Reef restoration at Gunshot reef, eastern Victoria

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Introduction

Shallow, rocky reef habitats are key components of temperate marine ecosystems, providing shelter, feeding and breeding grounds for a wide variety of organisms. Increasing abundance of the longspined sea urchin (*Centrostephanus rodgersii*), and associated denudation of algal communities, has severely impacted the health of some reef habitats in eastern Victoria. Overgrazing of macroalgae (i.e. kelp), to the extent that kelp beds become deforested, results in the formation of 'urchin barrens', that contain greatly reduced biodiversity compared to healthy reef systems.

In these ecosystems, urchins occur alongside other species such as abalone and compete with them for the same food source and space. This impacts upon the abundance of abalone by making the habitat less suitable and by inhibiting the settlement of new recruits to populations on affected reefs. The range expansion of urchins and the increase in number and area of barrens not only reduces reef biodiversity it also weakens resilience and limits productivity of commercial abalone stocks in the region. This in turn reduces prospects for sustaining a viable Eastern Zone Abalone Fishery.

In this project, funded by the Department of Environment, Land, Water and Planning, a reef restoration strategy was implemented at the Gunshot reef through collaboration between the Victorian Fisheries Authority and commercial shellfish divers. Divers made an extensive effort to remove urchins from the vegetated area, clearing them up to 100m from the current weed/barren junction in all directions. Abalone and urchin abundance, along with video transects were undertaken before and after removal of urchins to assess the effectiveness of reducing urchin density, and promoting subsequent habitat recovery. Spatiotemporal patterns in diver culling effort were evaluated by geospatial analysis of vessel and diver GPS logger data.

Although the project is ongoing, initial findings indicated positive signs of habitat recovery, and an increase in the proportion of the algal communities covering the reefs was observed due to the considerable reduction in urchin densities. Consistent with diver observations, data exploration revealed that further effort will be required to ensure that the removal of urchins from barrens and urchin patches is maintained, especially in boulder habitats where it is difficult to find and remove all urchins due to juveniles inhabiting inaccessible cryptic spaces. Persistence with culling will provide further opportunities for flora and fauna to recover to protect the biodiversity of the reef and prevent barrens from reforming so as to better sustain the Eastern Zone Abalone Fishery and improve the wellbeing of local rocky reef habitats and associated biodiversity in general.

Needs and objectives

The Gunshot reef is an important reef for Eastern Zone Abalone fishery with average annual blacklip abalone (*Haliotis rubra*) landings of 7.5t that have an approximate value of $350,000. However, abalone landings from the reef have declined from >18t in 2003 to <3t during the last few years. The reef also supports other commercial fisheries (e.g. banded morwong, bluethroat wrasse) and while the usage of the area for recreational activities is unknown, the Mallacoota coast is popular in general with both tourists and local boating enthusiasts.

The health of the Gunshot reef has been in rapid decline with the amount of vegetated reef area diminishing annually. The Eastern Zone Abalone Industry Association (EZAIA) diver group has been calling for action to address urchin barren expansion at the Gunshot Reef over the past decade because of the heightened risk that the reef may be lost entirely due to the destructive grazing behavior of sea urchins, *Centrostephanus rodgersii*, in particular. In addition, being surrounded by the Cape Howe Marine Park, the increasing abundance of urchins on the Gunshot Reef could negatively impact reefs within the Marine Park due to emigration and providing a source of large quantities of larvae.

Minimal commercial urchin harvesting occurs in the area due to the poor quality of roe caused by high urchin densities in habitat that is deteriorating in quality (Warren-Myers et al. 2020), leaving culling as the only viable control method to achieve rapid positive results. Therefore, a reef restoration program was funded by DELWP that aimed to 1) remove urchins from the middle of the vegetated area to prevent further habitat losses, 2) expand urchin culling outwards up to 100 m from the current weed/barren junction line or to a depth of 15 m (whichever occurs first) in all directions, 3) use vessel monitoring systems (Succorfish$^{®}$ units), depth sensors, data capture of culling rates/dive times to determine the spatial extent, effort and depth profile of culling activities, and 4) survey the area to determine the effect of culling activities on urchin/abalone abundance and habitat.

Methods

Project area and survey design

Gunshot reef is located in eastern Victoria, northeast of Gabo Island and is surrounded by the Cape Howe Marine Park (Figure 1 and 2). The area of the reef is estimated to be about 16 hectares. It is considered as an isolated platform reef, bordered by sand inwards (inshore) and deep reef to seaward. Anecdotal evidence from the EZAIA suggests that kelp beds (an underwater forest of vegetation dominated by large fucoid macroalgae) have retracted in size due to over-grazing in recent years, with a risk that the Gunshot reef, and potentially adjacent reefs within the surrounding marine park, will become completely denuded if intervention does not occur.

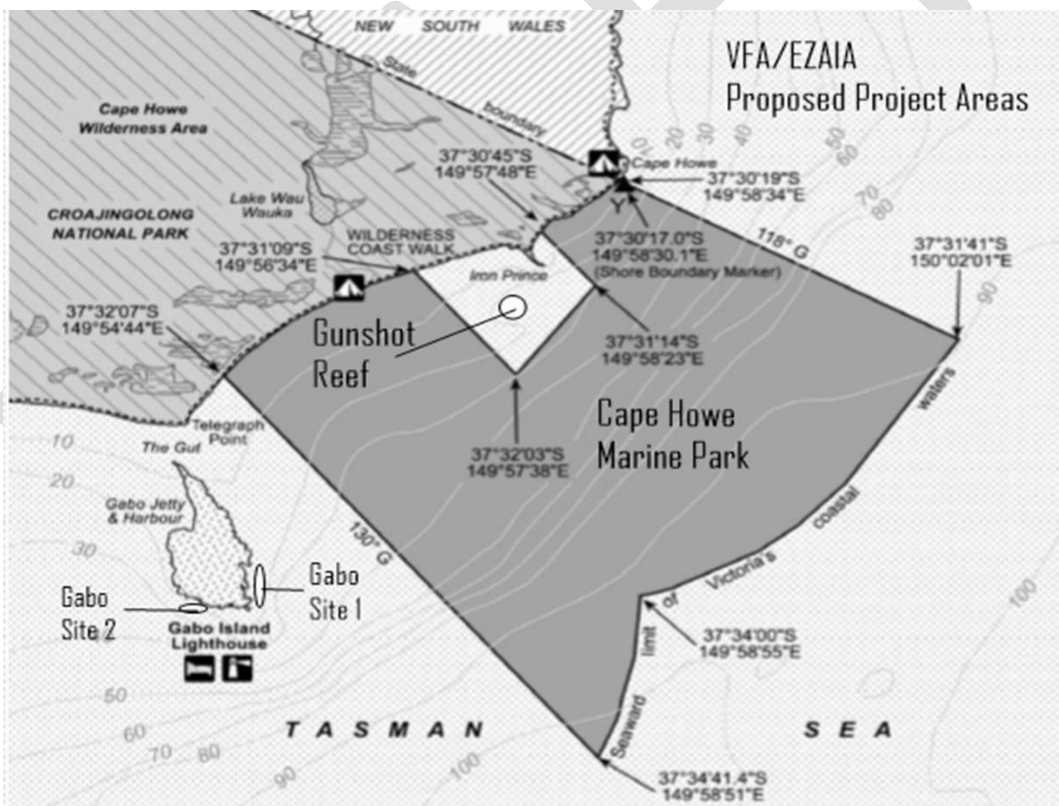

Figure 1. Map of Gunshot reef and Gabo Island in eastern Victoria, surrounded by the Cape Howe Marine National Park.

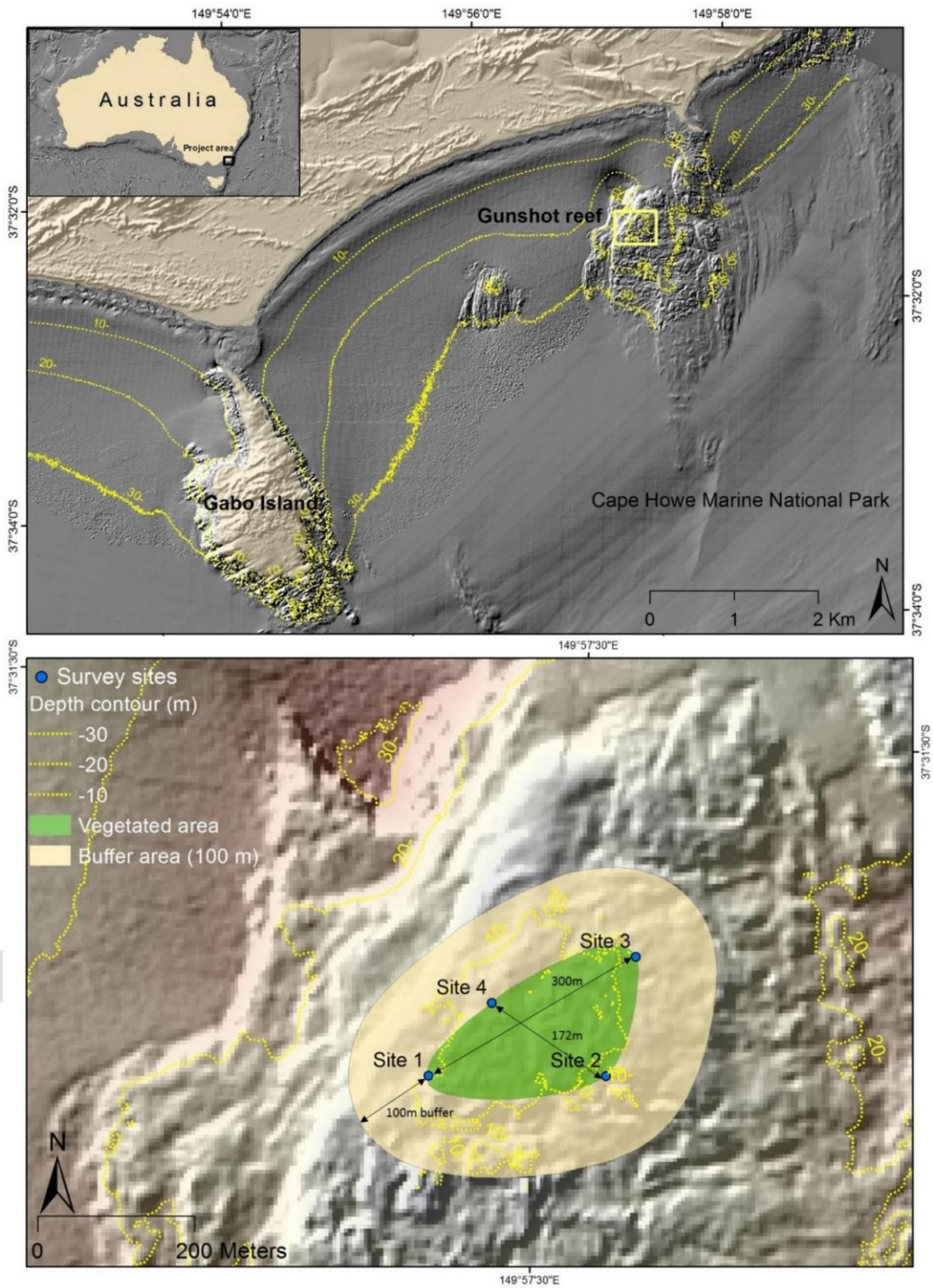

Figure 2. Map of the project area and survey sites in eastern Victoria, zoomed over Gunshot reef. Shaded relief of seafloor (LiDAR bathymetry at 5m spatial resolution) and depth contours are also shown, as is an approximation of the vegetated area and 100m area to be culled in the lower map.

Spatial, temporal and depth monitoring of culling activities

Under the Fisheries Regulations 2019, several commercial fisheries operating in Victorian waters, including abalone, are required to use vessel monitoring system (VMS) devices on their vessels. These VMS devices provide information on vessel position, bearing and speed. Abalone and sea urchin fisheries are currently equipped with VMS loggers called 'Succorfish®' units and these were allocated to vessels approximately mid-way through the current project.

Prior to the mandatory implementation of VMS, most vessels involved in this project were equipped with Succorfish® devices to provide locational information regarding vessel movements whilst divers were engaged in urchin culling activity. Where possible, divers were also equipped with Zebratech Paua Dive loggers (Turtles) that record a diver's position while on the surface, and depth plus dive time once they descend. It should be noted that there were insufficient dive Turtles for all divers, and sometimes vessels participated in the project without a functional VMS.

Dive times were recorded for each diver along with the number of urchins culled in each dive using a dive slate. In several instances, dive time and/or culling rates were not recorded: in these instances, daily averages were used to interpolate the culling effort of the diver(s).

Spatial analysis tools in ArcGIS software were used to generate hotspot and the minimum convex polygon (MCP) maps of vessel localities (Succorfish®) after removing outlier locations such as localities outside of the treatment area and while vessels were travelling at speed. These analyses were used to estimate the area of culling activities with the MCP map displaying the smallest range or extent of vessel localities.

Monitoring of habitat, abalone and urchin abundance

Prior to commencing urchin culling, abalone and urchin abundance surveys were conducted on the 26th August 2018. Abalone and urchin were counted along 25 meter belt transects, both inwards towards healthy habitat, and outwards towards the urchin barrens. Survey sites were located on the weed/barren boundary at each of four opposing directions (northeast, southwest, southeast, northwest) of the Gunshot reef. Abalone were grouped into three size categories (≤90, 90−120 and ≥120 mm maximum shell width) that align with VFA's abalone fishery independent survey program. A sample of fifty urchins were collected during a timed collection and grouped into three size categories (≤50, 50−100 and ≥100mm test width).

The above survey was repeated following the urchin reduction program on the 4th April 2021 to assess changes in abalone and urchin abundance.

To investigate changes in benthic habitat following the urchin reduction program, 100m weighted transect lines were radiated from each survey site outwards onto the urchin barrens. The GPS position at both ends of the transect line was recorded during the initial survey so that it was able to be re-laid in roughly the same position for the post-cull survey. A vertical video recording was made using a GoPro HERO 4 camera at one meter above the substrate along the length of the transect line starting at the vegetated part of the reef and swimming outwards onto the barren habitat.

Another video survey was recorded across the vegetated part of the reef with the diver being towed by the vessel from Site 2 to Site 3. Examples of typical habitats at survey site 3 before commencing the urchin cull activity are presented in Figure 3. These surveys are unsuitable for quantitative purposes so will not be discussed further herein, but are useful for descriptive purposes and to extract video/photo imagery for other purposes as the 100m vertical video is not very visually appealing (i.e. its sole purpose was for quantitative analysis of habitat recovery).

