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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Executive Summary

At low-levels of exploitation, commercial harvesting of long-spined sea urchins was found to prevent increase in urchin density. Adjacent unfished locations experienced an increase in both urchin density and grazed area over the 2014 – 2016 study period. Research sampling of populations remaining on reefs after fishing also found that mean urchin Test diameter and urchin age was smaller and younger respectively than on nearby unfished reefs, further supporting there is a measurable effect of urchin fishing on urchin populations even at low exploitation rates. These results demonstrate a clear potential for urchin fishing to reduce destructive grazing by urchins, or at least prevent further expansion of existing grazed areas even under a regime of low fishing pressure.

The Tasmanian commercial fishery of long-spined urchin either directly overlaps or is immediately adjacent to commercially fished abalone reefs. As the presence of barrens has a clear negative association with abalone abundance, the potential for urchin fishing to lower urchin densities in key reef habitats highlights the importance of an ongoing long-spined urchin fishery for protecting key abalone fishing grounds (recreational and commercial). The ability to capture fine-scale spatial data on both urchin and abalone fisheries was critical to evaluating the potential for urchin fishing to benefit the abalone fishery. A long-term strategy for fine-scale data collection using passive GPS and Depth data loggers will be fundamental to ongoing assessment of the benefits of urchin fishing to the abalone fishery, but also to the broader users of shallow coastal reef systems in Eastern Australia.There is also the potential for positive-feedback loops from urchin fishing, with reduction in densities increasing roe production and output, and therefore ensure that the industry can remain economically sustainable.

Cartographic Exposure Index software developed during this project showed some capacity to identify coastlines at risk to destructive grazing, but further data collection to underpin the predictive model is required. Production of a high-resolution bathymetric map of key coastal reefs is considered to be a high priority for ongoing spatial mapping and analysis of the expansion of the urchin fishery and its consequent effects on urchin density.

There is a clear benefit to the urchin fishers if they switch from compressed air to using Nitrox gas for diving safety and access to greater reef area. Current beach price and likely decline in catch rates as the fishery expands however, will mean that investment in Nitrox based breathing systems may be economically marginal. From a health perspective, a switch to Nitrox while retaining the current bottom time would have clear safety benefits.

This study demonstrated positive benefits for abalone habitat at very-low urchin exploitation levels, with the extent and spatial magnitude of benefits expected to rapidly increase with increasing urchin exploitation. It is unlikely that commercial harvesting will lead to eradication of the long-spined sea urchin, but there is clear potential for commercial fishing to be a primary contributor to mitigating the destructive grazing of this species.

Keywords

Long-spined sea urchin, fisheries, local serial depletion, spatial mapping, *Centrostephanus rodgersii*

Introduction

Tasmanian Commercial Dive Fishery

The Commercial Dive Fishery (CDF) is a dive capture fishery that has operated in Tasmanian waters since the 1980's. The fishery targets numerous minor species including Wavy Periwinkle (*Lunella undulata*), Shortspined Sea Urchin (*Heliocidaris erythrogramma*) and Long-spined Sea Urchin (*Centrostephanus rodgersii*).

Most target species are harvested by divers using surface supply compressed air (hookah) operated mainly out of small boats (<10 m in length). Species are collected by hand or with a single pronged hook or tongs, placed in a catch bag and then emptied into bins on board the fishing vessel for transport to a processing factory or purge site. Effort in the fishery is concentrated on the south and east costs of Tasmania, especially by fishers operating out of the ports of Hobart, Bicheno and St Helens. Not all of the 55 commercial dive licence holders are active in the fishery.

Historically the most valuable species harvested has been the Shortspined Sea Urchin. However, in the past decade catches of Wavy Periwinkle and have become increasingly valuable. The long-spined Sea Urchin, which is not endemic to Tasmanian waters, has been rapidly increasing in abundance over the last four decades and has been targeted by the fishery since 2009.

Commercial Urchin Fisheries

Globally urchin production peaked in 1995 with 120,306 tonnes landed that year (Andrew et al. 2002; Williams 2002). The largest commercial urchin fishery in Australia is based in Tasmania by divers collecting the native species (the Short-spined Sea Urchin) – catches peaked in 1988 with landings estimated to be of 359 tonnes live weight for that year, and around 120 tonnes per annum since (DPIPWE 2011). The demand for export of urchin roe has only increased since the commercial industry boomed in the mid-1990s, and although processing costs are high, urchin roe quality is variable and local markets have not been fully developed, therefore overseas export continues be the primary market (Worthington & Blount 2003). Growth and expansion of the urchin market peaked in the mid 1990s, with a three-fold increase in harvest since the beginning of the fisheries in approximately the 1970's (Williams 2002). A total of 113,654 tonnes of urchins were harvest in 1995 alone, with export of urchin roe to Japan valued at US $126 million in 1999, with predicted demand for roe only to increase with the growing global population, the economic value is only likely to increase (Williams 2002, but see DPIPWE 2011).

Currently a small-scale long-spined urchin fishery operates primarily out of Tasmania's north east coast, targeted by divers who use surface supply compressed air (hookah), operate out of small boats (<10m in length) and use means such as pronged hooks or tongs to place the urchins into catch bags (Pecorino 2012; Keane et al. 2014). Urchins are then emptied into fish bins and transported swiftly to the factory to ensure freshness at processing. For the Short-spined Sea Urchin, the fishery is constrained by Total Allowable Catches (TACs) which have been set administratively and not through resource assessment means (Dix 1977; Williams 2002, DPIPWE 2011). The long-spined urchin fishery has no legislation in Tasmania, including no set TACs or minimum harvest size, due primarily to the fact that as many commercial abalone divers would like to ensure there is progress in reducing the pest from Tasmanian waters (TSIC 2005). The only requirement to harvest long-spined urchin is a commercial dive licence for market sale (Andrew et al. 2002, DPIPWE 2011). Commercial diving in Tasmania is managed under the Living Marine Resources Management Act (1995) and the updated Fisheries (Commercial Dive) Rules (2011) (DPIPWE 1995; TSIC 2016).

Catch for long-spined urchin peaked in Tasmania in the 2013/2014 season with a total of 96 tonnes being removed for market sale (Figure 3) (DIPIPWE 2016). There is variation in the initial catch (tonnes) with the establishment of the fisheries as the search ranges were expanding and the year classes present in the catch would not otherwise appear in a species that had been previously harvested (Figure 3) (Williams 2002).

Commercial sea urchin fisheries have historically crashed; “boom and bust” cycles have occurred in countries such as Japan, Chile, California and the North American Pacific Coast from Mexico to Alaska (Lawrence & Guzmán 2004). Macroalgae depletion by urchins is a universal problem and has seen significant and rare species such as *Macrocystis* diminish or on the verge of extinction. This lead to rapid commercial fishing of the urchins outpacing fisheries management schemes, hence resulting in collapse in many countries (Lawrence & Guzmán 2004). In the case of the Tasmanian long-spined urchin populations, commercial fisheries could be an effective measure to mitigate an ongoing problem for Tasmania’s rocky-reef systems (IMAS 2016; Blount, Chick & Worthington 2016). The late development of this fisheries in Tasmania (2008) has meant that baselines surveys have been conducted well before the fishery was established, ensuring that if the fishery was to expand anytime soon, there would be no uncertainty into the quota that could be taken or if there was a need to set TACs (Smith 1993, Walters 1998; Lawrence & Guzmán 2004).

Barrens represent a large proportion of urchin population that are underutilised due to the poor quality of their roe; by reducing local densities, enhancements can be made to both the roe of long-spined urchin as well as the native habitat including re-growth of some macro-algae species (e.g. *Sargassum* or *Ecklonia*) and recruitment of abalone (Andrew et al. 1998; Andrew 1993; Lawrence & Guzmán 2004; Johnson et al. 2005). Reducing densities of long-spined urchin adults in barrens habitats by just 33% was seen to double the growth rate in the remaining population, thus reducing competition for the limited resources (such as macro-algae and foliose algae) and allowing rapid growth and maturation, reduced predation in juvenile stages, allowing for market ready urchins to be harvested at a much faster rate (Schiebling & Hamm 1991; Andrew 1993 a, b; Lawrence & Guzmán 2004).

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Ecology & Life History of the long-spined sea urchin

The long-spined sea urchin is a large diadematid urchin most abundant on boulder or crevice habitat in shallow rocky reef environments (0-35 m) in temperate waters of south Eastern Australia. They grow to a maximum test diameter of ca. 140 mm and are distributed from Byron Bay, NSW to eastern Tasmania. Their diet is known to include foliose and coralline algae, seagrass, tunicates as well as encrusting invertebrates such as sponges and bryozoan (Andrew 1993 & Underwood, 1994; Hill et al. 2003; Lawrence 2004; Andrew & Byrne 2013). With the ability to extensively overgraze lush kelp beds habitats, long-spined sea urchins shift rocky reef ecosystems dynamics to an alternate and stable ‘barren’ state (Ling 2008; 2009a, b). Barren formation results in significant loss of endemic flora and fauna, including isopods, amphipods, small crustaceans and cryptic fishes (up to *ca.* 370 algae species and 150 invertebrate species), and is only reversible by catastrophic change (Harrold & Reed 1985; Andrew 1991; Underwood et al. 1991; Andrew 1993ab; Ling 2008; Ling & Johnson 2009a; 2012; Flukes, Ling & Johnson 2012).

Expansion of the long-spined Sea Urchin southwards from southern New South Wales, through Eastern Victoria, the Bass Strait Islands to the Tasman Peninsular has occurred over the past few decades. They were first recorded in Tasmania (St Helens) in 1978 with populations now prolific and wide spread, with barrens reported as far south as the Tasman. The arrival of urchins in Tasmania has been attributed to marine climate change; the south east Australian region is termed a global “hotspot” with waters warming nearly four times faster than the global average due to the intensification of the East Australian Current (EAC) extension and more frequent large scale eddies extending south along the East Tasmania coastline (Ridgway 2007a, b; Richardson & Poloczanska 2008; Ridgway & Hill 2009; Last et al. 2011; Hughes et al 2013). This warming has resulted in mean winter temperatures off eastern Tasmania surpassing the 12ºC threshold, the minimum temperature required for larval survival (Johnson et al. 2005; Ling et al. 2008; Ling et al. 2009a). However, this does not imply that successful recruitment will occur from local Tasmanian spawning events. The EAC also facilitates a means of transport of larvae from NSW during its 3-month larval duration (Ling 2008).

Densities of long-spined urchin can be considerably high in barrens habitats with *ca.* 60 individual's m^{-2}, but importantly biomass densities do not differ between macroalgal and barrens habitat (Andrew & Underwood 1989; Lawrence & Guzmán 2004; Johnson et al. 2005; Ling & Johnson 2009). In comparison to NSW populations, long-spined urchin are found in slightly deeper Tasmanian waters in ranges approximately 10 – 45 m (Perkins et al. 2014) and extensive barrens can occur on >75% of boulder habitat types, but on average occur on *ca.* 33% resulting in incipient barrens (Lawrence & Guzmán 2004; Johnson et al. 2005; Ling & Johnson 2009; Ling et al. 2009a; Ling et al. 2016). Location, depth and extent of these barrens habitats is then dependent on relative proximity to topography, fringing reef habitats and exposure to wave surge (Lawrence & Guzmán 2004; Johnson et al. 2005; Ling & Johnson 2009).

Size and age structure, and spatial distribution of the long-spined Sea Urchin population found on Tasmania's east coast align with that of the physical, chemical and biological oceanographic changes seen, characteristic of the EAC (Ling 2009a). Urchins that inhabit extensive barrens, devoid of kelp were found to have smaller body size, slower growth rates, thinner test and on analysis of their stomach contents it was found to consist primarily of cropped-filamentous algae (Ling & Johnson 2009). Whereas urchins found on the fringing reefs or in incipient barrens where kelp was present, were larger, with thicker tests, short spines and had faster growth rates (Ling & Johnson 2009). Both morphologies can link back to life-history characteristics including phenotypic plasticity, which has enabled these urchins to colonize various marcoalgal reef communities along Tasmania's East Coast (Ling & Johnson 2009). This is why jaws (demipyramids) have been accepted as the best structure of an urchin to obtain estimates of urchin age, as they continue to grow throughout the lifetime of the animal (Pederson & Johnson 2007, 2008; Ling et al. 2009b; Ling & Johnson 2009). Estimates for long-spined urchin include 4-5 years of age when TD is *ca.* 50mm, sexual maturity for TD 40 – 60 mm and spawning occurring in winter above 12°C (lower thermal limit), and henceforth slower growth rates with TD of 114 mm after 25 years (Figure 1) (Williams 2002; Ling et al. 2008b; Ling et al. 2009a; Ling et al. 2012; Pecorino et al. 2012). The geographical, temporal and spatial extent of barrens habitat is dependent on biotic and abiotic parameters, such as feeding dynamics, reproduction and predation (Jones & Andrew 1990; Andrew 1993; Andrew & O'Neill 2000; Lawrence & Guzmán 2004; Pederson & Johnson 2006; Flukes et al. 2012; Ling 2009a; Ling & Johnson 2012).

Impacts and management

The habitat of the long-spined Sea Urchin overlaps the habitat requirements of two significant and well established commercially fisheries - blacklip abalone (*Haliotis rubra*) and rock lobster (*Jasus edwardsii*). Grazing activity by the long-spined sea urchin modifies the kelp over-storey by direct consumption of kelp, or by eroding and weakening of the kelp holdfasts, resulting in loss of the habitat structuring macro-algae, making the habitat unsuitable for abalone and rock lobster. Five options are available to manage population densities of the long-spined sea urchin to minimise its impact on other species:

1. maintain the status quo;
2. implement bio-control mechanisms by enhancing populations of natural predators;

3. direct intervention by urchin culling;
4. incidental removal of urchins during normal fishing (abalone) as a form of by-catch; and
5. increase the capacity of commercial harvesting of the long-spined sea urchin to minimise destructive impacts on kelp communities.

The primary region on the East Coast of Tasmania affected by the range expansion of long-spined Sea Urchin is the upper East Coast, particularly between St Helens and the Freycinet Peninsular. Over-grazing in shallow waters by long-spined urchin has resulted in extensive barrens, removing the over-story macroalgae that are essential component of the habitat requirement for adult abalone.

A large body of work over the last ten years has investigated the mechanisms underpinning the range expansion of long-spined urchin in Tasmania, and the ecological and biological implications of the spread of urchins into non-endemic areas. Feasibility of eradicating/controlling the urchin populations in areas already effected has been undertaken in New South Wales (Andrew et al 1998) and more recently in Eastern Victoria (Justin Bell, personal communication) and in Tasmania (e.g. Tracey et al., 2015). Direct removal of urchins is an expensive and time-consuming process, and maybe best suited to targeted remediation of highly impacted sites. Removal of urchins during the course of normal fishing (dive fisheries only) is cost-effective only where fishing effort is high and urchin abundance is low).

An effective ongoing urchin harvest, in parallel with targeted removal of urchins from key sites where barrens are extensive and the urchins are of little commercial value, offers the best short term solution for minimizing the fisheries and ecological impact of the range expansion of Centrostephanus rodgersii into Tasmania. Therefore, the development and ongoing management of a dedicated Tasmanian long-spined Sea Urchin fishery is considered to be an integral component of the overall strategy to moderate the negative effects of this species on shallow Tasmanian ecosystems and productivity of important rock lobster and abalone fisheries.

The extent of overlap in harvest locations of blacklip abalone, rock lobster and the long-spined Sea Urchin is unknown, and will have significant implications for managing the co-existence of these three fisheries. Urchin harvest from areas of high abalone or rock lobster productivity is expected to result in a synergistic relationship between the harvest sectors by limiting formation of unproductive barrens. Fine-scale spatial data on fishing activity of the target species is required to determine whether an urchin harvest industry will be synergistic or antagonistic with the existing abalone and lobster fisheries. In addition to quantifying overlap in harvest, fine-scale data on fishing location will be used to monitor the effectiveness of urchin harvest as a method of limiting urchin barren formation in shallow subtidal habitat. From this, the extent to which urchin harvest can increase the local productivity of abalone or lobster populations will be determined.

A key difference between the occurrence of long-spined Sea Urchin in New South Wales and Tasmania is that this species is widespread in shallow waters (< 10m) in New South Wales, but abundant at only a small number of sheltered locations in Tasmania within the same depth range. In Tasmania, Centrostephanus is more abundant, and destructive grazing has occurred more widely at depths of 15m to 30m on exposed coastlines. Routine harvesting of urchins at a depth-range of greater than 20m brings significant challenges to the safe and economic harvest of C. rodgersii. Investment in diving technology and the effort limitation imposed by safe-diving practices mean catch-rate driven harvesting strategies will be more acute in the urchin harvest fishery than in the abalone fishery. Scoping the limitations imposed by diving at depth addresses the need for ongoing economic viability of the harvest sector if it is to underpin urchin harvesting as a strategy for minimizing effects of long-spined urchin on shallow subtidal ecosystems.

Need

The long-spined Sea Urchin has gradually increased in extent and biomass on the East coast of Tasmania over the past three decades. Options for direct and indirect intervention are being considered to limit numbers of this urchin to that required to minimise the destruction of the kelp and understory habitat essential for other benthic species such as abalone and rock lobster. Over the past seven years a fledgling urchin harvest industry has developed in Tasmania, with the potential for market demands to create a significant fishery in terms of harvest biomass. Whether harvesting of urchins is beneficial (synergistic) to existing fisheries needs to be determined to inform development of a Harvest Strategy of all species reliant on healthy shallow (<20m) sub-tidal ecosystems. The efficacy of commercial urchin harvesting as a 'control tool' is dependent on the degree of spatial overlap with other fisheries (co-dependent on habitat), the capacity of urchin harvesting to minimise localised destructive grazing, and, whether the urchin harvest is economically sustainable given the practical limitations of harvesting at depth.

