Australia's National Science Agency

Strategies for the management of *Centrostephanus rodgersii* in Tasmanian Waters

Integrating ecological, economic and operational drivers for an adaptive approach to pest management

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June 2022

A report for the Abalone Industry Re-Investment Fund

Citation

Westcott DA, Fletcher CS, Chades I (2022) Strategies for the management of *Centrostephanis rodgersii* in Tasmanian Waters. CSIRO, Australia.

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Acknowledgments

This work was funded by the Abalone Industry Re-Investment Fund with support from the Tasmanian Government’s Department of Primary Industry, Parks, Water and the Environment. We are very grateful for the advice, expertise and good humour of the Officers of Water and Marine Resources Division of the Tasmanian Government’s Department of Primary Industry, Parks, Water and the Environment. Members of the Abalone Industry Re-Investment Fund Board provided critiques and advice as did a range of industry and research stakeholders and participants in the 2019 Centrostephanus Forum. We are extremely grateful for all these contributions.

Executive summary

Average ocean temperatures of coastal waters off eastern Tasmania have increased rapidly over the past several decades, and are projected to continue to warm by almost four times the global average rate in future, exacerbated by marine heatwaves that can raise ocean temperatures more than 2 °C above climatology. These changes have impacted marine ecosystem health, marine habitats and species, depleting kelp forests, and facilitated a poleward shift in some marine species, including the long-spined sea urchin, *Centrostephanus rodgersii* (*C. rodgersii* or Centro).

The expansion in range of *C. rodgersii* into Tasmanian waters constitutes a significant risk to the ecology of the Tasmanian reef ecosystems dealing with multiple stressors. Since its first record in the 1970s, *C. rodgersii* has invaded and overgrazed several hundred kilometres of Tasmanian coastline. Overgrazing results in the formation of 'barrens', transforming healthy kelp beds into low productivity rocky ecosystems. Once formed, reversing barrens to former kelp beds ecosystems is a challenging process that requires maintaining *C. rodgersii* densities at very low levels for significant periods.

Without intervention urchin barrens will continue to expand with the distribution of *Centrostephanus rodgersii*, further impacting Tasmania's rocky reef ecosystem, its existing fisheries, tourism and the livelihoods of the people that depend on this ecosystem. Unfortunately, there is no simple permanent solution; *C. rodgersii* cannot be eradicated and its persistence in Tasmanian waters will be further reinforced with on-going ocean warming. Moreover, these negative impacts are partially offset by the fact that *C. rodgersii* has itself become a targeted fisheries species in Tasmanian waters. Despite these complexities, a properly designed ongoing control program could reduce the impacts of *C. rodgersii* meaningfully at specific locations, or even across large regions with appropriate resourcing.

In short, a coordinated strategy is needed to control the spread and impact of *C. rodgersii* to ensure its densities are maintained below key ecological threshold densities (i.e., the densities at which barrens form or recover), and that biodiversity, social and economic values are protected. These issues have been the subject of significant industry discussion and of two forums attended by a wide spectrum of stakeholders, researchers and Government, the general consensus of which has been that some form of management intervention is required. Exactly what form that response should take, however, has been unclear and is complicated by a divergence in the perspectives and preferred outcomes of the different stakeholders. Lobster and abalone fishers, along with those concerned about biodiversity, see *C. rodgersii* as a threat, whereas the urchin fishery, while acknowledging and concerned about its impacts, see *C. rodgersii* as a commercial opportunity.

In its 2018-2019 Budget the Tasmanian Government made a significant co-investment into the Abalone Industry Reinvestment Fund with the Tasmanian Abalone Council Ltd as part of a co-management approach involving the Government, the abalone industry, and other stakeholders including other industry groups and researchers. Several priority initiatives were identified, with one key priority being the development of a Centrostephanus Response Strategy to guide on-going management and research to support it.