Vertical videos, before (pre-cull) and after (post-cull) urchin culling, were converted to images at intervals of two seconds. A random sample of 25 images was used to classify benthic habitat (total 200 images at pre-cull and post-cull stages). Images were then imported into 'Coral Point Count with Excel extensions' (CPCe software, https://cnso.nova.edu/cpce/index.html), and 25 points were overlaid onto each image (Figure 4). The underlying substrate and biota at each point were classified into one of the seven categories used in previous studies (Hamer et al. 2010, Gorfine et al. 2012):

- Encrusting and sessile invertebrates
- Encrusting algae
- Turf algae
- Erect algae
- Encrusting and articulate coralline

- Sand and silt matrix
- Bare rock

Further details of each class are provided in Table 1 and the various habitat types are depicted in Figure 5. After identifying the benthic classes, the data were automatically assembled and exported to Microsoft Excel for further exploration and statistical analysis. Multivariate analysis with non-metric multidimensional scaling (nMDS) was used to identify patterns of benthic cover classes at each survey site during both pre-cull and post-cull stages. Benthic coverage data were square-root transformed and a Bray-Curtis dissimilarity matrix was set for nMDS (Walker and Gilliam 2013). To test for changes in the proportional coverage of each habitat classification between the pre- and post-cull surveys, a one-way permutational multivariate analysis of variance (PERMANOVA) was undertaken with 'bray' selected as the method, which undertakes the analysis following Bray-Curtis dissimilarity transformation and 999 permutations were used. All multivariate analyses were performed using the vegan package within the R statistical program (Oksanen et al. 2015).

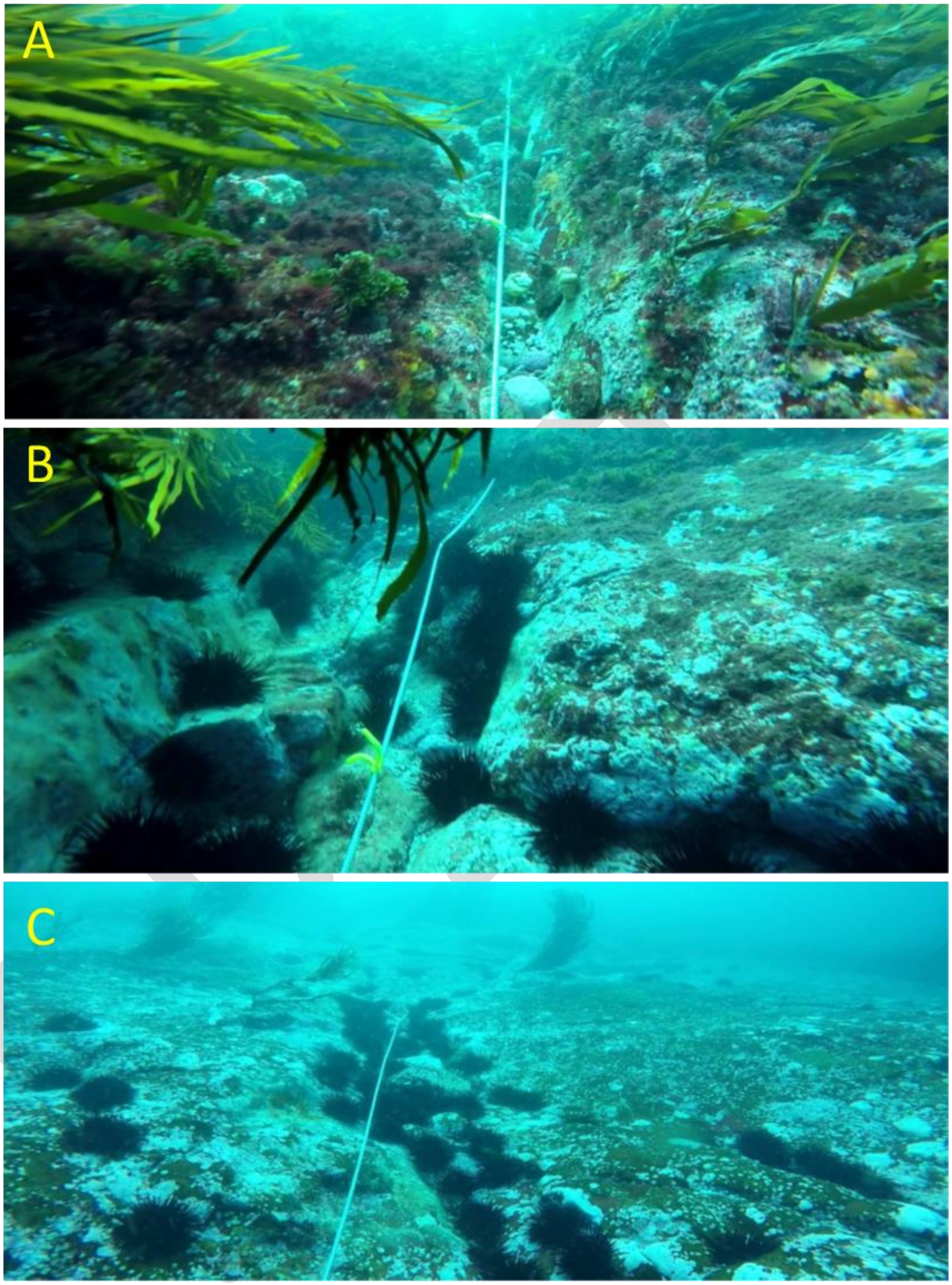

Figure 3. Typical habitat on the best parts of the reef inwards (inshore) at site 3 with a gutter containing abalone (A). Incipient barren within the inwards vegetated reef area at site 3 (B). Outwards (offshore) barrens habitat starting in 10 m depth on all sides of the reef at site 3, extending into the distance (C).

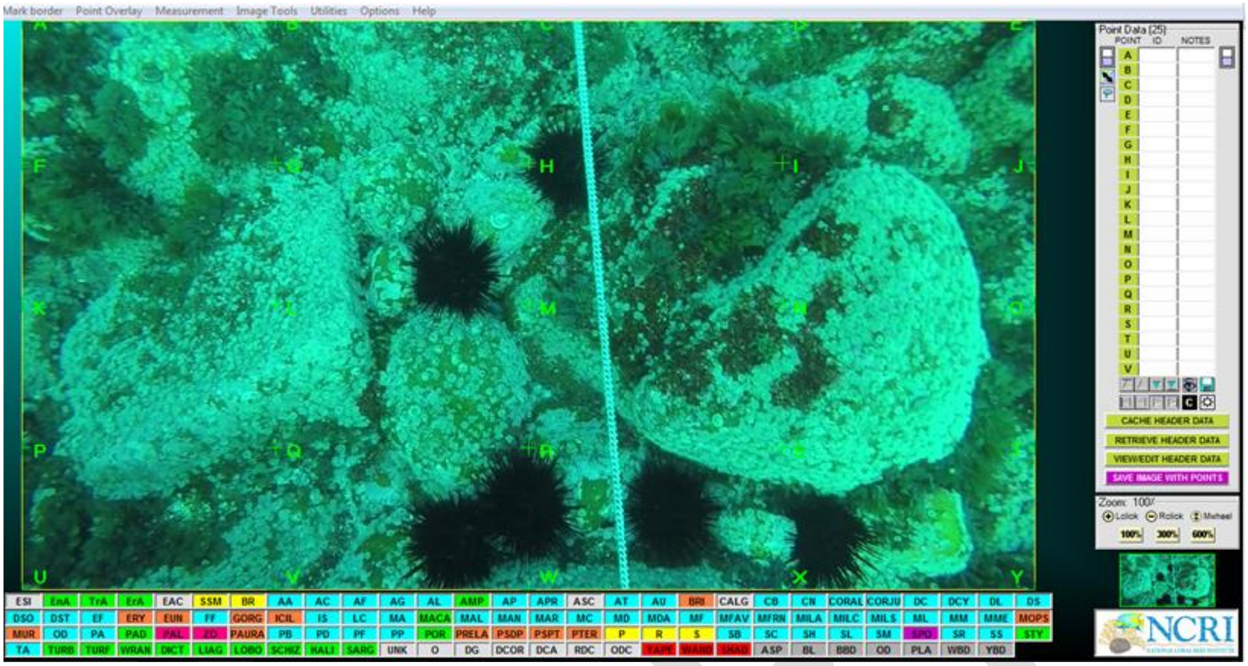

Figure 4. Example of the CPCe window showing image processing for benthic habitat classification.

Table 1: Summary of major benthic categories, taxa and category descriptions used in the photo analysis.

Major categories	Minor categories and descriptions
Encrusting and sessile invertebrates	Ascidiacea, Bryozoa, Porifera, Cnidarians, Bivalve molluscs, Crustacea, Polycheata
Encrusting algae	Encrusting algae
Turf algae	Green, red, brown algae, < 3 cm height above the substrate
Erect algae	Green, red, brown algae, ≥ 3cm height above the substrate with noticeable stripes.
Encrusting and articulate coralline	Smooth encrusting coralline, warty encrusting coralline and any articulate coralline.
Sand and silt matrix	Sand, aggregated combination of silt, sand, fine shell and or dead plant material forming a thin layer (generally <1 cm thick) on the rock surface.
Bare rock	Clean rock with no observable algal/invertebrate growth.

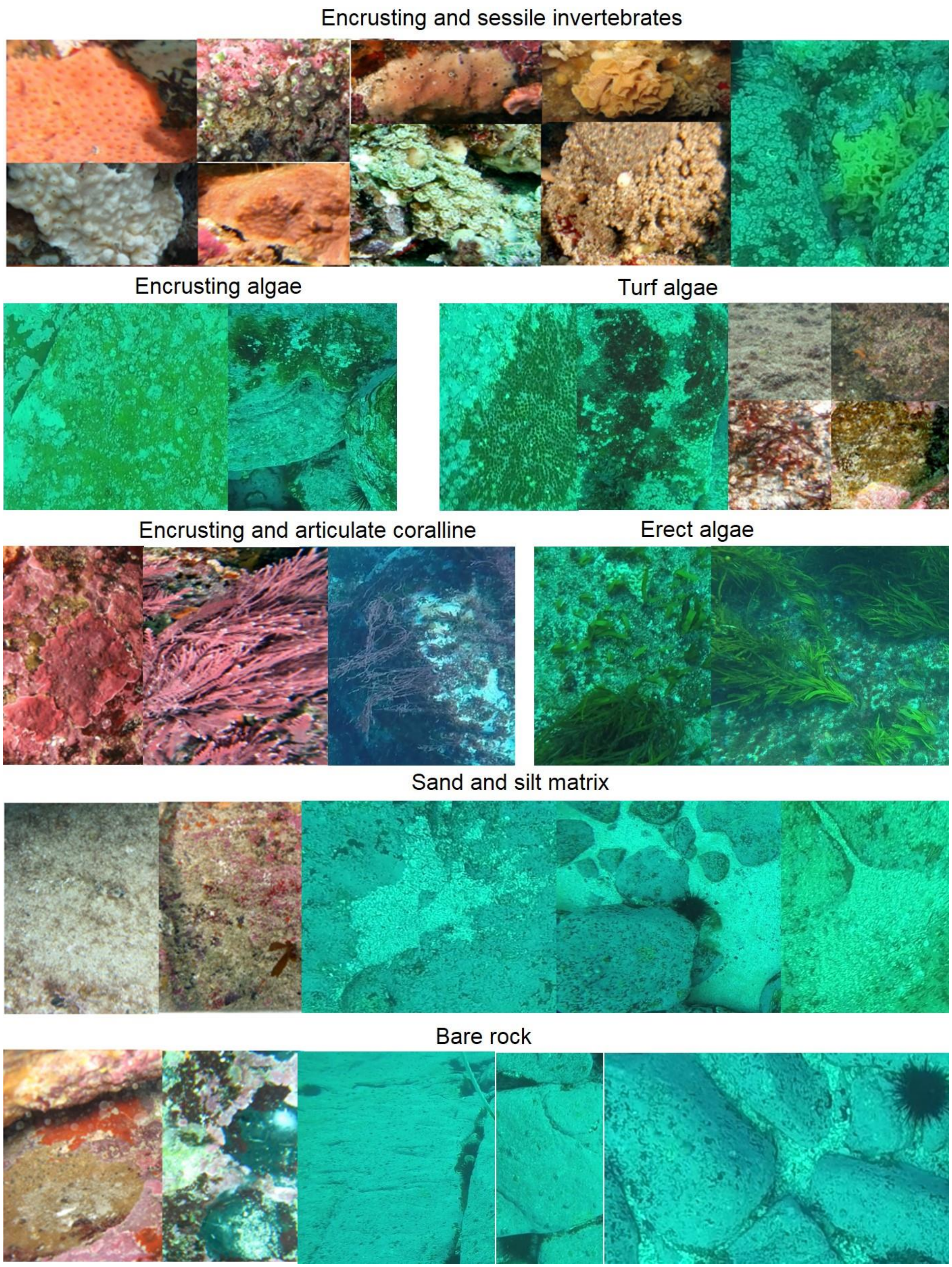

Figure 5. Example images of major benthic categories used for substrate and biota classification.

Results and discussion

Urchin abundance

Urchins were in higher quantities offshore at all survey sites, with numbers varying widely between sites (Figure 6). Inwards, at sites 2 and 4, urchin numbers were relatively low before the cull commenced, presumably because the habitat was relatively healthy at these sites before urchin eradication began. This is also consistent with urchins seeking shelter from turbulent sea conditions that are more prevalent in shallower than deeper habitats (Lissner 1980). There was a drastic reduction in urchin abundance following the urchin removal program, with five or less urchins observed at each of the sites with no appreciable difference between inwards and outwards.

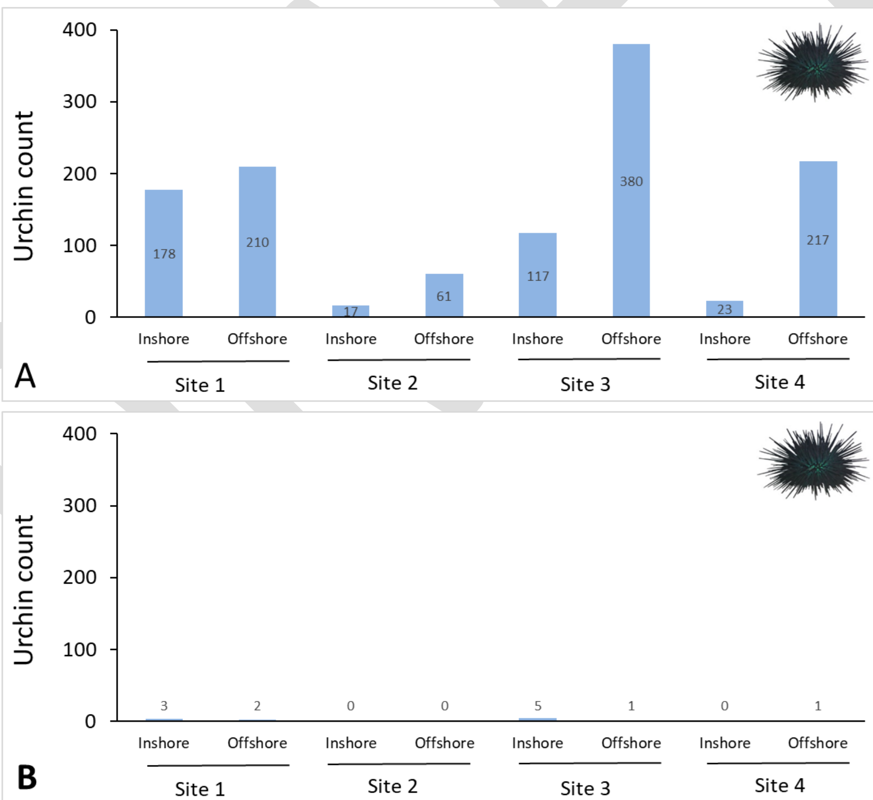

Figure 6. Urchin abundance at inwards (inshore) and outwards (offshore) sides of the survey sites at Gunshot reef at pre-cull (A) and post-cull (B) stages. Abundance values are also shown.