In theory, establishment and expansion of long-spined sea urchin populations will impact negatively on the local productivity of abalone and rock lobster populations, resulting in potentially significant loss of production of key commercial fisheries, as well as reduction in biodiversity. However, anecdotal information from urchin harvesters in Tasmania suggests the long-spined sea urchin is less tolerant of high wave energy habitats than abalone and rock lobster. Further it appears that several areas of high urchin productivity are adjacent to (spatially) but not directly overlapping with high productivity abalone fishing grounds, or are restricted to deeper water and therefore below productive abalone fishing ground. To quantify the spatial and depth overlap between abalone rock lobster and long-spined sea urchin fisheries, fine-scale spatial information and depth profiles of all three fisheries is required.

A key performance indicator of urchin harvesting as a mechanism to limit destructive grazing by long-spined sea urchins, is a decrease in urchin density and/or a decrease in expansion or development of barren areas. However, it is not known whether the catch rate at which it is economical for urchin fishers to harvest urchins is sufficient to prevent destructive grazing by urchins, or recovery of macro-algae in barren areas.

Anecdotal information from abalone fishers suggests there is a correlation between abalone abundance and resilience of shallow sub-tidal kelp communities to invasion by C. rodgersii. In Victoria expansion of urchin barrens was observed to be slower at sites where abalone abundance was higher or considered healthy, and rapid where local abundance of abalone had decreased. In New South Wales, expansion of abalone populations and increases in abalone abundance were observed on reefs where active urchin harvesting had taken place.

Centrostephanus rodgersii is only moderately adapted to high wave exposure locations. In low wave energy locations long-spined urchin can inhabit depths as shallow as 6m on the Tasmanian East Coast, but such locations are limited along the eastern, southern and western Tasmanian coastline. In moderate and high wave energy sites long-spined urchin populations appear to be restricted to depths greater than 15m. The extent of shallow subtidal reef at risk of invasion by the long-spined sea urchin is unknown. By correlating known spatial locations and depths of high density urchin populations and urchin barrens with wave energy and frequency of high/medium swell events, a map of locations at high risk of urchin impact can be established. Existing data collected by the Reef Life Survey Program will be utilised where possible.

Significant biomass of Centrostephanus is thought to exist at depths of 15 to 25m on substantial areas of the Tasmanian East Coast. To operate a harvest fishery at such depths brings additional expense to the fishing operation. An understanding of the harvest costs (technical equipment) and harvest limitations (safe no-decompression limits) imposed by fishing at this depth is important to the efficacy of urchin harvesting as a tool for reducing the destructive grazing of long-spined sea urchins. Depth-linked limitations on urchin harvesting may either preclude some areas from urchin harvesting, except where catch rates are very high, or limit harvesting to shallow depth bands.

Long spine urchins Centrostephanus rodgersii populations occur over a depth range from a few metres to 40 metres plus. Currently long-spined urchin are harvested by commercial divers using low pressure surface supply apparatus LPSSA commonly known as a “hookah compressor” This system delivers air to the diver via a hose from the dinghy. The divers typically operate from small aluminium dinghy’s less than 5 m in length and predominantly work at depths less than 15m. Commercially harvested populations of long-spined urchin do occur at depths between 15m and 25m on the East Coast of Tasmania particularly along the southern regions where incipient barren/barren formation has been observed. Urchin fishing activity at depths > 15m is currently uncommon because at the low current harvest levels there is sufficient urchins in shallower depths to supply demand. If demand for Long spine sea urchin roe increases, there will be a need to access urchins in deeper water. Commercial urchin divers are limited to the depth at which they can harvest due to the increased risk of decompression sickness (DCS) commonly known as the bends associated with fishing at depths greater than 15m. DCS is caused by nitrogen bubbles forming in the body tissues during or after ascent.

The options for urchin harvesters are to continue with Hookah as the method of providing air to divers, or to consider using alternative breathing mixes. The primary limitation with use of Hookah at depth is the limited bottom time available. Enriched Air Nitrox (EANX) - Nitrox is a breathing gas used by divers to reduce their risk of DCS by lowering the percentage of nitrogen in the mix and replacing it with oxygen. Air is approximately 21% oxygen and 79% nitrogen, nitrox may contain up to 40% oxygen and 60% nitrogen (EAN40). However, Oxygen toxicity is a problem which can occur at depth when using nitrox and each mix has a safe Maximum Operating Depth (MOD). Thus careful planning of dive based fishing operations is required, and it is essential that fishers dive in accordance with the Nitrox mix prepared for the day.

Objectives

The objectives of this project are:

1. Determine spatial location and extent of overlap between Centrostephanus and existing fisheries

2. Application of coastal exposure indices for identifying potential urchin harvest locations

3. Determine dive profile strategies to enable safe harvest of urchins at depths greater than 15m

Methods

Study area

The reefs surrounding St Helens, north eastern Tasmania, provided the location for this research. Benthic habitats are typified by fringing rocky reef composed of granite boulders, with *Phyllospora comosa* (Fucales) and *Ecklonia radiata* (Laminariales) being the dominant canopy forming macroalgal species between 5 and 25 m depth (Lucieer et al. 2007). Reef areas typically exhibited dense algae at shallow depths (<5m) with urchin grazing and barrens increasing to be extensive and wide spread at depth (>15m).

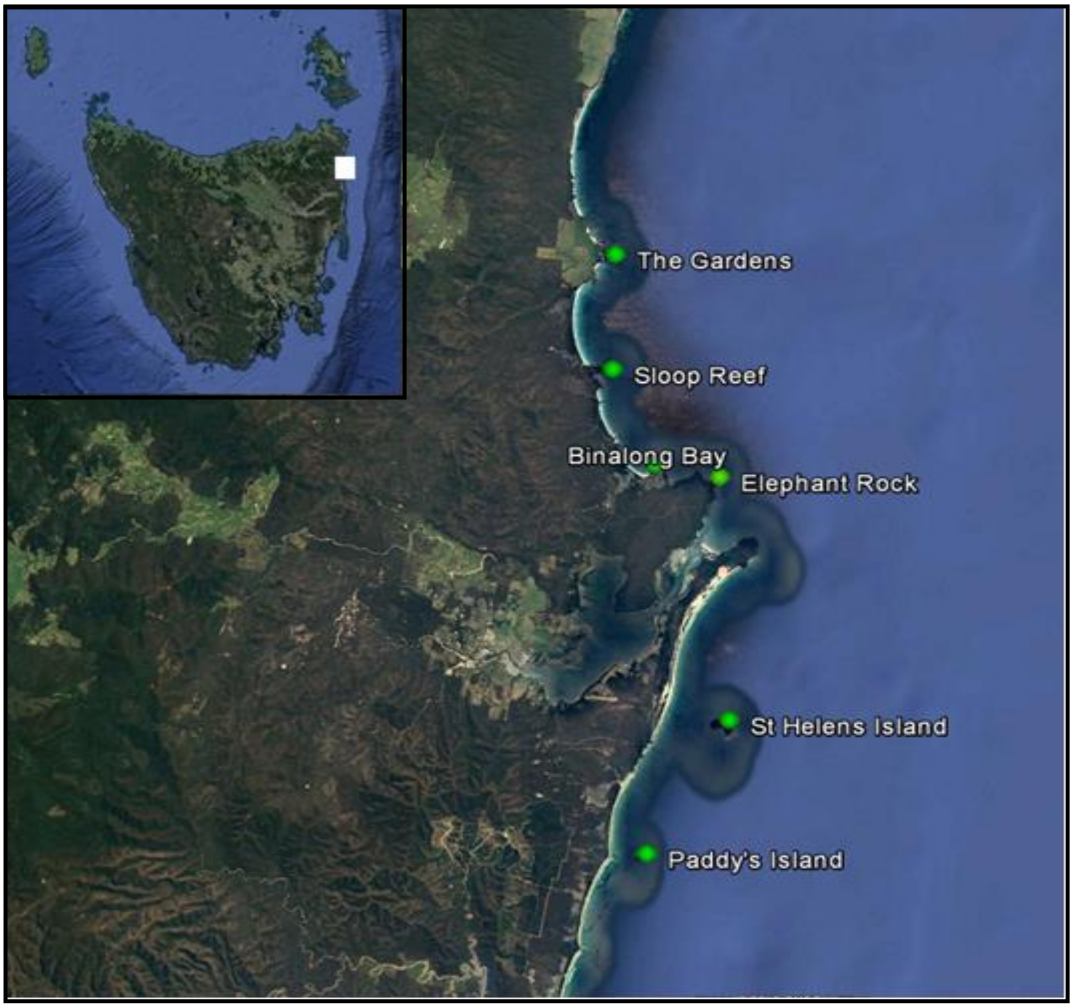


Figure 1. Location of reef in the St Helens district, Northern Tasmania (insert).

Commercial fishery data

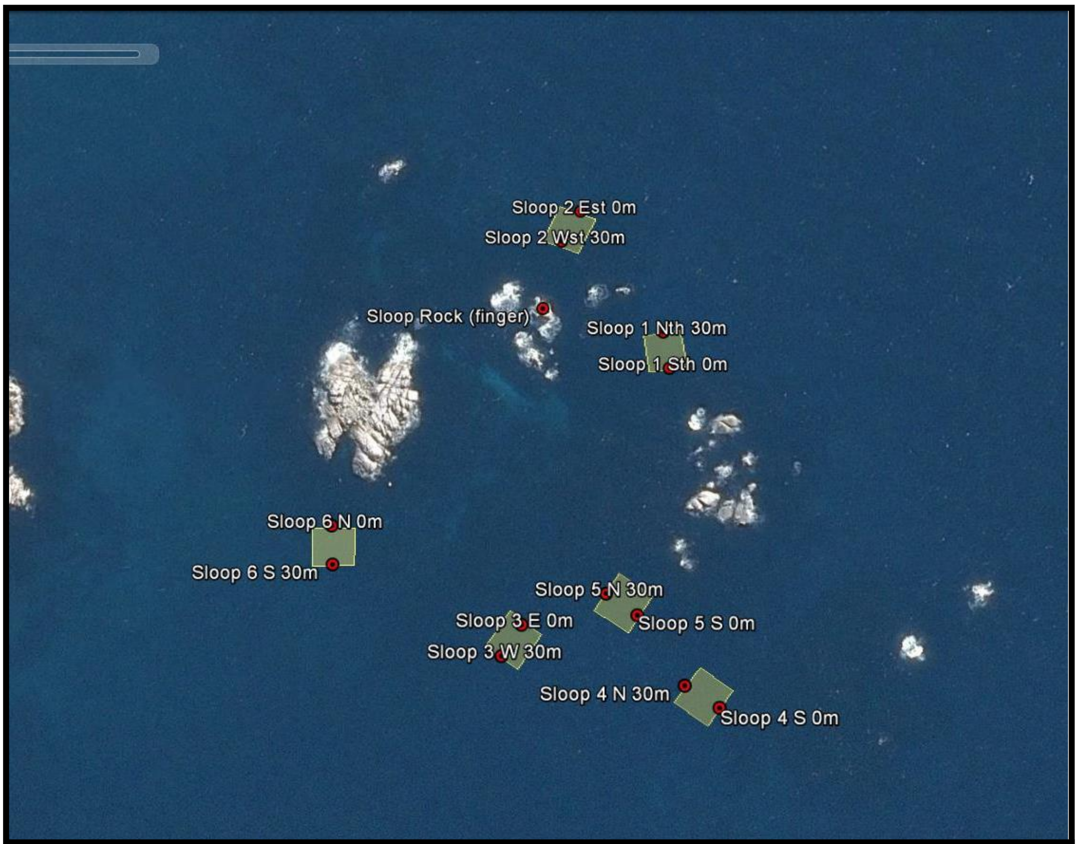
Commercial fishery information and data was sourced from fisheries logbook data, observations of commercial operations and discussions with key fishers. Logbook data, which is a requirement under the Commercial Dive Fishery Management Plan, comprised of fishing location/fishing block, daily catch (kg) and effort (hrs) data.

Commercial urchin divers were voluntary issued GPS and depth data loggers as currently used in the Tasmanian Abalone Fishery to record spatial location and dive depths. Data was managed and accessed using a parallel, but independent database structure, as established for AbTrack spatial logger projects (FRDC 2006/029; FRDC 2011/201). Overlay analyses as developed in FRDC 2006/029 were applied to fine-scale data from the abalone fishery to determine the spatial overlap in fishing grounds.

Impact of urchin harvesting on abundance and destructive grazing

Replicate research plots of size $900m^2$ (30m x 30m) were established across boulder reef habitat within both fished (Sloop Rock) and unfished (Elephant Rock Research Area) (Figure 2). Three plots were established in both the fished and unfished regions in Autumn/Winter 2014 and resurveyed in the same period in 2015 and 2016. Three additional plots were established in both regions in 2015 and resurveyed in 2016; the fished plots located at fished locations based on fisher GPS data.

The centreline of each research plot was laid parallel to shore at approximately 8-10 m depth. Plots were marked with permanent stainless steel bolts and sub-surface floats, divided into 72 2.5*5 m blocks. Each block was surveyed for species abundance and grazed area. Blocks that contained zero urchins or were 100% grazed throughout the study period were excluded from the analysis due to urchin fishing unlikely to occur in these blocks. Mean abundance and grazed area are presented with 95% confidence intervals for each survey year.


Sloop 2 Est 0m
Sloop 2 Wst 30m
Sloop Rock (finger)
Sloop 1 Nth 30m
Sloop 1 Sth 0m
Sloop 6 N 0m
Sloop 6 S 30m
Sloop 5 N 30m
Sloop 5 S 0m
Sloop 3 E 0m
Sloop 3 W 30m
Sloop 4 N 30m
Sloop 4 S 0m


ER1 E 30m
ER1 W 0m
ER4 0M
ER4 30m
ER6 30m
ER6 0m
ER5 30m
ER5 0m
ER 2 N 0m
ER 2 S 30m
Grants Point
ER3 30m
ER3 0m

Figure 2. Locations of research plots of size 900m^2 (30m x 30m) established across boulder reef habitat within both fished (Sloop Rock; top) and unfished (Elephant Rock Research Area; bottom).

Impact of urchin harvesting on size and age structure

To determine the impact of urchin harvesting on size and age structure sampling of was undertaken in the St Helens region where commercial fishing effort is concentrated, three sites were selected in heavily fished areas based on commercial catch history (Sloop Rock, Binalong Bay, and St Helens Island), with a further three sites located in areas where little or no harvesting had occurred, or were at depths below commercial diver depth (Elephant Rock Research Area, Paddy's Island and St Helens Island (deep). At each site approximately 300 individuals were collected from each site by divers from incipient kelp barrens at ~ 10 m depth, mimicking commercial harvest, except for St Helens Island deep, where urchins were collected from full barrens <20m deep.

The test diameter (TD) of urchins were measured to the nearest 0.1 mm and the Aristotle's Lanterns removed by dissection. A set of jaws dissected from the Aristotle's Lantern were placed into household bleach (4.2% sodium hypochlorite) for 48-hours to dissolve organic tissue and expose the individual jaw structures for measurement (jaw length, JL) to the nearest 0.1mm. The age of each urchin was estimated from applying the inverse logistic growth models on jaw length developed by Ling et al. (2009a) for long-spined urchin of Eastern Tasmania from tag-recapture experiments. The kelp growth model was applied for urchins collected from incipient kelp barrens, and a barrens model applied for urchins collected from extensive barrens (i.e. St Helens Island deep). To allow for the variation in collection dates, ages were standardised to the last date of collection, 9th August 2016.

The TD and age frequency distributions were compared using pair-wise Kolmogorov-Smirnov tests. To ensure the rate of Type I error for non-orthogonal tests was controlled alpha was adjusted via the Bonferroni correctional methods (Ling et al. 2009a; Ling & Johnson 2009). One-way ANOVA was used to test for mean differences between the "fished" and "unfished" treatment of sites no transformation was necessary as all assumptions of homoscedasticity and normality were met. A linear regression was undertaken using a generalised linear model to examine the relationship between increasing commercial harvest and sea urchin size and age. Commercial catch data logbooks were used to estimate total catch from each site, with an estimated 30 tonnes of long-spined urchin being removed from Elephant Rock Research Area (J.P. Keane 2016, pers. comm.).

Urchin jaws obtained from Tashimi Fish Pty Ltd urchin-processing factory in Launceston were used to reconstruct the commercial catch size structure. Jaws were obtained from the urchins harvested at 4 locations, namely Roundhill (41°245'S, 148°295'E), Gardens Reef (41°169'S, 148°294'E), Binalong Bay (41°241'S, 148°311'E) and Sloop Rock (41°209'S, 148°290'E). The linear allometric equation, TD = 4.12 x JL, was used to estimate the TD based on JL (2008; Ling et al. 2009a; Ling & Johnson 2009).

Impact of urchin harvesting on local productivity of abalone and rock lobster populations.

