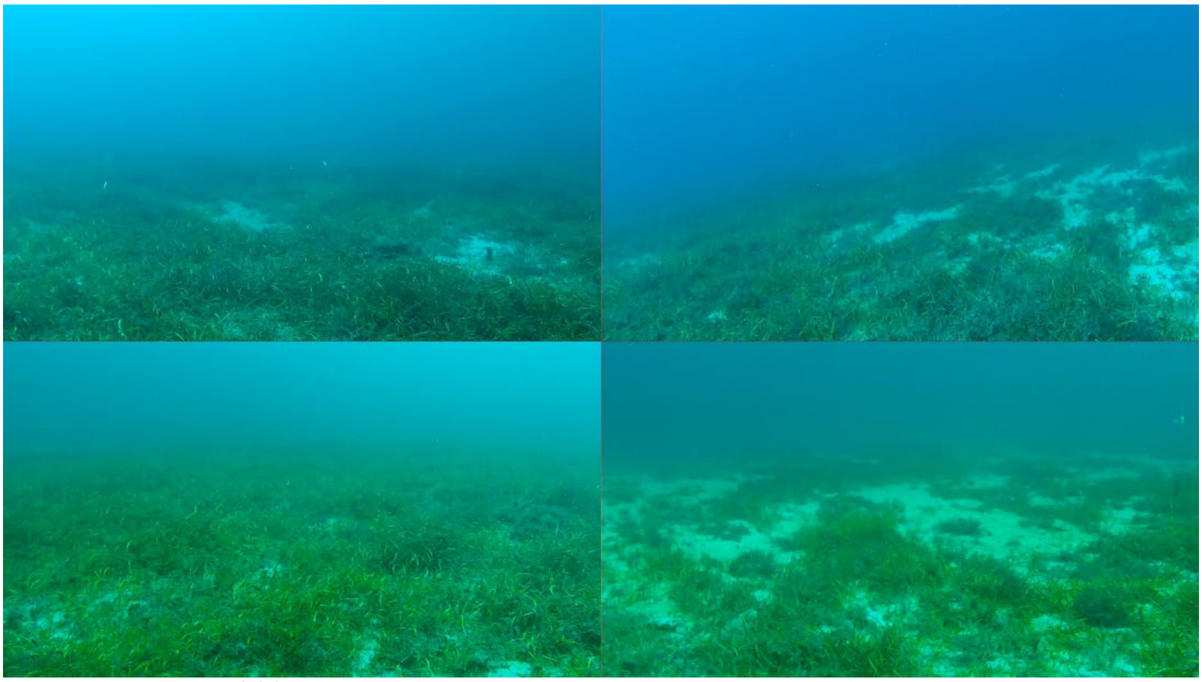

Figure 15. Example BOSS imagery highlighting dense *Posidonia australis* seagrass beds that dominated the shallow regions of the on Wadandi Sea Country (Geographe Marine Park).

Figure 16. Example BOSS imagery highlighting the outcropping reef features within the dense Posidonia australis seagrass beds on Wadandi Sea Country (Geographe Marine Park).

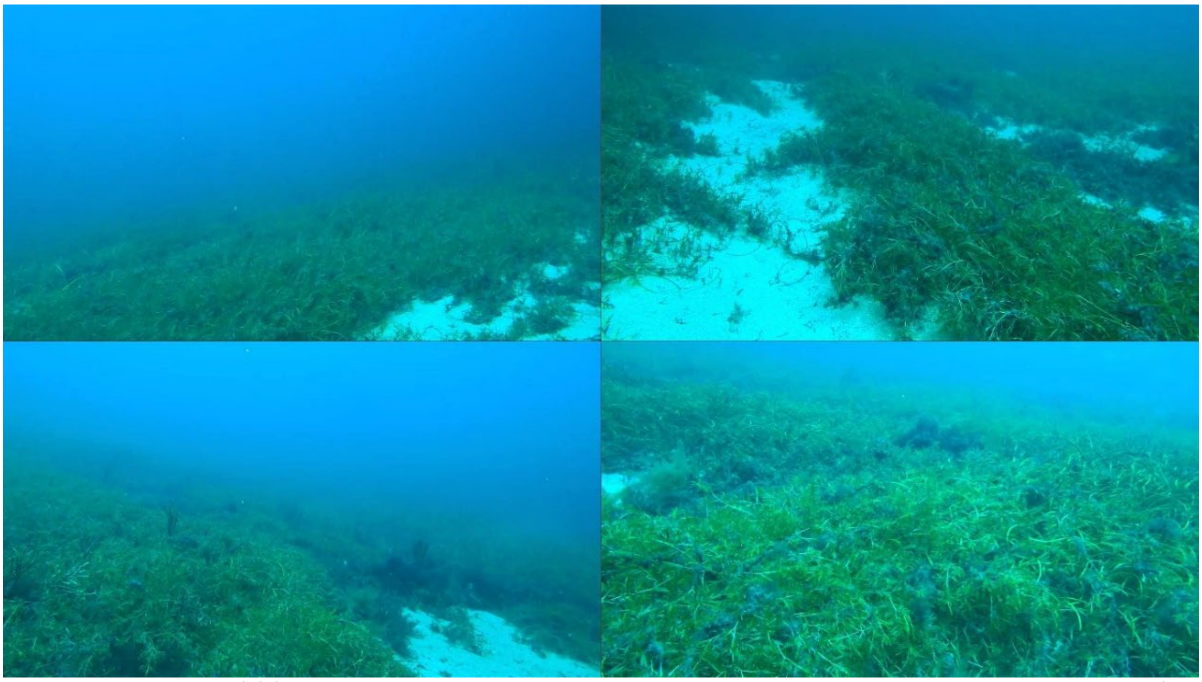

Figure 17. Example BOSS imagery highlighting the dense *Amphibolis antarctica* seagrass beds on Wadandi Sea Country (Geographe Marine Park).

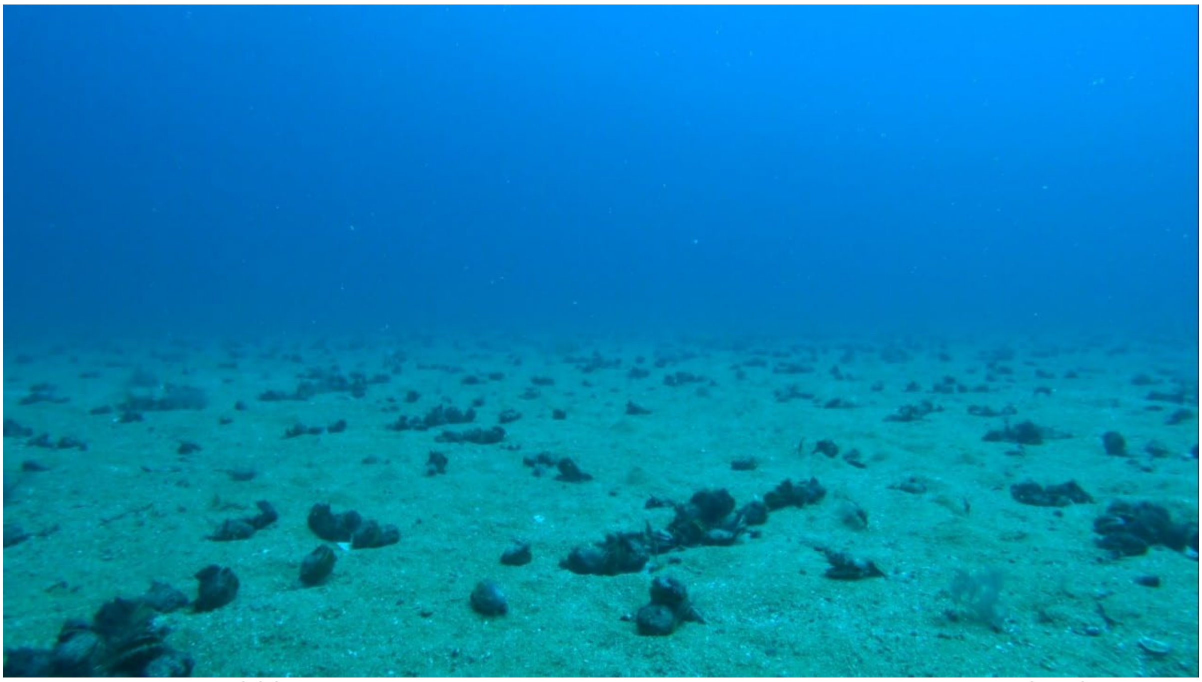

Figure 18. Example BOSS imagery highlighting the moderately dense scallop beds on Wadandi Sea Country (Geographe Marine Park) found in 20 m depth.

4.1.3 *Wadandi Sea Country* - South-west Corner Marine Park (western arm)

A total of 346 BOSS and stereo-BRUV drops were collated across the western extent of South-west Corner MP, with coverage in the NPZ and adjacent Special Purpose Zone (SPZ; Figure 19).

The southern NPZ and adjacent SPZ exhibited greater ecosystem diversity. Macroalgae dominated the shallow reefs in the eastern regions of this area (Figure 19; Figure 20). Additionally, in mesophotic depths, there were moderate amounts of bare reef, macroalgae, and sessile invertebrates observed (Figure 20). In contrast, the rariphotic depths were characterised by shelf unvegetated sediments and sessile invertebrates (Figure 20). Example images of these ecosystems are provided in Figure 21 to Figure 24.

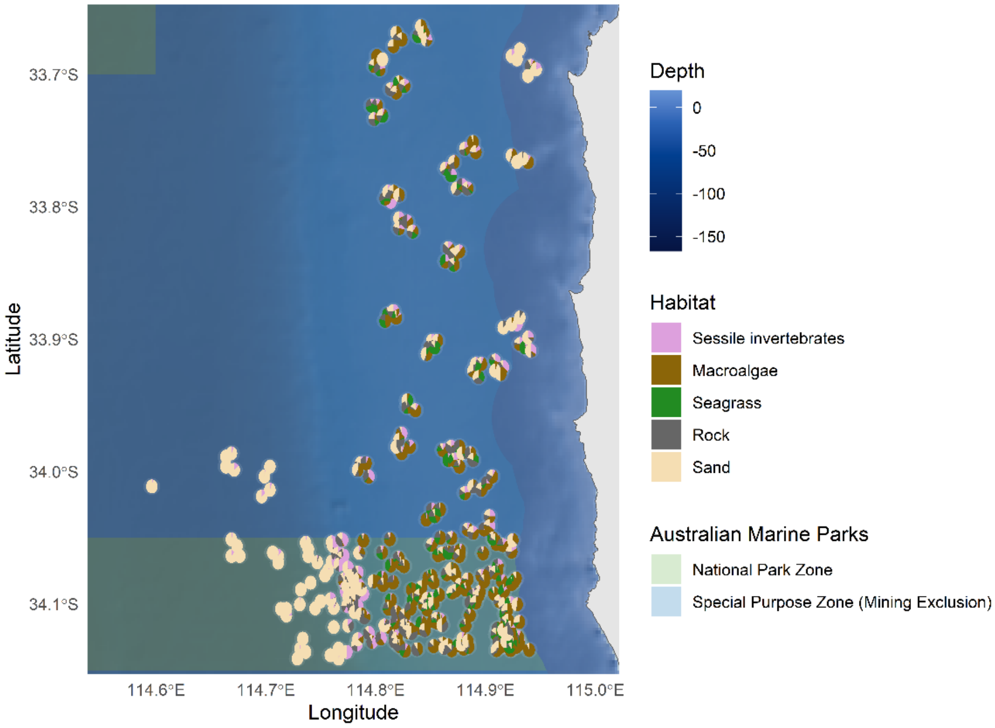

Figure 19. Spatial pie charts of habitat classification for deployments on Wadandi Sea Country (South-west Corner Marine Park). Dynamic link: https://seamapaustralia.org/map/#a220fc3d-0e82-424c-b00e-27b7f81c1178.

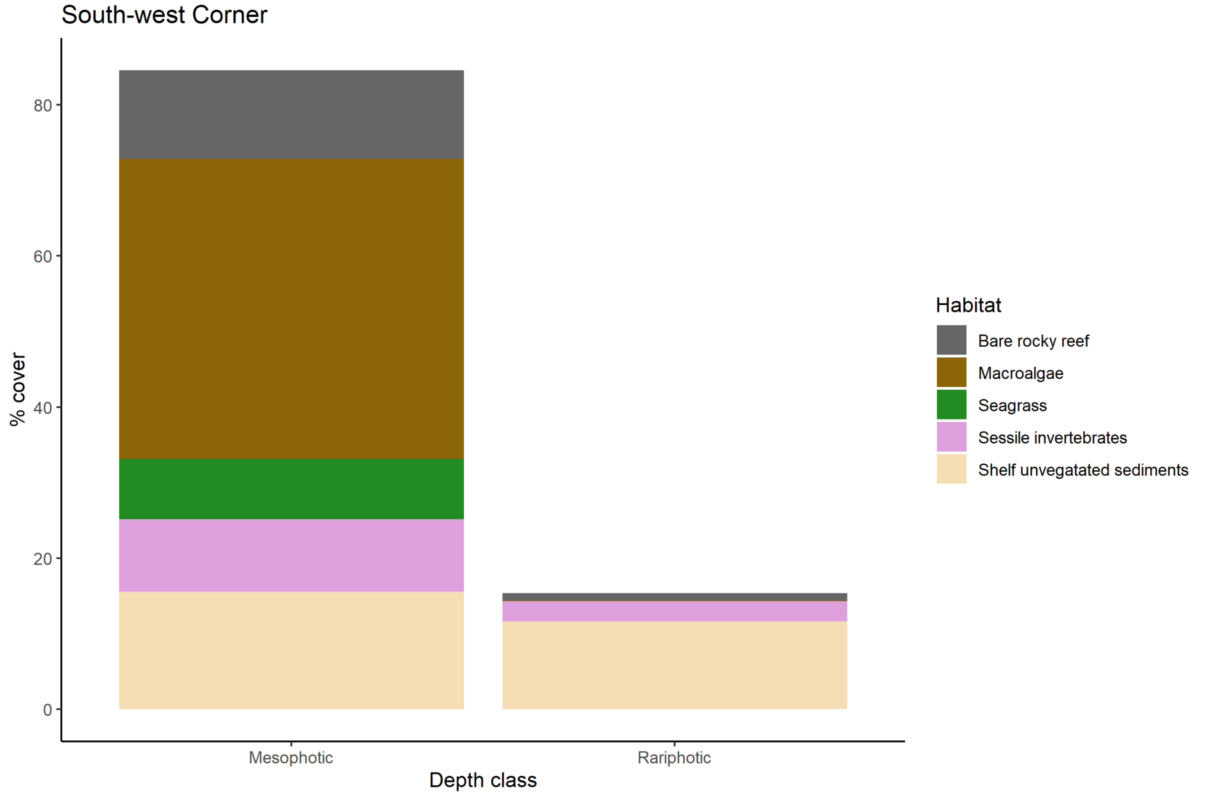

Figure 20. Percent cover of each habitat classification observed within each depth class on Wadandi Sea Country (South-west Corner Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

Figure 21. Example of mixed sessile invertebrates, including sponges, growing interspersed with the deepwater seagrass *Thalassodendron pachyrhizum* in the Special Purpose Zone (Mining Exclusion) on Wadandi Sea Country (South-west Corner Marine Park). This benthic community was observed in 43 m of water.

Figure 22. An example of the Golden Kelp (Ecklonia radiata) that dominates the limestone reef in the National Park Zone on Wadandi Sea Country (South-west Corner Marine Park) in 44 m depth.

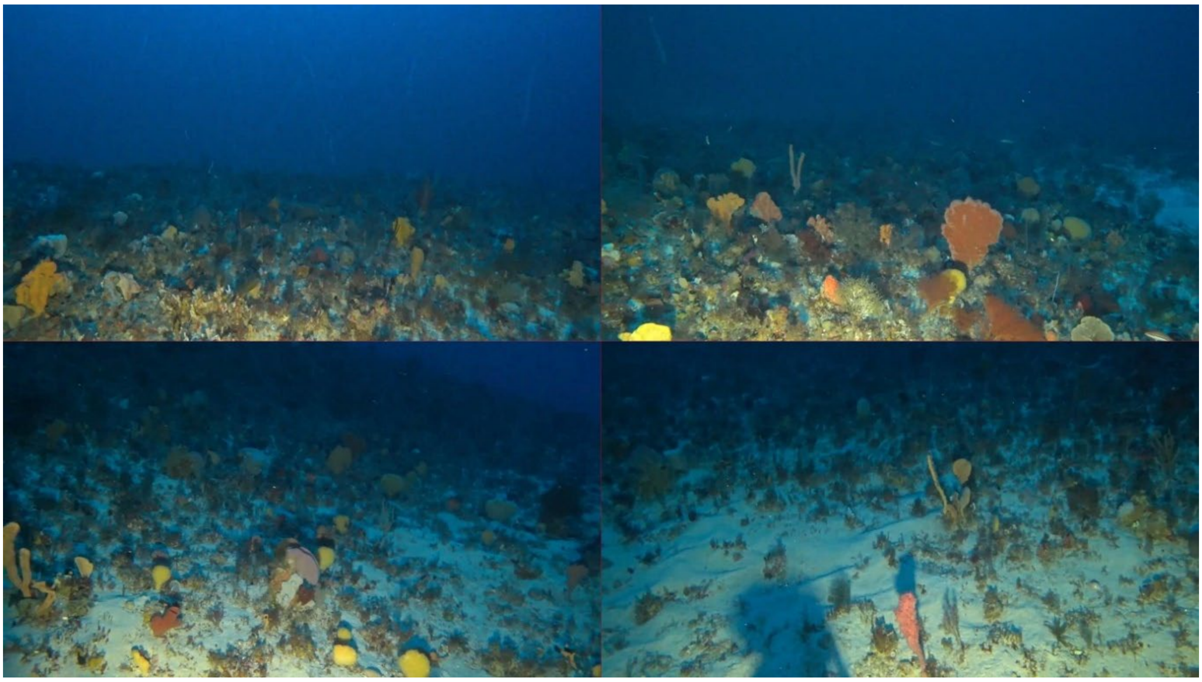

Figure 23. Low-profile reefs observed in the National Park Zone on Wadandi Sea Country (South-west Corner Marine Park) in 79 m of water. Erect sponges and small mixed sessile invertebrate communities dominate the benthic community.

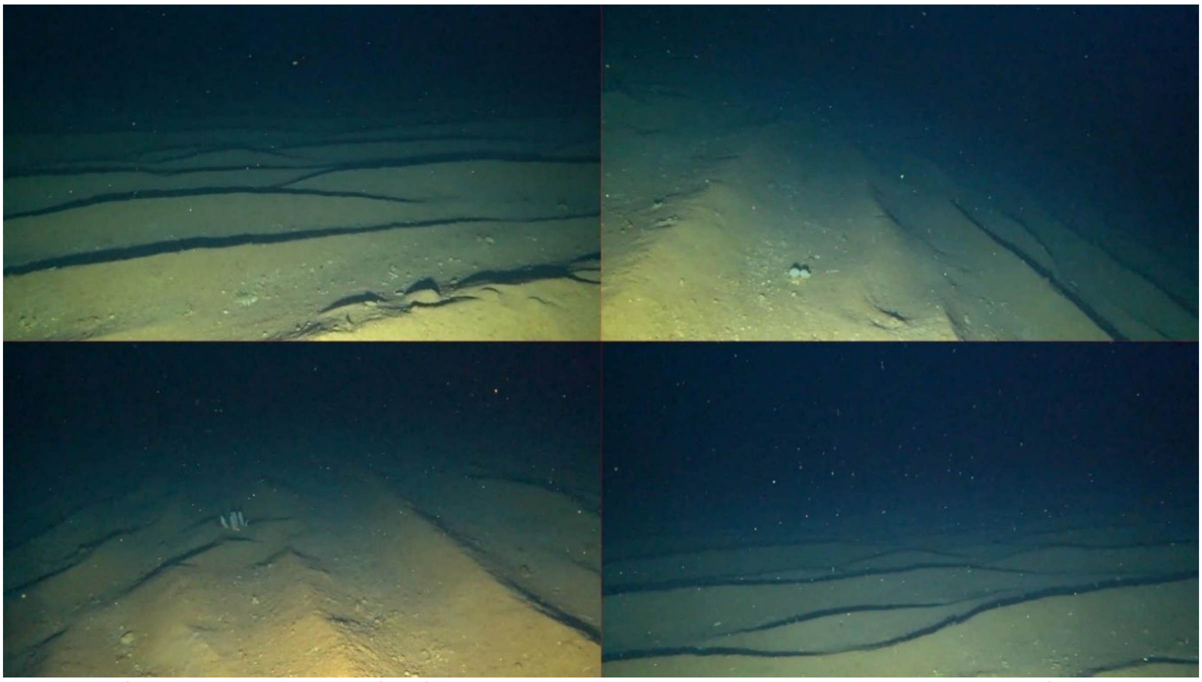

Figure 24. Course rippled sand on Shelf unvegetated sediments provide indications that wave and/or currents shape ecosystems at 120 m in the National Park Zone on Wadandi Sea Country (South-west Corner Marine Park).

4.1.4 *Mirrning / Wagyl-Kaip Sea Country* - Bremer Marine Park

A total of 130 BOSS drops were collected across the Bremer MP, with coverage in the NPZ and adjacent SPZ (Figure 25). Both the NPZ and SPZ exhibited similar habitat distribution, with unvegetated sediments dominating the mesophotic and rariphotic depths (Figure 26). Increased, cover in sessile invertebrates was observed towards the shelf break, while isolated beds of macroalgae appeared to increase in cover in the northern shallower regions of the mesophotic zone (Figure 26). Example images of these ecosystems are provided in Figure 27 to Figure 29.

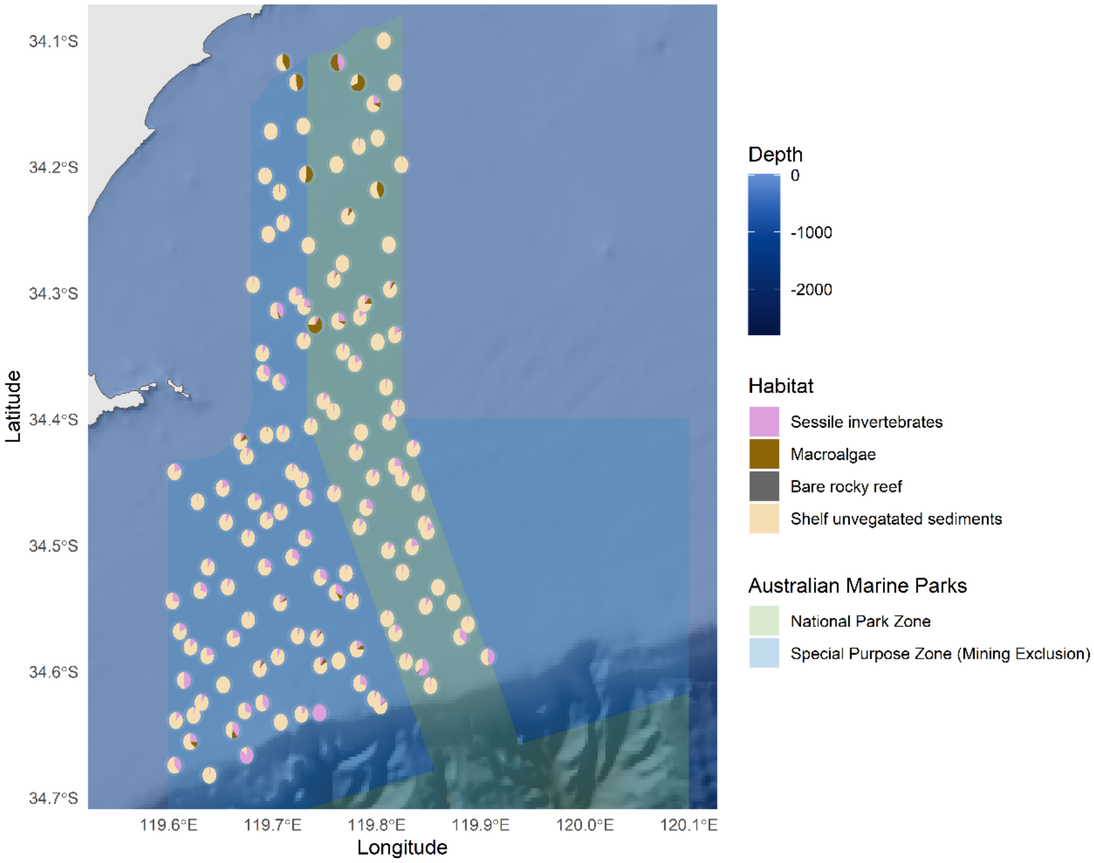

Figure 25. Spatial pie charts of habitat classification for deployments on Mirrning / Wagyl-Kaip Sea Country (Bremer Marine Park). Dynamic link: https://seamapaustralia.org/map/#df01f1f1-dc18-498b-adab-a556cce056b1.

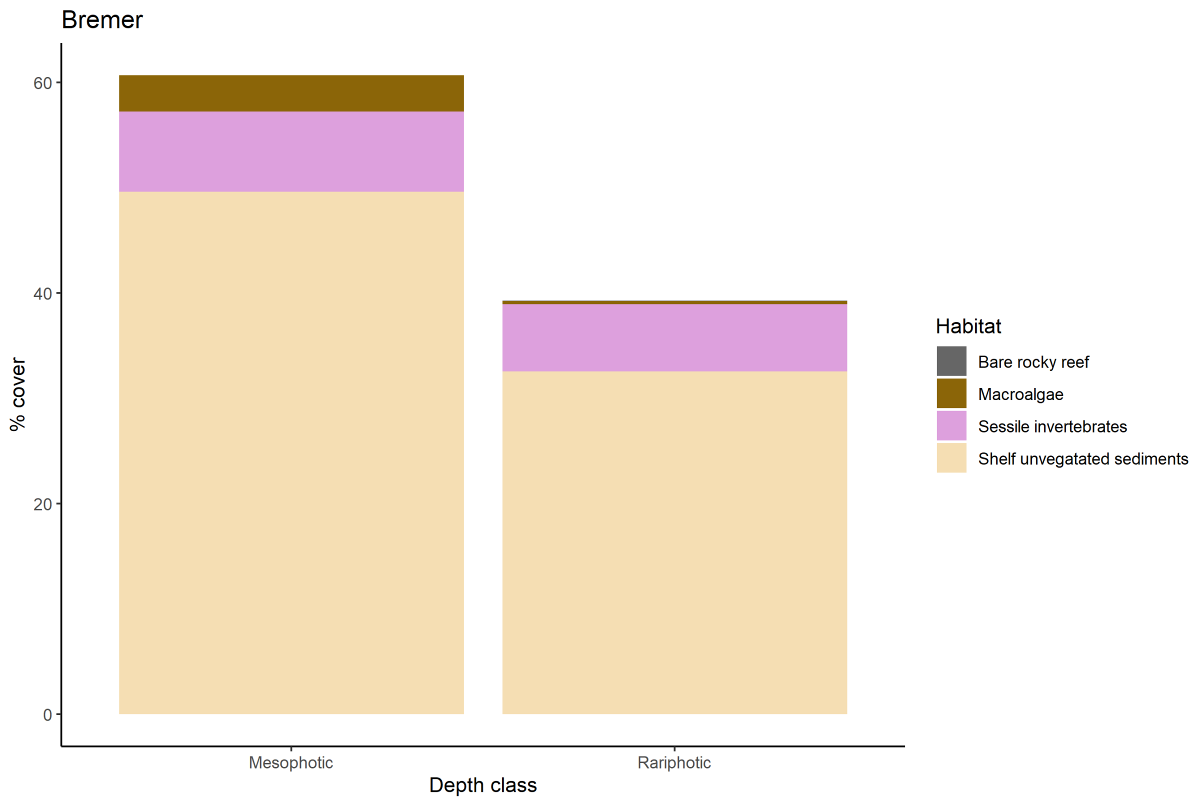

Figure 26. Percent cover of each habitat classification observed within each depth class on Mirrning / Wagyl-Kaip Sea Country (Bremer Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

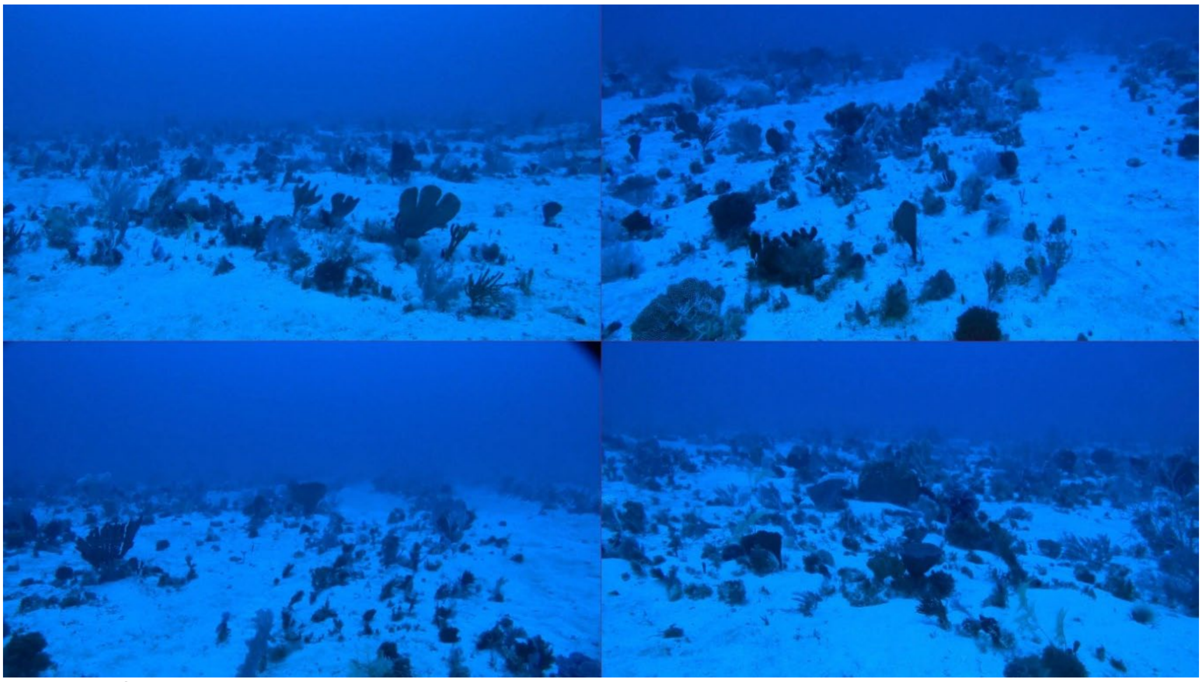

Figure 27. Sparse sessile invertebrate communities including sponges and octocorals observed in the National Park Zone in 76 m. This habitat was commonly observed in mesophotic and rariphotic depths on Mirrning / Wagyl-Kaip Sea Country (Bremer Marine Park).

