Trial of an industry implemented, spatially discrete eradication/control program for *Centrostephanus rodgersii* in Tasmania

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Executive Summary

Background

Over the past few decades, the distribution of the long-spined sea urchin, *Centrostephanus rodgersii* has expanded southwards from southern New South Wales, through Eastern Victoria, the Bass Strait Islands and down the east coast of Tasmania. In some areas of the *C. rodgersii* distribution in Tasmania abundance has increased substantially and the species has established in sufficient densities to form destructive grazing aggregations, removing the overstory macroalgae that are essential component of a healthy reef ecosystem. The degradation of these coastal reef systems has serious implication not only to biodiversity conservation and ecosystem value, but also to high value fisheries, with the potential to significantly compromise sustainable fisheries management practices.

A large body of work over the last ten years has investigated the mechanisms underpinning the range expansion of *C. rodgersii* 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 and more recently in Eastern Victoria. These two studies suggest different behavioural patterns of urchins leading to different process of barren formation. In Victoria, extensive barrens appear to be forming as urchins migrate from deep to shallow water, creating a 'feeding front'. In New South Wales, barren formation appears to be more discrete, with development of incipient barrens which transition into smaller and then larger barrens. The latter pattern is more consistent with observations in Tasmania to date.

Aims

This project aims to test the effectiveness of systematic culling in discrete areas as a strategy to reduce the density of *C. rodgersii* to minimise the potential for destructive over grazing, and secondly provide an estimate of the cost of culling areas of reef on the east coast of Tasmania. The culling experiment was conducted by the Institute for Marine and Antarctic Studies and the Tasmanian commercial and Abalone dive industries in 2011/12.

Methodology

To test the effectiveness of culling in discrete area the project applied an experimental design utilising multiple treatment ($n = 8$) and control plots ($n = 4$), each 1,500 m^2. These plots were assessed using a combination of randomised belt transects and census counts. An initial baseline survey was conducted by staff of the Institute for Marine and Antarctic Studies, followed closely by systematic culling in each of the eight treatment plots by members of the Tasmanian Abalone and commercial dive industries, under the direction of IMAS staff. Approximately two weeks post-culling the density of *C. rodgersii* within the eight treatment and four control plots was assessed using randomised belt transects, followed immediately by a second systematic cull within four of the treatment plots. Approximately 12 months after the

initial culling exercise the density of *C. rodgersii* in all 12 plots was re-assessed using randomised belt transects, and the eight treatment plots further assessed by a systematic census count.

Two bio-economic models were developed to determine the cost of culling areas across the east coast of Tasmania, as well as sub-areas (case study areas). The models were developed based on information on the cost of employing commercial divers to cull areas of reef down to 20 m, beyond which dive times were considered a limitation to implement a cost-effective culling program. Divers were asked to provide information on the amount of 'bottom time' (dive time) they would spend at a range of depths (< 20 m). These costing estimates were provided for both small trailer boats as well as larger motherships. Information gathered during the systematic culling exercise in Wineglass Bay facilitated estimates of culling rates as a function of urchin density as well as the effectiveness of culling based on urchin density. Finally the area of reef on the east coast of Tasmania (and sub-areas of) were provided by previous bathymetric and habitat mapping of the east coast of Tasmania. This information was combined to provide a coarse cost of culling across the east coast of Tasmania and at the scale of existing abalone management zones (Model I) and secondly for discrete reef areas (Model II). A major limitation of both models was a lack of contemporary data on urchin density along the coast.

Results

Systematic culling of *Centrostephanus rodgersii* in spatially discrete plots in Wineglass Bay on the east coast of Tasmania was highly successful with average urchin density reduced from 1.51 to 0.13 urchin.m^{-2} within treatment plots when assessed approximately one year post-culling. Systematic culling was also effective at significantly reducing the patchiness of urchin distribution, where high abundance patches are, in theory, more likely to destructively over graze a reef area. A total of eight treatment plots were culled equating to 12,000 m^2. The culled areas were typical of "incipient barrens" habitat. Four treatment plots were culled twice and the reduction in urchin abundance compared with the other four plots that were only culled once. The result was that there was no significant difference in the reduction of *C. rodgersii* between the single and multiple cull treatments. There was some evidence of *C. rodgersii* migrating into the culled plot areas with a significant edge effect adjacent to the along shore and deeper edges of the culled areas. We found that the culling efficiency of divers in relation to urchin density is similar to natural predatory responses with culling more efficient at higher densities – following a significant Holling's type response.

The cost of manually controlling an invasive species in the marine environment is inherently expensive due to the costs associated with mobilising logistics to a target area, and secondly the limitations of diver time in the water. In this report we present models that can be used to generate cost estimates to cull a given area based on urchin density and dive depth, with the maximum depth chosen having a great effect on the overall cost. A local scale model estimates the maximum cost to cull Wineglass Bay to a depth of 20 m at $1,617,802, based on a constant density estimate of 1.5 urchins.m^{-2}. The cost to cull reef areas within Fortescue Bay to a maximum of 20 m using the same model at $877,019 based on a constant density of 0.29

urchins.m^{-2}. Cost examples are also presented for two hypothetical case study areas. The first, Maria Island MPA and the second Acteons reef complex (both to a maximum depth of 20 m), while neither of these locations have *C. rodgersii* at a density that would be considered a concern, they are both high value areas in their own right, the former for biodiversity conservation while the latter has high industrial value (abalone fishery). The hypothetical examples explore the cost of culling these areas based on a hypothetical recruitment event resulting in an average urchin density of 0.5 urchins.m^{-2}. The costs were estimated as $1,959,359 for the Maria Island MPA and $23,582,183 for the Acteons reef complex.

The potential cost of not controlling over-grazing by *C. rodgersii* is likely to be significant for commercial, recreational and customary harvests. In NSW, where *C. rodgersii* are endemic, it is estimated that 50% of nearshore reef habitat has been lost, negatively affecting all benthic species that inhabit these areas including abalone.

Implications for relevant stakeholders

The implications of *C. rodgersii* overgrazing in Tasmania are expected to be significant, with evidence from NSW suggesting that up to 50% of nearshore reef habitat has been denuded by the species. Climate change projections indicate that the environmental conditions along the east coast of Tasmania will become increasing favourable for *C. rodgersii*. The effects of loss of reef habitat not only compromise the maintenance of healthy ecosystems and nearshore reef biodiversity in Tasmania, but also some of the largest, by revenue, fisheries in Australia, namely the Tasmanian Abalone and Southern Rock Lobster fisheries.

Minimising the probability of barren habitats transitioning from 'incipient' to 'extensive' is widely accepted as the priority for urchin management. It is highly unlikely that *C. rodgersii* will be eradicated from Tasmania, now that it is well established and as environmental conditions become increasingly favourable.

Contemporary research has indicated that a multi-faceted approach to minimise the density of urchins is the most likely management strategy to reduce the probability of transition between urchin barrens states. The control measures being considered include enhancement of natural predation to act on a broad spatial scale (entire coast), translocation of natural predators to target areas to act on a medium scale (areas of coast), and culling or harvesting to reduce density at a fine spatial scale (specific reefs or embayments). This report shows that systematic culling can significantly reduce the density of *C. rodgersii* in discrete areas. The implications of these findings are that culling can be considered a viable method in the management strategy evaluation of controlling the deleterious effects of *C. rodgersii.* The costing models provide tools to estimate the direct cost of implementing a culling strategy at a range of spatial scales across the east coast and can be manipulated to provide a bio-geographically accurate estimate of cost depending on the area (and size of area) selected.

These results are an important addition to the suite of information available to managers, with the potential implications of the use of this information being broad as the effects of *C. rodgersii* are currently an 'all of ecosystem' issue for coastal reef systems in Tasmania.

Recommendations

One of the primary limiting factors when considering whether to implement a culling program is an accurate and contemporary assessment of depth stratified urchin density data from key areas along the east coast of Tasmania. The last broad assessment, which would be considered the most comprehensive baseline survey to date, was in 2002. This knowledge gap is also of relevance to monitoring the effectiveness of other control methods, e.g. natural predation of large rock lobsters; developing new fisheries, e.g. the burgeoning *C. rodgersii* fishery on the east coast of Tasmania; and ultimately understanding the impacts of the range extension of *C. rodgersii* in Tasmania. An ongoing monitoring program that assesses both urchin density as well as the extent of both incipient and extensive urchin barren habitat on the east and southeast coast of Tasmania would address this knowledge gap.

Keywords

Invasive species, non-indigenous species, regime shift, phase shift, climate change, range expansion, temperate rocky reefs, kelp beds, sea urchin barrens, grazing, culling, population expansion control

Introduction

Invasive species constitute one of the greatest drivers for global biodiversity loss (Vitousek et al. 1996; Walker & Steffen 1997; IUCN 2000; Sala et al. 2000), and it is expected that the incidence of invasive species will increase with ongoing globalization (Mack et al. 2000). Not all migrants, however, whether they are introduced non-indigenous species or species that shift or expand their range are considered 'invasive', with this term reserved for those with a propensity to cause damage in their new environment and threaten native biota (IUCN 2000; Allendorf & Lundquist 2003). It is challenging to determine whether newly arriving species will become invasive or not, but a commonality is that if it can have deleterious effects within its native range, it is highly likely that such traits will be transferred to its new environment, particularly if the general ecosystem state is similar (Daehler & Gordon 1997; Allendorf & Lundquist 2003).

Biological invasions are most commonly associated with species that have been introduced from distant areas, often termed "non-natives". Another form of biological invasion stems from the range expansion of species from adjacent regions –climate-driven range expansions of indigenous species have been reported globally (Perry et al. 2005; IPCC 2007; Sorte et al. 2011; Last et al. 2011; Rius et al. 2014). In the marine realm, ocean warming has shifted the geographic location of thermal barriers, enabling species to move into, and ultimately reproduce in previously unsuitable regions (Dukes 2011; Rius et al. 2014).

Several species of sea urchins have demonstrated the propensity to significantly re-engineer coastal marine ecosystems worldwide. These herbivorous invertebrates have been reported globally to drive phase shifts from species rich kelp bed communities to sea urchin barrens relatively devoid of biodiversity (see reviews in: Filbee-Dexter & Scheibling 2014; Ling et al. 2015). Urchins will also displace and compete with other herbivorous invertebrates, including some important fishery resources (Pearse 2006; Strain et al. 2013). For example, the formation of urchin barrens in Tasmania, Australia threaten the productivity of the largest abalone fishery in the world, which supplies ~25% of the global wild harvest market.

In many cases, trophic cascades attributed to depletion of reef predators by fishing have been blamed for kelp bed overgrazing by sea urchins, including examples from Alaska (Watson & Estes 2011), East Africa (McClanahan 2000), eastern Canada (Hagan & Mann 1992), New Zealand (Shears & Babcock 2003) and Australia (Pederson & Johnson 2006; Ling et al. 2009a). The lack of natural predation on sea urchins facilitates the building of extreme abundances which leads to these species becoming "invasive" in their own native range - a term referred to as a "native invader" (Simberloff 2011).

In Australia, the long-spined sea urchin (*Centrostephanus rodgersii*) is endemic to the warm-temperate waters of New South Wales (Hill et al. 2003) and is also found in New Zealand (Banks et al. 2010). It has been estimated that as much as 50% of the nearshore reef area in NSW has been converted to barren habitat by grazing of *C. rodgersii* (Andrew & O'Neil 2000). Again it has been suggested that this native species has taken on destructive characteristics following the sustained

depletion of reef predators, including spiny lobster (*Jasus verreauxi*) and blue groper (*Achoerodus viridis*) (reviewed by Andrew and Byrne 2001).

The climate change driven extension of the East Australian Current has facilitated larval dispersal of *C. rodgersii* from NSW, across a 650 km aquatic barrier to the island state of Tasmania (Ling et al. 2009b). The waters adjacent to southeast Australia, including Tasmania are considered an ocean warming hotspot (Poloczanska et al. 2007; Hobday & Pecl 2013; Frusher et al. 2013) and are experiencing an increase in annual mean ocean temperature in the order of four times the global ocean average (Ridgway 2007). This warming coincides with reports of polewards range extension for several species in the region (Poloczanska et al. 2007; Last et al. 2011). The historically cooler waters of eastern Tasmania are now regularly above the thermal tolerance threshold for *C. rodgersii* larval development enabling viable reproductive populations of the sea urchin to be established (Ling et al. 2008, 2009b). Despite the wide distribution of *C. rodgersii* along the east coast of Tasmania, the effects of destructive grazing are not as advanced and widespread as in NSW. While "incipient barrens", small denuded patches of reef (> 10 m^2), are observed over large sections of the coast (Johnson et al. 2011), with only relatively restricted areas considered as "extensive barrens", i.e. bare areas of reef following sea urchin destructive grazing over 10 m^2-100 ha - as typically seen in NSW. While restoration of kelp beds on incipient barrens is possible if sea urchin density are kept low over ~18 months, the shift to extensive barren results in the persistent loss of habitat, productivity and species diversity and is difficult and expensive to reverse (Ling 2008; Ling et al. 2009a; Marzloff et al. 2013).

There is extensive literature dedicated to the study of biological invasions, including frameworks for control, mitigation or eradication (Simberloff 2003; Allendorf & Lundquist 2003 and reference therein). It is widely agreed that 'prevention is better than cure' (IUCN 2000), however the reality is that invasive species are often not recognized as being problematic before it is too late to avoid infestation (Allendorf & Lundquist 2003; Park 2004). The incursion of *C. rodgersii* into Tasmanian waters was first identified over 40 years ago and via a sustained shift in oceanographic conditions (Johnson et al. 2011), the broad regional scale of infestation means that targeted species eradication is not viable.

It is not too late however, to reduce the risk of extensive barrens developing from incipient barrens or from intact kelp beds (Ling et al. 2015). In order to minimise extensive barrens, the density of urchins needs to be reduced below a threshold so that the effects of the population grazing do not have an ecosystem level effect. To achieve this, a multi-faceted approach has been proposed (Johnson et al. 2014).

Given the broad distribution of *C. rodgersii* and changing environmental conditions expected to further facilitate establishment and persistence of their population in Tasmania into the future (Ling et al. 2008, 2009b), the most effective method proposed to reduce the abundance and likelihood of barrens formation across the entire range is natural predation (Ling et al. 2009a; Johnson et al. 2014). Although many reef species predate upon urchins, only a few sea urchin predators feed with sufficient intensity to affect population density (Guidetti et al. 2005; Guidetti

2006). Effective predators in temperate areas include lobsters (Pederson & Johnson, 2006; Ling et al. 2009a) and reef fishes such as sparids (Shears & Babcock, 2003), and labrids (Andrew 1993).

The geographic extent and depth range of *C. rodgersii* along the Tasmanian East Coast create substantial difficulties for implementation of direct action control of urchin density. The Southern Rock Lobster (*Jasus edwardsii*) is endemic to southeast Australian waters and large specimens have been identified as a key natural predator to *C. rodgersii* in Tasmania (Ling et al. 2009a; Ling & Johnson 2012). In recent years the abundance of lobsters on the east coast of Tasmania has become supressed by poor recruitment and furthermore the abundance of large lobsters is affected by a significant fishery for the species. The recent adoption of a spatial catch restriction will allow the east coast rock lobster stock to rebuild. The subsequent increase in natural predation on the urchin is predicted to significantly reduce the probability of extensive barren formation (Johnson et al. 2014). To further enhance urchin control at a local scale, translocation of large rock lobster to specific areas and low intensity urchin culling by commercial divers while they harvest abalone is also being trialled (Johnson et al. 2014). Finally intense systematic culling of *C. rodgersii*, the focus of this paper, is also considered as an alternative urchin control intervention in discrete localised areas of either high ecological or commercial importance.

Removal of invasive species is undertaken in a broad range of cases across terrestrial and marine ecosystems (Park 2004; Ellis & Elphick 2007). The method of removal can vary from capture and re-location to *in situ* extermination, with the appropriate methodology based on a range of ecological, economic and ethical considerations (Park 2004; Ellis & Elphick 2007). More recently, augmentative biocontrol of invasive species is being explored as a cost-effective and environmentally forgiving control option (Atalah et al. 2013). Given the high economic costs associated with invasive species control methods, particularly for sub-tidal pests, it is paramount that any proposed response program has a high chance of succeeding if implemented. In light of this, the objective of this study was to explore the effectiveness of systematic in situ extermination (hereafter culling) of *C. rodgersii* in spatially discrete areas on the east coast of Tasmania. The cost effectiveness of this approach has important consequences for impending decisions and actions in response to this climate-driven invasive species; and in particular the biogenic habitat-formers and broader benthic assemblages inhabiting a shallow, rapidly warming coastal marine environment.

Objectives

1. Determine the effectiveness of divers physically destroying urchins in situ to either eradicate or control spatially discrete aggregations to allow the re-establishment of native flora and fauna

2. Determine the cost effectiveness of objective 1 in regard to lost production for commercial, recreational and customary harvests.