The length frequency sample during pre- and post-cull stages also indicated variability in the number of urchins at different size classes across the survey sites. Smaller urchins were more abundant at sites 1 and 3, whilst a larger proportion of bigger urchins were present at sites 2 and 4 (Figure 7). There was a notable change in the size frequency between pre- and post-cull surveys with fewer small urchins present in the latter survey (Figure 7). In addition, differences in the number of urchins collected per minute (i.e. CPUE) revealed that few urchins were left after the cull at all survey sites (Figure 8).

When undertaking a program such as this, it is common to remove all observable urchins from an area, only to return sometime later and find the area recolonized. It is believed that this represents emergence of younger urchins that were hidden in cryptic spaces. Thus, the lack of small urchins late in the post-cull survey is likely because juveniles have had a chance to emerge several times in lieu of a lack of competition with adults, only to be culled themselves. It appears that eventually the majority of cryptic urchins have also been culled due to their successive removal over several years leaving very few young urchins available to recolonize. This is an important consideration for future culling operations, i.e. a once-off cull may be able to remove all visible urchins, but is unlikely to be successful in achieving complete eradication as emerging juveniles will soon occupy the niche left by their older kin. Thus, repetitive culling is more likely to have long term success, particularly in complex habitat.

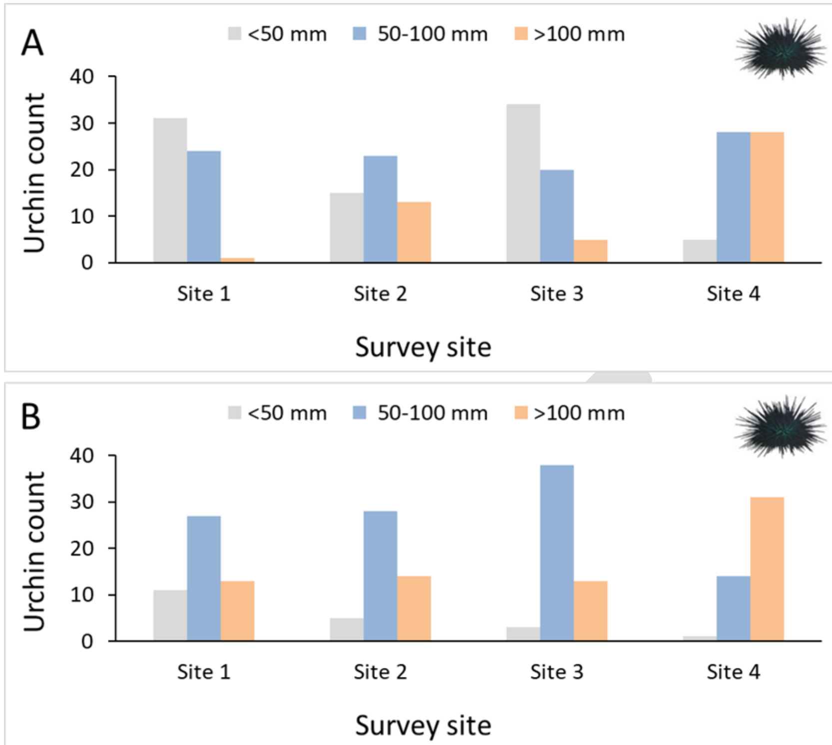

Figure 7. Urchin abundance in three size classes at four surveyed sites based on LVF survey at pre-cull (A) and post-cull (B) stages.

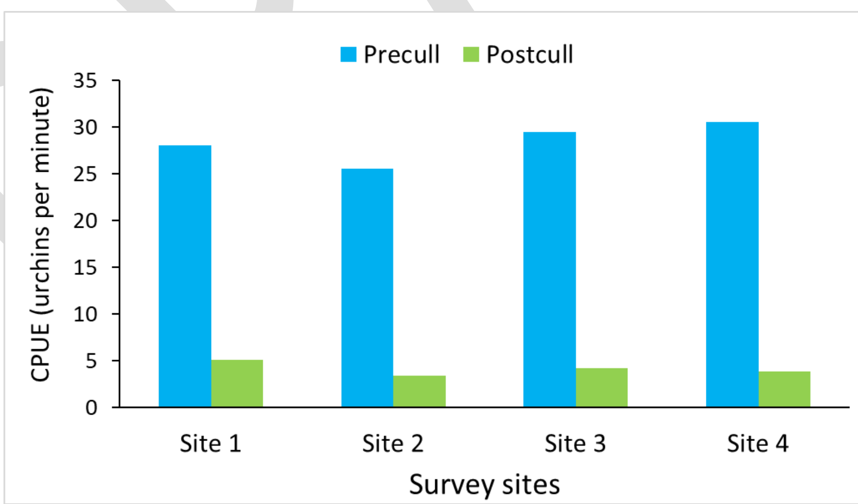

Figure 8. Urchin catch per unit effort (number of urchins collected per minute) for pre- and post-cull surveys.

Abalone abundance

Abalone were vastly more abundant inwards at the survey sites, which is not surprising given that is where the habitat was better and outwards was largely urchin barren (Figure 9). Abalone in the 90–120mm length category were the most abundant size class in almost all instances: again, this is unsurprising given that very small abalone are generally cryptic, and abalone >120mm are above the legal minimum length and therefore subjected to fishing. Interestingly, the proportion of abalone >120mm increased during the post-cull surveys, especially on the outwards (offshore) transects, which may be a result of the 90–120mm size class moving out onto the recently culled areas and growing through to the larger size category during the project. Growth of about 10mm per annum is anticipated for abalone of this size in this region. In this respect, abalone abundance (mean ± standard deviation) on outwards transects, for the >120mm size class, increased from 0.5 ± 0.5 abalone to 10 ± 5 abalone following the removal of urchins. In comparison, abundance for the size classes of 90–120 mm and <90 mm on outwards transects changed from 3.2±3 to 7.5±7 and from 1±1.2 to 1±1.4 abalone respectively.

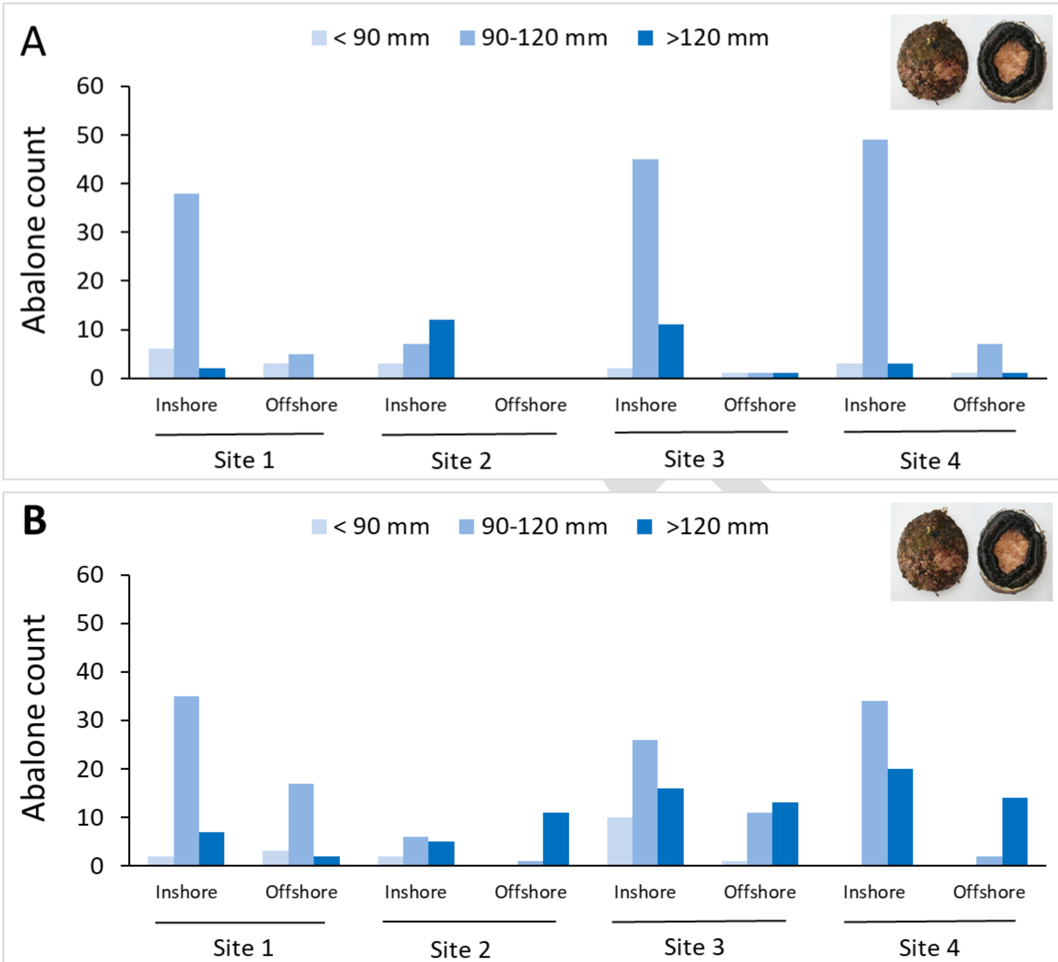

Figure 9. Abalone abundance at inwards (inshore) and outwards (offshore) sides of the survey sites at Gunshot reef at pre-cull (A) and post-cull (B) stages.

Urchin culling activity

Overall, in terms of 'diver effort', about 278 dive hours were required to remove about 514,000 urchins during the project (see Table 2 for a breakdown of daily effort and Appendix 1 for a detailed spatial breakdown of diving effort). Combined maps of vessel and diver activity indicated that divers generally stayed close to the vessels, largely because they were anchored whereas during most commercial diving to harvest abalone the vessels are 'live' and follow the divers as they remove abalone from the seabed, urchin abundance was so high that this was often unnecessary during the culling undertaken for this project (Figure 10).

The minimum convex polygon (MCP) of Succorfish® localities indicated that around 180 hectares of the reef area was treated (Figure 11). While culling effort occurred throughout the area, hotspot analysis indicated that culling was greater on the west and southwest of the reef (Figure 12) where boulder habitat is common, and urchins are more difficult to eradicate. More effort was generally applied to the barrens and margins, again where urchins were the most abundant. Several 'hotspots' also show up on the eastern side of the reef within the vegetated area that represent areas where insipient barrens had begun to form, and considerable effort was required to ensure that these were urchin-free to facilitate recovery.

Table 2: Daily diving effort and the number of urchins eradicated.

Dive date	Number of vessels	Number of divers	Dive time (hours)	Urchins culled (count)
19/04/2019	4	8	17	37500
20/04/2019	2	3	9	16000
24/04/2019	2	4	12	28100
22/05/2019	5	7	12	29500
23/05/2019	5	7	21	34500
24/05/2019	6	8	18	40000
25/05/2019	4	8	21	45500
5/07/2019	5	8	8	10200
7/07/2019	4	8	15	18000
17/12/2019	3	6	16	29600
28/03/2020	8	10	27	48720
30/03/2020	9	10	28	54100
31/03/2020	9	10	27	48900
1/04/2020	10	11	29	52450
28/11/2020	3	6	18	21300
Total	**79**	**114**	**278**	**514370**

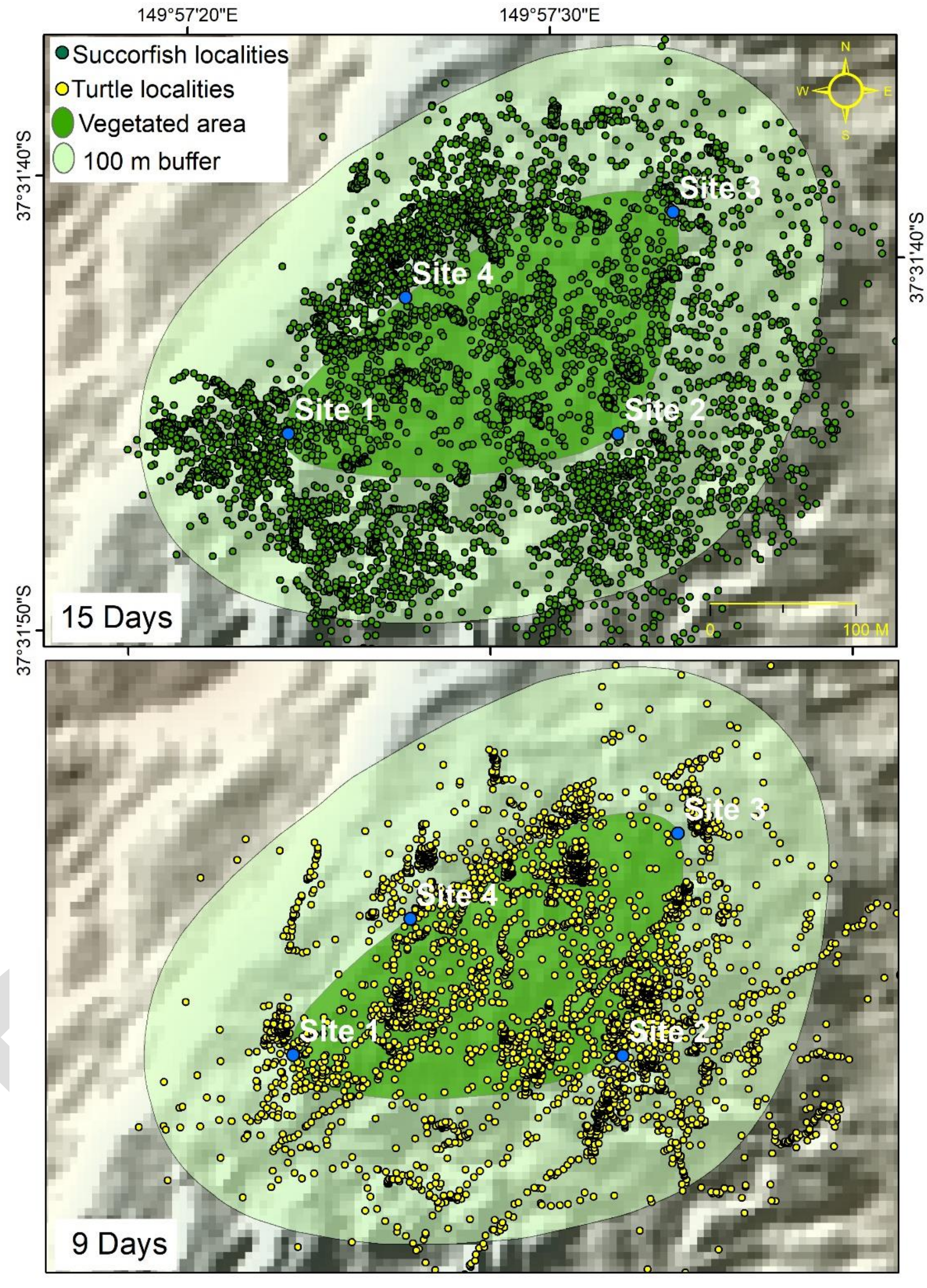

Figure 10. Combined maps showing distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) respectively over 15 and 9 days of urchin culling effort at Gunshot reef. Turtle localities were in access for 9 days so far, and Turtle outlier locations were not excluded from this map. Maps are overlaid over LiDAR-derived relief of seafloor.