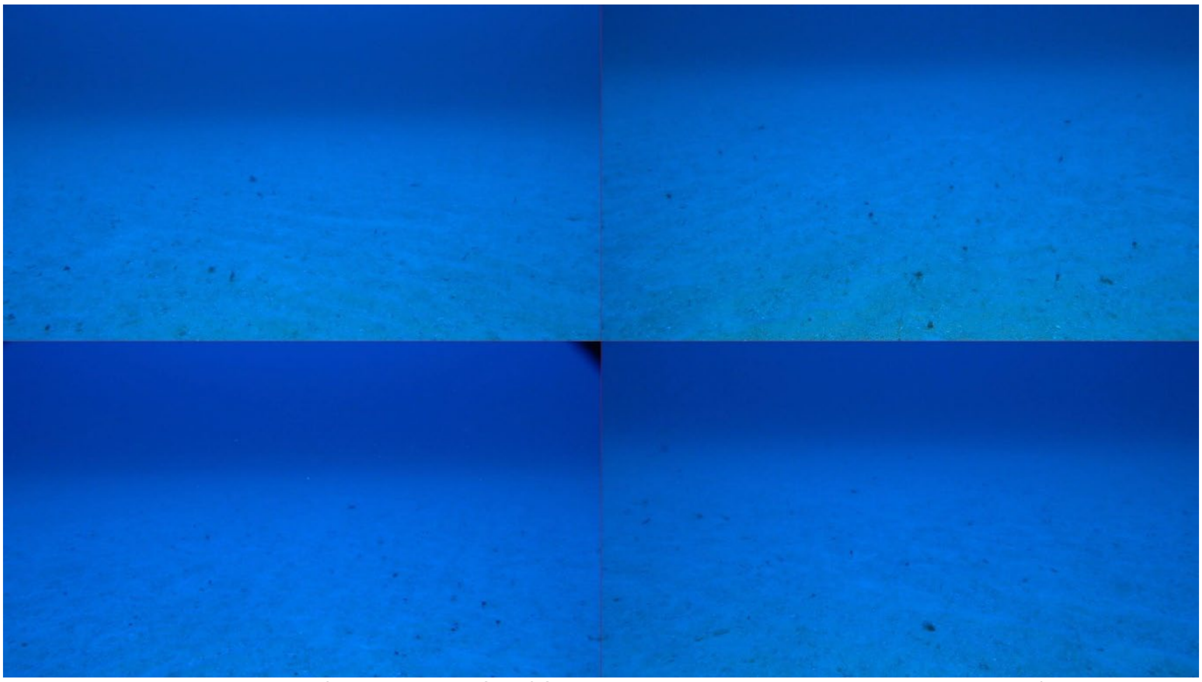

Figure 28. Fine rippled sand of Unvegetated Shelf Sediments in the rariphotic depths on Mirrning / Wagyl-Kaip Sea Country (Bremer Marine Park).

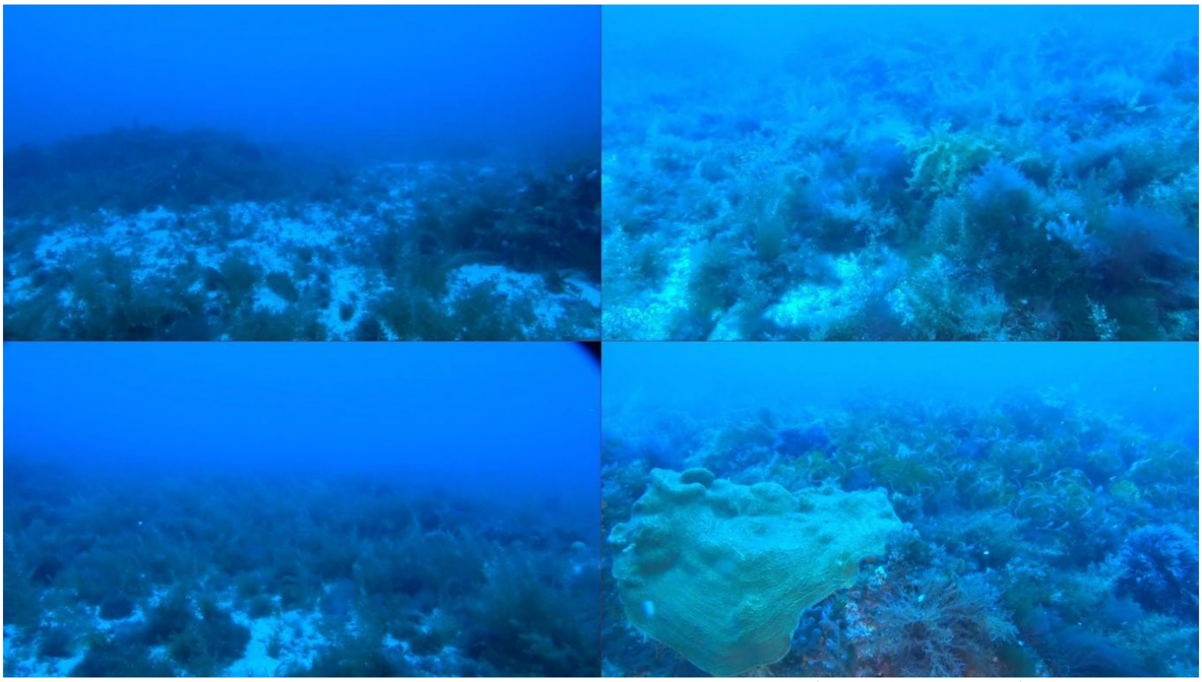

Figure 29. Extensive macroalgal beds with occasional encrusting hard coral (bottom right image) recorded in the mesophotic depths on Mirrning / Wagyl-Kaip Sea Country (Bremer Marine Park).

4.1.5 *Wudjari Sea Country* - South-west Corner Marine Park (eastern arm)

A total of 131 BOSS drops were collected across the western arm of the South-west Corner MP, with coverage in the NPZ and adjacent SPZ (Figure 30). In the shallow regions of the NPZ macroalgae, sessile invertebrate and seagrass habitats dominated (Figure 30). The cover in sessile invertebrates increased towards the shelf break in rariphotic depths (Figure 31), while isolated beds of macroalgae appeared to increase in cover in the northern shallow and mesophotic depths (Figure 31). Example images of these ecosystems are provided in Figure 32 to Figure 34.

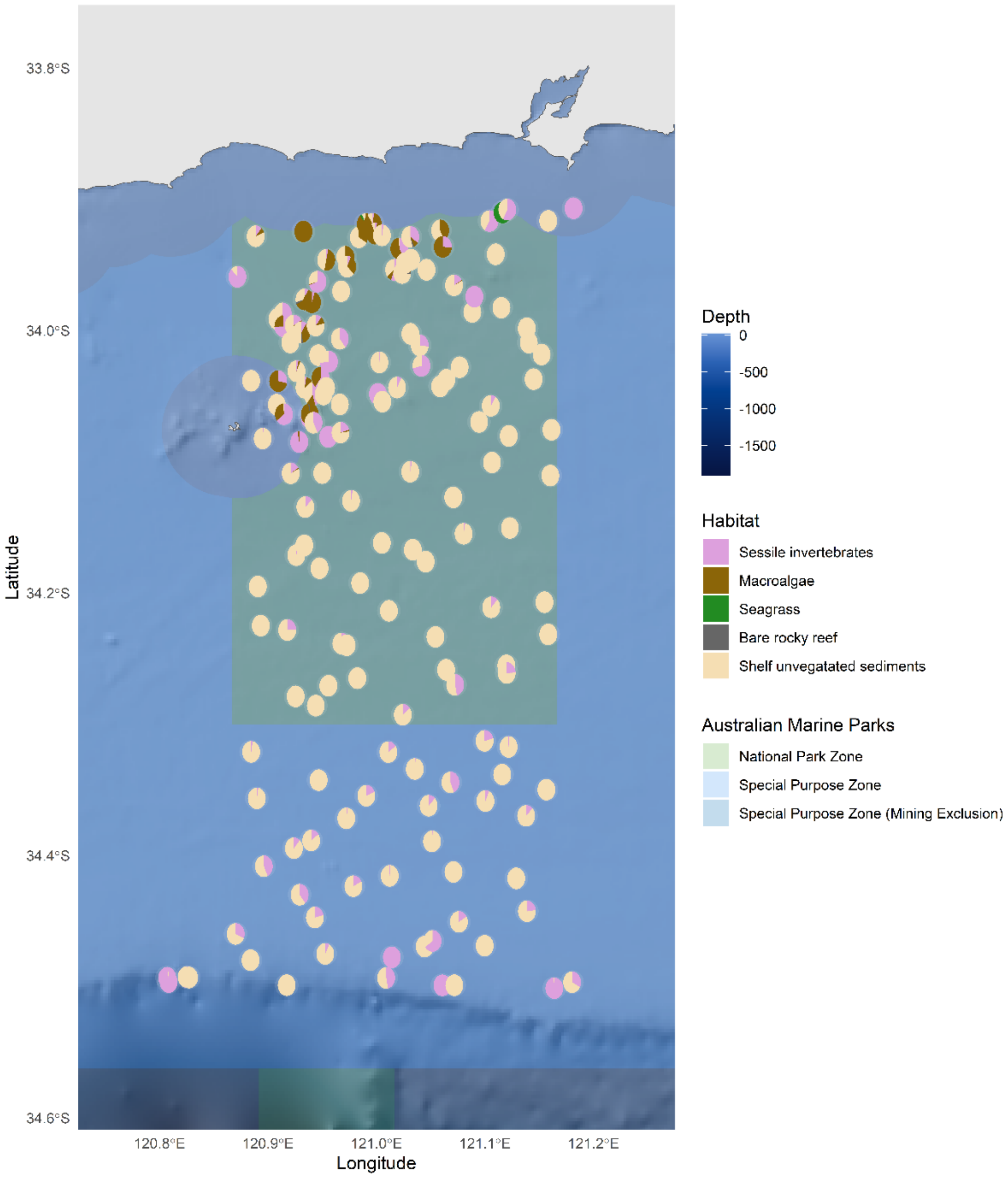

Figure 30. Spatial pie charts of habitat classification for deployments on Wudjari Sea Country (South-west Corner Marine Park – eastern arm). Dynamic link: https://seamapaustralia.org/map/#206c0175-5c5b-47a4-8525-4645fe89ed0d.

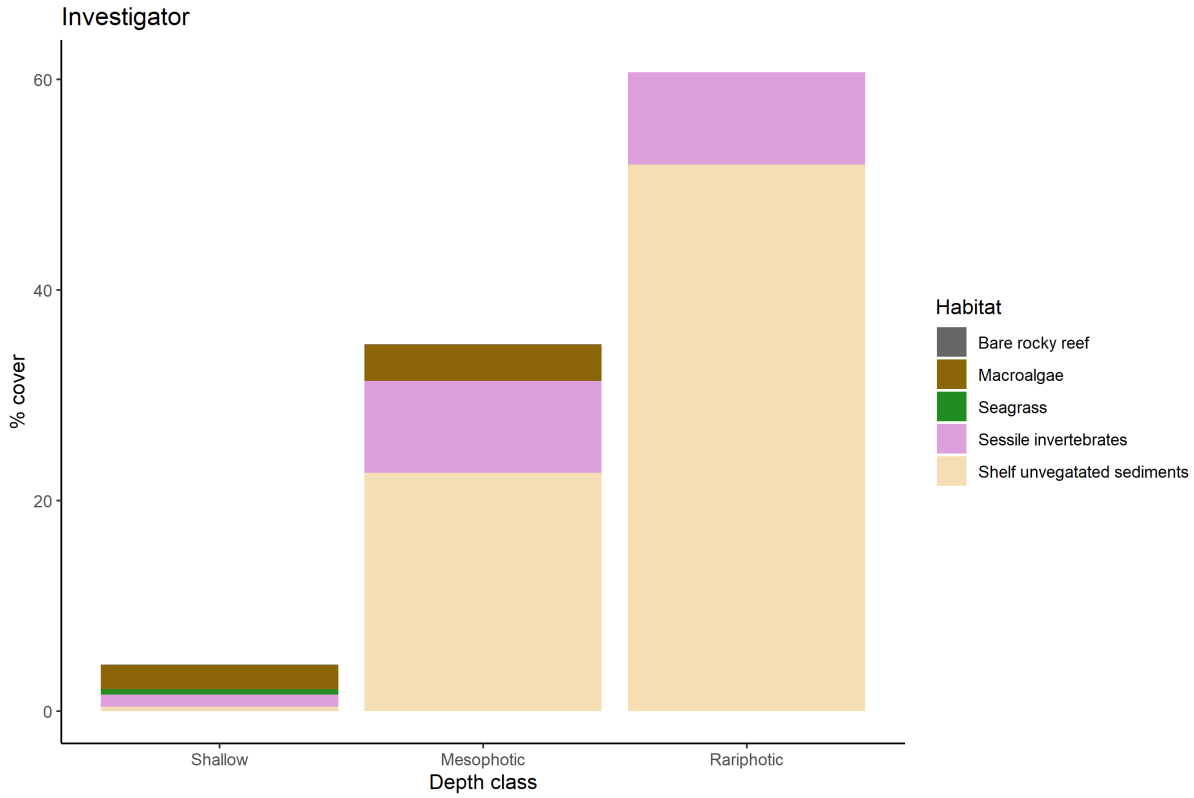

Figure 31. Percent cover of each habitat classification observed within each depth class on Wudjari Sea Country (South-west Corner Marine Park – eastern arm). Depth classes are: Shallow (0-30 m), Mesophotic (30-70 m), Rariphotic (70-200 m).

Figure 32. Closeup of the dense macroalgal beds recorded on shallow reefs on Wudjari Sea Country (South-west Corner Marine Park – eastern arm).

Figure 33. Extensive course rippled sand of the Shelf unvegetated sediments that dominated the mesophotic and rariphotic depths on Wudjari Sea Country (South-west Corner Marine Park – eastern arm).

Figure 34. Delicate mixed sessile invertebrates, including hard bryozoans and soft colonial ascidians that were observed in the mesophotic and rariphotic depths on Wudjari Sea Country (South-west Corner Marine Park – eastern arm).

4.1.6 *Wudjari Sea Country* - Eastern Recherche Marine Park

A total of 357 BOSS and stereo-BRUV drops were collected in and around the Eastern Recherche MP, with coverage in the NPZ and adjacent SPZ (Figure 35). The NPZ consisted mainly of shelf unvegetated sediments, with a small patch of macroalgae and seagrass in the north (Figure 35). Shelf unvegetated sediments dominated all three depths in both zones (Figure 36), with slightly higher cover in sessile invertebrates being recorded in the SPZ (Figure 35). Example images of these ecosystems are provided in Figure 37 to Figure 40.

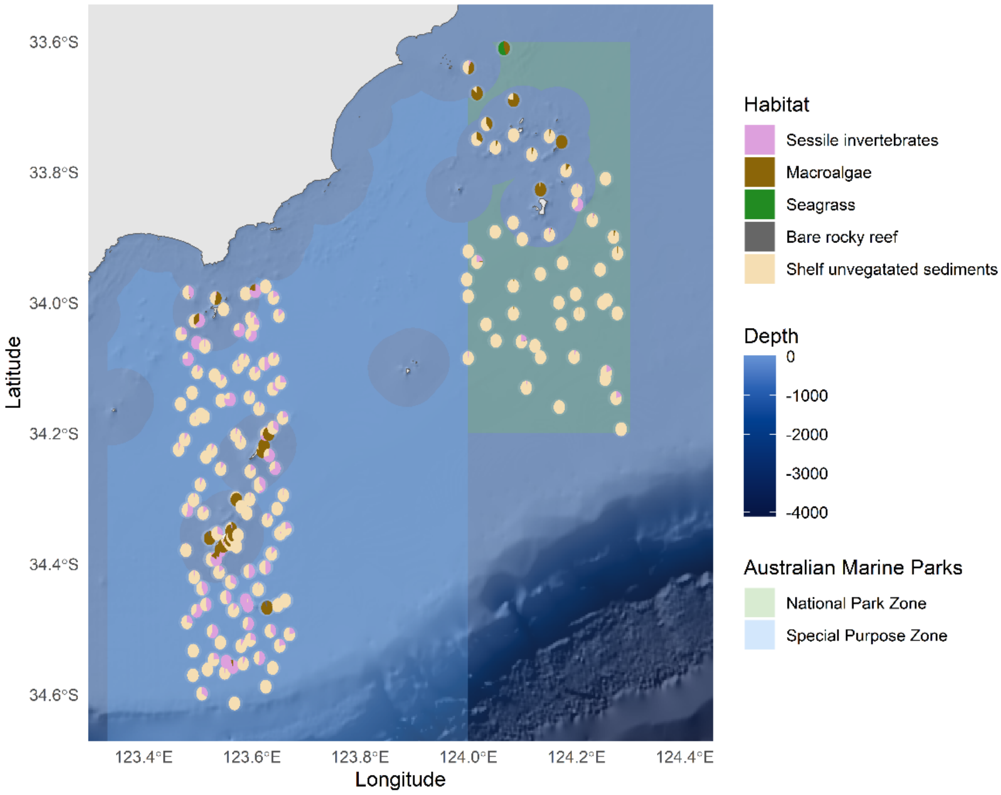

Figure 35. Spatial pie charts of habitat classification for deployments on Wudjari Sea Country (Eastern Recherche Marine Park). Dynamic link: https://seamapaustralia.org/map/#ee21ab86-0cbf-4c89-b2ff-d179aa0098cc.

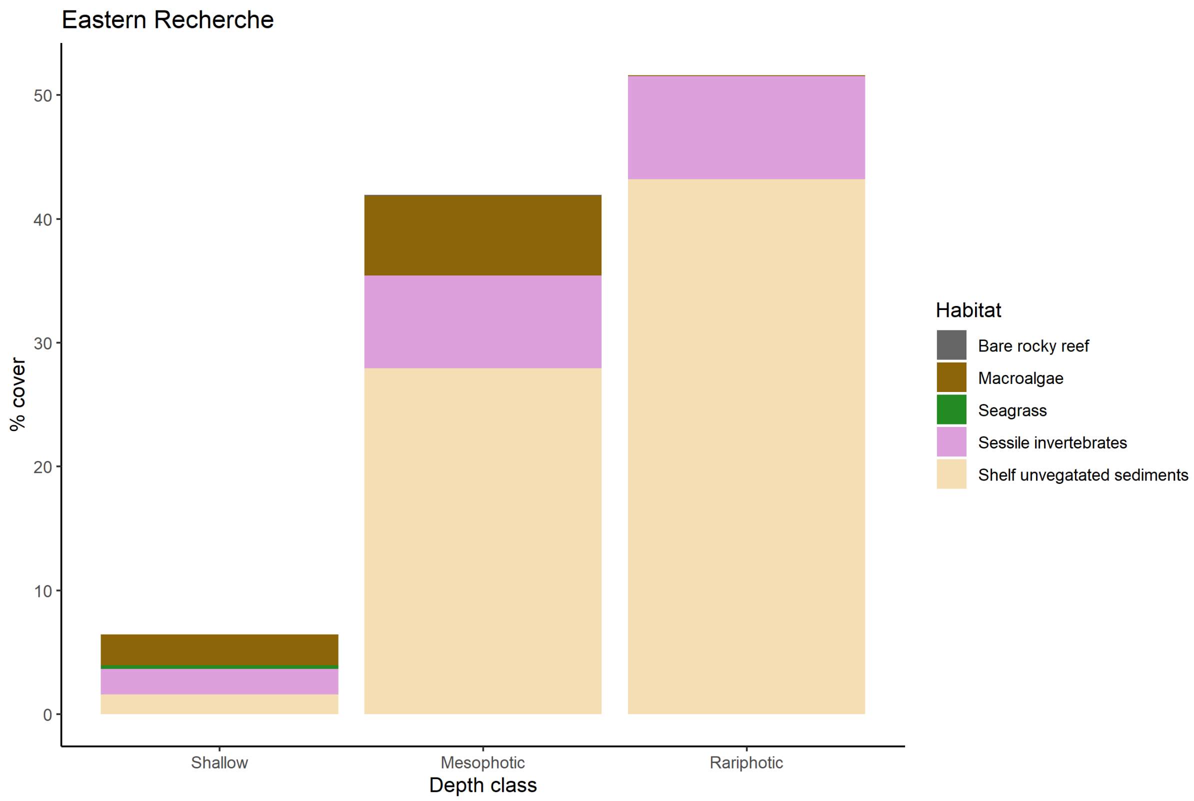

Figure 36. Percent cover of each habitat classification observed within each depth class on Wudjari Sea Country (Eastern Recherche Marine Park). Depth classes are: Shallow (0-30 m), Mesophotic (30-70 m), Rariphotic (70-200 m).

Figure 37. Dense golden kelp (*Ecklonia radiata*) beds that were observed in the shallow and mesophotic depths on Wudjari Sea Country (outside of the Eastern Recherche Marine Park).

Figure 38. Sessile invertebrates growing on sand inundated reefs on Wudjari Sea Country (Eastern Recherche Marine Park).

Figure 39. Dense and diverse sessile invertebrates growing on mesophotic and rariphotic reefs on Wudjari Sea Country (Eastern Recherche Marine Park).


Figure 40. Typical Shelf Unvegetated Sediments on Wudjari Sea Country (Eastern Recherche Marine Park).

4.1.7 *Wirangu Sea Country* - Murat Marine Park

A total of 18 stereo-BRUV drops were collated from Department for Environment and Water (DEW) across the Murat MP with coverage in the southern region of the NPZ (Figure 41). These drops showed that shelf unvegetated sediments dominated the mesophotic depths (Figure 42). An isolated patch of macroalgae was observed in the southern centre of the NPZ with sessile invertebrates observed in the south-east (Figure 41). No example images have been provided by DEW at this time.

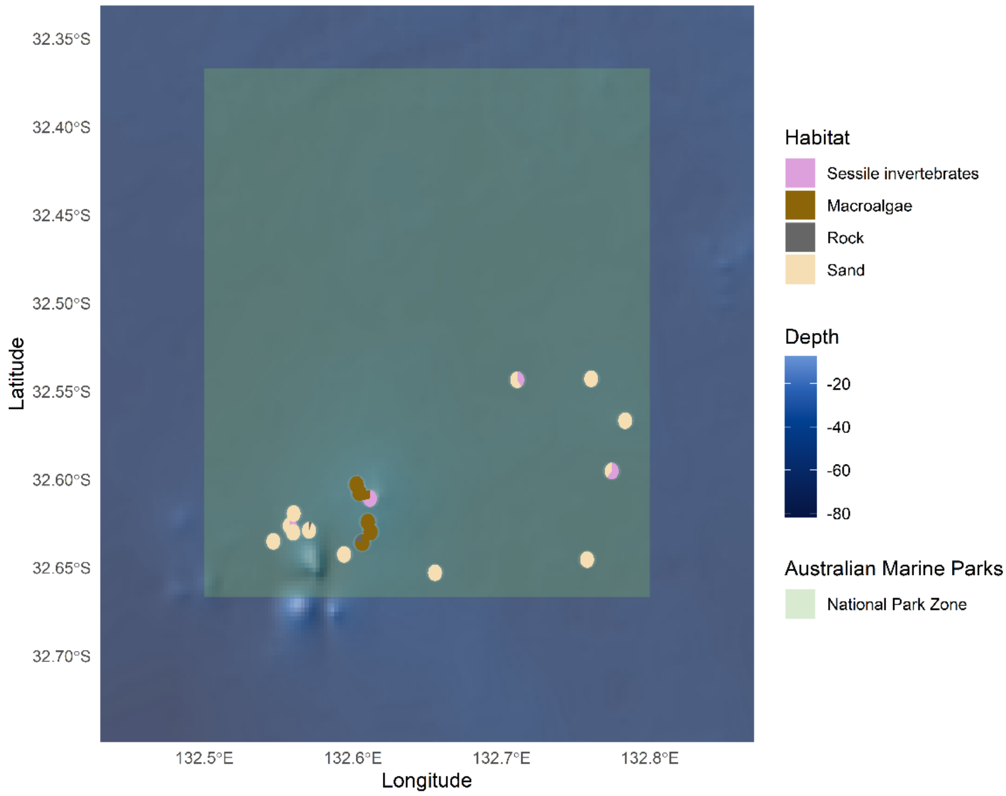

Figure 41. Spatial pie charts of habitat classification for deployments on Wirangu Sea Country (Murat Marine Park). Dynamic link: https://seamapaustralia.org/map/#d5c75cfc-594c-40df-9a17-b49ec7231be5.

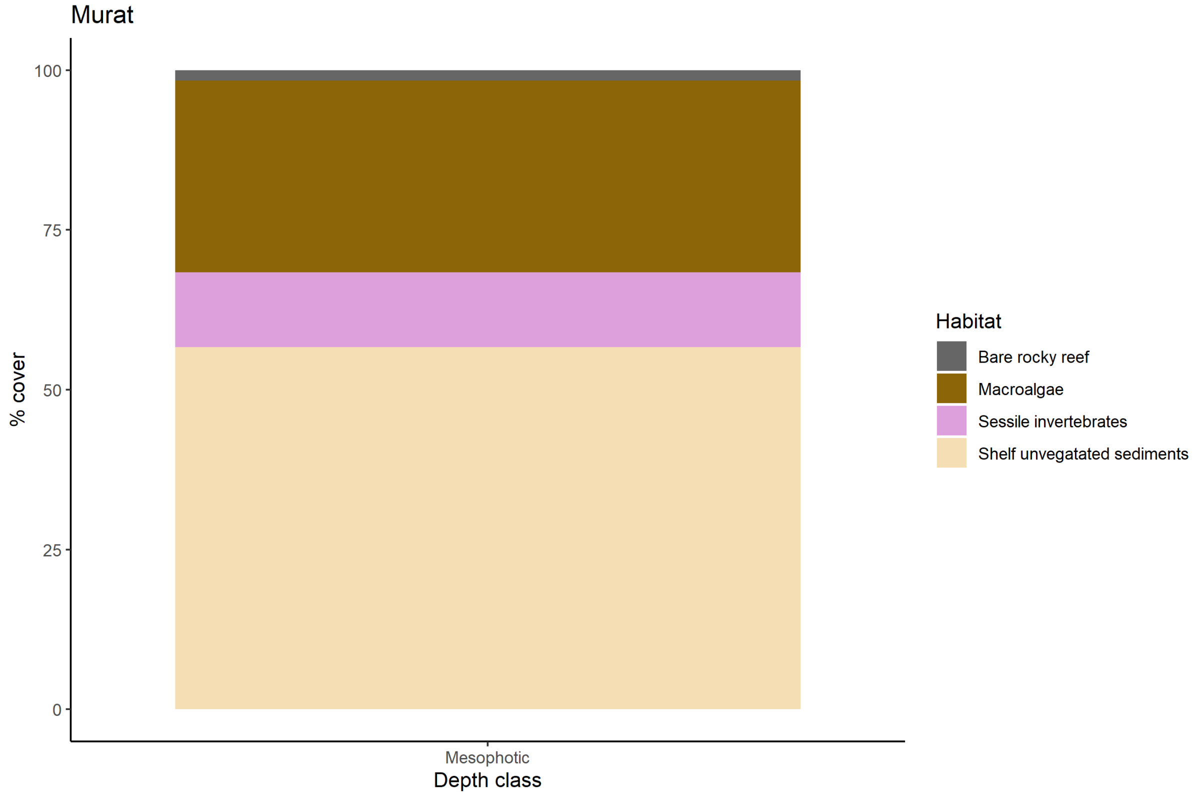

Figure 42. Percent cover of each habitat classification observed within each depth class on Wirangu Sea Country (Murat Marine Park). Depth class is: Mesophotic (30-70 m).

4.1.8 *Wirangu and Nawu Sea Country* - Western Eyre Marine Park

A total of 18 stereo-BRUV drops were collated from Department for Environment and Water (DEW) across the Western Eyre MP with coverage in the NPZ (Figure 43). These drops showed that shelf unvegetated sediments dominated the mesophotic depths (Figure 44). With two drops showing an isolated patch of macroalgae and sessile invertebrates in the north of the NPZ (Figure 43). No example images have been provided by DEW at this time.

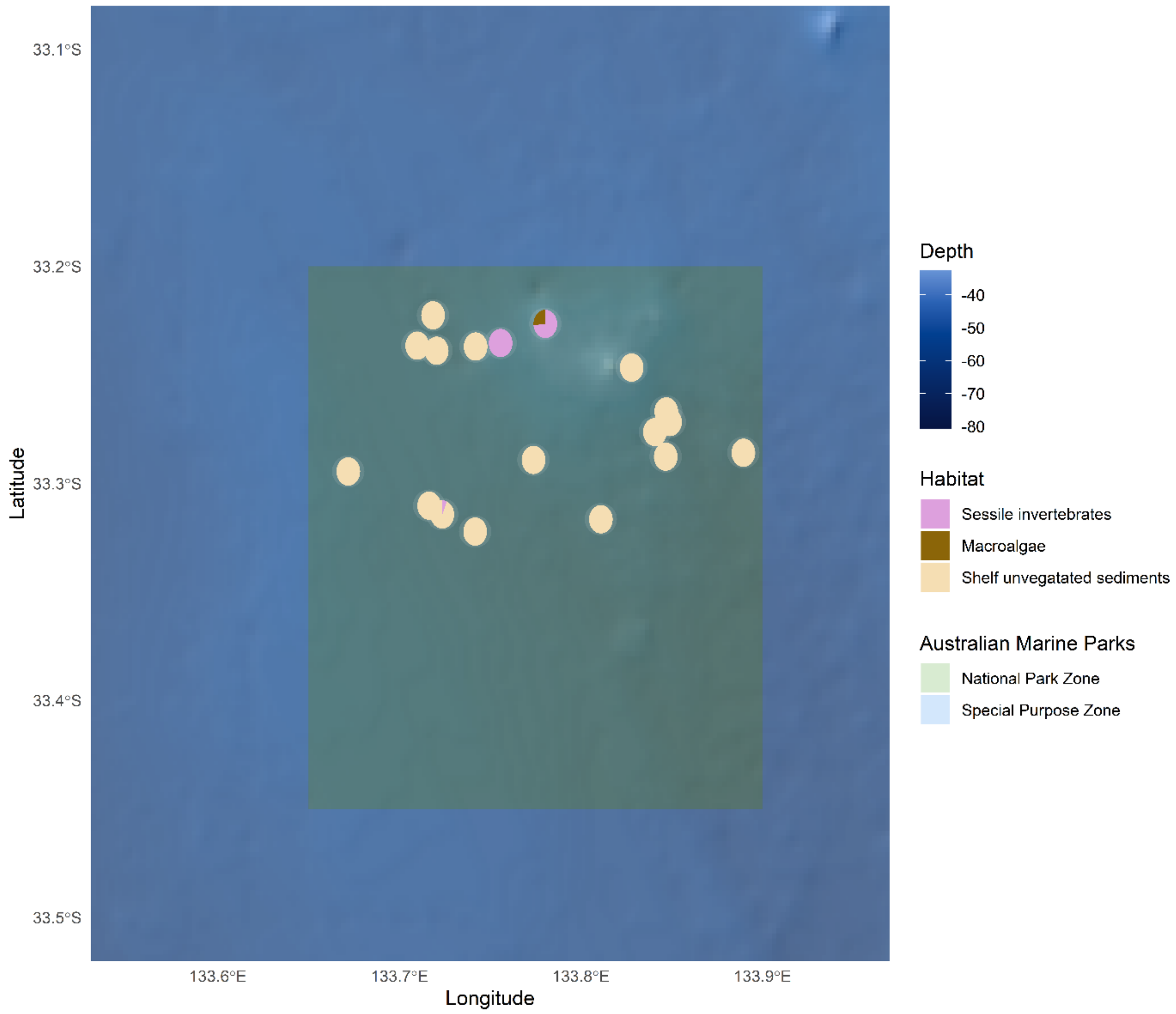

Figure 43. Spatial pie charts of habitat classification for deployments on Wirangu and Nawu Sea Country (Western Eyre Marine Park). Dynamic link: https://seamapaustralia.org/map/#b45e0ada-597c-4fd5-b4fb-cb1ed6a5f9a2.