Methodology

Study Area

Wineglass Bay, an iconic embayment on the East Coast of Tasmania, Australia and the immediate coastline extending north and south of this bay provided the location for this research (Fig. 1). The benthic habitats of this region are typified by fringing rocky reef composed of high-relief granite boulders that generally extended to the sand edge in 20 meters water depth, but in some areas down to 40 meters. The 0 – 5m depth range is dominated by *Phyllospora comosa* (Fucales) (50 – 90 % cover), with lesser amounts of *Ecklonia radiata* (Laminariales) (20-40% cover) and *Durvillaea potatorum* (Fucales) (0 – 10 % cover). From 10 – 40 m, *E. radiata* was the dominant algal species, with lesser amounts of *Caulerpa sp* (Bryopsidales) and foliose red algae from 10 –30 m. Sessile sponge abundance increased from 25 m and was the dominant biota below 35 m (Lucieer et al. 2007). The reef areas surveyed within Wineglass Bay are typical of incipient barrens where most sites exhibited dense foliose algae intermittently dispersed with grazed understorey and irregular denuded patches of 1-10 m^2.
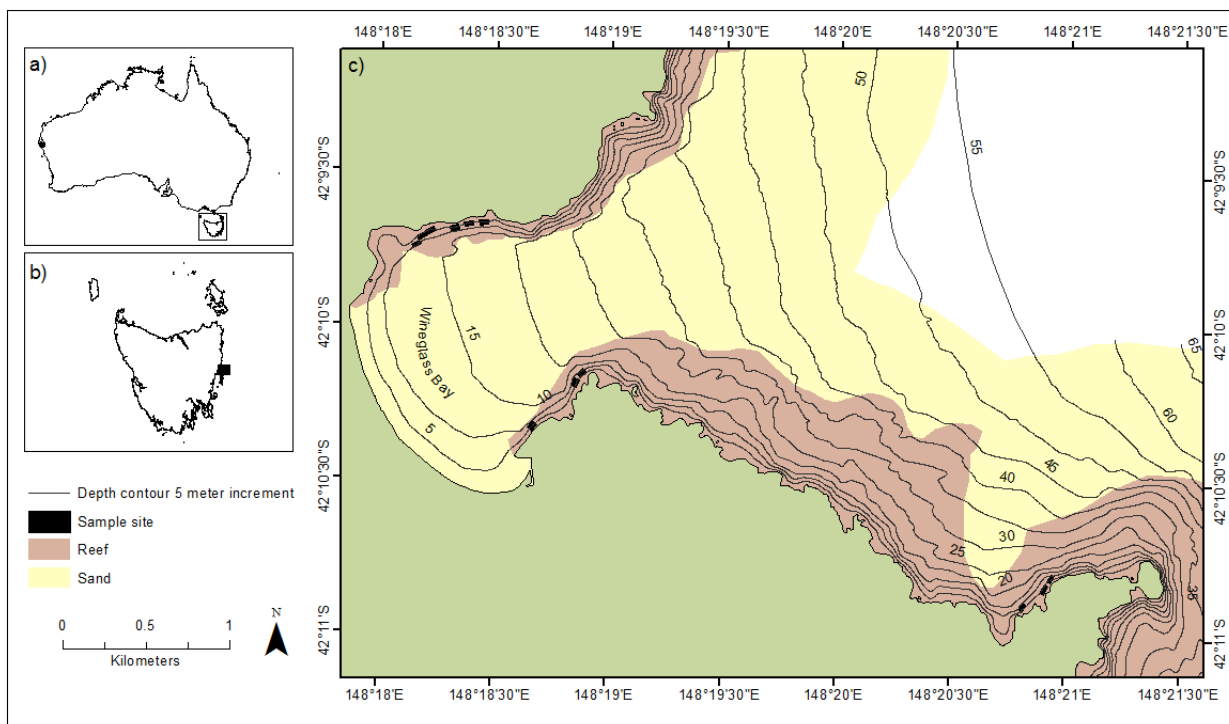
Figure 1. Map illustrating the study area in Wineglass Bay, Tasmania, Australia, including details of bathymetry and habitat structure. Survey plots are shown as black rectangles.

Replicate treatment and control plots were randomly assigned across four locations of continuous boulder reefs in Wineglass Bay (Fig. 1). There were three levels of treatment assigned within each location – two levels of culling treatment and a non-cull control. The first treatment involved a single, systematic cull of all visible *C. rodgersii*; Treatment two involved an initial cull of all visible *C. rodgersii* (as per the single cull) plus a second systematic cull approximately two weeks after the initial cull.

Each fixed plot was 50 m long x 30 m wide, with the long axis (centre line) parallel to the shoreline. To facilitate accurate geo-location of each site, stainless steel pins were fixed in place at each end of the centre line by drilling stainless wall plugs into the granite boulders. Sub-surface buoys were attached to the pins and their location recorded using a GPS. The removable centre line was then re-established on each sampling occasion. For the duration of each sampling occasion the centre line functioned as a baseline for transect counts, and for establishing a grid for contiguous quadrat surveys within each plot.

Initial baseline transect survey

In August 2012, prior to the commencement of the culling treatments, all plots were surveyed using belt transects. Eight 10 x 1 m transects were nested within each plot and surveyed perpendicular to the plot centre line. The plot size for the belt transect surveys was reduced to 50 x 20 m to remove any edge effects along deep/shallow margins. The position and direction of each transect (nested within plot) was randomized along the centre line. All visible live *C. rodgersii* were counted within each transect. Transect counts were then averaged within each plot to provide an overall estimate of abundance and density within each replicate plot.

Initial cull

The initial cull was conducted on the 2nd – 4th October 2012. A systematic cull treatment was achieved by dividing each plot into 15 x 2.5 m belt transects running perpendicular to the centreline (both sides) using lead core rope. Each band was further divided to create a series of contiguous quadrats (5 x 2.5 m) with each five meter increment identified by paint marks on the lead core ropes. All observed *C. rodgersii* were culled using a tool to crack the sea urchin test, and tallied within each quadrat. The time taken to cull each 15 x 2.5 m band was recorded to provide an estimate of the culling rate per diver (urchins culled.min^{-1}). The systematic culling across space and the spatially resolved cull rates therefore provided a census of observable urchin abundance within each plot.

Day after initial cull

Approximately 24 hours after culling three plots were re-visited opportunistically and a census count of live and intact urchins occurring in all contiguous quadrats was conducted. This census enabled the culling efficiency of the single culling treatment to be assessed.

Secondary cull

The additional cull for the multiple cull treatment was conducted on the 13th-14th October 2012 (approximately 10 days after the initial cull) using the same methodology as for the initial cull. All 12 replicate plots were also re-surveyed using the modified belt transect approach described for the baseline survey.

Final survey – One year post the initial cull event

Approximately 12 months after the initial cull (21st-23rd September 2013) a systematic census of all *C. rodgersii* occurring in each 5 m x 2.5 m quadrat within all eight treatment plots was conducted. All 12 plots were again re-surveyed using the modified belt transect approach described for the baseline survey.

Statistical analysis

Comparison between treatments and survey periods

The effectiveness of the urchin culling on *C. rodgersii* density was examined using a two-way fixed effects ANOVA of the factors Treatment (3 levels: 'SingleCull', 'DoubleCull', "No-Cull Control') and Period (3 levels: 'Before', 'Immediately After', and 'One year after' the initial cull). Specific significant differences were identified using a Tukey's Honest Significant Difference test. Box Cox transformation of $y^{0.3}$ was required to satisfy model assumptions of normality and homoscedasticity. Data used in this analysis were urchins.m^{-2} obtained from the replicated belt transect surveys.

Effects of culling on sea urchin spatial patterns

To examine the effects of Single and Double Cull treatments on spatial patterns in urchin abundance, a nested ANOVA was used to test the effects of Treatment, Plots (nested within Treatment), and Transects (nested within Plots and Treatment) at the *a priori* times of interest 'Before culling' and 'One year after culling'. A Box Cox power transformation of $y^{0.25}$ was applied to the data. This transformation satisfied model assumptions of normality and homoscedasticity. Data used in this analysis were urchins.m^{-2} obtained from the contiguous quadrat surveys.

Efficiency of culling

To assess culling efficiency, we estimated sea urchin density before the cull by adding the number of culled urchins during the initial cull treatment to the remaining urchin numbers 24 hours later in each of the 5 x 2.5 m quadrats (100 quadrats re-surveyed). We investigated culling efficiency (proportion of the standing density culled) as a function of sea urchin population density. Culling efficiency was also examined in terms of cull rate across the whole dataset using culled number per quadrat as a proxy for sea urchin density. Holling type I, II and III functional responses (Holling 1965) were fitted to culling efficiency and culling rate (as a function of sea urchin density using the nls function of the R language for statistical computing, version 2.12 (R Development Core Team 2010). Akaike Information Criterion (AIC), corrected AIC (AICc) and Bayesian Information Criterion (BIC) were computed to assess the relative quality of the alternative models (Burnham & Anderson 2004).

Edge effect of abundance one year post culling

A negative binomial Generalized Linear Model was used to compare urchin density in the contiguous quadrats at the edge of each replicate plot to those in the centre of the plot for both

treatment types. This analysis was restricted to the surveys 'immediately after' and 'one year after' the initial cull to investigate whether urchins were re-populating the plots from adjacent habitat. A negative binomial regression was chosen over a Poisson regression due to over dispersion of the data; the model choice was supported on the basis of a highly significant (χ^2 = 2,025; p<< 0.0001) likelihood ratio test when compared to the Poisson regression. Each quadrat within a plot was coded as being on the shallow boundary, deep boundary, longitudinal boundary or interior to the plot. An interaction term between the plot and the time since culling was included to account for plot and time specific density variations.

Bio-economic model

Two bio-economic models are presented here. The first builds on the 'urchin culling' scenario of a previous bio-economic study (Tisdell et al. 2011) which provided a direct cost analysis of alternative strategies for managing long-spined sea urchins off the east coast of Tasmania using Abalone management blocks as spatial boundaries. As culling effort is restricted with increasing depth, and culling rate is dependent on urchin density, a second model was developed using similar input parameters to the first model but includes a range of cull rates based on depth and urchin density. The second model is applied at a small spatial scale where detailed information is available – case examples including Wineglass Bay and Fortescue Bay as well as hypothetical examples if settlement of *C. rodgersii* occurred in the Maria Island Marine Reserve and the Acteon Reef complex.

Model I

Cost-effectiveness studies involve setting a target and then calculating the cost of alternative strategies for achieving that target. In that light this study makes initial estimates of the costs associated with reducing the population density of urchins from those found in the study of Johnson et al. (2005) and IMAS (2011) to a target level of 0.1 urchins m^{-2}, assuming all other factors are held constant. For abalone reporting blocks south of the eastern shoreline of the Tasman Peninsula (blocks 21 - 13), the urchin density was assumed to be below the target density of 0.1 urchins m^{-2}.

This work extends the original study (Tisdell et al. 2011) by including the cost data generated from interviews with commercial divers in Tasmania, cost data from the culling activity in Wineglass Bay and cost data from similar culling activities in Victoria. The model updates include (1) estimates of the cost of culling based on both Tasmanian and Victorian costings; (2) more detailed cost estimates of day trips; (3) mother ship costing; and (4) more detailed dive time estimates. These estimates have been included in the calculations of the relative cost for each Abalone management zones on the east coast of Tasmania (zones 13 – 30).

The model estimates the abundance of urchins within each abalone management zone as the area of reef (0 – 10 m and 0 – 20 m) multiplied by the reported urchin density (urchin m^2). The model then calculates the number of days required to reduce the urchin density within each management zone to the target density based on reported cull rates before converting to a cost

by multiplying the number of days required by the average daily cost (both Victorian and Tasmanian quoted costings), assuming incipient barren cull rates.

The model is based on several assumptions - constant marginal cost of culling in relation to urchin density, zero natural population change (recruitment), and urchin density is spatially homogenous within blocks. These assumptions are expanded on below:

Constant marginal cost of culling in relation to urchin density

The first assumption is that the marginal cost of culling an urchin is constant regardless of density. As the density of urchins declines so the marginal cost of harvest or culling would increase at an increasing rate. It should be noted that it is highly likely that the cost will increase in this manner in the culling of urchins across the barrens but data limitations did not allow for the relationship to be accurately estimated. As a result, a constant marginal cost was used. The stability of this assumption depends on the nature of culling and the range of density change required. If the method of culling involves systematically moving across the incipient barrens then the density could be assumed constant. Second, if the range of change is small (the difference between density and target) then the rate of change in the marginal cost may not be significant enough to change the relativities of policy options. Nonetheless, better estimates of non-linear marginal cost functions are required and caution should be applied when applying the findings to eradicating urchins in extreme (low or high) density areas.

Zero natural population change and constant rate of predation

The model does not explicitly encapsulate changes in urchin populations through time. Natural processes of recruitment and predation have not been considered. Anecdotally, recruitment of urchins occurs once every seven to ten years which can be used to gauge the effectiveness of different management options. These natural processes and predation rates may influence the costs associated with culling urchins and the time taken to achieve target levels and need to be considered in deliberations on policy options.

Urchin density and target

The study uses available research data and assumed urchin densities where data is lacking. No state-wide data on density exists at this time. Johnson et al. (2005) conducted a transect survey of urchin density in a number of blocks across the east coast of Tasmania. Their study sites included blocks 22-24 and 27-30. For these sites the cost effectiveness study used their estimated density. For those sites for which there was no estimate of urchin density, a default density of 0.15 was assumed. This report adopted a target urchin density of 0.1 urchins m^{-2} used in previous analyses by IMAS in reporting to DPIPWE (IMAS, 2011).

Depth band

The majority of abalone catch and effort occurs in less than 10 metres of water (~ 85%) (Tarbath & Gardner 2011) while urchin populations extend into much deeper waters. Much debate exists

concerning the merits of considering the costs associated with culling below 10 metres. This study reports the cost of removing urchins in waters less than 10 metres deep, given this is where the majority of potential lost abalone yield is concentrated. The option of considering the costs at < 20 metres is also included for consideration. This model assumes an average dive time of three hours per day irrelevant of depth.

Model II

This model provides information for management consideration at a fine scale, where target areas can potentially be selected based on the prioritization of stakeholder groups and with consideration of not culling areas that may be preferred by the *C. rodgersii* harvest industry. This format is complementary to the concept of urchin culling being used in small discrete areas as part of the broader, multi-faceted approach and is an appropriate scale of applying culling as recommended by this report and others (Johnson et al. 2014).

This model estimates a cost to systematically cull a given area of reef based on depth stratified urchin density within incipient barrens. The model was generated based on data collected on cull rates as a function of urchin density during the Wineglass Bay culling experiment. Given the systematic culling approach, the time taken to cull a given area based on urchin density could be calculated. This data was then integrated with estimates of depth stratified daily dive times collected from interviews with commercial divers that participated in the culling exercise. Specifically, the divers were asked their maximum dive time per day at 5, 9, 12, 15, 20 m depth. Combining this information provided a model surface of the area that could be culled per day as a function of depth and urchin density. The per day diver cost was then multiplied by the estimated area culled per day to provide a daily estimate of cost to systematically cull a reef (assuming an incipient barren state).

Four case study areas were chosen to apply the costing model. Wineglass Bay and Fortescue Bay both have contemporary estimates of *C. rodgersii* density. Maria Island Marine Reserve and the Acteon reef area do not currently have high densities of urchins, with no reported *C. rodgersii* on the latter. Both these areas, however, are of high value, the first in terms of marine biodiversity conservation and the second from an abalone fishery perspective. For these two areas a hypothetical scenario was created based on potential future settlement events in these areas, with an arbitrary, and constant, estimate of density applied at 0.5 urchins m^{-2}.

This model is also subject to the assumption of zero natural population change and constant rate of predation and provides an upper estimate of costing as all cull area calculations are performed on the deepest depth per depth range category. A final assumption is that the average density (whether stratified by depth) is spatially constant, hence not accounting for heterogeneity in urchin distribution.

Results

Culling trial in Wineglass Bay

The average density of *C. rodgersii* between replicate plots during the baseline survey ranged from 0.88 – 2.38 urchins.m^{-2} (mean = 1.51 urchins.m^{-2}). The highest densities were found in treatment plots 1 – 4 and 7.

A total of 15,166 urchins were destroyed during the initial culling exercise, which was carried out by 10 divers over three days and a total of 35.13 hours of culling effort. This equated to an average culling rate per diver of 7.0 urchins/min ± 0.4 SE (Table 1).

Table 1. The effort and associated number of urchins culled and associated cull rate. Noting that the hours of culling effort represents only the dive time associated directly with culling, excluding time taken to set up systematic culling lanes and dive safety stops.

Date	Number of divers	Hours of culling effort	Number of urchins culled	Cull rate (urchins/diver/min)
2/10/12	10	15.25	6887	7.5
3/10/12	10	14.87	6417	7.2
4/10/12	10	5.01	1862	6.2
Totals	30	35.13	15,166	Mean = 7.0

Culling efficiency (i.e. proportion of the urchin population culled) increased as urchin density increased up to ~one urchin.m^{-2} before reaching a plateau with > 90% of the urchin population culled for densities higher than one urchin.m^{-2} (Fig. 2). Culling efficiency significantly follows Holling functional responses (Table 2), in particular the type III response (Fig 2; Table 2).

Sea urchin cull rate increases linearly from 0 to 10 individuals per minute as urchin density builds from zero to ~ two urchins.m^{-2} (Fig. 3). Cull rates then plateau at around 10 individuals per minute for urchin density > two urchins.m^{-2}. Note, that while cull rate significantly follows Holling functional responses as a function of sea urchin density (Table 2) the spread of values around the mean increases with urchin density: for instance, at high sea urchin densities (> 2 urchins.m^{-2}), cull rates vary greatly between a minimum of 5 and a maximum of 14 individuals per minute. This suggests that factors other than sea urchin density influence divers' cull rates. Note that all divers demonstrated the same variability in culling efficiency with the exception of one diver, out of the 10 divers in total; this diver consistently misreported dive times and was thus removed from this data set as a clear outlier.