While it is not mandatory for the urchin divers to use the GPS and depth data loggers, the primary urchin fishers do use the equipment regularly, and provided sufficient data to determine the extent of overlap between the urchin and abalone fisheries for 2013 and 2014. Spatial information on the two fisheries were used to determine the extent of direct spatial overlap, and the overlap in fishing depth. To quantify spatial overlap, individual point data from the commercial urchin fishers was overlaid with the abalone dive polygons (Mundy FRDC 2006/029) from the 2013 and 2014 fishing years, and the proportion of urchin points contained within the abalone polygons determined. To compare the depth distributions of urchin and abalone fishing activity, the proportion of fishing effort in 5m depth bands was calculated for both fisheries in three abalone reporting blocks at the extent of the range of Centrostephanus (block 22 in the south and blocks 29 & 30 in the north).

Coastal exposure indices

The prevalence of urchin barrens and destructive grazing by the long-spined sea urchin on Tasmania's East coast appears to be linked to degree of wave exposure. Most of the extensive barrens in shallow water occur in wave-sheltered locations (Wineglass Bay, Sloop Rock), although urchin barrens have also developed in deeper water in exposed locations (Mistaken Cape). Assessing wave and wind climatology of a location requires combining the aspect of the shoreline and the pattern of wave and wind direction over the course of the year. Three dimensional numerical wave models are computationally intensive and require detailed bathymetry, and provide detailed information about wave energy within a small spatial domain. Such models provide more detail than required for assessing effects of wave exposure on ecological patterns, and are difficult to apply across large geographic scales such as required here. Simple cartographic fetch models that calculate exposure based on fetch distance (Burrows et al 2008, Hill et al 2010), have been shown to provide comparable indices of overall coastline exposure to more complex numerical wave models (Callaghan et al 2014, Sundblad et al 2014). The core of cartographic exposure modelling is the concept of 'openness', which attempts to capture the relative difference in exposure of shores, for example protected bay's versus the open coast. This is achieved by creating fetchlines that radiate from points and either intersect the coast or extend out to sea, usually to a distance over which gale force winds result in a fully developed swell. The sum of multiple fetchlines radiating from a point of interest provides the base model of wave exposure, or 'Openness'.

This project planned to use a published cartographic exposure model - GREMO (Hill et al. 2010). However, GREMO was developed in an earlier version of ArcGIS (v9.2) using VBA and the ArcObject spatial functions library, and is incompatible with current versions of ArcGIS (v10.2). Burrows (2012) also modified his original cartographic wave exposure model for use in ArcGIS. Version incompatibility is an ongoing limitation of ArcGIS based products, and in the absence of a working cartographic model, this project developed a platform independent cartographic exposure model in R (R-Core-Team, 2017), using *SP Package Spatial Objects* (Pebesma and Bivand, 2005). The code for the exposure model was developed as two independent sections 1) calculation of a fetch distance based index of openness and, 2) incorporation of wave and wind data to the Openness index.

For each level of fetchline angles, Openness was calculated as the sum of the fetchlines normalised by the product of the maximum fetch line length (650Km) and the number of fetchlines/point.

Calculations of Openness

The input data requirements for calculation of a fetch index are a coastline in digital form and a set of points from which to determine openness. For this exercise we used the 1:25,000 digital layer for the coastline of Tasmania, and the 1:100,000 digital coastline for southern mainland Australia. The code allows input of any coastline layer of interest. The points to be used as the basis for the fetchlines can be input from a pre-existing layer or generated internally by the code. For this study, the fetch points were obtained by creating regularly spaced sequence of points (100m) along a buffer line 50m seaward of the coastline layer (**Error! Reference source not found.**). For each p oint, fetch lines 650Km long were created at equidistant intervals. A range of fetchline angle spacing (45, 30, 15, 7.5) were trialled, with the computationally intensive but more informative 48 lines at 7.5 degree intervals used in this study. The distance to the first intersection with the coastline was determined for each fetch line using the *rgeos* package (1). Each line was clipped at the intersection point and the length of the fetch line calculated. An Openness index was calculated by dividing the fetch distance by 650 Km. Thus a fetchline that was completely open to a distance of 650 Km has a value of 1. The code produces both point and line objects as part of the output, with the fetch distance, angle and point unique identifiers.

Calculation of daily Wave and Wind exposure indices for each point

Data on swell direction, significant wave height, wave period, wind speed and direction were obtained from the high resolution 30-year wave hindcast re-analysis model available from the Bureau of Meteorology (http://www.bom.gov.au/climate/data-services/ocean-data.shtml). This model produced an hourly time series of wave and wind parameters in a 4-arc-minute gridded output, taking into account bathymetry. For each point used to calculate openness, wave (significant height, period, direction) and wind (speed, direction) parameters were extracted using a bilinear interpolation of the four nearest grid cells to the point, giving a time-series from 1979 to June 2016 and 1 hour time steps for each point. Wave energy (WE) was calculated as;

$$WE = (0.57 * (hs)^2) * tp$$

where hs = significant wave height (metres), and tp = wave period (seconds). For each step in the time-series, the Openness Index was mapped to both wave and wind values for each point by matching the direction of the wave/wind at that time step to the Openness Index for that direction. We used this final hourly dataset with indices of wave energy, wind strength and Openness, to generate a mean daily time series for the three different exposure indices for each point of interest.

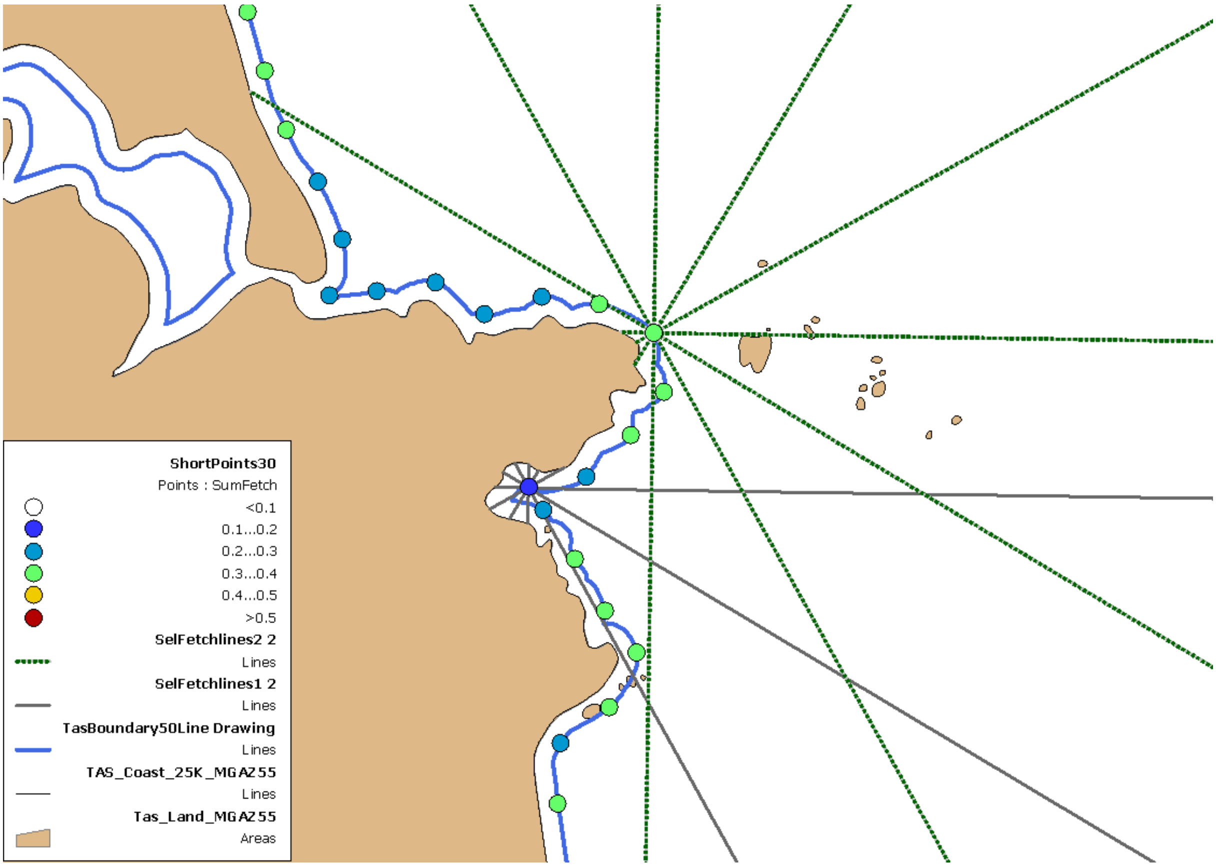


Figure 3. Example of fetchlines (30 angle spacing) in a protected bay vs prominent point

Wave and wind exposure case study: Barren prediction based on towed video datasets

Field data collection

A towed video based rapid assessment of the extent and type of urchin barrens was completed at several sites on the East coast of Tasmania. A towed video camera unit, which used a high definition handycam video camera, LED lighting and 2 parallel scaling lasers at a separation of 150 mm was lowered to the reef fringe/sand edge and towed normal or parallel to the shore along the reef contours where pre-existing data did not exist or where divers highlighted barrens extent to exceed a category 4 rating in the interviews (Ewing & Lyle 2017). Perpendicular transects covered depths of 1 – 45 m and parallel transects covered depths of 2 – 25 m, with tow time varying from 8 to 75 minutes depending on weather conditions and reef topography. Videos were then analysed in the SeaGIS program TransectMeasure. The percentage cover of algae and barren extent was scored on a five-part scale from each video transect. A score was recorded every ten seconds for the duration of the video. Time and spatial position (Latitude and Longitude) was also recorded.

Statistical analyses

Centroids of towed video transect segments were used to find the nearest point in the wave exposure index dataset, and wave and wind indices transferred to the towed video segment record. Depth from the vessel sounder was recorded and assigned to each towed video segment. Here we use Discriminant Function Analysis (DFA) to test how well the independent physical variables depth, wind exposure, wave exposure, Latitude and Longitude could be used to classify urchin barren class, with the aim of assessing whether a predictive model could be developed to identify sections of the coast at risk of urchin barren development. DFA tests hypotheses about group difference by a linear combination of the variables to maximise the probability of correctly assigning observations to their pre-determined groups, resulting in a likelihood success of the classification (Quinn & Keough 2002). The towed-video data were grouped into a 4-level barren classification with the following barren classes: ‘no barrens’, ‘barrens rare’, ‘barrens abundant’ and ‘barrens zone’. Three independent variables were included in the DFA analysis wave and wind exposure indices and depth. There was no collinearity between the variables in the DFA based on dissimilarity analysis, thus all variables were included in the model selection process. All assumptions of DFAs were met, in particular the homogeneity of the correlation matrices for both the LEK and video data sets. Standard checks were made using plot matrices and distribution plots to examine spread of points (Quinn & Keough 2002).

The ability of the DFA to correctly classify barren class from environmental variables was tested in a two-stage process. This involved randomly splitting the full data set into a training dataset and a test dataset, with the DFA applied to the training dataset to develop the Empirical Predictive Model (EPM), and then that EPM applied to the test dataset. The ability of the DFA to correctly classify barrens class was determined by the proportion of correctly classified records in both the training phase and the test phase.

Dive profile strategies for deep water harvest

To safely harvest urchins at depths of 15m to 25m, a well-designed dive plan will be required for multi-dive-multi-day harvest operations. Maximum Dive times for dives using different breathing mixes of air and enriched air nitrox (EAN) are compared, using DCIEM and EAN tables, as well as the Suunto dive computer algorithm. Dive time constraints in the context of catch rates required for economically sustainable fishing is discussed. To harvest using nitrox significant investment in infrastructure (safety equipment, NITROX) may also be required. We assess the advantages and disadvantages of four options to safely deliver nitrox to a diver in terms of purchasing and maintaining technical dive equipment.

Results

Fishery catch and effort

Urchins were first fished in 2009 and from then to the end of the 2016 season a total of 380 tonnes have been harvested. Catches averaged ca. 10 t pa. in the first two seasons before increasing to 64 tonnes in 2010/11 and subsequently peaking at 97 t in 2013/14 (Figure 4). Catches dropped substantially to 19 t in 2014/15 following the closure of the primary processor but rebounded to 40 t in 2015/16. Trends in total effort mirrored those of catch, peaking in 2013/14 at 154 fisher days spread across 11 divers. Since the establishment of the fishery CPUE has averaged 507kg/dive day and 266kg/hr. Monthly catch data indicates the bulk of the catch is landed between November and June (Figure 5).

Since the commencement of the fishery, urchins have been harvested predominately from the north east of Tasmania, particularly in the vicinity of St Helens (Figure 6). Over 95% of the catch (364 t) has come from four fishing blocks, with most fishing effort concentrated over a 12 nm stretch of coastline between St Helens Island and The Gardens (Figure 7). A further 5 fishing blocks have yielded between 1 and 5 tonne, while at 10 blocks the total catch has been <1 t.

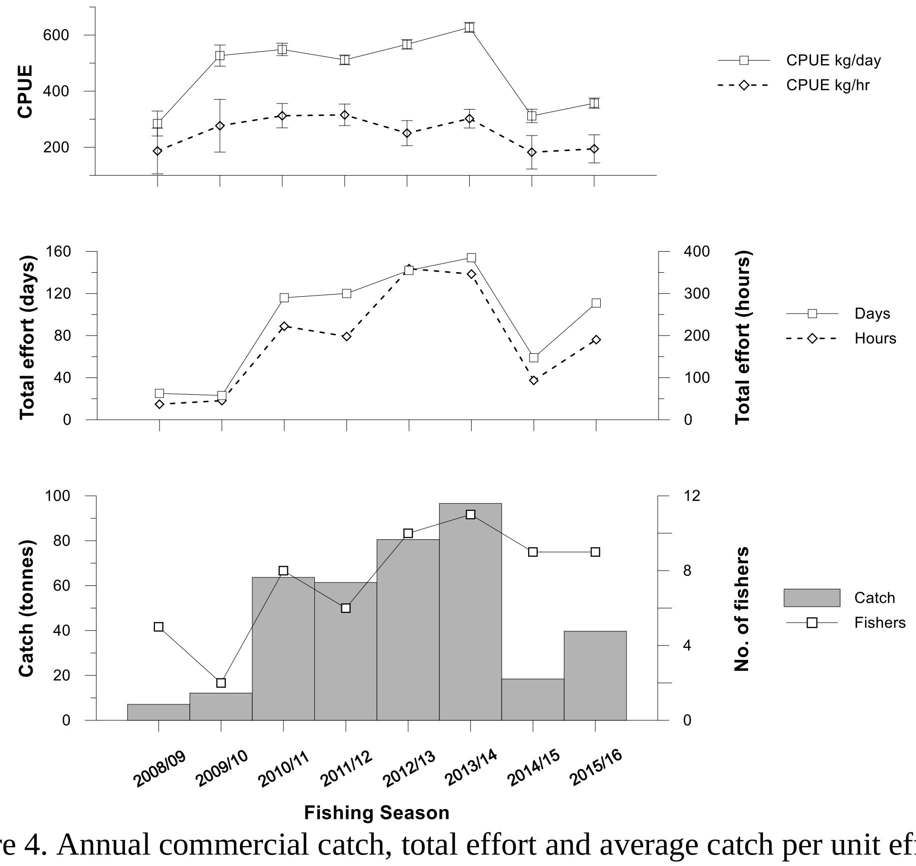


Figure 4. Annual commercial catch, total effort and average catch per unit effort (CPUE) (± 95% CI) of long-spined urchins harvested in Tasmania. Data is represented by fishing season (September-August).

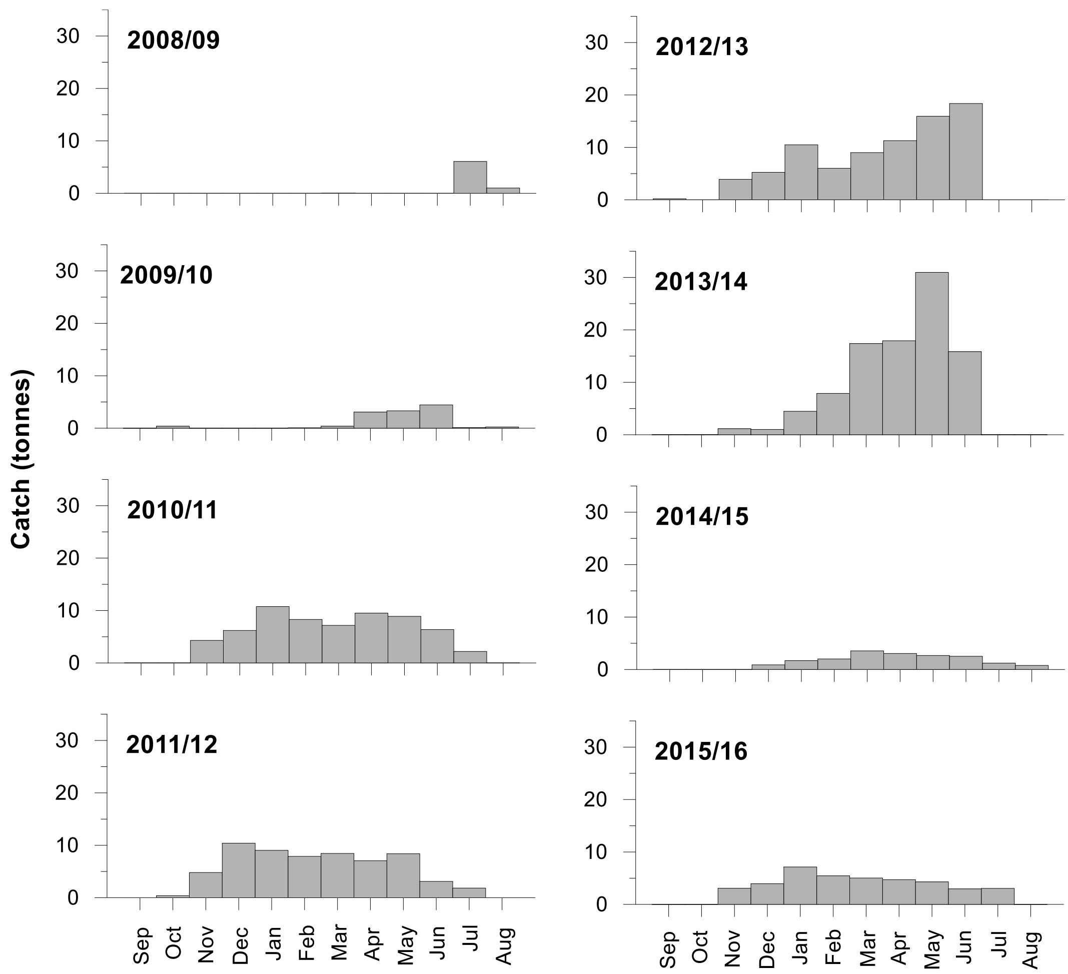


Figure 5. Monthly commercial catch of long-spined sea urchins since the establishment of the fishery in 2008. Data is represented by fishing season (September-August).

