# Scientific stock survey of sandfish and other sea cucumber species on Warrior Reef

**A report for the Australian Fisheries Management Authority**

**June 2025**
**Project 240818**
**Final Report**

### Acknowledgments

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# Scientific stock survey of sandfish and other sea cucumber species on Warrior Reef

**A report for the Australian Fisheries Management Authority**

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# Acronyms

| | |
|---|---|
| **AFMA** | Australian Fisheries Management Authority |
| **BDM** | Bêche-de-mer |
| **BlueBoat** | BlueRobotics BlueBoat automated surface vessel |
| **CFG** | Community Fisher Group |
| **CPUE** | Catch per Unit Effort |
| **FOV** | Field of view |
| **IP** | Intellectual property |
| **IUCN** | International Union for the Conservation of Nature |
| **mAh** | Milliamp hours |
| **PNG** | Papua New Guinea |
| **PZJA** | Protected Zone Joint Authority |
| **ROV** | Remotely operated vehicle |
| **Sandfish** | *Holothuria scabra* |
| **SDM** | Species distribution model |
| **TAC** | Total Allowable Catch |
| **TS** | Torres Strait |
| **TSRA** | Torres Strait Regional Authority |

# Reported sea cucumber species

Local names obtained from the Torres Strait Beche-dê-mer Fishery Management Arrangements booklet (AFMA, 2024).

| Common name | Local name | Scientific name |
|---|---|---|
| **Deepwater redfish** | Mamam Aber | *Actinopyga echinites* |
| **Stonefish** | Parak Aber | *Actinopyga lecanora* |
| **Surf redfish** | Teraber | *Actinopyga mauritiana* |
| **Deepwater blackfish** | Goleh-Goleh Aber | *Actinopyga palauensis* |
| **Leopardfish** | Kepkep Aber | *Bohadschia argus* |
| **Brown sandfish** | Susus Aber | *Bohadschia vitiensis* |
| **Lollyfish** | Wehwehsor Aber | *Holothuria atra* |
| **Snakefish** | | *Holothuria coluber* |
| **Black sea cucumber** | | *Holothuria leucospilota* |
| **Sandfish (common)** | Burbur Aber | *Holothuria scabra* |
| **Blackspotted sea cucumber** | | *Pearsonothuria graeffei* |
| **Greenfish** | Kerir Aber | *Stichopus chloronotus* |
| **Curryfish (common)** | Bambam Aber | *Stichopus herrmanni* |
| **Curryfish (ocellated)** | | *Stichopus ocellatus* |
| **Curryfish (vastus)** | Warwarr Aber | *Stichopus vastus* |
| **Snake sea cucumber** | | *Synapta maculata* |

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# Summary

The sandfish fishery on Warrior Reef in the Torres Strait has been closed since January 1998 due to overharvesting. Population surveys have been conducted periodically in 1995/96, 1998, 2000, 2002, 2004, and 2010 to assess the recovery of sandfish, *Holothuria scabra*, populations on Warrior and surrounding reefs. To assess the recovery of this population after 25 years of fishing closure, we conducted a survey on Warrior and Dungeness Reef to determine the relative abundance of sandfish and other sea cucumbers, in January and February 2025. Remote survey methods were employed to assess sandfish and other sea cucumber populations. A variety of tools were used, including remotely operated vehicles (ROVs), autonomous surface vessels (BlueBoat), and aerial drones.

In-water remote survey methods sampled approximately 19 hectares of reef over six consecutive survey days. Specifically, the ROV conducted 19 transects, totalling 45 km in length, amounting to 7.4 hectares. The BlueBoat performed 10 missions, surveying 102 km in length and an area of 11.5 hectares. Combined, these methods collected over 32 hours of underwater footage. Of this, 16.7 hectares of footage was collected at Warrior Reef and 2.4 from Dungeness Reef. The aerial drone conducted 28 flights, surveying 284 hectares of reef. For aerial surveys, 219 hectares of reef was collected from Warrior Reef over 24 flights and 65 hectares was collected from Dungeness over 4 flights. In total, remote underwater survey methods successfully detected and identified 2,040 sea cucumbers from 16 species. Footage assessed by the team from the ROV identified 1,398 sea cucumbers across 15 species, and footage from the BlueBoat identified 15 species, totalling 642 sea cucumber counts. Of this, sandfish (Holothuria scabra) was observed on 109 occasions, on seven BlueBoat transects and 14 ROV transects. A total of 74 sandfish were recorded on Warrior Reef and 35 on Dungeness Reef. Sandfish size ranged from 7 to 32 cm on Warrior Reef and 11 to 29 cm on Dungeness Reef, with no statistical difference for sandfish lengths between Reefs ($p > 0.05$).

Biomass assessments of sandfish suggest a total biomass of 64.69 t across both Warrior and Dungeness Reefs, and a fishable (> 18 cm TL) biomass of 52.84 t wet, or approximately 29.28 t gutted. This represents 60% of the available biomass estimated in the previous 2010 surveys, indicating the stock of sandfish has declined further despite an additional 15 years of fishery closures. The most likely explanation for these continued declines is unregulated ongoing fishing.

In addition to sandfish, stock estimates for the three next most abundant sea cucumbers are also presented: *Holothuria atra* (49% of total abundance), *Stichopus herrmani* (21%) and *S. vastus* (6.6%). The total estimated biomass for herrmanni curryfish (*Stichopus herrmanni*) of 856.13 t wet weight was approximately three times greater than in previous surveys. This may be in part due to the detection of this species in strata where it previously had not been detected, and due to higher densities recorded on Dungeness Reef. Other commercially important sea cucumbers were either observed in very low numbers (e.g., Deepwater redfish) or were not observed at all during the survey (e.g., hairy blackfish), rendering detailed assessment invalid.

# 1. Introduction

Marine resources have supported coastal communities for millennia, through food security, cultural practices and income opportunities. Tropical sea cucumbers are a conspicuous benthic invertebrate group that has been fished and traded for several centuries across southeast Asia. Demand for this valuable marine resource has increased globally, consequently increasing the risk of exploitation due to their high market value (Anderson et al., 2011). The sandfish, *Holothuria scabra*, has an important fishery in the Torres Strait, which provides opportunity for Islanders to generate substantial income at a community level, with dried product valued at US$300-500 per kg, equating to over $5 per kg in wet gutted weight.

The sea cucumber fishery in the Torres Strait historically harvests at least 22 different species at varying rates, however, fishing effort has declined in recent years due to the closure of fishing for high value species, such as sandfish (Plagányi et al., 2020). The sandfish fishery boomed in the Torres Strait in the early 1990s, with an estimated 1,200 to 1,400 t harvested in 1995 (Long et al., 1996). It was estimated that this harvest was equivalent to at least $6 M at the 2010 market price (Murphy et al., 2011). This triggered concerns of overharvesting and stock depletion, resulting in periodic fishery independent stock surveys being conducted at Warrior Reef. Initial surveys in 1995/96 found that the density of the breeding year class (2+ years old) was low, with an average density of ~ 45 adult sandfish per hectare, whereas the juvenile (< 14 cm) population had an average density of ~400 sandfish per hectare (Murphy et al., 2011). A second survey was conducted in January 1998 to assess recovery, which found that the population density had decreased since the 1995 survey, and that both the recruiting (1 yr +) and breeding classes (2 yr +) were depleted (Skewes et al., 1998). The sandfish fishery was subsequently closed in January 1998 as result of this finding.

Post closure, the sandfish population on Warrior Reef continued to be monitored, with further stock surveys occurring in 2000 (Skewes et al., 2000) and 2002 (Skewes et al., 2003), which exhibited small signs of recovery in numbers with an average increase of 36% in abundance since the January 1998 survey (Skewes et al., 2000). This slight increase in population density underpinned hopes that a strong recruitment event in the area may have occurred for the population(s). Following a further survey in early 2004, however, it was clear that sandfish density had returned to the depleted levels observed in 1998 (Skewes et al., 2006).

Once a sea cucumber population is depleted, recovery is often slow due to the biological constraints such as low fecundity, density dependent reproductive success, slow growth rates, connectivity barriers, low mobility and longevity (Hammond et al., 2023). Additionally, Warrior Reef has been subject to a degree of poaching on the Australian side of the border from Papua New Guinean Nationals, with evidence of illegal harvest of several species, including sandfish (Skewes et al., 2006; Murphy et al., 2011). The continued illegal harvesting of a depleted stock, throughout the closure period of the fishery, has been recognised as a major factor in the lack of recovery in the sandfish populations, particularly at Warrior Reef (Murphy et al., 2011). In response to these findings, the Australian Fisheries Management Authority (AFMA) led a surveillance operation at the Australia and Papua New Guinea (PNG) border at Warrior Reef to deter and apprehend poachers, with the goal of protecting the recovering sandfish stock from illegal fishing. This operation was active for three years (2006 to 2009) and was considered successful in its goal (Murphy et al., 2011).

As the surveillance operation had reduced the level of poaching from PNG and a decade of closure for sandfish fishing at Warrior Reef had passed, there was hope that these reduced anthropogenic stressors had allowed for greater recruitment and subsequent population recovery. Given this, managers and fishers supported a stock survey for sandfish, which occurred in January 2010 at Warrior Reef. Unfortunately, survey densities of sandfish were found at levels similar to those recorded in 2004; approximately 80% less than densities observed in the 1995/96 survey when the population was initially deemed overexploited (Murphy et al., 2011). This study suggested that the sandfish population at Warrior Reef is self-seeding, as indicated by the strong stock-recruitment relationship indicated by the survey data (Murphy et al., 2011). Limited gene flow commonly exists between sandfish populations on the Australian east coast (Uthicke & Benzie, 2001) and, given the lack of substantial sandfish populations in proximity to Warrior Reef, it is unlikely recruitment external to Warrior Reef plays a substantial role in population dynamics in this area. This highlights the importance of correct management of the Warrior Reef populations on population recovery (Murphy et al., 2011).

In 2024, our research team was employed to conduct another survey of the sandfish at Warrior Reef. The output objectives from our survey included (1) an analysis of the relative density of sandfish within available habitats of interest at Warrior and Dungeness Reefs compared to previous assessments, (2) high resolution habitat maps derived from aerial surveys, (3) a species distribution model for sandfish to predict suitable areas on Warrior Reef where sandfish are likely to occur, and (4) recommendations for future management strategies.

During our 2025 survey, we gathered data for all sea cucumber species encountered during surveys, including abundance, density estimates, as well as benthic habitat and structural complexity associations. Length data were also collected for all sea cucumbers to estimate population structure and available biomass. These data are in video and image format in addition to numeric format and thus present a permanent historic snapshot of the habitat that can be used to monitor environmental changes over time. Additionally, imagery generated through this survey provides opportunities for assessment of other species of interest, such as sea urchin, Trochus, or clam populations. The information from this survey will be implemented into the development of management frameworks to support the Torres Strait Hand Collectables Fishery.

## 1.1. Consultation

To ensure that the aims of the current survey aligned with those of the Torres Strait community, two half day consultations were run by our team on Iama Island as part of the development of the survey design. Discussions were facilitated by Charles David, a Iama Islander and TSRA representative, and were observed on the first day by Steve Harris from the Australian Fisheries Management Authority (AFMA). In attendance from Iama were members of the general community and local fishers, including people who had previously fished for sea cucumbers on Warrior Island.

PowerPoint presentations were given by Professor Jane Williamson and Dr Vincent Raoult on the history of the sandfish fishery surveys, the aims of the current survey, the new methods of data collection the current survey would use, and how these outputs would align to be directly comparable with those of previous surveys. A discussion then occurred with the audience and scientists, comprising questions about points within the presentation and capabilities of the new methods. Charles David was pivotal in this discussion, ensuring that all parties in the room were heard and comfortable in voicing their opinions. Attendees appeared to understand and approve the methods, timeline, and participation restrictions. Local IP was discussed and, as a result, our initial attendance sheet that included an IP clause was not individually signed but discussed at a community level. With the agreement of the community, local knowledge was incorporated in aspects of the survey design. This format of discussion was repeated over the two half days.

The reopening of the sandfish fishery on Warrior Reef was also discussed; however, it was made clear that our survey was independent of such a decision. While our data will be used by AFMA and the TSRA, our survey will make recommendations regarding the reopening of the fishery but will not be responsible for opening the fishery or continuing its closure.

After the discussion, a call for Islander participation was made and facilitated by the TSRA/Charles David. Two people local to Iama were chosen, however, one participant decided not to join surveys within days of the start of the survey. The other community researcher, Francis Filewood, was engaged as a Macquarie University contractor and attended the field survey.

## 1.2. Historic Warrior Reef Surveys

Previous surveys on Warrior Reef adopted stratified sampling methods relying on short (40–80 m) transects conducted via snorkel at high tide or walking at low tides. Historically, these surveys covered all strata of the reef, with some survey effort on Dungeness Reef in 2010 (Murphy et al., 2011). More recent surveys took a targeted approach that focused on the eastern side of Warrior Reef where more sandfish had been found previously (Murphy et al., 2011). In all cases, the methods used in previous surveys focused on surveying across the breadth of available reef area, rather than surveying larger total areas (Table 1).

Sandfish have various burying activity patterns across the diel cycle, which varies with age, season, time of day, tide and temperature (Mercier et al., 1999; Purcell 2010; Wolkenhauer & Skewes, 2009). Cryptic burying behaviours can lead to deflated estimates of biomass, reiterating the importance of conducting surveys at the same time of day, season and tide as previous surveys, to ensure comparability of results between present and past surveys.

***Table 1.*** *Summary of historic and current survey type, timing and sites/ transects assessed for sandfish stock on Warrior Reef, Torres Strait. The 2025 'sites' number represents the number of transects surveyed with remote survey methods. Historic survey summary information obtained from CSIRO 2011 Warrior Reef sandfish survey (Murphy et al., 2011).*

| Year | Date | Survey Type | Sites |
|---|---|---|---|
| 1995;1996 | 22-23/11/1995; 9/1/1996 | Full scale | 93 |
| 1998 | 14-17/1/1998 | Relative | 56 |
| 2000 | 19-24/1/2000 | Full scale | 165 |
| 2002 | 19-21/10/2002 | Relative | 56 |
| 2004 | 6-9/1/2004 | Relative | 56 |
| 2010 | 22-28/2/2010 | Relative | 173 |
| 2025 | 28-31/1/2025;1-2/1/2025 | Full scale | 29 (19 ha) |

# 2. Methods

## Study area – Warrior and Dungeness Reef

Historically, sandfish have only been found in high densities on Warrior Reef and Dungeness Reef. Warrior Reef is one of the largest reefs in the Torres Strait and is approximately 34 km long north-south, averages 5 km in width, and has an area of 165 $km^2$. It is one of three reefs in the Warrior Reefs Group, which comprise Warrior (Torres Strait), Auwamaza and Wapa Reefs (Papua New Guinea). The PNG reefs of the Warrior Reef Group are twice as large as Warrior Reef when combined, totalling 324 $km^2$ (Figure 1).

Warrior Reef is a unique reef located in the Northern Torres Strait, characterised by periodic exposure of the reef flat during low tides, and dense seagrass habitats. The eastern reef edge is ~1 m higher than the reef flat, central and back regions of the reef. The eastern reef crest is dominated by a continuous mat of coralline algae that are not common across the central regions of the reef (Long et al., 1996). Tucked behind the reef crest is a narrow transition zone of algae, coral, and rubble, with dense groups of the long spined sea urchin, *Diadema* spp. occupying interspersed shallow pools of water. Rubble and small rocks occur in higher density here than further across the reef flat. Small coral bommies are scattered here and while large bommies and rocks or boulders also occur, they are not common features. A dense swath of seagrass approximately 1.5 km wide occurs behind the reef crest transition zone. The seagrass thins out further west over the reef flat, forming a mixed habitat zone of sand and seagrass (Long et al., 1996). The western margin of the Reef is often lower in visibility and is characterised by a soft mud and sand substrate, with a shift in benthic diversity, with shell rubble, hydroids, sponges, corals and seagrass scattered throughout, before gradually dropping off to a muddy substrate at 5 m.

Dungeness Reef is approximately 6 km south of Warrior Reef with a large channel separating the two reefs. This reef has an area of 53 $km^2$, is 5 km long north to south, and an average of 4.5 km wide east to west. The eastern margin of Dungeness Reef is like that of Warrior Reef, with a wide coralline algae mat covering the edge. The reef crest consists of rubble and small coral and sponge structures, with sparse seagrass throughout. The reef flat is predominantly sparsely distributed seagrass and sand habitat, with some small coral structure and rubble present throughout.

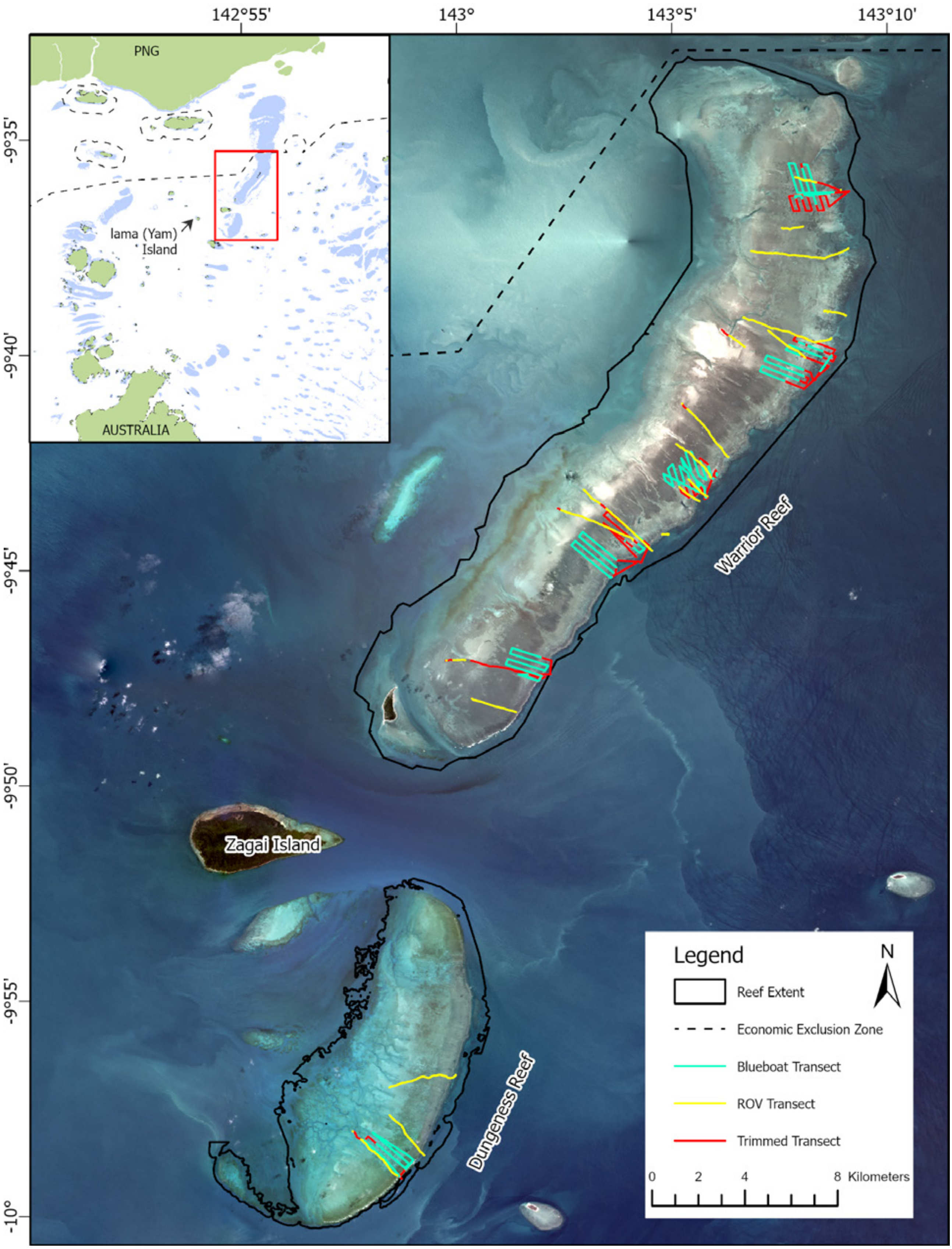



***Figure 1.*** *Underwater survey transects conducted by a Remotely Operated Vehicle (ROV, yellow line) and an autonomous surface vessel (BlueBoat, blue line), at Warrior and Dungeness Reefs, in January and February 2025 to assess the recovery of sandfish stocks, Holothuria scabra. Transects were trimmed (red line) for segments when visibility was too poor to process footage, so that area surveyed is accurately represented.*

## 2.1. Population survey – field sampling

Sampling was conducted over six days from the 28th January to 2nd February 2025, during Austral Summer. The survey period was timed to coincide with similar seasonal and tidal conditions as previous surveys to increase the ability to directly compare with other surveys. The first five days of sampling occurred at Warrior Reef, and the sixth day at Dungeness Reef.

Previous surveys were conducted as predetermined sites and assessed by either snorkelling at high tide and/or reef walking at low tide (Table 1). Our surveys used remote sampling to maximise the area that was assessed. As our survey used a different method to the previous surveys, and there was some uncertainty around the suitability of the new, remote methods with the local community, a decision matrix flowchart was designed to ensure that any risks arising using the new method could be quickly reduced and mitigated in the field (Figure 2). All sampling decisions were made using this framework, with footage reviewed upon the first day showing high levels of sea cucumber detection in remote survey footage. This matrix was used to assess the survey methodology at the end of each field day; examples of sandfish detection across both remote methodologies are shown in Figures 3 and 4. We also consulted with a local Torres Strait Islander (Francis Filewood) who assisted us during surveys and was familiar with the historical fishing of sandfishes on Warrior Reef, who confirmed he believed we should be able to see *H. scabra* given the quality of the footage and the locations we were surveying.

Surveys were carried out at approximately the same time of day (0900 hrs to 1500 hrs) and the same tide (high tide) as previous surveys to optimise comparison between successive surveys. Survey transects were performed by two remote in-water sampling methods:(1) an underwater drone (Remotely Operated Vehicle, ROV) and (2) an autonomous surface vessel (BlueBoat), with a mean transect length of 2.2 ± 0.2 km (mean ± S.E.) for the ROV and a mean total mission length of 9.5 ± 0.1 km for the BlueBoat. As previous surveys have surveyed repeated sites to compare sandfish stock over time, the transect start points were determined by proximity to sites assessed in previous surveys and were typically run in either a northwest or southeastern direction, across the length of the reef. Given previous surveys had focused on the eastern seagrass habitat side of Warrior Reef for *H. scabra* surveys, we focused most sampling effort in this area, though we attempted to extend ROV and BlueBoat surveys further towards the back reef and deep habitats where possible. The duration and length of a transect was determined by prevailing conditions such as wind, swell, depth and tide, as well as current consumption that related to battery endurance.