Table 2. Summary statistics for the 3 Holling type functional responses fitted to the culling efficiency (expressed either as proportion of sea urchin population culled, or as a cull rate; sea urchin individuals per diver per minute), or as a function of sea urchin density. Each Holling type functional responses can be defined with two parameter estimates (β and β'), βCR the culling efficiency (either proportion culled or cull rate; cf. 1st column) and N sea urchin density (individual. m^{-2}): Type I as: βCR = minimum of β N, or β'; Type II as: $\beta CR = \beta$ N / (1 + β' N); Type III as: $\beta CR = \beta$ N2 / (1 + β' N2). Data from 100 re-surveyed 2.5 m × 15 m quadrats. Models were fitted using the 'nls' function of the R software. The stars next to the parameters of the Holling type 1 functional response (β *; β' **) reflects that a 'broken-stick' regression was performed by splitting the data into two groups of data points with sea urchin densities respectively higher or lower than 1 individual. m^{-2}: β * statistics from a linear regression on the points associated with sea urchin densities < 1 individual per square metre; β' ** mean estimate and standard error are defined as mean and standard error of the mean of the points associated with urchin densities ≥ = 1 individual per square metre.

Response variable	Function	Parameter	Estimate	Std. error	t	Pr (>/t/)	df	RSE	AIC	AICc	BIC
Proportion culled	Type I	β *	1.085	0.045	24.0	2×10^{-16}	46	0.21	-10.2	-10.1	-6.5
		β' **	0.937	8.6×10^{-3}	-	-					
Proportion culled	Type II	β	3.21	0.39	8.2	1×10^{-12}	98	0.14	-105.6	-105.4	-97.7
		β'	2.73	0.44	6.3	9×10^{-9}					
Proportion culled	Type III	β	9.17	1.22	7.5	1×10^{-11}	98	0.13	-126.7	-126.6	-118.9
		β'	9.24	1.35	6.8	7×10^{-10}					
Cull rate	Type I	β *	11.9	1.4	8.8	7.2×10^{-11}	40	5.71	262.4	262.5	265.8
		β' **	9.06	0.69	-	-					
Cull rate	Type II	β	28.3	13.3	2.1	0.036	89	5.5	572.4	572.5	579.9
		β'	2.34	1.47	1.6	0.12					
Cull rate	Type III	β	69.7	36.9	1.9	0.063	89	5.4	568.9	569.0	576.5
		β'	6.8	4.0	1.7	0.095					
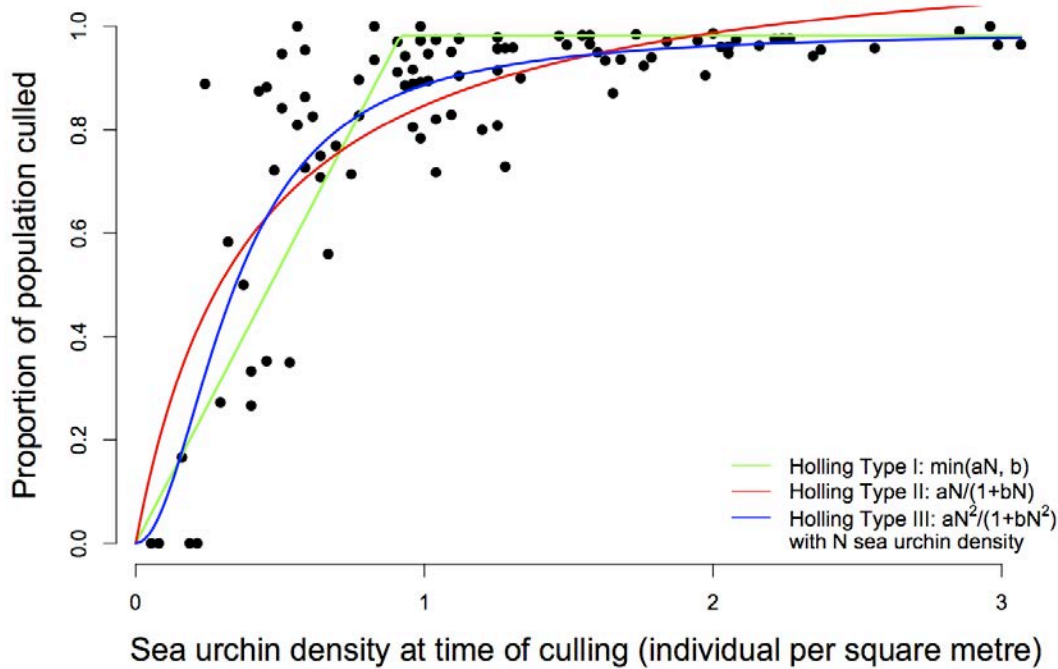
Figure 2. Culling efficiency, expressed as the proportion of the urchin population culled, as a function of sea urchin density at time of culling. Holling type I (green line), II (red line) and III (blue line) functional responses were fitted to culling efficiency information available from the 100 quadrats re-surveyed the day following the culling experiment (black points).
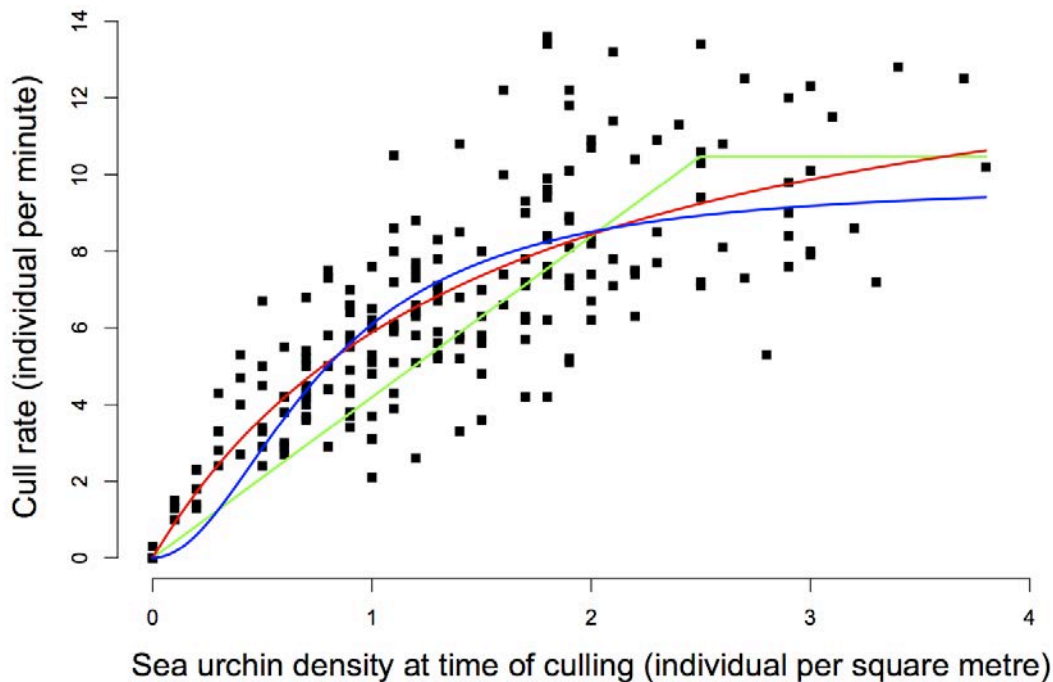
Figure 3. Culling efficiency, expressed in terms of cull rate (individual culled per minute), as a function of sea urchin density at time of culling. Holling type I (green line), II (red line) and III (blue line) functional responses were fitted to culling efficiency information available from the 100 quadrats re-surveyed the day following the culling experiment (black points).

The census counts reflected the variability in urchin density between plots reported from the baseline survey for all but one plot. Plot 7 produced a significantly lower abundance count during

the census, it is possible that some urchins may have been removed from this area between the baseline survey and the cull by the commercial fishery, there is also evidence that urchins may have been removed from control plot 11, which was located directly adjacent to treatment plot 7 (Fig. 4). For five of the eight treatment plots the census count was within the standard error of the baseline survey estimates (Plots 1, 2, 3, 5 and 6), providing confidence that the modified belt transect method is reasonably robust at representing the absolute population of urchins within each plot.

When the plots were re-surveyed 10 days after the culling exercise the density of *C. rodgersii* at the treatment sites had been reduced significantly (Table 3), ranging from 0.06 – 0.16 urchins.m^{-2} (mean = 0.12 urchins.m^{-2}), a reduction of between 85 and 97% (mean = 91%) (Fig. 4 & 5). In contrast, the density of urchins within the control sites did not vary by more than 5% between the baseline survey and the re-survey (Fig. 4 & 5). An exception was control plot 11, at which the average density of urchins had decreased by 65% - as discussed previously it is likely that this plot had urchins removed by commercial divers between the two survey events. At the completion of the re-survey a second systematic cull of all *C. rodgersii* was conducted in four of the treatment plots (1, 4, 5 and 8). A total of 317, 237, 238 and 138 *C. rodgersii* were culled in each plot respectively.

When all plots were re-surveyed approximately one year after the initial cull event the densities were similar to those reported from the survey soon after the culling event (Fig. 4 & 5), ranging from 0.05 – 0.24 urchins.m^{-2} (mean = 0.13 urchins.m^{-2}), and significantly less than that observed during the baseline survey (Table 3; Fig. 4 & 5). There was however, no significant difference between the estimated urchin counts for the single cull and multiple cull treatments when assessed one year post the initial culling (Fig. 5).
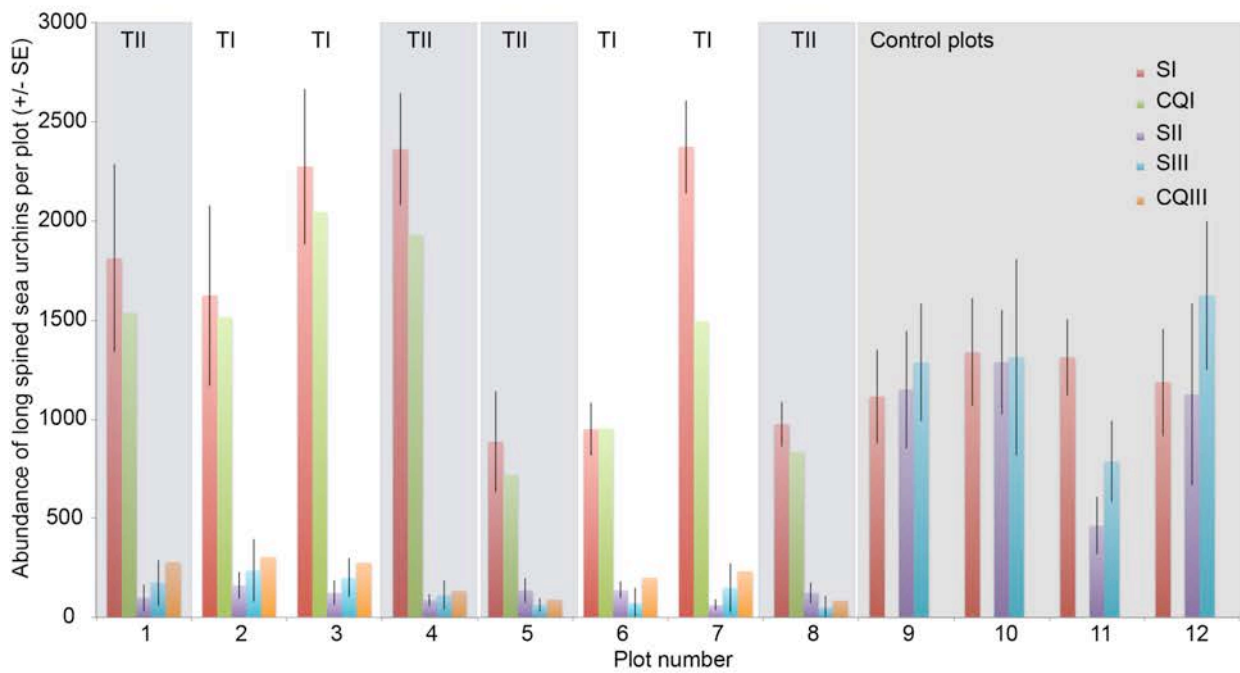
Figure 4. Abundance of long-spined sea urchin *Centrostephanus rodgersii* in each plot (50 x 20 m – noting reduced area to remove edge effect, see text for explanation) throughout the study period: pre-cull baseline survey (SI), first cull – contiguous quadrat census (CQI), one month post-cull survey (SII), one year post-cull survey (SIII) and one year post-cull contiguous quadrat census (CQIII). The shading behind columns represent the treatment type: treatment – single cull (TI), treatment – two cull (TII), and control plots.
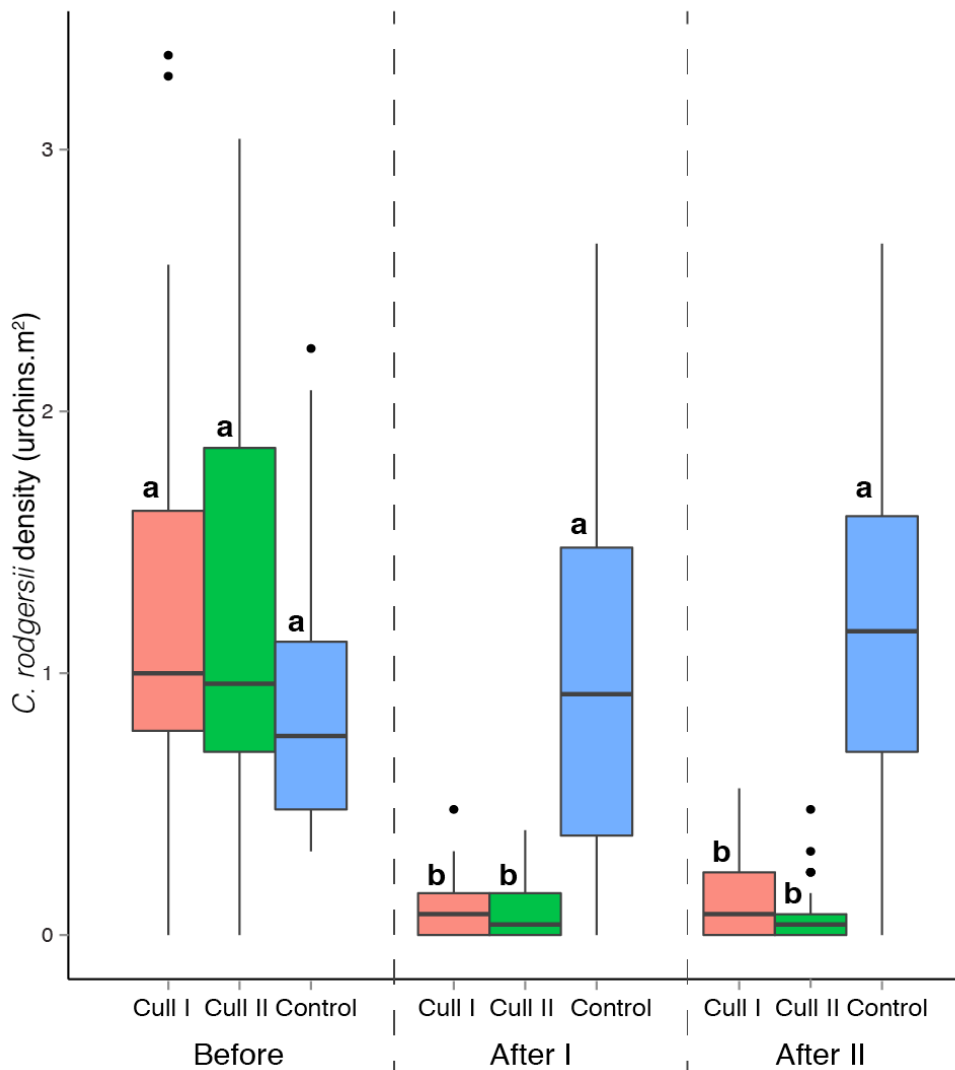
Figure 5. Density of *Centrostephanus rodgersii* (urchins.m^{-2}) across each culling Treatment (Cull I = Single Cull; Cull II = Double Cull; Control = non-culling Control) applied to reef plots (n = 4 replicate plots per Treatment) within Wineglass Bay: Prior to Culling (Before, Aug 2012), approximately 'two weeks after culling (After I, Oct 2012) and approximately one year after culling (After II, Sep 2013). Culling had significant effects on urchin density (2-way fixed effects ANOVA; 'Treatment', $F_{(1,284)} = 36.38$, $P < 0.0001$, 'Period', $F_{(1,284)} = 90.92$, $P < 0.0001$, 'Treatment × Period', $F_{(1,284)} = 30.36$, $P < 0.0001$) with the significant 'Treatment × Period' effect interpretable by examining the significant Tukey (honest significant difference) groupings shown by letters above each box.

Prior to culling, significant variability occurred between transects within plots (Table 4a), however one year after culling variability between transects within plots was no longer detectable for either single or double cull treatments (Table 4b). Notably, while culling reduced overall urchin densities (Fig. 5), significant variability was generated between treatment plots after culling was performed (cf. Table 4a & b; Fig. 6). This indicates that, in contrast to the smoothing effect on urchin densities observed within plots, variability in urchin densities between plots spanning different reef areas (100's to 1000's m separation) was not smoothed by culling in the same way (Table 4a & b). Thus the overall effect of culling on spatial patterns of *C. rodgersii* appears greater within plots. Therefore while culling across different reefs will reduce overall densities and impacts of urchins, culling is unlikely to achieve smoothing of urchin spatial patterns across increasingly large spatial scales.