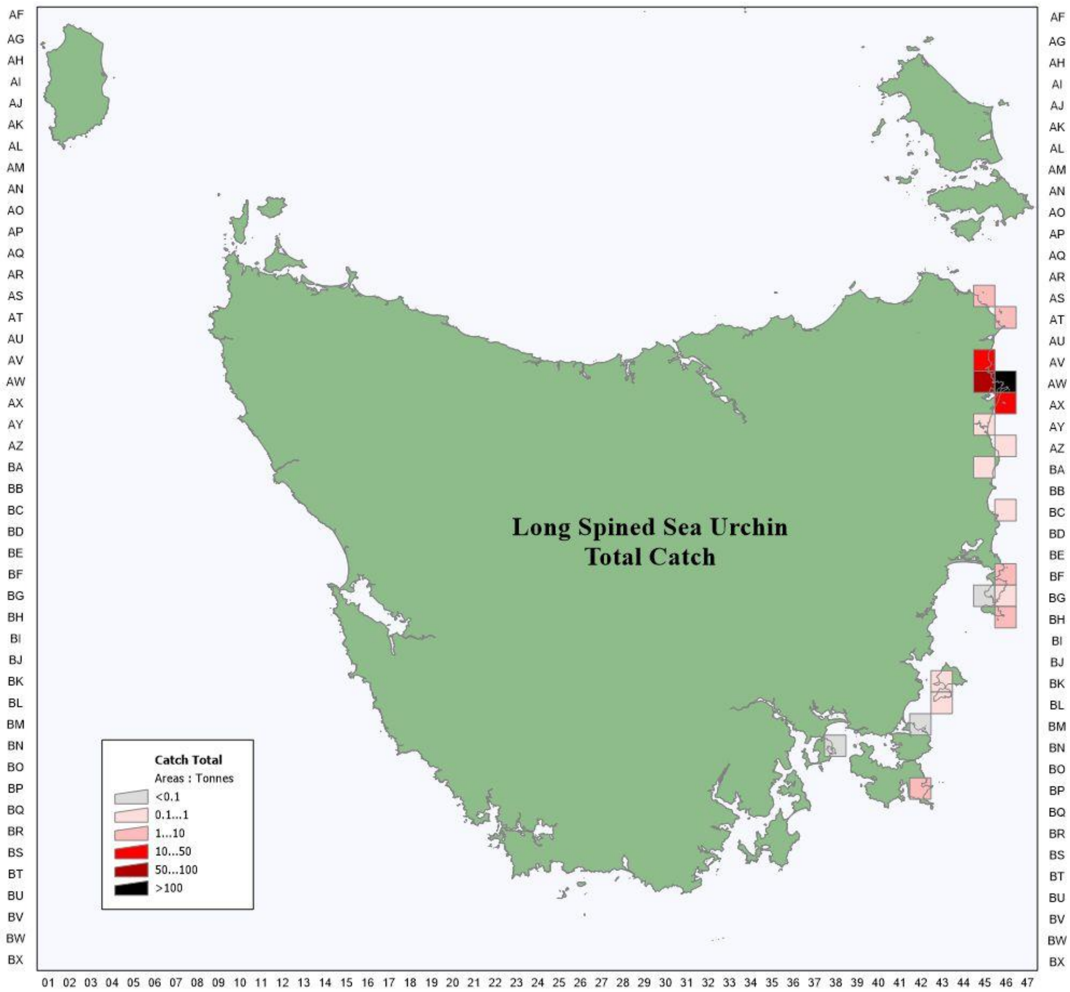


Figure 6. Combined long spined sea urchin catch by fishing block for the eight fishing seasons between 2008/09 and 2015/16. Fishing blocks are defined by the geographic coordinate system with borders 10 minutes latitude and 10 minutes longitude in length (c.a. 6 nm × 6 nm).

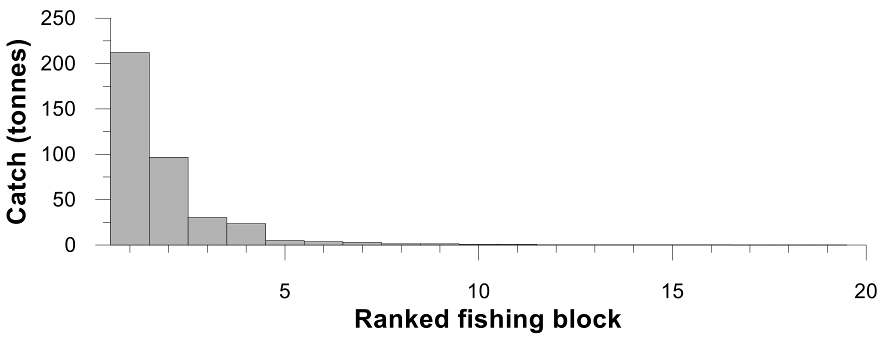


Figure 7. Combined total catch of long spined sea urchin catch by fishing block for the eight fishing seasons between 2008/09 and 2015/16.ranked in decreasing order of catch.

Impact of commercial harvesting on abundance and destructive grazing

No significant declines in urchin abundance were observed at Sloop Rock fished sites between 2014 and 2016 (Figure 8). This contrasted with trends at the Elephant Rock unfished sites where significant increases in abundance occurred at four of six sites in 2016 (Figure 8). At the only unfished site to record decreases in abundance during the 2015-16 period, site 1, evidence of urchin removal was apparent along the primary kelp-barren interface. Interestingly, mean abundance across fished sites across all periods (1.51 ± 0.06 / m^2) was significantly higher than that at unfished sites (1.07 ± 0.05 / m^2).

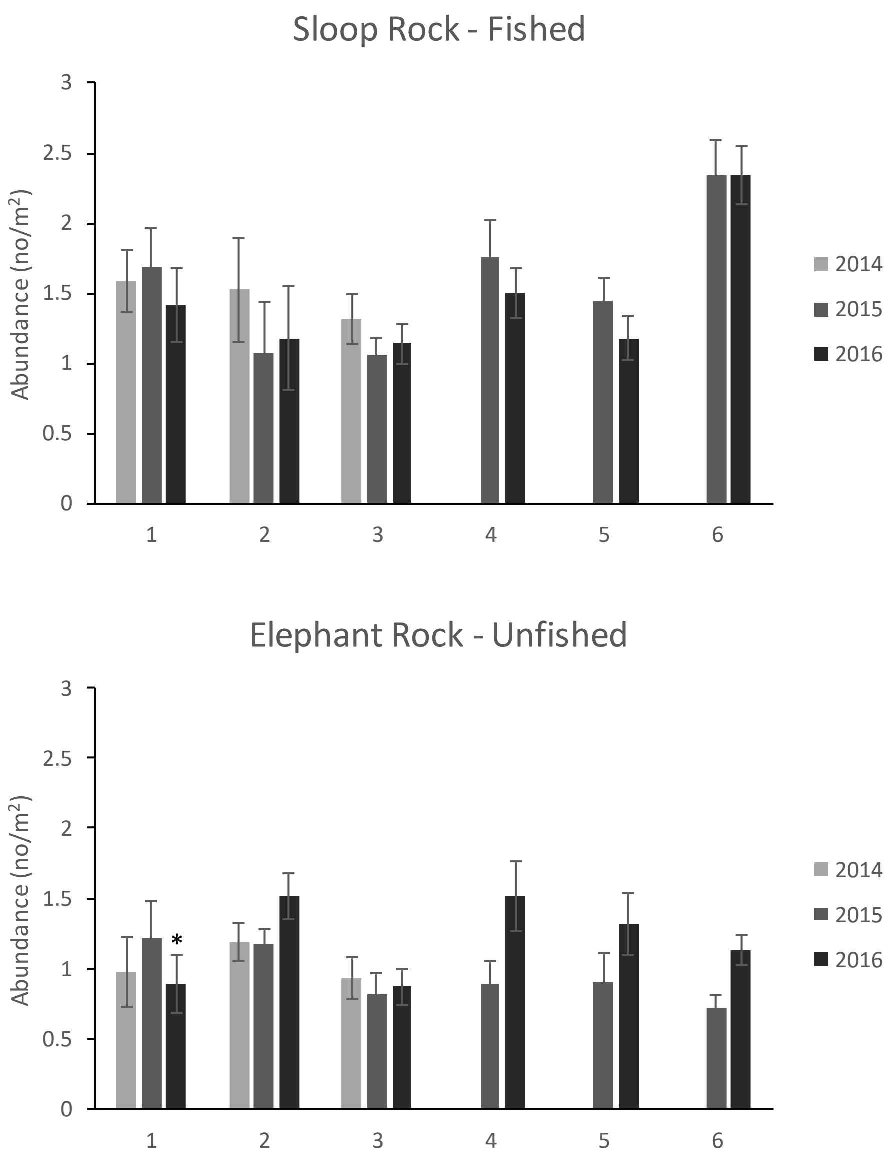
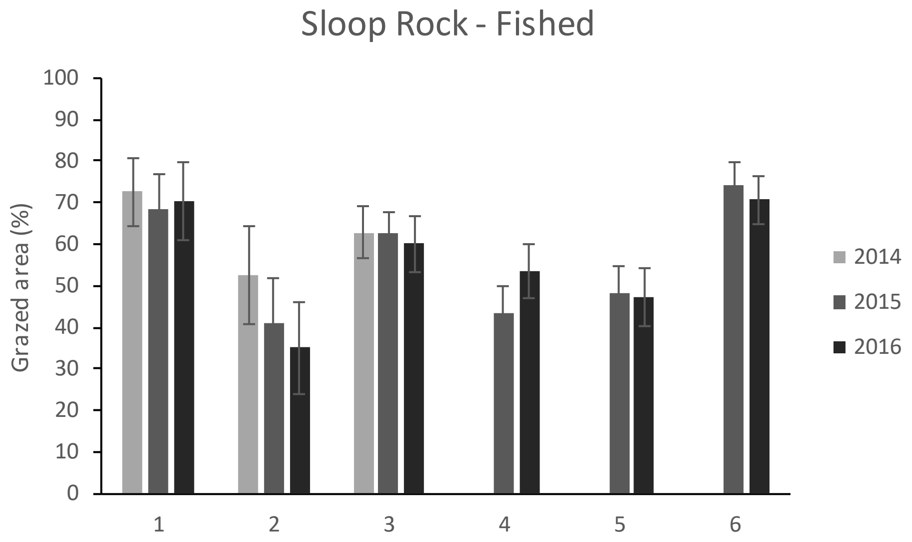


Figure 8. Long-spined sea urchin abundance (no/ m^2) from 2014 to 2016 at six sites within unfished (Elephant Rock) and Fished (Sloop Reef) regions. * Evidence of fishing was observed within the Elephant Rock research area at site 1 prior to the 2016 survey.



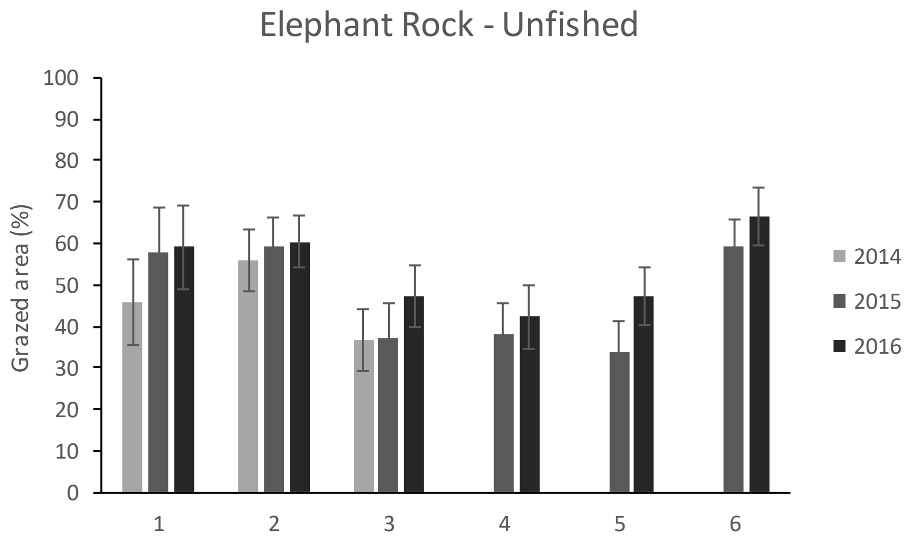


Figure 9. Grazed reef area (%) from long-spined urchins from 2014 to 2016 at six sites within unfished (Elephant Rock) and Fished (Sloop Reef) regions.

Impact of urchin harvesting on size & age structure

Size and age structure of local long-spined urchin populations in the St Helens region varied depending on fishing pressure. For test diameter (TD), frequency distributions display a clear shift in the population for sites that are fished, with test sizes being on average much smaller (Binalong Bay mean = 97.1mm, Sloop Rock mean = 93.1mm & St Helens Island (Shallow) mean = 99.1mm) than those in the unfished sites (Paddy's Island mean = 108.2mm, Elephant Rock mean = 101.5mm & St Helens Island (Deep) mean = 94.8mm) (Figure 10, Figure 11). Pair-wise Kolmogorov-Smirnov tests revealed all sites to be significantly different from each other to the adjusted Bonferroni alpha (α = 0.0034) except for the comparison of Elephant Rock and Binalong Bay P = 0.008 (Table 1).

Age frequencies showed a higher proportion of individuals were removed from the 15 – 25 years range in the fished sites, and there was a significantly higher proportion of older long-spined urchin in the unfished sites (Figure 12). There was a difference in the mean age range of fished versus unfished sites (Figure 10) including Binalong Bay mean = 20.87 years, Sloop Rock mean = 18.94 years, St Helens Island (Shallow) mean = 24.81 years, Elephant Rock mean = 24.54 years, Paddy's Island mean = 24.61 years and St Helens Island (Deep) mean = 28.7 years. All pair-wise Kolmogorov-Smirnov tests (Table 2) yielded significant differences except for the comparison of Paddy's Island and Elephant rock $P = 0.1069$. The pair-wise comparisons between St Helens Island (Deep) and Elephant Rock $P = 0.0073$ and St Helens Island (Deep) and Paddy's Island $P = 0.0221$ did not significantly differ from the adjusted Bonferroni alpha, α = 0.0034. (Table 2 N.b. All age frequencies were calculated from jaw).

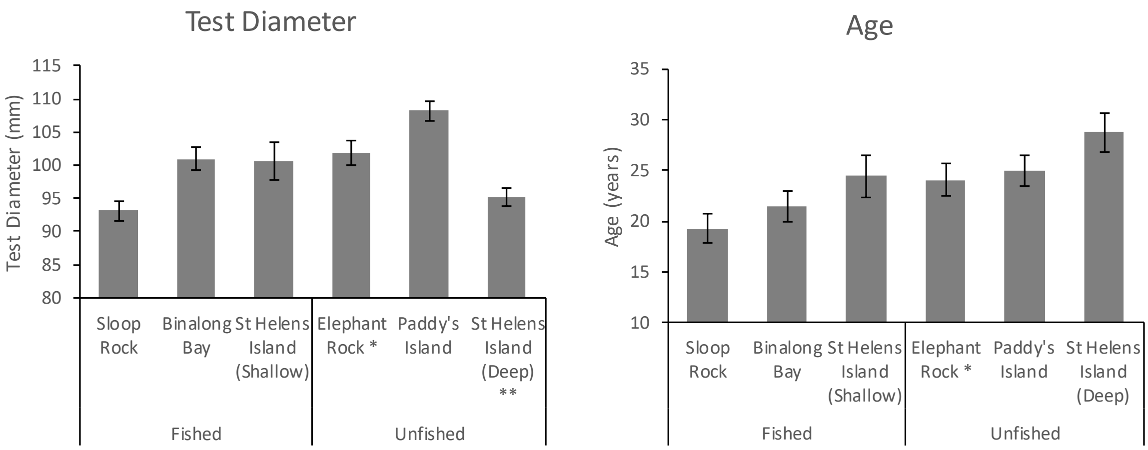


Figure 10. Mean test diameter (left) and age (right) of urchins at fished and unfished sites in the St Helens region as at August 2016. * Area subjected to illegal fishing and contains large rock lobsters which predate on urchins. ** deep water barren habitat shown to contain significantly smaller urchins.

Table 1. Pair-wise probability values of Kolmogorov-Smirnov comparisons of TD from three fished and three unfished sites. Comparisons all yielded significant differences (Bonferroni adjusted α =0.0034).