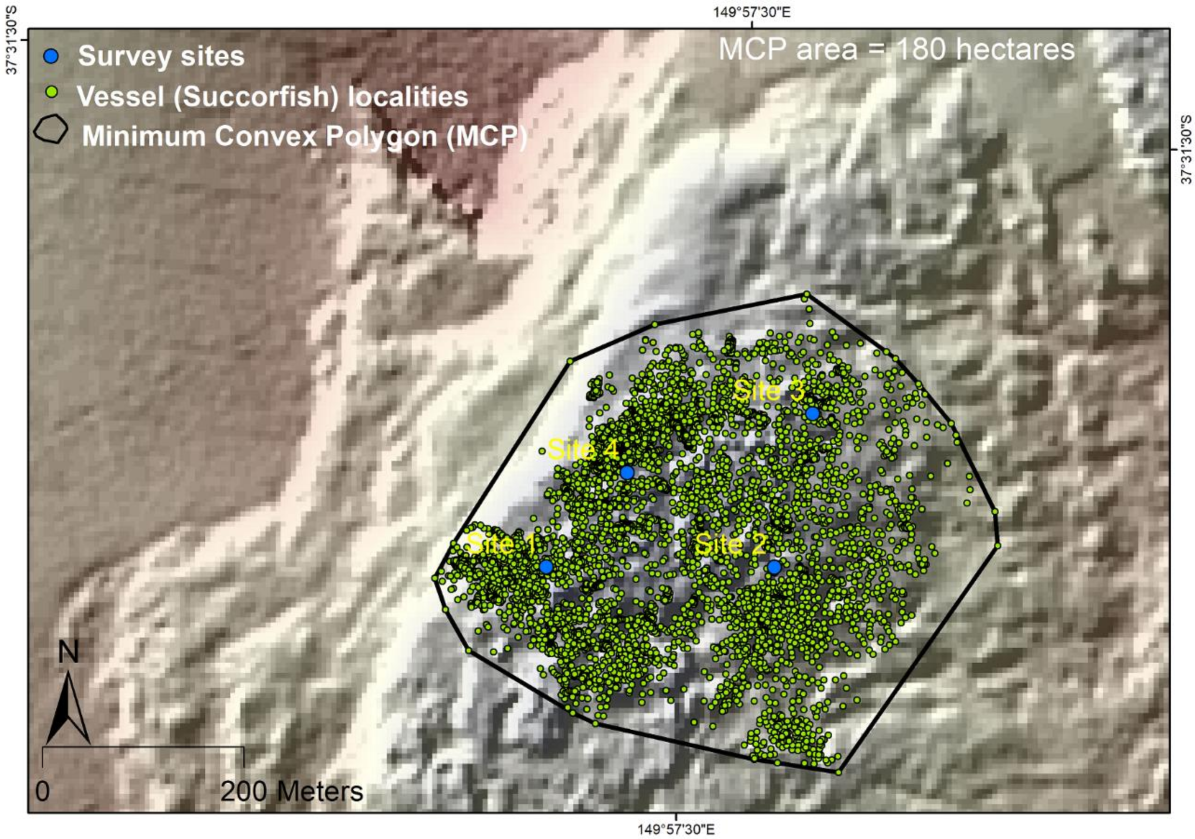

Figure 11. Minimum convex polygon (MCP) of vessel localities (Succorfish®) showing the boundaries of vessel activities combined over 15 days of urchin culling activity at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

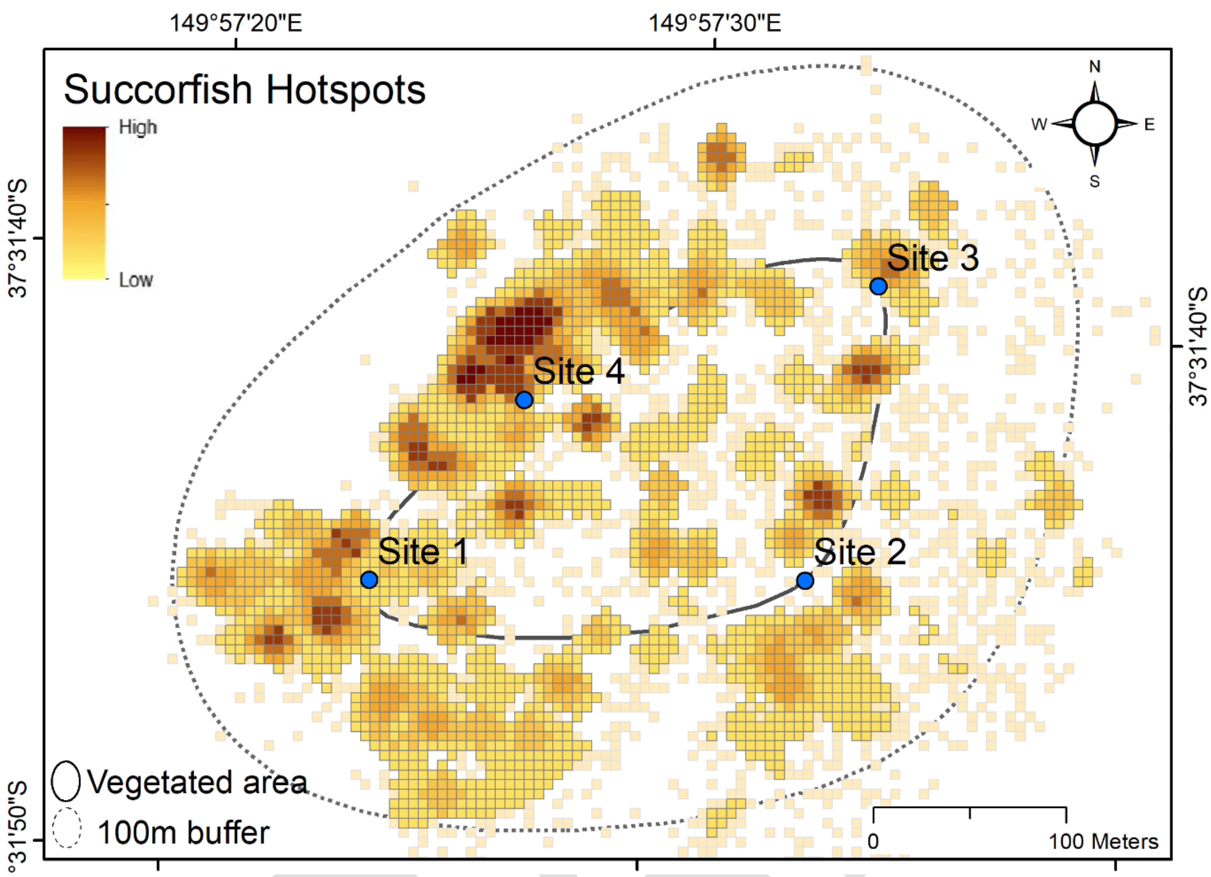

Figure 12. Heat map of vessel localities (Succorfish®) generated from hotspot analysis showing areas of low (light color) to high (dark color) vessel activities, combined over 15 days of urchin culling project at Gunshot reef.

Given that divers stay within relatively close proximity of the boat (their surface supply air hose is generally 100m or less), the heat map of Succorfish® localities can be an indication of the areas under concentrated culling effort. Intensity and size of hotspot clusters showed that larger patches of urchins occurred on the western side of the reef where rocky boulder habitats were common (Figure 12).

After removing vessel outlier locations based on the speed of the boat, and depth values extracted from LiDAR bathymetry (5m spatial resolution), it was found that urchin culling occurred at depths ranging from 7 to 17m, and at about 10m on average (Figure 13). It should also be mentioned that depth values obtained from of the Turtles include ascent and descent profiles, though these generally comprised only a few individual data points, so should not corrupt the analysis or interpretation of the data. These depth ranges can, however, be an indication of culling effort patterns considering the concentrated diving activity in the proximity of the vessel. The Turtle data shows a similar pattern to that of the LiDAR derived depths, with most culling effort occurring at depths of 8 to 10 m.

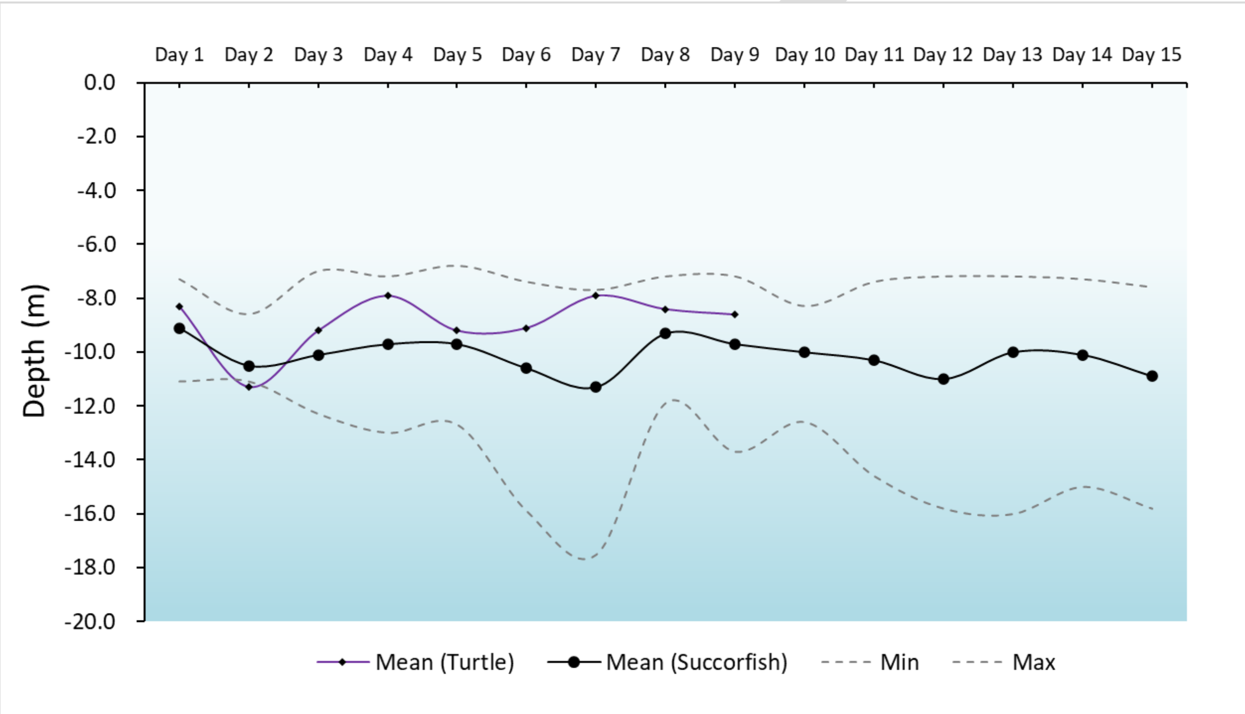

Figure 13. Depth ranges (mean, minimum and maximum values) of urchin culling activity based on Succorfish® and Turtle locations at Gunshot reef on each dive day. Turtle data were provided for 9 days.

It must be acknowledged that several factors influence the accuracy of the spatial information provided in this report, mostly resulting in an underestimate of the amount of area that was culled. The compounding effect of these factors means that the area culled is likely to be considerably larger than is observable in the heat maps, but not necessarily larger than that reported in the MCP. The abovementioned factors include:

- Diver is not at the location of the VMS e.g. longer hose length, or multiple divers at any one time. This would mean that the culled area is an underestimate.
- VMS was only used for 73% of the time that culling was undertaken.
- Turtles only provided start and end locations of each dive.
- Boats were anchored a lot of the time because urchin density was so high, meaning the VMS track is often more reflective of the boat yawing in the breeze than where diving occurred. Surface supply hose length (generally 100 m or less) dictates how far the diver can be from the boat and during a three hour dive the diver could be anywhere within a the hose length's radii of the vessel's position. Again, this results in an underestimate of the area covered by the diver. It is possible to use models (e.g. Brownian bridge movement models) that incorporate positional uncertainty to address this issue, and these would certainly have been utilized were data suitable available. However, given the boat is at anchor much of the time, the model would be estimating the uncertainty of the boat location (i.e. based on its movement while at anchor) rather than the position of the diver. This would introduce more, not less, error into the spatial information.

It is very difficult to estimate where divers are all of the time. It requires divers to either tow a buoy with a GPS, or very expensive equipment deployed in the area to triangulate their position using sonar. Both of these options were outside the scope of the current project: wearing a floating buoy causes considerable problems when diving with surface air supply (i.e. entanglement) and when the boat is not at anchor, the likelihood of entangling the buoy rope in the engines introduces unnecessary danger to the diver; the expense of the equipment required to triangulate the divers is prohibitory, takes considerable time to set up and calibrate, and in general is highly impractical as it would not have been possible for so many divers to be active at once while maintaining their position within range.

As per divers' observations, video surveys also showed that survey sites 1 and 4 (west and southwest of the reef) were predominantly comprised of boulders whilst flat, slab reef, habitats were predominant at survey sites 2 and 3 (east and northeast of the reef). This physical reef structure difference had implications in terms of both culling effort, and habitat recovery (described below): significantly more effort was applied to the western side of the reef and the recovery was less evident, at least in terms of erect algae. This pattern is similar to that observed previously [i.e. (Gorfine et al. 2012)] in which it is considerably more difficult to find all of the urchins in boulder habitat that contain a higher proportion of cryptic habitats. It also appears that juvenile urchins, presumably hidden amongst boulders, rapidly colonize the newly available habitat once their larger conspecifics have been removed. This means that boulder habitats need to be treated several times in order to reduce urchin densities to the point that habitat recovery occurs. This is not the case on flat areas where it is relatively easy to locate and cull essentially all the urchins, or at least sufficient of them to facilitate habitat recovery. On these habitats, return trips are still often required, however, to identify areas that were missed during initial efforts, which occurs because the urchins are often able to re-close their test after being split open. This makes it difficult to identify those habitats that have already been subjected to culling in a given area, particularly when culling activities are undertaken in a haphazard fashion as was the case in the present study. Other studies have undertaken urchin culling in a more systematic fashion, which has been shown to reduce urchin densities sufficiently to recover habitat in a single treatment (Tracey et al. 2015). The disadvantage with this latter approach is that it requires a far greater amount of organization to set up plots to enable divers to efficiently navigate underwater to ensure each plot is thoroughly treated. It also reduces culling rates as divers cannot target areas of high density as they are observed, having to concentrate on their allocated plots. As can be seen, both approaches are effective, and both have their advantages and disadvantages. It would perhaps be beneficial if a study were undertaken to determine which is the most cost-effective as both are able to achieve the ultimate goal of recovering habitat lost to urchin overgrazing.

Changes in benthic communities due to urchin removal

The PERMANOVA indicates that there was a significant change in the proportions of each habitat category between the pre- and post-cull surveys (Table 3). Investigation of the proportion of changes in individual benthic communities generally showed an increase in the percentage of algal communities, especially turf and erect algae, following urchin removal (Figure 14 and 15). Survey site 1 had a greater proportion of reef covered with encrusting and sessile invertebrates (41%) as well as bare rock (19%) before treatment compared to the remaining sites. Shifts in benthic communities were observed at this site with an increase in erect algae from 3% at pre-cull stage to 18% at post-cull stage as well as noticeable changes in the proportion of coralline algal communities after urchin removal, although a high proportion of bare rock was still evident at this site during the final survey. Site 2 displayed the largest increase in erect algae from 5% at pre-cull stage to 59% at post-cull stage, which was the highest increase in erect algae coverage observed during this project, despite less culling effort at this site. Perhaps this was due to the topography in this region (i.e. relatively flat slab reef) being more easily culled.