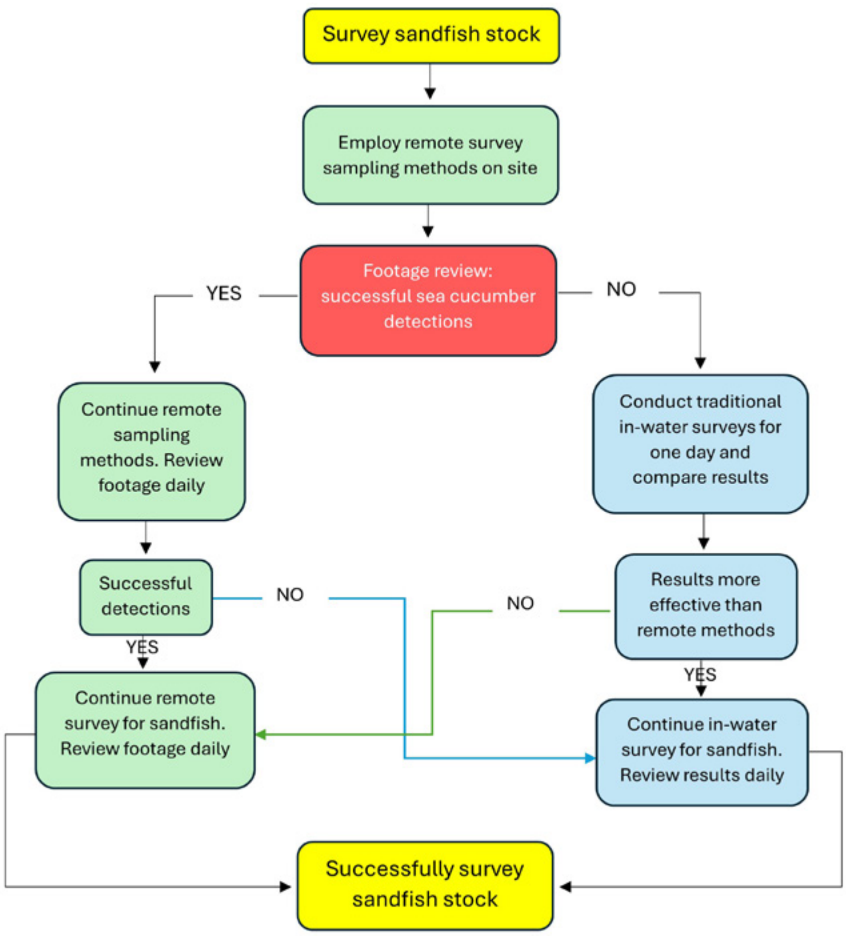



***Figure 2.*** *Fieldwork methods decision matrix flow chart used to assist researchers employ appropriate survey methods in the field, to ensure that a robust assessment of sandfish stock was conducted.*

### 2.1.1. Underwater drone (ROV) methodology

A Blue Robotics BlueROV2, fitted with a heavy lift kit, was used to conduct towed ROV transects on Warrior Reef to survey the sandfish population. The BlueROV2 was modified to operate in a towed capacity as described in Raoult et al., (2025) to reduce battery usage and enable the ROV to operate in stronger currents or tidal movements, which are characteristic of Warrior Reef. The ROV was fitted with a fish sounder (for altitude measurements), and two green wavelength parallel point lasers with a GoPro Hero12 positioned between. Both the lasers and camera were pointed straight down to the substrate, which allowed us to collect accurate count and length measurements of animals. The GoPro camera used a 256GB microSD card to capture and store high resolution footage of the benthos during transect surveys, with endurance batteries typically lasting 90 minutes in total. The GoPro camera would record continuous video at 4K resolution and 60 frames per second, with a wide-angle view setting and stabilisation, for the duration of the transect.

Between two to four ROV transects were conducted daily, with the number of transects determined by tide as a minimum of 0.8 m of water is required for the ROV and the vessel that tows it to safely survey across the reef flat. As described in Raoult et al., (2025), transect track coordinates (as seen in Figure 1) were collected by a GPS located on the tender. Once the ROV reached the transect start point the GPS was tracked by the pilot to follow the direction of travel of the tender conducting the tow. The ROV has an internal camera that is used to pilot the ROV. This is recorded at the commencement of the transect, and provides a second continuous video, and contains important environmental data in a subtext file that is overlayed, including depth, water temperature, and time of day.

ROV transects were run with the tide in a northwestern direction, or against it, travelling on a southeastern bearing. Whilst it is optimal for the ROV to travel at a height of 2.5 m above the substrate, this was not always possible during these surveys, due to the shallow reef edge and the poor visibility. Where the visibility was poor, the ROV pilot would adjust the ROV height above the substrate to ~1m, subsequently reducing the transect width. The ROV height above the substrate ranged from 0.8 to 2.5 m, depending on the characteristics of the habitat and the visibility. All changes in height were recorded and considered when determining densities. Transects ranged from 0.37 to 4.09 km, with survey durations between 13 minutes and 1 hour and 15 minutes.

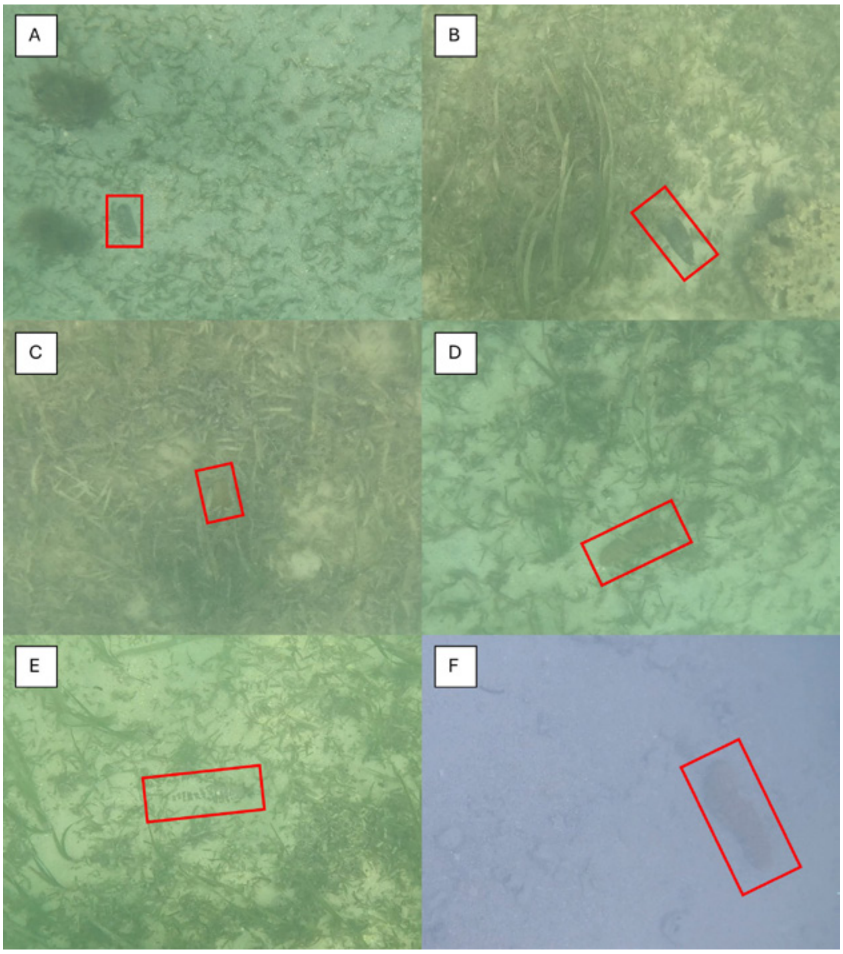



***Figure 3.*** *Examples of images collected from ROV footage, during the 2025 stock survey on Warrior Reef, Torres Strait. Red boxes delineate sandfish in each image.*

*(A) Juvenile sandfish (dark colour morph) fully exposed in sparse seagrass habitat.*

*(B) Adult sandfish (dark colour morph) partially buried in medium density seagrass.*

*(C) Adult sandfish (light colour morph) exposed yet obscured by dense seagrass, in low visibility.*

*(D) Adult sandfish (light) exposed in sparse seagrass.*

*(E) Adult sandfish (light) partially buried in sparse seagrass.*

*(F) Adult sandfish (light) fully exposed on sandy substrate, in low visibility.*

### 2.1.2. Autonomous surface vessel (BlueBoat) methodology

Autonomous surface vessel surveys were conducted using a Blue Robotics BlueBoat vessel. This automated vessel is 1.2 m long, powered by electric thrusters, and was modified with a DJI Action Pro 5 camera with a 256 Gb memory card fixed to the keel and facing straight down. This camera would record continuous video at 4K resolution and 50 frames per second, wide angle view setting, for the duration of the missions. The main control box was fitted with a panel antenna (~60° sensor direction) and fitted to a tripod, which was placed as high as possible on the main research vessel to increase reception likelihood. The BlueBoat was controlled from a Dell Rugged Latitude laptop and an Xbox One wireless controller. All missions were planned with QGroundControl software.

The BlueBoat surveys were constrained to shallow areas and high tides. Missions were designed to maximise survey efficiency, knowing that the approximate maximum spatial coverage of the vessel, equipped with 60,000 mAh battery payload, is approximately 10 km in distance (this aligns approximately with the onboard camera's battery endurance). The focal survey area was the area near the moored survey vessel, which was done to minimise time during which the BlueBoat was outside direct communication range. In general, this led to survey missions that were approximately 2 km long, with 250 m between parallel transects, in a lawn-mower pattern. Survey speed was set to 1 m/s, and the 'long' direction of the surveys were angled to be approximately with/against the prevailing waves to reduce the risk of the vessel capsizing. Tides permitting, two missions were run each day (approximately 20 km covered in total), one in the early incoming tide, and one just after the first mission.

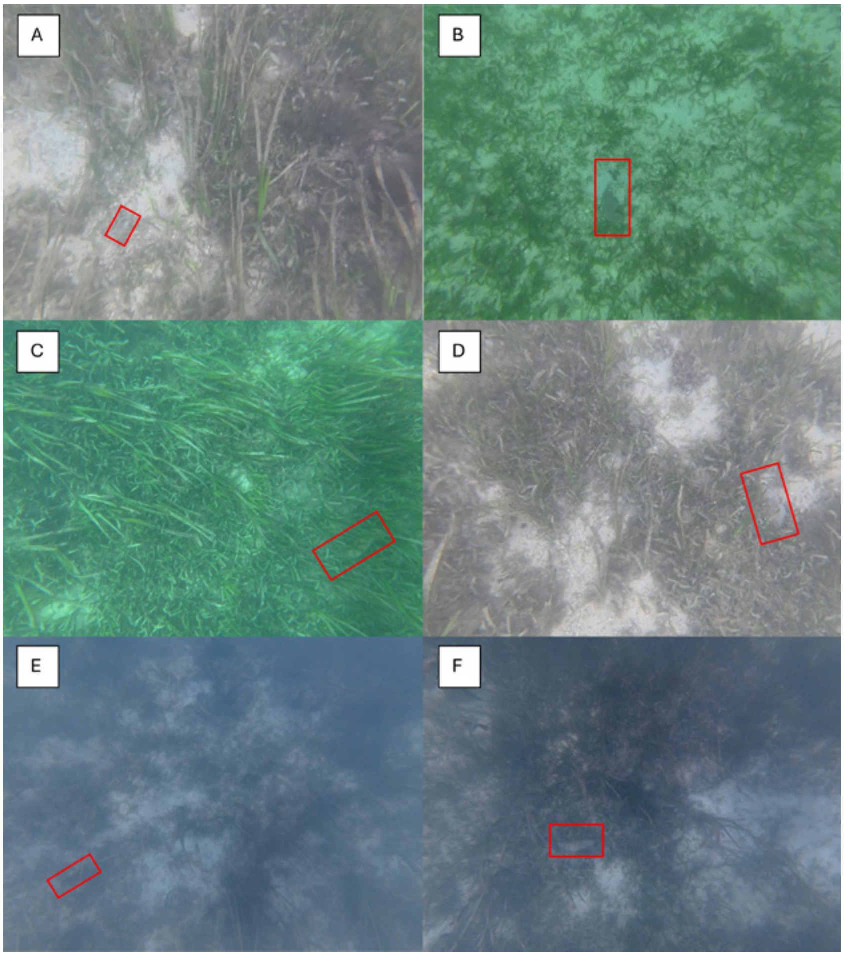



***Figure 4.*** *Examples of images from BlueBoat footage collected during the 2025 stock survey on Warrior Reef, Torres Strait. Red boxes delineate a sandfish in each image.*

*(A) Juvenile sandfish (light colour morph) detected in medium density seagrass, fully exposed.*

*(B) Adult sandfish (dark colour morph) partially buried in sparse seagrass.*

*(C) Exposed adult sandfish (light) in dense seagrass.*

*(D) Adult sandfish (light) fully exposed yet partially obscured by medium density seagrass.*

*(E) Adult sandfish (dark) in low visibility conditions, fully exposed in medium density seagrass.*

*(F) Adult sandfish (light), fully exposed in low visibility conditions in medium density seagrass.*

## 2.1.3. Underwater video survey data processing

Approximately 31 hours of underwater video footage was collected from transect surveys across Warrior and Dungeness Reefs, with 19 hours collected by the BlueBoat and 12 hours from the ROV. BlueBoat transects ranged from 9 to 10.2 km in length and took between 1 hr 50 min to 1 hr 58 min to complete. ROV transects ranged from 0.4 to 4.3 km and took between 13 minutes to 1 hour and 15 minutes to complete. Each transect video was watched in its entirety and time points were marked where the visibility was too poor (substrate not visible or high particulate matter in water column) to allow for accurate estimation of area surveyed (see Figure 1, red lines delineate trimmed transect). Footage was watched at a reduced playback speed of between 0.2 to 0.5 times, depending on the conditions of the transect, such as speed relative to substrate, visibility and habitat complexity.

### *ROV and BlueBoat transects*

For the ROV footage, video footage from the downward facing GoPro was watched in parallel to the video file generated by the internal ROV camera, to ensure that each sea cucumber was correctly timestamped, and the corresponding environmental data was attributed to the animal, such as depth and temperature (Raoult et al., 2025). BlueBoat transect footage was processed using the same methodology, however, the BlueBoat had no internal camera. To adapt to this, time of day was calculated from the known time at the start of the transect, and the timestamp on the DJI camera when a sea cucumber was observed. Additionally, a depth sounder onboard the BlueBoat recorded depth, time of day, as well as latitude and longitude, which was produced as a csv file for each transect. This csv file and the time of day was used to georeference each sea cucumber as well as deriving the depth. If the depth sounder had erroneous values, depth was linearly interpolated between the two last known points on the track. When a sea cucumber was observed on the ROV footage, it was identified to species by the processor, reviewed by an expert, then the depth and water temperature of the ROV was recorded from the footage collected by the ROV internal camera, which was watched in parallel to the GoPro imagery.

When a sea cucumber was observed during footage review, a unique ID was generated for the individual and a screenshot/ frame grab was taken, with the image file named accordingly (Figure 5, 6). Each sea cucumber was identified to species level, and where an identification was not possible, the animal was given a generic ID of ‘sea cucumber’. When sea cucumbers were identified to species level, the descriptions and images provided in the FAO’s ‘Commercially important sea cucumbers of the world - Second edition’ identification guide was used (Purcell et al., 2023). Benthic habitat classes (Table 2) were used to define the dominant (most abundant) habitat in the frame that sea cucumber was observed in, as per the Allen Coral Atlas categories (Allen Coral Atlas, 2022; Kennedy et al., 2021). A habitat complexity score was given to categorise the vertical structure, from low to high, adapted from benthic survey classifications defined by Long et al., (1996) and Hall and Kingsford (2021), and outlined in Table 3. The animal was recorded as either partially (partial) or fully (full) in the frame to improve accuracy when length measurements were taken. For an animal to be classed as ‘full’ in the frame, the whole animal had to be visible, from anterior to posterior end. If the animal was partially buried, or half of the animal was not in frame as the survey vessel travels over it, this is classed as ‘partial’. Each sea cucumber was then georeferenced to the ROV or BlueBoat track, based on the time of day, and assigned a geographic coordinate for later mapping.

***Table 2.*** *Benthic habitat classes used to document sea cucumber habitat preference, as defined in the Allen Coral Atlas.*

| Benthic habitat classification | |
|---|---|
| Coral/algae | Seagrass |
| Sand | Rubble |
| Rock | Microalgal Mat |

*Table 3. Definitions of habitat structural complexity.*

| Habitat structural complexity | Definition |
|---|---|
| Low | Flat substrate such as sand, no features such as rubble, coral bommies, or rocks present, (0 to 0.5 m). |
| Medium | Mostly flat substrate, with some rubble present, small coral bommies with spacing in between, or small to medium rocks, (0.5 to 1 m). |
| High | Limited flat substrate, rubble present, medium to large coral bommies with little flat space between, or medium to large rocks, (> 1 m). |

### 2.1.4. Size frequency data processing

Once footage processing was complete, each image/ sea cucumber was identified by its coordinates then measured for its total length using NIH Image and ImageJ (Schneider et al., 2012). The segmented line tool was used to measure the sea cucumber from anterior to posterior end and followed the centre line along the curve of the animal, considering the animal's height above the sea floor (Figure 6). If visible, the distance between the two green parallel point lasers was measured to determine any error in measurements (Figure 6). Each line was analysed for its pixel count, and measurements were exported as a csv file.

The following equations were used to determine the length of each animal. The width of the nadir (directly above) camera field of view was determined using the following equation, as the width varies as the survey vessels height above the substrate varies:

$$FoV_{width(m)} = 2 \times H \times tan(\tfrac{\theta}{2})$$

Where,

$H$ is the height above the substrate in meters, and

$\theta$ is the camera angle in degrees

The pixel to meter ratio was calculated using the following equation:

Where,

$FoV_w$ is the width of the camera's field of view in meters, and

$pixels$ is the width of the image (screenshot) in pixels

To convert the sea cucumbers length in pixels to cm:

$$Length_{sea\ cucumber\ (cm)} = (length_{(pixels)} \times pixel\ to\ meter\ ratio) \times 100$$

Where,

$length_{sea\ cucumber\ (cm)}$ is the length of the sea cucumber in pixels

$pixel\ to\ meter\ ratio$ is the ratio determined by image width $(pixels)$ and $FoV\ (m)$

***Figure 5.*** *An example screenshot of a sea cucumber identified for underwater processing. Footage is paused when a sea cucumber is in the frame (red box), and the green parallel point lasers are visible (red arrows). A screenshot is taken every time a sea cucumber is observed, and the image file is named and saved for length measurement processing.*

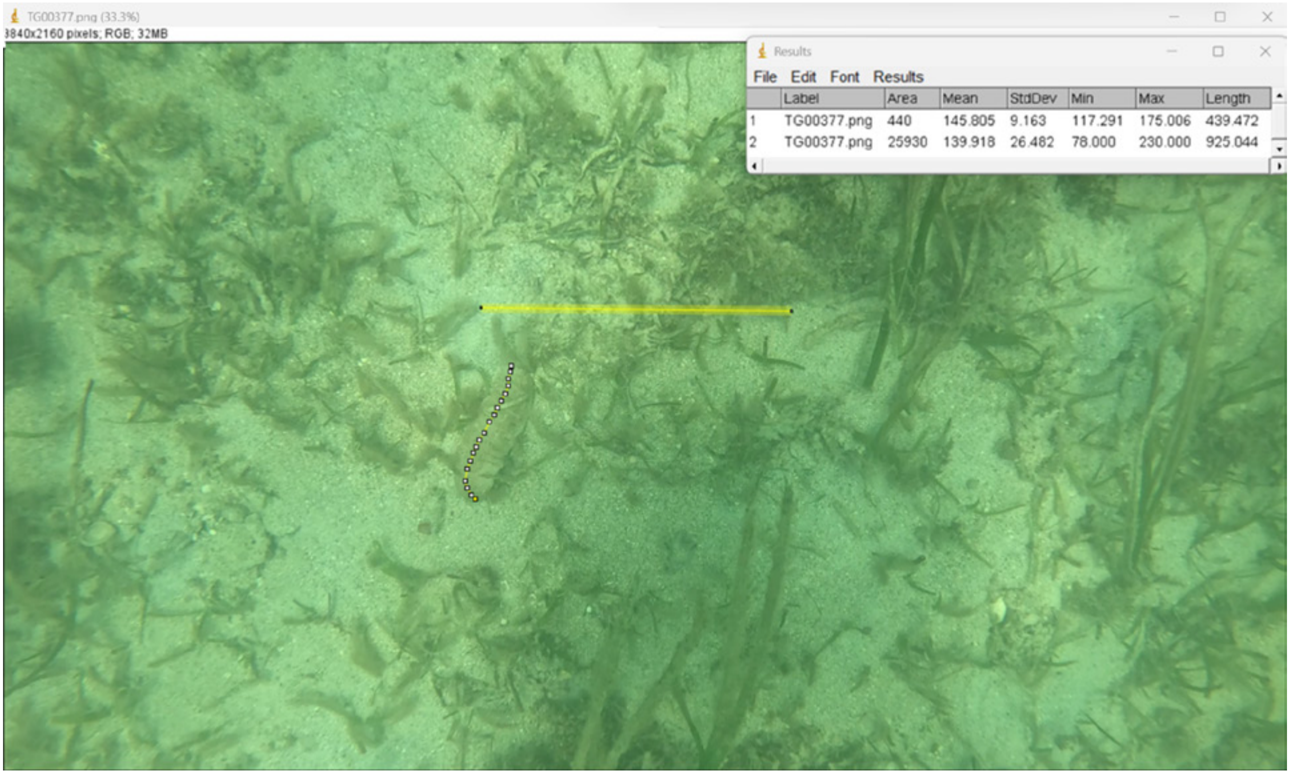



***Figure 6.*** *ImageJ was used to measure the length of each sea cucumber from anterior to posterior, following the curve of the animal. Where visible, the distance between the two green parallel point lasers is measured to determine the measurement accuracy.*

## 2.2. Habitat assessment - aerial drone

### 2.2.1. Aerial drone data capture and pre-processing

Aerial imagery was captured across representative habitats on Warrior and Dungeness Reefs using Autel EVO 2 and DJI Phantom 4 Pro drones. Survey sites were selected to encompass diverse habitats based on recent satellite imagery and feedback from the ROV and BlueBoat teams. Flights were conducted exclusively at low tide to minimize water column effects and outside midday hours to reduce sun glint.