Table 3. Two-way fixed effects ANOVA testing effects of Treatment, Period, and Treatment*Period on sea urchin density (stabilising transformation= urchin density$^{0.3}$). Numerator and denominator degrees of freedom (*df*) of the F-tests are shown as subscripts preceding F-values. The significant 'Treatment × Period' effect is interpretable by examining the significant Tukey (Honest Significant Difference) groupings shown by letters above each box in Fig. 5.

	df	*MS*	*F*	*P*
Treatment	1	20.18	$F_{1,284}= 36.38$	5.05E-09
Period	1	50.45	$F_{1,284}=90.92$	<2.00E-16
Treatment × Period	1	16.84	$F_{1,284}=30.36$	8.06E-08
Residuals	284	0.55		

Table 4. Nested ANOVA was used to test the effects of 'Treatment' (single cull vs. double cull), 'Plots' nested within 'Treatment', and 'Transects' nested within 'Plots' at (a) the *a priori* times of interest 'Before culling' and (b) 'One year after culling'. A Box Cox transformation of y$^{0.25}$ was required to satisfy model assumptions of normality and homoscedasticity. Numerator and denominator degrees of freedom (*df*) of the *F*-tests are shown as subscripts preceding *F*-values.

(a) Before culling (Transformation: urchin density$^{0.25}$)

	df	*MS*	*F*	*P*
Treatment	1	1.725	$F_{1,2}=0.15$	0.73
Plot(Treatment)	2	11.181	$F_{2,2}=1.50$	0.40
Transect(Plot(Treatment))	2	7.472	$F_{2,954}=12.27$	<0.0001
Residuals	954	0.609		

(b) One year after culling (Transformation: urchin density$^{0.25}$)

	df	*MS*	*F*	*P*
Treatment	1	0.954	$F_{1,2}=0.11$	0.78
Plot(Treatment)	2	9.059	$F_{2,2}=23.63$	0.04
Transect(Plot(Treatment))	2	0.383	$F_{2,954}=0.90$	0.41
Residuals	954	0.424		

There were significant edge effects on the along shore axis (*t* = 7.39; *p* <<0.01) with a density increase of 0.99 ± 0.13 urchins.m^{-2}and on the deep water edge (*t* = 4.74; *p* <<0.01) where the increase was 0.54 ± 0.11 urchins.m^{-2}. However there was no significant effect on the shallow water edge (*t* = -1.37; *p* = 0.16), suggesting urchins are not moving into the plots from shallow water (Fig. 6).
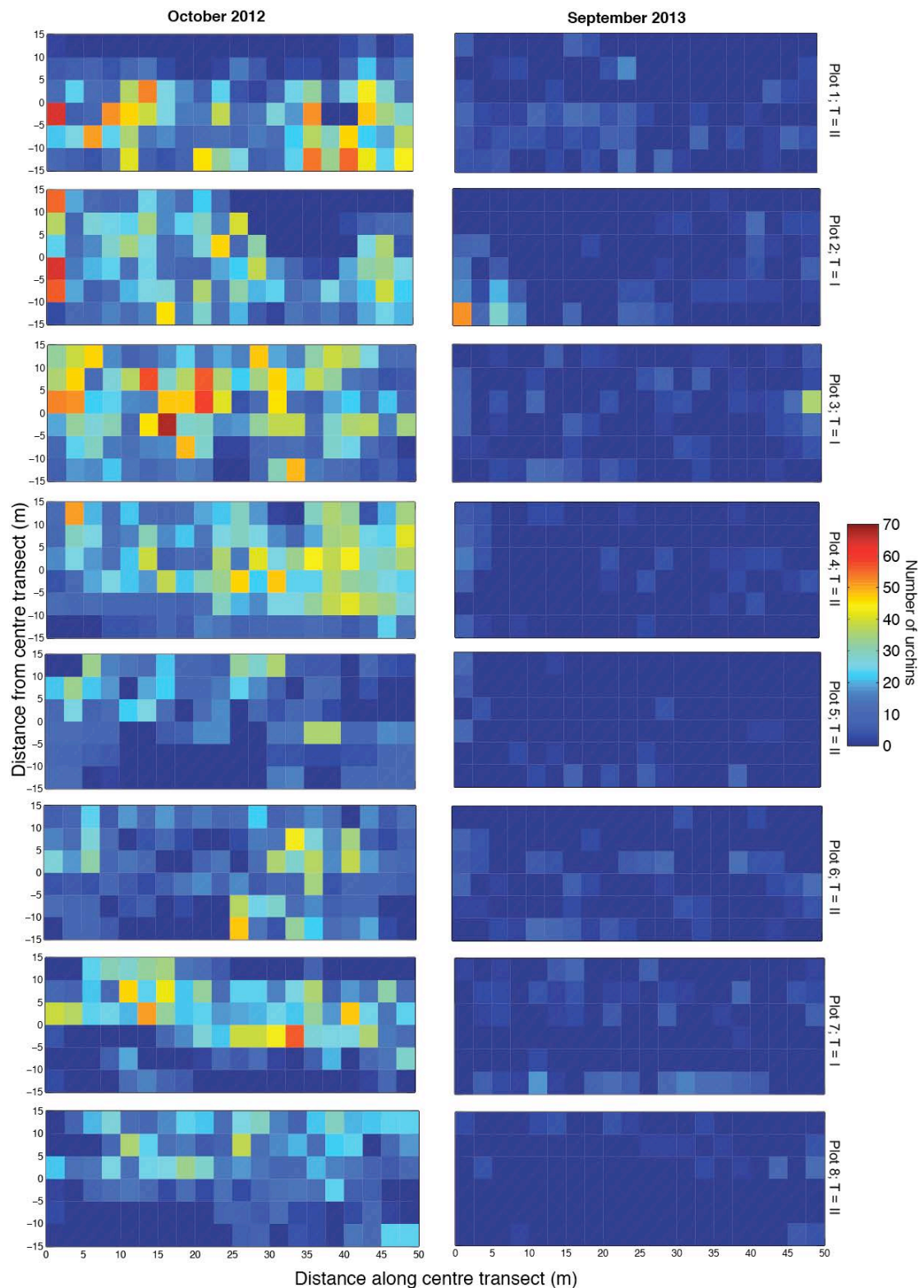
Figure 6. The spatial distribution of long-spined sea urchin *Centrostephanus rodgersii* abundance in eight treatment plots (50 x 30 m) within Wineglass Bay, Tasmania. Each coloured cell is 2.5 x 5 m. The column on the left shows spatial patterns in abundance as recorded during a systematic culling event in October 2012. The column on the right shows spatial patterns in abundance approximately one year after the cull event (September 2013). The plot number are listed down the right hand side of the figure and correspond to positions illustrated on the map in Fig. 1, the treatment types are also indicated: treatment – single cull (TI), treatment – two culls (TII).

Bio-economic model

There was a large difference in the quoted costs per day to conduct culling of urchins from a small vessel, with the Tasmanian cost in the order of twice the cost reported from Victoria (Table 5). The most cost effective method, based on quotes from Tasmanian divers, is to engage a small boat with an additional diver, with the average daily rate estimated as $2,080 or $2.77 $/kg for culling within incipient barren habitat (Table 5). Engaging a mothership, which would be necessary to access remote areas, would raise the cost per kilogram of urchin culled to $5.16 in incipient barren habitat.

Table 5. The cost of culling *Centrostephanus rodgersii* in either incipient or extensive barrens habitat based on quotes provided by Tasmanian divers and cost data reported from culling exercises conducted in Victoria. Mean cull rates and an arbitrary cull time per day are shown and used to calculate the cost ($/kg).

Culling scenario	Mean cull rate[1] (kg/hr)	Mean daily rate[2]	Assumed Culling time (Hrs/Day)	Cost ($/kg)
Tasmanian costs (incipient barrens) [1 diver]	125	$1,380	3	$3.67
Tasmanian costs (incipient barrens) [2 divers]	250	$2,080	3	$2.77
Victorian costs (incipient barrens)	125	$646	3	$1.58
Tasmanian costs (extensive barrens)	351	$1,380	3	$1.31
Victorian costs (extensive barrens)	351	$646	3	$0.62
Tasmanian charter boat cost[3] (incipient barrens)	437	$6,756	3	$5.16

[1]The mean cull rate for incipient barrens in Tasmania was calculated from the culling trials in Wineglass Bay, the Victorian cull rates were calculated from Gorfine et al. (2012), in both instance the average weight of an urchin was estimated at 0.33 kg.

[2]The daily rate for Tasmanian divers was the average price quoted from four divers (who participated in the Wineglass Bay culling project) to participate in a day culling using a small vessel with a single diver and crew (and with additional cost of a second diver on the boat). Six divers were asked to provide quotes, the highest and lowest were excluded due to extreme variability. The daily rate for Victorian divers was calculated from values presented in Gorfine et al. (2012), where it is assumed that culling is occurring predominately in extensive barrens habitat.

[3] Mothership quote includes 2 days travel to and from site and 3 days on site with 3 divers, 2 deckhands, food supplied and prepared, fuel for mothership, fuel for outboards, two small boats for diving, hire of boat and skipper. The reported cost is the average of three cheapest quotes from a tender process.

Model I

The direct cost of reducing the density of *C. rodgersii* on the east coast of Tasmania to 0.1 urchins.m^{-2} from previously reported, or estimated densities and based on reported costs from either the Victorian culling program or costs quoted by Tasmanian dive fishers (commercial dive for urchins, periwinkles, abalone) varied substantially (Table 5). It should be noted that Model I is heavily reliant on assumptions (see methods) and is particularly sensitive to the density of urchins within a given abalone management zone. At this stage the completeness of *C. rodgersii* density estimates along the east coast of Tasmania is tenuous at best, with large areas remaining unsurveyed, and where survey data is available, the last comprehensive survey was conducted in

2002. Costings from Model I (Table 6) do not take into consideration other control methods in place and the potential benefits of these methods (e.g. capping the east coast of Tasmania Southern Rock Lobster fishery to allow rebuilding of stocks, in particular large lobsters, to increase natural predation on *C. rodgersii* and the further development of a harvest fishery for *C. rodgersii*.

Table 6. The estimated cost of employing divers to cull *Centrostephanus rodgersii* on the east coast of Tasmania. The block numbers represent commercial Abalone fishery management zones (shown in Fig. 6). Costs are based on quotes provided by Tasmanian commercial/abalone divers who were familiar with the culling process as well as estimates based on the cost of culling urchins as reported from Victoria (Gorfine et al. 2012). The costs assume cull rates common to incipient barrens habitat.

	Culling to 10m depth		Culling to 20m depth		
	Cost of culling (Tasmanian quotes)	Cost of culling (Victorian quotes)	Cost of culling (Tasmanian quotes)	Cost of culling (Victorian quotes)	Economic yield of Abalone fishery (p.a)
East Coast (Abalone blocks 13 -30)	$3,402,178	$2,324,762	$9,971,681	$6,813,807	$26,966,381
30	$2,800,506	$1,913,630	$6,130,928	$4,189,359	$161,089
29					$837,665
28					$289,961
27			$1,549,627	$1,058,885	$1,739,766
26	$314,127	$214,648	$628,254	$429,296	$96,654
25	$287,545	$196,484	$575,090	$392,968	-
24			$1,087,782	$743,299	$2,255,253
23					$676,576
22					$1,804,202
21					$1,868,638
20					$2,319,689
19					$64,436
18					-
17					$515,486
16					$2,029,728
15					$96,654
14					$2,964,047
13					$9,246,537

Commercial size limits and zones for blacklip abalone
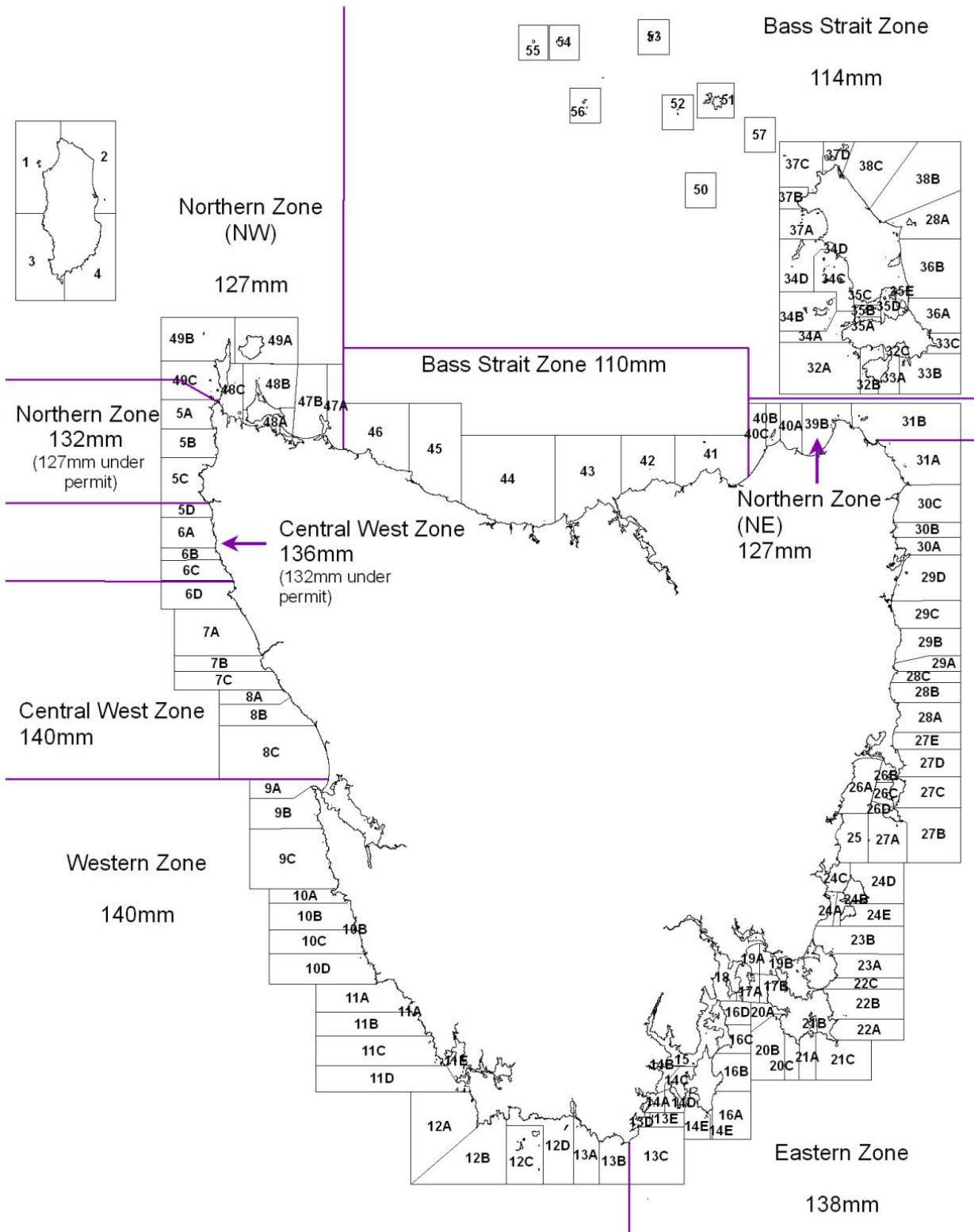
Figure 6. Map of Tasmania illustrating Abalone management zones.

Model II

The inclusion of two additional parameters, depth and urchin density, into the costing model highlights the consequences of ignoring the considerable constraints or influences of these parameters on economic evaluation of alternate strategies. The area of reef that can be culled during a day of diving increases significantly as both depth and urchin density decreases. Within incipient barren habitat at shallow depths and with low urchin density it would be possible to systematically search an area up to 3,500 m^2 while culling urchins in a day (Fig. 7).
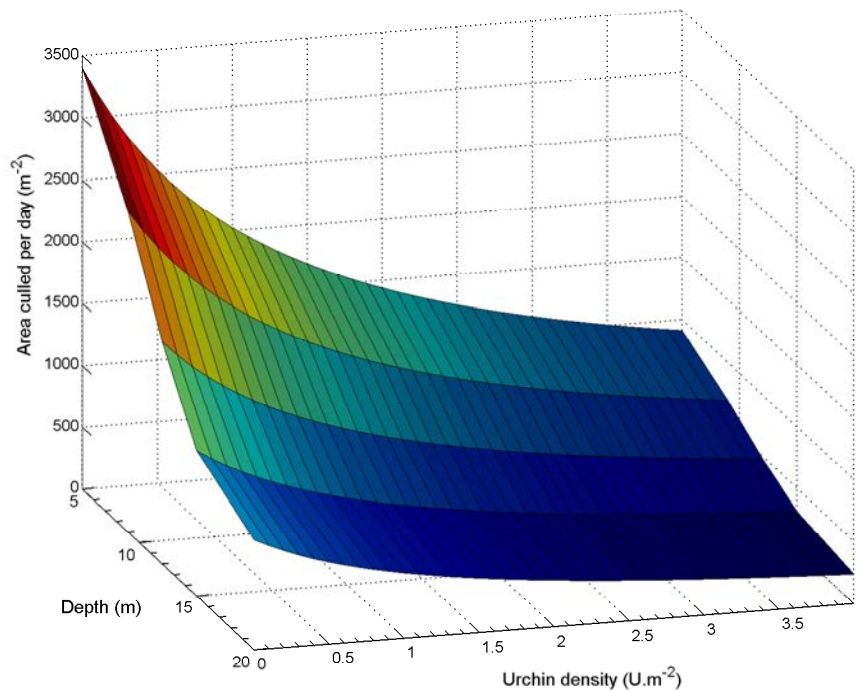
Figure 7. Surface plot illustrating the estimated area culled per day (m^{-2}) as a function of the urchin density (U.m^{-2}) and depth (m).