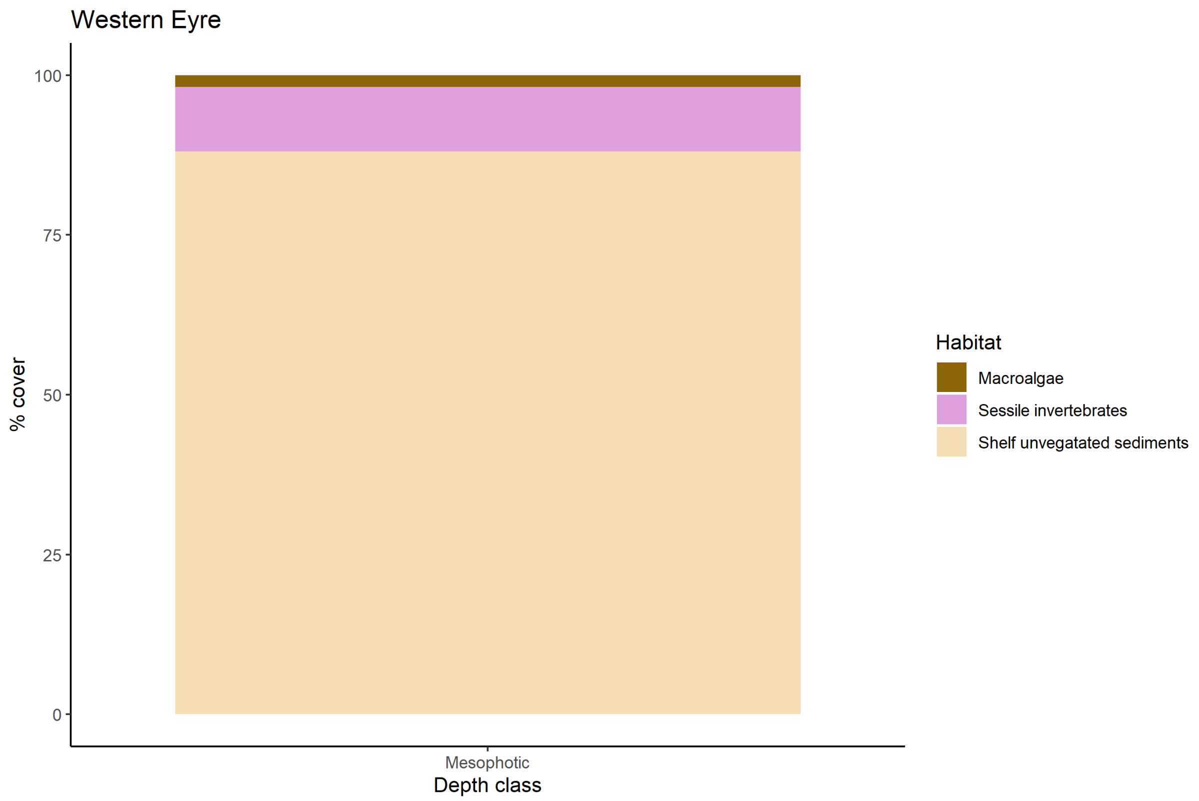

Figure 44. Percent cover of each habitat classification observed within each depth class on Wirangu and Nawu Sea Country (Western Eyre Marine Park). Depth class is: Mesophotic (30-70 m).

4.1.9 *Ngarrindjeri Sea Country* - Western Kangaroo Island Marine Park

A total of 15 stereo-BRUV drops were collated from Department for Environment and Water (DEW) in and around the Western Kangaroo Island MP, with coverage in NPZ (Figure 45). These drops showed equal coverage of Shelf Unvegetated Sediments and Sessile Invertebrates in the mesophotic depths (Figure 46). No example images have been provided by DEW at this time.

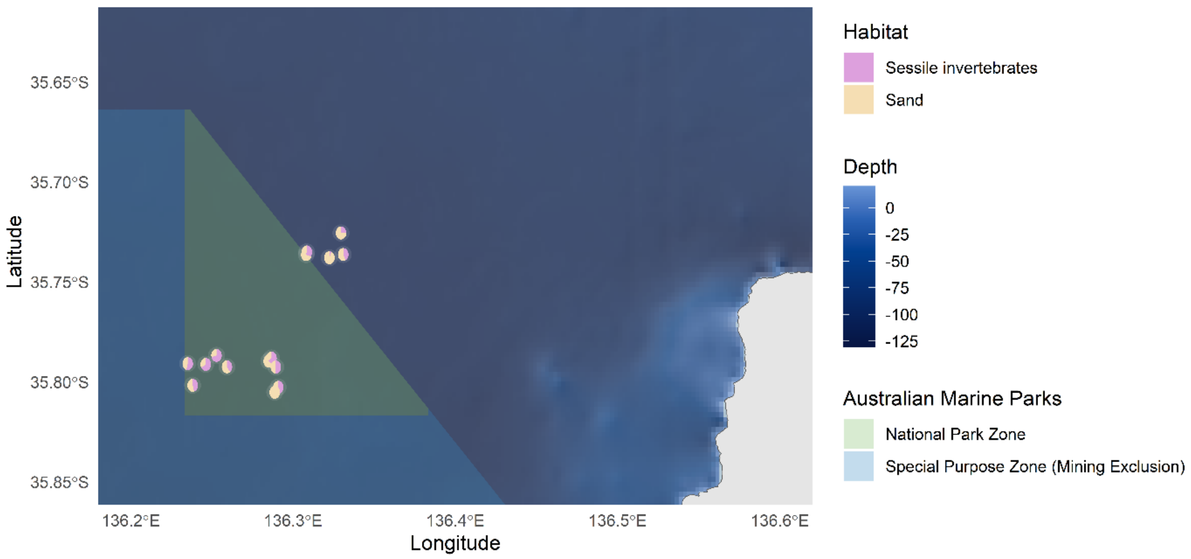

Figure 45. Spatial pie charts of habitat classification for deployments on Ngarrindjeri Sea Country (Western Kangaroo Marine Park). Dynamic link: https://seamapaustralia.org/map/#23696f52-c40b-4c78-9353-829f1db898c0.

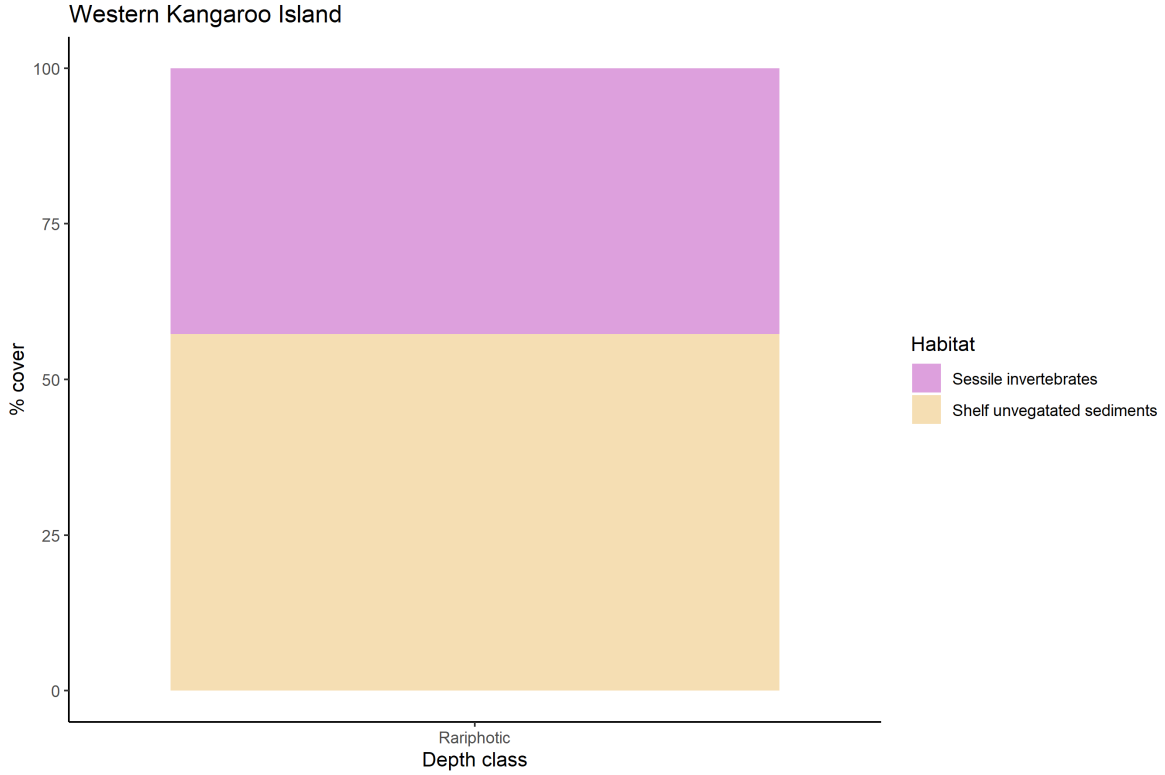

Figure 46. Percent cover of each habitat classification observed within each depth class on Ngarrindjeri Sea Country (Western Kangaroo Island Marine Park). Depth class is: Rariphotic (70-200 m).

4.1.10 *Ngarrindjeri Sea Country* - Murray Marine Park

A total of 165 BOSS drops were collected across the Murray MP, with coverage in the southern region of the MUZ (Figure 47). These drops showed that both the mesophotic and rariphotic zones were dominated by shelf unvegetated sediments (Figure 48).

Is should be noted that during the survey (~6 months after the 2022-23 Murray river floods), we found that the shallower areas of the MP (depths shallower than 50m) were generally not accessible for surveying due to high turbidity levels, likely associated with remaining riverine sediment resuspension (Figure 47; Figure 49). However, the limited successful drops in this shallow region revealed predominantly sediment habitats with occasional low-profile reefs that supported beds of red macroalgae (Figure 50).

The mid shelf region of the MP appears to be primarily characterised by fine- and coarse-rippled sediment (Figure 51). Additionally, occasional pavement reefs were observed (Figure 52), indicating the presence of diverse benthic structures.

Notably, large course-rippled features (>20cm in height) were commonly observed (Figure 53). These "mega-ripples" seem to be stable enough to support a diverse assemblage of sessile invertebrates. The dominant species in this habitat were the hard Bryozoan *Adeona grisea* (Figure A47, bottom image) and sponges.

Deeper along the shelf break, particularly in the western region of the MP, limited reef structures were observed. These structures appeared to support white *Nephtheidae* octocorals (Figure 54), black corals, and sea whips (Figure 55).

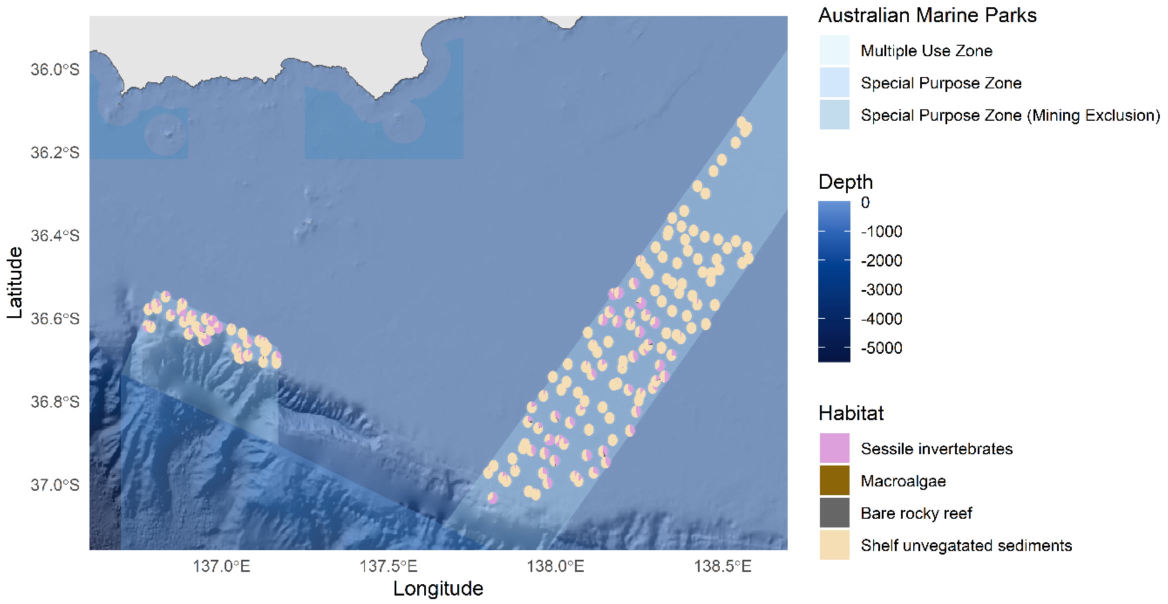

Figure 47. Spatial pie charts of habitat classification for deployments on Ngarrindjeri Sea Country (Murray Marine Park). Dynamic link: https://seamapaustralia.org/map/#d00666fd-ce00-4b99-aec3-a673771b202f.

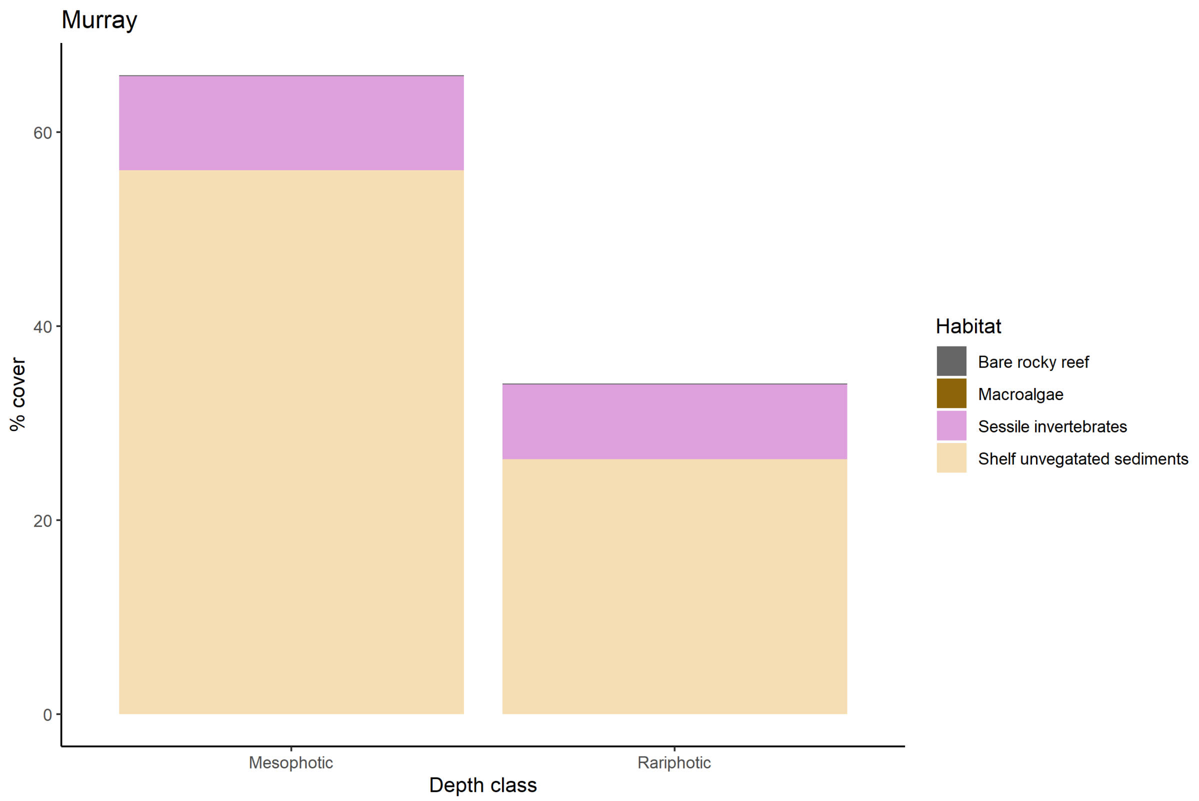

Figure 48. Percent cover of each habitat classification observed within each depth class on Ngarrindjeri Sea Country (Murray Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

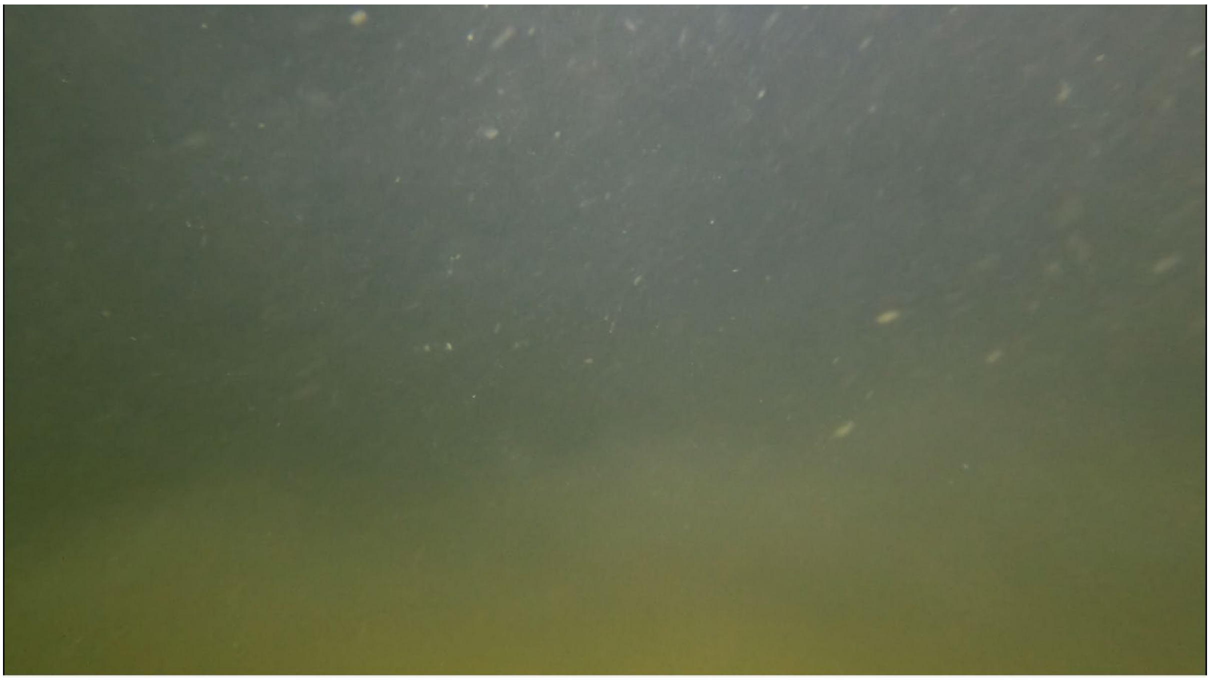

Figure 49. Example of turbidity plume found in the shallow northern extent of the AMP (<50 m).


Figure 50. Example of the mesophotic reefs (~50 m depth) that support short red macroalgae.

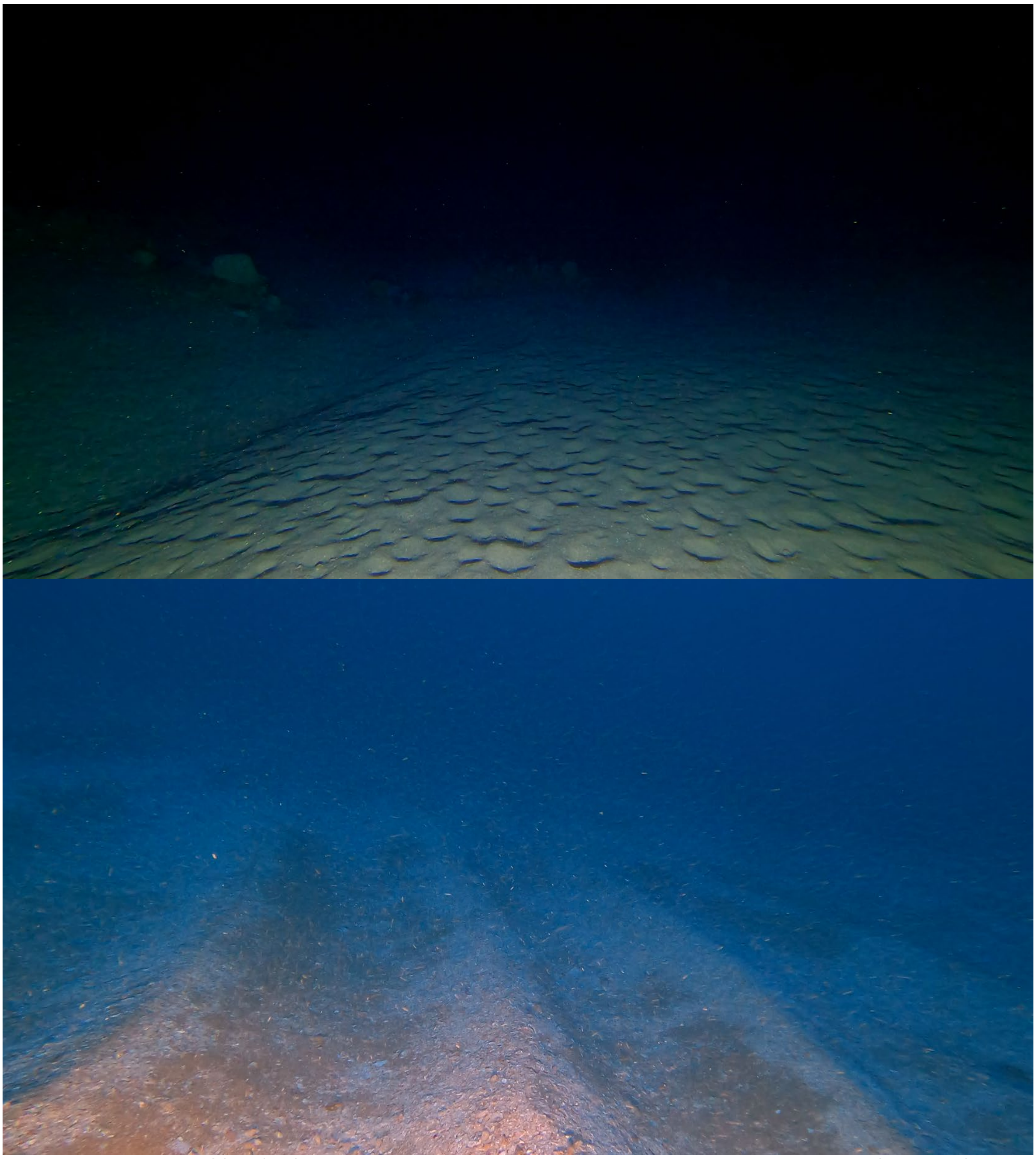

Figure 51. Examples of fine (top) and coarse rippled sediments that appear to dominate the shelf region of the Murray AMP.

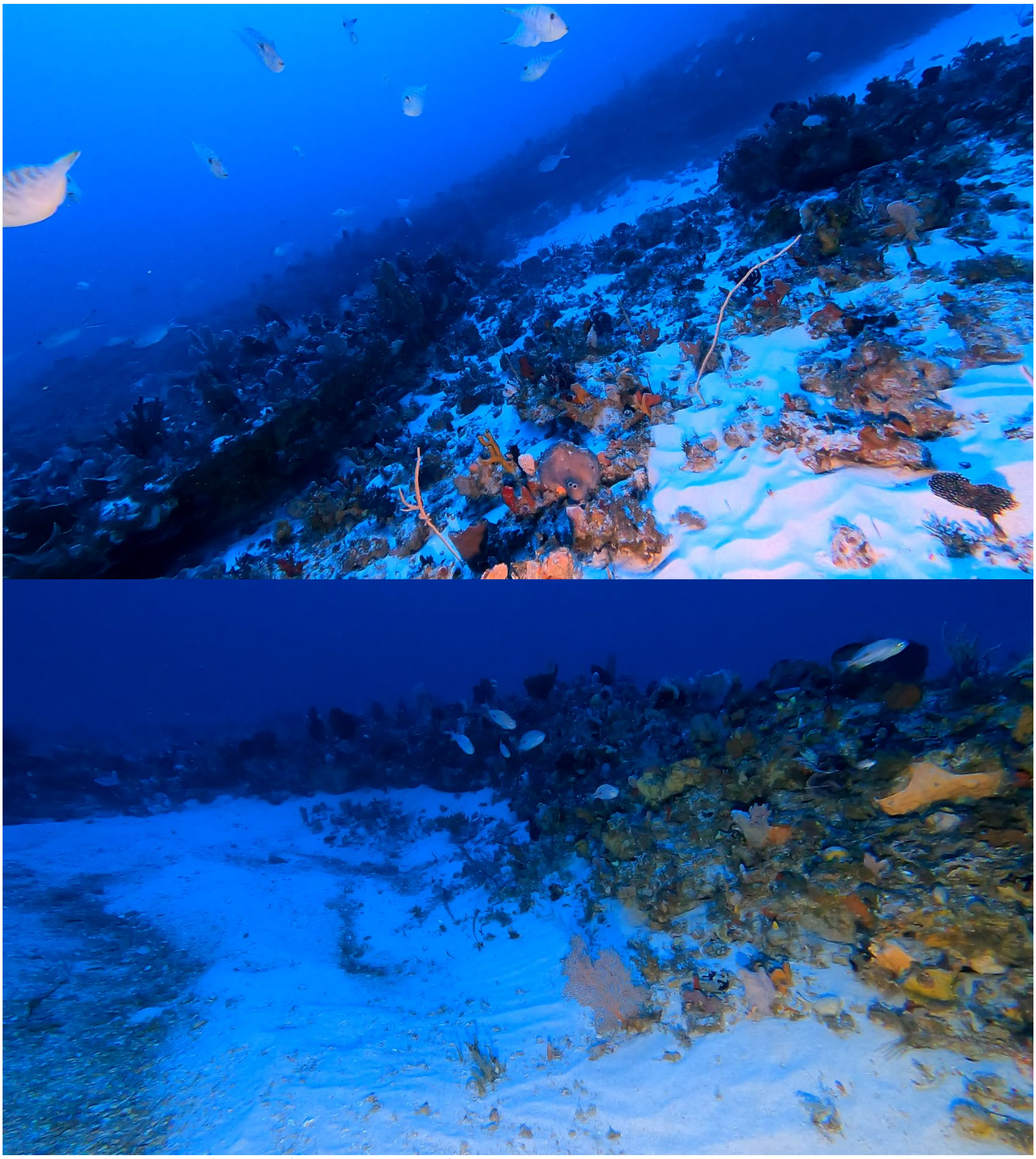

Figure 52. Examples of low-profile pavement reefs that support complex sessile invertebrate assemblages dominated sponges, octocoral and bryozoa.

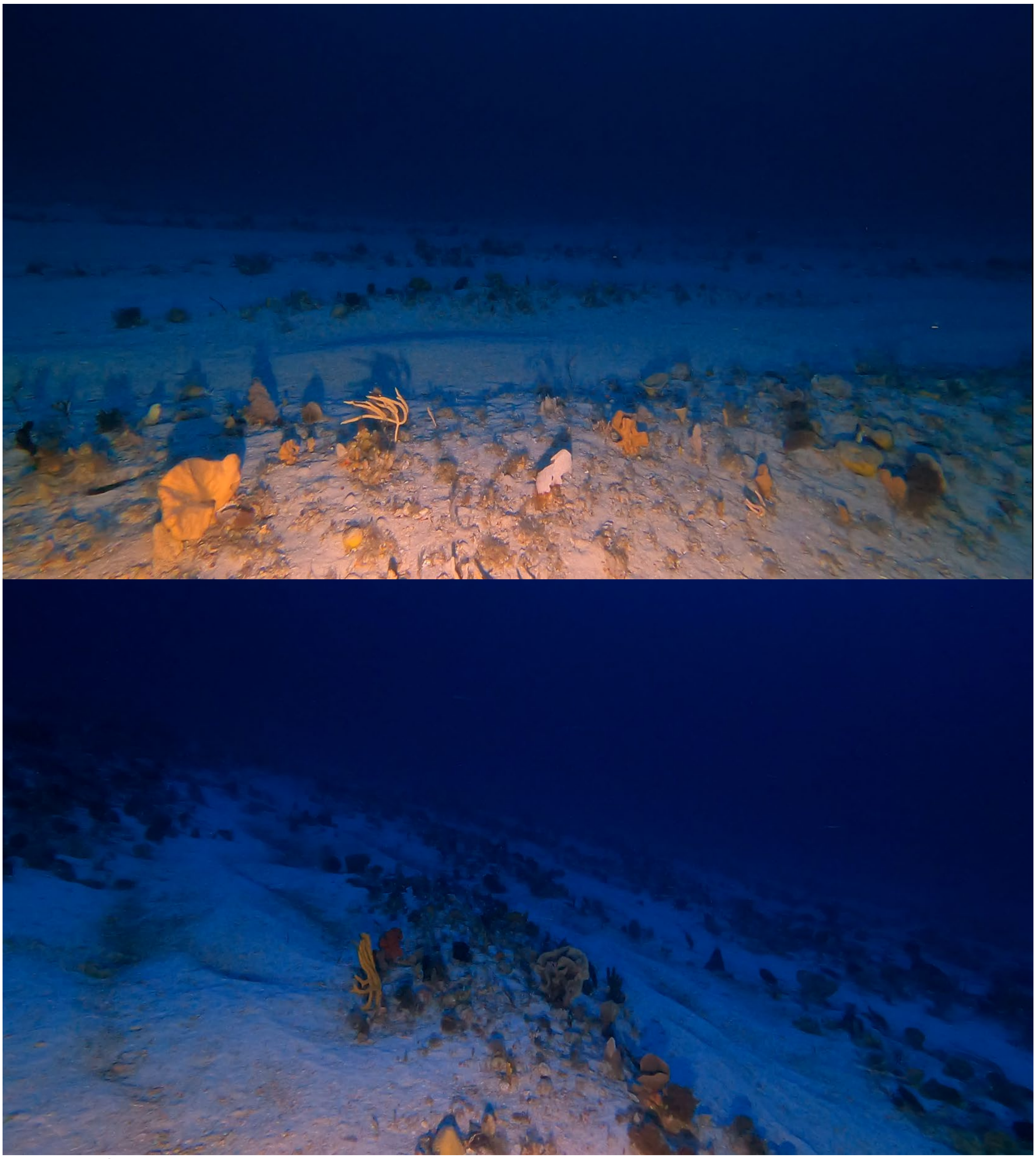

Figure 53. Coarse sediment ripples known as "mega-ripples" that appear to be stable enough to support sessile invertebrate assemblages such as *Adeona grisea* (cauliflower looking individual in centre of bottom image) and sponges.

Figure 54. Examples of soft *Nephtheidae* corals that appear a common feature in the western region of the Murray AMP.

Figure 55. Examples of black coral (white individual in top image) and sea whips (bottom image) that appeared in the western region of the Murray AMP.