This report outlines this Centrostephanus Response Strategy, a key component of which is the development of the strategy for a Centrostephanus Control Program (CCP). The report is the product of a process that has involved:

i) Formal and informal discussions and workshops with Government, Industry and research stakeholders
ii) Attendance and participation in AIRF Forums and Meetings
iii) A review of related scientific and grey literature

iv) Review and analysis of existing data from *C. rodgersii* control and research programs
v) Application of extensive past experience in designing and implementing large-scale, successful marine pest management programs.

The report begins by reviewing the current understanding of key biological and ecological processes driving the invasion in Tasmanian waters, as well as interactions between current marine industries. It summarises the fundamental principles of ecologically-informed pest management and how these principles would apply in the specific case of *C. rodgersii*. It then considers the objectives of the CCP and the likely values that it would seek to protect before considering the implications of these various factors for how the program should operate and the likely control methods to be used. This includes identification of key ecological drivers and the management thresholds that need to be targeted to achieve ecologically-meaningful outcomes. We use this information as a foundation for the development of two strategies for implementing *C. rodgersii* control on Tasmania's east coast. The strategies developed reflect two different levels of resourcing and centralised planning and control. These strategies are further operationalised in the companion DNRE report '*An operational plan for Centrostephanus control*'.

The first strategy is an 'Initial Implementation Strategy' and would function to transition control activities from an unstructured harvest to a structured and strategic approach to *C. rodgersii* control, one that would achieve CCP objectives today while serving as a foundation for CCP refinement and expansion. This strategy is based on current *C. rodgersii* control capacity and arrangements but provides a framework to ensure that control is targeted at priority locations, and, where control investment is made, that it achieves ecologically meaningful outcomes and does so efficiently. Implementing this program would incur some additional costs and require some changes to current operations, but these would be reasonable. The strategy outlined could be implemented almost immediately.

The second strategy outlines a Full-Scale Program managed and implemented at a state-wide scale, with potential links to a larger multi-state initiative, and is clearly a longer-term prospect requiring significant resourcing and development. Because the resourcing and arrangements that would ultimately define such a program are not currently known, we have described this program in general terms only. Importantly, although the two strategies could be implemented independently, they are also designed to be implemented sequentially; instituting the Initial Implementation Strategy in the short-term would both make significant progress in controlling *C. rodgersii* at key locations, while simultaneously building vital experience and relationships while collating information on a range of key parameters important to the effective implementation of a Full-Scale Program.

Finally, the key research gaps required to underpin the successful implementation of these two strategies are identified.

In summary, this report outlines strategies for developing and implementing *C. rodgersii* control in Tasmanian waters at two scales. These strategies are based on an understanding of the system's processes and dynamics and form a comprehensive, integrated and action-oriented framework targeted to efficiently achieve the AIRF's three stated, strategic objectives: i) stop growth of existing barrens, ii) prevent establishment of new barrens, and, iii) promote recovery of full barrens.

1 Introduction

Average ocean temperatures of coastal waters off eastern Tasmania have increased rapidly over the past few decades (Hobday and Pecl 2014) and are projected to continue to warm by almost four times the global average rate in future (Ridgway 2007), exacerbated by marine heatwaves that can raise ocean temperatures more than 2 °C above climatology (Oliver et al. 2018). These changes have impacted marine ecosystem health, marine habitats and species, depleting kelp forests (Mabin et al. 2019), and facilitated a poleward shift in some marine species (Johnson et al. 2011, Hobday and Pecl 2014).

One of these, the long-spined sea urchin *Centrostephanus rodgersii* (*C. rodgersii* or Centro), is a recently arrived species in Tasmania's marine ecosystems, and in particular, its rocky reef habitats (Ling et al. 2008, Ling et al. 2009c). While it is a recent arrival, *C. rodgersii* is not an introduced species, but rather has extended its range from mainland Australia south into Tasmanian waters and established itself there since the late 1970s (Department of Primary Industries 2018). This range extension appears to have been driven by warming waters off the east coast and the influence of a stronger East Australian Current down the east coast of Tasmania (Ling et al. 2009c, Johnson et al. 2011).