Test Diameter	**Elephant Rock**	**Paddy's Island**	**St Helens Island (Deep)**	**Binalong Bay**	**Sloop Rock**
Paddy's Island	< 0.0001				
St Helens Island (Deep)	< 0.0001	< 0.0001			
Binalong Bay	0.0080	< 0.0001	< 0.0001		
Sloop Rock	< 0.0001	< 0.0001	0.0002	< 0.0001	
St Helens Island (Shallow)	< 0.0001	0.0007	< 0.0001	< 0.0001	< 0.0001

Table 2. Pair-wise Kolmogorov-Smirnov comparisons of estimated age from 3 fished and 3 unfished sites. Comparisons all yielded significant differences except for the comparisons of Elephant Rock and Paddy's Island P=0.1069 (Bonferroni adjusted α =0.0034).

Age	Elephant Rock	Paddy's Island	St Helens Island (Deep)	Binalong Bay	Sloop Rock	St Helens Island (Shallow)
Elephant Rock						
Paddy's Island	*0.1069*					
St Helens Island (Deep)	*0.0073*	*0.0221*				
Binalong Bay	*0.0005*	*< 0.0001*	*< 0.0001*			
Sloop Rock	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*		
St Helens Island (Shallow)	*0.0018*	*0.0002*	*< 0.0001*	*0.0003*	*< 0.0001*	

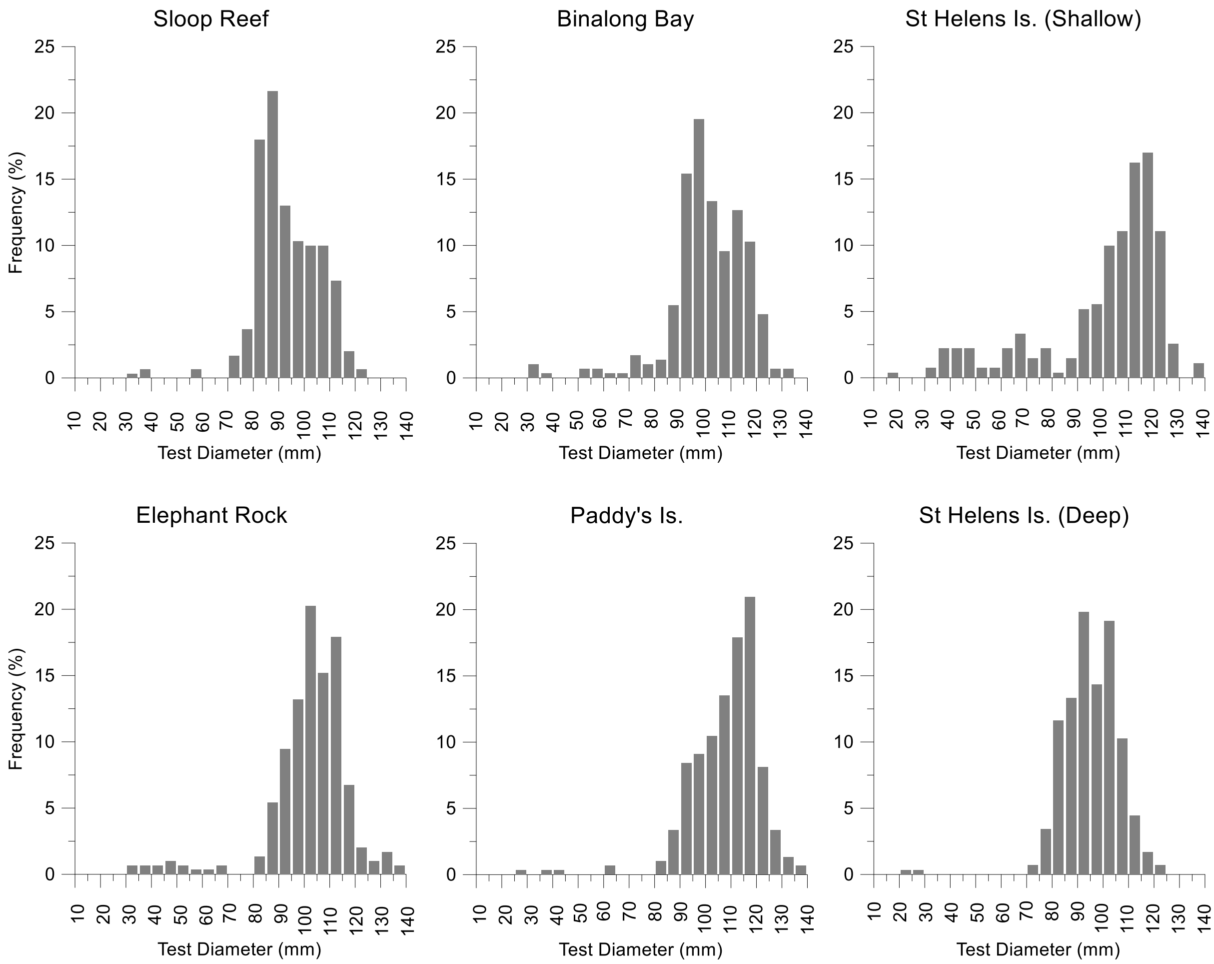


Figure 11. Frequency distributions of TD in long-spined urchin from three commercial fished sites and three sites that are not commercially harvested from. a) n = 295, b) n = 296 & c) n = 294 are all sites that commercial fishing does not occur on. d) n = 291, e) n = 299 & f) n = 270 are all sites targeted by commercial divers. Pair-wise Kolmogorov-Smirnov tests revealed all sites to be significantly different from each other to the adjusted Bonferroni alpha, $\alpha = 0.0034$ except for the comparison of Elephant Rock and Binalong Bay $P = 0.008$ (Table 2 Appendix I). N.b. All data from incipient barrens 10 – 15m except St Helens Island (Deep) that is from full barrens 18 – 20m.

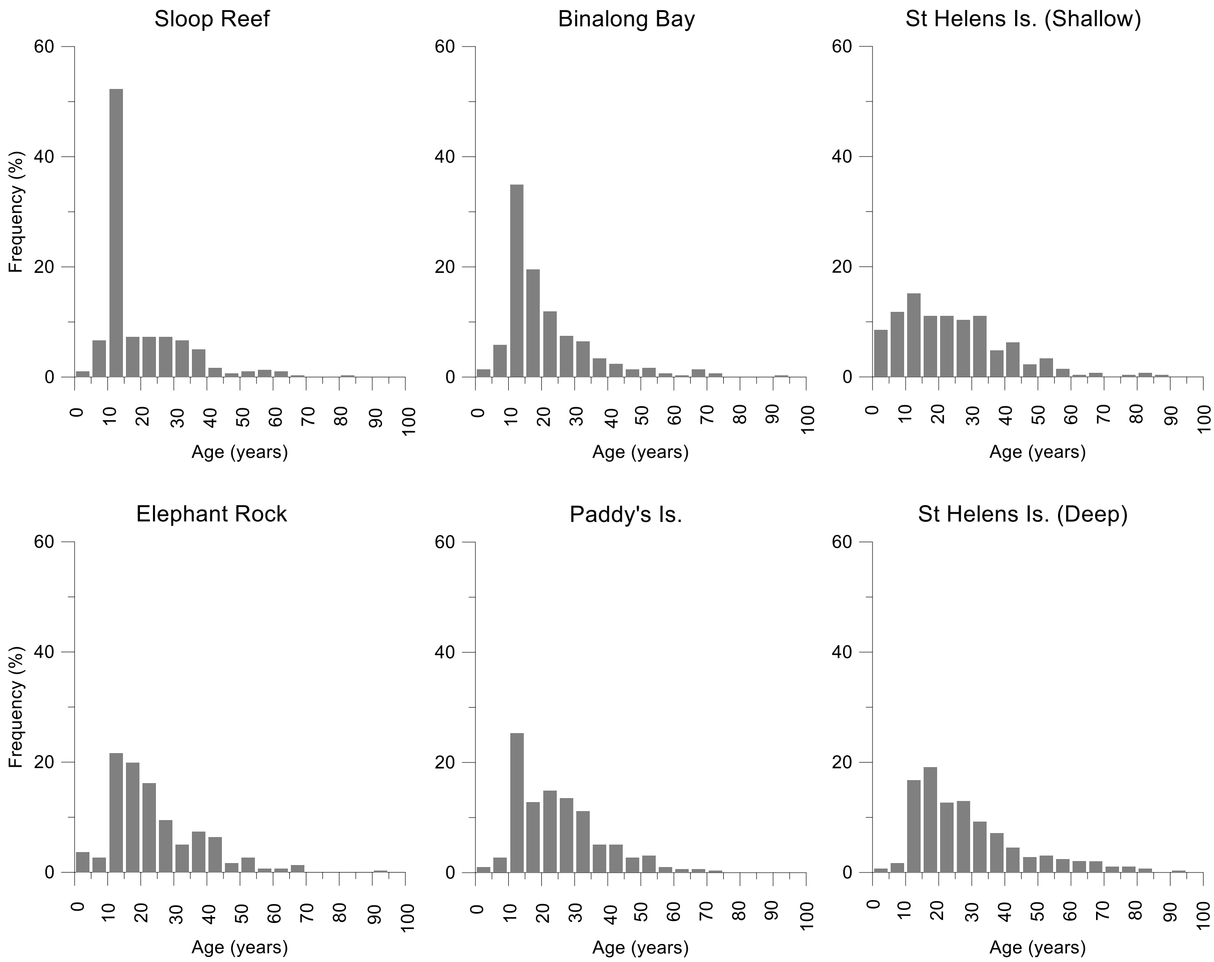


Figure 12. Frequency distributions of age in long-spined urchin from three commercial fished sites and three sites that are not exposed to commercial harvesting. a) n = 295, b) n = 296 & c) n = 294 are all sites that commercial fishing does not occur on. d) n = 291, e) n = 299 & f) n = 270 are all sites targeted by commercial divers. Pair-wise Kolmogorov-Smirnov tests revealed all sites to be significantly different from each other to the adjusted Bonferroni alpha, $\alpha = 0.0034$ except for the comparison of Elephant Rock and Binalong Bay $P = 0.008$ (Table 2). N.b. All data from incipient barrens 10 – 15m except St Helens Island (Deep) that is from full barrens 18 – 20m.

Average Test Diameter and age of the urchin population at each of the six surveys sites was contrasted with the total catch at each site since the long-spined urchin fisheries first commenced in 2008. More than 70% of the variation in mean TD was explained by the magnitude of catch over the previous eight years (Figure 13a), and more than 80% of the variation in mean age was explained by catch history (Figure 13b).

The abundance of different size classes recorded during research surveys is strongly reflected in the 2016 commercial catch size structure (Figure 14a). Research survey size frequencies were dominated by urchins between 80 mm and 130 mm TD, with the 2016 commercial catch comprised of urchins between approximately 90 mm and 130 mm. The size structure (TD) of the 2016 commercial catch also appears unchanged from the size structure observed during the 2010/2011 and 2013/2014 fishing years (Figure 14b), with little change in either the size range or the modal size class.

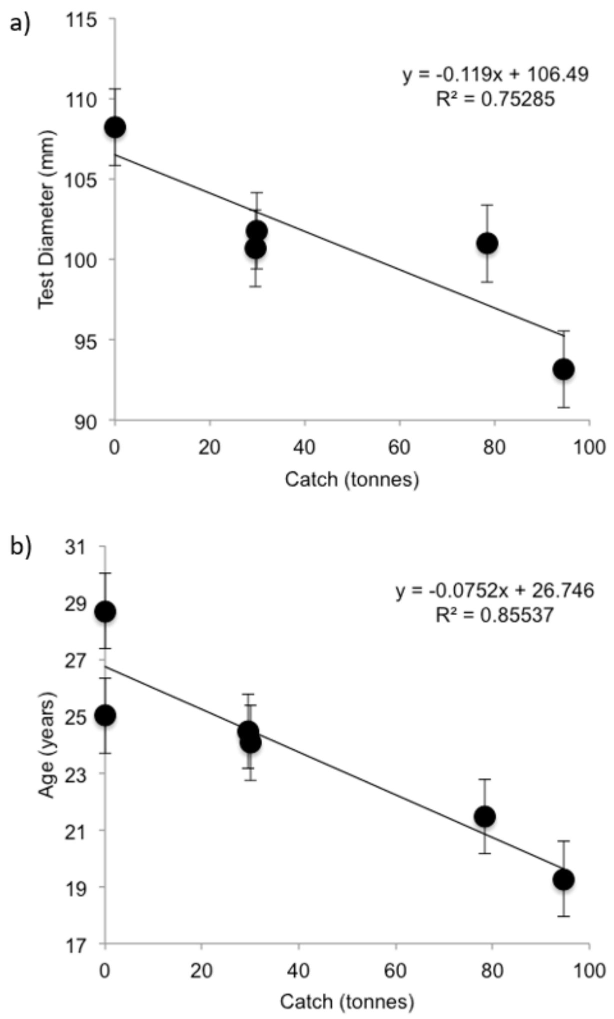
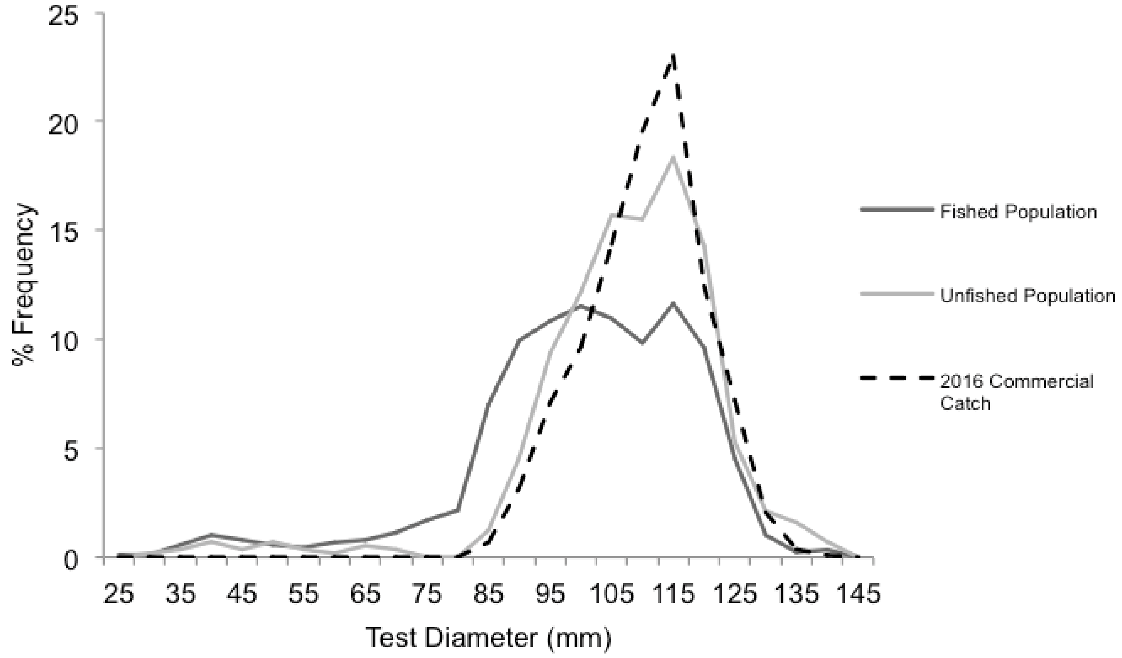


Figure 13. Trend of declining size and age with increasing catch volume (2008 – 2016) in St Helens region (see Figure 1). a) Relationship between Total Catch and TD - R^2 = 0.75285. b) Relationship between Total Catch and Age - R^2 = 0.85537. N.B. St Helens Island (Deep) was removed from TD regression due to the difference in habitat (full barrens).

Table 3. Mean Test Diameter and estimated age among unfished and fished populations, as well as the structure of the commercial catch during 2016.

	2016 Unfished Population	2016 Fished Population	2016 Commercial Catch
n	593	863	2194
μ(TD) (mm)	105.0	98.2	108.0
μ(age) (years)	24.5	21.7	31.0



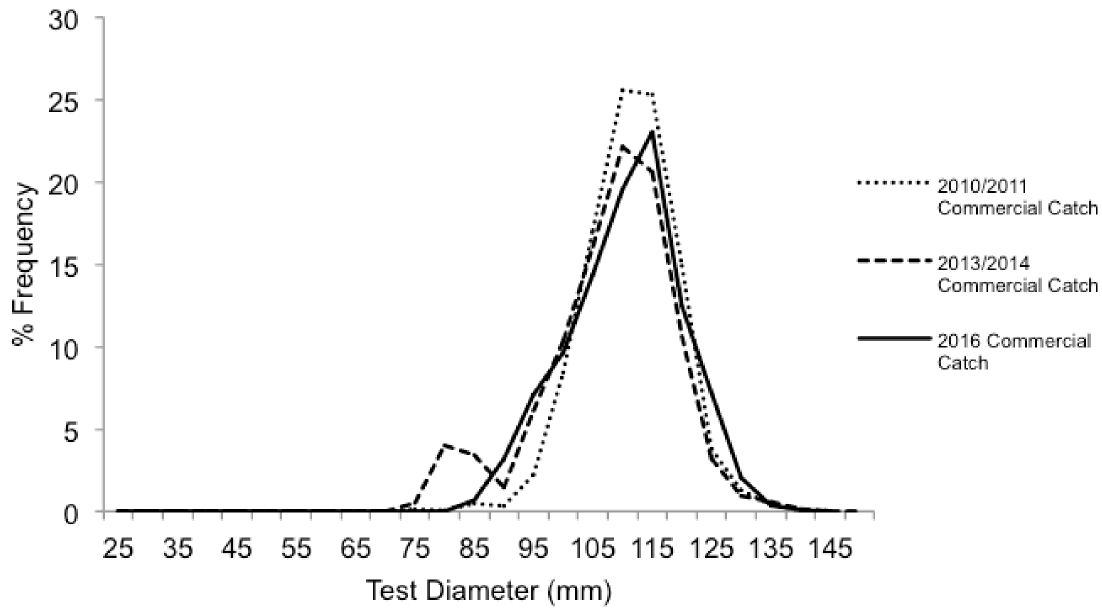


Figure 14. Frequency distributions of Test Diameter (TD) in *C. rodgersii*. a) Research size frequency of TD (unfished and fished sites pooled) and 2016 commercial catch size frequency data. b) Time-series of commercial catch size frequency from the 2010/2011 and 2013/2014 fishing years.