4.1.11 *Gadubanud Sea Country* - Apollo Marine Park

A total of 50 stereo-BRUV drops were collated from Deakin University with coverage in the north-west of the MUZ (Figure 56). These drops showed that the northern region is dominated by a high coverage of sessile invertebrates in both mesophotic and rariphotic depths (Figure 56).

It should be noted that it is extremely unlikely to have macroalgae and such high coverage of sessile invertebrates at these depths in this region. Initial checks of imagery suggest this macroalgae represents a misidentification of sessile invertebrates, likely foliose bryozoans (Figure 58). Furthermore, while there is sessile invertebrates present (Figure 59) their cover is likely an overestimate (Figure 60). Data has been corrected following discussions with data custodian.

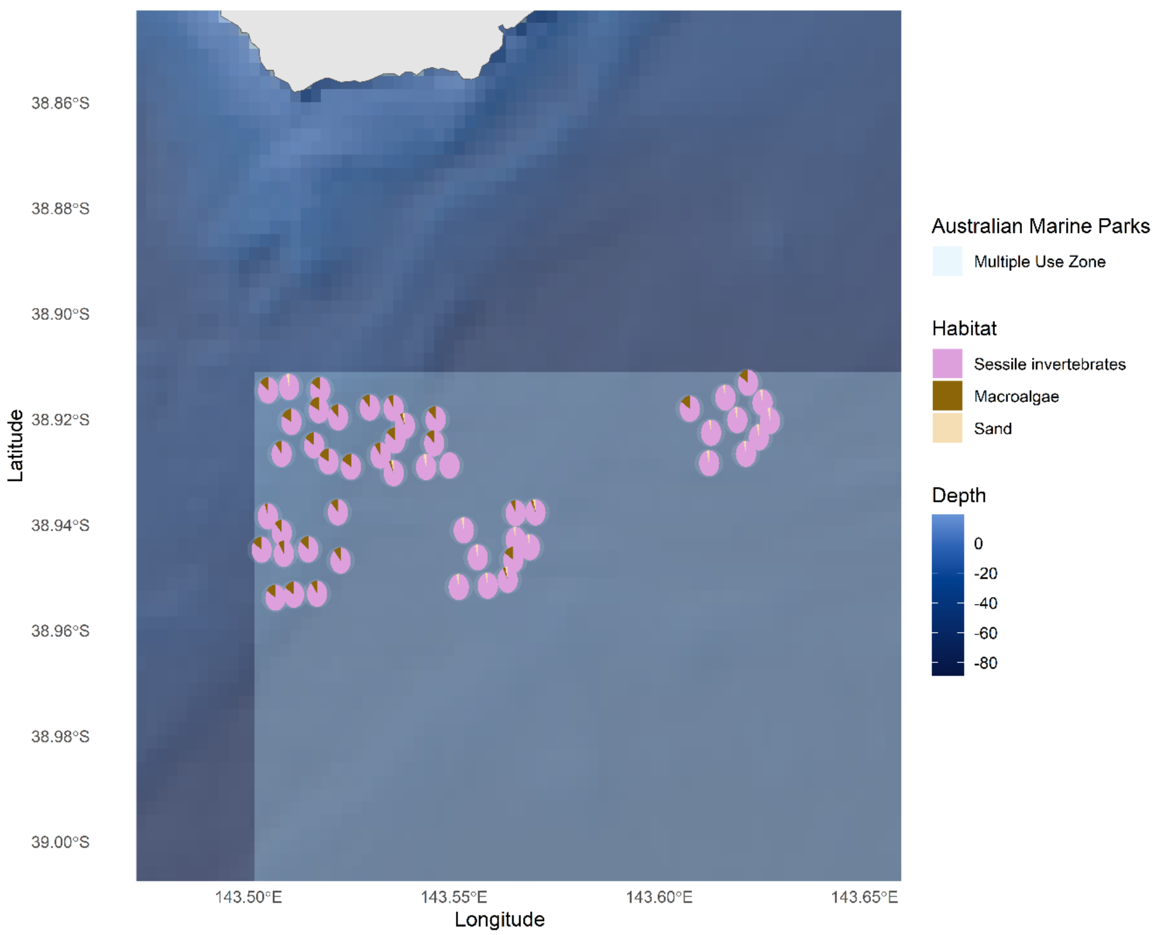

Figure 56. Spatial pie charts of habitat classification for deployments on Gadubanud Sea Country (Apollo Marine Park). Dynamic link: https://seamapaustralia.org/map/#ea18cf21-bc05-440b-9443-61a9e69c23e2.

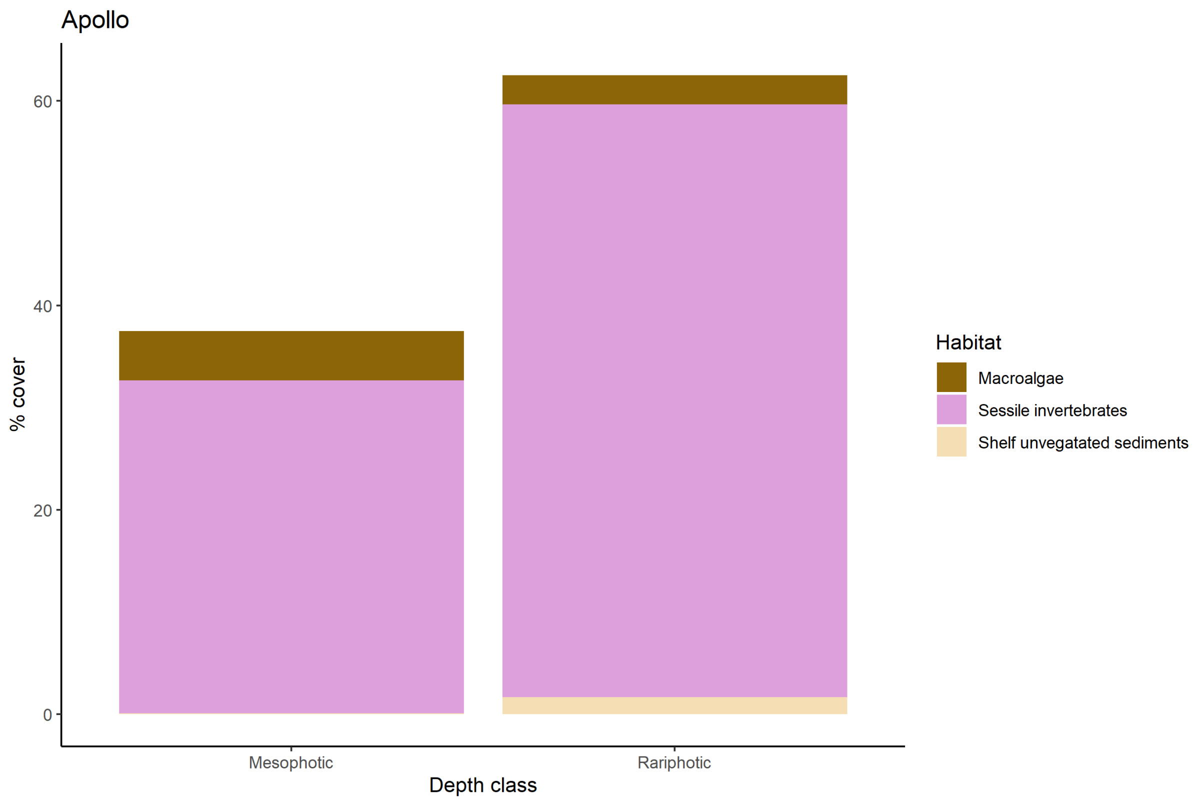

Figure 57. Percent cover of each habitat classification observed within each depth class on Gadubanud Sea Country (Apollo Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

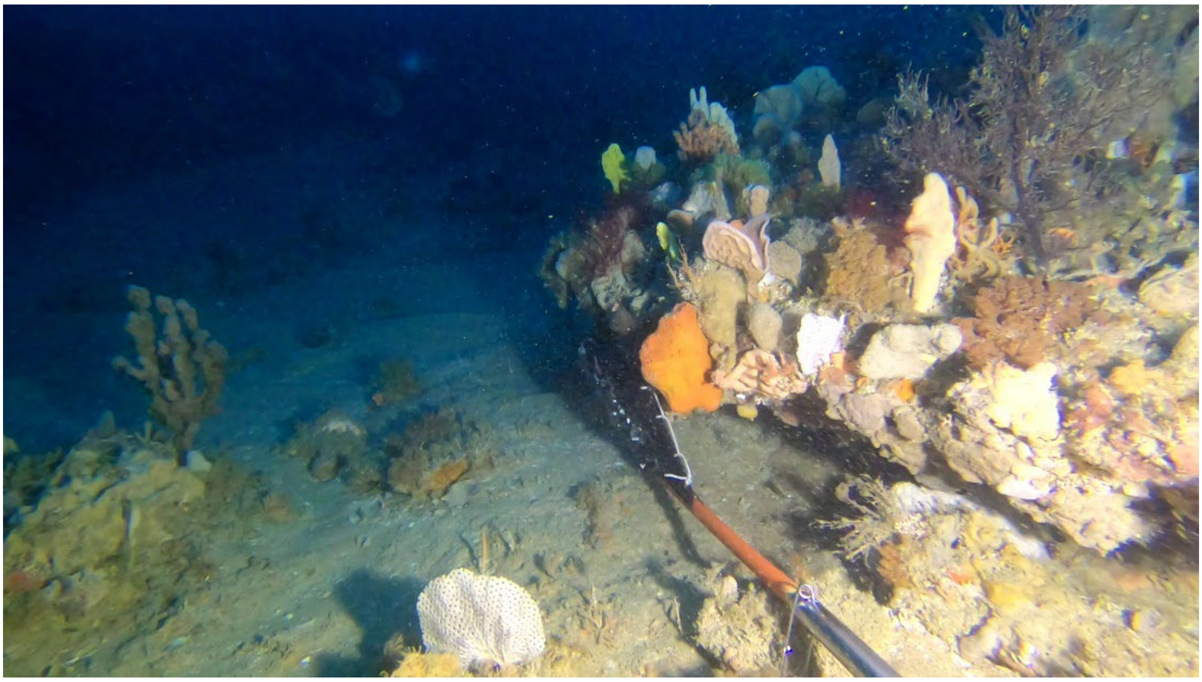

Figure 58. Examples of bryozoans and red hydroids (above to the right of bait bag) that were misidentified macroalgae.

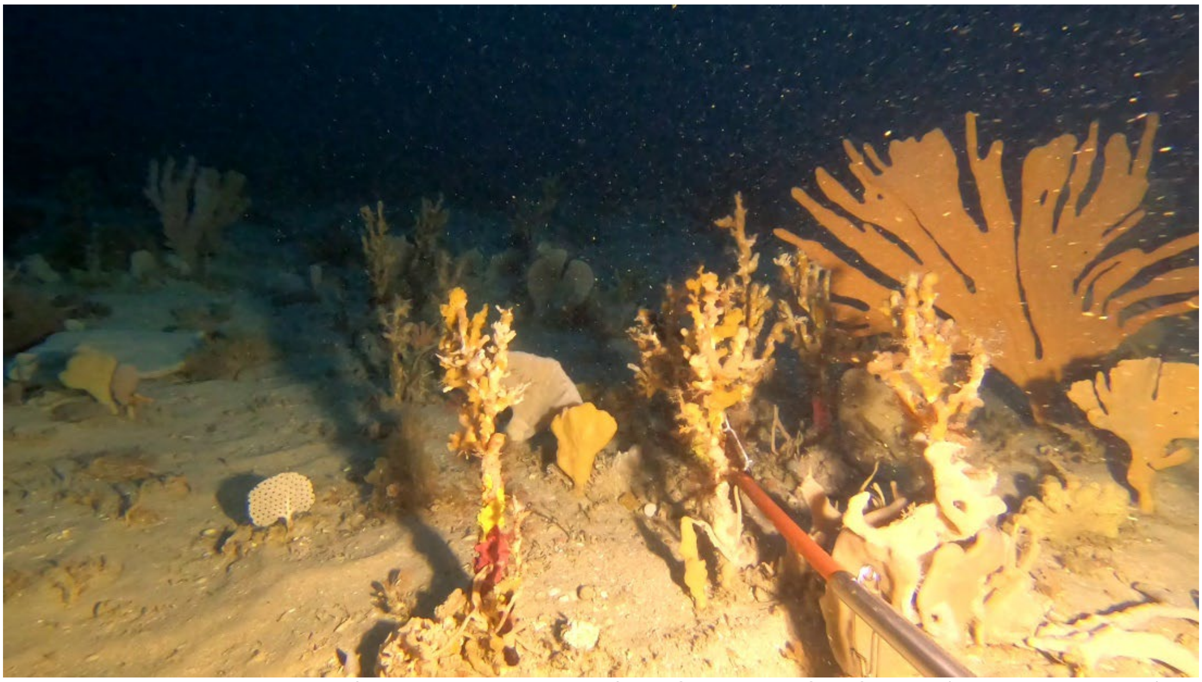
Figure 59. Tall sponges growing from sand inundated reefs on Gadubanud Sea Country (Apollo Marine Park).

Figure 60. Fine (top) and course (bottom) rippled sand of Shelf Unvegetated Sediments on Gadubanud Sea Country (Apollo Marine Park).

4.1.13 Zeehan Marine Park

A total of 300 BOSS drops were collated from IMAS in the Zeehan MP, with coverage in the MUZ (Figure 61). The MUZ consisted mainly of shelf unvegetated sediments (Figure 62, Figure 63), with small patches of outcropping and sand inundated reefs that support diverse sessile invertebrate assemblages (Figure 64).

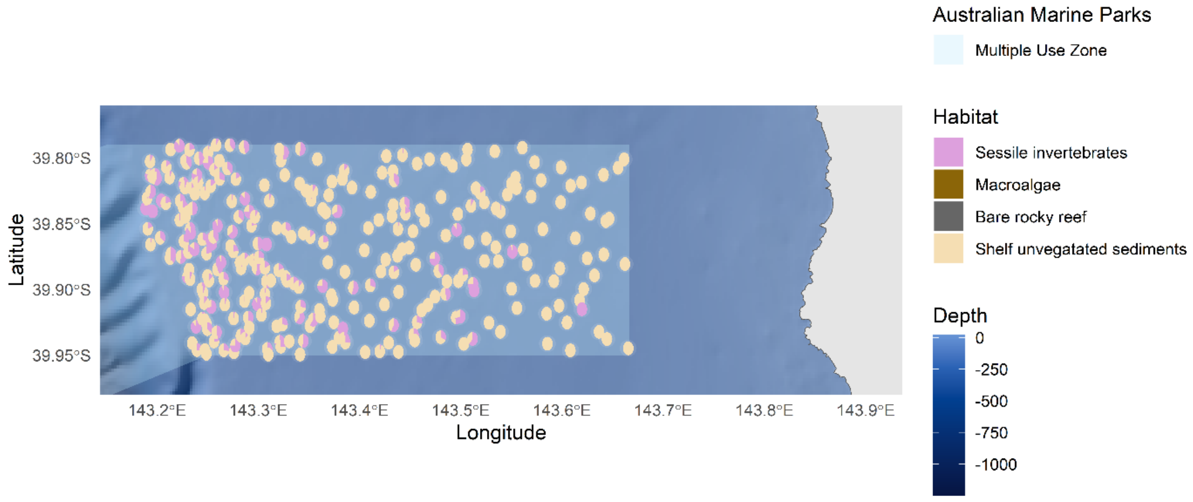

Figure 61. Spatial pie charts of habitat classification for deployments in Zeehan Marine Park. Dynamic link: https://seamapaustralia.org/map/#2470fd7f-5d9b-4aee-aada-00b9cf3d054c.

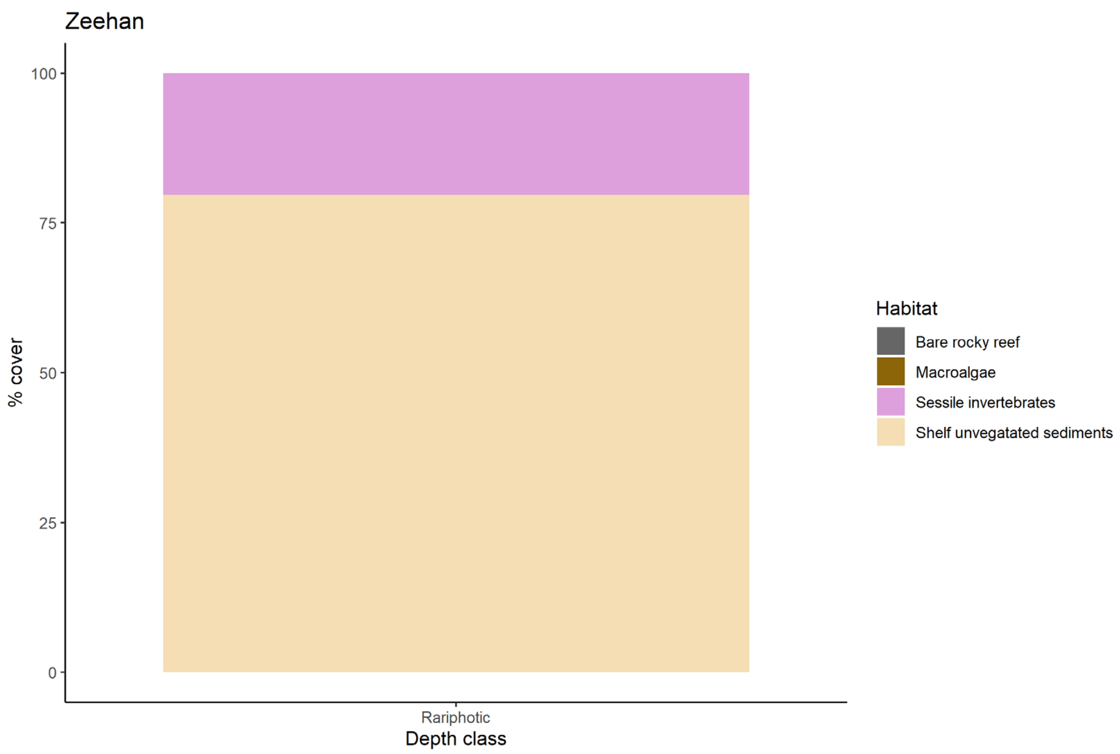

Figure 62. Percent cover of each habitat classification observed within each depth class in Zeehan Marine Park. Depth classes are: Rariphotic (70-200 m).

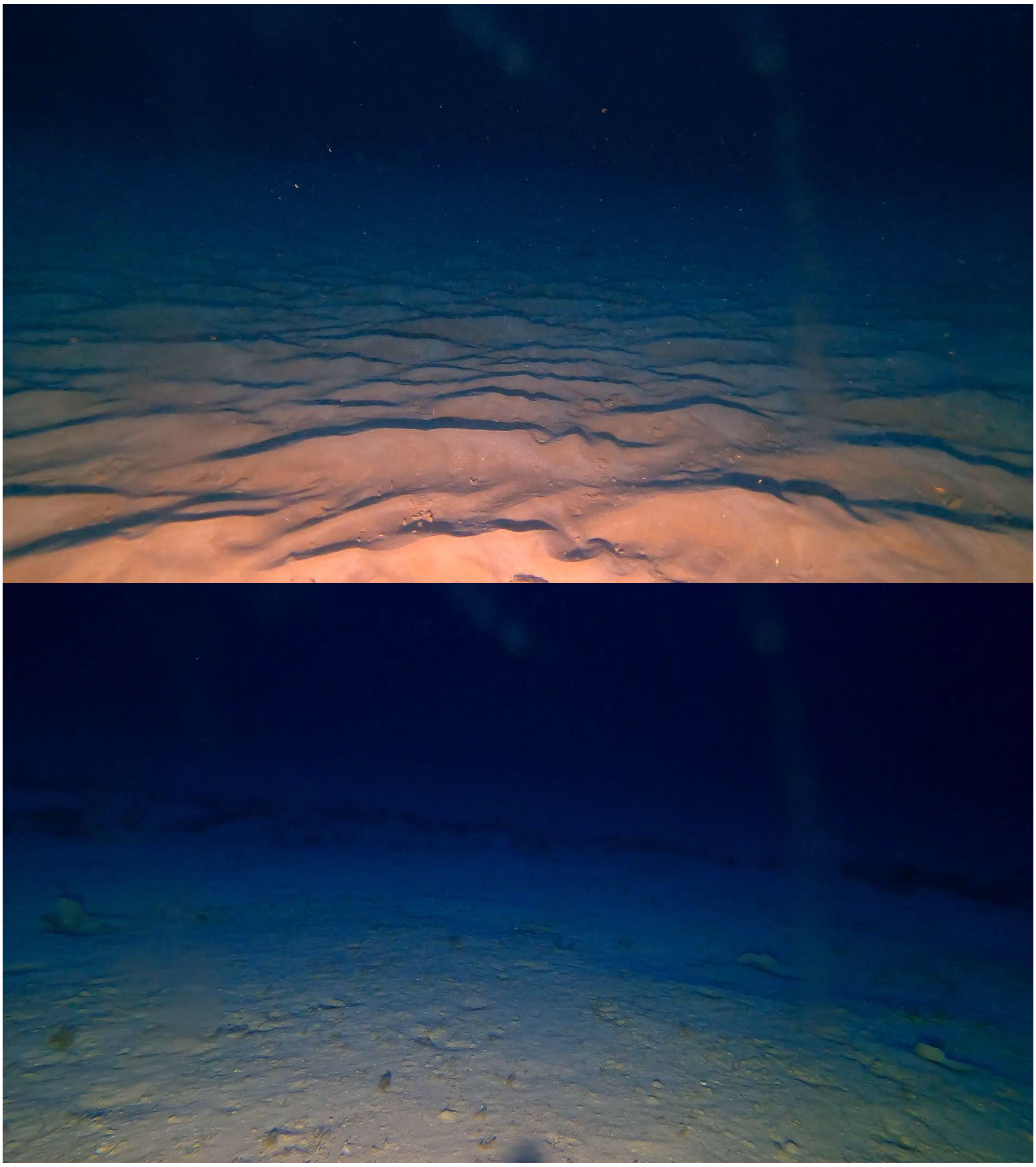

Figure 63. Coarse (top) and fine (bottom) rippled sand of Shelf Unvegetated Sediments in the Zeehan Marine Park.

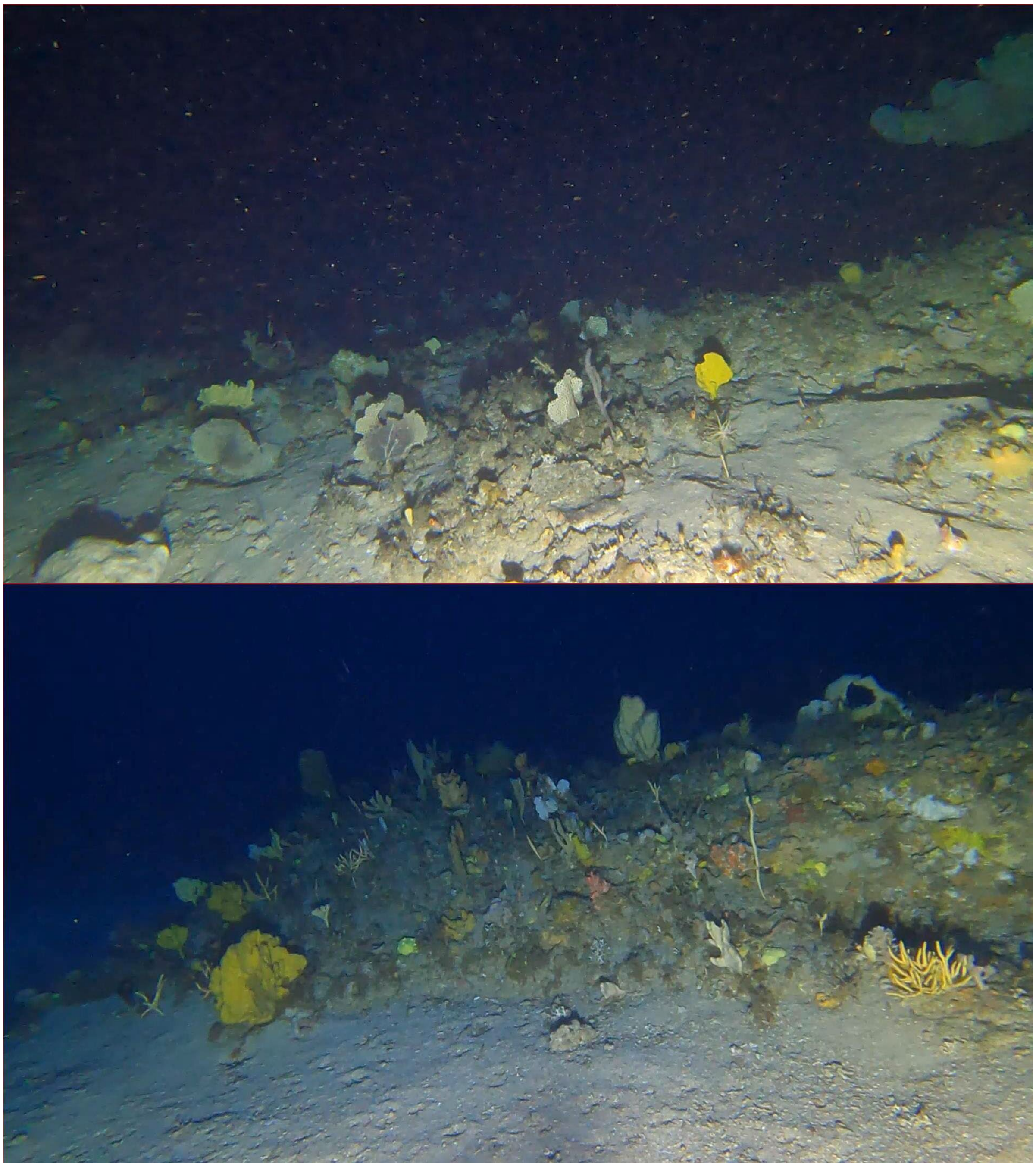

Figure 64. Mixed sessile invertebrates growing on low-profile reefs in the Zeehan Marine Park.

4.1.14 *Peerapper Sea Country* - Franklin Marine Park

A total of 281 BOSS drops were collated from IMAS in the Franklin MP, with coverage in the MUZ (Figure 65). The mid to southern regions of the MUZ consisted mainly of shelf unvegetated sediments (Figure 66, Figure 67), with a substantial mesophotic reef along the north boundary that supports Golden kelp (*Ecklonia radiata;* Figure 68) and diverse sessile invertebrate assemblages (Figure 66; Figure 69). Shelf unvegetated sediments dominated the rariphotic zone, with lower profile reef features along the south-eastern region of the MP (Figure 70).

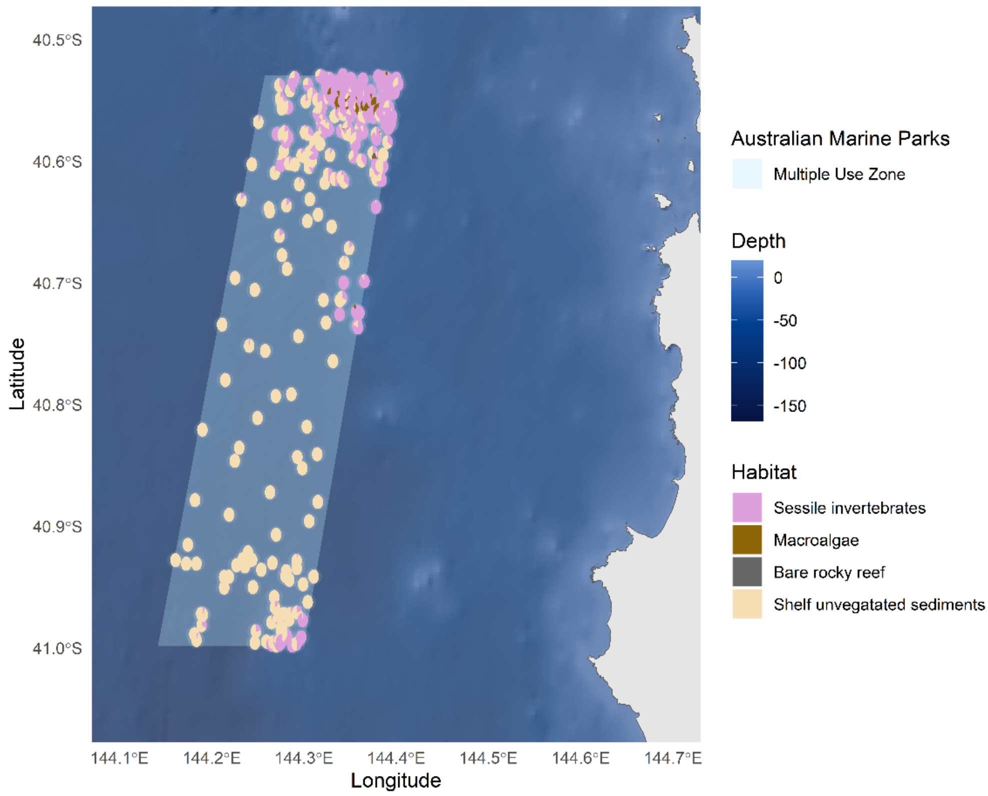

Figure 65. Spatial pie charts of habitat classification for deployments on Peerapper Sea Country (Franklin Marine Park). Dynamic link: https://seamapaustralia.org/map/#ccd15274-7035-4db4-bd8d-dab61f551cf9.