Centrostephanus rodgersii constitutes a significant risk to the ecological balance of the important Tasmanian rocky reef ecosystems, both in its own right, and as a compounding factor exacerbating other threats. Once established on a reef, *C. rodgersii* graze on kelp and other marine plants resulting in what are referred to as 'urchin barrens' (Andrew 1993, Johnson et al. 2005, Andrew and Byrne 2007, Ling 2008b). These are areas of rocky substrate that are devoid of emergent macro-algae and seaweeds and have associated with them similarly depauperate ecological communities. The formation of urchin barrens impacts not only the biodiversity of rocky reef habitats (Ling 2008a, Ling and Johnson 2009) but also has major and negative consequences for important recreational and commercial fisheries, particularly abalone, rock lobster and some scale fish species (Pecl et al. 2009, Strain and Johnson 2009, Gorfine et al. 2012, Holbrook and Johnson 2014). This fisheries impact is to some extent offset by the fact that *C. rodgersii* is itself a targeted fisheries species in Tasmanian waters and one with emerging uses and markets. Recent surveys of the east coast indicate that the species' range continues to expand and that its population density within that range continues to increase. Associated with this has been an increase in the number and size of individual barrens and a commensurate increase in the proportion of rocky reef that has converted from kelp dominated to urchin barren.

Evidence from elsewhere in the world indicates that, without intervention or changes in ecological function, urchin barrens will continue to expand, with the potential to spread along much of Tasmania's east coast (Filbee-Dexter and Scheibling 2014). This is an alarming prospect given the now substantial scientific literature on the impacts of *C. rodgersii*'s expansion on ecological processes, biodiversity, key fisheries and social and economic activities (Andrew et al. 1998a, Johnson et al. 2005, Ling 2008b, Ling et al. 2009a, Strain and Johnson 2009, Gorfine et al. 2012, Madin et al. 2012, Department of Primary Industries 2018). Unfortunately, there is no simple solution; *C. rodgersii* cannot be eradicated and its persistence in Tasmanian waters will be further reinforced with on-going ocean warming. As a consequence, the focus of any intervention needs to be on minimising the species' impacts.

These issues have been the subject of significant industry discussion and of two forums attended by a wide spectrum of stakeholders, researchers and Government, the general consensus of which has been that some form of management intervention is required (Department of Primary Industries 2018). Exactly what form that response should take, however, is unclear and is complicated by a divergence in the perspectives and preferred outcomes of the different stakeholders. Lobster and abalone fishers along with conservationists see *C. rodgersii* as a threat whereas the urchin fishery, while acknowledging and concerned about its impacts, see *C. rodgersii* as a commercial opportunity (Department of Primary Industries 2018, Cartwright et al. 2019b).

In its 2018-2019 Budget the Tasmanian Government made a significant co-investment into the Abalone Industry Reinvestment Fund with the Tasmanian Abalone Council Ltd. The AIRF governance model is a co-management approach of cooperative planning and expenditure between the Government and the abalone industry, with scientific input provided by IMAS and other researchers. The broad objectives of the fund are to support and increase the sustainability and productivity of the abalone fishery both biologically and economically. The abalone industry has identified a number of initiatives which should be among a suite of projects developed. One such area is addressing the impacts of *Centrostephanus* and a key priority identified was the development of a comprehensive Centrostephanus Response Strategy.

In this report, we outline a Centrostephanus Response Strategy that is a comprehensive, integrated and action-oriented framework targeted to achieve the AIRF's three stated, strategic objectives: i) stop growth of existing barrens, ii) prevent establishment of new barrens, and, iii) promote recovery of full barrens. The strategy canvases the full suite of potential management response options in the near and longer term. The strategy integrates knowledge, expertise and resources from a range of sources to describe the structure of a Centrostephanus Control Program (CCP) that would address the threats posed by *C. rodgersii* and identifies the research gaps that inhibit its effective implementation. The strategy is focused on achieving in-water outcomes that directly contribute to the strategic objectives of the program but is intended to be adaptive to ensure on-going refinement and improvement as well as allowing responsiveness to changing values and drivers. The principles and design of the strategy outlined is further operationalised in the companion DNRE report '*An operational plan for Centrostephanus control*'.