A total of 28 surveys were completed, covering approximately 285 hectares. Two flight altitudes were used: 100 m to maximize regional coverage and 10 m for highly detailed mapping of targeted habitats. All missions were flown with 80% forward overlap and 80% sidelap, with images geotagged at capture. Orthomosaic images were generated post-flight using the GeoNadir platform for further habitat analysis.

### 2.2.2. Aerial imagery and habitat mapping

Drone imagery and satellite data were used to develop a quantitative habitat map over Warrior Reef and surrounding reefs. The objectives were to (1) create a foundation satellite image composite, (2) map benthic habitat categories in focus areas, and (3) scale quantitative habitat assessment across the region.

#### *Satellite Image Composite*

Given the large area and persistent cloud cover, a cloud-minimized composite was generated from Sentinel-2 Level-2A imagery (January 2023–December 2024). Processing steps in Google Earth Engine included cloud and shadow masking using the classification band, filtering to scenes with <50% cloud cover (n = 194), interquartile range filtering, and producing a median composite. The final 25th percentile composite was exported as a GeoTIFF for analysis. This composite represents typical surface conditions but integrates multiple dates and tidal stages.

#### *Habitat Classification*

Shallow reef areas were identified in the Sentinel-2 composite image using GeoNadir's magic wand segmentation tool. Multiresolution segmentation (eCognition) grouped similar pixels into ~216 segments, of which 22 were manually labelled as deep water, coral and algae, sand, or potential seagrass. The labelling was informed by the higher resolution drone data as well as underwater imagery from the ROV and BlueBoat. A random forest model was trained in RStudio on these labelled segments and used to classify all polygons across the study area, producing a map of inferred habitat types.

#### *Quantifying Seagrass Density*

Drone imagery was manually and automatically digitised to delineate seagrass patches. These were overlaid with a 10 × 10 m grid matching Sentinel-2 resolution. Within each grid cell, seagrass percent cover (0–100%) was calculated. Reflectance values (red, green, blue) from the satellite composite were extracted for each cell. A statistical model was then developed to predict seagrass density from reflectance, allowing estimates to be scaled across the satellite composite beyond drone-surveyed areas.

## 2.3. Data analysis

All ROV and BlueBoat transects were trimmed to remove portions of transects where footage analysis was not possible due to low visibility, and trimmed transects were used to derive accurate length surveyed per transect (Figure 1). The area of a transect was determined by multiplying the average field of view (1.8 m) with the transect length. For visualising sandfish density comparable to methods used in previous studies, each transect was divided into 200 m segments, and the midpoint coordinates marked for each segment, which were used when mapping density per segment.

All data analysis was performed in R version 4.4.1 and all map figures were created in ArcGIS Pro version 3.2.2.

### 2.3.1. Density and biomass

Densities of sea cucumbers were calculated using whole transect sections for each species and categorized according to which zone they were, using the same zones (stratas) identified in previous surveys (e.g., Murphy et al., 2011, Figure 13). Since some transects overlapped between zones due to their length, transect 'zone' was attributed using the georeferenced mid-point of the transect.

Biomass was calculated using an approach similar to Murphy et al., (2011). Using the mean strata density for each species of interest and its standard deviation, the estimated standing stock (n individual sea cucumbers) for each strata and species was calculated using the known areas of each strata and the associated mean densities. This standing stock was then transformed into biomass using known length-weight relationships of sea cucumbers and the mean length of the relevant size group as measured in this survey. Wet or gutted weight of the sea cucumber species (if relevant) was estimated using length weight relationships available in Skewes et al., (2000) for *H. scabra*, and McSpadden et al., (2024) for all other species. To provide conservative and best-case scenarios for biomass, 90% lower and higher confidence intervals of biomass were also calculated.

### 2.3.2. Species distribution models

Sea cucumber presence data were obtained from ROV and BlueBoat transect surveys, as described in the methods sections 2.1.3 above. The Presence-only Prediction (MaxEnt) in ArcGIS Pro (version 3.2.2) was used to model and predict the likely distribution of sandfish, and other sea cucumbers of interest, specifically curryfish herrmanni, curryfish vastus and lollyfish. Models were built progressively, per species, to determine which high resolution environmental variables provided the best predictions and create the most suitable models. Freely available environmental variable layers tested in initial models included bathymetry, slope, geomorphic zone, distance to reef, distance to land, tide, bulk carbonate percentage and sand percentage. All environmental variable layers were resampled to a cell size of ~33, using the cell size from the bathymetry layer as a reference, and projected to GDA2020 MGA54. The Geomorphic zone layer was derived from the Allen Coral Atlas (2022) and was modified to fit the model area. This included creating new classes for features such as Islands and the extensive deeper water. Additionally, two layers were created for the model area (Warrior and surrounding reefs), which included a habitat zone layer and seagrass density layer, which used drone imagery captured on the 2025 field survey, as described in Section 2.2. All models were trained using a predefined model area of interest, which included Warrior Reef, Dungeness Reef, and surrounding Islands such as Iama and Zagai. A mask was applied for Islands, as this was out of the habitat bounds for each species.

Based on a review of the testing models performance and layer suitability from training models, the environmental variables from the best-performing models (highest AUC and lowest omission rate) were retained for the final species distribution model, for each species (Table 4).

***Table 4.*** *Final iteration Presence-Only Prediction Model performance indicators and parameters for all four species.*

| Species | Layers | Model settings | AUC | Omission rate | Presence correctly classified (%) | Presence misclassified (%) | Background classified as potential presence (%) |
|---|---|---|---|---|---|---|---|
| ***H. scabra*** | Seagrass density, Habitat zone, Geomorphic zone | Basis function: Linear<br>Spatial thinning: 100 m<br>Weight of background points: 50<br>Cutoff: 0.5<br>Allow predictions outside data range: No<br>Sampling groups: Random, 3 | 0.9510 | 0.0615 | 93.85 | 6.15 | 11.03 |
| ***S. herrmanni*** | Seagrass density, Habitat zone, Geomorphic zone, distance to land | Basis function: Linear, Quadratic<br>Spatial thinning: 50 m<br>Weight of background points: 30<br>Cutoff: 0.5<br>Allow predictions outside data range: Yes<br>Sampling groups: Random, 3 | 0.9547 | 0.0381 | 96.19 | 3.81 | 8.65 |
| ***S. vastus*** | Seagrass density, Habitat zone, Geomorphic zone | Basis function: Linear<br>Spatial thinning: 100 m<br>Weight of background points: 50<br>Cutoff: 0.36<br>Allow predictions outside data range: Yes<br>Sampling groups: Random, 3 | 0.9582 | 0.0779 | 92.21 | 7.79 | 10.11 |
| ***H. atra*** | Seagrass density, Habitat zone, Geomorphic zone, distance to reef | Basis function: Linear, Quadratic, Product<br>Spatial thinning: 100 m<br>Weight of background points: 100<br>Cutoff: 0.5<br>Allow predictions outside data range: Yes<br>Sampling groups: Random, 3 | 0.9462 | 0.0263 | 97.37 | 2.63 | 11.97 |

# 3. Results

The Warrior Reef 2025 sandfish stock survey conducted population surveys across 16.7 ha on Warrior Reef, and 2.4 ha on Dungeness Reef. Whilst sandfish were the target species for the survey, at least 15 other species were also recorded on transects and subsequently analysed (Figures 7 and 8). These results begin with a habitat assessment (Section 3.1), analyse the sandfish stocks (Section 3.2), and assess 'other' sea cucumbers (Section 3.3), where the stocks of curryfish herrmani, curryfish vastus and lollyfish are analysed. For all sections, results are presented for both Warrior and Dungeness Reefs. An additional objective of this survey was to document the presence of other hand collectables, such as trochus and pearl shell, however, these were not detected during the 2025 survey. A total of 16 sea cucumber species were detected across all surveys. Of those species, the lollyfish (*Holothuria atra*) occurred in the highest densities, followed closely by curryfish herrmanni (*Stichopus herrmanni*; Figures 7 and 8). Most species, including commercially important curryfish vastus (*S. vastus*) and sandfish (*Holothuria scabra*) occurred in densities below 10 per hectare, on average (Table 5).

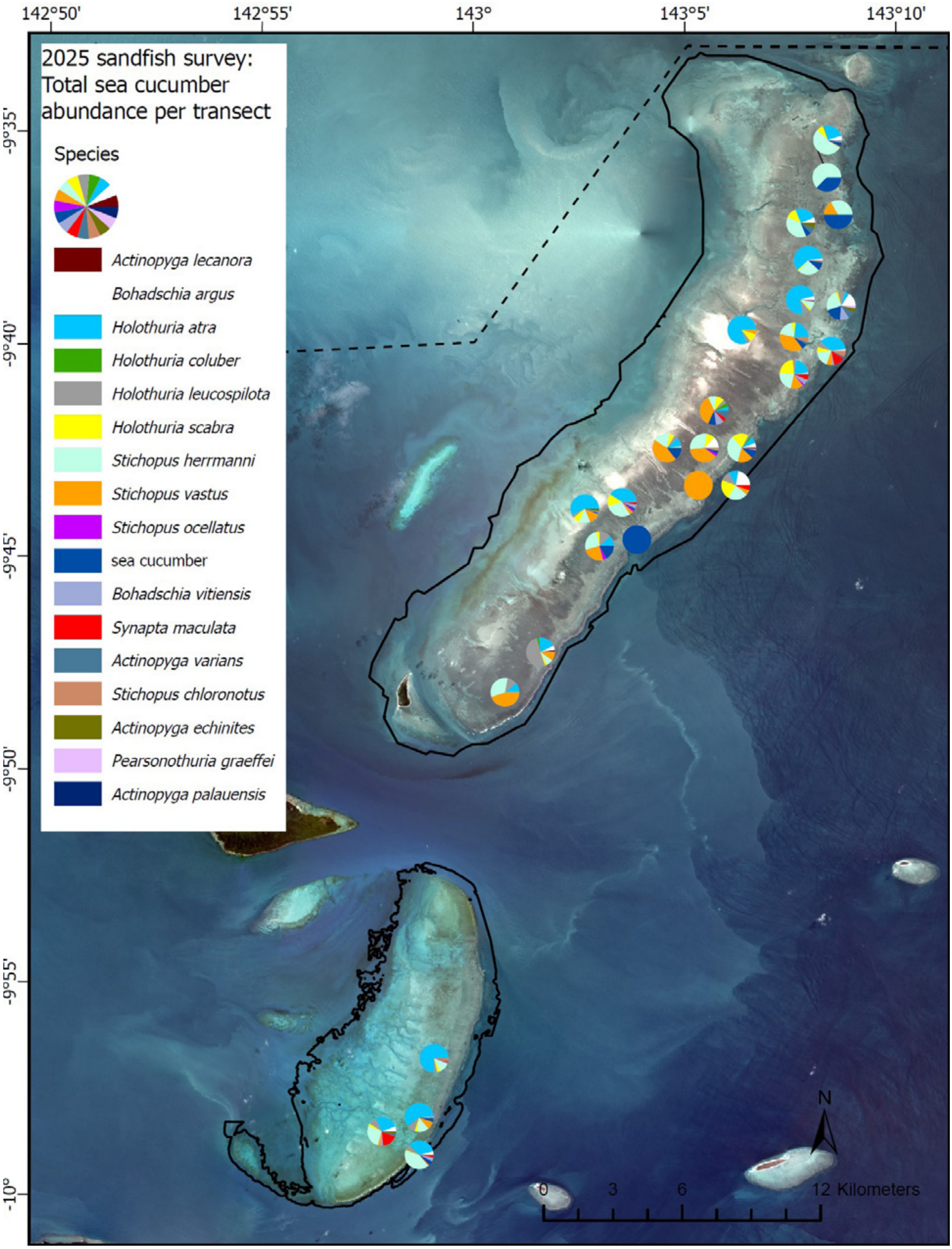



***Figure 7.*** *Mid-point location of transect surveys, on Warrior and Dungeness Reefs, showing proportion of species observed per transect. The group 'sea cucumber' is used when there is a sea cucumber present in the footage, but an identification cannot be determined, generally due to low visibility.*

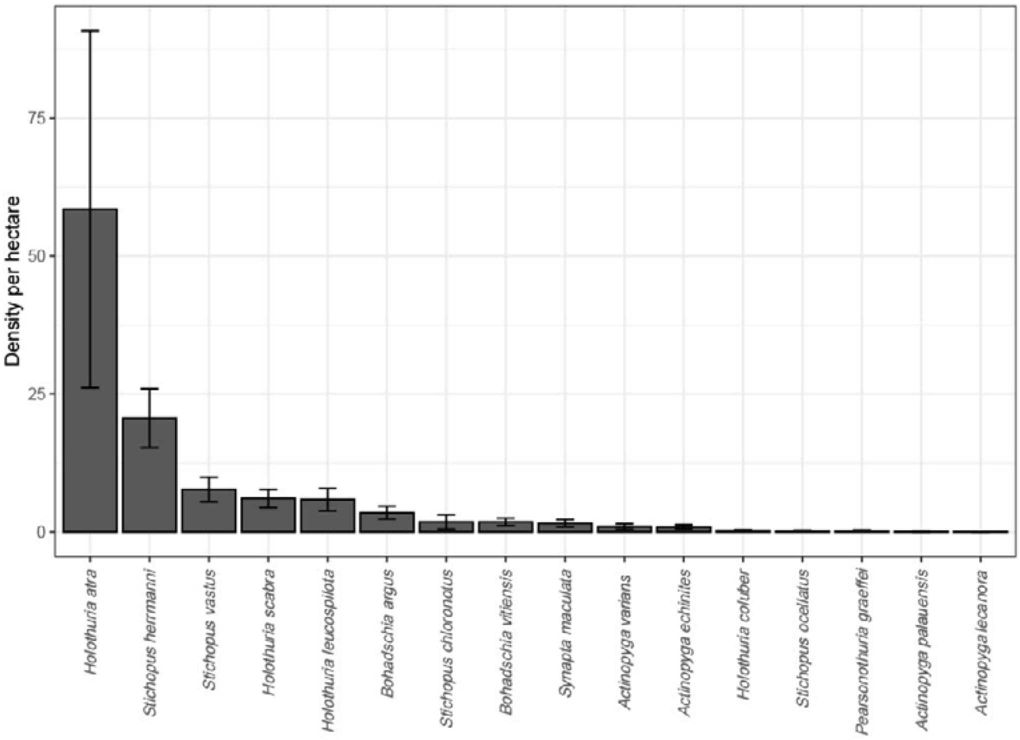



***Figure 8.*** *Mean ± S.E. densities of sea cucumbers for all species detected during the 2025 Warrior Reef surveys.*

***Table 5.*** *Summary statistics for densities of sea cucumbers across all transects and reefs.*

| Species | N transects | Density per ha | SD | SE | CI |
|---|---|---|---|---|---|
| *Actinopyga echinites* | 29 | 0.913 | 2.176 | 0.404 | 0.828 |
| *Actinopyga lecanora* | 29 | 0.022 | 0.121 | 0.022 | 0.046 |
| *Actinopyga varians* | 29 | 0.979 | 2.757 | 0.512 | 1.049 |
| *Actinopyga palauensis* | 29 | 0.083 | 0.447 | 0.083 | 0.170 |
| *Bohadschia argus* | 29 | 3.511 | 6.255 | 1.161 | 2.379 |
| *Bohadschia vitiensis* | 29 | 1.810 | 3.714 | 0.690 | 1.413 |
| *Holothuria atra* | 29 | 58.477 | 174.177 | 32.344 | 66.253 |
| *Holothuria coluber* | 29 | 0.267 | 0.621 | 0.115 | 0.236 |
| *Holothuria leucospilota* | 29 | 5.870 | 10.699 | 1.987 | 4.070 |
| *Holothuria scabra* | 29 | 6.081 | 8.681 | 1.612 | 3.302 |
| *Pearsonothuria graeffei* | 29 | 0.180 | 0.847 | 0.157 | 0.322 |
| *Stichopus chloronotus* | 29 | 1.814 | 7.089 | 1.316 | 2.696 |
| *Stichopus herrmanni* | 29 | 20.615 | 28.730 | 5.335 | 10.928 |
| *Stichopus ocellatus* | 29 | 0.185 | 0.551 | 0.102 | 0.210 |
| *Stichopus vastus* | 29 | 7.701 | 12.046 | 2.237 | 4.582 |
| *Synapta maculata* | 29 | 1.591 | 3.541 | 0.658 | 1.347 |

## 3.1. Habitat assessment – aerial drone

To remain consistent with previous surveys, we used the habitat mapping shown above for the modelling contained in this report. However, it is clear from our own field and image analysis experience that these habitat maps are limited in the detail that they provide. As such, we present here the preliminary results of our independent habitat assessments as per the methods detailed in Section 2.2.

From all the suitable Sentinel-2 images in the archive, the composite image represents a cloud-free scene of the region (Figure 9). This figure also demonstrates the clear challenge of cloudiness and using satellite remote sensing for benthic habitat assessments. However, this technique is reproducible in any region around the world using a large archive of freely available data. Further, as Sentinel-2 captures data on a regular basis (hundreds of times per year per location), this base map can be updated as needed.

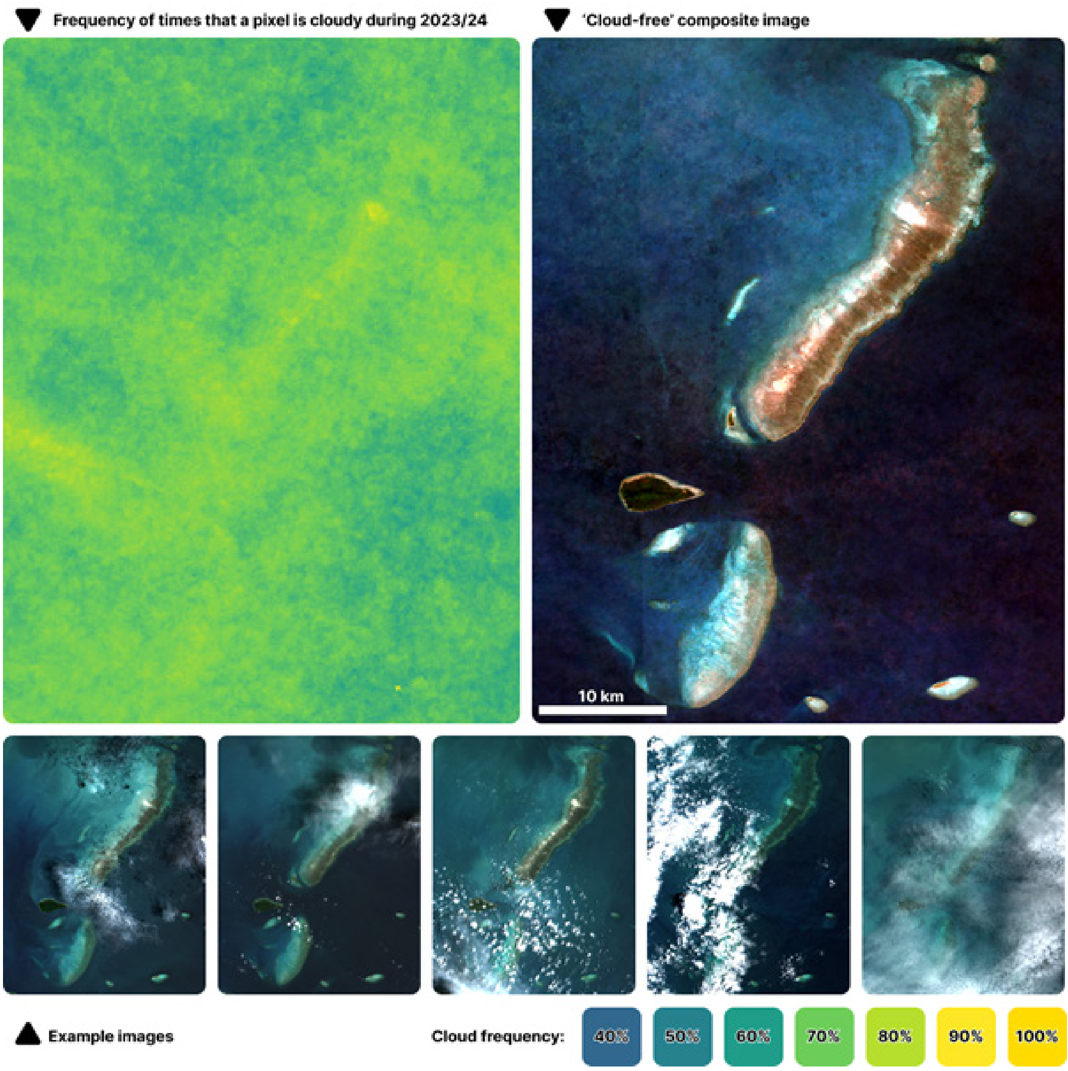



***Figure 9.*** *High percentages of cloud coverage in the Warrior Reef region demonstrate the challenge with using satellite imagery for benthic habitat assessments. Most of the region is cloudy in more than 70% of the images captured (example images show the varying extent). The processed Sentinel-2 image is a composite of 194 images across 2023-2024.*

In recognition of the high seagrass coverage on Warrior Reef that has previously not been sufficiently documented, our 'seagrass potential' map (Figure 10) allows us to delve deeper into the relationship between sea cucumber presence and seagrass density. Where previous studies have simplified the habitats into simple categories (e.g. sand, seagrass, coral...), our approach recognises the habitat heterogeneity, and that more than one category will exist within a single satellite image pixel.