Table 3. One-way PERMANOVA testing the effect of survey (i.e. pre- and post-cull) on the multivariate response (i.e. habitat classification).

	df	Sum of squares	R^2	F	p-value
Survey	1	6.6	0.17	40.8	0.001
Residuals	198	32.4	0.82		
Total	199	39.0	1.00		

Site 3 responded similarly to Site 2, with erect algae increasing from 14% to 42%, again this was despite relatively little culling effort in the area. At site 4, a general progression from bare rock, encrusting and sessile invertebrates, and encrusting algae was observed towards turfing (from 3% to 13%), coralline (from 0.5% to 9%) and erect algae (from 3% to 27%) dominated substrates.

Overall, mean coverage of the benthic classes from the data combined across all surveyed sites before and after urchin removal indicated a considerable change in erect algae from 6% at pre-cull to 36% at post-cull, and diver video surveys also illustrated initial signs of habitat recovery with improved growth of algal communities as shown in Figure 16.

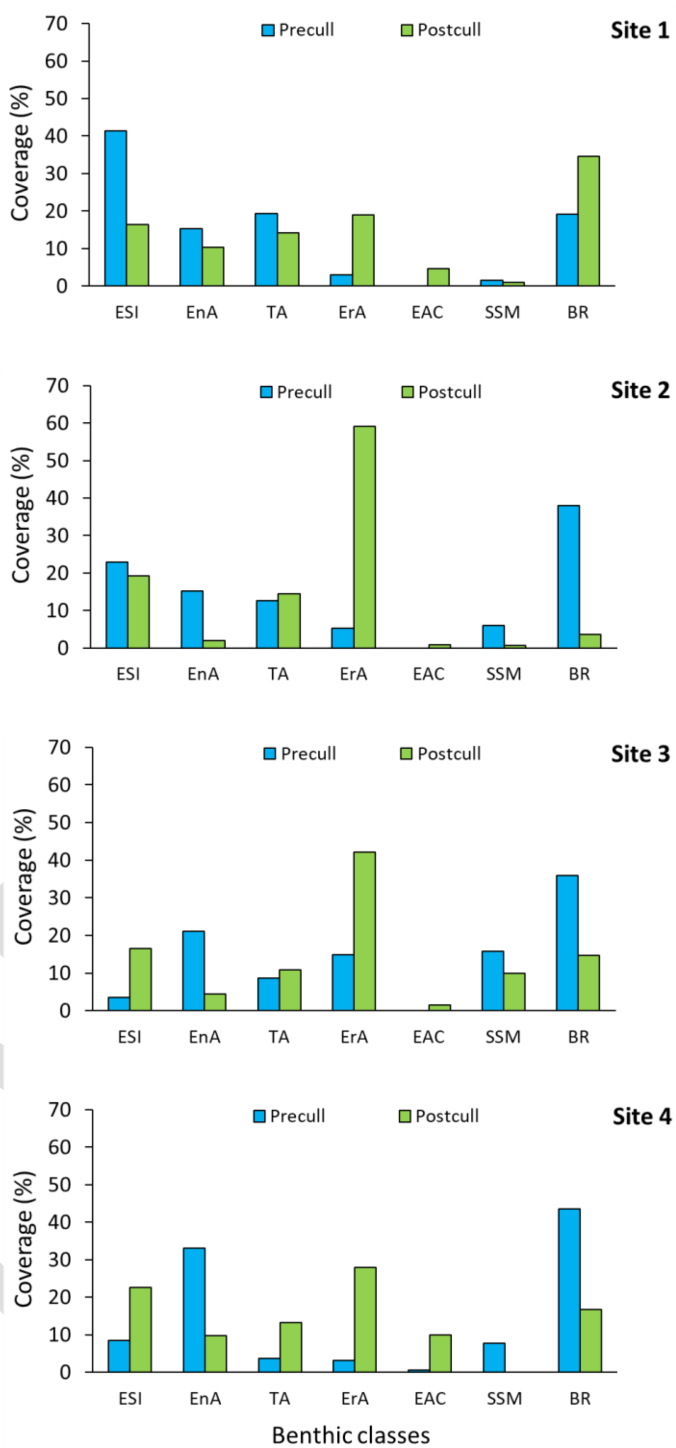

Figure 14. Proportion (%) of the benthic classes cover at each surveyed site before (Precull) and after (Postcull) urchin removal at Gunshot Reef. Encrusting and Sessile Invertebrates (ESI), Encrusting Algae (EnA), Turf Algae (TA), Erect Algae (ErA), Encrusting and Articulate Coralline (EAC), Sand/Silt Matrix (SSM) and Bare Rock (BR).

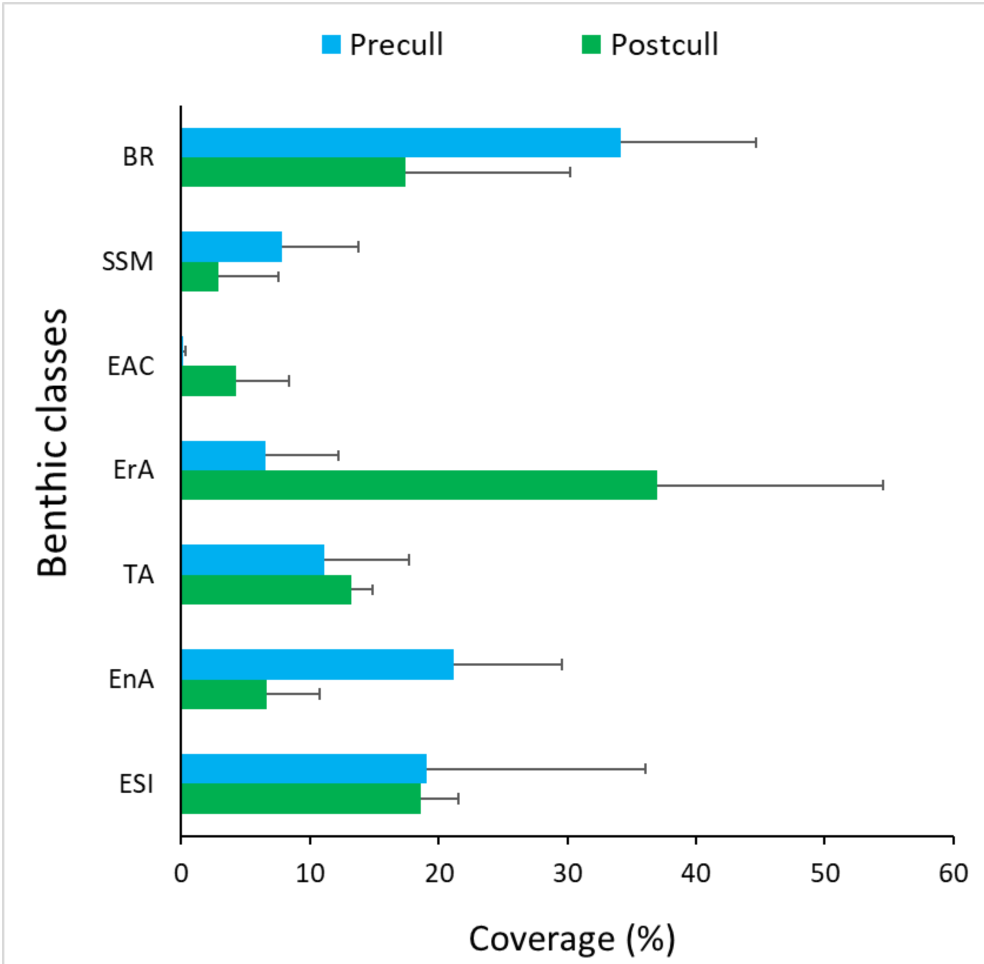

Figure 15. Mean coverage (%) of the benthic classes from the data combined across the surveyed sites before (Precull) and after (Postcull) urchin removal. Encrusting and Sessile Invertebrates (ESI), Encrusting Algae (EnA), Turf Algae (TA), Erect Algae (ErA), Encrusting and Articulate Coralline (EAC), Sand/Silt Matrix (SSM) and Bare Rock (BR). Standard deviations ~~are~~ also shown for each class.

Figure 16. Examples of algal growth and benthic habitat recovery following the removal of sea urchins.

Multivariate analysis of non-metric multidimensional scaling (nMDS) indicated patterns in benthic categories at the surveyed sites before and after urchin removal (Figure 17). In this case, nMDS indicates that all four sites behaved similarly following urchin removal, showing a progression from bare rock, encrusting algae and sand/silt (left side of the nMDS) towards the various algal categories on the right side of the nMDS plot.

Algae community succession was particularly evident Sites 2, 3 and 4 at the completion of the study. At Site 1, however, bare rock had increased throughout the duration of the study, with a reduction in encrusting sessile invertebrates and minimal change in the other benthic classes. The largest change in erect algae community occurred at site 2 from around 5% to 59%. Relatively similar changes in the patterns of erect algae community were observed at sites 3 and 4.

Spatial patterns in the responses of these benthic communities to urchin culling is likely to be due to the function of the reef structure at each survey site with Sites 1 and 4 comprised of boulders whilst Sites 3 and especially Site 2 were mostly comprised of flat reef, which affects culling efficiency. As per the divers' observations, data exploration revealed that further effort will be required to ensure that the removal of urchins from barrens and incipient barrens is maintained, especially in boulder and cryptic habitats as illustrated in Figure 18.

Although these early signs of habitat recovery are of considerable importance, erect algae communities have only just started to recover, hence the proportional cover will increase through time. This will allow the macroalgal communities to recruit and grow sufficiently to colonize enough reef surfaces to produce the tangible benefits that are expected to become apparent in a few years. Previous investigations of urchin removal by Gorfine et al. (2012) in eastern Victoria indicated that it may take several years for the macroalgae community to resemble normal reef, especially in the case of *Ecklonia radiata* which appears to grow more slowly. Previous attempts at recovering canopy-forming algae on reef habitats after removal of sea urchins in Tasmania, and other geographic areas, also indicated gradual algal community restoration in the longer term (Ling et al. 2010, Piazzi and Ceccherelli 2019, Layton et al. 2020). Continued urchin culling effort and allowing the growth of macroalgae will provide further opportunities for flora and fauna to recover to protect the biodiversity of the reefs and prevent barrens from reforming so as to better sustain the Eastern Zone Abalone Fishery and the health of the Gunshot Reef more generally.

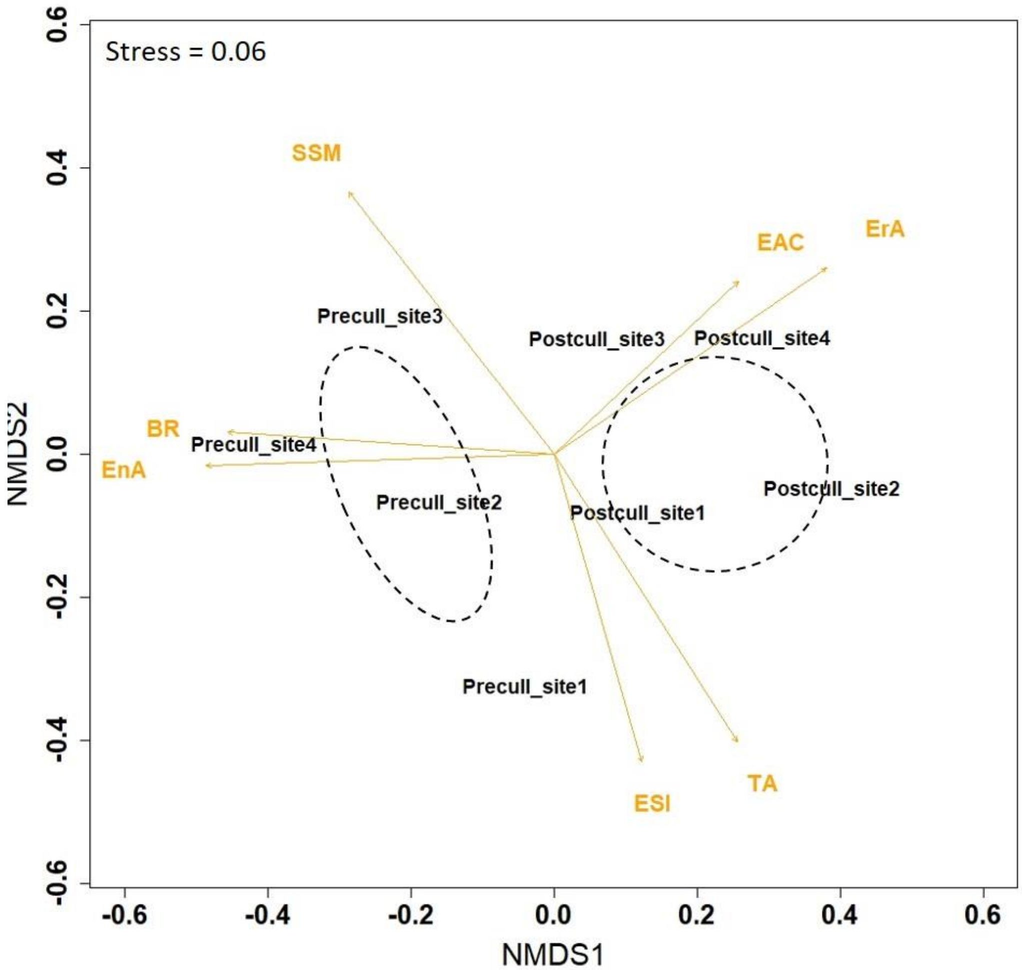

Figure 17. Multivariate nMDS plot illustrating patterns in benthic classes across survey sites before (Precull) and after (Postcull) urchin removal. Encrusting and Sessile Invertebrates (ESI), Encrusting Algae (EnA), Turf Algae (TA), Erect Algae (ErA), Encrusting and Articulate Coralline (EAC), Sand and Silt Matrix (SSM) and Bare Rock (BR). Ellipses are also shown indicating 95% confidence intervals fitted into the spatial ordination.

Figure 18. Example images of the vegetated edge (left panel) and barren edge (right panel) of the surveyed transects at gunshot reef, illustrating boulder and flat slab reef.

Conclusions

- A total of 114 diver days of culling was undertaken during the current project for a total of 278 hours of bottom time.
- An estimated 514,370 urchins were removed from the reef habitat.
- The minimum convex polygon of diving effort indicates that a maximum of 180 hectares was culled, though it is possible, if not likely, that some areas within these bounds were missed. It was not possible to determine how much may have been missed given the limitations of using vessel location as a proxy for diver location.
- Considerably more effort was directed toward the west of the reef as this area was comprised of boulders making it more difficult to find all of the urchins.
- On boulder habitats, it was necessary to make several return trips to remove urchins that had presumably emigrated out of crypsis to colonise the newly available habitat that their conspecifics had previously inhabited.
- On flat slab reef, on the north and east of the reef, less effort was necessary to cull urchins from the reef.
- Surveys indicate that urchin density was greatly reduced as a result of the culling and abalone density increased at some sites.
- At all sites, urchin densities were reduced to the point that enabled habitat recovery and given the spread of effort, this is likely to have been the case for the majority of the Gunshot Reef within diving depths.
- The culling resulted in a large reduction in the proportion of bare rock, encrusting algae and sand/silt with a progression towards the various algal categories, particularly erect, coralline and turfing alga.
- Despite culling effort being disproportionately high in boulder habitats, recovery was less evident in these areas, presumably because some urchins were missed by divers due to the complexity of this habitat and the cryptic nature of juveniles.
- It is likely that the results presented herein represent an underestimate of the benefits that the current project has had at the Gunshot Reef as the algae are relatively slow growing and thus their proportional coverage will continue to increase for some time.