2 Background (Ecology)

2.1 The Problem – *Centrostephanus rodgersii* in Tasmania

The long-spined sea urchin, *Centrostephanus rodgersii,* was first recorded in far north-eastern Tasmanian waters in the 1970s and from the east coast of Tasmania itself in 1978. Native to New South Wales, *C. rodgersii* has since expanded its range to south-eastern and south-western Tasmania (Cartwright et al. 2019a). *Centrostephanus rodgersii* has since invaded and overgrazed several hundred kilometres of Tasmanian coastline. Overgrazing results in the formation of 'barrens', transforming healthy kelp beds into low productivity rocky ecosystems. Once formed, reversing barrens to former kelp bed ecosystems is a challenging process that requires maintaining *C. rodgersii* densities at very low levels for significant periods; typically these densities are much lower than the densities at which barrens form (Filbee-Dexter and Scheibling 2014, Ling et al. 2015, Ling et al. 2019). A coordinated strategy to control the spread and impact of *C. rodgersii* is needed to ensure its densities are maintained below threshold densities of barren formation, and biodiversity, social and economic values are protected.

2.2 Urchins and urchin barrens

Sea urchins (Echinodermata: Echinoidea) are a highly diverse and ecologically important group of invertebrates found in marine habitats throughout the world's oceans, particularly on hard substrata. Urchins play a key role in marine food webs both as prey and as grazers (they are largely herbivorous) and are particularly noteworthy in that when sufficiently abundant they can act as ecosystem engineers, markedly altering habitat structure. These impacts have been reported in both tropical and temperate ecosystems but are particularly common and pronounced in coastal temperate and boreal kelp forest ecosystems where their grazing can remove virtually all macroalgae creating alternate habitats known as urchin barrens. Barrens can be extensive and persistent, leading to the characterisation of kelp forests and urchin barrens as alternate stable states on temperate reefs (Miller 1985, Filbee-Dexter and Scheibling 2014, Ling et al. 2015). The topic of alternate stable states in Kelp/Urchin systems has received considerable scientific attention over the past 50 years both because of the significant economic and ecological changes that are associated with the transition from kelp forest to urchin barrens, but also due to the intrinsic interest in the topic of alternate states from a scientific and theoretical perspective (Filbee-Dexter and Scheibling 2014, Ling et al. 2015).

Kelp provides habitat and food resources for a host of other plants and animals and its loss from temperate coastal habitats can cause reductions in both biodiversity and productivity, including impacts on fisheries (Breen and Mann 1976, Andrew et al. 1998a, Johnson et al. 2005, Pecl et al. 2009, Gorfine et al. 2012, Holbrook and Johnson 2014). Consequently, there has been a desire to understand and manage these impacts. As in other parts of the world, the expansion of urchin barrens in Tasmania has raised concerns about biodiversity as well as the sustainability and profitability of existing fisheries that rely on Tasmania's kelp forest ecosystems. There has been significant research carried out on the functioning of Tasmanian reef ecosystems and the interactions of *C. rodgersii* with its key components (kelp, abalone, lobsters) (e.g., Johnson et al. 2005, Ling 2008b, Frusher et al. 2009, Banks et al. 2010, Johnson et al. 2011, Flukes et al. 2012, Johnson et al. 2013, Ling et al. 2018, Cartwright et al. 2019b).