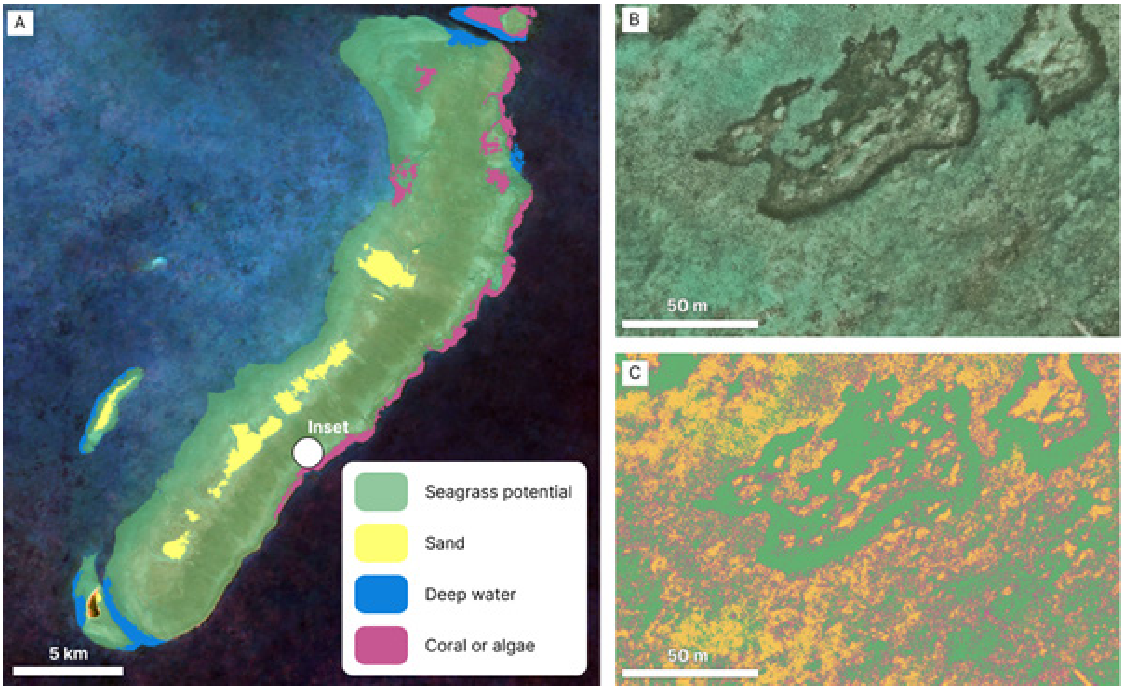



***Figure 10. (a)*** *The vast majority of Warrior Reef is covered by seagrass in some proportion. Green areas represent anywhere from 1-100% seagrass coverage at the scale of a Sentinel-2 image pixel (10x10m). Drone imagery* ***(b)*** *clearly shows the dark dense seagrass patches that have been classified as such* ***(c)*** *to be scaled back as density across the satellite imagery.*

Taking the high-resolution drone mapping classification of seagrass presence (Figure 10c) to the satellite image scale gives us seagrass density between 1-100% (Figure 11). This recognises that each pixel contains more than one benthic category but simplifies it to consider the amount of seagrass. This same technique can be used for other habitats of interest but is completed with seagrass here as a key co-variant of sea cucumber presence.

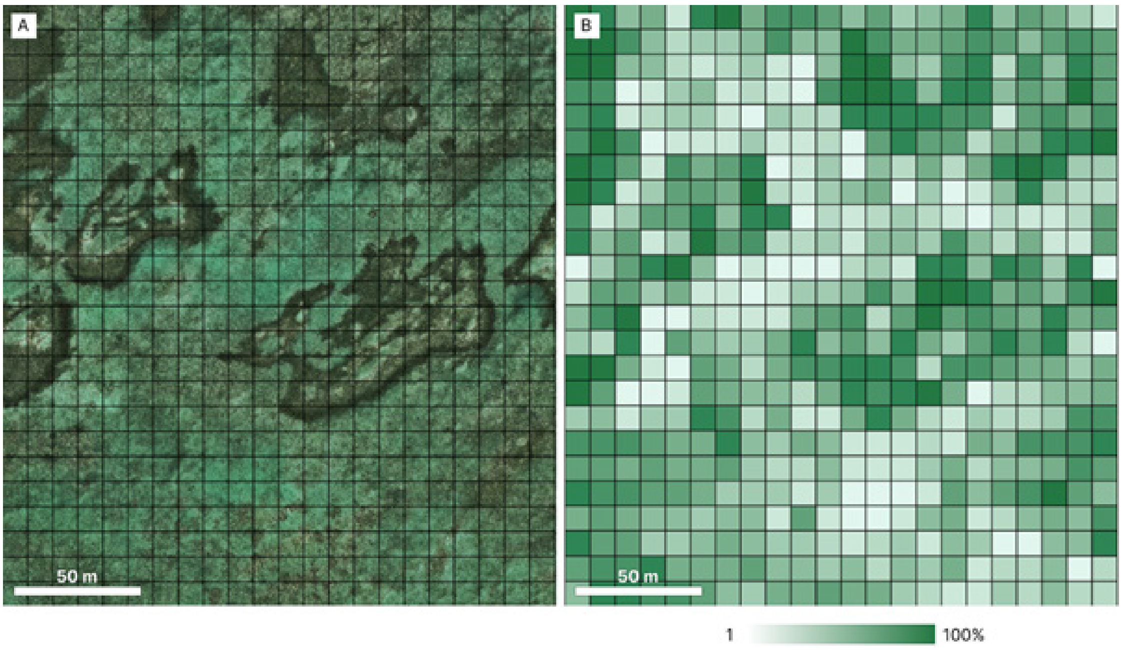



***Figure 11. (a)*** *Drone imagery superimposed with a grid representing the pixel size of Sentinel-2 image data (10 x 10 m);* ***(b)*** *Calculated seagrass density from 1-100% within each Sentinel-2 pixel.*

## 3.2. Population survey (Sandfish)

### 3.2.1. Sandfish, *Holothuria scabra*

Across both reefs, a total of 2,040 sea cucumbers from 16 species were recorded during transect surveys. Previous studies conducted transects, approximately 40 m in length, with a range of 56 to 173 sites sampled at Warrior and surrounding reefs. The previous survey in 2010 covered approximately 5.6 ha, at Warrior Reef. Sandfish were detected on 7/9 BlueBoat missions and 11/16 ROV transects at Warrior Reef. Sandfish were detected on all BlueBoat and ROV transects at Dungeness, where historic detections have been low, with no sandfish located in 2010 (Figure 12).


***Figure 12.*** *Densities per hectare of sandfish at Warrior and Dungeness Reef from observed counts on transect surveys, when divided into 200m segments to correspond to previous surveys. These smaller sections of transects were exclusively to act as visual aids, analyses used full survey lengths.*

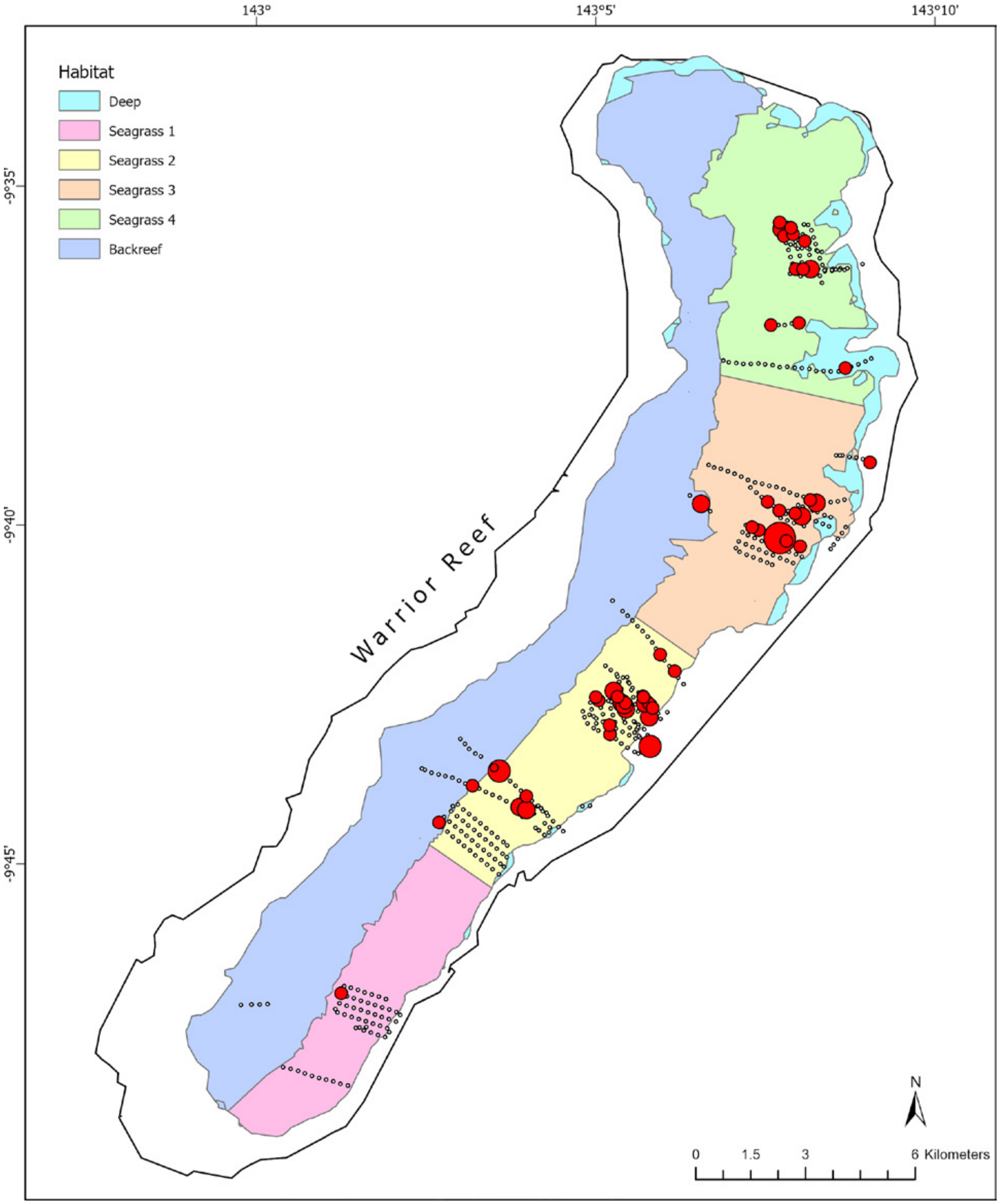



***Figure 13.*** *Strata type classifications on Warrior Reef as developed by CSIRO, from habitat and survey data (Skewes et al., 2001), with 2025 sandfish density overlaid. These strata classes informed stratified density estimates. To facilitate visual comparison to 2010 surveys and help identify locations where H. scabra was more abundant, whole transects were partitioned into 200 m sections.*

### 3.2.2. Sandfish biomass relative to historical values

Relative densities of *H. scabra* on Warrior Reef in 2025 were much lower than in all previous surveys (Figure 14, Tables 6, 7, 8, 9), and almost four orders of magnitude below estimated virgin *H. scabra* densities (Figure 15). Total biomass estimates of *H. scabra* were at approximately 60% of the levels in the prior 2010 survey, however, this was largely due to the added areas where *H. scabra* was not found in 2010 (e.g., Dungeness, deep reef) but detected in 2025 (Figure 16). Remaining biomass was approximately 3.8% of estimated virgin biomass of 1,666 tons prior to 1995 (Long et al., 1996).

#### *Sandfish Biomass (all reefs, all age groups)*

***Table 6.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025 (all reefs, all age groups). Strata layers obtained from CSIRO.*

| Strata | N transects (total area m²) | Strata Area (ha) | Mean density (per ha) | SD | 95% CI |
|---|---|---|---|---|---|
| **Seagrass 1** | 2 (18,939) | 1718.64 | 0.325 | 0.46 | 4.13 |
| **Seagrass 2** | 9 (56,137) | 1889.02 | 6.103 | 6.79 | 5.22 |
| **Seagrass 3** | 3 (23,673) | 2496.78 | 6.100 | 2.33 | 5.78 |
| **Seagrass 4** | 4 (24,628) | 2419.34 | 4.652 | 5.55 | 8.82 |
| **Backreef** | 3 (9,839) | 6897.42 | 5.681 | 4.93 | 12.26 |
| **Deep** | 4 (21,585) | 916.63 | 2.141 | 1.95 | 3.10 |
| **Dungeness** | 4 (31,502) | 5289 | 14.563 | 19.600 | 31.19 |

***Table 7.*** *Stratified mean and 90% confidence intervals of standing stock estimates for sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025 (all reefs, all age groups). Strata layers (Location) obtained from CSIRO.*

| Location | Standing stock (n individuals) | Biomass (t whole weight) | Biomass (t, gutted weight) | Lower 90% ci (t, gutted weight) | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|---|
| **Seagrass 1** | 559 | 0.23 | 0.13 | -0.08 | 0.33 |
| **Seagrass 2** | 11,529 | 4.76 | 2.59 | 1.01 | 4.17 |
| **Seagrass 3** | 15,230 | 6.29 | 3.42 | 2.18 | 4.66 |
| **Seagrass 4** | 11,255 | 4.64 | 2.53 | 0.05 | 5.00 |
| **Backreef** | 39,184 | 16.17 | 8.79 | 1.55 | 16.04 |
| **Deep** | 1,963 | 0.81 | 0.44 | 0.11 | 0.77 |
| **Dungeness** | 77,024 | 31.79 | 17.29 | -1.85 | 36.42 |
| **TOTAL** | **156,743** | **64.69** | **35.18** | **23.88** | **46.48** |

### *Sandfish Biomass (fishable size > 18 cm)*

***Table 8.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of fishable (> 18 cm) standing stock estimates for sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025. Strata layers obtained from CSIRO.*

| Strata | N transects (total area m2) | Strata Area (ha) | Mean density (per ha) | SD | 95% CI |
|---|---|---|---|---|---|
| Seagrass 1 | 2 (18,939) | 1718.64 | 0.325 | 0.46 | 4.13 |
| Seagrass 2 | 9 (56,137) | 1889.02 | 3.893 | 4.72 | 3.63 |
| Seagrass 3 | 3 (23,673) | 2496.78 | 4.529 | 0.92 | 2.28 |
| Seagrass 4 | 4 (24,628) | 2419.34 | 2.412 | 2.84 | 4.52 |
| Backreef | 3 (9,839) | 6897.42 | 3.655 | 3.33 | 8.27 |
| Deep | 4 (21,585) | 916.63 | 1.683 | 1.97 | 3.14 |
| Dungeness | 4 (31,502) | 5289 | 11.569 | 16.41 | 26.11 |

***Table 9.*** *Stratified mean and 90% confidence intervals of standing stock estimates for fishable (> 18 cm) sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025. Strata layers (Location) obtained from CSIRO.*

| Location | Standing stock (n individuals) | Biomass (t whole weight) | Biomass (t, gutted weight) | Lower 90% ci (t, gutted weight) | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|---|
| Seagrass 1 | 559 | 0.30 | 0.17 | -0.11 | 0.44 |
| Seagrass 2 | 7,354 | 3.89 | 2.20 | 1.27 | 3.13 |
| Seagrass 3 | 11,308 | 5.99 | 3.38 | 2.90 | 3.86 |
| Seagrass 4 | 5,835 | 3.09 | 1.74 | 0.87 | 2.62 |
| Backreef | 25,210 | 13.35 | 7.54 | 3.34 | 11.73 |
| Deep | 1,543 | 0.82 | 0.46 | 0.11 | 0.81 |
| Dungeness | 61,188 | 32.40 | 18.29 | 1.34 | 35.25 |
| **TOTAL** | **112,997** | **59.84** | **33.78** | **25.79** | **41.77** |

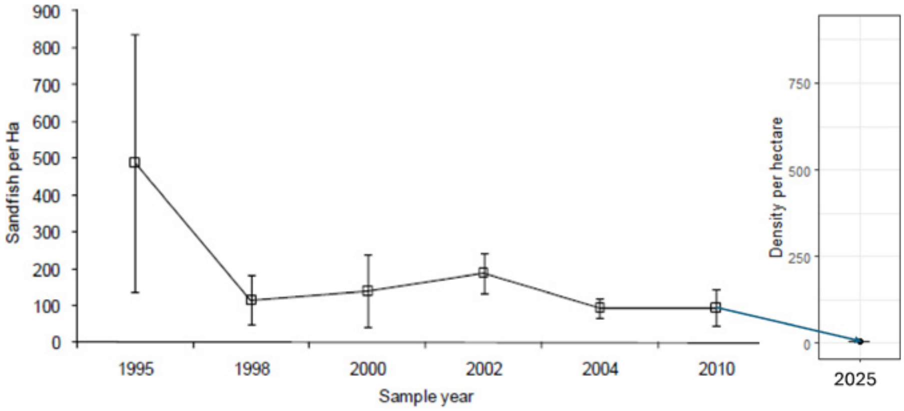



*Figure 14.* *Relative density of H. scabra compared to historic surveys, including the first survey in 1995 on Warrior Reef (including Dungeness in 2025). Figure adapted from Murphy et al., (2011).*

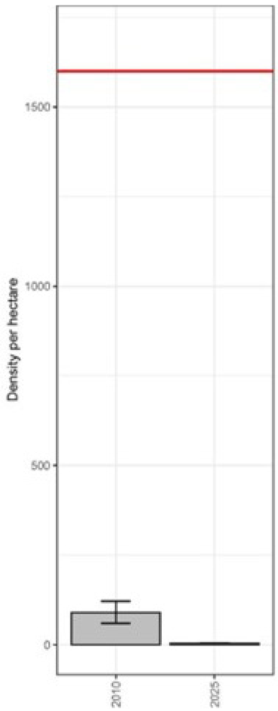



*Figure 15.* *Density of H. scabra ± S.E. across all surveys in 2010 and 2025. Red horizontal line indicates estimates of virgin (pre-fishing) densities prior to 1995, taken from Skewes et al., (1996). Historic density records were obtained from CSIROs 2010 survey on Warrior Reef, as shown in Murphy et al., (2011).*

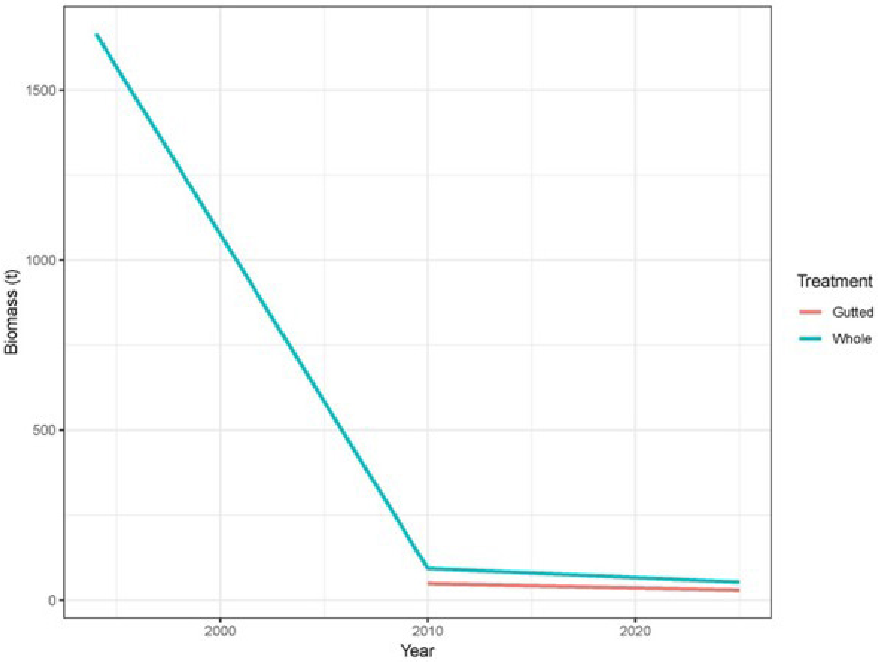



*Figure 16.* *Total H. scabra biomass estimates in Warrior Reef (including Dungeness, though none were found in 2010 surveys). 2010 biomass values obtained from the CSIRO (Murphy et al., 2011) and virgin biomass estimates from Long et al., (1996).*

### 3.2.2.1. Size frequency

The length frequency of sandfish collected during the January to February 2025 survey ranged from 7.4 to 32.4 cm (Figure 17). Due to the cryptic nature of small sandfish, it is likely that animals less than 10 cm are underrepresented in surveys. This is likely to cause an upwards bias due to low sampling effort for smaller juveniles, however, is a common issue across previous surveys at Warrior Reef. *In-situ* length data from the 2025 survey showed a greater proportion of the population surveyed is at a fishable size, with 68% of sandfish measured above the minimum size limit for the fishery, at 18 cm. It is possible that *in-situ* measurements resulted in a higher length bias relative to the *ex-situ* measurements of previous surveys due to the contractile response of sea cucumbers when out of the water, though this will be dependent on whether *ex-situ* measurements were done with sea cucumbers partially relaxed or not. The 1995/96 survey had elevated levels of juvenile sandfish, with most of the population sampled totalling < 14 cm in length (Murphy et al., 2011). This was similar for the 1998, and 2000 surveys, however the 2002 and 2004 showed a higher proportion of adults >14 cm, but below the minimum finishing limit (18 cm) (Murphy et al., 2011). The length results presented here are proportionally similar to those of the most recent study in 2010, with the majority of individuals measured adults at a fishable size (Figure 17).

Length frequency distributions were also compared by reefs for the 2025 study, with relatively similar distributions between Warrior and Dungeness Reefs (Figure 18). The size distribution ranged from 11 to 29.5 cm at Dungeness Reef.