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Appendix 1: daily culling activity

19 April 2019: Day 1

This date was the first day of urchin culling at Gunshot reef. A film crew was engaged to obtain the required video footage of the reef habitat and urchin culling activities. Surface buoys were set at all four sites and vessels were anchored near a buoy. It was also ensured that all divers wore turtles, and collected and recorded data as directed. Clear water and calm seas provided good filming conditions, although the cloud cover created low light conditions for most of the day. Filming boats, divers, reef habitat, flora and fauna was undertaken by the film crew as per the specification for the media project. Divers generally worked close to their vessels, although at times they also worked to the length of their hose behind the vessel in line with the tide. Vessels were at anchor all day and rarely changed their anchorage (Figure 19). All divers recorded urchin counts on dive slates for the entire duration of the dive. The culling rate was consistently estimated at more than 6,000 urchins culled per diver for a 3-hour dive (Table 4). Remarkable amounts of urchins were observed encroaching pristine habitat and on healthy reef. Divers culled extensive urchin barrens taking over heavy reef. At site 4, the bottom comprised of boulders and crevices with only a few patches of kelp cover amongst the extensive barrens.

Table 4. Total amount of dive time and urchin culling rate on the first day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
16.9	90	10	30000	7500

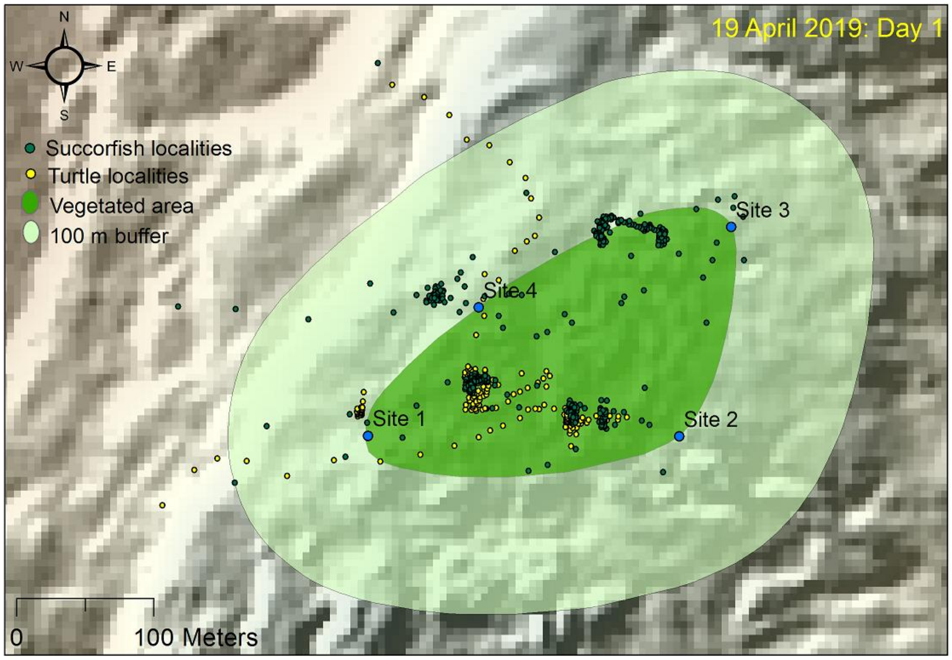

Figure 19. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 1 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

20 April 2019: Day 2

On the second day of urchin culling, surface buoys were set at Sites 1 to 4. One boat anchored on the Site 1 buoy, and the other was at about 30 m north of this vessel's position (Figure 20). Vessels stayed on the same anchorage all day, and divers also tried to work within 30m of their vessels. Diving was difficult due to strong swell conditions and thus diving shifted from shallow into deeper areas. The seafloor habitat type was observed to be in the form of a boulder structure. In front of site 1 the bottom found to be mostly flat before turning bouldery when working back towards Gabo Island. On the flat areas, large gutters of urchins filled the cracks in a similar manner to the behavior of abalone on the healthy reef habitats. The urchins were extremely dense and the divers concentrated their efforts clearing urchins from these gutters. Moreover, due to difficulties with swell and sea conditions, the culling rate was not recorded on this day, although an estimated rate was provided by the divers (Table 5).

Table 5. Total amount of dive time and urchin culling rate on the second day of reef restoration project at Gunshot reef. Note: cull rate is an estimated rate on this day.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
9	95	5	16000	0

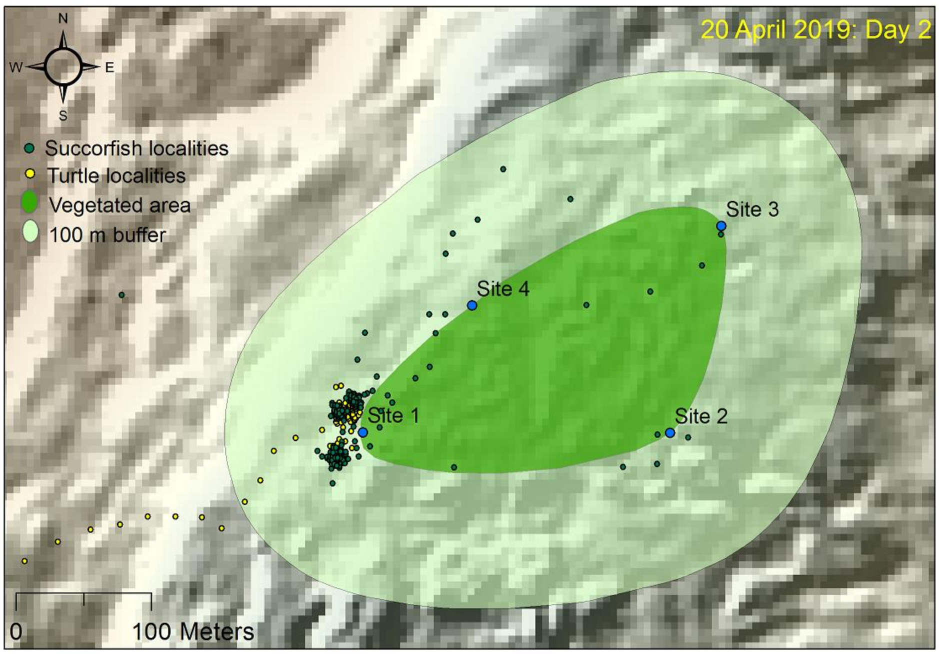

Figure 20. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 2 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

24 April 2019: Day 3

On the third day of urchin culling, one of the vessels worked along the weed/barren edge from site 3 to site 2, changing anchor position a number of times. The pair of divers were on T-Piece from a single umbilical air hose to the vessel, which is the normal practice when working two-up. The second vessel started near site 1, working live so that the diver could follow the weed/barren edge to Site 2 (Figure 21).

Dead urchins were found from the previous day's efforts and the culling effort was focused over the missed areas. Many abalone were also spotted in this area especially near kelp patches. The culling rate was high as the substrate was mostly flat with high urchin density. Divers also observed areas of weed surrounded by large numbers of urchins. The culling rate was estimated to be about 7000 urchins per 3 hours dive time (Table 6).

Table 6. Total amount of dive time and urchin culling rate on the third day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
12.3	90	10	28000	100

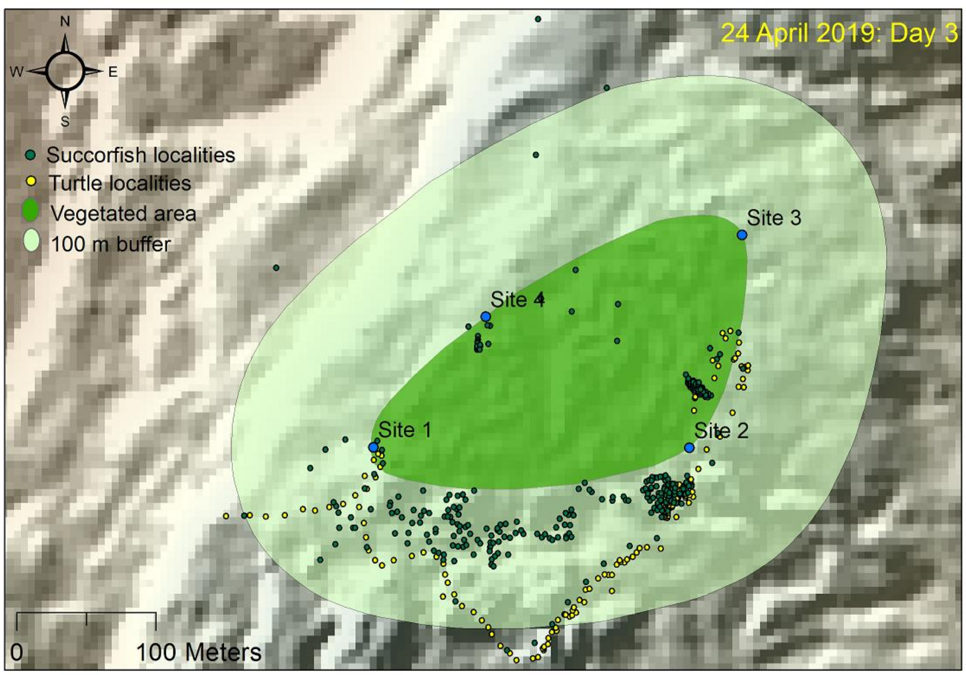

Figure 21. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 3 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

22 May 2019: Day 4

On this day, divers started to focus on culling from the weed edge aiming to cull 100m onto the barren (Figure 22). Massive urchin patches were evident on the southern end of the reef, concentrated on areas with small amounts of weed. Divers focused on clearing urchins out of the limited remaining abalone habitat as well as interconnecting sections between these areas and other healthier yet denuded, abalone bottom (boulders and gutters). Divers reported an culling efficiency rate of 1 urchin per second for 80% of the time (Table 7).

Table 7. Total amount of dive time and urchin culling rate on the fourth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
12	80	20	29000	500

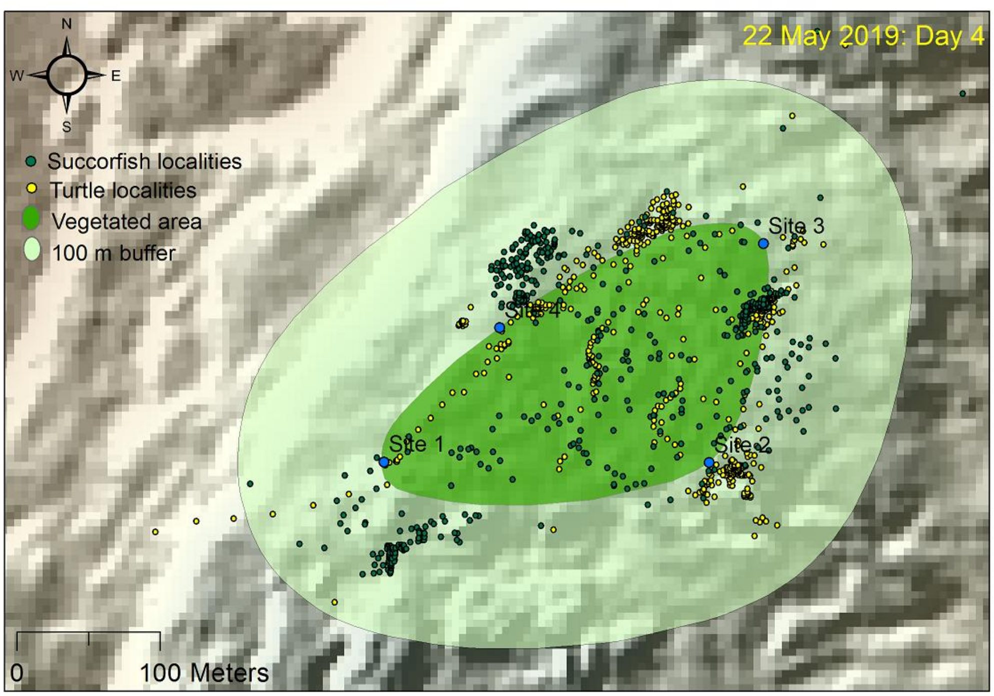

Figure 22. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 4 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

23 May 2019: Day 5

Divers continued urchin culling on the fifth day at all sites (Figure 23). A video production team also participated for day 2 of filming. Some divers had issues on using Turtle device such as having water ingress the units, rendering them unable to download data or recharge. The visibility in water was good on this day which also provided great filming conditions. One diver started 100 meters from site 1 and moved straight out to sea (east) and observed massive urchin patches with small amounts of weed. Many urchins in small sizes of about tennis ball were also found, and a good rate of urchin removal was reported on this day (Table 8).

Table 8. Total amount of dive time and urchin culling rate on the fifth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
21	95	5	33000	1500

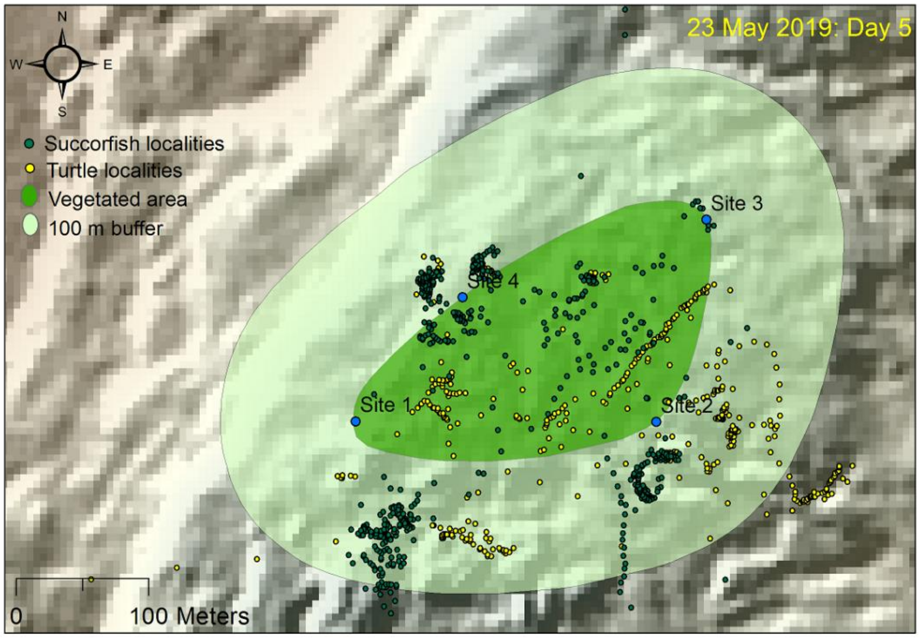

Figure 23. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 5 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

24 May 2019: Day 6

Divers continued culling from where they finished on the fifth day, and started to expand the culled area towards 15m depth range (Figure 24). Boats and divers had to move around on this day to find fresh ground as areas already culled. Divers tried to concentrate on large urchin barrens. Some parts of the reef were mostly flat with ledges that made the culling rate very high for the whole dive. Divers also reported an efficient effort of above one urchin cull per second in some cases (Table 9).