Hypotheses to explain the processes leading to the formation and persistence of barrens, and their reversion back to kelp forest, include both natural and anthropogenic factors and range from broad-scale regime shifts, e.g. climate driven, to the loss of top-down control of urchin populations (Filbee-Dexter and Scheibling 2014). A commonly identified driver of the transition from rocky reef to barrens habitat has been the loss of the top-down control exerted on ecosystems by predators, e.g. through fishing or other harvest, or disease (Estes and Palmisano 1974, Duggins 1981, Schultz et al. 2016, Burt et al. 2018). The re-introduction of top-down control, e.g. through recovery or establishment of predator populations (Estes and Palmisano 1974, Blamey et al. 2013, Smith et al. 2021) or the introduction of urchin harvest (Steneck et al. 2013), generally results in recovery of kelp. These interactions can be modified by the interaction between predation and ocean warming and its impact on both predator and kelp populations (Bonaviri et al. 2017, Rogers-Bennett and Catton 2019).

While barren recovery has been observed when urchin populations are reduced, this can require very major population reductions. This is because the barren formation / recovery process appears to operate as a discontinuous phase shift process (Scheffer et al. 2001), i.e. a process where the pressure to move the system from one state to another is less than the pressure required to return it to the original state. In the case of urchin barrens, the grazing pressure required to drive the transition from a stable kelp state to a barren stable state is lower than the kelp recovery pressure require to restore a barren to a stable kelp ecosystem. In Tasmania, evidence of discontinuous phase shift was provided by Ling et al. (2009a, 2015) who estimated that urchins become incapable of maintaining barrens at a biomass below approximately 70 g m^2, whereas the biomass of sea urchins required to form barrens in the first instance is approximately 700 g m^2. While this is certainly a consideration in the development of management strategies, examples of both natural and anthropogenically driven transitions from barrens to kelp from around the world clearly indicate that such a transition is feasible (Estes and Palmisano 1974, Steneck et al. 2013, Bonaviri et al. 2017, Smith et al. 2021)

2.3 *Centrostephanus rodgersii* Biology and Ecology

2.3.1 **Affinities and distribution**

Centrostephanus rodgersii is a relatively large and robust urchin found on the coasts of south-eastern Australia and north-eastern New Zealand. It is a member of the family Diadematidae, and the genus is found in the north Pacific (*Centrostephanus coronatus*) and Indian Oceans (*Centrostephanus tenuispinus*). *Centrostephanus tenuispinus* is very similar to *C. rodgersii* and is endemic to the temperate west coast of Australia. On the Australian east coast, *C. rodgersii* is now found as far north as the Solitary Islands, and as far south as the south-western corner of Tasmania (Ling et al. 2009c). Its range has been expanding rapidly southward along the Tasmanian coast over the past 15 years. Densities of *C. rodgersii* in New Zealand and eastern Australia are relatively low although they do occur in small aggregations around topographic features such as ledges and boulders. High densities of *C. rodgersii* leading to barrens formation occur only in south-eastern Australia.

The behaviour of *C. rodgersii* is typically nocturnal. Individuals seek shelter during the day in crevices or under and around boulders, foraging outward at night over distances of up to 10m to feed. In some high-density barrens populations, the use of crevices or other shelters by larger (>60mm TD) "emergent" urchins may not be obligate (Andrew and O'Neill 2000, Johnson et al. 2005, Ling and Johnson 2009). The underlying causes of these differences and the extent to which they relate to variations in predator abundance are not understood.

2.3.2 **Life-history**

Centrostephanus rodgersii is a typical echinoid in that it has separate sexes with external fertilization and a planktotrophic larval phase (Byrne and Andrew 2013). At settlement *C. rodgersii* are approximately 0.5 mm diameter, but grow rapidly in the first year (Andrew and Underwood 1993). Juveniles recruit into adult habitat and appear to require shelter showing a strong preference for the same shelters as adults, although they do not appear to require the presence of adults for shelter as seen in some other urchins. Growth can be relatively rapid over the first 7-8 years (Andrew and Byrne 2007). In Tasmanian water, however, studies estimate growth of up to 50mm test diameter (TD) in the first 4-5 years followed by slower growth to an estimated average maximum TD of 114 mm within 25-35 years (Byrne and Andrew 2013). Growth appears to be faster in warmer waters (Pecorino et al. 2012) but larger maximum sizes are reached in cooler waters with maximum recorded TD of 120 and 133 mm in NSW and Tasmania respectively (Ling and Johnson 2009, Pecorino et al. 2012). Asymptotic size is approached at around 100-120mm TD and individuals can live for more than 35 years (Byrne and Andrew 2013).