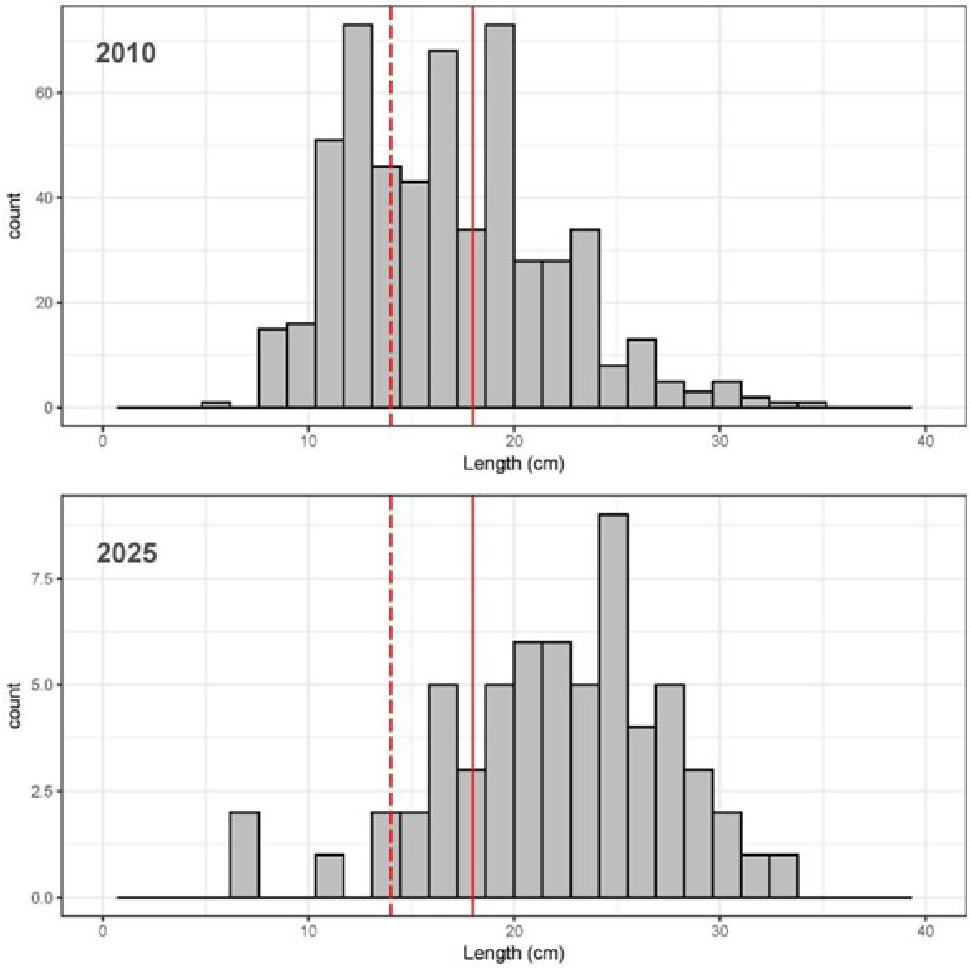



***Figure 17.*** *Length frequency distributions of all* ***Holothuria scabra*** *observed during the 2010 and 2025 Warrior Reef surveys. The 2010 length frequency data was obtained from the CSIRO (Murphy et al., 2011). Red dashed line indicates adult size (> 14 cm) and red line indicates minimum fishable size (> 18 cm). Note that the 2025 surveys used* ***in-situ*** *lengths, which may inflate sea cucumber lengths compared to the 2010 surveys which measured sea cucumbers ex-situ. Only* ***H. scabra*** *that were fully visible in the video frame and not buried were included in these measurements.*

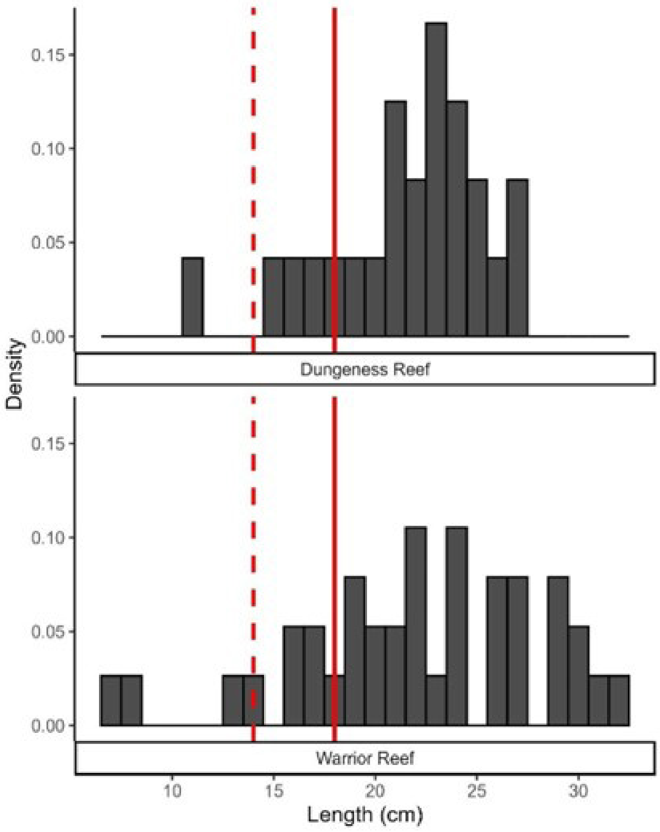



***Figure 18.*** *Length histogram of sandfish per reef, from the 2025 survey. The dotted line represents the size at maturity (14 cm) and the solid represents the minimum legal-size limit of the fishery (18 cm). Only sandfish that were fully visible in the frame and not buried have been included in the length histogram. Note that the 2025 survey used in-situ measurements.*

## *Diel proportions and behaviour of Sandfish*

Burying behaviours of sandfish reveals differences in activity patterns across the diel cycle, with the number of sandfish fully emerging on the surface of the substrate generally increasing throughout the day (Figure 19). The opposite effect was observed for burying behaviours, with a greater number of partially exposed (buried but dorsally visible) sandfish in the mornings, with this trend decreasing in the afternoon. These trends are distinct, with a significant interaction found between time of day and the burying behaviour exhibited by the sandfish (p = 0.01).

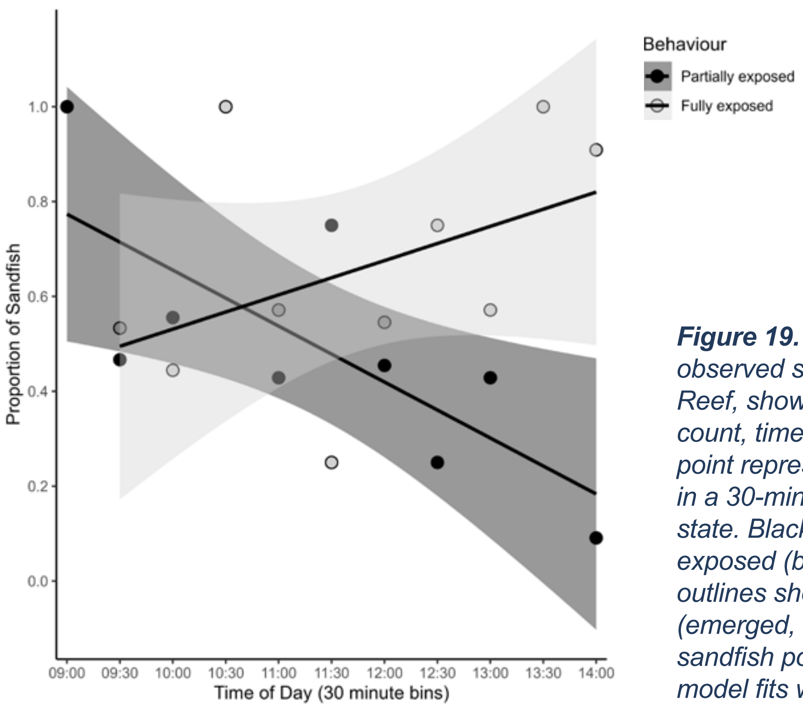



***Figure 19.*** *Emergent and burying patterns of all observed sandfish on Warrior and Dungeness Reef, showing the relationship between sandfish count, time of day, and behaviour types. Each point represents the number of sandfish observed in a 30-minute time bin, separated by behavioural state. Black circles show animals that were partially exposed (but fully visible), and grey circles with black outlines show individuals that were fully exposed (emerged, on the sediment surface) during the 2025 sandfish population surveys. Trend lines show linear model fits with 95% confidence intervals.*

### 3.2.2.2. Species Distribution Model

Best-performing species distribution models for *H. scabra* suggest the most suitable habitat for the species is in the central and northern parts of Warrior Reef, and this may represent a more constrained area than what was previously believed (Figure 20). 'Optimal' habitat (probability of presence > 0.75) covered just 20% of Warrior Reef area and 2% of Dungeness (Table 10). On Warrior Reef, 67% of the area had a greater than 50% chance (0.5 - 0.75) of presence of sandfish, whereas Dungeness had 79% (Table 10). Low suitability habitat (probability of presence < 0.5) was 13% at Warrior, and 19% at Dungeness (Table 10). Using the species distribution model probability layers rather than the stratified layers used previously results in a small decrease in fishable biomass, with a total whole animal biomass across Warrior Reef of 27.17 tons, and 26.46 tons on Dungeness Reef (Table 11). Interestingly, the probability of sandfish presence positively increased with seagrass density cover (Figure 21).

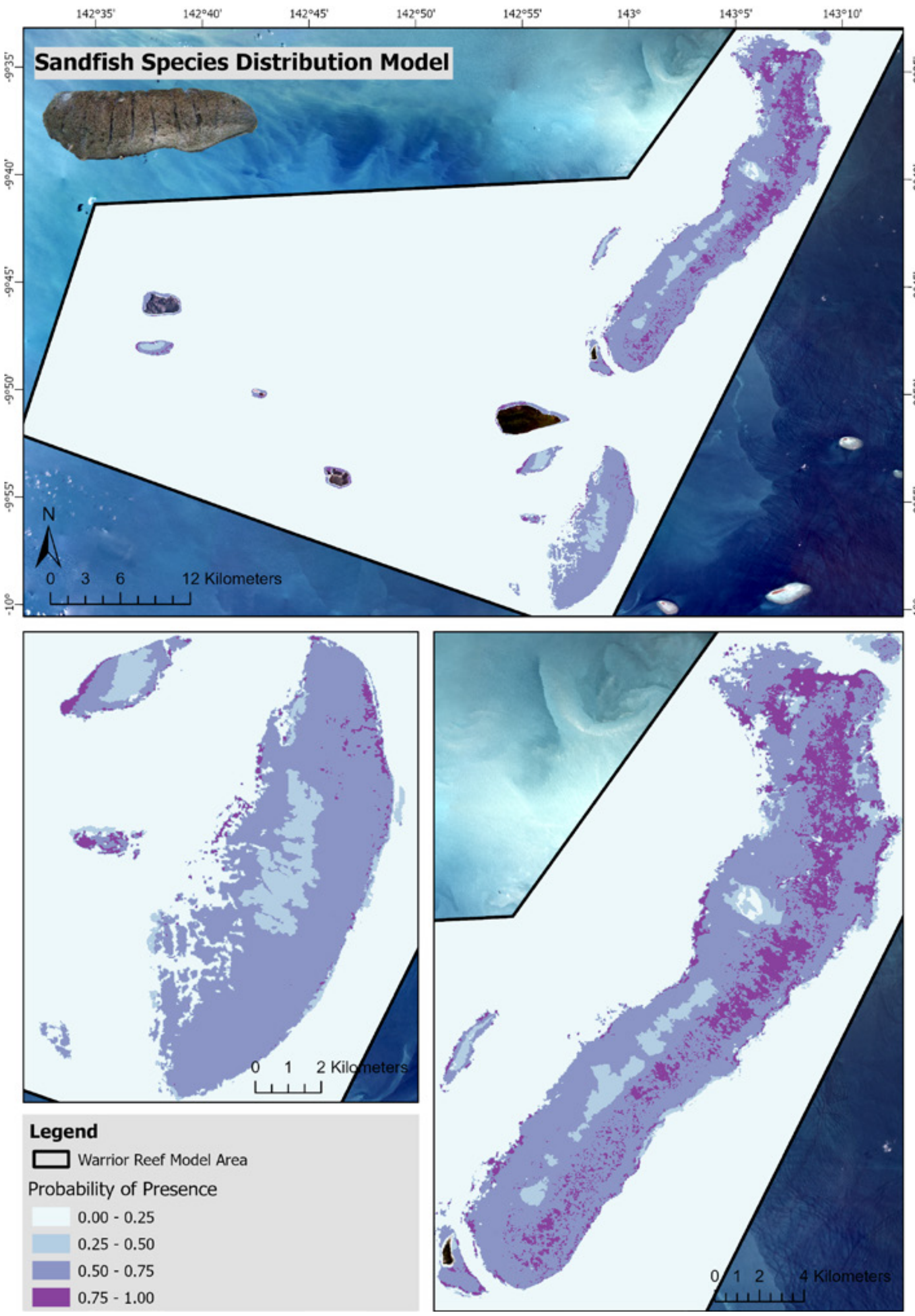



***Figure 20.*** *Species Distribution Model using the Presence-Only MaxEnt tool in ArcGIS Pro, showing the suitability of habitat for Holothuria scabra, based on known presence points.*

***Table 10.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for fishable (> 18 cm) sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025 (all reefs).*

| Reef | Probability area | N transects (area, $m^2$) | Strata Area (ha) | Mean density (per ha) | SD |
|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | 2 (4,774) | 821 | 0 | 0 |
| **Warrior** | 0.25 - 0.5 | 1 (10,903) | 1,281 | 0.917 | N/A |
| **Warrior** | 0.5 - 0.75 | 12 (90,689) | 10,900 | 3.370 | 4.141 |
| **Warrior** | 0.75 - 0.1 | 10 (60,950) | 3,301 | 3.526 | 2.605 |
| **Dungeness** | 0 - 0.25 | 0 | 427 | N/A | N/A |
| **Dungeness** | 0.25 - 0.5 | 0 | 593 | N/A | N/A |
| **Dungeness** | 0.5 - 0.75 | 4 (31,501) | 4,172 | 11.566 | 16.406 |
| **Dungeness** | 0.75 - 1.0 | 0 | 95 | N/A | N/A |

***Table 11.*** *Stratified mean and 90% confidence intervals of standing stock estimates for fishable (> 18 cm) sandfish (Holothuria scabra) for Warrior Reef surveys conducted in January 2025. Note that 0.25, 0.5 and 1.0 probability areas were not calculated for Dungeness since surveys were not conducted in those areas.*

| Reef | Probability area | Standing stock (n individuals) | Biomass (t whole weight) | Biomass (t, gutted weight) | Lower 90% ci (t, gutted weight) | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | 0 | 0 | 0 | 0 | 0 |
| **Warrior** | 0.25 - 0.5 | 1,175 | 0.64 | 0.35 | N/A | N/A |
| **Warrior** | 0.5 - 0.75 | 36,737 | 20.14 | 10.98 | 4.57 | 17.39 |
| **Warrior** | 0.75 - 0.1 | 11,640 | 6.38 | 3.48 | 2.14 | 4.82 |
| **Dungeness** | 0 - 0.25 | | | | | |
| **Dungeness** | 0.25 - 0.5 | | | | | |
| **Dungeness** | 0.5 - 0.75 | 48,253 | 26.46 | 14.43 | -2.40 | 31.26 |
| **Dungeness** | 0.75 - 0.1 | | | | | |
| **TOTAL** | | **97,805** | **53.62** | **29.24** | **18.57** | **39.91** |

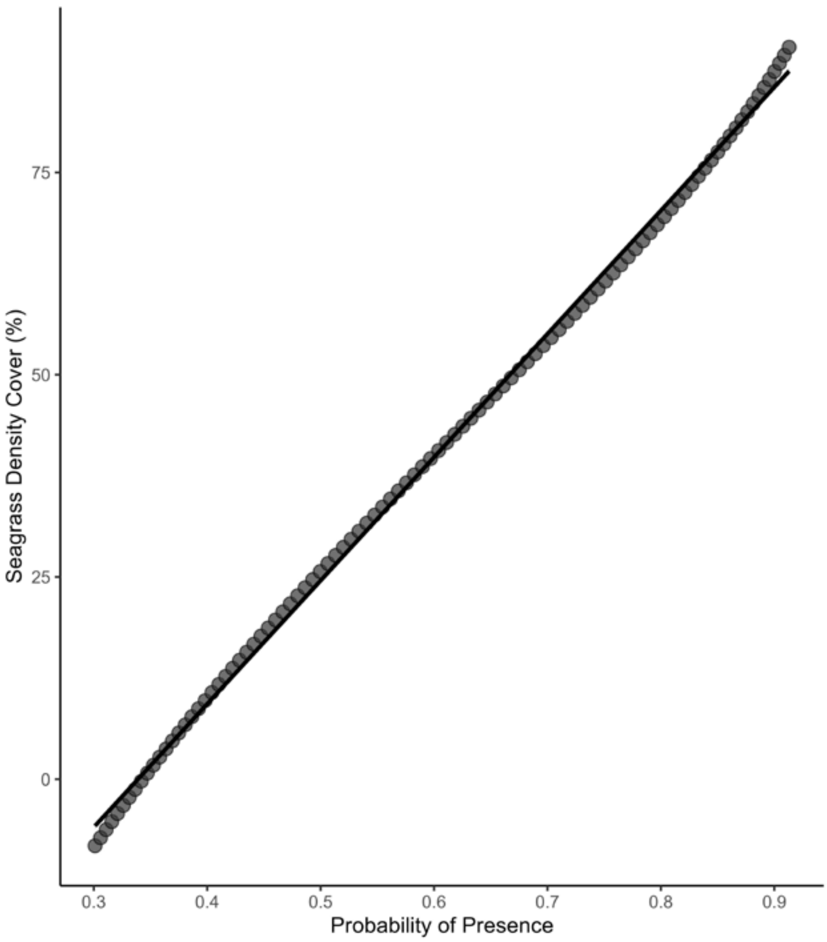


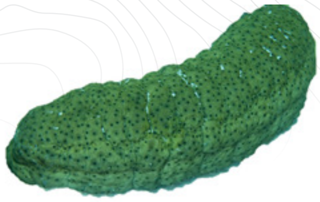

***Figure 21.*** *The partial response curve for sandfish (H. scabra) showing the probability of this species occurrence in relation to the percentage cover of seagrass density. Trend lines show linear model fits with 95% confidence intervals. Refer to Section 3.1 for descriptions of how this continuous raster layer was created.*

## 3.3. Population survey (other sea cucumbers)

Whilst sandfish was the primary target of the population survey, data were also collected on all other sea cucumber species encountered. Here we present an estimation of stocks of the three most abundant sea cucumbers found on Warrior and Dungeness Reef, including two curryfish species (*Stichopus herrmanni*, *S. vastus*) and lollyfish (*Holothuria atra*). Curryfish species combined accounted for approximately 28% off all sea cucumbers recorded during the sandfish stock survey on Warrior and Dungeness Reef. Of all sea cucumbers, 21% were *Stichopus herrmanni*, 6.6% *S. vastus*, and 0.2% were *S. ocellatus*. Curryfish species are of medium value in the bêche-de-mer market and have a TAC of 60 t in the Torres Strait BDM fishery. Lollyfish (*Holothuria atra*) were the most common species, making up 49% of all sea cucumber detections, more specifically *H. atra* accounted for 34% of sea cucumber detections on Warrior Reef and 61% at Dungeness. Lollyfish is a low-value species, with a minimum size limit of 15 cm in the Torres Strait BDM fishery and is open to fishing with a basket TAC of 50 t (for all ‘other’ sea cucumbers, AFMA, 2024). These results in Section 3.3 analyse the stocks of curryfish herrmanni, curryfish vastus and lollyfish.

## 3.3.1. Curryfish, *Stichopus herrmanni*

### 3.3.1.1. Curryfish herrmanni biomass



#### *Relative density, Stichopus herrmanni*

*S. herrmanni* was the second most common species of sea cucumber observed beyond sandfish, and was detected across all reef zones, at both Warrior and Dungeness Reefs, and in almost all transects (Figure 22). Relative to the 2000 surveys, *S. herrmanni* densities appeared stable, however, in 2025 we also detected *S. herrmanni* in the other habitat zones of Warrior Reef (deep, backreef) in relatively high densities, as well as on Dungeness Reef (Table 12). As a result, calculating total biomass led to a much larger population estimate (over 500,000), approximately three times greater than the estimates from the 2000 survey (Table 13), with a total estimated biomass of 856 tons. We also note that 2000 surveys likely pooled *S. herrmanni* and *S. varigatus* (now *S. horrens*), and so this difference is likely to be larger.


***Figure 22.*** *Relative densities of S. herrmanni across all transects. Note that large transects here were broken up into 200 m sections to facilitate visual interpretation relative to previous surveys.*

***Table 12.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for curryfish (Stichopus herrmanni) for Warrior Reef surveys conducted in January 2025. Strata layers obtained from CSIRO.*

| Strata | N transects (total area m²) | Strata Area (ha) | Mean density (per ha) | SD | 95% CI |
|---|---|---|---|---|---|
| Seagrass 1 | 2 (18,939) | 1718.64 | 5.184 | 4.57 | 41.08 |
| Seagrass 2 | 9 (56,137) | 1889.02 | 10.834 | 9.99 | 7.68 |
| Seagrass 3 | 3 (23,673) | 2496.78 | 16.689 | 8.25 | 20.49 |
| Seagrass 4 | 4 (24,628) | 2419.34 | 25.317 | 23.77 | 37.82 |
| Backreef | 3 (9,839) | 6897.42 | 4.346 | 12.85 | 18.70 |
| Deep | 4 (21,585) | 916.63 | 16.333 | 7.53 | 27.81 |
| Dungeness | 4 (31,502) | 5289 | 65.067 | 55.34 | 88.06 |

***Table 13.*** *Stratified mean and conservative 90% confidence intervals of standing stock estimates for curryfish (Stichopus herrmanni) for Warrior Reef surveys conducted in January 2025. Strata layers (Location) obtained from CSIRO.*

| Location | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci t, whole weight) | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|
| Seagrass 1 | 8,909 | 8.86 | -0.37 | 29.63 |
| Seagrass 2 | 20,466 | 36.90 | 16.61 | 50.60 |
| Seagrass 3 | 41,669 | 54.40 | 36.30 | 100.55 |
| Seagrass 4 | 61,250 | 166.70 | 22.91 | 178.24 |
| Backreef | 29,976 | 52.61 | -89.00 | 187.45 |
| Deep | 14,971 | 27.24 | 15.26 | 33.91 |
| Dungeness | 344,139 | 540.64 | 169.79 | 960.40 |
| **TOTAL** | **521,381** | **856.13** | **633.66** | **1078.60** |

### 3.3.1.2. Species distribution model

For curryfish herrmanni, the best-performing species distribution model suggests the most suitable habitat for the species is in the central region, particularly along the reef edge and the back reef edge of Warrior Reef, and the northern reef edge of Dungeness (Figure 23). The 'optimal' habitat (probability of presence > 0.75) for curryfish herrmanni covered just 16% of Warrior Reef area and 4% of Dungeness (Table 14). On Warrior Reef, 50% of the area had a greater than 50% probability (0.5 - 0.75) of curryfish herrmanni presence, whereas Dungeness had 76% (Table 14). Low suitability habitat (probability of presence < 0.5) was 34% at Warrior, and 20% at Dungeness (Table 14).