Table 9. Total amount of dive time and urchin culling rate on the sixth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
18	95	5	40000	50

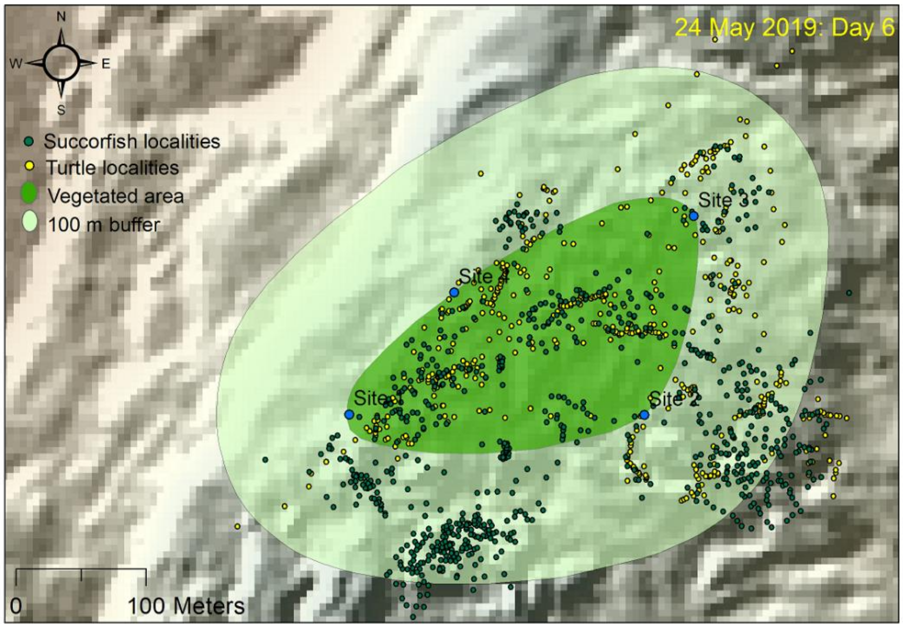

Figure 24. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 6 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

25 May 2019: Day 7

On this day, divers aimed to find the weed edge and continue culling, focussing on expanding area outwards around the east and south eastern side of the reef (Figure 25). Divers reported vast areas of urchins have been cleared and areas linking up together. In addition, boats and divers had to keep moving and swimming in order to find urchins that hadn't been culled within the project area with great amount of effort (Table 10). It was also planned to wait for a few weeks for the dead urchins to be washed away so that divers can more easily target what is left in the future.

Table 10. Total amount of dive time and urchin culling rate on the seventh day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
21	90	10	45000	500

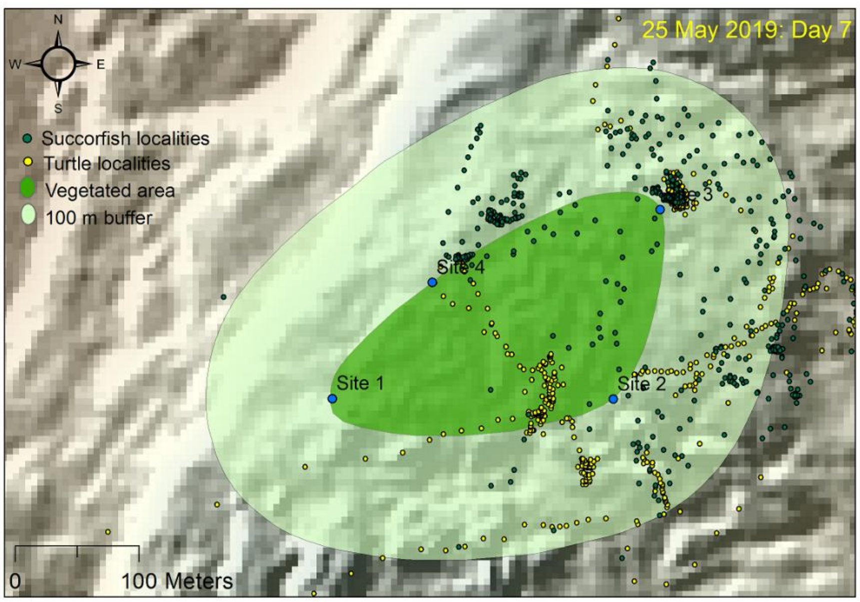

Figure 25. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 7 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

05 July 2019: Day 8

On this part of the project, maintenance of culling commenced, and the effectiveness of previous culling activity was investigated. In addition, divers aimed to target areas of urchin patches missed from previous culls as urchin abundance appeared to remain very high on some parts of the reef especially on boulder structures at sites 1 and 4 (Figure 26). Swell and wind caused a very rough sea condition on this day, and culling efficiency was reduced by 50 % as divers struggled with stability required to cull urchins (Table 11).

Table 11. Total amount of dive time and urchin culling rate on the eighth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
8.5	95	5	10000	200

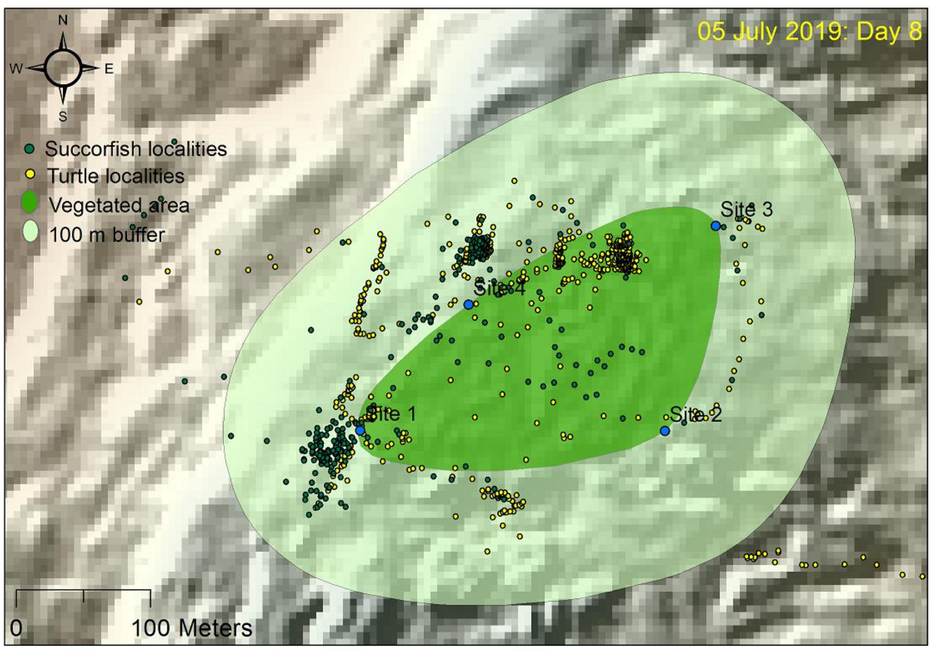

Figure 26. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 8 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

07 July 2019: Day 9

On day 9, as per the previous day, divers focused on expanding the culled area to 15m depth (Figure 27). It was also aimed to assess the effectiveness of previous culling and to spend time removing patches that had been missed before. Better sea and weather conditions were observed compared to the previous day, allowing for effective exploration and culling effort.

Two divers spent the first hour of dive searching between sites 2 and 3, from 10 to 12m depth. They reported that previous culling had been effective with only a few crevices of urchins remaining though it appeared as if urchins had re-settled into some preferred sites. Other boats anchored between sites 3 and 4 culling out about 100m from the weed edge, and urchins were very thick through this boulder and habitat. Another diver noted that on Site 2, with flatter ground and no boulders, it was easy to see where the reef had been culled and continue culling the remaining urchins that have moved back into the cracks and gutters. Divers also moved between Site 3 and Site 4 knowing it to be more boulder and cryptic and therefore requiring more urgent work. The divers also mentioned that the area where they culled looked as though no culling effort has been made previously, and stated that more work required in this area and of ground around 10m depth. On completion, moving in towards the healthy reef, abalone quickly became present. Divers observations indicated algal growth within culled areas. Divers effort information is given in Table 12.

In general, divers mentioned that more culling effort still required in this area and also between site 4 and 1, being more cryptic in terms of seafloor structures. This concludes the culling effort for year 1 of the project with all milestones having been completed and budget close to fully expended.

Table 12. Total amount of dive time and urchin culling rate on the ninth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
15	95	5	18000	0

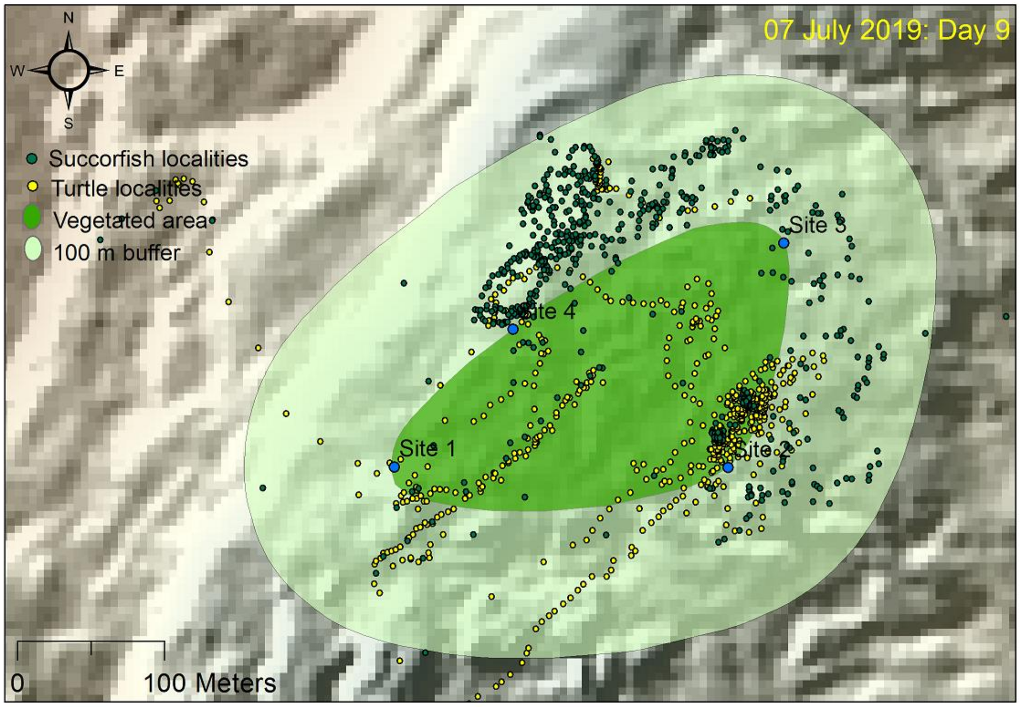

Figure 27. Spatial distribution patterns of vessel localities (Succorfish®) and diver localities (Turtle) on Day 9 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor.

17 December 2019: Day 10

This date was the commencement of the second year of urchin cull at Gunshot reef. Divers focused their efforts within the areas where high densities of urchins have recently been observed (Figure 28). It was reported that 6 divers were active on this day with an estimated culling rate of around 29000 urchins.

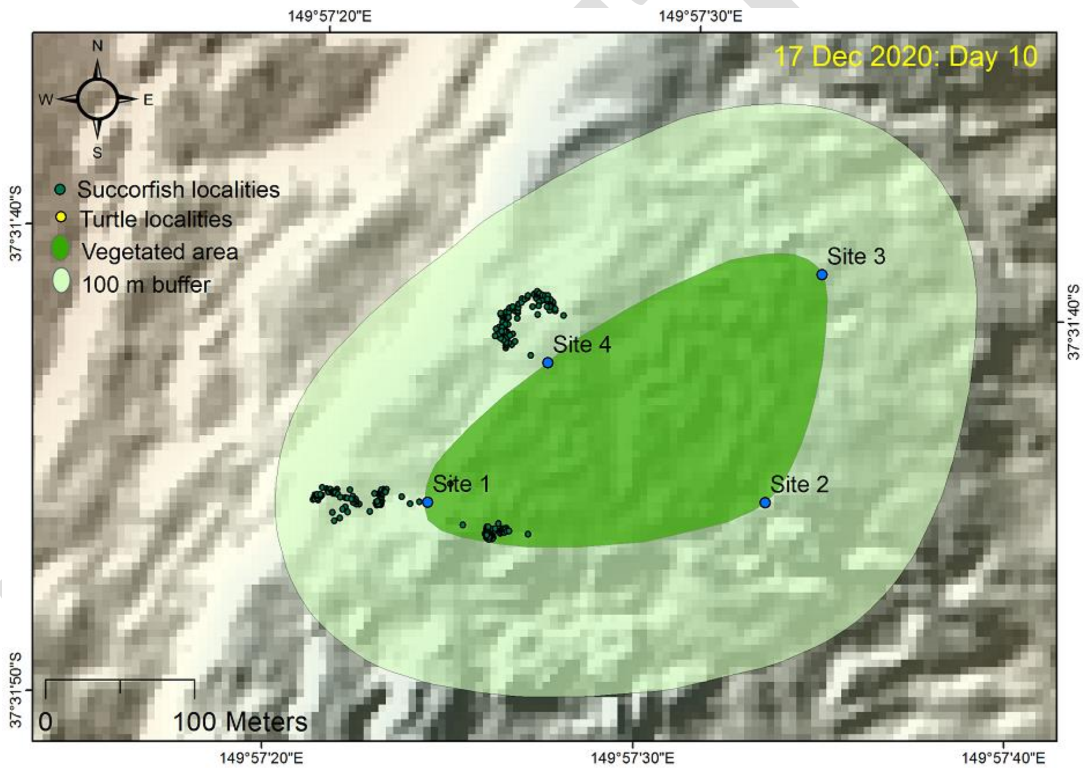

Figure 28. Spatial distribution patterns of vessel localities (Succorfish®) on Day 10 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided on this day.

28 March 2020: Day 11

Urchin culling effort was applied to several sections of the reef to clean up any re-emergence of urchins on this day. Boats were also spread out on all sides of the reef (Figure 29). It was observed that reef areas on the north, north east and eastern side that were previously cleared of urchins remained relatively clear although some urchins have emerged or moved into cracks and crevasses. Divers mentioned that there is still scope to remove urchins further into greater depths, particularly in the 13 to 15m depth range that have not yet been culled. Substantial abundance of urchins remained or migrated to the south, south west and western edges of the project area, and therefore, major effort will be required to cull these urchins. In particular, the western (inside / beach side edge) of the reef, still holds very high abundance of urchins in boulder rocky habitat. It was reported that 10 divers were active on this day and around 48000 urchins were culled.