Impact of long-spined urchin on short-spined urchin, abalone and rock lobster populations

Dive surveys of urchin, abalone and rock lobster densities were undertaken at three sites near St Helens, north eastern Tasmania, namely Sloop Reef, Elephant Rock and St Helens Island, in October 2013. These three sites represent the two areas intensively fished by urchin fishers (Sloop Rock, St Helens Island), and the Elephant Rock research area (closed to all fishing). At each of the three sites, 6 transects were surveyed perpendicular to the kelp-barren interface. Transects extended 30 m either side of the interface and were 1 m wide. Abundances were recorded at 5 m intervals.

The total number of long spined sea urchins (n=1146) was greater than all other species recorded in both the barren and kelp zones (Table 4). Abundances of long spined sea urchins in the barren zone (1.804/ m^2) were 3.1 times greater than that in the kelp zone (0.583/ m^2) (Figure 15).

Abalone was abundant in the kelp zone with 68 individuals being recorded across all transects. By contrast they were rare in the barren zone with only 2 individuals observed (Table 4). This related to a 34 fold increase in density from 0.004/ m^2 to 0.142/ m^2 from the barren to kelp zone (Figure 15). However, this trend is confounded with depth, particularly as abalone are typically more abundant at shallow depths, and with most of the fishery sourced from reef habitat above 10m. Densities of the purple sea urchin in kelp zone were higher than in barren zone, but no significant difference was detected. Abundance of lobster was low and no meaningful results could be determined.

Densities of both long spined sea urchin and abalone did not change significantly throughout the barren zone with varying distances from the kelp-barren interface (Figure 16). By contrast, abalone showed a general trend of increasing abundances with increasing distance from the kelp-barren interface. Highest densities of abalone (0.325/ m^2) were recorded in the kelp zone the furthest distance from the kelp-barren interface (25-30/ m^2). Furthermore, the density of abalone was inversely related to the density of long spined sea urchin (Figure 16).

Table 4. Total number of urchin, abalone and rock lobster recorded in barren and kelp zones.

Zone	Long spined sea urchin	Purple sea urchin	Abalone	Lobster
Barren	866	38	2	3
Kelp	280	61	68	3

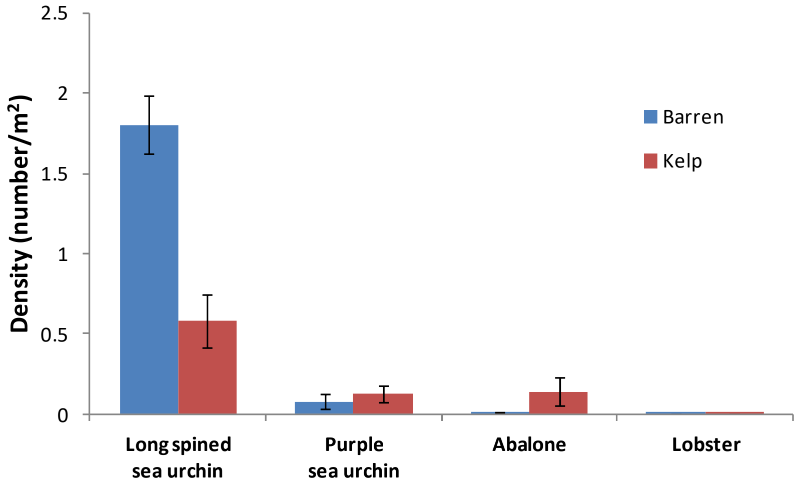


Figure 15. Mean density (no./m^2) of long spined sea urchin, purple sea urchin, abalone and rock lobster recorded in barren and kelp zones (Sites pooled).

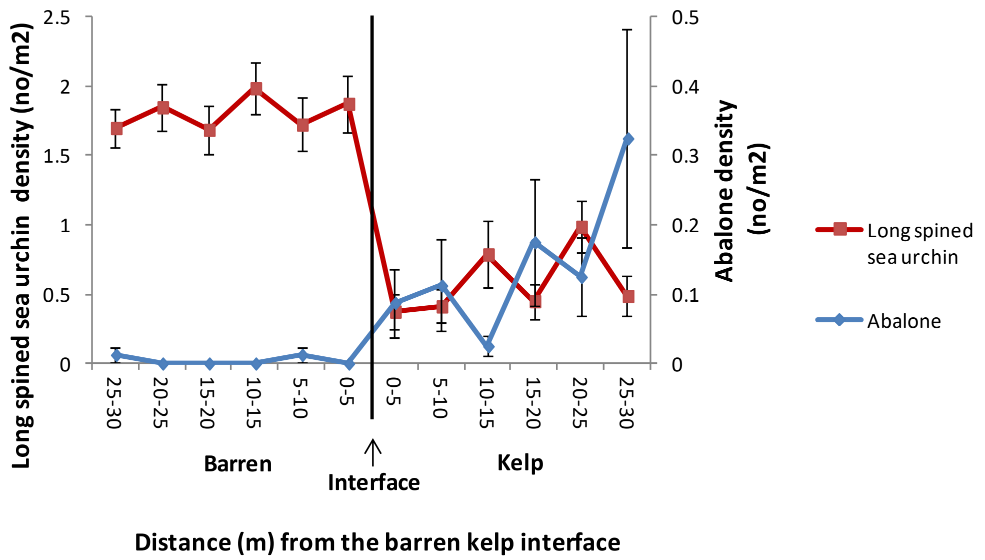


Figure 16. Mean density (no./m^2) of long spined sea urchin and abalone at 5m intervals from the barren-kelp interface (sites pooled).

Spatial location and extent of overlap between long-spined urchin and existing fisheries

Of considerable interest is the extent to which abalone fishing grounds overlap with areas utilised by the long-spined urchin fishery. In terms of direct overlap, in 2013 around 50% of logged urchin fishing activity overlapped spatially with logged abalone fishing activity (Table 5), with the remainder of the urchin fishing occurring adjacent to the abalone fishing grounds, but deeper. For 2014, this percentage dropped to ~ 20% (Table 5). As not all areas are fished in all years, a further comparison was made examining overlap based on all data pooled across years. When both years were combined for urchin and abalone fishing the level of overlap is greater than 50% (Table 5). The extent of direct spatial overlap between the urchin and abalone fisheries suggests there is good reason to expect that urchin fishing as currently observed could have direct benefits for the abalone fishery in terms of reducing abundance of urchins within or adjacent to key abalone fishing grounds (Figure 17, Figure 18, Figure 19).

Table 5. Number and percentage of urchin fishing points that overlap with abalone fishing polygons. Rows 2013 and 2014 represent the overlap of urchin fishing in that year with abalone fishing in that year. The row 'Total' represents the spatial overlap between urchin and abalone fishers with data pooled across years for both urchins and abalone.

Year	Total Urchin Point Count	Overlap Point Count	% overlap
2013	23,836	12,291	51.6%
2014	69,143	14,464	20.9%
Total	92,979	51,567	55.5%

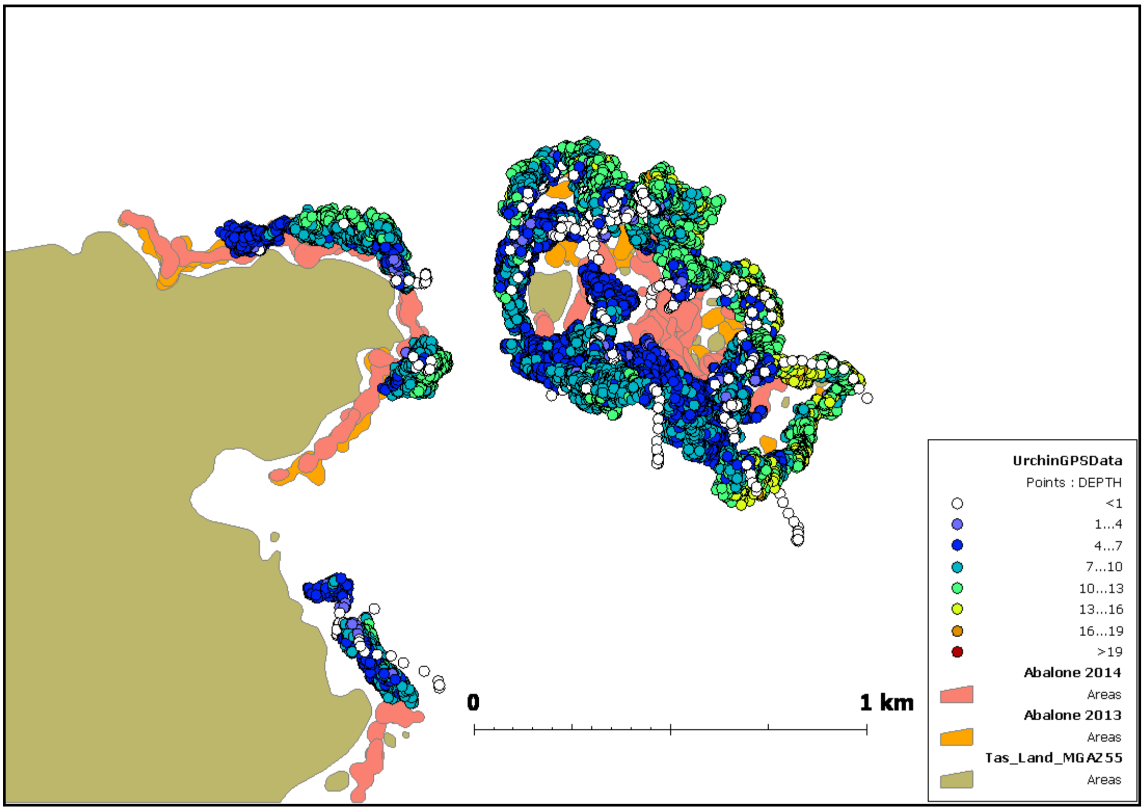


Figure 17. Spatial overlap between urchin fishing (points) and abalone fishing (polygons) at Sloop Rock, NE Tasmania. Points are colour coded by depth.

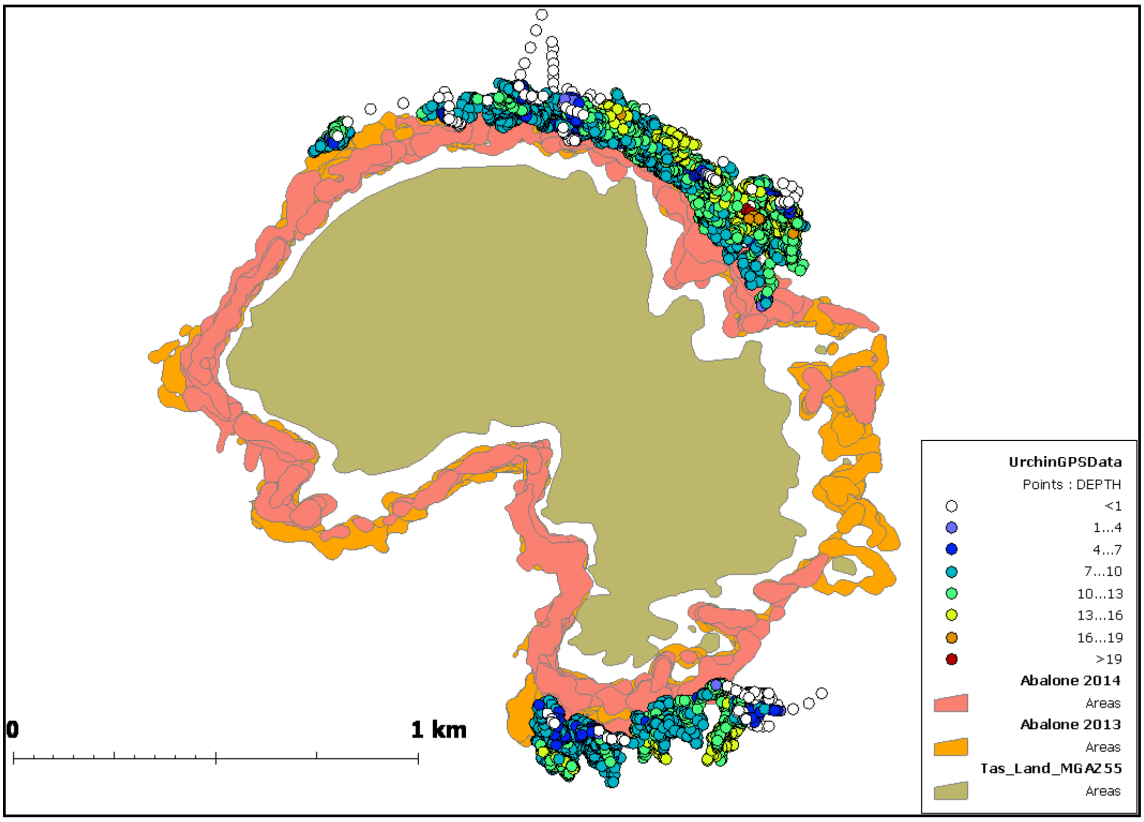


Figure 18. Spatial overlap between urchin fishing (points) and abalone (polygons) fishing at St Helens Island. Points are colour coded by depth.

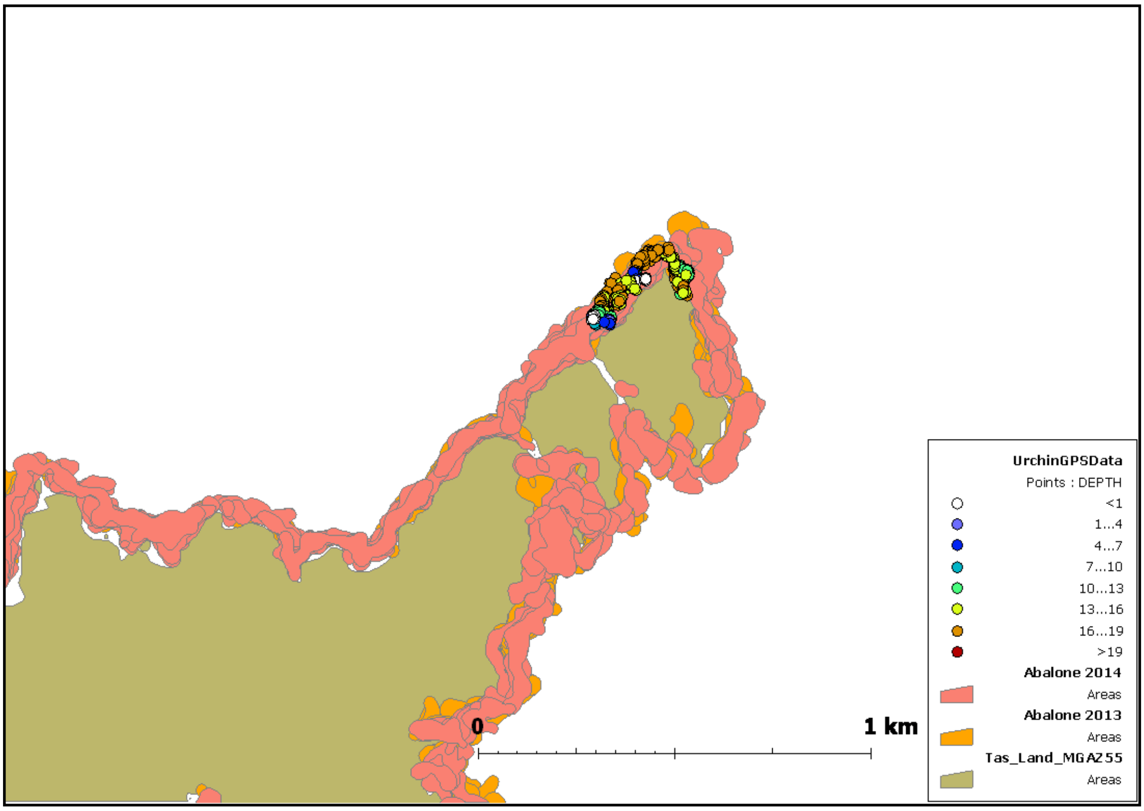


Figure 19. Spatial overlap between urchin fishing (points) and abalone fishing (polygons) on the Tasman Peninsular. Points are colour coded by depth.

Analysis of fishing effort by depth within abalone Sub-Blocks shows that current urchin fishing while in close spatial proximity to abalone fishing grounds, is spread over a deeper depth range. Urchin fishing to a larger extent occurs in deeper water than abalone fishing with around half of the urchin fishing taking place in or greater than 11m (Figure 20). In contrast the abalone fishery is primarily shallower than 11m, with block 22 (Tasman Peninsular) the exception (Figure 19, Figure 20). This is consistent with the research survey results of urchin and abalone abundance in kelp and barrens habitat presented in the previous section.