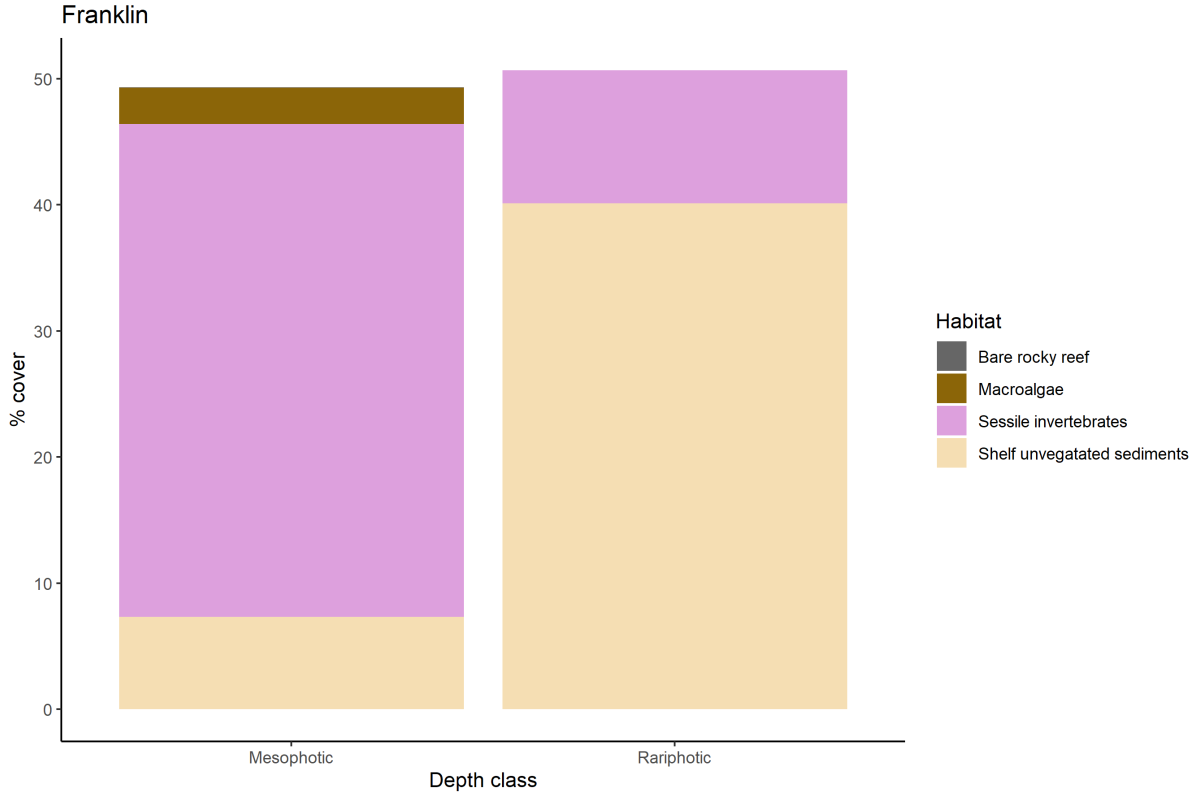

Figure 66. Percent cover of each habitat classification observed within each depth class on Peerapper Sea Country (Franklin Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

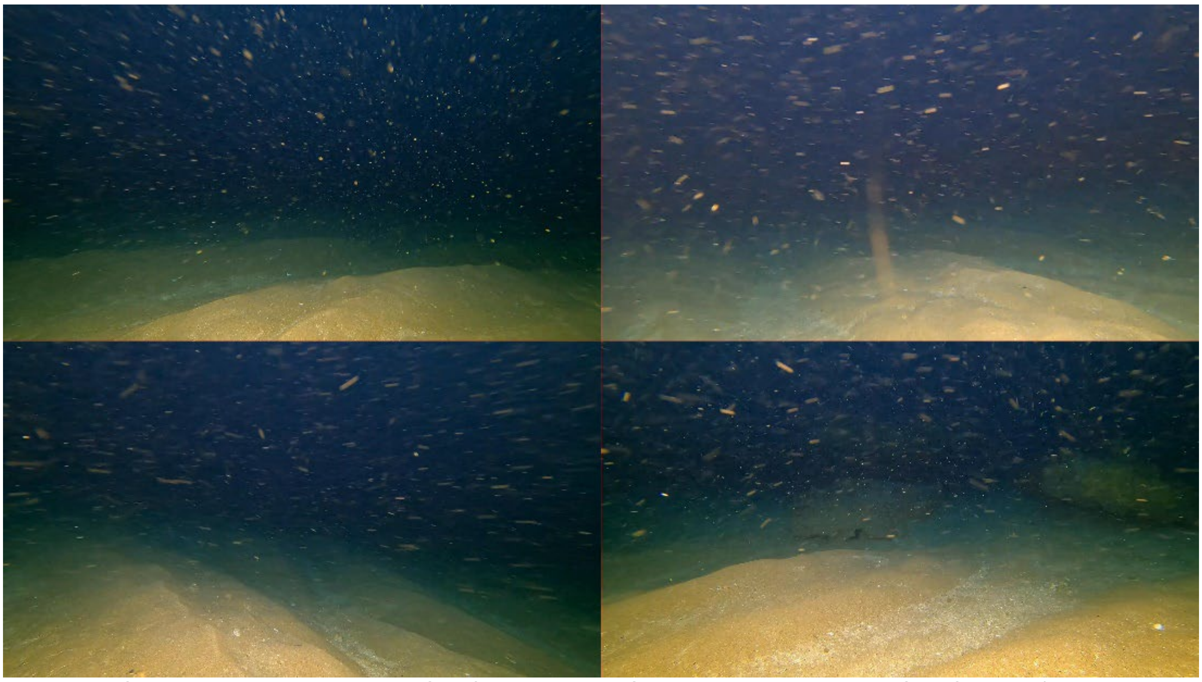

Figure 67. Coarse rippled sediments in Shelf Unvegetated Sediments on Peerapper Sea Country (Franklin Marine Park).

Figure 68. Golden kelp (*Ecklonia radiata*) growing on high-profile mesophotic reefs on Peerapper Sea Country (Franklin Marine Park).

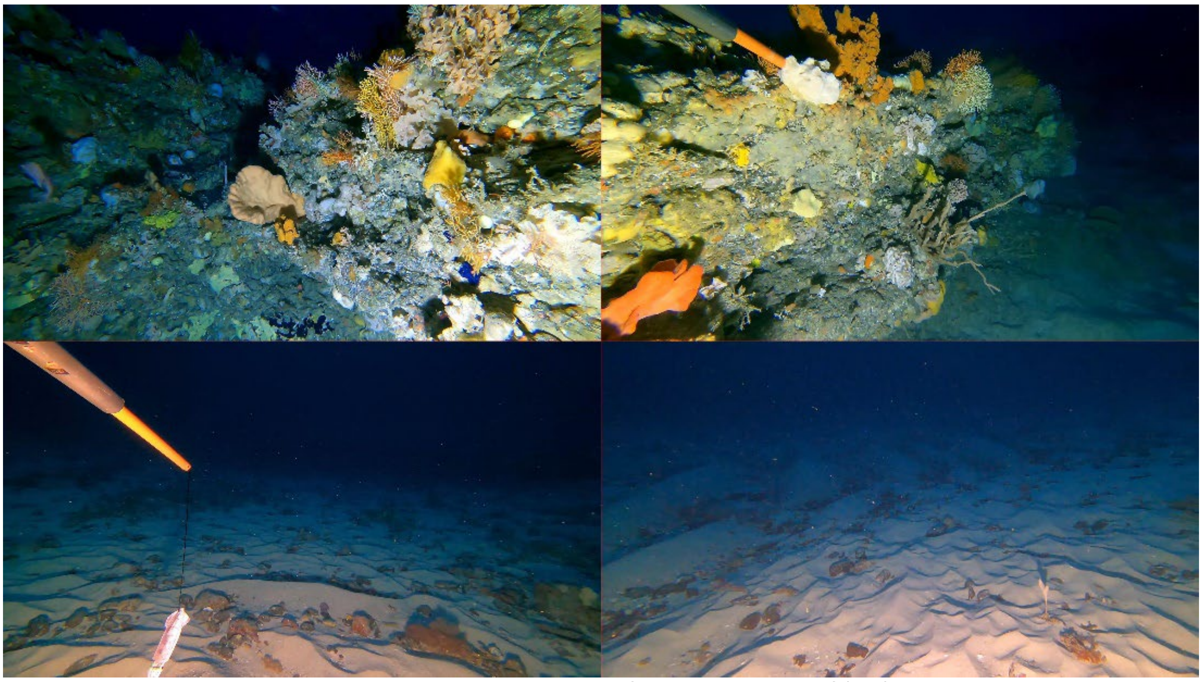

Figure 69. Mixed sessile invertebrates growing on high-profile mesophotic reef (top) and coarse rippled sediments (bottom) on Peerapper Sea Country (Franklin Marine Park).

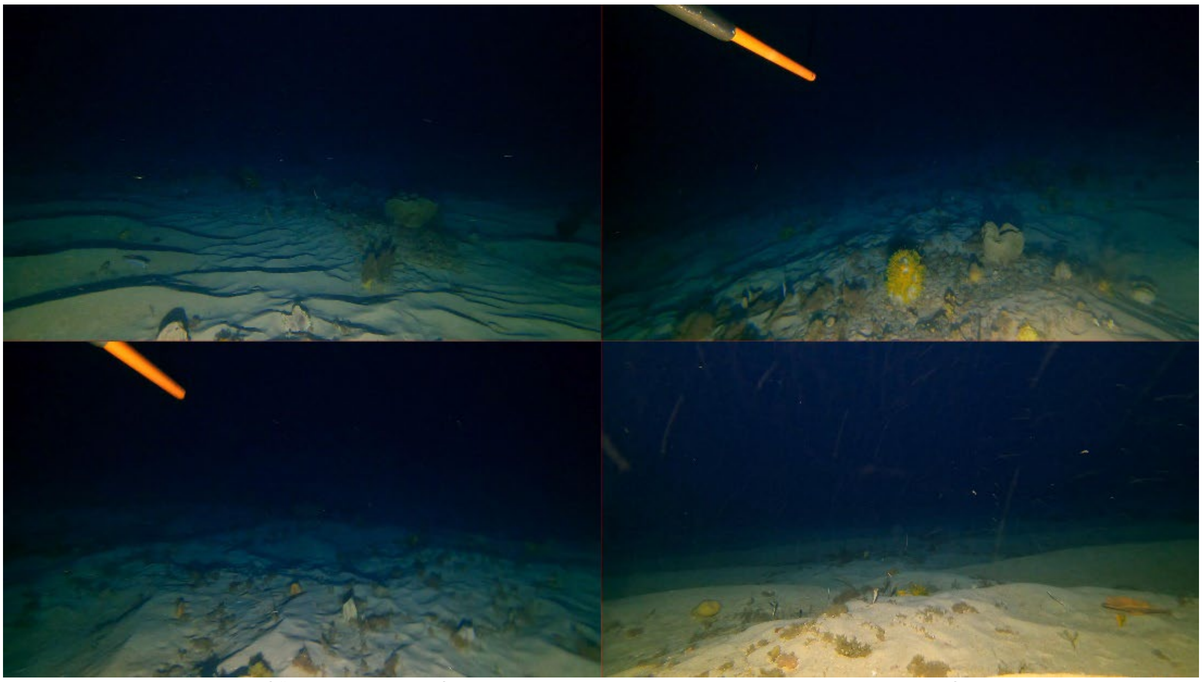

Figure 70. An example of “Functional reef” with mixed sessile invertebrates growing out of sand in the rariphotic zone on Peerapper Sea Country (Franklin Marine Park).

4.1.15 *Toogee Sea Country* - Tasman Fracture Marine Park

A total of 111 stereo-BRUV drops were collated from IMAS in and around the Tasman Fracture MP, with coverage in the NPZ, MUZ and adjacent (Figure 71). Both the MUZ and NPZ consisted of a mixture of shelf unvegetated sediments and sessile invertebrates attached to high-profile rariphotic reefs (Figure 72). Shallow and mesophotic depths only occurred outside the MP and exhibited similar assemblages. Example images of these ecosystems are provided in Figure 73 to Figure 76.

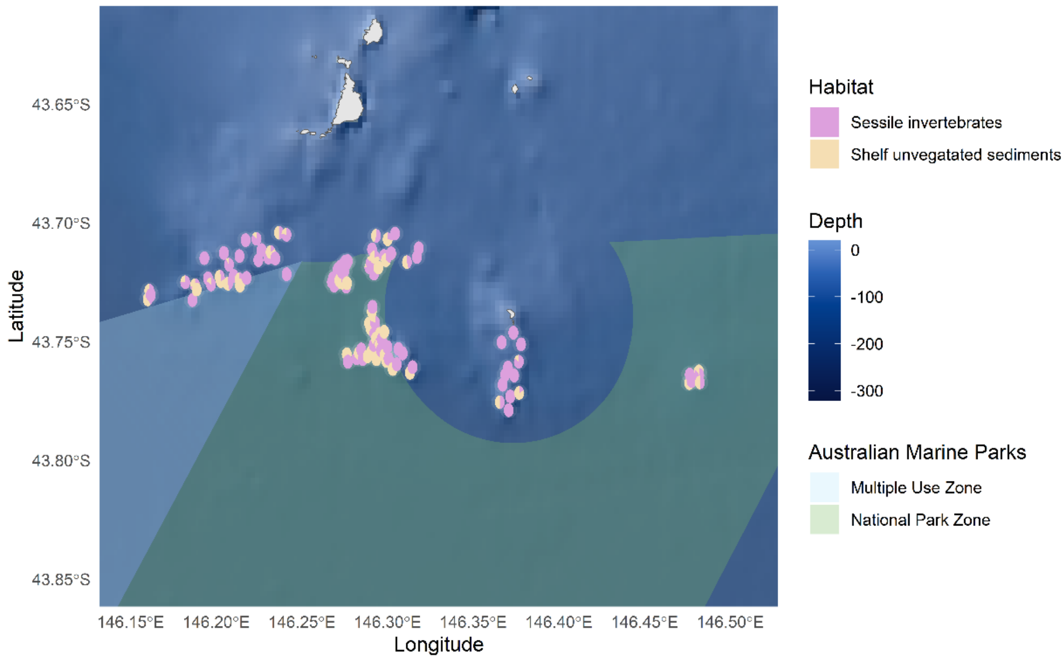

Figure 71. Spatial pie charts of habitat classification for deployments on Toogee Sea Country (Tasman Fracture Marine Park). Dynamic link: https://seamapaustralia.org/map/#2145bf31-95a5-4c42-8500-505634747ddf.

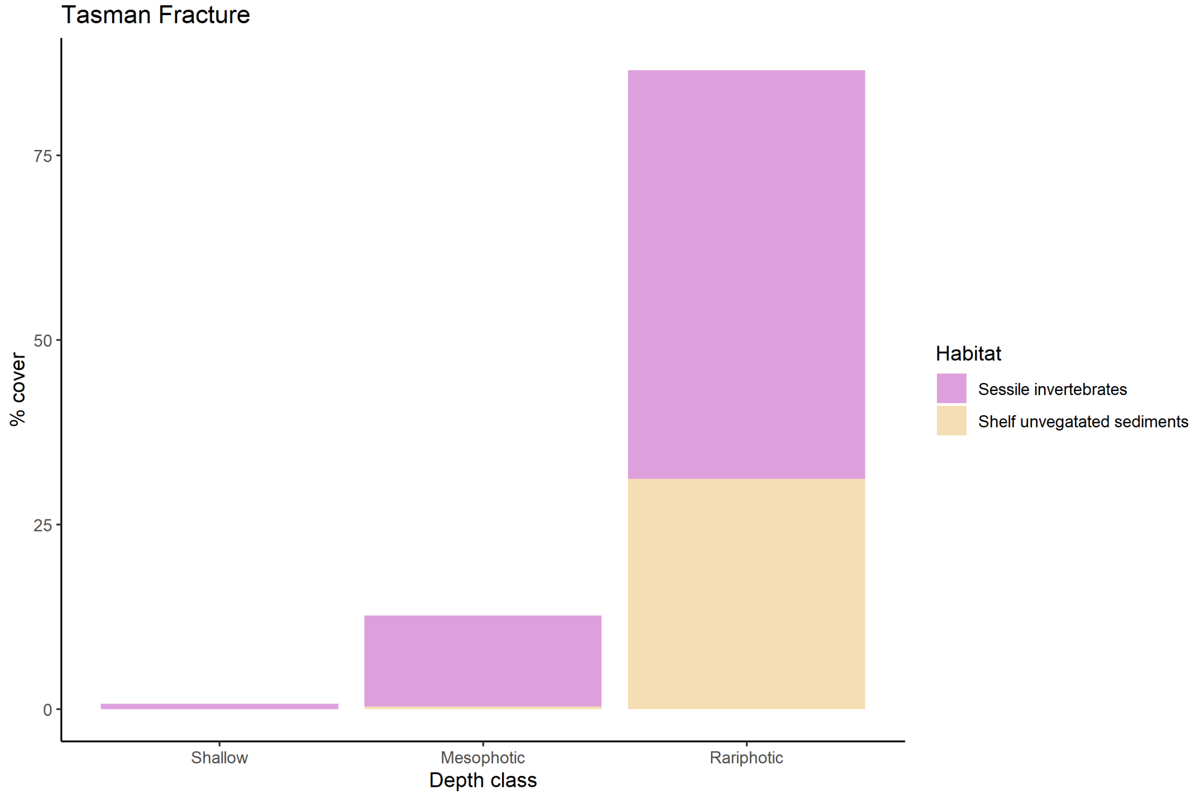

Figure 72. Percent cover of each habitat classification observed within each depth class on Toogee Sea Country (Tasman Fracture Marine Park). Depth classes are: Shallow (0-30 m), Mesophotic (30-70 m), Rariphotic (70-200 m).

Figure 73. Red *Pteronisis* like gorgonians feature frequently in imagery on Toogee Sea Country (Tasman Fracture Marine Park).

Figure 74. Diverse sessile invertebrates covering high-profile reefs on Toogee Sea Country (Tasman Fracture Marine Park).

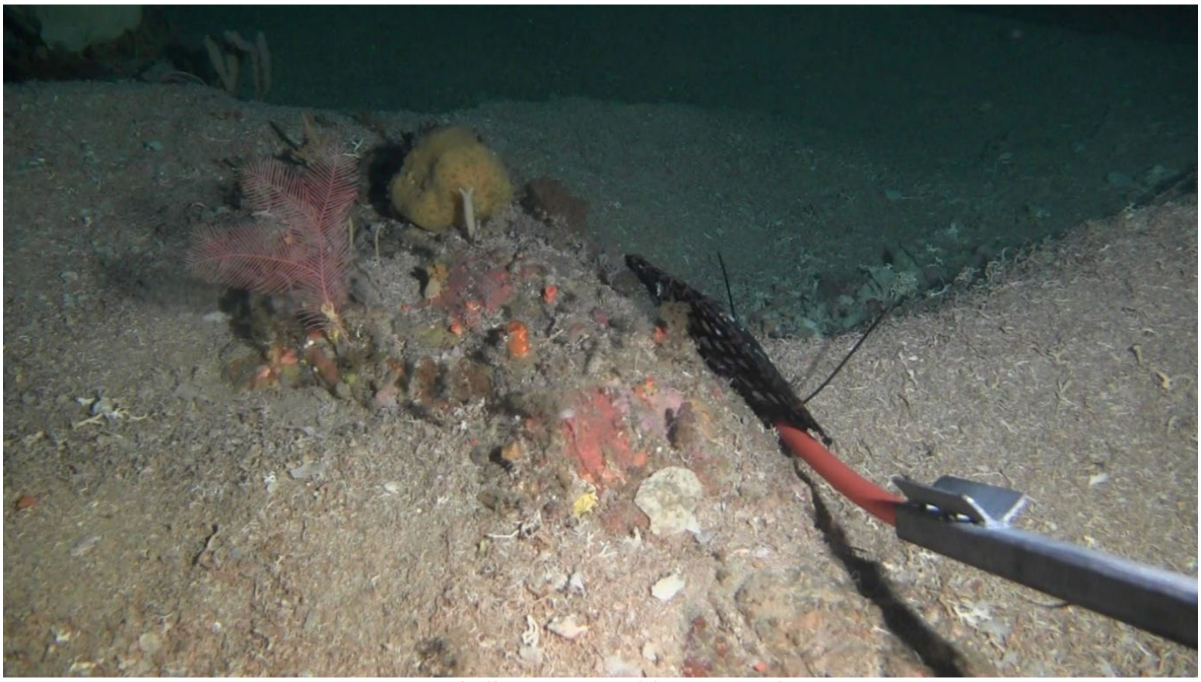

Figure 75. Isolated sessile invertebrate reefs (functional reefs) emerging from coarse rippled sediments on Toogee Sea Country (Tasman Fracture Marine Park).


Figure 76. Coarse rippled sediments on Toogee Sea Country (Tasman Fracture Marine Park).

4.1.16 *Nuenonne Sea Country* - Huon Marine Park

A total of 167 stereo-BRUV drops were collated from IMAS in the Huon MP, with coverage in the MUZ (Figure 77). The mesophotic zone was dominated by sessile invertebrates attached to high-profile reefs and included an isolated patch of Golden kelp (*Ecklonia radiata*) along the north-eastern boundary of the MP (Figure 78, Figure 82). Rariphotic depths contained equal coverages of sessile invertebrates and shelf unvegetated sediments (Figure 78). Example images of these ecosystems are provided in Figure 79 to Figure 82.

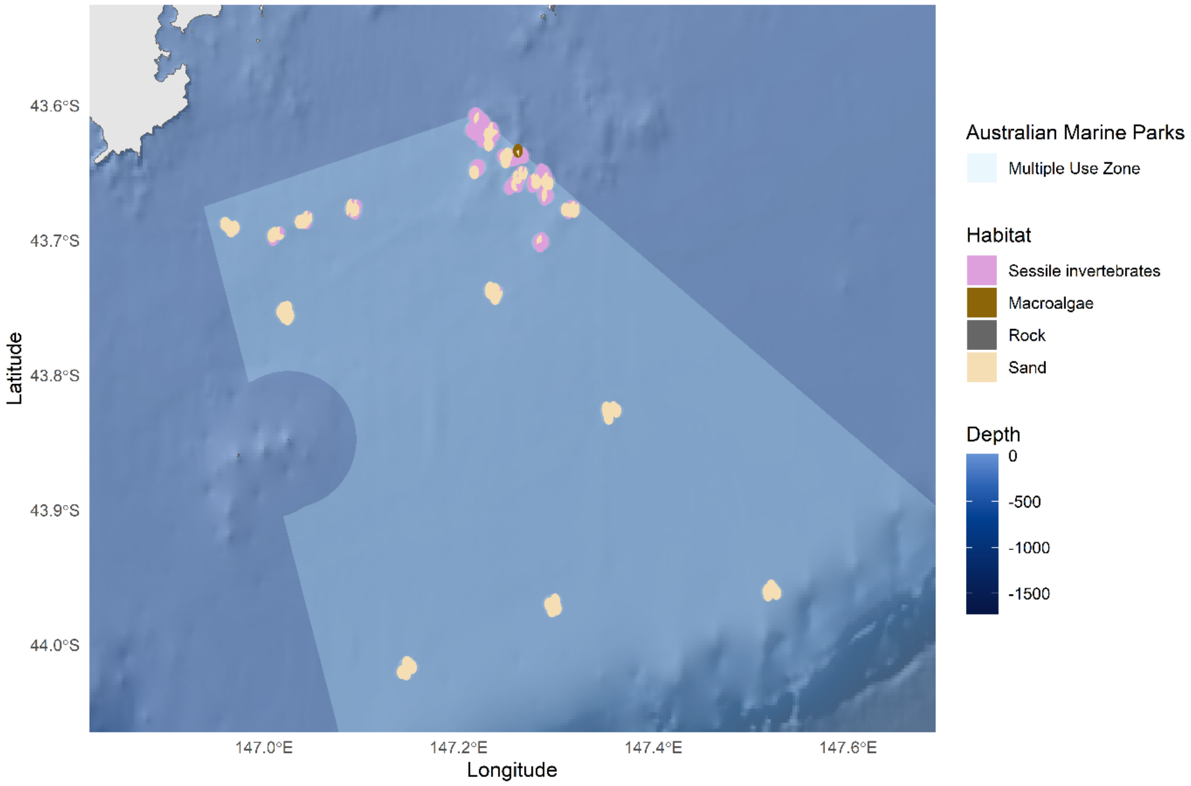

Figure 77. Spatial pie charts of habitat classification for deployments on Nuenonne Sea Country (Huon Marine Park). Dynamic link: https://seamapaustralia.org/map/#830a3254-ec2a-4aa6-8c55-96dc4e326f67.

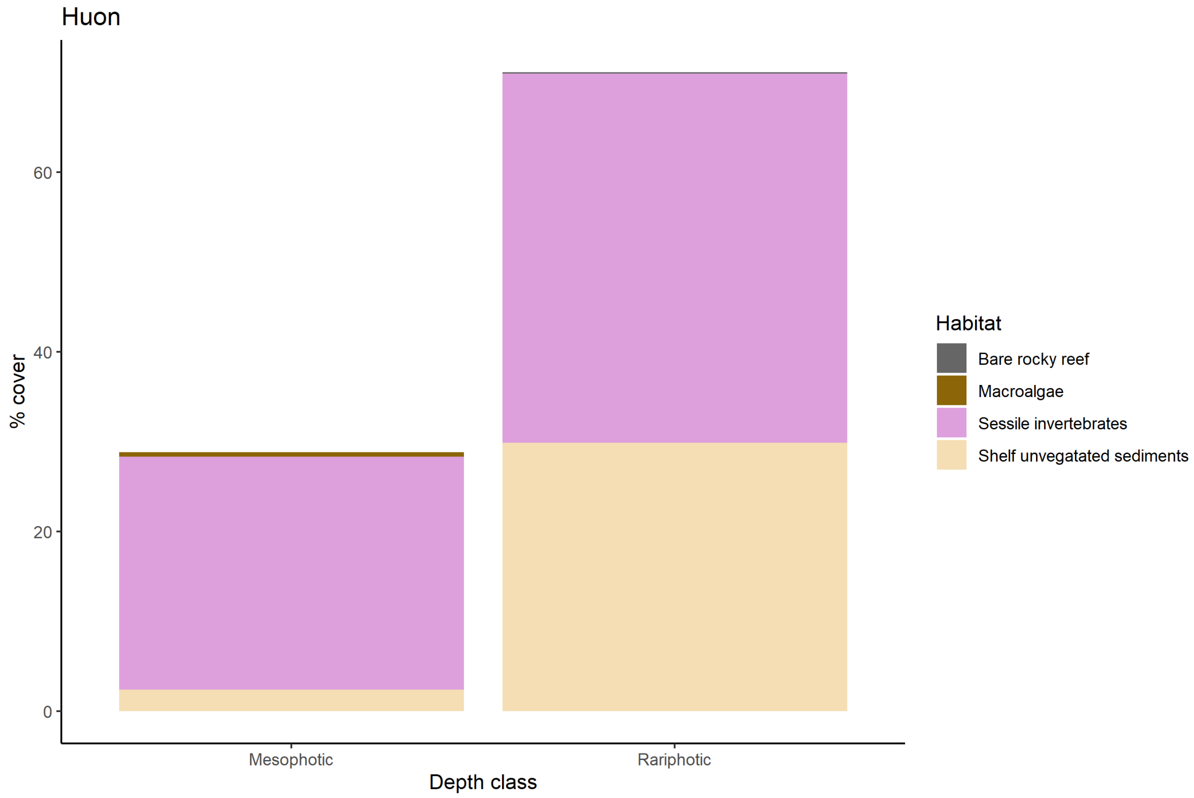

Figure 78. Percent cover of each habitat classification observed within each depth class on Nuenonne Sea Country (Huon Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

Figure 79. Diverse sessile invertebrates growing at the base of a high-profile reef structure in the mesophotic zone on Nuenonne Sea Country (Huon Marine Park).

Figure 80. Diverse sessile invertebrates growing rariphotic reef structures on Nuenonne Sea Country (Huon Marine Park).

Figure 81. Coarse rippled sediments with brittle stars on Nuenonne Sea Country (Huon Marine Park).

Figure 82. Golden kelp (*Ecklonia radiata*) growing on the mesophotic reefs on Nuenonne Sea Country (Huon Marine Park).

4.1.16 *Paredarerme Sea Country* - Freycinet Marine Park

A total of 284 stereo-BRUV drops were collated from IMAS in and around the Freycinet MP, with coverage in the MUZ and RUZ (Figure 83). The mesophotic zone was dominated by sessile invertebrates attached to the top of the high-profile reef structure known as Joe's Reef (Figure 84). The rariphotic zone consistent of sessile invertebrates, shelf unvegetated sediments and bare reef (along the shelf break) (Figure 84). It is important to note that the majority of the sessile invertebrates found in the rariphotic depths were found to be attached to bryozoan thicket/rubble (functional reef) (Figure 85). Example images of these ecosystems are provided in Figure 85 to Figure 88.

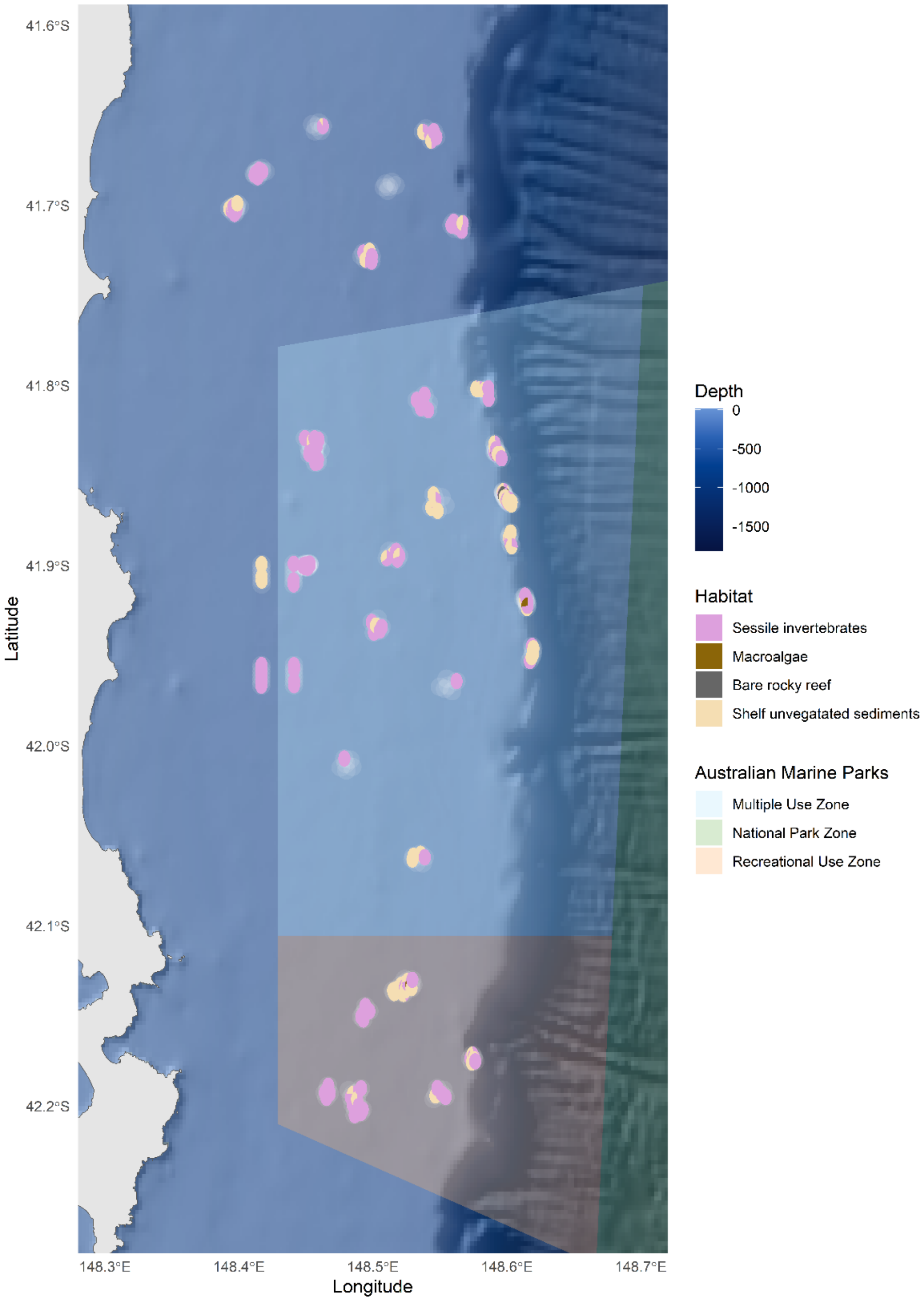

Figure 83. Spatial pie charts of habitat classification for deployments on Paredarerme Sea Country (Freycinet Marine Park). Dynamic link: https://seamapaustralia.org/map/#cea3b0c6-1bc2-45f6-87fb-fff8b5a60166.