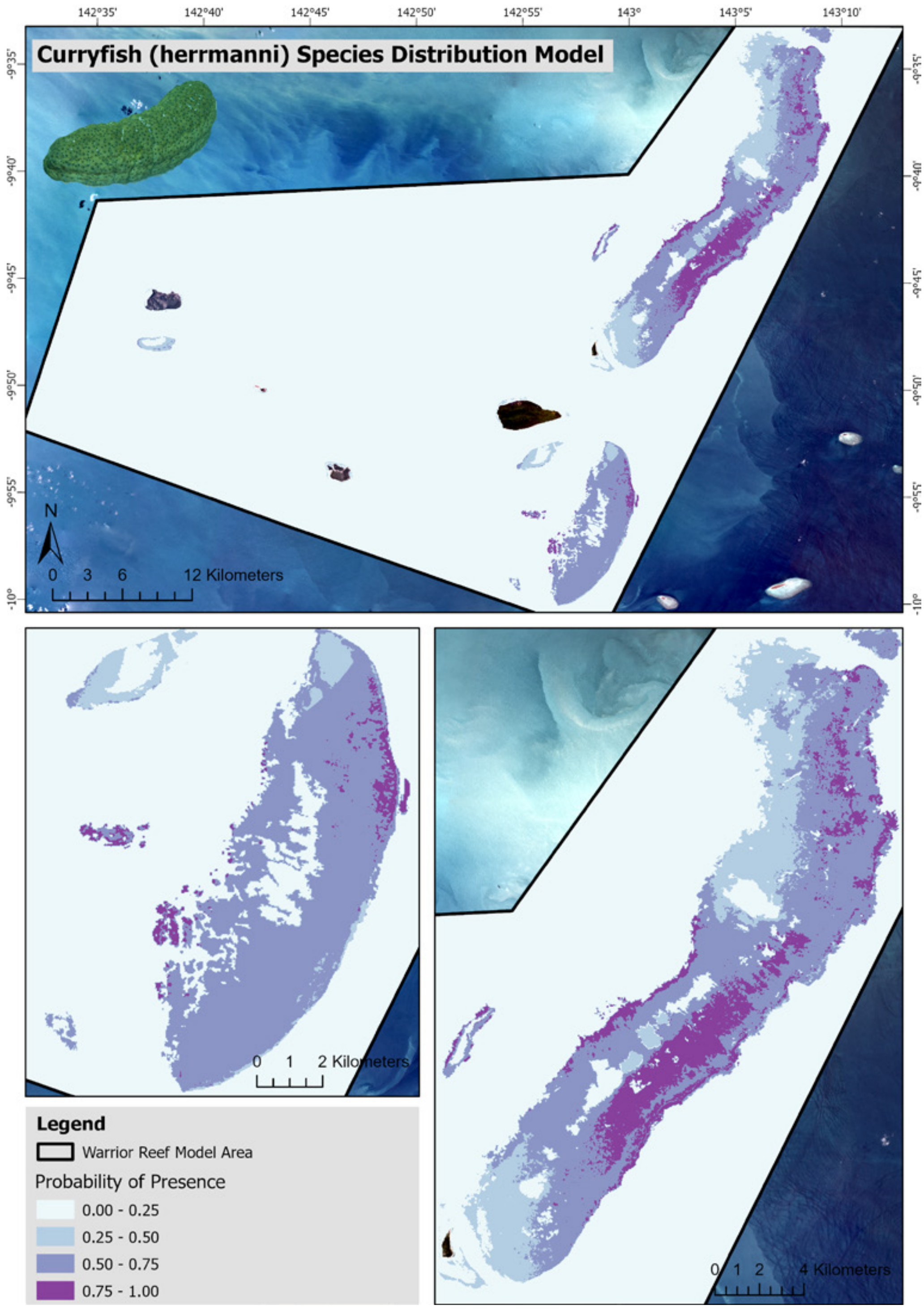



***Figure 23.*** *Species Distribution Model using the Presence-Only MaxEnt tool in ArcGIS Pro, showing the suitability of habitat for Stichopus herrmanni, based on known presence points.*

Using the species distribution model probability layers rather than the stratified layers used previously results in an approximate 25% decrease in available biomass, with a total across Warrior Reef of 260.35 tons, and 427.64 tons on Dungeness Reef (Table 15). This reduction is likely caused in part by a lack of detections of *S. herrmanni* in lower probability strata in Warrior Reef, representing approximately 40% of available habitat.

***Table 14.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for all curryfish herrmanni (Stichopus herrmanni) for Warrior Reef surveys conducted in January 2025 (all reefs).*

| Reef | Probability area | N transects (area, $m^2$) | Strata Area (ha) | Mean density (per ha) | SD |
|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | 0 | 1814 | | |
| **Warrior** | 0.25 - 0.5 | 2 | 3456 | 0 | 0 |
| **Warrior** | 0.5 - 0.75 | 16 | 7887 | 10.708 | 10.064 |
| **Warrior** | 0.75 - 0.1 | 7 | 3119 | 23.750 | 18.312 |
| **Dungeness** | 0 - 0.25 | 0 | 867 | | |
| **Dungeness** | 0.25 - 0.5 | 0 | 182 | | |
| **Dungeness** | 0.5 - 0.75 | 4 | 4,002 | 65.067 | 55.339 |
| **Dungeness** | 0.75 - 1.0 | 0 | 231 | | |

***Table 15.*** *Stratified mean and 90% confidence intervals of standing stock estimates for curryfish herrmanni (Stichopus herrmanni) for Warrior Reef surveys conducted in January 2025. Note that 0.25, 0.5 and 1.0 probability areas were not calculated for Dungeness since surveys were not conducted in those areas.*

| Reef | Probability area | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci (t, whole weight) | Upper 90% ci (t, whole weight) |
|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | | | | |
| **Warrior** | 0.25 - 0.5 | | | | |
| **Warrior** | 0.5 - 0.75 | 84,454 | 138.70 | 85.09 | 192.30 |
| **Warrior** | 0.75 - 0.1 | 74,076 | 121.65 | 63.33 | 179.97 |
| **Dungeness** | 0 - 0.25 | | | | |
| **Dungeness** | 0.25 - 0.5 | | | | |
| **Dungeness** | 0.5 - 0.75 | 260,398 | 427.64 | 128.49 | 726.79 |
| **Dungeness** | 0.75 - 0.1 | | | | |
| **TOTAL** | | **410,075** | **673.65** | **511.22** | **864.77** |

## 3.3.2. Curryfish, *Stichopus vastus*

### 3.3.2.1. Curryfish vastus biomass

***Relative density, Stichopus vastus***

*S. vastus* was common across the surveys but occurred in lower densities than *S. herrmanni* (Figure 24). Mean density was highest in strata zone 'seagrass 3' on Warrior Reef at 19.036 per hectare (Table 16). Estimated total biomass was 309.62 tons across the survey area (Table 17).

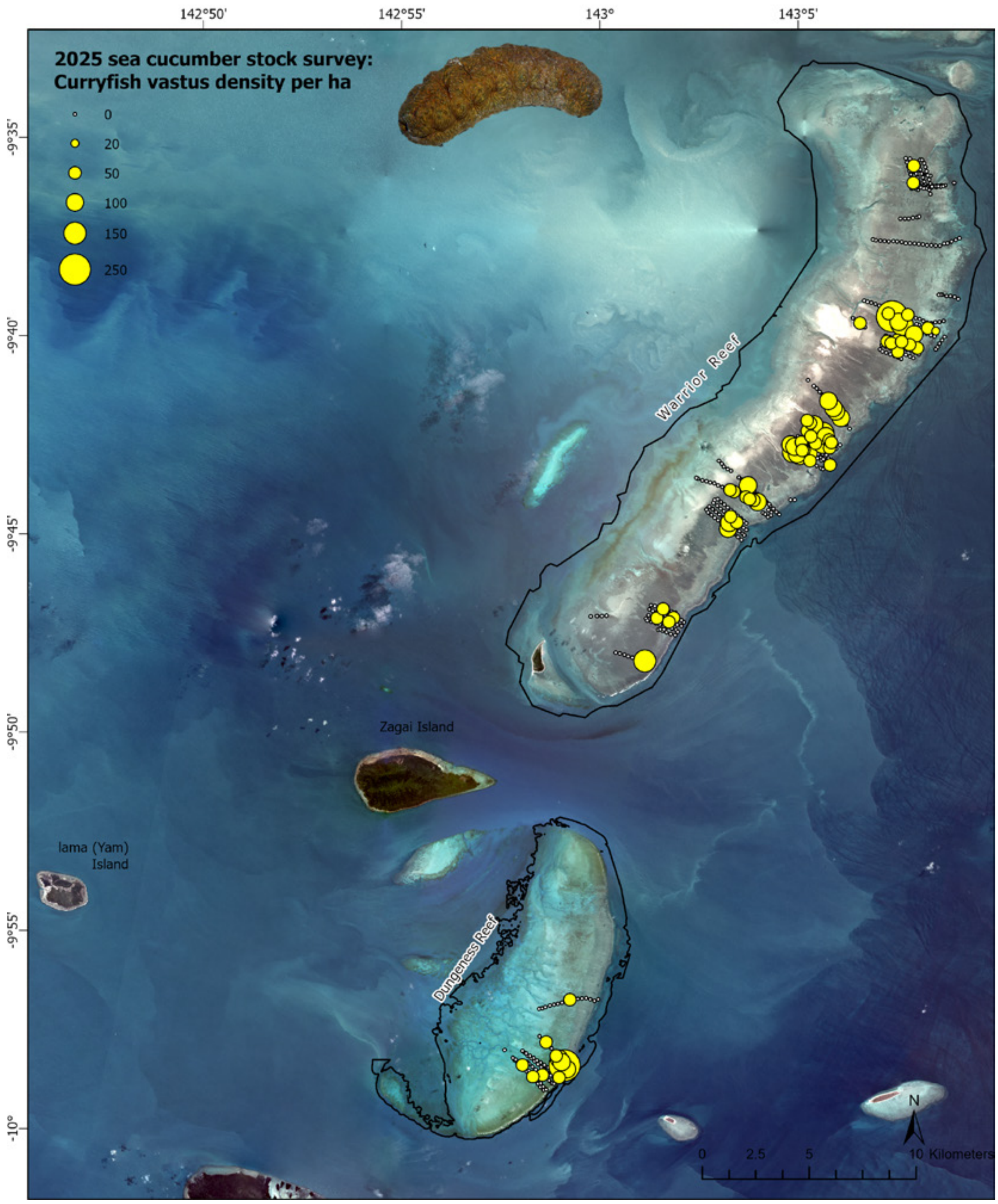



***Figure 24**. Relative densities of S. vastus across all transects. Note that large transects here were broken up into 200 m sections to facilitate visual interpretation relative to previous surveys.*

***Table 16.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for curryfish (Stichopus vastus) for Warrior Reef surveys conducted in January 2025. Strata layers obtained from CSIRO.*

| Strata | N transects (total area $m^2$) | Strata area (ha) | Mean density (per ha) | SD | 95% ci |
|---|---|---|---|---|---|
| **Seagrass 1** | 2 (18,939) | 1718.64 | 6.912 | 6.10 | 54.77 |
| **Seagrass 2** | 9 (56,137) | 1889.02 | 9.792 | 9.41 | 7.23 |
| **Seagrass 3** | 3 (23,673) | 2496.78 | 19.036 | 27.11 | 67.35 |
| **Seagrass 4** | 4 (24,628) | 2419.34 | 0.346 | 0.69 | 1.10 |
| **Backreef** | 3 (9,839) | 6897.42 | 5.828 | 6.63 | 16.46 |
| **Deep** | 4 (21,585) | 916.63 | 0.917 | 1.83 | 2.92 |
| **Dungeness** | 4 (31,502) | 5289 | 10.43 | 17.14 | 27.27 |

***Table 17.*** *Stratified mean and conservative 90% confidence intervals of standing stock estimates for curryfish (Stichopus vastus) for Warrior Reef surveys conducted in January 2025. Strata layers (Location) obtained from CSIRO.*

| Location | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci (t, whole weight) | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|
| **Seagrass 1** | 11,879 | 21.02 | -13.59 | 55.64 |
| **Seagrass 2** | 18,497 | 32.74 | 18.85 | 46.62 |
| **Seagrass 3** | 47,529 | 84.12 | 72.07 | 96.17 |
| **Seagrass 4** | 837 | 1.48 | 0.74 | 2.23 |
| **Backreef** | 40,198 | 71.14 | 31.54 | 110.75 |
| **Deep** | 841 | 1.49 | 0.36 | 2.61 |
| **Dungeness** | 55,164 | 97.63 | 7.14 | 188.11 |
| **TOTAL** | **174,945** | **309.62** | **236.35** | **382.89** |

### 3.3.2.2. Species distribution model

The best-performing species distribution model for curryfish vastus suggests the most suitable habitat for the species is in the central and northern regions, across the reef flat and along the reef edge of Warrior Reef, and the central to northern reef edge of Dungeness (Figure 25). The 'optimal' habitat (probability of presence > 0.75) for curryfish vastus covered just 19% of Warrior Reef area and 2% of Dungeness (Table 18). On Warrior Reef, 48% of the area had a greater than 50% probability (0.5 - 0.75) of presence of curryfish herrmanni, whereas Dungeness had 29% (Table 18). Low suitability habitat (probability of presence < 0.5) was 33% at Warrior, and 69% at Dungeness (Table 18).

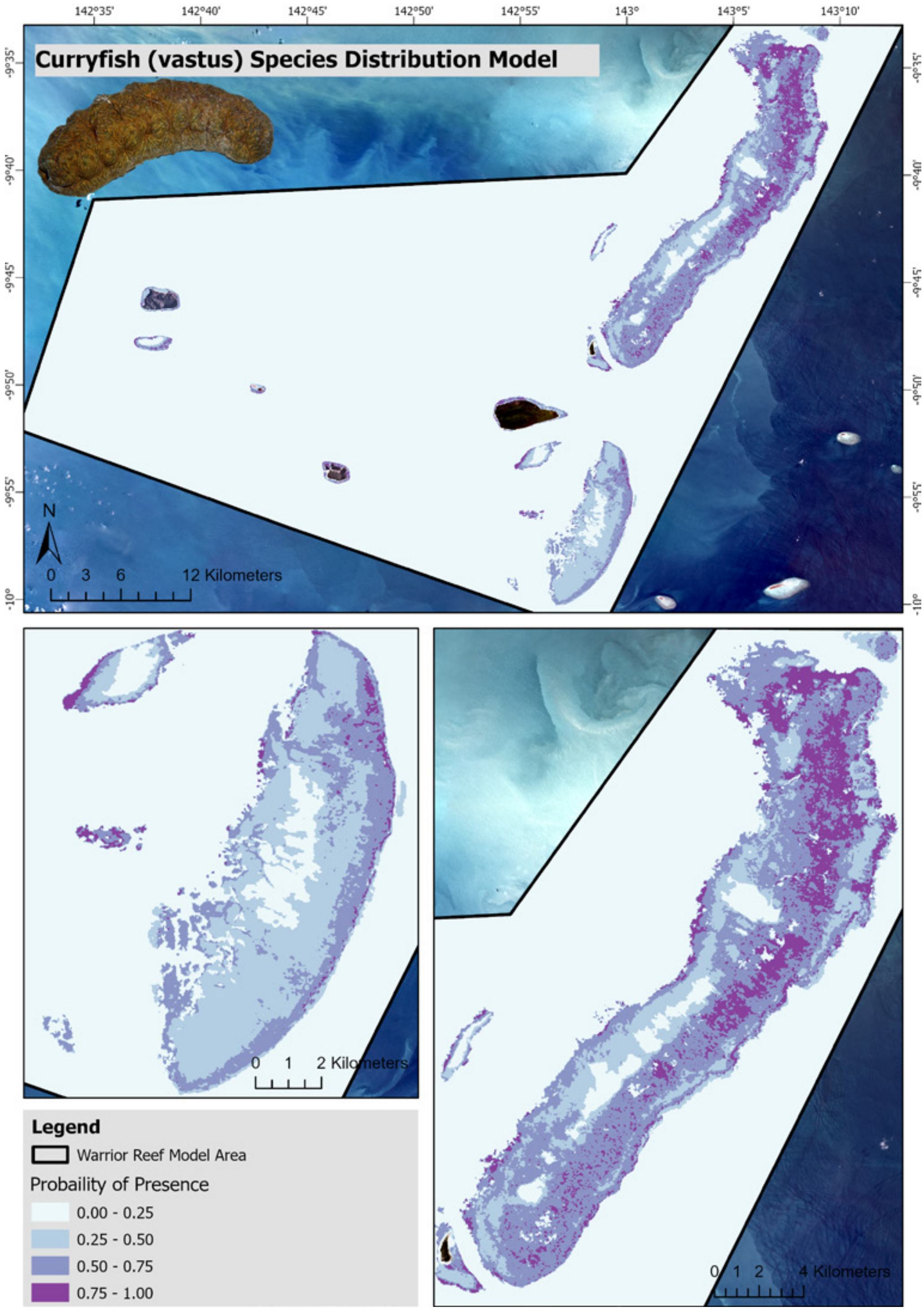



***Figure 25.*** *Species Distribution Model using the Presence-Only MaxEnt tool in ArcGIS Pro, showing the suitability of habitat for Stichopus vastus, based on known presence points.*

Using the species distribution model probability layers rather than the stratified layers used previously results in an approximate 20% decrease in available biomass for curryfish vastus relative to the other approach, with a total across Warrior Reef of 150.78 tons, and 106.73 tons on Dungeness Reef (Table 19).

***Table 18.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for all curryfish vastus (Stichopus vastus) for Warrior Reef surveys conducted in January 2025 (all reefs).*

| Reef | Probability area | N transects (area, m²) | Strata area (ha) | Mean density (per ha) | SD |
|---|---|---|---|---|---|
| Warrior | 0 - 0.25 | 0 | 1841.65 | | |
| Warrior | 0.25 - 0.5 | 6 | 3456.56 | 4.393 | 4.786 |
| Warrior | 0.5 - 0.75 | 7 | 7887.262 | 5.183 | 10.064 |
| Warrior | 0.75 - 0.1 | 12 | 3119.414 | 9.339 | 18.312 |
| Dungeness | 0 - 0.25 | 0 | 907.4047 | | |
| Dungeness | 0.25 - 0.5 | 3 | 2763.463 | 1.859 | 0.119 |
| Dungeness | 0.5 - 0.75 | 1 | 1526.765 | 36.135 | N/A |
| Dungeness | 0.75 - 1.0 | 0 | 86.09249 | | |

***Table 19.*** *Stratified mean and 90% confidence intervals of standing stock estimates for curryfish vastus (Stichopus vastus) for Warrior Reef surveys conducted in January 2025. Note that 0.25, 0.5 and 1.0 probability areas were not calculated for Dungeness since surveys were not conducted in those areas.*

| Reef | Probability area | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci (t, whole weight) | Upper 90% ci (t, whole weight) |
|---|---|---|---|---|---|
| Warrior | 0 - 0.25 | | | | |
| Warrior | 0.25 - 0.5 | 15,185 | 26.87 | -7.18 | 60.93 |
| Warrior | 0.5 - 0.75 | 40,880 | 72.35 | 14.58 | 130.12 |
| Warrior | 0.75 - 0.1 | 29,132 | 51.56 | -11.30 | 114.42 |
| Dungeness | 0 - 0.25 | | | | |
| Dungeness | 0.25 - 0.5 | 5,137 | 9.09 | | |
| Dungeness | 0.5 - 0.75 | 55,170 | 97.64 | N/A | N/A |
| Dungeness | 0.75 - 0.1 | | | | |
| **TOTAL** | | **145,503** | **251.51** | **200.01** | **315.02** |

## 3.3.3. Lollyfish, *Holothuria atra*

### 3.3.3.1. Lollyfish biomass

*H. atra* were by far the most common sea cucumber detected across the survey areas, with mean densities of over 50 per hectare across the surveyed area (Figure 26). Relative to 2000 surveys, 2025 surveys detected them in Seagrass 1 and Deep zones where they were not recorded previously, and mean densities were generally lower, though overall densities were the highest recorded in Dungeness (< 300 per ha, Table 20). Total estimated biomass of *H. atra* was approximately 10 times higher than the 2000 survey (Table 21). This was likely a result of the habitats recording large numbers of these in 2025, where these were not recorded previously.


***Figure 26.*** *Relative densities of H. atra across all transects. Note that large transects here were broken up into 200 m sections to facilitate visual interpretation relative to previous surveys.*

***Table 20.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for lollyfish (Holothuria atra) for Warrior Reef surveys conducted in January 2025. Strata layers obtained from CSIRO.*

| Strata | N transects (total area $m^2$) | Strata Area (ha) | Mean density (per ha) | SD | 95% CI |
|---|---|---|---|---|---|
| **Seagrass 1** | 2 (18,939) | 1718.64 | 4.005 | 1.69 | 15.23 |
| **Seagrass 2** | 9 (56,137) | 1889.02 | 5.225 | 8.20 | 6.30 |
| **Seagrass 3** | 3 (23,673) | 2496.78 | 59.487 | 70.57 | 175.30 |
| **Seagrass 4** | 4 (24,628) | 2419.34 | 11.723 | 13.59 | 21.62 |
| **Backreef** | 3 (9,839) | 6897.42 | 45.297 | 39.97 | 99.28 |
| **Deep** | 4 (21,585) | 916.63 | 15.779 | 16.42 | 26.13 |
| **Dungeness** | 4 (31,501) | 5289 | 304.107 | 426.24 | 678.24 |

***Table 21.*** *Stratified mean and conservative 90% confidence intervals of standing stock estimates for lollyfish (Holothuria atra) for Warrior Reef surveys conducted in January 2025. Strata layers (Location) obtained from CSIRO.*

| Location | Standing stock (n) | Biomass (t whole weight) | Upper 90% ci | Upper 90% ci (t, gutted weight) |
|---|---|---|---|---|
| **Seagrass 1** | 6,883 | 0.89 | 0.45 | 1.33 |
| **Seagrass 2** | 9,870 | 1.28 | 0.18 | 2.38 |
| **Seagrass 3** | 148,526 | 19.24 | -2.44 | 40.91 |
| **Seagrass 4** | 28,362 | 3.67 | 0.17 | 7.18 |
| **Backreef** | 312,432 | 40.46 | 6.55 | 74.37 |
| **Deep** | 14,464 | 1.87 | 0.02 | 3.72 |
| **Dungeness** | 1,608,421 | 208.30 | -31.83 | 448.44 |
| **TOTAL** | **2,128,958** | **275.71** | **164.79** | **386.64** |

### 3.3.3.2. Species distribution model

The most suitable habitat for lollyfish, as suggested by the best performing species distribution model, occurs along the reef edge in the lower central and northern region of Warrior Reef, and along the central reef edge of Dungeness(Figure 27). 'Optimal' habitat (probability of presence > 0.75) for lollyfish covered just 3% of Warrior Reef area and 3% of Dungeness (Table 22). On Warrior Reef, 91% of the area had a greater than 50% probability (0.5 - 0.75) of presence of lollyfish, whereas Dungeness had 87% (Table 22). Low suitability habitat (probability of presence < 0.5) was 6% at Warrior, and 10% at Dungeness (Table 22).