The total area of reef considered in Wineglass Bay is 2.35 km^2 of which 1.14 km^2 is at a depth equal to, or less than 20 m, equating to 45% of total rocky reef area (Fig. 8A; Table 7). The estimated number of diver days to systematically cull the reef system less than 20 m depth is 1556, based on an average and homogeneous urchin density of 1.5 urchins.m^{-2}. The cost of applying this program, based on the Tasmanian quote estimates (2 divers – small boat) is $1,617,802 (Table 7).

Table 7. Wineglass Bay - The reef area (less than 20 m depth), the diver days required and the associated cost of systematically culling urchins under a range of costing scenarios. The area represented is shown in Fig. 8. The proportion of reef less than 20 m depth in the figure (but not greater than 50 m) is 0.45. Based on average urchin density of 1.5 urchin.m^{-2}.

Depth range (m)	Reef area (km^2)	Required diver days	Cost – Tas quote One diver	Cost – Tas quote Two divers
<5	0.31	187	$258,009	$194,441
5 – 10	0.25	196	$270,386	$203,769
10 – 15	0.27	461	$635,705	$479,082
15 – 20	0.31	712	$982,599	$740,509
Total	1.14	1556	$2,146,698	$1,617,802
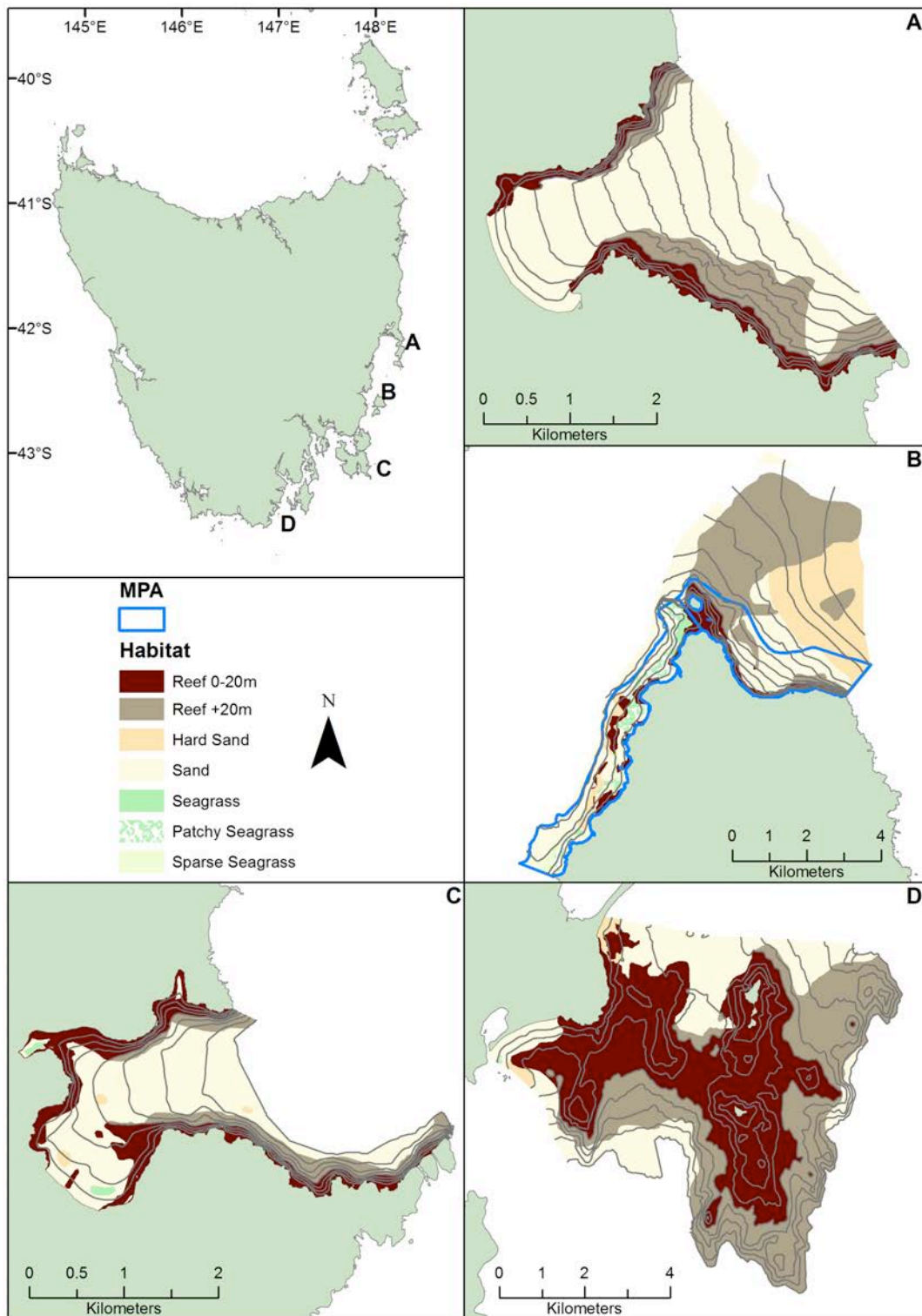
Figure 8. Map illustrating the location of four case study areas on the east and southeast coasts of Tasmania where the bio-economic Model II was applied. (A) Wineglass Bay, (B) Maria Island Marine Reserve, (C) Fortescue Bay, and (D) Acteon reef. Grey lines in A –D represent 5 m depth contours. The dark brown shading (as per figure legend) represents reef at depths equal to or less than 20 m. The costing model only considers culling of urchins to this depth.

The total area of reef considered in Fortescue Bay is 1.75 km² of which 1.16 km² is at a depth equal to, or less than 20 m, equating to 66% of rocky reef area (Fig. 8B; Table 8). The estimated number

of days to systematically cull the reef system less than 20 m depth is 843 diver days, based on an average and homogenous urchin density of 0.29 urchins.m^{-2}. The cost of applying this program, based on the Tasmanian quote estimates (2 divers – small boat) is $877,019 (Table 8).

Table 8. Fortescue Bay - The reef area (less than 20 m depth), the diver days required and the associated cost of systematically culling urchins under a range of costing scenarios. The area represented is shown in Fig. 8B. The proportion of reef less than 20 m depth in the figure (but not greater than 50 m) is 0.66. Based on average urchin density of 0.29 urchin.m^{-2}.

Depth range (m)	Reef area (km^2)	Required diver days	Cost – Tas quote One diver	Cost – Tas quote Two divers
<5	0.42	150	$206,509	$155,630
5 – 10	0.25	114	$157,571	$118,749
10 – 15	0.26	266	$367,351	$276,844
15 – 20	0.23	313	$432,306	$325,796
Total	1.16	843	$1,163,737	$877,019

The total area of reef considered in the Maria Island marine reserve is 3.90 km^2 of which 2.60 km^2 is at a depth equal to, or less than 20 m, equating to 67% of rocky reef area (Fig. 8C; Table 9). The estimated number of days to systematically cull the reef system less than 20 m depth is 1884 diver days, based on a <u>hypothetical</u> and homogeneous urchin density of 0.5 urchins.m^{-2}. The cost of applying this program, based on the Tasmanian quote estimates (2 divers – small boat) is $1,959,359 (Table 9).

Table 9. Maria Island MPA - The reef area (less than 20 m depth), the diver days required and the associated cost of systematically culling urchins under a range of costing scenarios. The area represented is shown in Fig. 8C. The proportion of reef less than 20 m depth in the figure (but not greater than 50 m) within the reserve area is 0.67. Based on <u>hypothetical</u> average urchin density of 0.5 urchin.m^{-2}.

Depth range (m)	Reef area (km^2)	Required diver days	Cost – Tas quote One diver	Cost – Tas quote Two divers
<5	0.98	385	$531,889	$400,844
5 – 10	0.76	391	$540,092	$407,026
10 – 15	0.58	664	$916,906	$691,001
15 – 20	0.29	443	$611,031	$460,487
Total	2.61	1884	$2,599,918	$1,959,359

The total area of reef considered in the Acteon reef area is 34.63 km^2 of which 19.52 km^2 is at a depth equal to, or less than 20 m, equating to 56% of rocky reef area (Fig. 8D; Table 10). The estimated number of days to systematically cull the reef system less than 20 m depth is 22,675 diver days, based on a <u>hypothetical</u> and homogeneous urchin density of 0.5 urchins.m^{-2}. The cost of applying this program, based on the Tasmanian quote estimates (2 divers – small boat) is $23,582,183 (Table 10), or 3.5 times the annual harvest value (Table 6).

Table 10. Actaeon Reef - The reef area (less than 20 m depth), the diver days required and the associated cost of systematically culling urchins under a range of costing scenarios. The area represented is shown in Fig. 8D. The proportion of reef less than 20 m depth in the figure (but not greater than 50 m) is 0.56. Based on hypothetical average urchin density of 0.5 urchin.m^{-2}.

Depth range (m)	Reef area (km^{-2})	Required diver days	Cost – Tas quote One diver	Cost – Tas quote Two divers
<5	1.22	481	$663,230	$499,825
5 – 10	3.17	1638	$2,261,072	$1,703,997
10 – 15	6.50	7439	$10,265,416	$7,736,256
15 – 20	8.63	13117	$18,102,024	$13,642,105
Total	19.52	22675	$31,291,742	$23,582,183

Discussion

Efficacy of direct intervention on a range expanding ecosystem engineer

Systematic culling of *C. rodgersii* within spatially discrete, incipient barrens habitat effectively reduced the mean density of urchins from 1.51 prior to intervention to 0.13 urchins.m^{-2} when re-surveyed 12 months post the culling exercise. Due to the heterogeneous distribution of urchins within the habitat and restricted individual home ranges (Flukes et al. 2012), the effect of sea urchin overgrazing is patchy, which has created a mosaic of kelp and 'incipient' localised barren patches at scale of 10s m^2 in the study area. The positive results of culling demonstrate this method can facilitate reductions in urchin abundance in the "incipient barren" phase before critical densities are locally reached triggering a shift to an "extensive barrens" state, which is very difficult to reverse (Marzloff et al. 2013; Johnson et al. 2014; Ling et al. 2015). A significant finding here relevant to the cost-benefit of culling was that, providing culling was carried out systematically, then there is no significant benefit in performing multiple culls.

Several studies have explored the relationship between reduced urchin density and the capacity for recolonisation by algal species and associated invertebrates (Pace 1981; Fletcher 1987; Andrew and Underwood 1992; Leinaas & Christie 1996; Wright et al. 2005; Ling et al. 2010; Taino 2010; Watanuki et al. 2010). In general, results indicate variable recovery of algal species within the context of relatively small ecological time scales (months). However, recovery is possible in the longer term (~18 months to 2 years) provided sea urchin densities remain low in target areas (reviewed by Ling et al*.* 2015). This presents positive evidence for this method of control for the Tasmanian east coast and the potential capacity for ecological restoration (as detailed by Ling 2008) and recovery of abalone densities as observed in NSW when foliose algae recovered post removal of *C. rodgersii* (Andrew et al. 1998).

While the process of systematic culling was effective within a spatially discrete area there are several limitations to the broader effectiveness of this control strategy on its own. Similar limitations have been reported in the control of crown-of-thorns starfish outbreaks (Kenchington & Kelleher 1992), a tropical ecosystem engineer with many analogies to the invasive behaviour of *C. rodgersii*. The cost of culling species in sub-tidal marine environments is challenging as the logistics are often great. In situ culling by SCUBA divers might be achievable on shallow reef (< 15m) but becomes prohibitive at deeper depth as safe diving time is shortened due to decompression considerations. Subsequently, the overhead costs and logistical complications seriously compromise the feasibility of applying a culling method at either increasing depth or across increasingly large spatial scales.

Despite the logistic challenges inherent in dive activities, we propose however, that culling of *C. rodgersii* can play an important role in the multi-faceted control of this species. Enhancement of natural predation by increasing the population of Southern Rock Lobster (*Jasus edwardsii*, Palinuridae) is predicted to have a significant effect at reducing the probability of urchin barren formation by reducing the density of urchins throughout their distribution in Tasmania (Ling et al.

2009a; Johnson et al. 2014). Our results confirm that systematic culling of *C. rodgersii* is highly effective over small spatial scales for reducing urchin density well below levels that are reported to lead to the formation of incipient barrens. Inclusion of culling in an urchin management program is best applied to local areas that are reasonably easy to access (to reduce costs), are high conservation value reef sites with high biodiversity and/or areas of high commercial value. For instance, specific target sites for dedicated urchin culling could be areas that meet the above restrictions (accessibility, shallow reef) and either hold high abundances of commercially important species such as abalone and rock lobster, or areas of interest to commercial tourist ventures. Similarly, these were also important consideration for the spatial implementation of crown-of-thorns removal programs on the Great Barrier Reef (Pratchett et al. 2014).

Parallels between cull effectiveness and animal predator success: implications for future cull programs

Density-dependent detectability and/or accessibility of sea urchins to divers while culling or harvesting are typical of a trophic interaction between a predator and a prey population. Since Holling proposed his three model types to quantify predation rate as a function of prey density (Holling 1965, 1966), many alternative formulation of functional responses have emerged to describe predation rates. Functional responses have been applied to study prey-predator dynamics for a wide range of marine taxa, even large marine mammals (Mackinson et al. 2003), but rarely has human fishing efficiency been inspected as a function of target species abundance in a prey-predator sense. Here, we applied classical predation functional responses to sea urchin culling efficiency by divers.

While animal foraging behaviour theory has been directly transferred to the spatial strategy of fishing vessels (Bertrand et al. 2007), only a few studies have related fishing efficiency to target fish abundance mostly because accurate fishery-independent estimates of target species abundance are rarely available (e.g. Harley et al. 2001). Here, assessments of sea urchin abundance before and after culling revealed that sea urchin culling efficiency by divers significantly follow Holling's functional responses. Thus human fishing behaviour, sea urchin culling by divers in this case, follows similar patterns to those observed in animal foraging. Hence, our work provides further direct support to the conclusion of Bertrand et al. (2007) that human fishing (or underwater culling here) behaviour can be related to natural predators' behaviour. While Bertrand et al. (2007) demonstrated that the spatial strategy of the Peruvian anchovy fishing fleet follows optimal movement patterns as observed in natural predators, we here model the effect of sea urchin density on the proportion of the population culled as a typical prey-predator functional response (Holling 1965, 1966): at low densities (< 1 individual per square metre), sea urchin individuals are less conspicuous to divers hence more likely to survive the cull; conversely, in densely populated patches, divers are aware of the presence of sea urchins and more actively look for hidden individuals.

An increase in cull rates with sea urchin density also followed classical prey-predator functional for C. rodgersii (Ling & Johnson 2012; Marzloff et al. 2013), however a wide range of cull rates (5-14 individuals culled per minute) was observed in areas of high urchin density. This suggests that

other factors (e.g. shelter provision by canopy-forming macro-algae, complex boulder habitat or the presence of crevices) contribute to divers' culling efficiency. Notably, habitat complexity and the provision of shelter is a key factor significantly increasing *C. rodgersii* survival in the presence of large predatory rock lobsters (Ling and Johnson 2012). Therefore, the ability of sea urchins to hide in crevices is highly likely to slow down culling activity by divers in complex reef habitat. Habitat type and complexity of cull sites are therefore important considerations in the calculation of time and cost.

The accelerated settlement and associated increase in recruitment of *C. rodgersii* in eastern Tasmania will act against management interventions to control sea urchin densities. Sea urchin recruitment can be highly variable through space and time (Hernandez et al. 2006; Hereu et al. 2005). As our current understanding of *C. rodgersii* recruitment dynamics in Tasmania is fairly coarse (Ling et al. 2009b), regular monitoring of local settlement and peak recruitment events will be essential in planning and scheduling of systematic culling interventions to be optimised to minimise the ecological impacts of the long-spined sea urchin in eastern Tasmania and improve cost efficiencies.

Circumstances when it's acceptable to intervene in a natural process

Sorte et al. (2010) identified that marine range shifts are likely to occur at a rate slower than marine introductions, but found that the community-level effects could be as great. Fortuitously we can draw on our understanding of invasion biology to inform on the impacts of climate change-driven shifts as well as provide insight into formal assessment and potential control methods.

There are many complexities around the management of introduced species, and possibly more so for range shifting species. For range shifting native species, despite potential impacts, management options may be constrained through environmental or biodiversity legislation. Where range expansions or shifts may lead to major shifts in biota, species extinctions and a subsequent loss of biodiversity, population control may be limited to small-scale permits or, establishment of a commercial harvest industry, without compromising the integrity of biodiversity protection legislation. Protection of ecosystem functioning, structure and ecological values often justify the implementation of introduced species management programs. In each case the decision process is often challenged by conflicting political, economic, social and conservation concerns between stakeholder groups (Kenchington & Kelleher 1992). Such diverging interests can slow down the decision process and hinder the opportunity to intervene in a timely manner so as to avoid widespread ecological consequences associated with the range shifts (Allendorf & Lundquist 2003). The decision to actively manage climate-driven range shifts (fundamentally climate change adaptation) eventually comes down to political and economic feasibility, as well as the acceptance of the levels of risks and uncertainty associated with interventions in complex ecological dynamics.