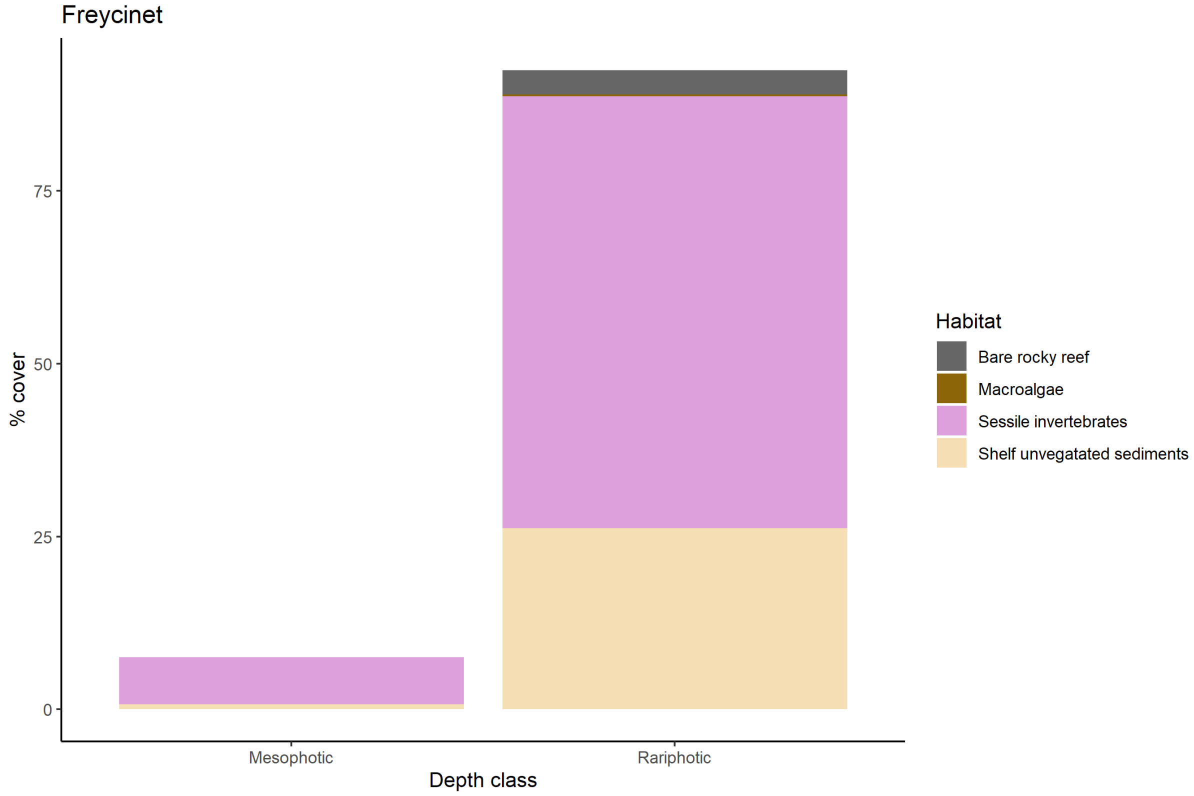

Figure 84. Percent cover of each habitat classification observed within each depth class on Paredarerme Sea Country (Freycinet Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

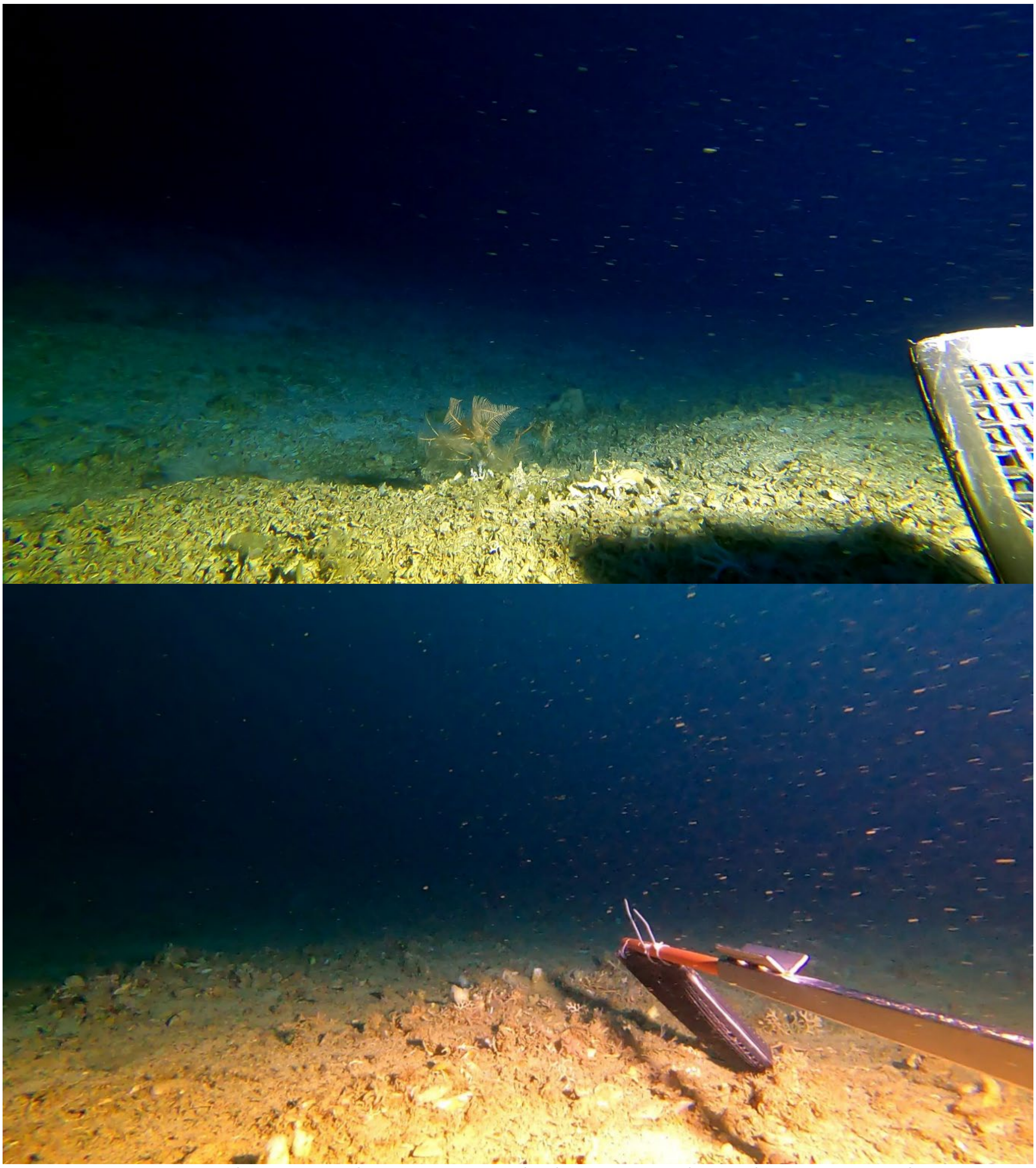

Figure 85. Functional reef consisting of bryozoan rubble (top) and thickets (bottom) are a common feature on Paredarerme Sea Country (Freycinet Marine Park).

Figure 86. Overhanging reef of “Joes Reef” showing diverse invertebrate assemblages on Paredarerme Sea Country (Freycinet Marine Park).

Figure 87. Delicate sessile invertebrates on the top of “Joes Reef” showing diverse invertebrate assemblages on Paredarerme Sea Country (Freycinet Marine Park).

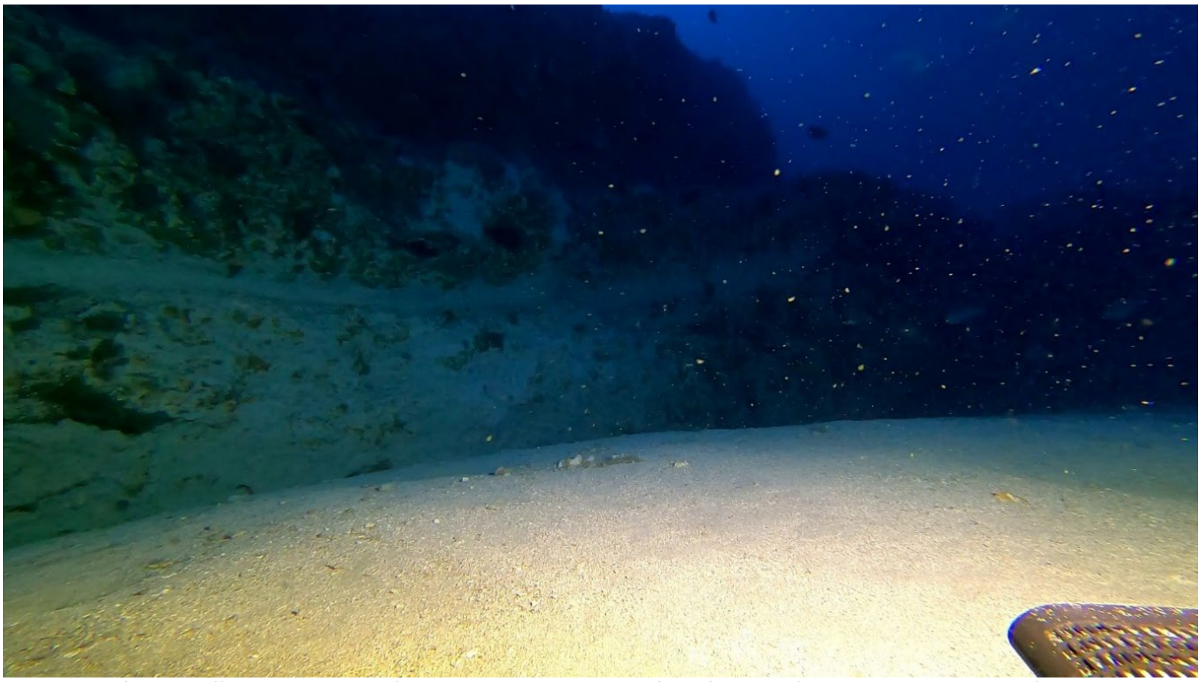

Figure 88. Steep cliffs along the shelf break on Paredarerme Sea Country (Freycinet Marine Park).

4.1.17 *Palawa, Gunaikurnai and Bunurong peoples Sea Country* - Beagle Marine Park

A total of 127 stereo-BRUV drops were collated from IMAS in and around the Beagle MP, with coverage in the MUZ (Figure 89). The mesophotic and rariphotic zones were dominated by sessile invertebrates attached to the low-profile reefs or scallop and bryozoan thicket/rubble beds (functional reef) (Figure 89). Example images of these ecosystems are provided in Figure 91 to Figure 94.

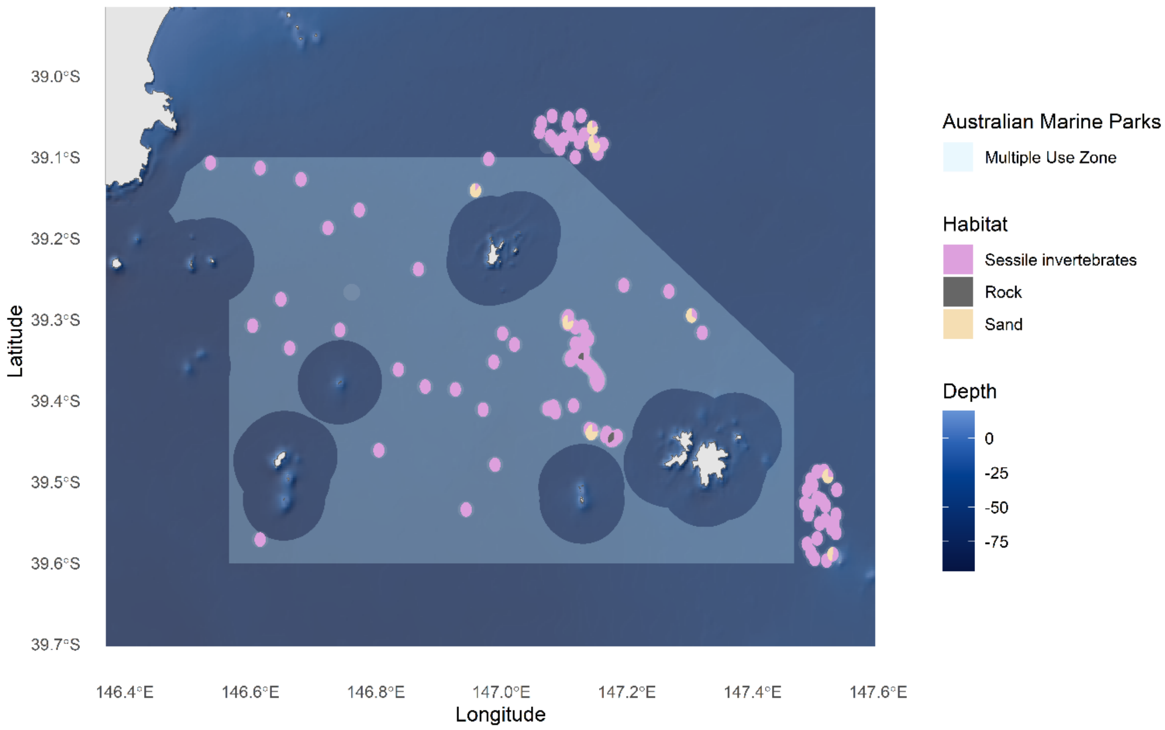

Figure 89. Spatial pie charts of habitat classification for deployments on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park). Dynamic link: https://seamapaustralia.org/map/#921701bd-d106-469c-a11d-1c979d9c2a95.

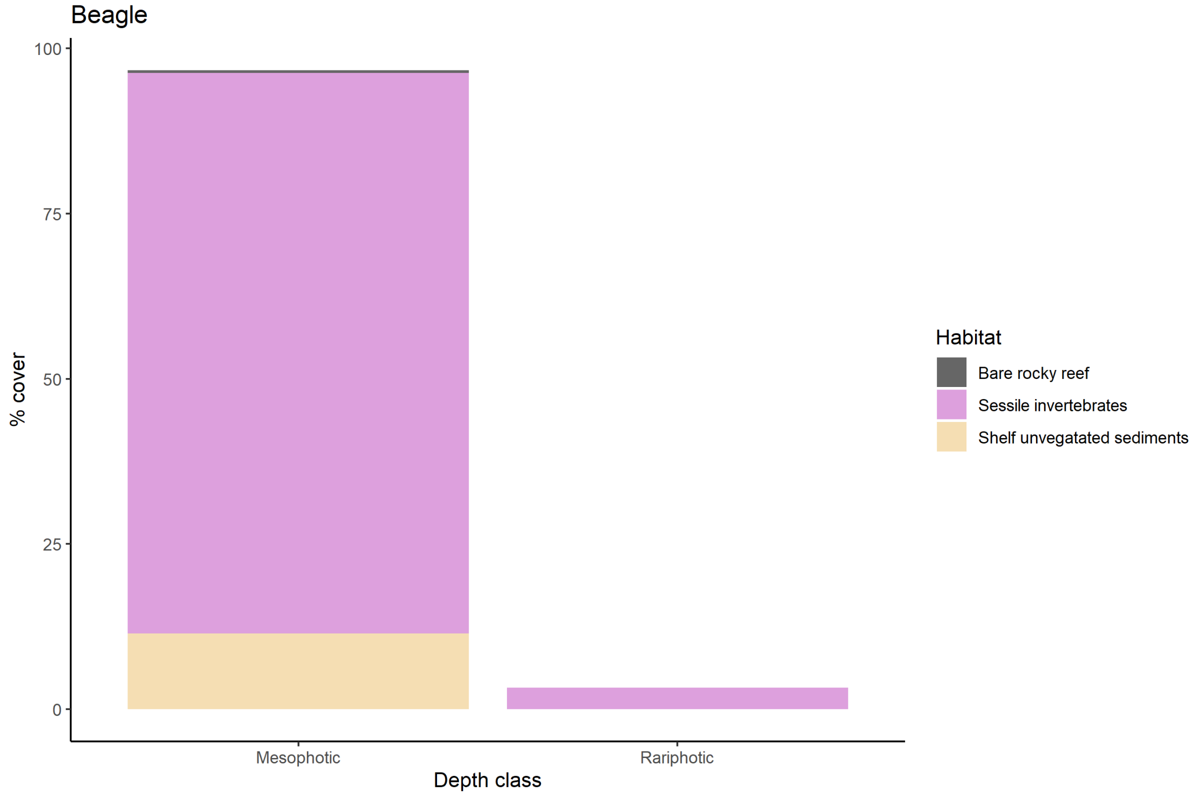

Figure 90. Percent cover of each habitat classification observed within each depth class on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park). Depth classes are: Mesophotic (30-70 m), Rariphotic (70-200 m).

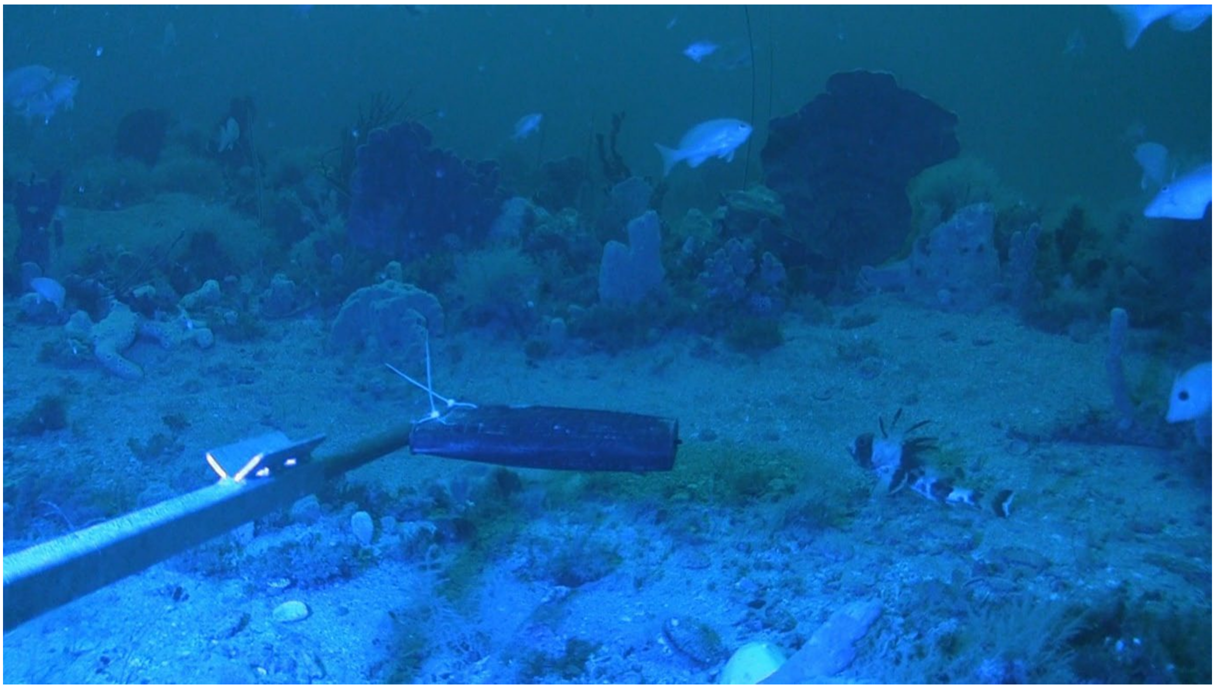

Figure 91. Diverse sessile invertebrate communities growing from sediment inundated reef features on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park).

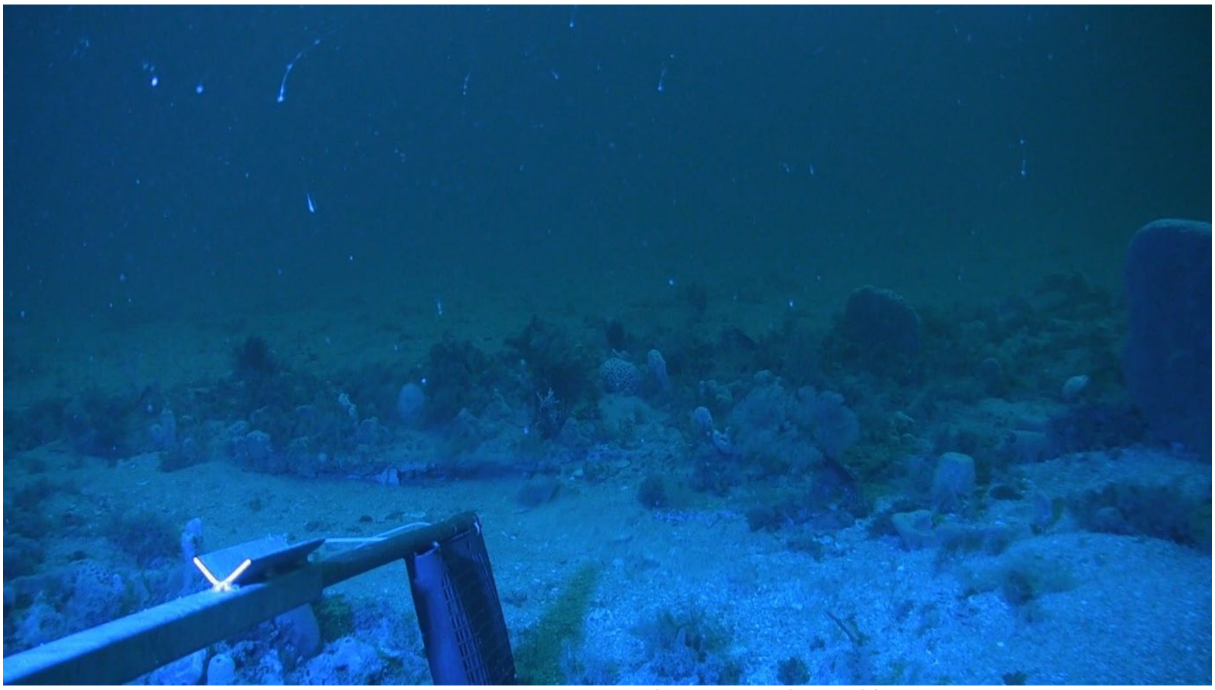

Figure 92. Diverse sessile invertebrate communities growing from low-profile reef features on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park).

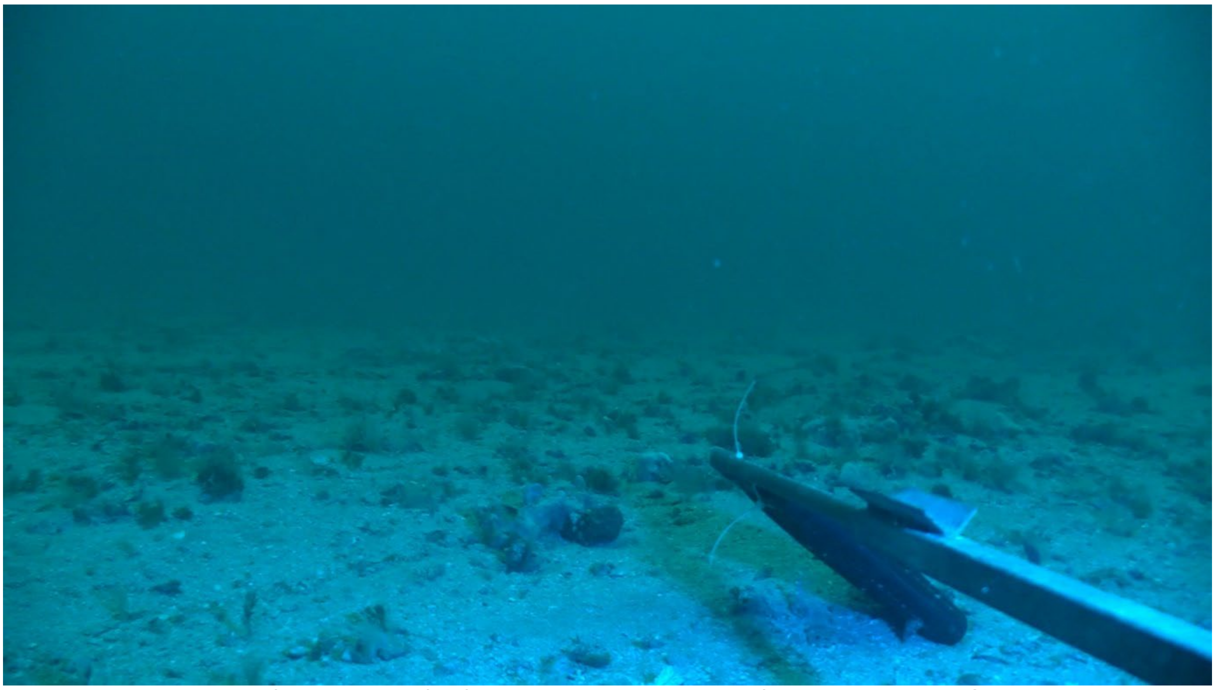

Figure 93. Functional reefs consisting of soft bryozoans are a common feature on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park).

Figure 94. Sea whips forming a functional reef on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park).

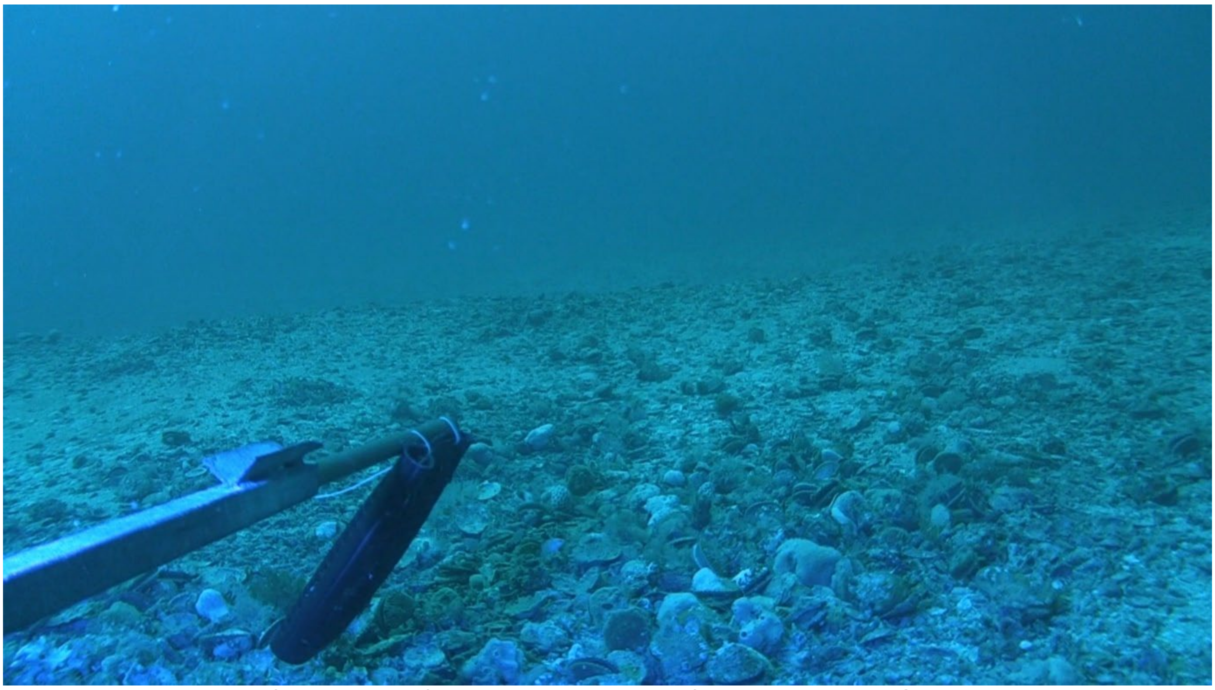

Figure 95. Functional reefs consisting of scallops are a common feature on Palawa, Gunaikurnai and Bunurong peoples Sea Country (Beagle Marine Park).

4.2 Binomial Functional Reef Model

4.2.1 Estimation of important parameters

After some model testing, we settled on independent quadratic polynomials for latitude, longitude, depth, roughness, bathymetric slope, bathymetric aspect, topographic position index (TPI), terrain ruggedness index (TRI) and annual mean bottom stress. We present the trace plots for the intercept, longitude and depth in Figure 96 to demonstrate convergence of parameters across multiple chains.

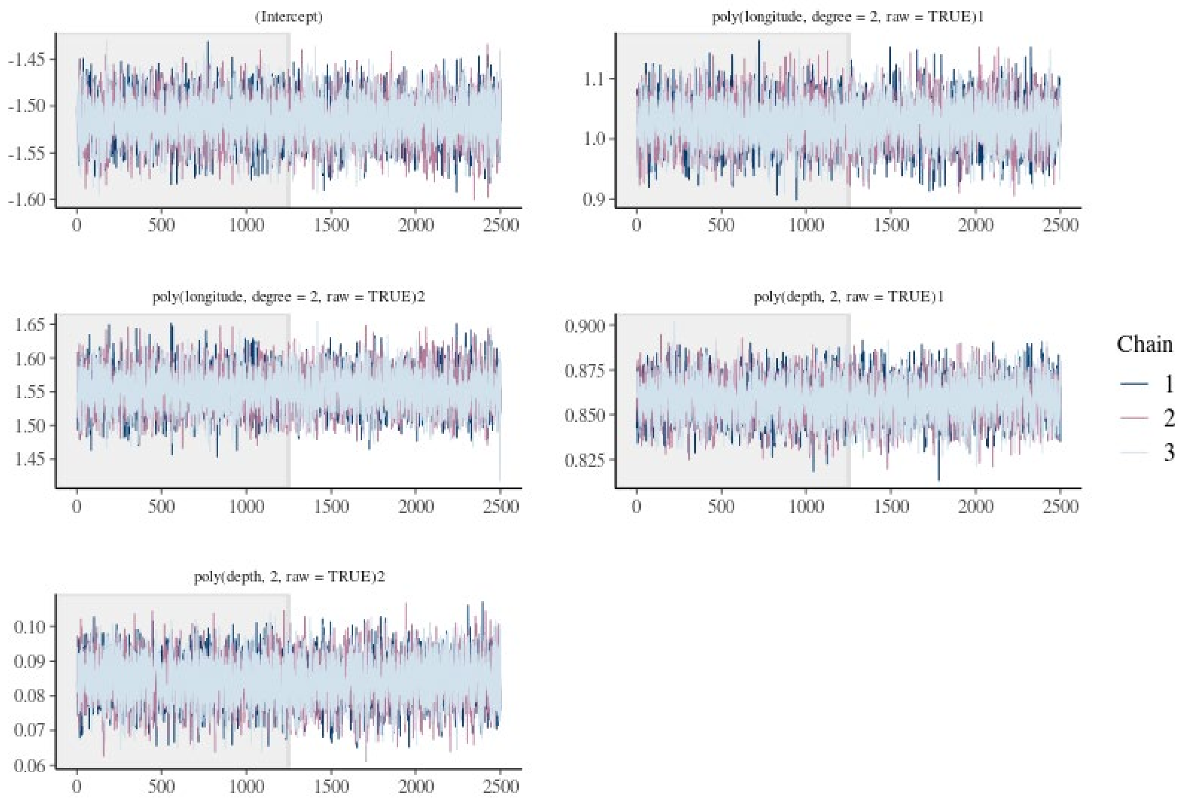

Figure 96. Trace plots for the intercepts, longitude, and depth for functional reef. The grey areas represent the burn-in samples. The trace plots are well mixed and demonstrate that the model is converging on a unimodal distribution for each parameter displayed.