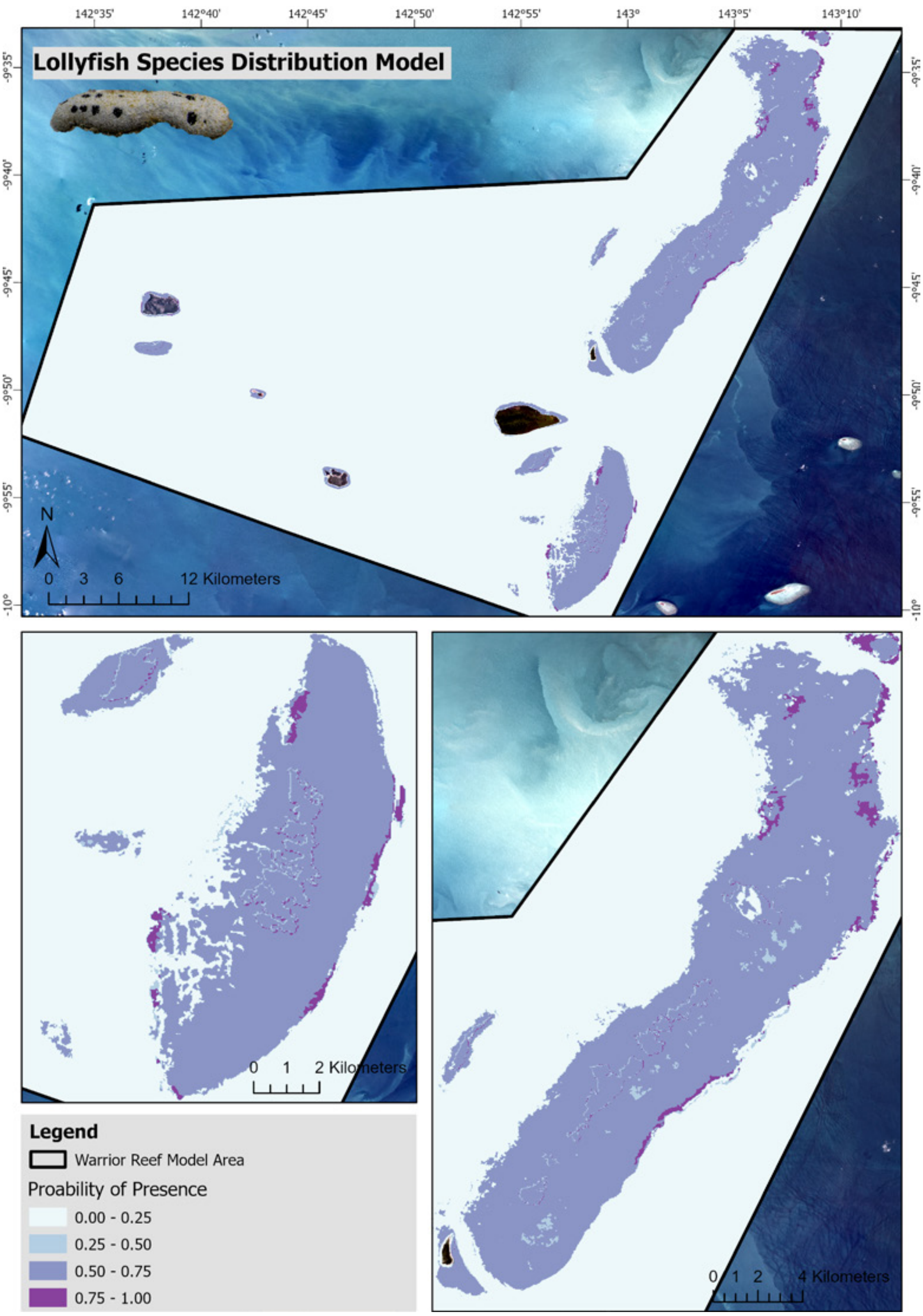



***Figure 27.*** *Species Distribution Model using the Presence-Only MaxEnt tool in ArcGIS Pro, showing the suitability of habitat for Holothuria atra, based on known presence points*

Using the species distribution model probability layers rather than the stratified layers used previously results in an approximate 25% decrease in available biomass for lollyfish, with a total across Warrior Reef of 41.13 tons, and 181.36 tons on Dungeness Reef (Table 23).

***Table 22.*** *Strata mean abundance, standard deviation and 95% confidence intervals for the calculation of standing stock estimates for all lollyfish (Holothuria atra) for Warrior Reef surveys conducted in January 2025 (all reefs).*

| Reef | Probability area | N transects (area, m²) | Strata Area (ha) | Mean density (per ha) | SD |
|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | 2 | 818.4355 | 0 | 0 |
| **Warrior** | 0.25 - 0.5 | 0 | 315.0283 | | |
| **Warrior** | 0.5 - 0.75 | 22 | 14756.51 | 21.082 | 33.546 |
| **Warrior** | 0.75 - 0.1 | 1 | 414.9105 | 15.591 | N/A |
| **Dungeness** | 0 - 0.25 | 0 | 405.8695 | | |
| **Dungeness** | 0.25 - 0.5 | 0 | 115.0647 | | |
| **Dungeness** | 0.5 - 0.75 | 4 | 4604.897 | 304.107 | 426.241 |
| **Dungeness** | 0.75 - 1.0 | 0 | 157.894 | | |

***Table 23.*** *Stratified mean and 90% confidence intervals of standing stock estimates for lollyfish (Holothuria atra) for Warrior Reef surveys conducted in January 2025. Note that 0.25, 0.5 and 1.0 probability areas were not calculated for Dungeness since surveys were not conducted in those areas.*

| Reef | Probability area | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci (t, whole weight) | Upper 90% ci (t, whole weight) |
|---|---|---|---|---|---|
| **Warrior** | 0 - 0.25 | 0 | 0.00 | 0 | 0 |
| **Warrior** | 0.25 - 0.5 | 0 | 0.00 | | |
| **Warrior** | 0.5 - 0.75 | 311,097 | 40.29 | 17.81 | 62.77 |
| **Warrior** | 0.75 - 0.1 | 6,469 | 0.84 | N/A | N/A |
| **Dungeness** | 0 - 0.25 | 0 | 0.00 | | |
| **Dungeness** | 0.25 - 0.5 | 0 | 0.00 | | |
| **Dungeness** | 0.5 - 0.75 | 1,400,381 | 181.36 | -27.22 | 390.43 |
| **Dungeness** | 0.75 - 0.1 | 0 | 0.00 | | |
| **TOTAL** | | **1,717,947** | **222.49** | **100.22** | **344.75** |

## 3.4. Stratified stock estimates – comparison of methods

Previous surveys have used a stratified approach to estimate the stocks of sandfish and other sea cucumbers on Warrior Reef (Murphy et al., 2011; Skewes et al., 2000). Throughout this report we have followed this approach, using the strata layer developed by the CSIRO, which categorises Warrior Reef into 5 categories including four seagrass zones and the back reef (Skewes et al., 2000). Previous surveys either did not survey, or did not detect sandfish on Dungeness Reef. As sandfish and other sea cucumbers were detected on Dungeness Reef in the 2025 survey, we included an additional category which included the entire area of the reef, resulting in six categories used for this approach. An additional method was introduced in this report, where the outputs of species distribution models (SDMs) for each species were used to develop stock estimates, with the probability of presence layer used to conduct stratified estimates based on the suitability of habitat within each reef. Overall, the strata layer developed by CSIRO for the purpose of stratified stock estimates at Warrior Reef had higher estimates of standing stock and overall biomass estimates (whole weight) when compared to stock estimates that used the species specific SDM output layer, which used probability of presence categories (Table 24). The difference in biomass (whole weight) between the CSIRO strata layer and the SDM probability layer was approximately 20% with slight differences occurring between species (Table 24). The suitability of a reef to support sea cucumber populations is likely dependent on many environmental factors such as habitat availability, structural complexity, bathymetry, tide range, aspect and slope. Additionally, each species of sea cucumber has a unique preference and range within each of these environmental factors, which highlights the importance of incorporating species distribution models into future estimates of stock.

***Table 24.*** *Comparison of stratified layers from previous surveys and species distribution models (SDMs) developed from the 2025 Warrior Reef survey. The total standing stock, biomass (whole weight) and upper and lower 90% confidence intervals are shown for both the CSIRO strata layer and the SDM probability layer developed for each species. The difference in biomass between the two stratified layers is shown as a percentage.*

| Species | Stratified layer | Standing stock (n individuals) | Biomass (t whole weight) | Lower 90% ci (t, whole weight) | Upper 90% ci (t, whole weight) | Difference in biomass (whole) |
|---|---|---|---|---|---|---|
| ***H. scabra*** | SDM | 97,805 | 53.62 | 18.57 | 39.91 | 18.71 % difference |
| | Strata | 156,743 | 64.69 | 23.88 | 46.48 | |
| ***S. herrmanni*** | SDM | 410,075 | 673.65 | 511.22 | 864.77 | 23.86 % difference |
| | Strata | 521,381 | 856.13 | 633.66 | 1078.60 | |
| ***S. vastus*** | SDM | 145,503 | 251.51 | 200.01 | 315.02 | 20.71 % difference |
| | Strata | 174,945 | 309.62 | 236.35 | 382.89 | |
| ***H. atra*** | SDM | 1,717,947 | 222.49 | 100.22 | 344.75 | 21.36% difference |
| | Strata | 2,128,958 | 275.71 | 164.79 | 386.64 | |

# 4. Discussion

Population surveys for sandfish in 2025 show that the fishable biomass at Warrior and Dungeness Reefs indicate a high level of over exploitation. Despite 27 years of closure for the sandfish fishery in the Torres Strait, populations have not recovered from the over harvesting that occurred in the mid 1990's, and the much lower densities recorded relative to 2010 surveys suggest that there has been some degree of continued harvesting or loss of animals despite the closure. Survey densities of sandfish in the 2025 survey are lower than 2010, with observed densities per hectare comparable to levels seen in 2000 (Murphy et al., 2011). The levels of sandfish observed in 2010 and 2004 on Warrior Reef were approximately 80% less than observed in 1995/96, when the population was considered over exploited (Murphy et al., 2011). The estimated biomass of *H. scabra* from the current survey is approximately 60% lower than that of the previous study in 2010 (Murphy et al., 2011), and fishable biomass is still a fifth of the initial 250 t TAC set during the 90s. Relative to the estimated virgin biomass of *H. scabra* 1,666 tons, current biomass, including Dungeness Reef, represents less than 4% of the initial population.

After an additional 15 years of fishery closure from the last survey, *H. scabra* populations have continued to decrease, and there are only a few plausible explanations for this pattern. The most likely is continued unregulated, unreported or illegal fishing, or from continued take from the small indigenous fishing from within the region. While continued fishing pressure is likely to be substantially contributing to the low biomass of sandfish, several other factors could also contribute. While sandfish are relatively well studied compared to other species of sea cucumber, our understanding of the impacts of increasing climate change on their ecology is poorly understood, and sandfish in the Torres Strait are most likely increasingly exposed to marine heatwaves, increasing freshwater associated with increased storm events, and increasing ocean acidification impacts, all of which could impact disease prevalence, predator-prey interactions, habitat availability, reproductive output, and/or metabolism (Poloczanska et al., 2013). Developing an understanding of these linkages will form a key part of managing these populations into a changing future (Plagányi et al., 2012).

Acknowledging and incorporating local knowledge has been beneficial for the 2025 survey. Initial discussions with TS islanders on Iama Island helped focus and direct the timing and positioning of the transects. Moreover, understanding the history, methodology, and collapse of the fishery from a local perspective has been invaluable in understanding some of the lesser documented stressors within the fishery and gaining a more holistic understanding of the sandfish stock. Local knowledge consultations have been part of these fishery-independent surveys in the past, and future assessments of the sea cucumber fisheries in this region should continue such consultations if possible.

The incorporation of new survey methods in ongoing survey programs is associated with uncertainties that data produced by the new methods are directly comparable to previous approaches. In this case, we used exclusively remote sensing approaches that leverage much higher survey efficiency, in contrast with the more traditional snorkel and transect surveys used in previous studies. While it is possible that lower sandfish densities detected throughout our study are a result of the method rather than real declines, comparative research from the Great Barrier Reef shows that there is often no significant difference in sea cucumber detections in ROV compared to traditional survey approaches (Williamson et al., under review). This would also run counter to work in similar environments that highlights that longer transects covering larger areas generally produce more reliable data (Rojo et al., 2021). In addition, we recorded very comparable densities of non-fished species (*H. atra, S. herrmanni*) across the survey area, which would be unlikely to be the case if there were significant issues with the approach. In fact, our approach allowed the detection of species, including sandfish, in areas they had previously not been recorded (e.g., Dungeness) using traditional methods. This leads us to believe that the further declines of sandfish densities recorded herein are directly comparable to previous survey results.

The use of species distribution models informed by more detailed continuous habitat layers always resulted in a more conservative estimate of biomass, for all species assessed, with a reduction in available biomass that ranged from 20 to 30% relative to approaches used in previous surveys. The literature is clear that the incorporation of species distribution models is beneficial for fisheries management (e.g. Stock et al., 2020; Frans et al., 2022), especially given their ability to predict changes that would result from climate change (Zhang et al., 2019). The main driver for the differences in the two methods to assess biomass here are likely because the use of species distribution models better characterises the available habitat for each species, and how observed sea cucumber densities relate to those optimal habitats. Since all assessments informed by species distribution models resulted in more conservative biomass values, it is likely that re-analysis of previous surveys would produce similar results. This suggests that historical assessments of the stocks of sea cucumbers on Warrior Reef may have been less conservative than those informed by species distribution models, and ‘true’ sea cucumber biomass may have been lower than previously thought. If more similar surveys are conducted into the future, it should be possible to incorporate those data into the produced species distribution models to make them even more effective at characterising optimal habitat, which should increase the accuracy of stock estimates into the future.

## 4.1. Future surveys

One of the key benefits of the remote methods used for this survey, especially the BlueBoat, is that using the previously used pre-planned survey missions, identical surveys, covering the exact same transect lines, could be repeated in the near future, providing a direct comparison of sea cucumber numbers over time. This would allow very precise tracking of population trends, offering similar benefits as permanent transects often used in coral reef habitats (e.g., Kuo et al., 2022). We note that the BlueBoat (or comparable automated surface vessels) are very well adapted to surveys on Warrior and Dungeness Reefs due to their relatively shallow habitats (we covered over 100 km of transects with 1 vessel across 6 days), and future surveys on these reefs should consider a broader use of these techniques, for example but concurrently running missions with several automated vessels, which is feasible with a small crew of researchers.

Warrior Reef is unique in that vast areas of the reef flat are covered by very dense seagrass communities. This can make it difficult to determine whether sandfishes are actively using those habitats, as they can be obscured from view. Previous surveys addressed this somewhat by conducting surveys at low tide when the sandfishes were completely exposed, though this can greatly limit the extent of survey effort, or by physically touching seagrass to identify hidden sandfish (Skewes, pers. comm., 2024). The data from this survey, relying exclusively on remote methods, could not definitively determine whether counts of sandfish in dense seagrass areas were a product of the method or reflecting absolute densities. We recommend a small pilot study run concurrently to future surveys to assess whether there is a difference in sandfish detection between in-water and remote methods, particularly in seagrass habitats of varying density, to develop a transformation specifically for this species and habitat type. This pilot study could occur at a site in the Torres Strait with suitable habitat, or at a future survey at Warrior Reef.

Species distribution models suggest that the best habitat for sandfish may be smaller in extent than previously believed. However, species distribution models can be biased by a lack of sampling in habitat strata, and for these surveys we targeted the east side of the reef as per Murphy et al., (2011). If it is a long-term objective to better quantify the real extent of suitable habitat for these or other sea cucumber species, future surveys should attempt to more extensively survey the back and deep reef areas, and validate the low numbers of sandfish detected in the southern part of Warrior Reef where they had been observed previously (Murphy et al., 2011). Having a clearly defined spatial layer of habitat suitability should enable more accurate biomass assessments in the future by classifying strata on optimal habitat suitability rather than the north/south orientation that has been defined for this and previous sea cucumber surveys on Warrior Reef.

Another key challenge for the species distribution model is its reliance on input layers—particularly habitat data. For this report, we used the previously provided habitat layer to maintain consistency; however, we acknowledge its limitations. To improve the reliability of the model, we recommend further work to incorporate a more suitable habitat layer for Warrior and the surrounding reefs. We have already completed initial work to generate an alternative habitat layer, which should now be compared with the original data to assess improvements in model accuracy.

While separated by legislative boundaries, it is likely the population of sandfish in Warrior Reef and its productivity is closely linked to that of the more northern PNG section of the reef. To gain a more comprehensive understanding of the stock status of sandfish in this area, direct collaboration and surveying of Warrior Reef in both PNG and Australian waters would be preferable, as has been done in the past (e.g., Long et al., 1996).

As per the 2011 survey report (Murphy et al., 2011), identifying population threats and recruitment more clearly using a small-scale experimental fishing exercise would be beneficial to any future management or fishing. It would enable a more accurate understanding of how survey methods relate to ‘true’ densities, and the short- and longer-term impacts of low-level fishing effort.

Several other commercially important sea cucumbers within the remit of this survey to assess were recorded in very low numbers (e.g., deepwater redfish) or were entirely absent from the surveys (e.g., hairy blackfish, *Actinopyga miliaris*), preventing robust assessment. Future surveys should also monitor these important species.

## 4.2. Management recommendations

Warrior Reef has been closed since 1998 for fishing sandfish due to the low biomass of the species observed in recent surveys (Skewes et al., 2000). Following the surveys of Warrior Reef and those of the eastern Torres Strait waters since the closure (e.g., Skewes et al., 2002, Skewes et al., 2010), a pre-agreed harvest strategy for the Torres Strait Beche-de-Mer (sea cucumber) fishery was implemented by AFMA in 2019 to provide clarity as to current and future management requirements to ensure the fishery remains sustainable into the future (Plagányi, et al., 2019). This strategy provides guidelines and primary indicators for assessing species recovery that can be used to inform managers as to whether the fishery can be reopened. Minimum size limit, which allows animals the opportunity to reproduce prior to capture, is set at 180 mm length for sandfish (Murphy et al., 2014). Virgin biomass ($B_0$), which is an estimate of the biomass of the stock prior to fishing or in the absence of fishing, is set at 1,666 tons for sandfish in this area (Murphy et al., 2011). As the fishery is currently closed, the TAC and CPUE are both currently zero.

The sea cucumber fishery at Warrior Reef is by the Protected Zone Joint Authority (PZJA), which comprises AFMA, the Queensland Department of Primary Industries , and the TSRA. The harvest strategy requires the following conditions for the opening of a closed fishery, such as that of sandfish on Warrior Reef: (1) the stock must be above a limit point level as evidenced by a fishery-independent survey; (2) the monitoring plan and management of the stock must be adequate and continuing into the future; and (3) if the previous conditions are met, then a trial opening is possible but under the adherence of specific precautionary conditions (AFMA, 2019).

The main remit of the current survey is to provide fishery data for sandfish on Warrior Reef, including Dungeness Reef, to assess whether this species has recovered sufficiently to re-open the fishery. Our survey shows that 68% of the sandfish measured were above the minimum size limit of 18 cm length. This is promising as there is a greater number of individuals over the minimum size limit than reported in 2010, although it should be noted that there is an unequal sample size between years, with a greater number of individuals recorded in 2010. It is also possible that *in-situ* measurements of lengths as in our survey could inflate length frequency distributions relative to *ex-site* measurements from previous studies. Nevertheless, is it hopeful that most individuals recorded in the current survey were over the minimum size limit for the species and would thus be reproductively mature and able to contribute to the stock.

Our estimated biomass of 52.84 ton of fishable (>18 cm) sandfish stock in the current survey is substantially lower than that of the previous survey in 2010 (Murphy et al., 2011). Fishable biomass has been diminished relative to estimated virgin biomass for the past several surveys, including this survey, and remains at approximately one fifth of the initial 250-ton TAC set during the 90s. Our survey results show no signs of sandfish recovery, with the stock sitting at less than 4% of the estimated virgin stock ($B_0$) in Long et al., (1996). Our recorded densities are below the documented threshold of 10 individuals per hectare – below which sea cucumber reproduction is commonly considered to be compromised (Bell et al., 2008) – indicating that the Warrior Reef stock in its current form has a diminished ability to recover. Murphy et al., (2021), however, suggest a threshold of only four individuals per hectare for recovery of sea cucumbers, and it is important to ensure that a threshold specific to sandfish on Warrior and Dungeness Reefs is generated to more fully understand recovery viability.

Due to the substantially low biomass (well below the limit point level set), we recommend continued closure of the sandfish fishery for Warrior Reef and associated sites such as Dungeness Reef, and continued fishery-independent surveys to assess stock size and biomass of this species at regular intervals. Details on the types of surveys recommended are discussed in Section 4.1.

Assessment of other species of sea cucumber during the survey revealed a moderate biomass of herrmanni curryfish (*Stichopus herrmanni*) that is now approximately three times higher (856.13 t wet weight) than observed in the previous surveys. As this fishery is open, with a TAC of 60 t for Curryfish *herrmanni* and *vastus* (catch to be reported by species), these findings support continued fishing on Warrior Reef, however should be monitored periodically (AFMA, 2024). Processing *S. herrmanni* requires a different and potentially more time-consuming method than sandfish (Purcell, 2014), which could impact initial expansion costs of this fishery. This curryfish has also been listed as Vulnerable on the IUCN Redlist of Threatened Species (Conand et al., 2013), indicating that any collection of this species would require careful and ongoing consideration of its impact, and the population structure, habitat use, and ecology of the species to ensure sustainability.