Direct cost of Culling in Tasmania

Implementing a control program in the marine environment is inherently costly. Divers are limited, via decompression requirements, in the amount of time they can spend in the water at a given depth within a day. Access to coastal areas can also be costly, with launching points limited. Weather is also a significant limiting factor on exposed coastal areas. In Australia, an analogue to the *C. rodgersii* issue is the corallivorous crown of thorn starfish (COTS) outbreak cycle on coral reefs, particularly on the Great Barrier Reef, which support both tourism and harvest industries. Gladstone (1992) reviewed the early history of COTS control, noting that control success of an outbreak of COTS was limited to a specific set of circumstances. These included early detection, localised outbreak population, and adequate personnel to achieve high success. Costs of removing 2,000,000 COTS were estimated at A\$3.5million, based on a two-person dive team, working for four hours per day. This equates to \$1.75/starfish compared to ~\$0.90/urchin (Table 9), although COTS rarely occur in densities comparable to *C. rodgersii*. In a rare success, Mahando & Lanshammar (2008) demonstrated localised control of COTS in Zanzibar was effective at removal of COTS and subsequent recovery of local coral communities. The mixed success of COTS control programs generally (Fisk and Power 1999) is largely attributed to the large-scale movement patterns of *A. planci*, which is distinct from the sedentary nature of *C. rodgersii* (Flukes et al. 2012). Nonetheless, previous experience with COTS outbreaks across the Indo-pacific, suggests successful direct action control of *C. rodgersii* is likely to be limited to localised areas of high commercial or biodiversity value. It is also crucial to recognise the future recruitment will compromise any control method, in particular systematic culling that is designed the significantly reduce the density of urchins in a given area.

There was a dramatic difference in the cost quotes between Tasmanian and Victorian divers. If a culling program is implemented in Tasmania it would be prudent to understand this difference. A possible solution to reduce the individual diver cost, relative to the average costs presented in this study, would be to engage divers via a tender process. Reducing the 'per diver cost' to the program would significantly reduce the overall cost.

Both costing models presented here require a reasonable estimate of *C. rodgersii* density in the area being considered for culling, whether that is an abalone management zone (Model I) or a specific reef area or embayment (Model II). The presentation of results here relies heavily on the assumption of urchin density and proposed costing could vary dramatically. Both models, however, can be re-parameterized with contemporary density information, if and when it becomes available.

Model I is an extension of a costing scenario developed by Tisdell et al (2011). It presents information on the cost of culling urchins within abalone management zones on the east coast of Tasmania. Costs presented are likely to underestimate the true costs as they do not account for the search time required to find areas of *C. rodgersii* abundance that would warrant implementing culling. This is due to the high heterogeneity of *C. rodgersii* on the east coast of Tasmania, and that data are not available for search efficiencies across large (10s of hectares) reef areas. This

model cannot account for the search time across extensive areas of coast line with occasional patches of high densities of *C. rodgersii*.

Model II addresses this in part by focusing on smaller areas of coastline, in accordance with the spatial scale of implementation recommended by this report and others (Johnson et al. 2014). The costings presented for Model II are anticipated to be upper estimates. Primarily due to the model estimating the most conservative dive time limits for a given depth band (i.e. 6 – 10 m is calculated at the 10 m dive time). This model is also subject to biases related to the heterogeneity of urchin distribution as mentioned above. Areas of Wineglass Bay are likely to have areas where no urchins are present or that the density is lower than 0.13 urchins m^{-2}; which was the effective remnant density of *C. rodgersii* post-culling.

Prior to this study most urchin culling exercises have occurred predominately in areas categorised as extensive urchin barrens, that is the vast majority, if not all of the benthic flora has been removed. One of the main considerations when comparing culling exercises between extensive and incipient barrens types is the realised cull rate. In the case of extensive barrens, cull rates will be higher as the urchins tend to be more exposed (visible), while in an incipient barren divers will have to search in and under dense foliose algae slowing the cull rate.

Conclusion

The coastal reef habitats around Tasmania are a stronghold of temperate marine biodiversity, as well as the source of one of the most productive abalone fishing industries in the world (Mayfield et al. 2012). There are serious concerns regarding the potential expansion of the catastrophic effects of overgrazing on these ecosystems should *C. rodgersii* become established further south along the east coast of Tasmania. This study shows that it is possible to reduce the abundance of *C. rodgersii* urchins in small discrete areas via culling. However, the cost of implementing culling programs across an extended spatial scale may be prohibitive so this method should be considered as a component of a broader suite of control measures.

The logistic, legislative, and end-user implications of urchin control measures, demands an unemotional and objective evaluation process for management options. Conceptual approaches such as structured decision-making framework may help define the most effective combination of methods to best minimise the consequences of sea urchin overgrazing for the different stakeholder groups. Critical to any attempt to identify optimal management measures is a more thorough understanding of the spatial extent of urchin barrens and their ongoing establishment along the east coast of Tasmania. A key consideration of direct action control measures such as culling is an understanding of recruitment periodicity and further study on the recruitment dynamics of *C. rodgersii* in Tasmania. Increase in urchin recruitment rates is likely under ongoing climate-driven changes in regional oceanographic conditions and this will significantly affect the long-term outcomes (and cost-benefit) of any control program.

The potential cost of not controlling over-grazing by *C. rodgersii* is likely to be significant for commercial, recreational and customary harvests. In NSW, where *C. rodgersii* are endemic, it is estimated that 50% of nearshore reef habitat has been lost, negatively affecting all benthic species that inhabit these areas including abalone. The estimated cost of systematically culling case study reef areas are presented within this report. The estimated costs are heavily reliant on the density of urchins within a target area as well as the maximum depth that is chosen to cull down to.

Implications

We present here that systematic culling of *Centrostephanus rodgersii* can significantly reduce their abundance in discrete areas. The resulting densities are at a level where model predictions indicate a very low probability of barren formation (Johnson et al. 2014). The main limitation to implementing this method at a broader scale is cost. Systematic, manual culling of marine biota is expensive due to the need for divers who are limited in the amount of time they can spend in the water each day as well as the expenses related to mobilising effort to coastal regions. The study does indicate that culling could be a useful tool to reduce the threat of urchin overgrazing in discrete areas of interest, for example marine protected areas established to preserve marine biodiversity, areas of high commercial value (e.g. productive abalone reefs), or areas of eco-tourism value (e.g. dive tourism). An understanding of the costs and benefits of culling, in addition to, the multi-faceted management approach already proposed (and implemented in the case of enhancing natural predation by improving Southern Rock Lobster stocks) for controlling the effects of over-grazing by *C. rodgersii* in Tasmania will be an asset to resource managers, with many potential flow-on benefits to a range of stakeholder groups.

The finding that multiple culls of an area do not significantly alter the reduction in urchin density after a 12 month period are being considered by commercial divers in the Victorian Eastern Abalone Zone who conduct industry funded culling of *C. rodgersii* on discrete reef patches. In the past, they will re-visit patches of reef to re-cull areas already covered. By adopting a single cull approach they can increase the spatial extent of their culling efforts without significantly reducing the benefits in the areas they have already culled for the same cost.

The results will contribute to the international peer reviewed literature on control of sessile marine invasive species through publication in an international journal.

Recommendations

One of the primary limiting factors when considering whether to implement a culling program is an accurate and contemporary assessment of depth stratified urchin density data from key areas along the east coast of Tasmania. The last broad assessment, which would be considered the most comprehensive baseline survey to date, was in 2002. This knowledge gap is also of relevance to monitoring the effectiveness of other control methods, e.g. natural predation of large rock lobsters; developing new fisheries, e.g. the *burgeoning C. rodgersii* fishery on the east coast of Tasmania; and ultimately understanding the impacts of the range extension of *C. rodgersii* in Tasmania. An ongoing monitoring program that assesses both urchin density as well as the extent of both incipient and extensive urchin barren habitat on the east and southeast coast of Tasmania would address this knowledge gap.

Further development

- Re-survey relative to baseline survey of urchin density and barren habitat along the east and southeast coast of Tasmania.

- Develop engagement with citizen science initiatives (REDMAP) to promote the reporting of *C. rodgersii*, particularly in areas where they have limited distribution currently, for example, south of Tasman Island.

- Ongoing monitoring to assess changes in urchin distribution and abundance as a result of current control programs and potential future recruitment.

Extension and Adoption

The project has been communicated to end users, including managers, researchers and industry representatives since its inception to delivery of the final report. Below are a summary of communication through a range of mediums.

Presentations and briefings to fishing and management related stakeholders
- National workshop on overview of methods to control over-grazing of *Centrostephanus rodgersii* (1)
- Meetings with DPIPWE (4)
- Meetings with project steering committee (3)
- Articles in "Fishing Today" (2)
- Articles in "FISH" (1)
- International peer reviewed publication (1)

Project materials developed

If the project creates any products such as books, scientific papers, factsheets, images these should be outlined in this section outline and attach them where possible.

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Appendix 2: Contributing Personnel

The following people contributed to the project:

1. Institute for Marine and Antarctic Studies (IMAS), University of Tasmania
   - Dr Sean Tracey
   - Dr Craig Mundy
   - Dr Klaas Hartmann
   - Dr Vanessa Lucieer
   - Dr Martin Marzloff
   - Mr Mike Porteus
   - Mr Simon Talbot
   - Mr Ivan Hinojosa
   - Mr Travis Baulch
   - Dr Justin Bell
   - Mr Ruari Colquhuon
   - Mr David Faloon
   - Miss Emma Flukes

2. Other University of Tasmania staff
   - Prof John Tisdell (School of Economics)

3. Commercial and Abalone divers and crew engaged in the project to undertake the initial cull
   - Mr Brian Denny
   - Mr Robert Langdale
   - Mr Damian Johnson
   - Mr Wayne Blacklow
   - Mr Andrew Knight
   - Mr Pieter van der Woude
   - Mr Sean Larby
   - Mr Julian Larby
   - Mr Nigel Wallace
   - Mr Scott Weinreich
   - Mr Luke Swanson
   - Mr Timothy Glazebrook
   - Mr Anthony Stewart
   - Mr Daniel Flack
   - Mr Randall Lynema
   - My Guy Dunkley

4. Project steering committee
   - Mr Grant Pullen (DPIPWE[1])
   - Mr Matthew Bradshaw (DPIPWE)
   - Mr Dean Lisson (Tasmanian Abalone Council)
   - Mr Rob Rex (Tasmanian Abalone Council)
   - Dr Sean Tracey (IMAS)
   - Dr Craig Mundy (IMAS)

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[1] Tasmanian Department of Primary Industries, Parks, Water and the Environment

Appendix 3: Intellectual Property

There are no overriding intellectual property issues.

Appendix 4: Workshop Summary Report

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***WORKSHOP to discuss strategies to control the effects of overgrazing by long-spined sea urchins* SUMMARY**

Tuesday 18th March 2014

08:45 -17:00

2nd floor IMAS Board Room

IMAS Waterfront Building

This workshop was funded by the Fisheries Research and Development Corporation and the Tasmanian state government as a component of project 2011/087: Tactical Research Fund: trial of an industry implemented, spatially discrete eradication/control program for Centrostephanus rodgersii in Tasmania.

Workshop objectives and agenda

Present and discuss contemporary research results relating to controlling the overgrazing effects of the long-spined sea urchin. The workshop will focus on four control scenarios:

1. Abalone divers culling long-spined urchins while harvesting
2. Dedicated culling of long-spined urchins
3. A commercial harvest fishery for long-spined sea urchins
4. Enhancement of natural predation on long-spined sea urchins

An assessment of the direct cost of each of these scenarios will be presented. The workshop will focus primarily on the Tasmanian case, but will draw on and share mutually beneficial experiences and knowledge with participants from other states.

The afternoon session will feature a discussion around the application of a structured decision making process that can be used to assist management decisions. The process includes an assessment of the costs and benefits of a range of management options that combines scenarios presented in the morning sessions. Following this will be a presentation to stimulate discussion around planned research, and set the stage for a structured session to prioritise knowledge gaps and future research.

Introduction and workshop objectives
8:45 – 9:00 Ian Cartwright

Sea urchin overgrazing: a Tasmanian & global management problem
9:00 – 9:20 Scott Ling

Scenario 1: Abalone divers culling long-spined urchins while harvesting abs
9:25 – 9:45 Craig Johnson

Scenario 2: Dedicated culling of long-spined urchins
9:50 – 10:15 John Minehan/ Justin Bell– Victoria
10:20 – 10:40 Sean Tracey – Tasmania

10:45 – 11:05 Morning tea

Scenario 3: A commercial harvest fishery for long-spined sea urchins
11:10 – 11:30 John Keane

Scenario 4: Enhancement of natural predation on long-spined sea urchins
11:35 – 11:55 Martin Marzloff
12:00 – 12.20 Craig Johnson

12:25 – 13:00 Lunch
Economic analysis of the direct cost of control scenarios
13:00 – 13:30 John Tisdell

Discussion topic -**Structured decision making to inform management strategies**
13:30 – 15:00 Discussion led by Lucy Robinson &Martin Marzloff

15:05 – 15:20 Afternoon tea

Discussion topic -**Summary and implications of knowledge gaps and planned research**
15:20 – 16:45 Knowledge gaps and research prioritization session led by Craig Johnson & Ian Cartwright

16:45 – 17:00 **Workshop summary, thanks and close -** Ian Cartwright

Attendance list

Ian Cartwright	(Chair)
Mark Nikolai	(TARFish)
David Allen	(Processor/Commercial Dive)
Jon Bryan	(Tasmanian Conservation Trust)
Neil Stump	(Tasmanian Seafood Industry Council)
John Minehan	(Victorian Abalone diver)
Greg Woodham	(Tasmanian Abalone Council Limited)
Dean Lisson	(Tasmanian Abalone Council Limited)
John Sansom	(Tasmanian Rock Lobster Fishermen's Association)
Craig Johnson	(IMAS)
Klaas Hartmann	(IMAS)
John Keane	(IMAS)
Martin Marzloff	(IMAS)
Emma Flukes	(IMAS)
Scott Ling	(IMAS)
Lucy Robinson	(IMAS)
Vanessa Lucieer	(IMAS)
Justin Bell	(IMAS)
Travis Baulch	(IMAS)
Sean Tracey	(IMAS)
Robert Gott	(DPIPWE)
Grant Pullen	(DPIPWE)
Hilary Revill	(DPIPWE)
Greg Ryan	(DPIPWE)
John Tisdell	(UTAS – school of economics)

Absent

Matt Bradshaw	(DPIPWE)

Apologies

Colin Buxton	(IMAS)
Craig Mundy	(IMAS)
Caleb Gardner	(IMAS)
Harry Gorfine	(DEPI Victoria)
Bryan Denny	(Tasmanian Commercial Divers Association)
Geoff Ellis	(Eastern Zone Abalone)
Harry Peeters	(Western Abalone Divers Association)
Duncan Worthington	(NSW Abalone Council)
Crispian Ashby	(FRDC)
Rob Rex	(Tasmanian Abalone Council Limited)

NOTE: Mr Rodney Treloggen of the TRLFA was invited to the workshop. On the morning of the workshop, both Mr Treloggen and Mr John Sansom also of the TRLFA presented at the workshop. Before the commencement of proceedings Mr Treloggen and Mr Sansom were advised by the workshop convenor that people who had not been invited to attend the workshop had approached the workshop convenors seeking that they be allowed to attend. These requests had been declined. Mr Treloggen and Mr Sansom were provided with the option that in the event they both wished to participate in the workshop, then the convenor would contact another person whose request the previous day to attend had been declined, providing that person with an opportunity to now attend. Alternatively, Mr Samson could decide not to attend. Mr Treloggen expressed his disappointment in the position being taken by the workshop advising that he would forgo his attendance so that Mr Sansom could participate.

1.   Chair's opening remarks

The Chair welcomed attendees to the meeting and clarified that the purpose of the workshop was primarily as a research showcase to present the four different *Centrostephanus* control measures currently being investigated. It was stressed that the workshop was not a decision making forum; but an environment in which to discuss the proposed control measures, explore some preliminary economic analyses, identify research needs, and investigate ways in which to create more objective and participatory methods of decision-making. It was clarified that the list of workshop attendees was chosen to ensure representation of each of the major stakeholder groups, with a weighting towards research and management. This approach was taken in acknowledgment of the purpose of the workshop as primarily a research showcase and forum for discussing, but not making recommendations or reaching conclusions, on urchin control measures. It was explained that, given the nature of the workshop, there would be no consideration of weight in numbers summarising the views of the participants. Participants were advised that they should brief their colleagues on discussions undertaken at the workshop, and that the summary report of the workshop and presentation slides would be provided to assist with disseminating information. An invitation was extended for any opening comments or questions.

General comments from forum

It was remarked that at some point a firm decision would need to be made regarding management actions for *Centrostephanus* control, but attendees were reminded that this current workshop was not the place for taking such decisions. Some discussion took place about the highly political nature of the *Centrostephanus* issue, and it was noted that while management recommendations and advice would incorporate information from a range of different sources, it was emphasised that ultimately management decisions lay with the Government and Minister.