We also want to be able to assess if the posterior distributions for the parameters are unimodal and do not have any odd bimodal or other features (long tails) that would suggest a poor fit. We can see that for all functional reef parameters, the posterior distributions are unimodal (Figure 97). We can also see that for some covariate posterior distributions such as the linear term for slope and the linear term for TRI, the parameters are much more uncertain. The wider posterior distributions reflect the higher uncertainty in those parameters.

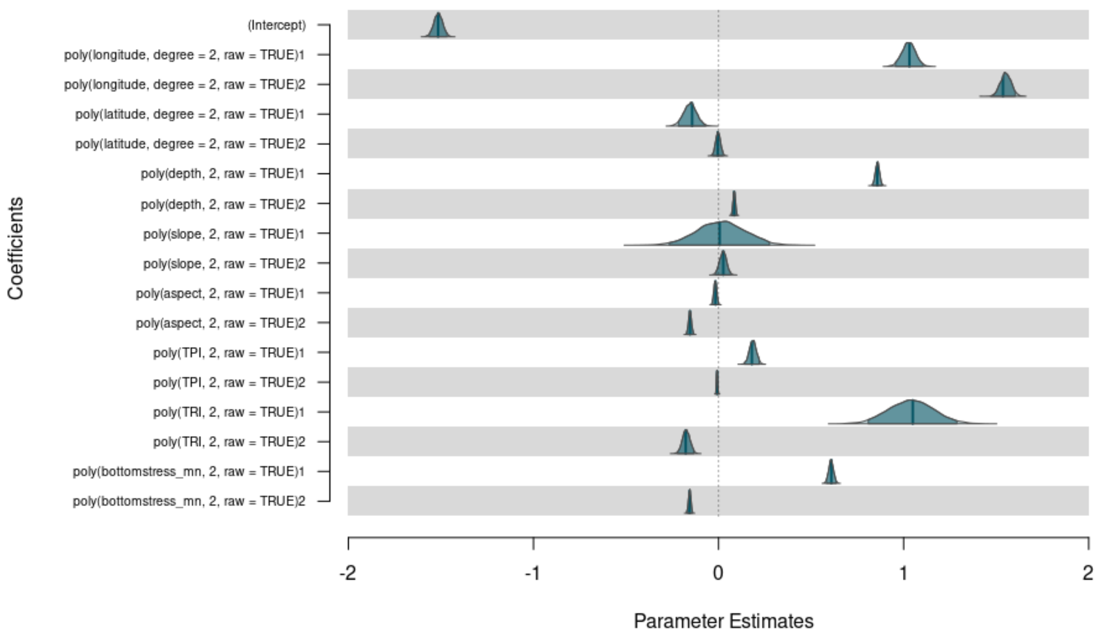

Figure 97. Posterior distributions for each functional reef parameter estimated in the model. The shaded area represents the 80^th credible interval, and the line represents the median for each distribution.

We can see from the partial response plots in Figure 98, that there are some clear relationships between the distribution of functional reef and environmental covariates. For example, we can see that there is a strong longitudinal effect, as a geographical surrogate to account for bioregional variance, where there the model is capturing more functional reef in eastern Australia regions. We can also see a positive relationship with shallower depths, TPI, bottom stress and aspect. There tends to be negative relationships with higher latitudes (suggesting more reef in temperate areas), slope, and higher values of TRI.

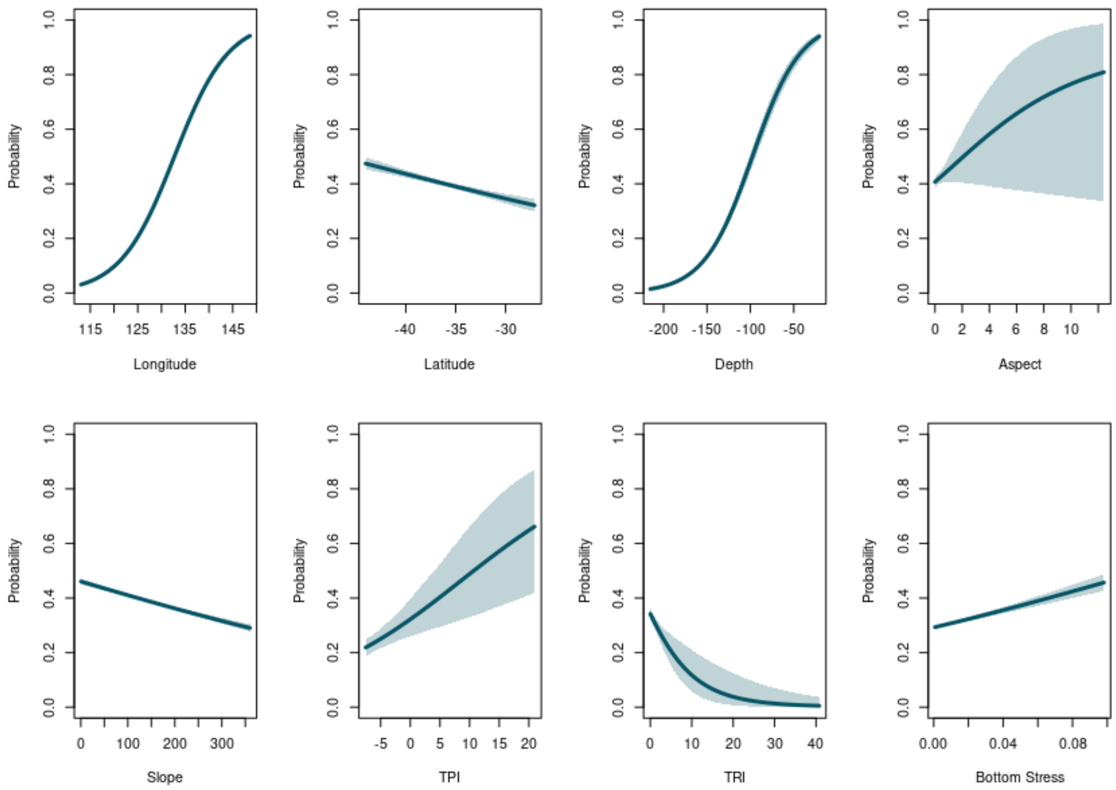

Figure 98. Partial response plots for functional reef. These present the marginal effect of each covariate on the overall response of functional reef to covariates. For instance, we can see that functional reef appears to have a higher probability of occurrence in areas of higher longitude, shallower depts, low values of slope, high values of aspect, TPI, and higher bottom stress (current speed).

4.2.2 Model performance

We can see based on the Bayesian cross-validation that the model seems to predict the median well, suggesting that it is capturing the median response of functional reef in prediction (Table 3). However, we can see for both the 50th and 90th central intervals are under dispersed. The values do not equal 50% and 90%, respectively. This suggest that the model can distinguish between function reef and sediment sites but is under predicting the true count of functional reef observations when comparing the against the counts of functional reef observed in the hold-out dataset.

Results for the classic cross-validation show that the model has approximately a 75% chance of correctly predicting functional reef based on the mean probabilities from the posterior predictive probabilities at each site (Table 4). We can see the model is slightly better at predicting non-reef sites compared to reef sites (78.5% vs 69.3%). However, this just might reflect the greater number of non-reef sites in the hold-out dataset.

Table 3. Cross validation predictive densities for functional reef predictions from the binomial model. We present the proportions of hold-out datasets that were below the median, within the 50% and within the 90% central intervals obtained from the corresponding predictive posterior distributions. If the model perfectly predicted the hold-out data, the values should be 50%, 50% and 90% for each the median, within the 50% and within the 90% central intervals, respectively.

Cross Validation Metric	Cross Validation Score
Cross Validation Median	0.508
Cross Validation 50th Central Interval	0.130
Cross Validation 90th Central Interval	0.304

Table 4. Confusion matrix for binomial cross validation prediction. Here we compare the predicted reef to each site of the hold-out data vs the sites with the greatest prevalence of reef from the hold-out data. You can interpret the confusion matrix by looking at the diagonal of the matrix, this shows you how many are classified correctly, while the off diagonals show the misclassification numbers. For this single hold-out dataset test, our model resulted in 74.7% correct classification rate for these data.

	True non-reef	True reef	Precision
Predicted non-reef	226	62	78.5%
Predicted reef	62	140	69.3%
Total	288	202	74.7%

4.2.3 Functional Reef Prediction

The higher probability of functional reef occurring is shown in darker blues in the Figure 99. Key patterns include large areas of functional reef occurring in the southeast of Bass Strait and around Tasmania through to King Island (Figure 99). Additionally, high probabilities of functional reef occurring were also present along the paleoshoreline features (generally around 70 and 110m depths). These were a unique feature in model predictions particularly in the south-west and Bonney upwelling regions (Figure 99). We observed a general increase in uncertainty further from ground sampling locations, with moderately elevated levels of uncertainty around eastern Bass Strait, northern Tasmania, along the continental shelf break, and throughout the Great Australian Bight (Figure 99).

An alternative method to illustrate uncertainty was developed using a bivariate map for functional reef (Figure 100). In this map, the colours represent two axes: one for the mean probability of functional reef and the other for the uncertainty in those predictions. This creates a straightforward way to display both probability and uncertainty in the same figure. The approach emphasises areas with higher predicted uncertainty, shown in yellow to green hues in Figure 100. This highlighted the uncertainty in predicted functional reef, particularly in eastern Bass Strait, around Tasmania and the south Australian Gulfs.

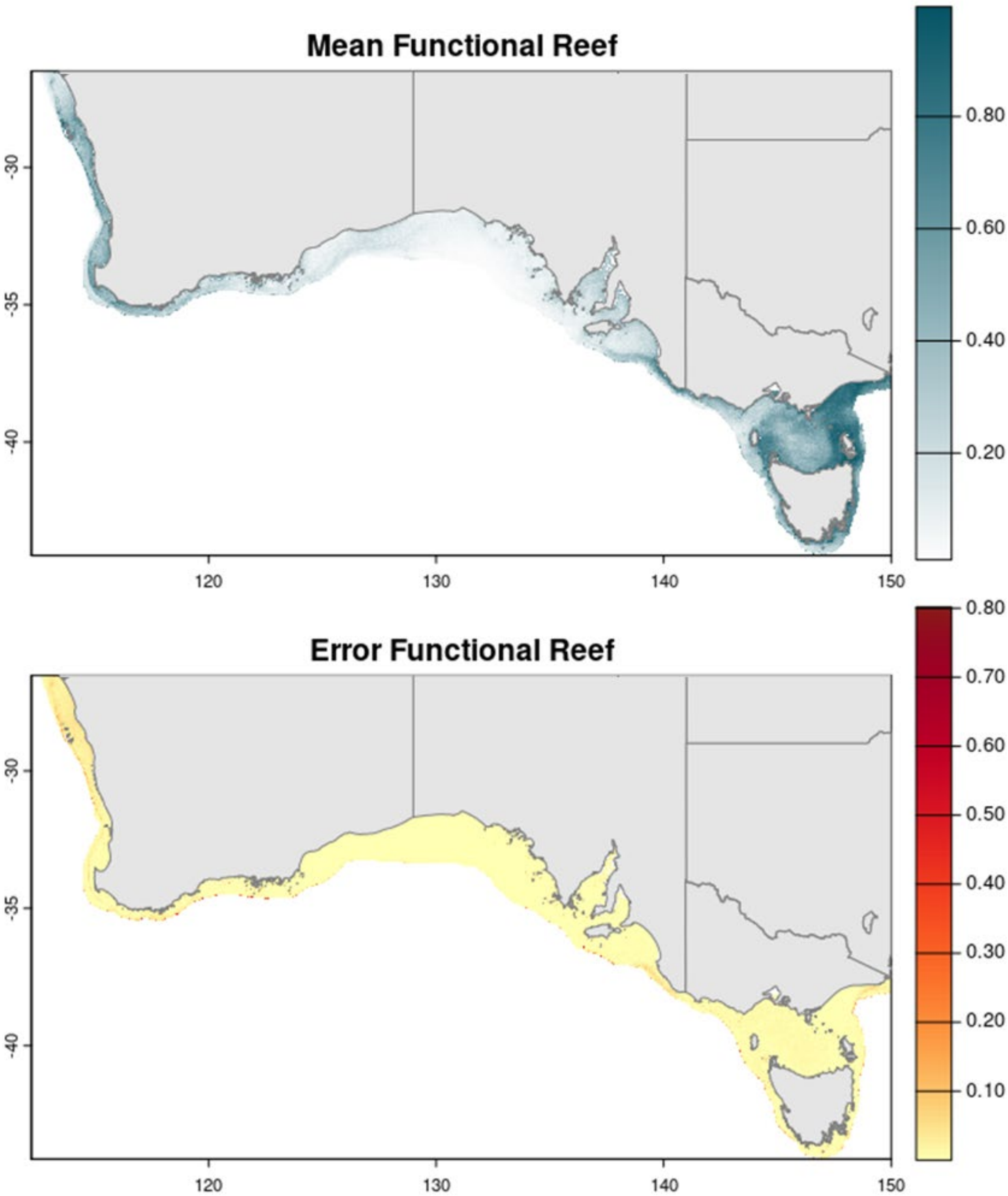

Figure 99. The mean prediction from the posterior predictive distribution for Functional Reef, uncertainty is reported as the absolute difference between the 25th and 75th credible intervals from the posterior predictive distribution. The colours for each class highlight areas of higher probability where the colours for each class are bolder. The uncertainty in the functional reef predictions is represented by cells that are a stronger shade of red. For a dynamic version see: https://seamapaustralia.org/map/#b0567869-6e98-4467-84f3-82d61a747f48.

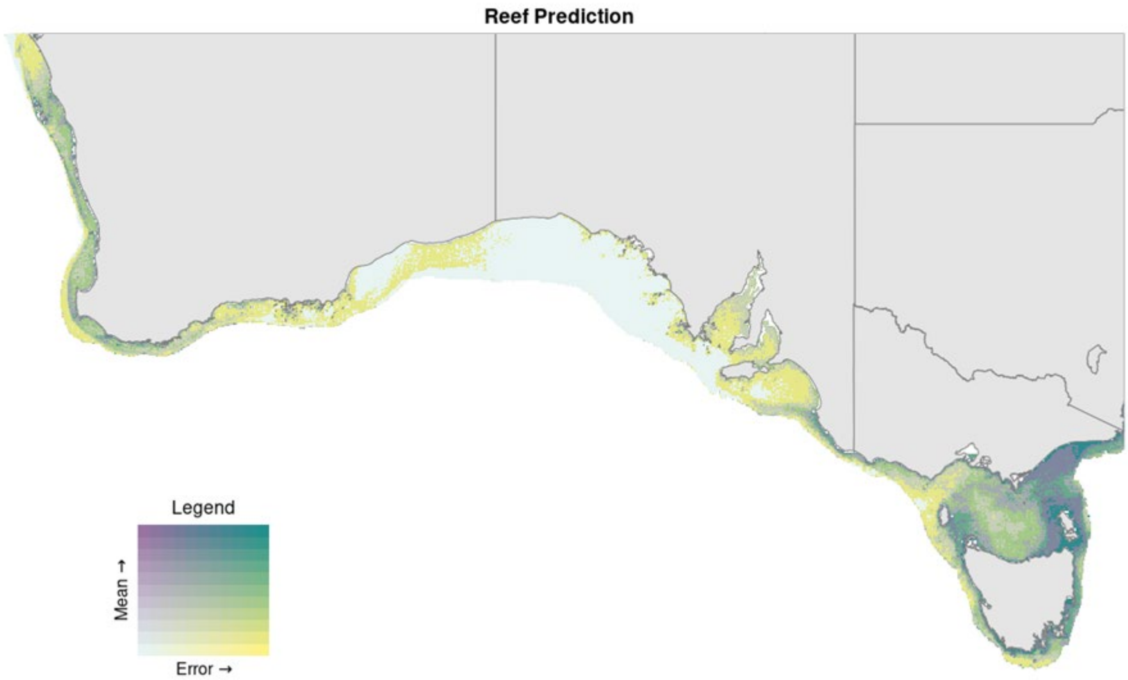

Figure 100. Bivariate uncertainty map for functional reef. In this map, the colours represent two axes one for the mean probability of functional reef and the other axis for the uncertainty in those predictions. For a dynamic view see: https://seamapaustralia.org/map/#97ea33cc-5e63-4487-ad21-d218099e5955

4.3 Multinomial Ecosystem Component Model

4.3.1 Estimation of parameters

When trying to fit the multinomial ecosystem component model we removed one extra covariate, aspect. Compared to the functional reef model, this was the only parameter that would not converge based on the inspection of multiple Monte Carlo Markov Chains. All other covariates converged well across multiple chains. Here we present the intercept and longitude to demonstrate chain convergence for each of the ecosystem types (Figure 101).

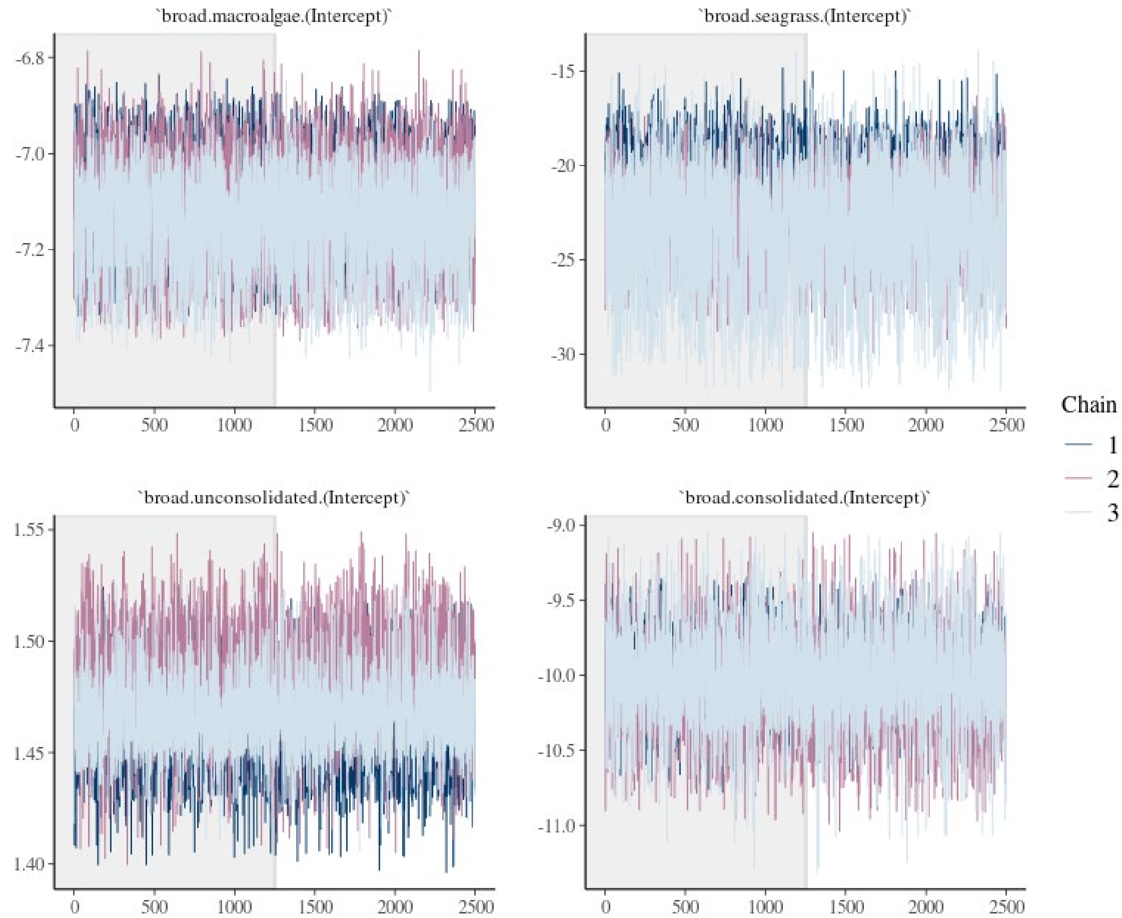

Figure 101. Trace plots for the intercepts for each ecosystem components. The grey areas represent the burn-in samples The trace plots are well mixed and demonstrate that the model is converging on a unimodal distribution for each intercept.

Like with the functional reef models, we also assessed if the posterior distributions for the parameters were unimodal and do not have any odd bimodal or other features (long tails) that would suggest a poor fit. We can see that for all parameters for each ecosystem component, the posterior distributions are unimodal (Figure 102). We can also see that for some ecosystem components, such as seagrass, the parameters are much more uncertain, with wider posterior distributions reflecting the higher uncertainty in those parameters.

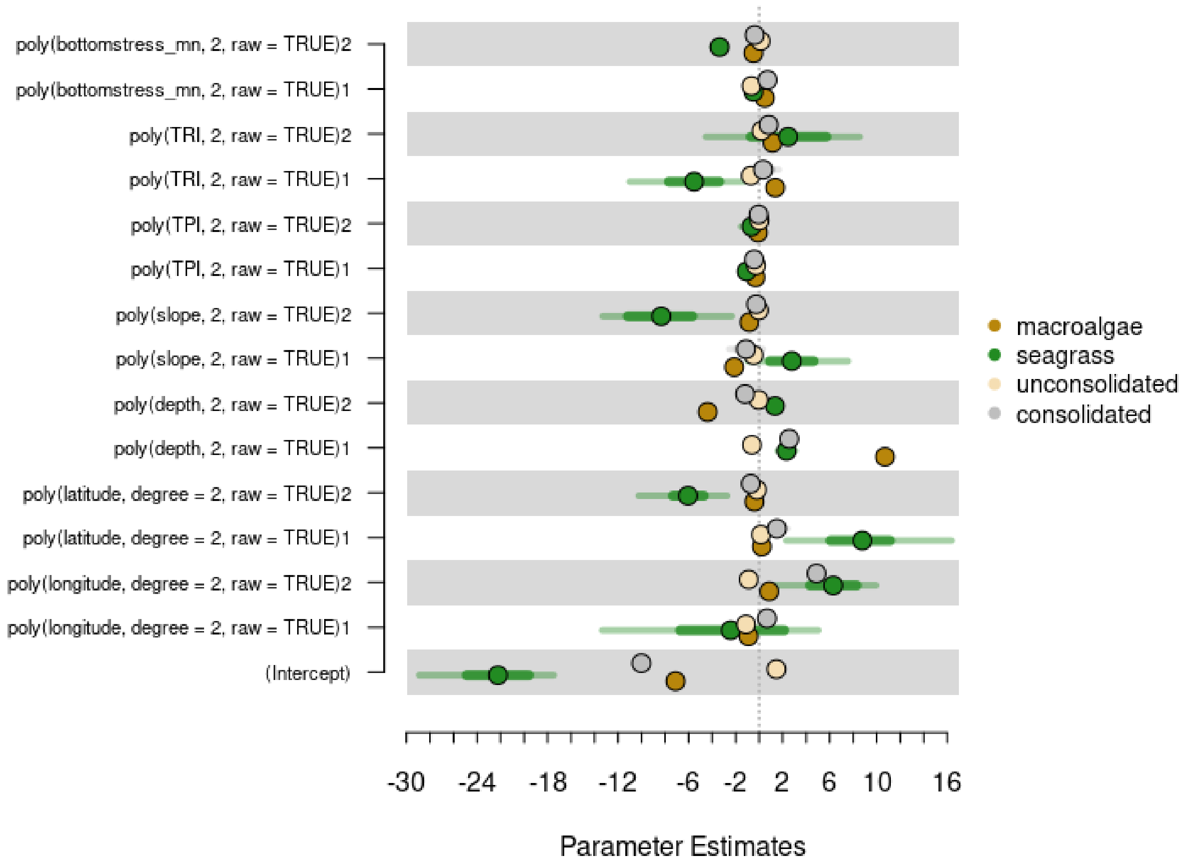

Figure 102. Posterior parameter estimates for each ecosystem component. The light thin lines represent the 95th percentile credible interval, the darker thinker lines represent the 80th percentile and the dot represents the mean.

The partial response plots for each ecosystem component are plotted against each covariate used in the model (Figure 103). We can see that sessile invertebrates have a positive response to higher values of longitude, depths around 50 m, higher values of slope (areas of greater turnover in depth, such as the shelf break) and higher values of bottom stress (where current speeds are higher). For unconsolidated sediments we can see a preference for deeper regions, lower values of TPI, lower regions of bottom stress, and areas of low bathymetric slope values. We can see with seagrasses that they tend to be constrained to very shallow depths and high values of TRI. Macroalgae also appear to prefer areas of higher TRI. Finally consolidated tend to be predicted to be in larger longitudes and relatively low value of TRI.

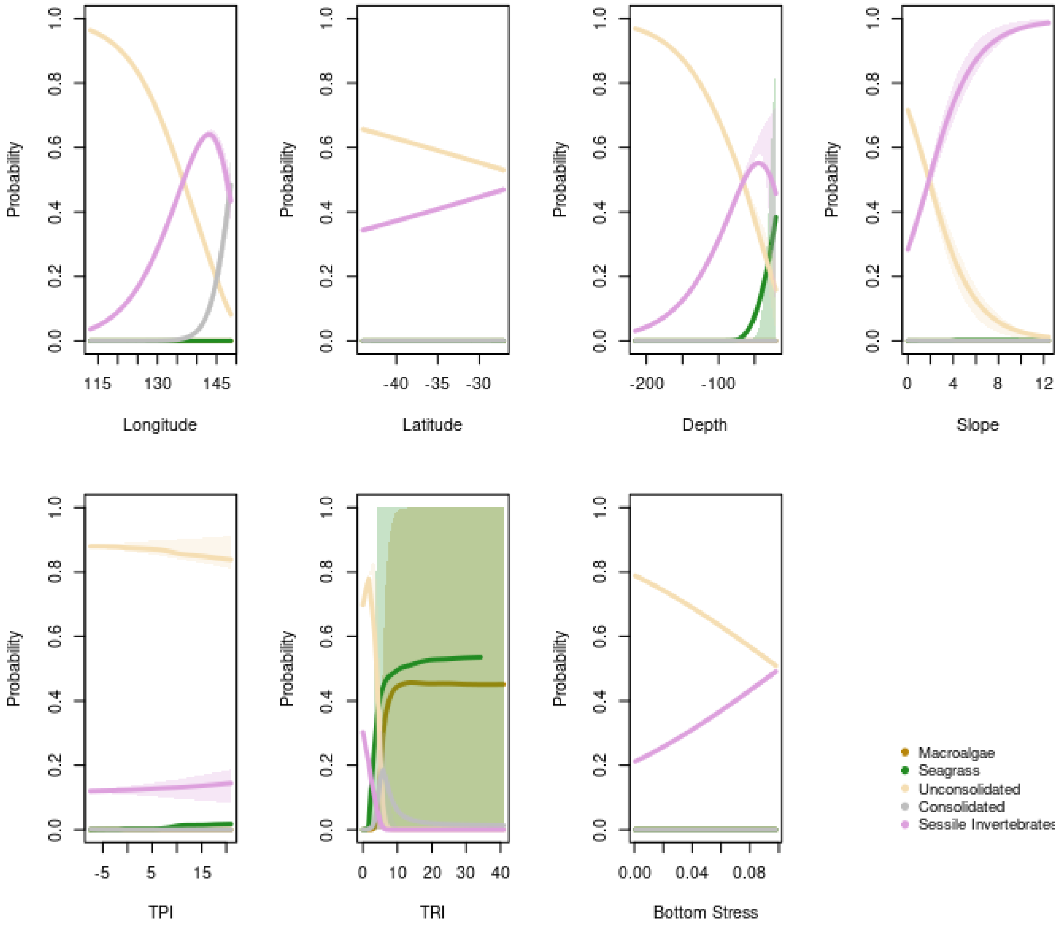

Figure 103. Partial response plots for all ecosystem types. We report the 80th credible intervals as the shaded regions around the lines.

4.3.2 Model performance

Results from the Bayesian cross-validation approach demonstrates for the more abundant groups, unconsolidated and sessile invertebrates, the median cross validation is close to 50% (Table 5). However, for unconsolidated and sessile invertebrates to underrepresent in the 50th and 90th central cross-validation predictive intervals. While for seagrass, consolidated and macroalgae is a greater proportion of observed values from the holdout datasets predicted within the 50th and 90th central cross-validation predictive intervals than expected.

Based on the confusion matrix results based on the classic hold-out cross-validation approach, we can see that the model gets the class classification (the class with highest probability per-site) right 72.8% of the time. We can see from Table 6, that for macroalgae, unconsolidated and sessile invertebrates, we get the classification right most of the time, however, for seagrass and consolidated we tend to under predict the classification. But this might also be due to rarity of those classes in the hold-out dataset. We can also see that the greatest cross classification is between unconsolidated and sessile invertebrates, suggesting that most of the miss classification occurs when the model misclassifies unconsolidated as sessile invertebrates and vice versa.

Table 5. Cross validation predictive densities for each ecosystem type from the multinomial model. We present the proportions of hold-out datasets that were below the median, within the 50% and within the 90% central intervals obtained from the corresponding predictive posterior distributions. If the model perfectly predicted the hold-out data, the values in the table should be 50 for the median, 0.5 for the interquartile range (50% central interval) and 0.9 the 90% central interval.

	Macroalgae	**Seagrass**	**Unconsolidated**	**Consolidated**	**Sessile inverts**
Cross Validation Median	0.232	0.083	0.440	0.100	0.557
Cross Validation 50th	0.726	0.887	0.148	0.830	0.151
Cross Validation 90th	0.808	0.924	0.300	0.900	0.348

Table 6. Confusion matrix for multinomial cross validation prediction. Here we compare the predicted class per site for the hold-out data (the class with the highest probability per-site) vs the observed data with the greatest prevalence per-stie for the hold-out data. For this single hold-out dataset test, our model resulted in 72.8% correct classification (total precision) rate for these data. We also report the class precision with is an indication of true positive and the false positive rate, once again the closer this value to 100% the more accurate the classification for that ecosystem class.

	True Macroalgae	**True Seagrass**	**True Unconsolidated**	**True Consolidated**	**True Sessile Inverts**	**Precision**
Predicted Macroalgae	38	0	8	1	1	79.2%
Predicted Seagrass	6	1	3	0	0	10.0%
Predicted Unconsolidated	9	2	222	2	45	79.3%
Predicted Consolidated	3	0	2	1	2	12.5%
Predicted Sessile inverts	2	0	46	0	92	65.7%
Total	58	3	281	4	140	72.8%

4.3.3 Ecosystem Component Prediction

Like the functional reef predictions, two approaches are presented: a multinomial probability of mean prediction and associated uncertainty (Figure 104), and the bivariate uncertainty map for each ecosystem component (Figure 105). Generally, the higher probabilities of occurrence for macroalgae were mostly constrained to the depths shallower than 30m. The exception to this was in the southwest where macroalgae was predicted to extend to ~50m. Seagrass was predicted to occur mainly in the southwest, which is more likely a result of our predictions being constrained to depths >10m, meaning that the extensive seagrass beds known to occur around Flinders Island and in the Bays and Inlets of the southeast are not represented in our models. Paleo-shoreline features in 70 and 110m across the southwest and Bass Strait were predicted to support the highest probability of sessile invertebrates, with the greatest uncertainty in this prediction occurring in western Bass Strait and around Shark Bay in the north-west.