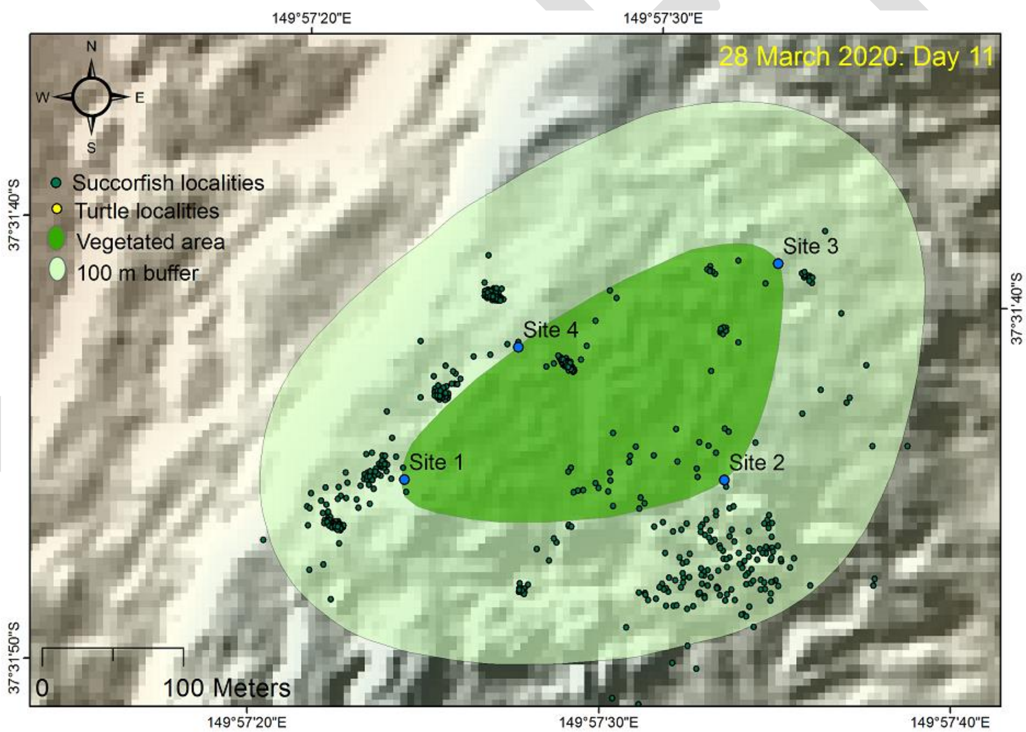

Figure 29. Spatial distribution patterns of vessel localities (Succorfish®) on Day 11 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided on this day.

30 March 2020: Day 12

On the twelfth day, divers continued their culling activity across all sides of the reef, with major focus around the southern and western sides (Figure 30). Estimates indicated that divers removed around 54000 urchins on this day.

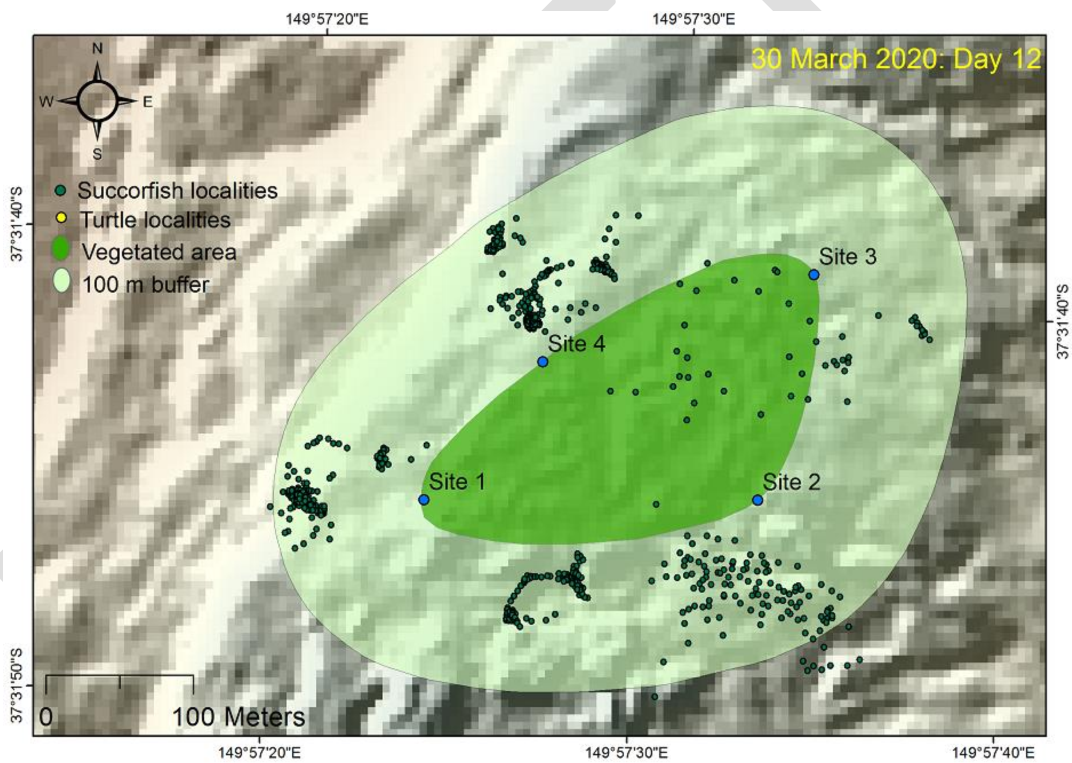

Figure 30. Spatial distribution patterns of vessel localities (Succorfish®) on Day 12 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided on this day.

31 March 2020: Day 13

Divers continued their culling activity across the areas left from the previous day (Figure 31). Urchin cull rate reported to be 48900 urchins and 10 divers were active on this day.

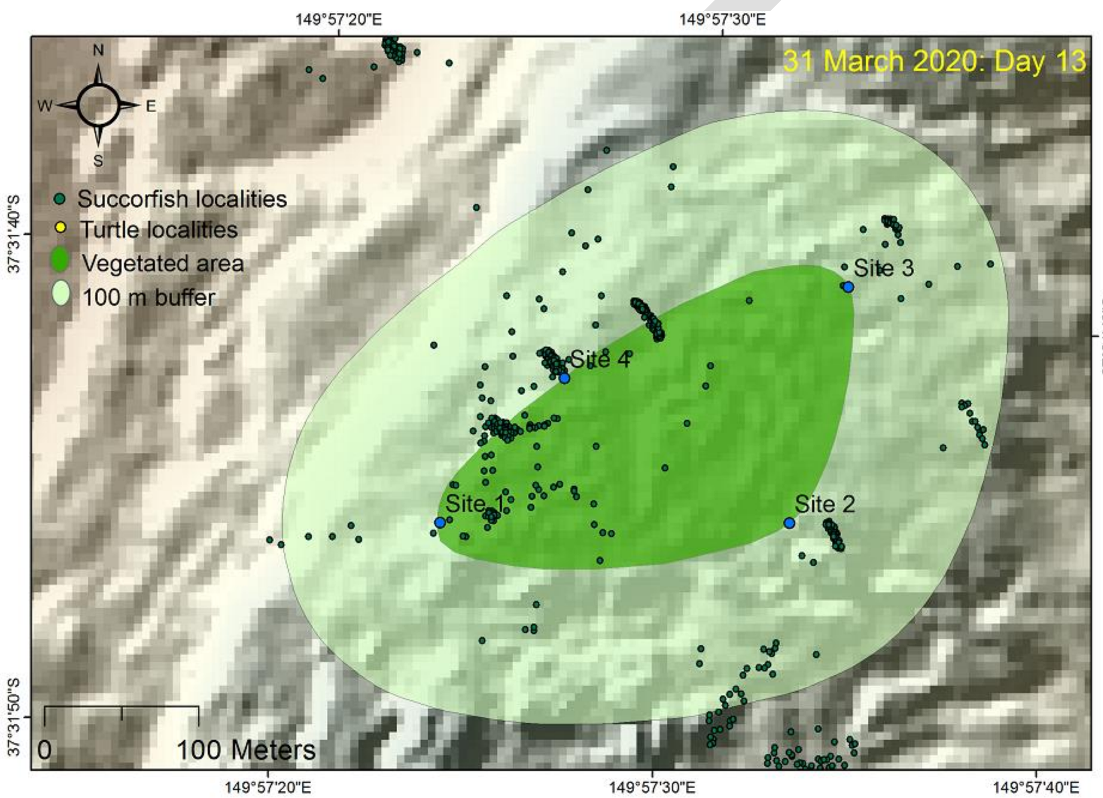

Figure 31. Spatial distribution patterns of vessel localities (Succorfish®) on Day 13 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided on this day.

01 April 2020: Day 14

Inside edge of the reef was targeted to cull urchins on the boulder habitat, especially on the western side of the reef (Figure 32). It was decided to take a break from culling for a few months to allow the dead urchins to be washed off the reef by the next large swell and to allow weed growth to begin. This will assist by allowing the dive team to target any patches of urchins remaining. It was reported that 11 divers were active on this day and 52000 urchins were also removed.

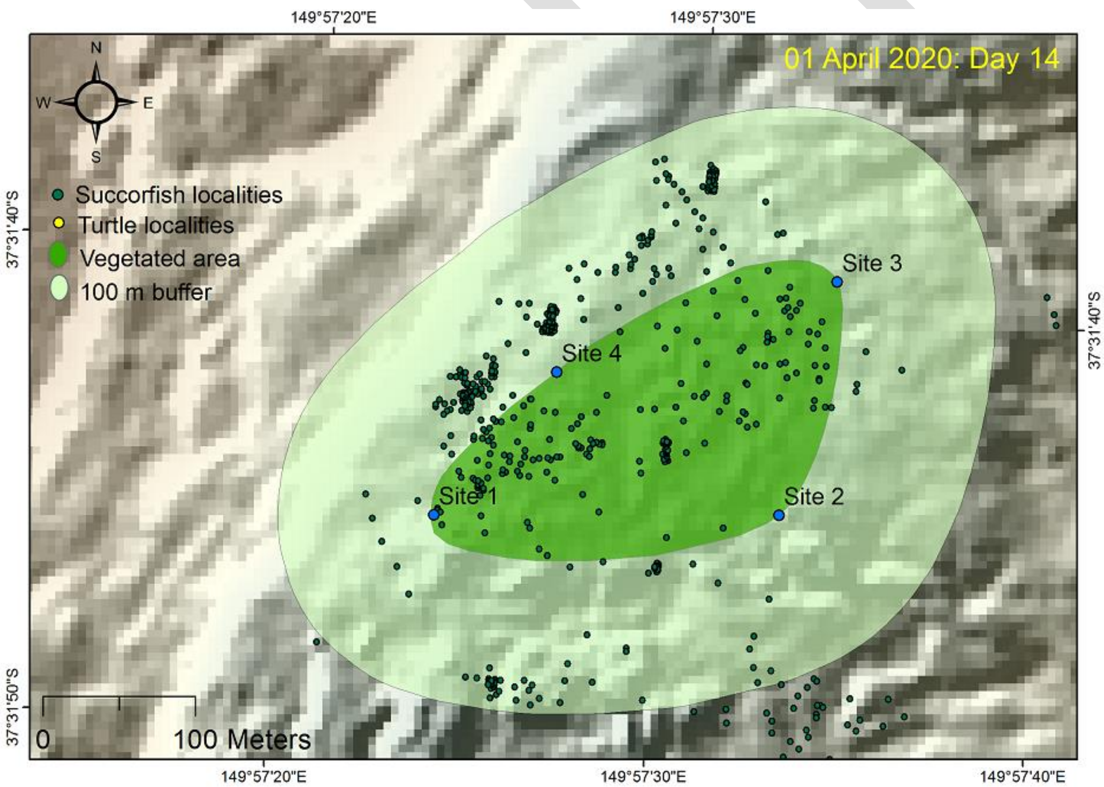

Figure 32. Spatial distribution patterns of vessel localities (Succorfish®) on Day 14 of urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided on this day.

28 November 2020: Day 15

On this date, divers worked around site number 2 for the first half of dive and culled back to halfway between site 2 and site 1. The regrowth was looking great but less than a foot high. Divers then moved over to site 3 for second half of dive and worked back towards site 2 and also site 4 (Figure 33). The quadrants were also looking well cleared between the marks in the flat country and then pushed out to the new weedline which was much untouched and more bouldery at around 13m depth. Improvement of weed growth was observed and abalone seemed abundant. 3 vessels and 6 divers were active on this dive day (Table 13).

Table 13. Total amount of dive time and urchin culling rate on the ninth day of reef restoration project at Gunshot reef.

Total dive time (h)	Time spent on barren (%)	Time spent on healthy reef (%)	Cull rate on barren (count)	Cull rate on healthy reef (count)
18	-	-	21300	-

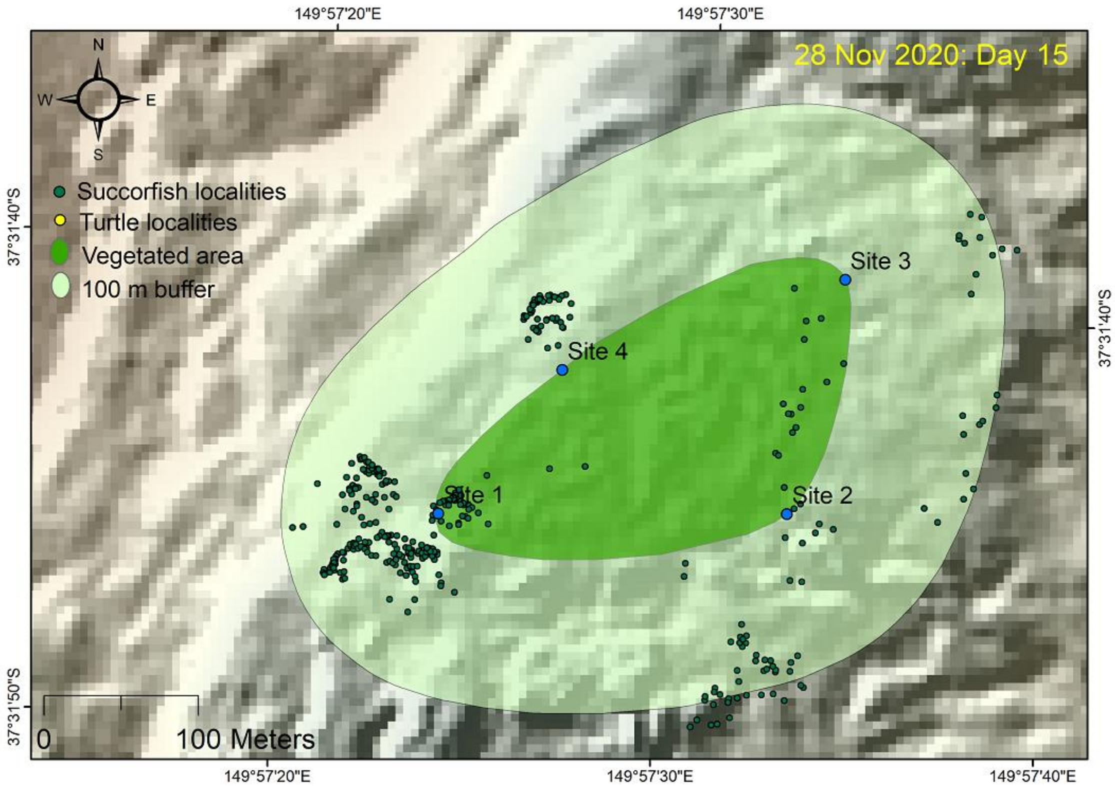

Figure 33. Spatial distribution patterns of vessel localities (Succorfish®) on Day 15 of the urchin culling project at Gunshot reef. Maps are overlaid over LiDAR-derived relief of seafloor. Turtle localities have not been provided for this day.