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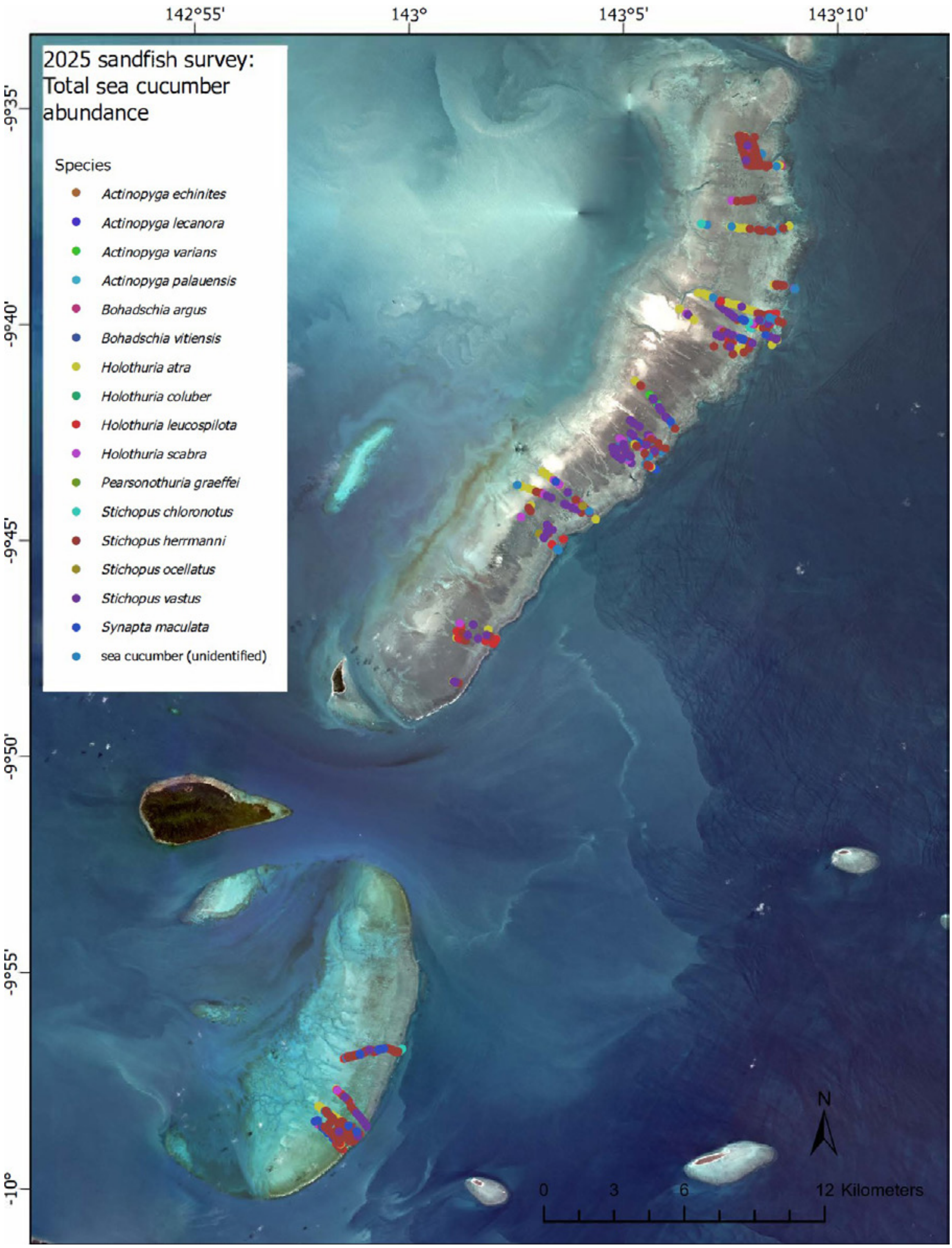
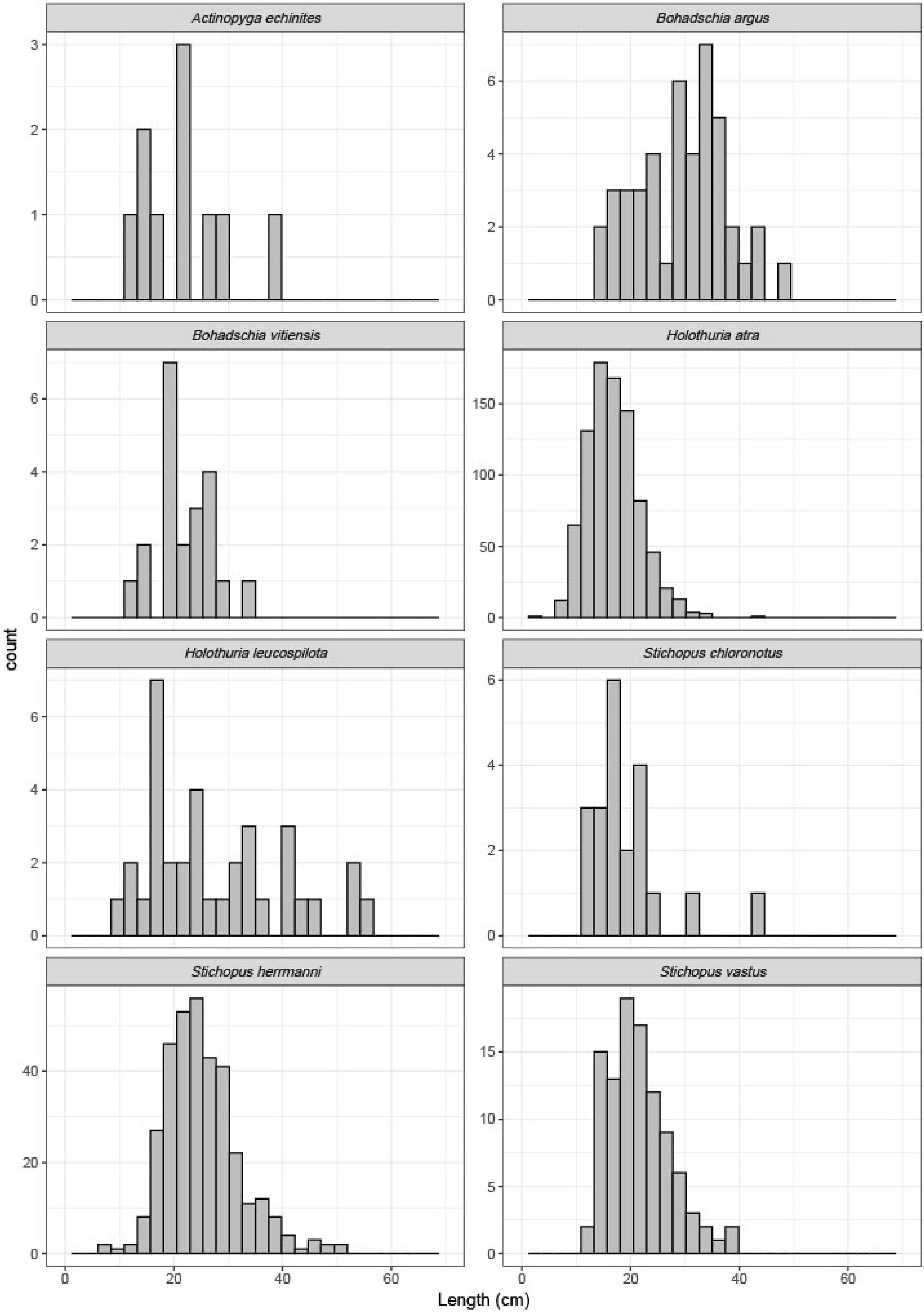
# 6. Appendix

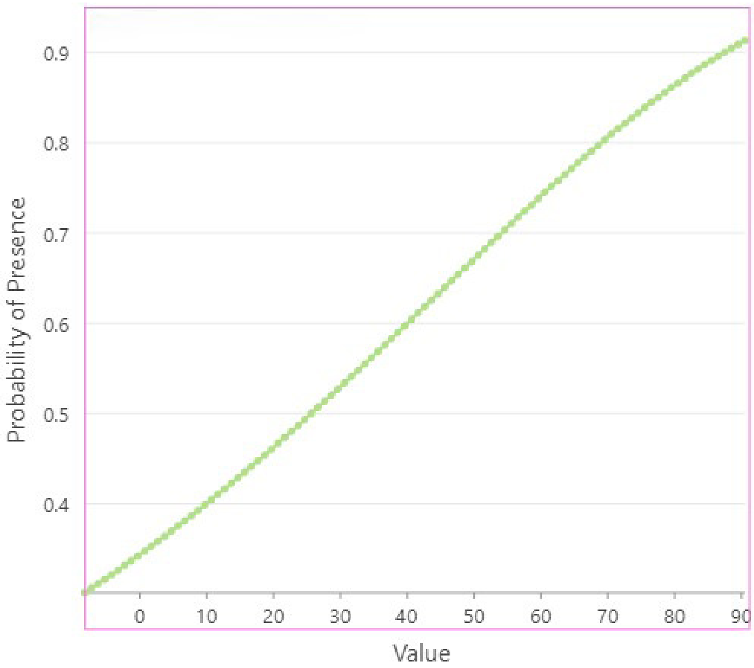
## 6.1. Total detections of all sea cucumber species surveyed in the 2025 survey



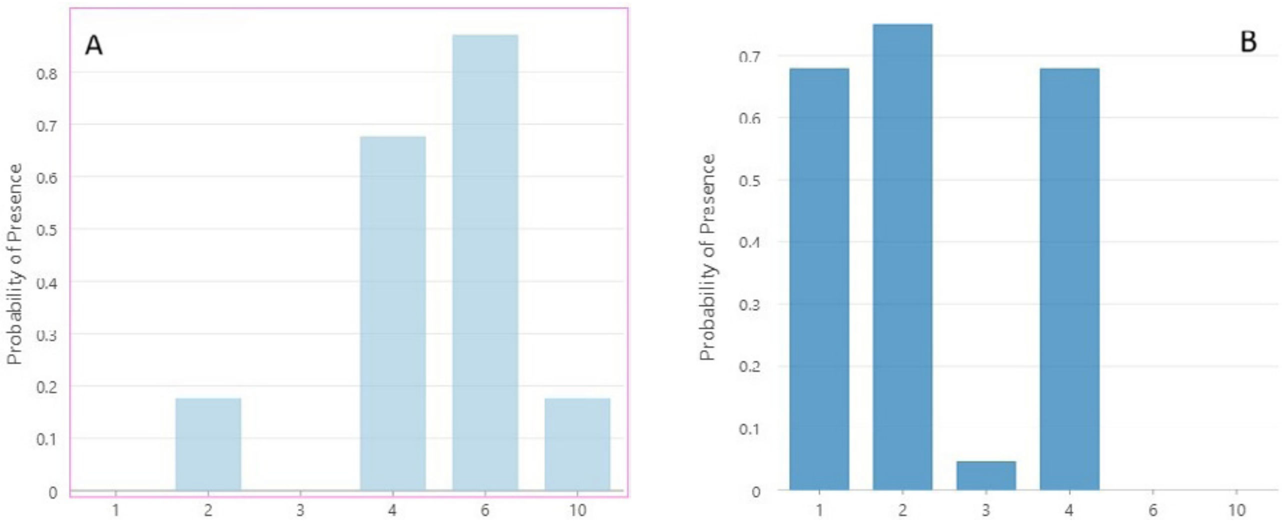
## 6.2. Length frequency distributions of species of interest recorded in sufficient numbers at Warrior and Dungeness Reefs in the 2025 survey



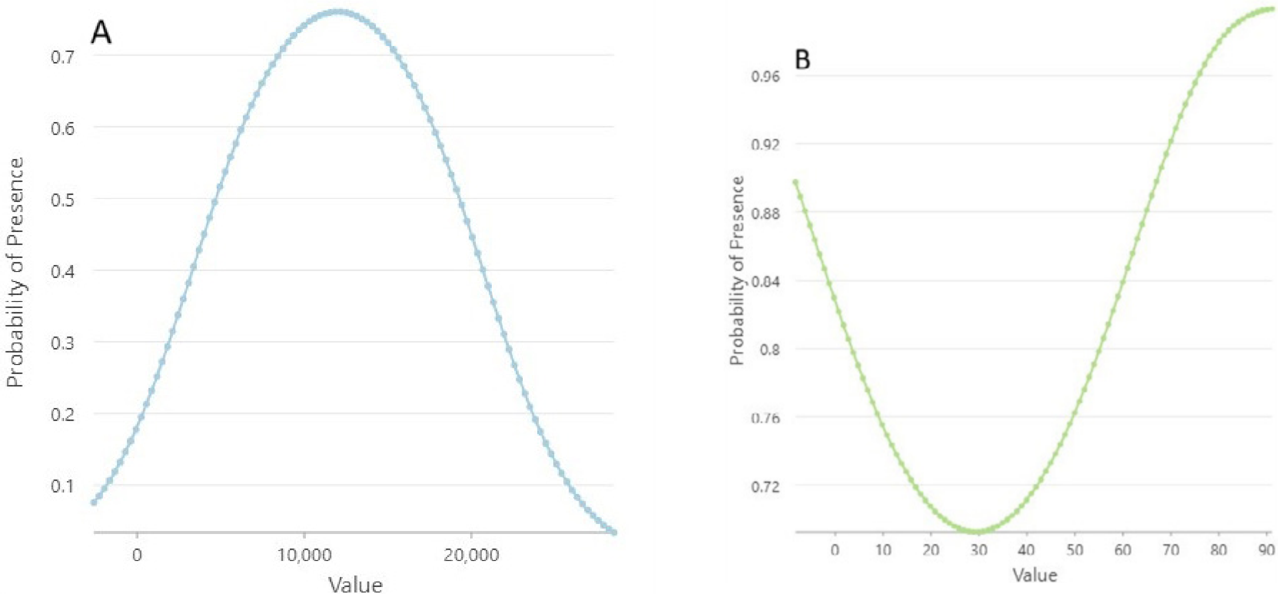
### 6.3. Partial response plots of spatial continuous variable, seagrass density, for sandfish species distribution model



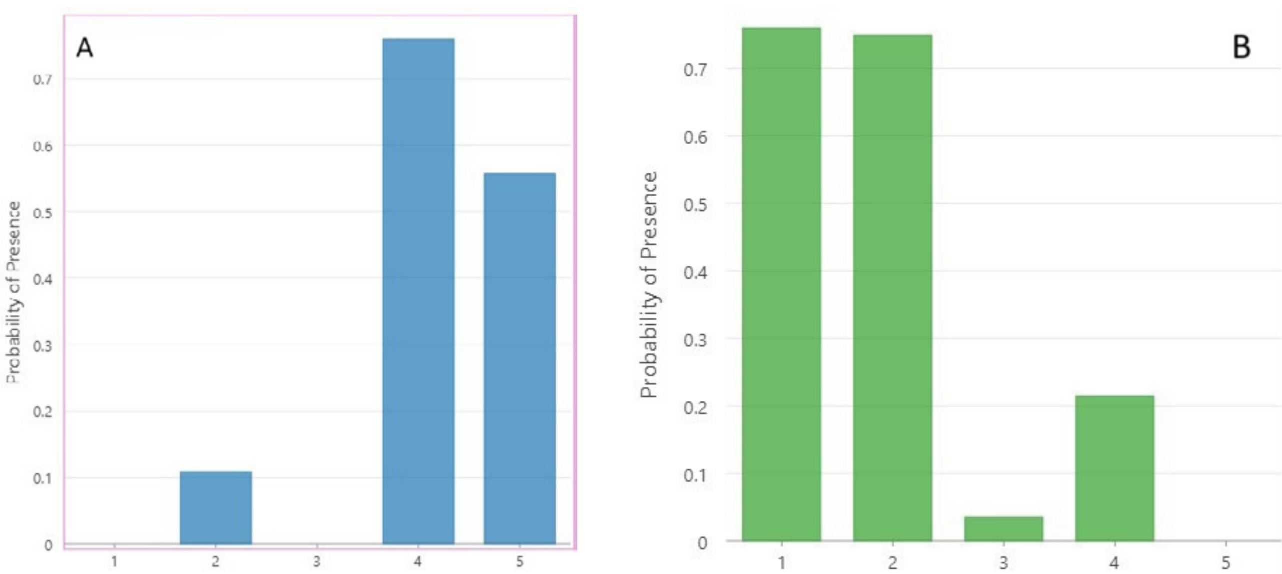

### 6.4. Partial response plots of spatial categorical variables (geomorphic zone (A) and (B) habitat zone), for sandfish species distribution model



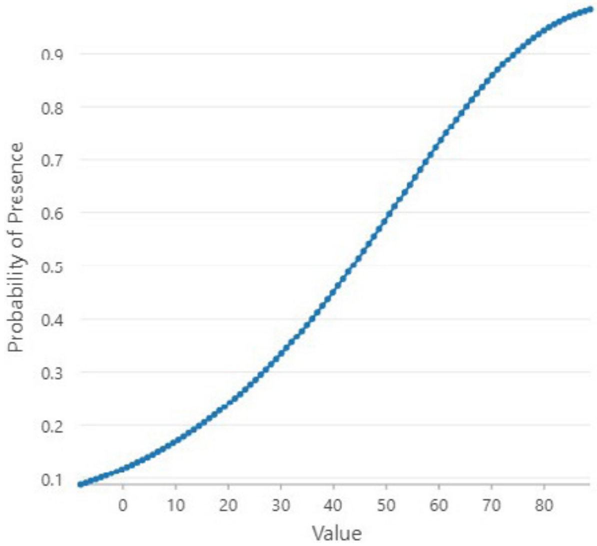
6.5. Partial response plots of spatial continuous variables (Distance to land (A) and (B) seagrass density) used for species distribution models of curryfish herrmanni



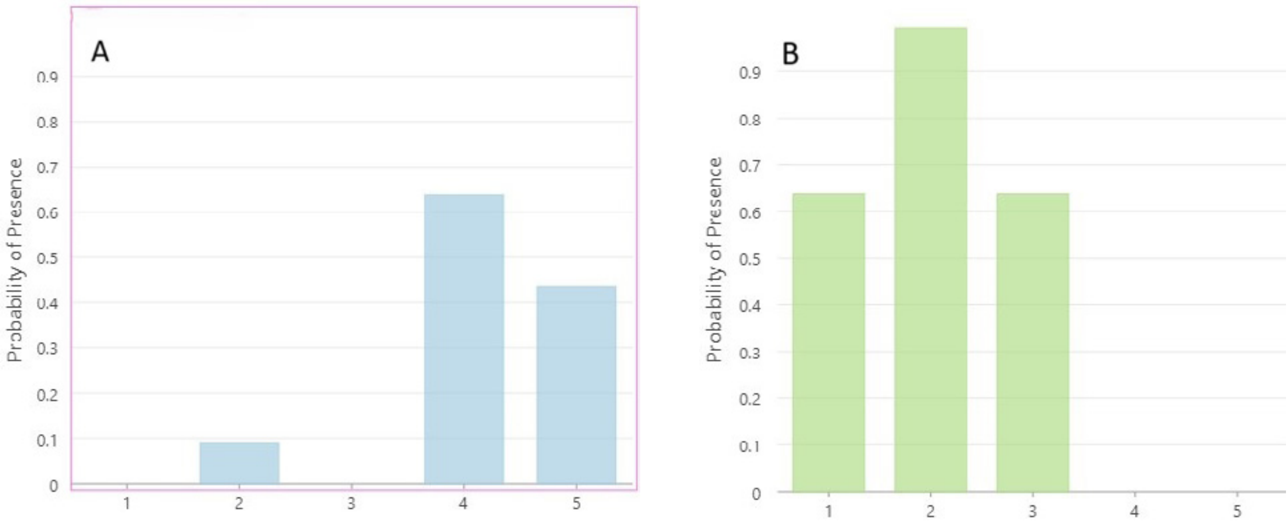

6.6. Partial response plots of spatial categorical variables (geomorphic zone (A) and (B) habitat zone) used for species distribution models of curryfish herrmanni



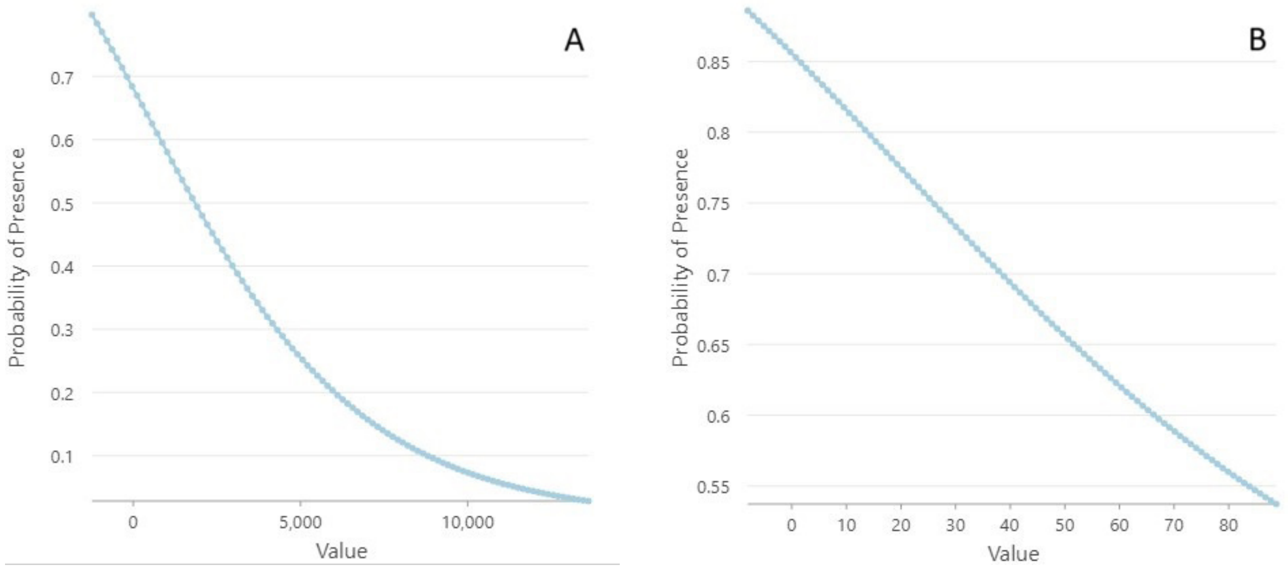
## 6.7. Partial response plots of spatial continuous variables used for species distribution models of curryfish vastus




## 6.8. Partial response plots of spatial categorical variables (geomorphic zone (A) and (B) habitat zone) used for species distribution models of curryfish vastus



## 6.9. Partial response plots of spatial continuous variables (Distance to reef (A) and (B) seagrass density) used for species distribution models of lollyfish




## 6.10. Partial response plots of spatial categorical variables (geomorphic zone (A) and (B) habitat zone) used for species distribution models of lollyfish