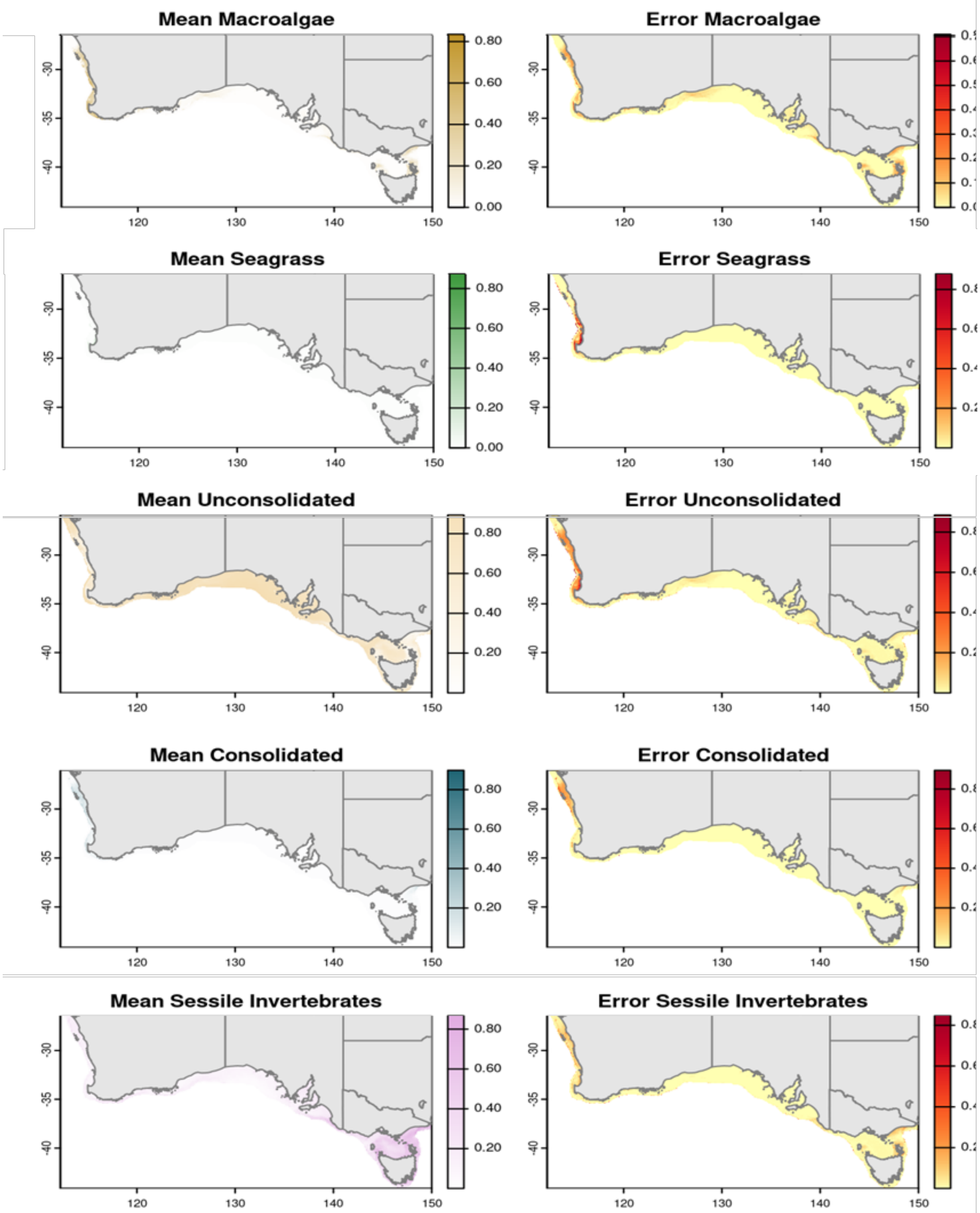

Figure 104. The mean prediction from the posterior predictive distribution for each ecosystem type, uncertainty is reported as the absolute difference between the 25th and 75th credible intervals from the posterior predictive distribution. The colours for each class highlight areas of higher probability where the colours for each class are bolder. The uncertainty in these predictions is represented by cells that are a stronger shade of red. For a dynamic view see: https://seamapaustralia.org/map/#95cbbf2d-20c2-4a68-a151-5ca0befaa027.

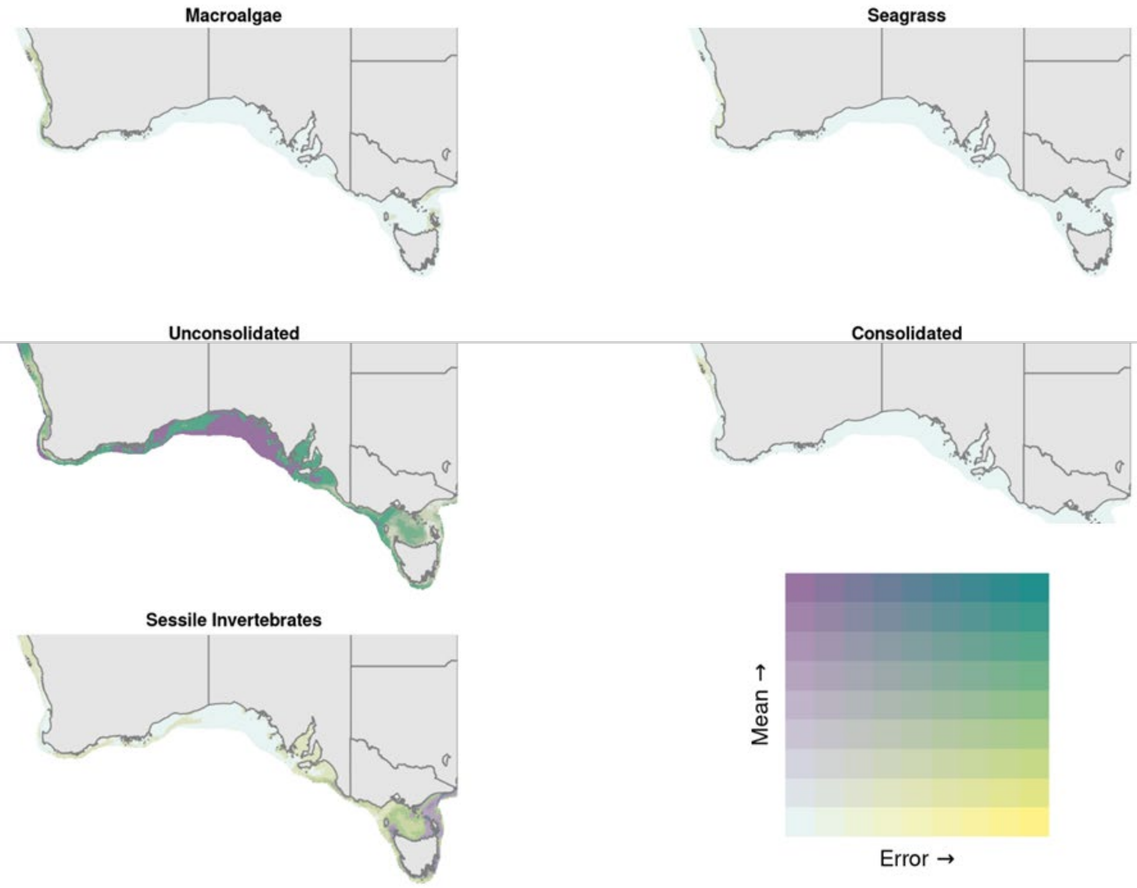

Figure 105. Bivariate uncertainty map for each ecosystem component. In this map, the colours represent two axes one for the mean probability of an ecosystem class and the other axis for the uncertainty in those predictions. For a dynamic view see: https://seamapaustralia.org/map/#e25cacfd-d27b-4cfc-8fac-80ecf9c74d4b.

5 How to use predictions in Seamap Australia

The predictions for functional reef and ecosystem components can be accessed in Seamap Australia. Figure 106 outlines a suggested workflow for loading these layers to reduce complexity in understanding the various layers (e.g., bivariate and probability layers). By loading both the layers and the underlying imagery hosted in SQUIDLE+ in the order provided below, you can understand the ground-truthing data used and better grasp the uncertainty of the layers. This also allows you to contextualise what each ecosystem may look like with images captured at those locations (where available). Direct links to each AMP is provided in Table 7.

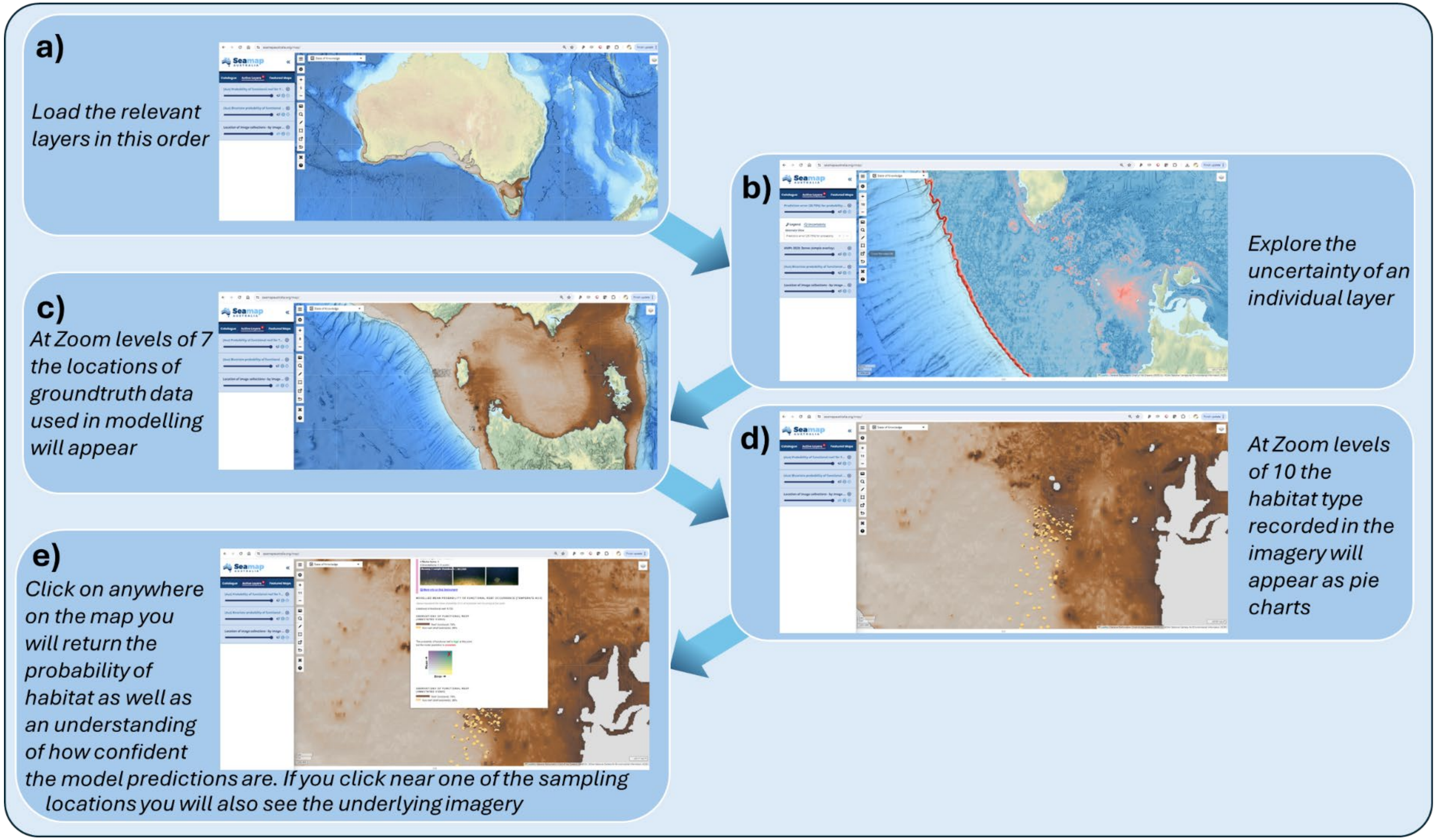

Figure 106. Suggested workflow using the functional reef layer as an example to load and use the predictions in Seamap Australia. Dynamic link to Seamap Australia: https://seamapaustralia.org/map/#5625dbb8-23be-4341-994c-ed48c2172b02.

Table 7. Dynamic links to the functional reef and ecosystem component mapping using the order provided above.

AMP	Functional Reef Link	Ecosystem component link
Abrolhos	https://seamapaustralia.org/map/#7697520d-4888-4785-a65c-6467cb4aa51f	https://seamapaustralia.org/map/#14218b5c-ac92-4ea7-b783-02fecc5498f3
Jurian	https://seamapaustralia.org/map/#a1f9c306-9e32-4a31-be0c-80f14d000e26	https://seamapaustralia.org/map/#6544fd52-27fb-44c6-9db4-055d6a131372
Two Rocks	https://seamapaustralia.org/map/#cec20552-bf08-464a-be11-6ef9badb38df	https://seamapaustralia.org/map/#8e284535-5e03-4adb-beef-ff9b5a617984
Geographe	https://seamapaustralia.org/map/#f9a82e12-6f6c-437a-9c57-d043e5f46dcc	https://seamapaustralia.org/map/#c7950520-eabd-44f8-a347-e642bab11989
South-west Corner	https://seamapaustralia.org/map/#4cfdde58-c248-4c2c-878c-4902390c7e5f	https://seamapaustralia.org/map/#23c88791-bf31-454a-ad53-baafb26c8c27
Bremer	https://seamapaustralia.org/map/#948e2cc0-0af3-4ce3-94a3-9c25ca051991	https://seamapaustralia.org/map/#afdd54a6-207c-413f-b136-aec223e26242
Eastern Recherche	https://seamapaustralia.org/map/#948e2cc0-0af3-4ce3-94a3-9c25ca051991	https://seamapaustralia.org/map/#7de33f11-2af0-4ed7-b18a-6f2e09870e4e
Two Rocks	https://seamapaustralia.org/map/#b88b3775-0071-4488-b0bb-029cbe527c6c	https://seamapaustralia.org/map/#87934321-542a-49a4-9836-c42099320bf6
Great Australian Bight	https://seamapaustralia.org/map/#a630d334-039c-4c17-bcac-053d8ca1bd6b	https://seamapaustralia.org/map/#4b2a8753-3931-44cf-ba37-79298d0036d1
Murat	https://seamapaustralia.org/map/#3fc7b1f1-d3e8-4c72-a830-099a2ccbb301	https://seamapaustralia.org/map/#7323640c-e62c-4e64-abe1-314c04dcb949
Western Eyre	https://seamapaustralia.org/map/#3c88a60e-e0a9-46f8-af18-1dc7d1ea2386	https://seamapaustralia.org/map/#f9d531e4-8290-4a83-b00a-37145f4b0933
Western Kangaroo Island	https://seamapaustralia.org/map/#d4871d99-31ce-46f4-bad0-72f0d3c5c8b6	https://seamapaustralia.org/map/#88fc05a0-d226-4a73-8134-fad9afafcf75
Southern Kangaroo Island	https://seamapaustralia.org/map/#15731bcc-a04c-4794-b89e-dd03b54d36e0	https://seamapaustralia.org/map/#88fc05a0-d226-4a73-8134-fad9afafcf75
Murray	https://seamapaustralia.org/map/#800fd963-27fb-412f-b8f0-a5c80f9eafb5	https://seamapaustralia.org/map/#38f5616e-5b05-49bd-8c0f-563f61544c23
Apollo	https://seamapaustralia.org/map/#e26db97e-bec5-4db9-9535-5b5fcd6ac783	https://seamapaustralia.org/map/#15e043d3-d8ad-4427-b29c-a871114adb37

Zeehan	https://seamapaustralia.org/map/#e26db97e-bec5-4db9-9535-5b5fcd6ac783	https://seamapaustralia.org/map/#c402140e-4dbd-4eab-afe2-3197597563fb
Franklin	https://seamapaustralia.org/map/#7a40f353-b712-4c5e-94a3-9d30fce7f78d	https://seamapaustralia.org/map/#a7d48109-7002-4b36-b661-7447dca4f210
Boags	https://seamapaustralia.org/map/#faaca4b5-5378-4a4e-9c97-37b35de4cfa1	https://seamapaustralia.org/map/#c900fa1d-8b83-47ab-ae35-4dcf0a2b6aaf
Tasman Fracture	https://seamapaustralia.org/map/#b2de5378-0451-4ff5-84dc-8f397d592d5c	https://seamapaustralia.org/map/#3e1ade23-1c2c-4d4a-b8b0-32a772071928
Huon	https://seamapaustralia.org/map/#930e39c1-ef60-4833-9c20-26b35ab46f51	https://seamapaustralia.org/map/#c6efb41b-2df9-4717-a536-8cabfd7a910a
Freycinet	https://seamapaustralia.org/map/#dbd1bcbe-36cf-4c07-8767-d2ec8876be6d	https://seamapaustralia.org/map/#c5c6d362-e6ce-44ec-acf5-d17ad89c144d
Flinders	https://seamapaustralia.org/map/#66823b64-0feb-4472-a7ae-4cc1684c5df2	https://seamapaustralia.org/map/#67844cdb-b41d-47f1-bba7-f9beecc35e85
Beagle	https://seamapaustralia.org/map/#2f602b9d-ef92-4e52-ba09-81fa960ac9e6	https://seamapaustralia.org/map/#671b1ba4-9880-46f4-92a7-7ed9323a7c5e

6 Summary and identified limitations to predictions

This project has substantially enhanced our understanding of functional reef habitats and their associated ecosystem components across temperate Australia, especially in the mid to outer shelf waters (50-200 m depths) where information has been limited. The project has generated models that were moderately accurate in predicting functional reef and non-reef areas, with precision values of 78.5 % and 69.3 %, respectively, and an overall accuracy of 74.7 %. The models of ecosystem components achieved an overall accuracy of 72.8 %, with individual classes ranging from 10-79 % precision (i.e. mixed invertebrates (79.3 %), macroalgae (79.2 %), unvegetated sediments (65.7 %), bare reef (12.5 %), seagrass (10.0 %)). These prediction accuracies are reasonable, considering the broad biogeographic scale and coarse resolution of the models, except for the seagrass and bare reef classes, which have smaller ground-truth sizes, resulting in lower accuracies. Importantly, this project has highlighted the utility of wide field of view of horizontally-facing habitat imagery, from stereo-BRUVs (Langlois et al. 2020) and the BOSS (Langlois et al in review). Coarser scale national 250 m resolution bathymetry products have been shown to be suitable for creating representative habitat maps and therefore at much larger spatial scales than previously achieved (e.g. Langlois et al. 2022).

Importantly, the modelling approach provided a novel and accessible way to present spatial uncertainty associated with model predictions. The uncertainty surfaces demonstrated that increased uncertainty occurs the further from ground truthing sampling locations, particularly around the eastern Bass Strait, Northern Tasmania, along the continental shelf break, mid shelf regions north of Perth and throughout the Great Australian Bight. We recommend further sampling in these regions to improve model predictions. Currently the production of these spatial models relies on geographical surrogates to account for bioregional variance. We recommend that future updates of these habitat and ecosystem models should consider limiting their spatial extent to within smaller biogeographic boundaries, for example, by considering the relatively distinctive south-west and south-east bioregions separately.

The models were generated for the 10-200 m depth range, leading to a likely underprediction of shallow-water seagrasses and canopy-forming macroalgae, especially in the southeast (e.g. around the western and southern areas within the Furneaux groups of islands for seagrasses). Therefore, we suggest using our model predictions as an initial, broad-scale inventory of an area and prefer validated finer-scale mapping data where available, such as the Seamap Australia National Benthic Habitat Layer.

This data product covers an area of 585,039 km² and significantly improves the description of the extent and distribution of seabed habitats throughout the temperate continental shelf region of Australia, particularly beyond State waters where most of the fine-scale habitat mapping has previously occurred. Within this temperate continental shelf region, the validated National Benthic Habitat Layer (NBHL) available in Seamap Australia covers 22,166 km², accounting for just 3.8 % of the area mapped in this project. It should be noted that publicly available fine-scale bathymetric mapping, derived from LiDAR or multibeam echosounder technologies, covers 23,058 km² of this region (3.9 %) and is gridded at a high resolution of 10 m or finer, equivalent to State-level mapping resolutions. Future mapping efforts could explore the use of multi-resolution bathymetry composite surfaces, maintaining the native resolution of data products and mosaicking them with the coarse 250 m bathymetry used in the modelling approach described in this project. It is important to note that considerable cleaning of the data is likely to be needed to remove artifacts that will occur in the mosaicking process. Taking this approach, there is opportunity to expand the fine-scale mapping coverage by 19,330 km² (a further 3.4 % of the temperate Australian shelf not already covered by Seamap Australia's NBHL; https://seamapaustralia.org/map/#f8f9adee-fd78-45d0-bf7d-8d4e0f0505bd), better resolving the fine-scale features lost in the coarse resolution bathymetry and potentially further refining the accuracy of model predictions.

Seamap Australia has enabled the dynamic visualisation and exploration of predictions, offering spatial pie charts of habitat composition of ground-truthing locations. The synthesised ground-truthing annotation data has been made available on GlobalArchive, using controlled annotation schema, with links to underlying images hosted in SQUIDLE+ and accessible through Seamap Australia. Visit https://seamapaustralia.org/map/#704ac727-4a63-4789-a06d-b07fed6b4294 to access these features.

The data products have the potential to be further improved by additional correction and QA/QC of annotations. This underscores the importance of platforms like SQUIDLE+, which allow for easy 'third-party' verification of annotations against the underlying imagery without the need for specialised software typically used in annotating habitats in stereo-BRUV imagery. The annotation of horizontally facing imagery was not available in SQUIDLE+ during this project but is now possible. A recommendation from this work is that future attempts to annotate such imagery and synthesis their products should utilise SQUIDLE+, and its QA/QC pipelines to enhance the quality of ground-truthing data which should occur before the modelling activity.

New bathymetric and ground-truthing data is regularly being collected by research programs around Australia. Most relevant to the mid-outer continental shelf regions are projects associated with the National Marine Facility (NMF) and the HydroScheme Industry Partnership Program, which regularly collect fine-resolution bathymetry datasets. The NMF also collects considerable amounts of towed-video datasets during cruises (e.g. CSIRO led IN2024_V03), and while access these datasets remains difficult, they do offer potential for expanding bathymetry and ground-truthing coverage for future updates to models. To facilitate these future updates to the predictions, we have created an R-based workflow. This workflow sources imagery-based ground-truthing annotations hosted on GlobalArchive and SQUIDLE+ using controlled annotation schema, annotated according to the National Field Manuals for Marine Sampling, and replicates the modelling approach. It is stored in an open-access Git repository (https://github.com/UWA-Marine-Ecology-Group-projects/nesp-2.1), enabling easy updates using the same methods.

The data products from the models are intended to serve as one of foundational layers in the update to the National Values Ecosystems layer and potentially a new Ecosystem Components layer, used by Parks Australia in their management effectiveness system. This update is expected to take place in late 2024 or early 2025, pending decisions by Parks

Australia. Additionally, the outputs from this work hold potential for future research projects. For instance, NESP Projects 4.20 and 4.21 will use these outputs from this project as inputs for ecosystem modelling (e.g., Ecospace models) and to refine monitoring programs for Parks Australia. The findings are also directly relevant to research on the impacts of demersal trawling, providing evidence that trawling over functional reef areas would considerably affect the benthic assemblages of flat, sediment dominated regions of seabed. This is crucial to consider as trawling continues in many Australian Marine Park zones.

More broadly, understanding the extent of benthic habitats is crucial for guiding sustainable ocean development and preserving essential ecosystem services. This knowledge supports ecosystem-based fisheries, conservation efforts, and infrastructure management associated with the Australian government's Nature Repair Market, Sustainable Ocean Plan and Environmental-Economic Accounting efforts. Additionally, it provides a foundation for assessing cumulative anthropogenic and environmental impacts associated with the emerging offshore renewables sector.

7 References

Dunstan, P.K., Woolley, S.N.C., Monk, J., Barrett, N., Hayes, K.R., Foster, S., Howe, S.A., Logan, D., Samson, C.R., Francis, S.O. (2023). Designing a targeted monitoring program to support evidence-based management of Australian Marine Parks: National Implementation. For the National Environmental Science Program (Marine and Coastal Hub).

Foster, S.D., Hosack, G.R. Lawrence, E., Przeslawski, R., Hedge, P., Caley, M.J., Barrett, N.S., Williams, A., Li, J., Lynch, T., Dambacher, J.M., Sweatman, H.P.A, Hayes, K.R. (2017). Spatially Balanced Designs That Incorporate Legacy Sites. Methods in Ecology and Evolution. 8:11 1433-42.

Foster, S.D., Monk, J., Lawrence, E., Hayes, K.R., Hosack, G.R., Langlois, T., Hooper, G., Przeslawski, R. (2024). Statistical considerations for monitoring and sampling. In Field Manuals for Marine Sampling to Monitor Australian Waters, Version 3. Przeslawski R, Foster S (Eds). National Environmental Science Program (NESP).

Gelfand AE. 1996. Model determination using sampling–based methods. In: Gilks WR, Richardson Spiegelhalter DJ, eds. Markov Chain Monte Carlo in Practice. London: Chapman & Hall/CRC, 145–161.

Gibbs, J.W., 1902. Elementary principles in statistical mechanics: developed with especial reference to the rational foundations of thermodynamics. C. Scribner's sons.

Harvey ES, McLean DL, Goetze JS, Saunders BJ, Langlois TJ, Monk J, Barrett N, Wilson SJ, Holmes TH, Ierodiaconou D, Jordan AR, Meekan MG, Malcolm HA, Heupel MR, Harasti D, Huveneers C, Knott NA, Fairclough DV, Currey-Randall LM, Travers MJ, Radford BT, Rees MJ, Speed CW, Wakefield CB, Cappo M, Newman SJ (2021) The BRUVs workshop – an Australia-wide synthesis of baited remote underwater video data to answer broad-scale ecological questions about fish, sharks and rays. Marine Policy, 127: 104430

Hayes, K.R., Dunstan, P., Woolley, S., Barrett, N., Howe, S.A., Samson, C.R., Bowling, R., Ryan, M.P., Foster, S., Monk, J., Peel, D., Hosack, G.R., Francis, S.O. (2021). Designing a targeted monitoring program to support evidence-based management of Australian Marine Parks: A pilot on the South-East Marine Parks Network. For the National Environmental Science Program (Marine Biodiversity Hub).

Hayes, K. R., Walsh, P., Barrett, N., Cook, C. N., Dunstan, P., Flukes, E., Francis, S., Grammer, G., Hosack, G. R., Howe, S., Ierodiaconou, D., Langlois, T., Lawrey, E., Lieb, N., Logan, D., Lucieer, V., Monk, J., Williams, J., Woolley, S. N. C. (2024). Improving knowledge transfer to support Australian Marine Park decision making and management effectiveness evaluation. Report to the National Environmental Science Program. CSIRO, Hobart, Australia.

Hoffman, M.D., Gelman, A. (2014). The No-U-Turn sampler: adaptively setting path lengths in Hamiltonian Monte Carlo. Journal of Machine Learning Research, 15(1), pp.1593-1623.

Horn, B.K.P. (1981). Hill shading and the reflectance map. Proceedings of the IEEE 69, 14–47.

LaFrance, M., King, J. W., Oakley, B. A., Pratt, S. (2014). A comparison of top-down and bottom-up approaches to benthic habitat mapping to inform offshore wind energy development. Continental Shelf Research, 83: 24-44.

Langlois, T., Goetze, J., Bond, T., Monk, J., Abesamis, R., Asher, J., Barrett, N.S., Bernard, A., Bouchet, P., Birt, M., Cappo, M., Currey, L., Driessen, D., Fairclough, D., Fullwood, L., Gibbons, B., Harasti, D., Heupel, M., Hicks, J., Holmes, T., Huveneers, C., Ierodiaconou, D., Jordan, A., Knott, N., Malcolm, H., McLean, D., Meekan, M., Miller, D., Mitchell, P., Newman, S., Radford, B., Rolim, F., Saunders, B., Stowar, M., Smith, A., Travers, M., Wakefield, C., Whitmarsh, S., Williams, J., Harvey, E. (2020). A field and video-annotation guide for baited remote underwater stereo-video surveys of demersal fish assemblages. Methods in Ecology and Evolution, 11: 1401-1409

Langlois, T., Spencer, C., Gibbons, B.A., Griffin, K.J., Adams, K., Aston, C., Barrett, N., Bastiaansen, A., Beach, D., Bernard, A., Bond, T., Carey, G.R., Caselle, J.E., Cieri, K., Cummins, G.H., Cure, K., de Lestang, S., Fitzhardinge, J., Giraldo-Ospina, A., Grammer, G., Guilfoyle, D.R., Henderson, C., Hickey, S., Hicks, J., Hovey, R., Huveneers, C., Ierodiaconou, D., Keesing, J., Knott, N., Lavers, J.L., Lindfield, S., Lindholm, J., Mastrantonis, S., Matthews, K., Navarro, M.L., Partridge, J., Pellieter, D., Piggott, C., Przeslawski, R., Radford, B., Rees, M., Reynolds, R., Rolim, F.A., Smith, A., Spencer, F., Starr, R., Thompson, S., Webb, I., Webb, W., Whitmarsh, S., Williams, J., Monk, J. (in review) Benthic Observation Survey System (BOSS) to survey marine benthic habitats. Methods in Ecology and Evolution

Langlois, T., Spencer C., Griffin, K., Gibbons, B., Navarro, M., Giraldo, A., Webb, W., Webb, Z., Carey, G., Guilfoyle, D., Monk, J., Huang, Z., Nichol, S., Barrett, N. (2022). South-west Corner Marine Park Survey Report. Report to the National Environmental Science Program. University of Western Australia.

Langlois, T. J., Wakefield, C. B., Harvey, E. S., Boddington, D. K., & Newman, S. J. (2021). Does the benthic biota or fish assemblage within a large targeted fisheries closure differ to surrounding areas after 12 years of protection in tropical northwest. Marine Environmental Research. 170: 105403

Mastrantonis, S., Radford, B., Langlois, T., Spencer, C., de Lestang, S., Hickey, S. (2024). A Novel Method for Robust Marine Habitat Mapping Using a Kernelised Aquatic Vegetation Index. ISPRS Journal of Photogrammetry and Remote Sensing. 209: 472-480.

Neal, R.M. (2011). MCMC using Hamiltonian dynamics. Handbook of markov chain monte carlo, 2(11), p.2.

Stan Development Team. (2020). RStan: the R interface to Stan. http://mc-stan.org/

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H. (2019). Welcome to the tidyverse. Journal of Open Source Software. 4, 1686.

Wilson, M.F.J., O'Connell, B., Brown, C., Guinan, J.C., Grehan, A.J. (2007). Multiscale Terrain Analysis of Multibeam Bathymetry Data for Habitat Mapping on the Continental Slope. Marine Geodesy. 30 (1-2): 3–35.

Marine and Coastal

National Environmental Science Program

CONTACTS

Jacquomo Monk

jacquomo.monk@utas.edu.au

University of Tasmania

Tim Langlois

tim.langlois@uwa.edu.au

The University of Western Australia

This project is supported with funding from the Australian Government under the National Environmental Science Program.