The close spatial proximity of the urchin fishery to known abalone fishing grounds has two important ramifications. Firstly, that if urchin harvesting operations can be expanded, there is a very real possibility that a sustainable, ongoing urchin harvest operation will diminish the destructive grazing activities of the long-spine sea urchin. Secondly, that if urchin harvesting for human consumption of roe declines and fails, there is likely to be ongoing and further impact on abalone fishing grounds through destructive grazing by the long-spine sea urchin.

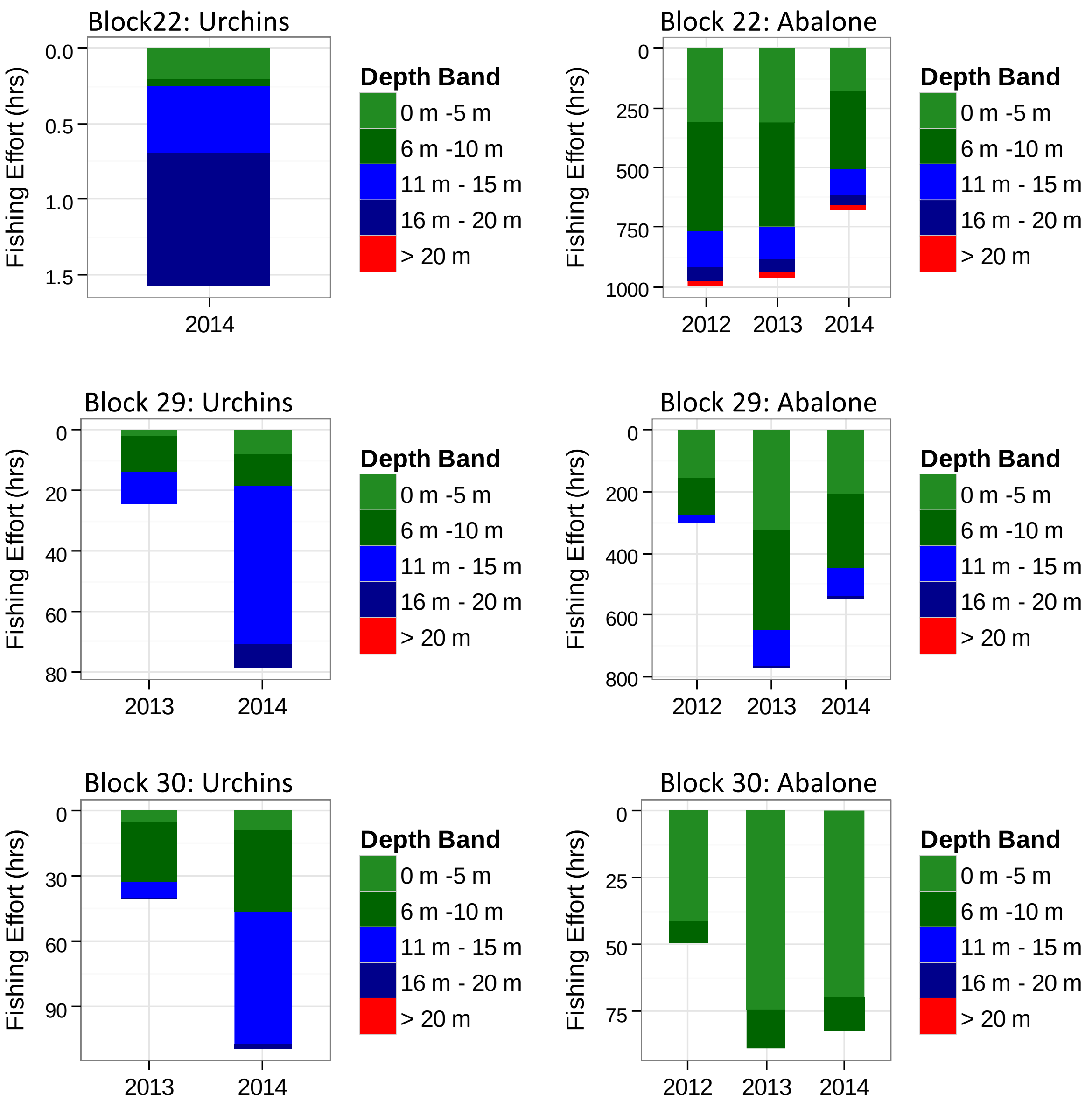


Figure 20. Fishing by Year, depth and abalone reporting block for long-spined urchin and abalone harvesting in Tasmania.

Application of coastal exposure indices for identifying potential urchin harvest locations

Towed video surveys were done in two regions as a rapid classification of reefs into different Barren classes (St Helens in the north and Maria Island/Tasman Peninsular in the South). Mean values for the three independent variables (wind, wave and depth) across the four Barren classification groups appeared to be invariant in the northern dataset (Table 6). For the southern dataset, wave and wind exposure indices followed a pattern consistent with increasing prevalence of barrens with decreasing exposure (Table 6). The southern dataset only was further analysed using Discriminant Function Analysis (DFA) to determine whether a predictive model based on wave, wind and depth could be used to assign a likely barren class to broader reef systems. As there were only 15 towed video segments for the large-scale barren class in the southern dataset, this class was removed from the DFA. The first discriminant dimension accounted for 83% of the separation among the three barren classes for the training dataset (Figure 21). There was overlap in the modes for all three Barren Class groups, with the local maxima for Groups 1 (barrens abundant) and 2 (barrens rare) overlapping. Tails of the distribution of groups along the first discriminant function also overlap.

Overall, there was only 44% successful classification of the test dataset based on the Empirical Predictive Model (EPM) developed from the training dataset, with the group level success for 'barrens rare', 'barrens abundant' and 'no barrens' being 11%, 7%, and 84% respectively. The towed video segments in the 'barrens abundant and 'barrens rare' were primarily misclassified as 'no barrens'. Interaction plots of Wave and Wind exposure indices by Barren Class and Depth class (5m depth bands) reflected the overall pattern of barren class means. Wave exposure index was always higher for video segments with healthy kelp (no Barrens) and lower where incipient barrens were abundant across all depth bands (Figure 22). Wind exposure index followed a similar pattern with depth to the wave exposure index for the first three depth bands (0 – 5m, 5m – 10m, 10m 15m), but not at the deeper depth bands (Figure 23). While these results from the southern reefs conform to the common perception that development of urchin barrens is dependent on wave exposure, there is substantial variation among affected areas with respect to environmental parameters and no apparent threshold of wave and wind exposure that permits development of urchin barrens. However, the pilot towed-video data collected for this study was restricted to tow key areas, and the design of the towed video sampling program may require revision to collect data from more areas where there is no effect of urchins, as well as areas where the urchins have created complete barrens.

Table 6. Mean values for exposure indices (Wave, Wind) and depth for northern and southern reefs index across four Barren state classification classes.

Region	Barren Class	Wave Index	Wind Index	Depth	n
North	No Barren	111.4	51.7	18.3	229
North	Incip Barren Rare	93.4	50.1	13.9	233
North	Incip Barren Abundant	105.6	50.4	16.2	563
North	Barren Zone	118.6	50.2	20.3	486
South	No Barren	54.4	23.4	14.2	1464
South	Incip Barren Rare	43.5	20.7	14.8	834
South	Incip Barren Abundant	26.6	17.1	12.7	718
South	Barren Zone	1.4	6.2	11.2	15

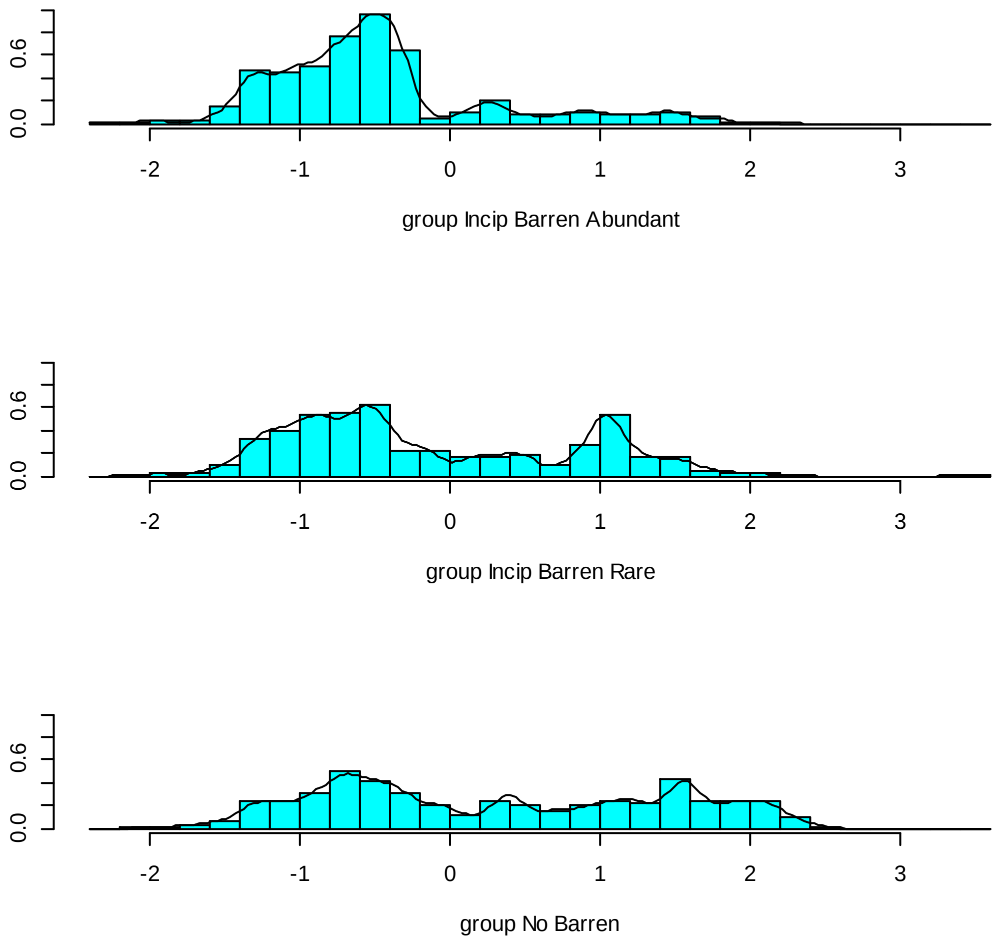


Figure 21. Histograms of the first linear dimension of the predictive model for the 'training' towed video data. 83% of variation in the classification of barren classes can be explained in the first linear dimension. All Groups present multimodal distribution, with no clear separation between Barren class along LD1.

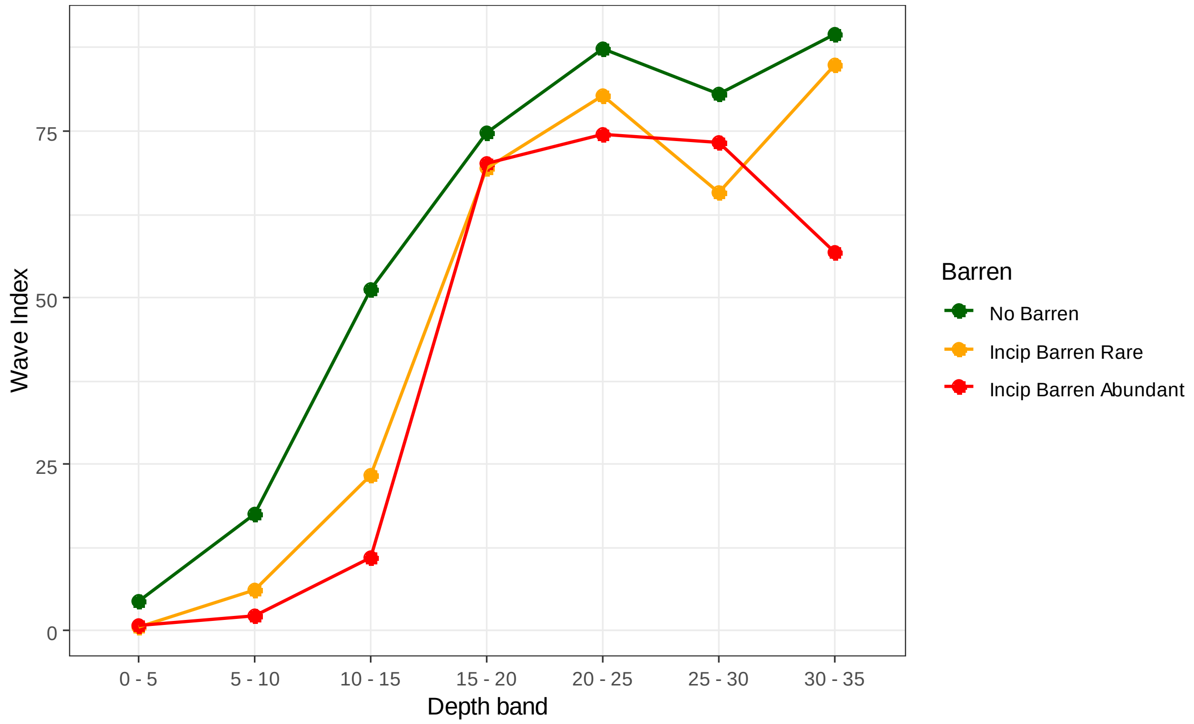


Figure 22. Interaction plot of Wave Index for towed video data Maria Island and Fortescue region. Towed video segments were classified in 5m depth bands.

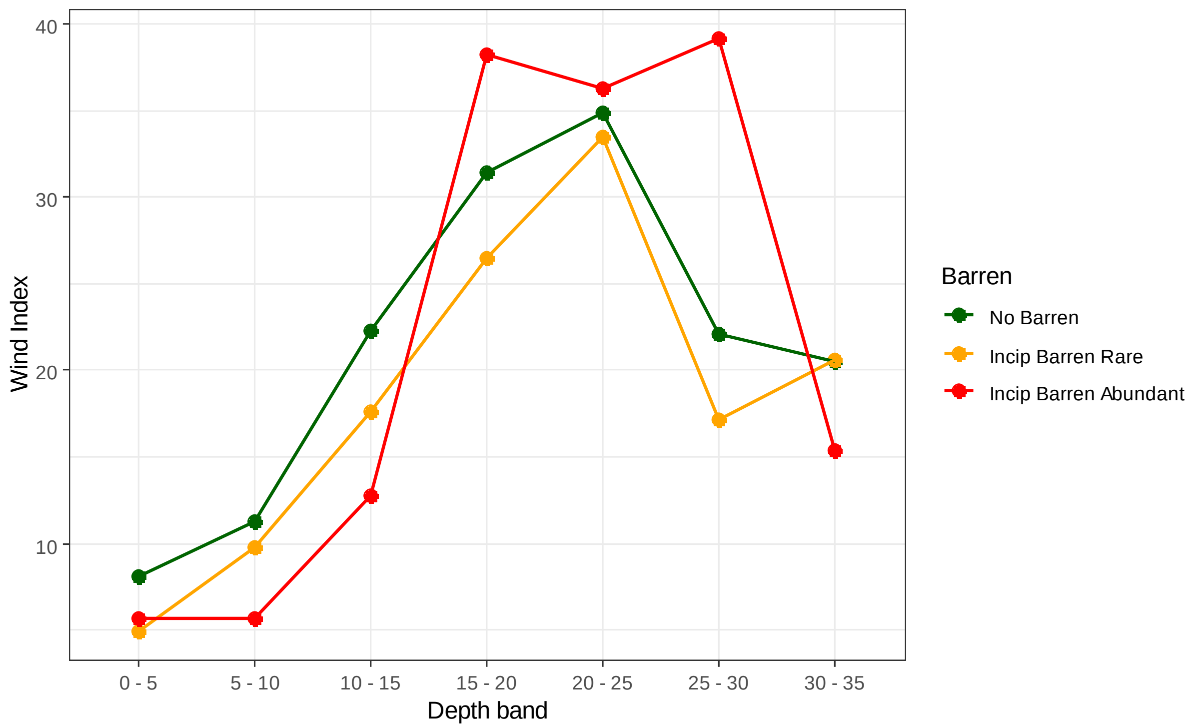


Figure 23. Interaction plot of Wind Index for towed video data Maria Island and Fortescue region. Towed video segments were classified in 5m depth bands.

Dive profile strategies to enable safe harvest of urchins at depths greater than 15m

The majority of extensive barrens along the East coast of Tasmania occur at depths greater than 15m. Significant dive activity for urchin harvesting or other urchin control options at this depth is constrained by safe no-decompression dive limits on compressed air. The use of readily available mixed gas blends such as Nitrox could facilitate greater bottom time, and potentially expand the current depth range where urchin based activity is undertaken (Box 1).

Box 1. Advantages and disadvantages of Nitrox to extend the depth range for safely harvesting urchins.

Advantages and disadvantages of nitrox

Benefits of Nitrox

- Less risk of decompression sickness,
- Longer dive times,
- Longer repetitive dive times,
- Shorter surface intervals are possible on repetitive dives,
- Less fatigue reported by many divers.

Disadvantages of Nitrox

- Need a dedicated supply of Nitrox (own Nitrox compressor)
- Expense of purchasing Nitrox filling station/com
- Maintenance of Nitrox equipment,
- Nitrox dive training required,
- Oxygen toxicity risks
- Oxygen exposure limits- max 3 hours diving per 24 hours at Maximum Operating Depth (MOD)
- Increased risk of fire.