It was queried whether different stakeholders/FACs would need to make individual decisions and feed this back into a management context, or whether at some point discussions would be held engaging with a range of stakeholders and aggregated recommendations made. Some concern was expressed as to how different recommendations put forward by various stakeholder groups would be handled. The Chair emphasised that this forum should not be confused with previous multi-stakeholder meetings called to discuss urchin issues. It was suggested by some attendees that a cross-sector *Centrostephanus* meeting should be reconvened soon after this workshop to discuss future action on *Centrostephanus.*

2. Presentations[2]

Sea urchin overgrazing: a Tasmanian & global management problem (Dr. Scott Ling)

Dr Scott Ling provided a recap of the mechanisms of urchin barren formation and progression from intact kelp beds through to widespread barrens. The alternative stable state concept as it applies to marine ecosystems where kelp beds undergo a forward shift to barrens state, and the extreme difficulty in return to kelp bed habitat were described. Data was presented from a recent global review conducted by Dr Ling that identified coherent forward and reverse shifts for urchin barrens systems worldwide. The review determined that the mean density of urchins required to induce the forward phase shift (to barrens) was approx. 700 g urchin m^{-2} (exclusive of urchins with "feeding front" behaviour whereby highly mobile populations climb and weigh down kelps), whereas kelp recovery required urchin biomass reduction to below 70 g urchin m^{-2} (i.e. an order of magnitude difference). The message that "an ounce of prevention is worth a ton of cure" was emphasised, as it is very difficult for an ecosystem to recover from this fundamental change once it occurs.

The four different management scenarios to be discussed at this workshop were briefly described: (1) direct control via culls while fishing; (2) direct control via dedicated culling; (3) direct control via development of the urchin fishery; and (4); indirect control via enhancement of large predators. Dr Ling emphasised that the effectiveness of management relies on whether a "proactive" or "reactive" approach is applied, i.e. whether widespread barrens have already formed or whether management intervention occurs before this change has taken place. Most of Tasmania's east coast is still intact kelp and thus is currently in the "proactive" management phase where prompt appropriate management action can make a big difference.

A series of figures were shown that demonstrated the rebuilding of large lobster biomass in the North Bay Research Reserve via translocation of lobsters to the area and closure to fishing. Further figures showed declining densities of *Centrostephanus* and *Heliocidaris* urchins in North Bay and a corresponding shrinking of monitored incipient barrens patches, whereas reference sites in Fortescue Bay and Cape Paul Lemanon showed increasing urchin numbers and growing barrens areas over the same period.

Questions and comments raised by the forum at the conclusion of the presentation:

> When a reef is damaged or stressed enough via fishing pressure, it appears that *Centrostephanus* will take hold. Concern was raised that the rapid rate of change in urchin impacts tended to outstrip that of management decisions to address the problem. The forum agreed that making timely decisions with regards to this issue was critical.

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[2] All presentations were made available to attendees of the workshop

Scenario 1: Abalone divers culling long-spined urchins while harvesting abalone (Professor Craig Johnson)

Professor Craig Johnson provided a presentation that focused on abalone divers culling while harvesting abalone, rather than dedicated culling efforts. Research outcomes were presented showing the concept of *Centrostephanus* "fidelity" to specific barrens areas, meaning that urchins tend to remain in their particular barren patch over several months. Movement data was also shown demonstrating that urchin foraging is highly nocturnal. It was explained that urchins do not seem to cross the border of incipient barrens patches into the surrounding kelp bed, so that if urchins are removed from a targeted patch of reef it is likely to take several months – or longer – before the areas are recolonised. Three months monitoring of tagged urchins in and around incipient barrens patches showed their long-term displacement was effectively confined by the boundaries of the patch, and chemical tagging of urchins on a small patch (4 * 4 m area) of extensive barrens resulted in >40% recovery of tagged urchins more than one year after tagging took place. A consistent relationship between grazed area and density of sea urchins was demonstrated, with each urchin maintaining approximately 0.6 m^2 grazed reef. It was emphasised the results of this research provide both good and bad news for culling: the good news is that barrens patches will take some time to be recolonised following culling so that effective culling is likely to prove effective in regenerating seaweed; the bad news is that the nocturnal nature of urchins means they are likely to be cryptic within crevices during the day and thus a certain proportion will always be missed during daytime culling activity.

Data showing the relationship between abalone diver behaviour and cull rates of urchins was then presented. Cull rates declined with both abalone catch and dive time, because when divers come across a good patch of abalone they will focus less on urchin culling and stay in the water for longer. Most urchins were killed on short dives when abalone fishing was poor. Data from experimental culls at three different sites was presented. It was demonstrated that at the "site" scale, an estimated 7-10% reduction in urchin numbers could not be detected as a change in urchin density and had no detectable effect on total barrens extent, but at the scale of targeted "patches" (i.e. the small-scale area from which urchins were removed), recovery of seaweeds within cleared patches occurred within ~9 months. A reminder was provided at this point that due to diver safety issues, urchin barrens at depths > 15-20 m are relatively inaccessible, so we need to be realistic about the depths at which divers can reasonably work.

Professor Johnson provided a recommendation that abalone divers should be encouraged to clear urchins from "pet patches" (i.e. targeted removal from important fishery areas), but also provided the caution that divers clearing urchins while fishing for abalone are unlikely to have any detectable or meaningful effect on the overall numbers and impact of *Centrostephanus* in an area.

Questions and comments raised by the forum at the conclusion of the presentation:

- While the effect of individual abalone divers conducting culls may be minimal, there are collectively many thousands of hours spent diving on the east coast of Tasmania. It was suggested that if divers were to see a visible effect of their culling efforts, they may be more motivated to conduct culls. It was pointed out that abalone divers may also be able to identify areas that are on the verge of being problematic, and provide valuable information on patches that are worth targeting in culls, particularly in the absence of current survey data.

- Culling by divers might be seen as a complementary management issue once urchin density is already reduced, as a way to maintain low density rather than create it.

- If prompt management action is taken with regards to culls, urchin numbers may only need to be reduced by a relatively modest amount to prevent urchins from establishing in key areas, whereas culling will be far less effective if urchins are allowed to reach damaging levels.

Scenario 2: Dedicated culling of long-spined urchins (John Minehan / Dr. Justin Bell)

Dr Justin Bell provided an overview of a pilot study that has since been adopted by the Eastern Zone in Victoria. The basic design of the study was explained, with photo quadrats and video transects used to monitor kelp recovery over time. GPS loggers were used on divers to track entry and exit points of the water to obtain measures of spatial coverage, and some divers carried a clicker to record how many urchins were culled. The enormous density of urchins in this area meant divers spent a lot of time covering very little ground, and most of the diver effort was focused along the 'urchin front' while little culling was conducted at depths greater than 13 m due to restrictions related to safe dive time.

Some videos were shown demonstrating the recovery of macroalgae in urchin barrens at three and seven months post-removal of urchins. It was noted by John Minehan that no real recovery of abalone had been observed in the full study even following 2.5 years of culling efforts, but this recovery may vary depending on sites. A further video transect on an area following 2.5 years of urchin culling showed complete recovery of the kelp canopy.

A brief discussion followed regarding reasons why abalone may not have moved into recovering kelp beds, and queries were raised regarding how long it would take for abalone to re-colonise an area that was previously barren. Professor Johnson briefly mentioned a study conducted in Tasmania where abalone were removed from a habitat and a shift in understory community was observed, with encrusting red algae replaced by a matrix of filamentous algae and benthic invertebrates (sponges etc.) that trapped a high quantity of sediment. It was shown that abalone would not return to these areas, and the study concluded that over-harvesting of abalone causes a shift to undesirable benthic habitat. Professor Johnson suggested that the re-population of understory species following kelp canopy recovery from urchin grazing may follow a similar process. Some general discussion followed about how dire a loss of habitat can be, and the importance of preventing phase shifts to barrens before they occur was again highlighted.

John Minehan continued the presentation of *Centrostephanus* culling in Victoria by discussing some of the direct costs of the Victorian culling program, including the differences in vessel size (small vessels only) and personnel (restricted to a core group of 8 divers), and cull areas (very exposed reefs and large areas of extensive barrens) relative to pilot work conducted in Tasmania. It was pointed out that these differences will likely make the economics of culling in eastern Victoria different to Tasmania. The goals of the abalone industry in Victoria were briefly discussed. These were, in order of importance, to (1) "stop the rot" by reducing further decreases in TAC, which has dropped 76 t over the past 6 years and has been largely attributed to *Centrostephanus*; (2) recover lost abalone habitat; (3) recover lost abalone stocks.

The eastern Victorian program operates on a budget of $50,000 per year which allows for maintenance of 25.75 ha of reef. Future plans were discussed for translocation of abalone into experimental cull sites and potentially focusing culling efforts in relation to existing areas of high abalone productivity. Some of the statistics and outcomes of the culling program were presented, including a breakdown of operating costs and levels of culling achievable by divers. A third site has recently been added to the Victorian culling program.

Questions and comments raised by the forum at the conclusion of the presentation:

- Mr Minhehan was asked if "maintenance dives" involve divers returning to exactly the same areas that were cleared initially, or just nearby reefs, as this could potentially raise important questions regarding patch fidelity of urchins in Victoria? It was clarified that urchins in Victoria do appear (anecdotally) to show fidelity to home patches of reef as occurs in Tasmania, and that divers were returning only to an approximately similar area on reefs for culls, thus "maintenance dives" are a mixture of revisiting specific sites, and expansion of existing cull area.

- Clearing areas of invasive species in terrestrial systems costs around $50-100 per hectare, so the ~$2000 per hectare currently of reef cleared here is not an unreasonable cost.

Proposal of an industry implemented, spatially discrete culling program for Centrostephanus rodgersii in Tasmania (Dr. Sean Tracey)

Dr Sean Tracey commenced by discussing some of the mechanisms that have been successfully implemented for removal of invasive species from terrestrial and marine environments elsewhere. It was pointed out that it can be useful to invest money in early removal efforts even if more research is required, as damage can be prevented before it occurs. In the case of *Centrostephanus* in Tasmania, he made the point that it is too late to stop the infestation of the urchin, but that there is still opportunity to prevent the deleterious affects of the phase shift from incipient to extensive barrens states. The objectives for this presentation were outlined as being to determine the effectiveness of divers physically destroying urchins *in situ* in Tasmania to either eradicate, or control spatially discrete aggregations, and to determine the cost of that objective. The second objective was covered in John Tisdell's presentation later in the afternoon.

The design and results from a culling project conducted in Wineglass Bay, East Coast Tasmania were presented. Four different locations representing different exposure/substrate regimes were used, with three treatments applied in each: unculled, culled once and culled plus a follow-up cull 10 days later (it was noted that these culls were systematic, dedicated culls intended to clear all urchins from the experimental area). Each treatment at each site was applied over a 50 x 30 m area (i.e. total culled area = 4 sites x 2 culling treatments x 1500 m^2 = 12,000 m^2). Opportunistic re-surveys of some plots 24 hours following culling indicated that ~15% of urchins were missed during the initial culls. A systematic census of sites was conducted 12 months after the initial culling where the average density was ~0.1 urchins m^{-2} indicating an overall mean reduction of 91%, which was concluded to be very successful. It was also shown that multiple culls in an area was no more effective in reducing urchin density long-term (12 months) than a single cull.

The average cull rate was 6.4 urchins per minute, with a maximum cull rate of 14 urchins per minute. It was pointed out that this was far less than the 30 urchins per minute achieved by divers in Victoria, but that divers in the Tasmanian study were conducting culls in a systematic manner to clear pre-designated areas rather than following patches of high densities as occurs in Victoria. It was also noted that a significant proportion of the Victorian culling occurs in extensive barrens where the absence of foliage means that the urchins are easier to find, thereby increasing cull rates.

The question was asked as to how urchin density counts convert to biomass. Some general discussion followed regarding the high degree of variability in urchin mass depending on body size and condition, but it was agreed that an average adult urchin weighs approximately 300 g, so a density of 0.1 urchin m^{-2} translates to an urchin biomass of ~30 $g.m^{-2}$. It was pointed out that this 0.1-0.2 urchins m^{-2} (30-60 $g.m^{-2}$) translates closely to the ~70 $g.m^{-2}$ threshold for kelp bed recovery demonstrated earlier by Dr Ling in his meta-analysis of global urchin grazing systems.

Calculations were shown regarding the time cost of expanding the project to cull urchins in the broader Wineglass Bay area. Habitat mapping indicated the culled area in this study represented 0.012% of available reef at depth less than 15 meters. Based on average figures, expanding the culling program to clear the whole of Wineglass Bay at depths less than 15 meters of *Centrostephanus* (assuming the whole bay was in the same state as the area already surveyed) would take ~1,736 diver days (3 hours per diver per day).

The following conclusions were provided regarding culling in eastern Tasmania:

- Culling is a very effective method of reducing abundance in small discrete areas for at least 12 months

- Culling could be applied to protect areas of high ecological or commercial value

- Culling during this project only covered a very small area, and to expand the methodology would be expensive

- Future recruitment events could be problematic, with the analogy given that you can "shovel snow as much as you want but next time it snows again the work is undone"

Questions and comments raised by the forum at the conclusion of the presentation:

- If urchins are nocturnal, aren't surveys and culling conducted during the day missing a lot of urchins? It was agreed that some urchins would be missed by daytime surveys because of this cryptic behavior, but the relative reduction in urchin abundance in the culled sites was a positive sign that the culling had a significant impact on the abundance of urchins within these areas.

Scenario 3: A commercial harvest fishery for long-spined sea urchins (Dr. John Keane)

Dr John Keane presented an overview of the Tasmanian commercial urchin fishery, and discussed some of the research objectives of a current FRDC project focused on the urchin fishery. Some basic figures regarding the Tasmanian commercial dive fishery were presented. It was estimated that 0.56-0.67 million individual *Centrostephanus* have been removed by the urchin fishery since its inception in 2008, equating to ~31-37 hectares of reef cleared of urchins. Some statistics on the commercial harvest fishery of *Centrostephanus* were presented and discussed.

The recent move to classify urchin roe quality was described. This is achieved using a tiered system where fishers are paid more money depending on the proportion of roe that is of A-grade quality, and it was pointed out that this has led to divers collecting an increasing proportion of urchins with A-grade quality roe (i.e. divers are not having difficulty in locating urchins with high quality roe).

A new FRDC project which Dr Keane has recently begun working on was described. The objective of this project is to determine whether commercial harvest of *Centrostephanus* can feasibly reduce the impact of urchin grazing on abalone and lobster fisheries. The specific aims were outlined as being to identify spatial areas where urchin harvesting was already occurring and other areas where it could feasibly occur; and to determine what effect urchin harvesting has on the rest of the ecosystem. Dr Keane briefly presented some of the methods currently being employed with an ultimate view to assess kelp recovery and/or urchin recruitment at different fishing pressures, and to define areas in which kelp beds may recover following urchin fishing.

There was discussion about whether there is potential for the *Centrostephanus* fishing market to grow. Dr Keane suggested that there is sufficient demand for urchin roe, but the challenge lies in making the fishery profitable. The point was raised that most of the big urchin fisheries worldwide have collapsed due to overfishing driven by huge consumer demand, so this is encouraging in the context of the potential to use commercial harvesting as a means of reducing the damage of *Centrostephanus*.

The question was raised as to how the residual urchin density on reefs following urchin harvesting would relate to the "critical" density of ~0.1-0.2 urchins m^{-2} discussed earlier in the day as being the threshold estimated by modeling for kelp beds to recover from *Centrostephanus* grazing. It was questioned that, if urchin fishing of an area did not reduce densities to a sufficiently low level, what additional actions could be taken to further reduce *Centrostephanus* density to enable kelp bed recovery? Some brief general discussion followed about the possibility of implementing targeted low-level culling following urchin fishing in an area to maximise the chances of kelp recovery. It was agreed that this issue would be discussed in greater detail at a later point in the day.

Dr Keane briefly outlined a further aim of the FRDC project, which is to model wave energy and create a map predicting areas that are, or could be, affected by urchins in the future; and calculate the extent of shallow subtidal reef that could be at risk of invasion by *Centrostephanus*. Plans were discussed for further work to look at strategies to facilitate safe harvest of urchins at depth and conduct a bioeconomic analysis on the viability of dive site constraints at depth, use of nitrox etc. in the context of determining the effective catch rates required for sustaining a financially viable fishery.

The forum had no questions or comments for Dr Keane regarding this presentation.

Scenario 4: Enhancement of natural predation on long-spined sea urchins (Dr. Martin Marzloff, Professor Craig Johnson)

Dr Martin Marzloff outlined the purpose of his presentation as an attempt to piece together urchin grazing, predation by lobsters, fishing pressure (both lobster and urchin), in combination with a range of environmental variables into a multispecies model of east coast Tasmanian reef community dynamics. The main rationale behind the development of this model was to inform management interventions for

Centrostephanus. A brief recap of the ecological hysteresis concept was provided, followed by an introduction to the TRITON model (**T**emperate **R**eefs **I**n **T**asmania with l**O**bsters and urchi**N**s). Data derived from empirical observations and model outputs was presented, illustrating the hysteresis concept in this system. It was shown that the results were very similar (=model validation).

The importance of the model in identifying thresholds in reef dynamics and target points associated with an acceptable level of risk of extensive barrens formation was explained. It was stressed that the 0.1 urchins m^{-2} may not be a "magic number" above which barrens will form; but it certainly represents a conservative figure for minimising barrens formation (i.e. 5% risk of extensive barrens forming), and is in keeping with the empirical estimate explained earlier in the workshop by Professor Johnson. TRITON modelling identified that the two key drivers of barrens formation are (1) urchin recruitment; and (2) lobster fishing mortality. A plot was presented showing the probability of barrens formation as a function of RL fishing mortality under different urchin harvesting and rock lobster management scenarios, with a second plot showing the probability of seaweed bed recovery from barrens state under these same scenarios. These illustrated that it was virtually impossible to rehabilitate seaweed cover on extensive urchin barrens even in the total absence of rock lobster fishing, and it was again emphasised that taking steps now to prevent barrens from forming is critical, as "curing" extensive urchin barrens is very difficult and likely to take several decades.

A figure was shown demonstrating that (1) rock lobster maximal sustainable fishing yields derived from the multi-species TRITON model are less on reefs that are in danger of forming widespread barrens than is predicted using a species model, as this does not take into account loss of lobster productivity in barrens habitats; and (2) optimal yields for lobster on reefs exposed to urchin grazing are reached at lower levels of fishing than on urchin-free reefs.

The effects of adopting various measures in reducing the risk of barrens formation by applying various measures were described. These measures were additional controls on top of the east coast cap (e.g. urchin culls, urchin harvesting, lobster translocation). Urchin removal, via harvesting or culling, appears to increase reef productivity for abalone more than by translocating lobsters onto eastern Tasmanian reefs; but it was stressed that this work is still very preliminary.

It was explained that, under modelling simulated by TRITON, the long-term consequences of implementing a 200t east coast cap will limit further development of extensive barrens formation to only 20% of reef habitat, supporting the 200t east coast cap for rock lobster as having a positive impact on reducing the impacts of *Centrostephanus.*

Questions and comments raised by the forum at the conclusion of the presentation:

- It is important to be careful with the use of the word "cap", as 200 t is the target limit for total removal of rock lobster from the east coast, and the commercial catch cap trigger of 120 t falls within the 200t target limit. There was some concern that urchin culling and harvesting can realistically only occur down to depths of ~15 m. It was explained that the model incorporates this consideration in that culling can be 'turned on' in representing depths less than 15 m and 'turned off' in representing depths greater than 15 m.

- The comment was made that it is important to have full transparency about the assumptions made by the model. This was acknowledged and Dr Marzloff explained that he would like to receive as much feedback as possible from all people in the room to ensure that the parameters fed into the model for example size class assumptions were as accurate as possible.

Urchin population model
Professor Craig Johnson took the floor to explain the development of a population model for *Centrostephanus*, which relates current urchin density to the extent of existing barrens. It was explained that there are two ways in which to approach this predictive problem: (1) to determine what we deem to be

an "acceptable" cover of barrens, and calculate the target lobster density required to limit barrens formation to this "acceptable" level; or (2) for a given east coast lobster catch, estimate the likely barrens cover.

An outline of the workings of the population model was provided, including its use of size-specific fecundity of urchins from empirical observations of east coast size and age structure, size-specific predation by lobsters, and other empirically-based parameters.

Some plots were presented showing that addition of large translocated lobsters reduced the density of urchins in incipient barrens areas, but not in extensive barrens, with the suggestion made that lobsters are less effective at reducing urchin density on established widespread barrens because the urchin populations are so vast (consumption of an estimated ~85,000 *Centrostephanus* by lobsters at Elephant Rock had no detectable effect on urchin density).

Projections of the density of large (>140 mm) rock lobsters over time based on the rock lobster stock assessment model were shown under a number of different catch cap scenarios, ranging from cessation of fishing to 'status quo' (note that 'status quo' in this context represents the management scenario of 2012/13 (prior to the east coast cap) which involved a state-wide TACC of 1103 t, no regional commercial management, and estimates of annual recreational catch in East Coast areas 1-3 of 50 t). These were used to create trajectory forecasts for urchin populations, and then to generate a 'likelihood' of widespread barrens formation over time based on the currently observed relationship between urchin density and barrens extent in eastern Tasmania. The use of likelihood forecasts was explained as being useful to dictate the framework in which an "acceptable" level of risk can be agreed upon.

The reverse scenario was examined, where rock lobster densities were 'set' based on different rock lobster fisheries management scenarios, and the likelihood of extensive barrens formation examined under these different scenarios. Some example statistics from this population forecast model were:

- Rock lobster fishing *status quo*:* 39% barren (east coast areas 1-3) by 2021, 49% barren by 2032
- Rock lobster fishing *200 t p.a.* (cap): 31% barren (east coast areas 1-3) by 2021, 20% barren by 2032

*note that this management scenario reflections the status quo of 2012-13 and includes a state-wide TACC of 1103t with no regional commercial management measures.

It was pointed out that although they were developed in completely different ways, both the TRITON model and urchin population model give very similar predictions, e.g. mean cover of 20% urchin barrens with an east coast cap of 200 t.

The difficulty in recovering kelp beds from an 'extensive barrens' state was again visited using this population model. It was demonstrated that, even using a very conservative figure of 0.25 urchins m^{-2} permitting kelp bed recovery, the likelihood of being able to reduce urchins to this density was virtually zero under all rock lobster fishing scenarios.

It was concluded that, because of the strong hysteresis, it is extremely difficult to recover extensive barrens, and the more restraint that is exercised now in rebuilding rock lobster stocks, the greater the long-term benefit to both the ecosystem and the fishery. It was pointed out that modelling suggests it is possible to significantly reduce the risk of urchin barren formation whilst maintaining a viable rock lobster fishery, but that this raises important questions about how to effectively limit the recreational catch so that recreational fishing doesn't simply remove the 'excess' of lobsters as the population rebuilds. It was suggested that this issue was one of the most significant challenges facing management at the moment. Emphasis was also placed on the need to acknowledge that, as more areas shift to extensive barrens, the rock lobster fishery will need to be further reduced in order to maintain the accepted level of risk across the shrinking remaining area of kelp beds.

The question was asked if it would be worth considering total cessation of rock lobster fishing in areas where barrens formation was being observed, and it was noted that this was effectively what had been done in research reserves such as North Bay.

The limitations of the modelling process were briefly discussed, as follows:

- There are currently no empirical demonstrations of the urchin density required for recovery of kelp beds – the TRITON model predicts ~0.20 urchins m^{-2} which accords with Dr Ling's global meta-analysis and other forecasts, but has not been experimentally demonstrated.

- This model applies to the whole east coast area as an overall average, so at a smaller spatial scale there will be deviations from these forecasts.

- It has been assumed that the ecological responses observed in research reserves closed to fishing are representative of the whole east coast, which may not be realistic.

- The model predicts the risk of barrens formation, not a known certainty.

The comment was made that it would be good to quantify an urchin density at which divers engaged in urchin culling can 'move on' from an area, as Victorian divers are currently making judgment calls based on gut feelings rather than scientific assessments.

It was noted that there are currently two different scientific models – TRITON (ecosystem model) and the *Centrostephanus* population model – coming at this problem from different directions, but that the two different approaches were suggesting very similar behaviours.

The comment was made that consistency is required in whether urchin counts or biomass are used as a terminology for urchin density. It was pointed out that average size (and therefore biomass) of urchins varies strikingly across eastern Tasmania, and thus biomass may be a more ecologically relevant metric.

Economic analysis of the direct cost of control scenarios (Professor John Tisdell)

Professor John Tisdell made the forum aware that he is an economist, and thus his biological knowledge of the ecosystem under consideration was based on what had been communicated to him by scientists, industry and management, and was quite basic. The purpose of his presentation would be to demonstrate the use of a new economic model to quantify a direct cost analysis of urchin control measures under a range of different scenarios.

Some of the assumptions made by the model and the limitations of each were briefly discussed. The forum was urged to ask questions and provide feedback on the biological input parameters. Some discussion was had about the specifics of some of the parameters such as rock lobster dollar value after processing (i.e. "net" value). It was emphasised that the use of a spreadsheet format provided full transparency and the flexibility of the tool was demonstrated by modifying input parameters to affect the end value.

The forum was taken through an example scenario for estimating the cost of culling, or fishing, urchins in Tasmania and Victoria. It was demonstrated how this cost could be broken down into a final dollar figure per kg of urchin removed. Professor Tisdell explained that these costings would vary depending on whether the use of a mothership or a small boat was more appropriate for a particular zone, and demonstrated how a target reduction of urchins could be set for individual zones, and the tool used to determine how long it would take (and at what cost), to reduce the current urchin density of that zone down to a user-defined target (of, for example, 0.1 urchins m^{-2}).

It was concluded that commercial harvesting of urchins under a full commercial cost scenario (not subsidised), is not currently financially feasible in Tasmania using the estimates of diver and vessel costings quoted. It was emphasised that this tool was currently populated with current urchin densities and targets for each abalone assessment block, but still requires more accurate estimates of diver costings (and other parameters) which he acknowledged would likely change throughout different assessment blocks.

It was noted that this tool provides an important first step for an elementary costing analysis of both opportunistic smashing and harvesting of urchins in both Victoria and Tasmania, but the point was made that it doesn't currently link into the TRITON model. It was suggested that this would be the next logical stage for the tool, as it would allow a risk framework to be built in. The point was raised that this tool is a **direct costs** analysis, but not a full economic analysis which would require additional considerations such as quantifying the cost of losing more habitat to urchin barrens. The forum agreed that the further development of this tool would require incorporating existing social and recreational values, and the cost of losing or gaining fisheries habitat.

> ***Discussion topic*** *- Structured decision making to inform management strategies (led by Dr. Lucy Robinson & Dr. Martin Marzloff)*

Dr Lucy Robinson explained that her interest in the *Centrostephanus* problem comes from the broader context of using decision processes for considering options for the management of this species as a case study to trial the application of a decision support tool called Structured Decision Making (SDM) that combines decision analysis, behavioural research, and applied ecology, to develop strategies and ultimately make management recommendations.

The steps of the SDM process were outlined as follows:
1) Clarify decision context

2) Define objectives and measures

Two **example** objectives were proposed: (1) to meet a 20% virgin biomass target for east coast rock lobster fishery by 2021; (2) to identify the most cost effective management option to reduce urchin biomass to target density of 0.1 urchins m^{-2} to allow seaweed recovery.

3) Develop strategies

A number of different strategies and scenarios have been bundled into the tool, and it was acknowledged that some may be more useful (and realistic) than others.

4) Estimate consequences

Some coarse numbers were presented in the form of a *consequence table* as an example of output. It was explained that this enables stakeholder groups to see how different performance measures fare under various strategy bundle scenarios. The importance of receiving input from various stakeholder groups on each of the input parameters and objectives was stressed.

5) Evaluate trade-offs and select

This step allows trade-offs based on stakeholder input to be quantified and evaluated. One method called 'swing weighting' was presented, which generates weightings for various performance measures which are used in conjunction with values of the performance measure (as assigned by stakeholders) to generate an overall preference score for each stakeholder.

The forum was invited to provide feedback on whether the concept of this SDM tool was understood, and input was requested. The following comments and questions were raised:

- It was queried whether co-management would need to be in place to effectively implement this tool. It was pointed out that this tool has previously been successfully used in other (non co-management) government contexts, but it was emphasised that a strong involvement and participation of stakeholders is required.

- It was suggested that bringing structure to the existing decision-making processes was useful, and that providing a standardised framework in which to compare different scenarios could be a powerful way of presenting aggregated stakeholder interests to the Minister. Some general discussion followed regarding the use of this tool in helping to create structured and directed discussions, and the advantages in representing the perspectives of all stakeholders on a "single piece of paper".

- The comment was made that adoption of decision-making methodology is extremely difficult in the political environment of fisheries management, as individuals or groups dissatisfied with the outcome of a SDM process may attempt to bypass the process and seek political intervention. The important point was raised that, while ultimately management decisions lie with the Minister, all individual stakeholders must first unanimously support the use of the tool in order for the Minister to endorse the use of decision making methodology.

- It was clarified that expressions of interest in the tool by the forum were not commitments to use it, but a gauge of interest and support at this point in time to determine whether efforts should be invested in further developing the tool.

- The question was asked as to how the initial objectives would be derived. It was explained that this was up to the individual stakeholders and what they thought would work best, but the use of one-on-one discussions was suggested. There was some discussion about whether consultation with a single spokesperson from each stakeholder would be sufficient, or whether feedback should be sought within stakeholder groups rather than from a single representative. There was some concern that obtaining feedback from all stakeholders could be a lengthy process and thus consultation with a single spokesperson for each was recommended, with the suggestion to restrict feedback sourcing to the people in attendance at the current workshop. It was suggested that the ad-hoc *Centrostephanus* working group might be a good forum for stakeholders to put forward their objectives within a defined time frame.

- There was some question about why multiple objectives were needed, when the primary interest of all stakeholders is to keep urchin density below a level in which destructive grazing, and hence barren formation, occurs. It was explained that there is a lot of flexibility in setting objectives, and the SDM process could be performed with a single objective (and multiple strategy bundles) if agreed upon by all stakeholders, or multiple objectives could be specified and evaluated if consensus could not be reached.

- It was commented that different management actions may need to be applied at different times as part of a single action plan, as some steps may have an immediate effect while others may take several years.

- It was suggested that the pilot study would provide a useful a "proof of concept" of the tool; after obtaining these preliminary results a draft a proposal of what could be achieved if the model were allowed to expand could be provided to determine if there was support for further development of the concept.

There was some discussion about how long the process might take, as the importance of making prompt management decisions was becoming increasingly evident. It was estimated that the pilot study would be completed over the next 2 months, but whether this would be subsequently expanded to a full study depends on the interest of stakeholders. There was some hesitation from the forum in expressing interest in the tool, but after reassurance that this did not lock any stakeholders into accepting the use of the tool at a later date, all representatives agreed to provide information for the pilot study when requested by Lucy or Martin, and judgment on future use of the tool could be reserved until after seeing the outcomes of the pilot study. It was clarified that this tool was not intended to provide a single management solution, but to facilitate the decision making process.

> ***Discussion topic -*** *Summary and implications of knowledge gaps and planned research (knowledge gaps and research prioritization led by Professor Craig Johnson & Ian Cartwright)*

Craig Johnson provided an overview of research planned and currently taking place to move forward with the *Centrostephanus* issue.

PROPOSED RESEARCH #1: Regional model for decision support
Different areas of the east coast have different dynamics, and not all areas will respond to urchin grazing and management in the same way. A regional model will enable different spatial management to be applied to different areas. It requires the following components:

1. A fine-scale map of current urchin barrens extent on the east coast, with priority given to the area ~10-30 m depth. The regional map will be used to validate models, and as a starting point for future projections. Acoustics are proposed to generate these maps, which can detect urchin barrens with ~75% accuracy.

2. Empirical estimates (not just those derived from TRITON) of the target urchin density that will allow recovery of seaweed in extensive barrens areas.

3. More data on how the urchin larval characteristics (development rates and survivorship) change with temperature in the context of predicted climate change for this area.

These components will allow a series of independent local models to be run in small blocks spanning the east coast. These blocks will connect with each other via larval advection simulations, and will deliver region-specific projections. Once the biological models have been created, a number of different management scenarios can be run, and then linked in with a full economic model.

The costs of creating the regional model over a 4 year period were discussed. Craig expressed an intention to apply for ARC Linkage funding, but explained that success of this application will depend on some financial contribution from 'industry' (non-university) source(s).

PROPOSED RESEARCH #2: Maintaining research sites (+ model validation)
The importance of continued reporting and monitoring of North Bay and Elephant Rock research reserves was stressed. Craig will be attempting to source funding to continue this.

PROPOSED RESEARCH #3: Monitoring of urchin population development
The last time extensive urchin surveying was conducted was in 2001, which allowed determination of detailed population structure. Re-surveying of these areas is critical to get an indication of population development. Funding for this is not currently secured.

Some general discussion took place. The concern was raised that the recreational rock lobster catch will increase under the east coast cap, and that this needs to be limited in some way to ensure that the total catch does not exceed 200 t. The point was raised that efforts should focus on rebuilding lobster densities in the depth zone 0-40 m where urchins are most problematic, and that management efforts should be largely restricted to this depth zone. It was queried whether steps had been taken to prepare for potential issues

with boat fleet management as rock lobster biomass increases under the east coast cap, but it was explained that the regional based modelling incorporates changing fleet dynamics (targeting of prime areas and moving on).

The forum discussed where they thought the biggest gaps in knowledge were and the following research prioritization table was drawn up, with a representative from each of the different stakeholder groups identifying their highest priorities (1-5, with 1 as highest priority).

Research gap, or *current barriers to progress*	Abalone (commercial)	Centro divers	DPIPWE	TCT	Recreational	Rock lobster
Locating source reefs for Centro spawning biomass				5		
Resource sharing as recreational catch increases under east coast CAP			2	3		1
Habitat mapping and regional modelling	1	1	1	2	1	2
Effect of rock lobster predation on other key species as biomass increases						
Monitoring urchin settlement (post-recruitment) and a "stocktake" (age and size structure)		4			2	4
Urchin density that is "economic" for fishers vs density necessary to avoid barren formation						
SDM (Structured Decision Making)		3		1		
Shallow water rock lobster density on a large scale (beyond intensely targeted research sites)				4		
Achieving consensus between stakeholders on what to do / who pays		2	3		3	3
Communication, establishing "pet patches" etc.						5

Mapping the extent of urchin barrens and feeding this information into regional models was identified as the top research priority across the majority of stakeholders from the list above.

The important point was raised that discussions should take place between research and other stakeholders to determine how to maximise the chances of success at obtaining research grants to conduct the barrens mapping project. Some discussion took place about the importance of financial contributions from external stakeholders.

A number of attendees during the meeting expressed frustration at what they perceived as a lack of action on urchin management. However, at various points during the day it was noted that some actions had been taken, including a decision on a range of measures to restrict the catch of rock lobster as part of a strategy to rebuild East Coast rock lobster stocks. Multiple models predict that the catch cap measure on commercial fisheries measure is likely to have a more significant impact on *Centrostephanus* than any other alternatives at this time. It was further noted that there will be pressure on that strategy over time, as recreational catch and effort increase as stocks improve. Other current actions raised included support for a commercial *Centrostephanus* fishery (including a FRDC project), and the active trialing and quantitative analysis of culling, both by commercial divers during fishing and as a dedicated process.