There are substantial benefits of using Nitrox for fishing/research at depth. Effectively, for a single dive at a given depth the use of Nitrox enables twice as much time at depth than using normal compressed air via Hookah (Table 7). One caveat here is that most dives, either fishing or research rarely occur at a single depth stratum and more commonly range of multiple depths. Thus, calculations of the exact limits and benefits of use of Nitrox for urchin fishing operations is difficult to determine. Notwithstanding this limitation, the increase in dive time through use of Nitrox will be approximately double (Box 2).

Table 7. Maximum Dive times for single dives using different breathing mixes.

Depth	**Air**		**EAN35**		**EAN40**	
	DCIEM Tables	Suunto Dive Computer	Nitrox Tables	Suunto Dive Computer	Nitrox Tables	Suunto Dive Computer
5m	720	Unlimited	720	Unlimited	720	Unlimited
10m	150	165	300	Unlimited	720	Unlimited
15m	75	65	150	156	300	205
20m	35	35	75	66	75	88
25m	20	22	35	41	50 MOD	56 MOD
30m	15	15	25 MOD	29 MOD	> MOD	> MOD

Box 2. Example of maximum dive times for repetitive dives for compressed air and Nitrox.

Example: Maximum dive times for repetitive dives

Dive 1 - 25 metres
Surface Interval 1 Hour
Dive 2 - 25 metres

Maximum dive times on Air
Dive 1 20 mins + Dive 2 11 mins = TOTAL TIME 31mins
Maximum dive times on Nitrox
EAN40 Dive 1 50 mins + Dive 2 29 mins = TOTAL TIME 79mins

There are several options available to commercial divers wanting to use nitrox while urchin fishing, from minimal investment in equipment to more significant investment in equipment and training. The simplest system involves use of SCUBA cylinders prefilled with Nitrox (Option 1) from a commercial Nitrox gas provider (Box 3). A more advance system retains the benefits of a surface supply diving program, by using large volume cylinders (e.g G cylinders) pre-filled with Nitrox (Option 2), again with Nitrox gas sourced from a commercial Nitrox gas provider (Box 4). More advanced solutions involve feeding output from a Nitrox membrane compressor through a standard Hookah compressor (Option 3), or a standalone combined Nitrox low pressure compressor (Option 4) (Box 5, Box 6).

A key restriction for options 1) and 2) is that there are a limited number of Nitrox filling stations around Tasmania. Options 3) & 4) are unsuitable for small dinghy operations typical in urchin and abalone fisheries, and would be restricted to larger shark cats or similar size vessels. One possibility is that Option 2) combined with a portable shore-based Nitrox compressor which is used to fill the G cylinders overnight. This however requires a suitable storage location for the compressor during the day while the fishers are on the water.

Catch rates for current urchin fishing is around 150 Kg/Hr to 300 Kg/Hr. The divers are paid either by green weight or by the roe recover and roe quality. On the basis of current payments made to divers, at depths of 25 m or greater the fishers would require catch rates at or greater than the upper limits of what divers are currently achieving (~ 300 Kg/Hr) to make it financially viable to fish for urchins at these depths on air. There are also several challenges with working at this depth in terms of increased time for deck hands to retrieve nets containing urchins from the diver and delivering empty nets back to the diver. The simple conclusion here is that harvesting of urchins at depths of 25m or greater using compressed air and conforming to safe diving limits will not be economic. The investment in Nitrox equipment will be cost-effective if the urchin fishery expands, and, divers are able to secure significant quantities of the catch required to amortise the cost of their investment in specialised equipment over a reasonable time frame, or a readily available source of Nitrox becomes available to fishers in their area of operation.

Option 1: Scuba - using scuba equipment and nitrox dive cylinders

Box 3. SCUBA + Nitrox comparison. Setup cost: Regulator, Buoyancy Vest, 5 x 12L 300bar cylinders = $4650

SCUBA + Nitrox: Advantages and disadvantages

Advantages:

- Low setup cost,
- Suitable for small vessels,
- Less work for deckhand,
- Silent operation,
- Gas can be analysed and mix confirmed before dive
- Less risk of contamination from exhaust fumes of compressor
- No breakdown risk, less maintenance
- Minimal problems with salt water corrosion

Disadvantages:

- Divers used to hookah don't like wearing bulky cylinders,
- Limited supply of gas so shorter dive times e.g. working diver 60mins at 20 metres
- Need a nitrox fill station near fishing location,
- Increased workload to get cylinders filled daily
- Cost of nitrox fills $15-20 per cylinder

Option 2: HPSSA: High pressure surface supply apparatus using two large G cylinders and a dive control panel to supply nitrox via a hose to the diver

Box 4. Surface Supply + Nitrox. Setup costs: 2 x 300Bar G cylinders, control panel with regulator = $6200

HPSSA + Nitrox: Advantages and disadvantages

Advantages:

- Low setup cost,
- Suitable for small vessels,
- Less work for deckhand,
- Silent operation,
- Gas can be analysed and the mix confirmed before dive
- Less risk of contamination from exhaust fumes of compressor
- No breakdown risk, less maintenance
- Minimal problems with salt water corrosion
- Gas supply equivalent to 8 scuba cylinders e.g. working diver 480mins at 20 metres

Disadvantages:

- Need a nitrox fill station near fishing location,
- Increased workload to get cylinders filled daily,
- Cost of nitrox fills $75-100 per cylinder.

Option 3: Nitrox Generator linked to existing LPSSBA (Hookah Compressor)

Box 5. Production of Nitrox from an onboard generator. Setup costs: $32450

Nitrox generator: Advantages and disadvantages

Advantages:
- Unlimited supply of nitrox
- Can use existing hookah with or without nitrox

Disadvantages:
- High setup and maintenance costs
- Breakdown risk
- Gas must be analysed regularly
- Size and weight makes it unsuitable for small vessels (260kg 1.5m high)
- More work for deckhand monitoring equipment
- Noisy due to larger engine
- Greater risk of contamination from exhaust fumes

Option 4: Nitrox LPSSBA (Nitrox Hookah Compressor)

Box 6. Low pressure surface supply with nitrox. Setup costs: Nitrox EAN36 Compressor $37,400

LPSSA + Nitrox: Advantages and disadvantages

Advantages:
- Unlimited supply of nitrox

Disadvantages:
- High setup and maintenance costs
- Breakdown risk
- Gas must be analysed regularly
- Size and weight makes it unsuitable for small vessels (288kg 1.9m high)
- More work for deckhand monitoring equipment
- Noisy due to larger engine
- Greater risk of contamination from exhaust fumes

Discussion

The Tasmanian Fishery increased gradually from 2018 peaking at around 100 t in 2013/2014 with expectations of harvests climbing to over 600 t annually by 2018. The primary long-spined urchin processor experienced financial difficulties in 2014 and folded before the end of the fishing, year with catches in subsequent years falling below 40 t (Figure 4). As a consequence, the fishing pressure observed on target reefs during this study is considered to be very light, and interest in using the GPS and depth dataloggers provided to map urchin fishing activity and develop spatial indicators also diminished resulting in a much smaller dataset than anticipated. Urchin harvesting is highly localised at present with a few small reefs around St Helens heavily exploited and a number of other reefs contributing minor amounts of catch (Figure 7). Thus overall exploitation is considered to be low, and localised fishing pressure is also considered to be low between 2014 and 2016.

Conservation & preservation of healthy reefs through commercial fishing

At low-levels of fishing pressure, harvesting of long-spined sea urchins appeared to maintain both urchin density and grazed area at stable levels, whereas nearby unfished locations experienced increasing urchin density and increased grazed area over the 2014 – 2016 study period (Figure 8, Figure 9). Research sampling of populations remaining on reefs after fishing also found that mean urchin Test diameter and urchin age was smaller and younger respectively than on nearby unfished reefs (Figure 10). These results demonstrate a clear potential for urchin fishing to reduce destructive grazing by urchins, or at least prevent further expansion of existing grazed areas even under a regime of low fishing pressure. Commercial urchin fisheries around the world appear vulnerable to collapse from high exploitation levels, suggesting that the long-spined sea urchin is more than likely to be vulnerable to overexploitation (Blount & Worthington 2002; Lawrence 2007). Finding the balance between a level of commercial exploitation that maintains a viable fishery, but at a low level is a key challenge in the development and expansion of long-spined urchin fisheries in Australia. Complete collapse of urchin stocks will lead to loss of markets, and risk of the cycle of damage returning with the next large recruitment event.

Abalone abundance was found to be negligible within the heavily grazed barren zone, with moderate density within the adjacent kelp zone. Abalone abundance also increased with increasing distance away from the kelp-barren boundary zone (Figure 15, Figure 16). There are a number of factors that may contribute to this pattern. The most likely primary factors are the absence of sheltering habitat on barrens through loss of overstory kelp species, and the increased visibility of abalone both to fishers and predators. High levels of local exploitation on the long-spined urchin may allow kelp some kelp recovery, and expansion of reef area suitable for abalone at the kelp/barren boundary.

Fine-scale spatial analyses of urchin fishing activity found direct spatial overlap with abalone fishing activity. Across 2014 and 2015 fishing years pooled, around 50% of the urchin fishing activity directly overlapped with abalone fishing activity in those years (Figure 17, Figure 18, Figure 19, Figure 20). The remaining urchin fishing activity that did not directly overlap abalone fishing grounds was however directly adjacent to the abalone fishing areas. The results from the spatial fishery dependent data program combined with the research monitoring of urchin fishing effects on urchin abundance, and the clear negative association between urchins and abalone, indicate that urchin fishing will have clear and demonstrable benefits to the abalone fishery.

Commercial fishers have avoided taking long-spined urchins from barrens areas due to the fact that there is little nutritional benefit from this part of the reef due to grazing effects on the habitat (Byrne et al.1998; Blount & Worthington 2002). Their quality and size of roe is much poorer and not suitable for market – thus divers have a tendency to harvest urchins from the fringe reef or incipient barrens, which is characterised by foliose algae and whereby roe quality and size is increased and colour is preferential (Underwood et al. 1991, Lawrence & Guzmán 2004; Agatsuma 2013). Thereby, reducing the ecosystem gains through the removal of urchins. Reducing competition for habitat and resources through removal of urchins in order to decrease density has however been shown to enhance roe size, colour and quality in wild populations, therefore reducing fishing effort for divers (Williams 2002: James & Heath 2008; Miller & Nolan 2008; Steneck 2013; Blount, Chick & Worthington 2016). A large proportion of long-spined urchin in Tasmanian waters, like the NSW population is unfished due to lack of high quality food in the barrens habitats, therefore resulting in unmarketable roe (Blount, Chick & Worthington 2016). On varying spatial and temporal scales quality, yield and colour of long-spined urchin roe increased after 3 months by removing 33% from barrens habitat, and up to 66% removal can see roe yield and colour increase 212% and 133% respectively after 2 years (Worthington & Blount 2003; Blount, Chick & Worthington 2016). It was recognised that although the quality of the roe did not match that of the long-spined urchin found in the fringe habitats, that the increase in roe quality, yield and colour in the barrens by reducing the densities of individuals was improved to such a level that was suitable for export and market because of the reduced competition for resources (Worthington & Blount 2003).

Like terrestrial systems, productivity can be increased when the species, in this case long-spined urchin is controllably harvested (Branch & Branch 1980; Thomas et al. 1999; Lawrence & Guzmán 2004). The quality of roe determines its market value but is not a feature that is visible to commercial divers during the harvesting process. From investigations on NSW populations of long-spined urchin it was found that the urchins with small TDs and heavier roe had preferential colour for the market but not the granularity or texture that is desired (Blount & Worthington 2002). Habitat types along with physical characteristics have been classified in order to enable the divers to pick the urchins that have the probability of containing the highest market value roe (Blount & Worthington 2002). Market roe is not characterised by the size, but high emphasis is placed on quality, defined by colour, texture and granularity (Blount & Worthington 2002). According to Williams (2002) the demanded by the Japanese market for roe, has called for fishing to commence on “virgin” stock, which would be reflective of Tasmanian long-spined urchin stocks. Increasing Tasmanian commercial harvest could be an immediate solution to increase the amount of urchins that would become harvestable to sell to market, as well as allow some recovery in barrens habitats (Andrew & O’Neill 2000; Lawrence & Guzmán 2004; Johnson et al. 2013; IMAS 2016). Commercial long-spined urchin fisheries would need to be managed in such a way that allows for maximum economic yield, sustaining urchins to a level where fishing can continue to occur (optimal annual productivity) without causing complete collapse (Williams 2002).

Identifying coastline vulnerable to destructive grazing by long-spined urchins

The R based cartographic exposure index (CEI) was only moderately successful as a tool to identify reefs that may be at high risk of destructive grazing by urchins due to their wave and wind climatology and depth strata. The sampling design for the raw data collection by towed-video was more than likely the key limiting factor in this approach, and a much larger base dataset is required to develop a more robust predictive model. Nevertheless, mean Wave based CEI was always higher in non-barren areas and lower in areas where incipient barrens had formed, lending support for the common observations that the depth of urchin barrens locally is dependent on wave exposure. Wind based CEI appeared to be consistent with wave-based CEI, but only for the shallow depths (Figure 22, Figure 23).

Increasing access to productive urchin populations

High abundances of the long-spined sea urchin occur at depths between 10m and 25m. Effective bottom time at these depths is very short, and high catch rates must be experienced for fishing using compressed air at these depths to be economically viable. Use of mixed gas, in particular Nitrox to increase the effective bottom time is a potential solution to enable safe diving at the depths were urchin abundance is highest and facilitate fishing at high catch rates. As well as the ability to access deeper reefs in areas currently fished, Nitrox could open up additional reefs on higher wave energy coastlines which are not currently fished.

There are however limitations in the use of Nitrox for urchin fishing and will require additional training and certification requirements. There are very few retail Nitrox gas providers in Tasmania, which creates some restriction on the potential use and will likely restrict fishing to reef systems within easy access to a Nitrox filling station.

Conclusion

The Tasmanian commercial fishery of long-spined urchin has the potential to lower urchin densities in key reef habitats important the the abalone and rock lobster fisheries (recreational and commercial). There is also the potential for urchin fishing, through reduction in densities to increase roe production and output, and therefore ensure that the industry can remain sustainable and most importantly may promote habitat restoration and preservation. This in-turn benefits the other commercial fisheries by mitigating socioecological, ecological and economic threats through loss of productive reef habitat. Currently 25% of the global abalone wild harvest is supplied by Tasmania valued at AUD $800 million and the Southern Rock Lobster industry is valued at AUD $80 million (ABARE 2004; Johnson et al. 2005; Banks et al. 2010; FRDC 2014; Ling et al. 2015; IMAS 2016; Ling et al. 2016).

This study demonstrated positive benefits for abalone habitat at very-low urchin exploitation levels, with the extent and spatial magnitude of benefits increasing with increasing urchin exploitation. Management strategies to help facilitate increased fishing rates of this problematic species will help in conserving and potentially restoring the broader reef ecosystem (Banks et al. 2007; Ling 2009a; Ling & Jacques 2009). It is unlikely that commercial harvesting will lead to eradication of the long-spined sea urchin, but there is clear potential for commercial fishing to be a primary contributor to mitigating the destructive grazing of this species.

Implications

Low levels of commercial exploitation of the long-spined urchin had demonstrable positive effects on stabilising abundance of this species and can clearly be considered an important tool for mitigating destructive grazing in shallow coastal reef systems. As with many benthic invertebrates subject to commercial exploitation by hand harvesting, the Tasmanian fishery appears to be highly spatially structured. Fine-scale data on urchin fishing pressure is essential to document, quantify and demonstrate the positive effects of urchin fishing on coastal reef systems. Harvest levels need to be increased to the point of spatial serial depletion. Low levels of exploitation evenly spread across fishing grounds are unlikely to have the desired outcome – maintenance of current healthy reefs and recovery of existing barrens areas.

Recommendations

The facilitation of an economically viable long-spined urchin fishery must be a high priority as a tool to mitigate destructive grazing by this species of shallow coastal reefs. The long-term objective is to establish a self-sustaining fishery producing high proportions of high grade roe.

The use of GPS and depth dataloggers in the long-spined urchin fishery should be mandatory. Without access to this data, it will be challenging to determine whether local fishing pressure triggers the target objective of local serial depletion.

The long-spined urchin fishing community will need to work collaboratively to secure a readily available supply of Nitrox gas in close proximity to fishing grounds to provide greater diving safety.

A higher resolution nand updated bathymetric map of the Tasmanian East Coast region (Cape Pillar to Eddystone Point) is required to facilitate a better understanding of the current and future spatial and depth distribution of the long-spined sea urchin.

Repeat surveys of the six research sites established during this project should be conducted in light of the rapid escalation in fishing activity during 2018.

Further development

Further work is required to improve the classification of coastline at risk to incursion by the long-spined sea urchin and subsequent destructive grazing. In particular, a more extensive data set should be acquired using towed-video methods to enable a more robust predictive model to be developed using the depth, wave and wind climate indices;

- If high resolution bathymetry becomes available, the Cartographic Exposure model could be improved by incorporating a depth attenuation coefficient.
-

Extension and Adoption

The results of this project were presented at numerous workshops, industry meetings, and to Government. A summary of the research findings were presented at the DPIPWE convened Centrostephanus workshop held in Hobart in December 2018.

A group of long-spined urchin divers have invested in a Nitrox membrane compressor system, and have commenced fishing along the lines of Option 2 (Box 4)

DPIPWE have funded the purchase of additional GPS and Depth dataloggers to enable complete coverage of the long-spined urchin fishing sector.

Support for the long-spined urchin fishery is increasing. In 2018 and 2019 this included a subsidy to fishers to encourage higher levels of fishing and to kick-start a long-spined urchin roe export market.

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