2.3.3 **Reproduction and larval development**

Gonad development in *C. rodgersii* commences at around 40-60mm test diameter, or around 3-4 years of age (Ling 2008b, Pecorino et al. 2012), although at 50mm not all individuals spawn reliably. Gonad development accelerates in May during autumn (Byrne and Andrew 2013) and final maturation of gametes appears to be related to (and likely regulated by) day length, as gamete maturation is initiated in the weeks before the winter solstice and spawning appears to occur only after the shortest day of the year, regardless of temperature (Byrne and Andrew 2013). The spawning season is relatively short in the northern extent of the species' range, lasting perhaps a month, but is more extended in the southern parts of its range where spawning lasts for some 3-4 months, up to November in southern Tasmania (Byrne and Andrew 2013). It is not clear whether there is any diel or lunar pattern in the timing of spawning within the season, but *C. coronatus* on the north pacific California coast shows a clear lunar periodicity in spawning (Kennedy and Pearse 1975).

Fecundity, that is the number of eggs spawned per season by *C. rodgersii,* is not known, nor is anything known in relation to the factors that affect fertilisation success (i.e. synchrony of spawning, minimum densities for successful fertilization). Data on both egg production and fertilization success are key factors to understand if populations are to be successfully managed in relation to limiting larval production and recruitment of this species.

Larval development proceeds via a somewhat unusual two-armed larval form *(Echinopluteus transversus)* that allows *C. rodgersii* larvae to be identified visually in plankton samples (Doo et al. 2012, Byrne and Andrew 2013). Larvae have a particularly long larval development phase of 3 - 4 months, providing the potential for large dispersal distances, and metamorphosis can be induced by the presence of a range of macroalgae and algal products (Swanson et al. 2012). Larvae of *C. rodgersii* respond morphologically to variations in food availability but critical food concentrations for successful development are not well understood. Normal larval development occurs between temperatures and 12 and 21 C but is negatively affected by increasing pH (Ling et al. 2008, Doo et al. 2012).

2.3.4 **Diseases**

Diseases of *C. rodgersii* have not be reported in the literature although the north Pacific congener *C. coronatus* suffers from parasitic infestations of the gonads (Pearse and Timm 1971). These do not appear to always be lethal but have detrimental effects on individual reproductive output (Hagen 1995). The presence of such parasitism in populations could be highly problematic for the development of urchin roe fisheries and may have consequences for the potential for such an industry.

2.4 Ecology

2.4.1 **Diet**

Experimental studies have shown that the kelp *Ecklonia radiata* is the preferred food of *C. rodgersii,* and though other brown algae were consumed in roughly similar proportions, some species (e.g. *Sargassum vestitum*) are less preferred (Hill et al. 2003). These preferences did not appear to be significant in the field. Red algae are also readily consumed by *C. rodgersii* (Andrew and Underwood 1993, Strain and Johnson 2009), which is also reported to graze on invertebrates opportunistically (Byrne and Andrew 2013). These preferences are important as the dominant kelp *E. radiata*, and to a lesser extent the large fucoid brown algae such as *Sargassum* spp., are important habitat formers along the coasts of temperate south-eastern

Australia. Average daily consumption of algae by urchins in experimental conditions has been measured at 3.23 $g.day^{-1}$ (Hill et al. 2003).

2.4.2 **Population dynamics**

Recruitment of *C. rodgersii* appears to be variable and episodic from one year to the next, at least based on observations of juvenile urchins (Byrne and Andrew 2013). Such variability in recruitment is common in echinoderms (Uthicke et al. 2009). Little is known about the spatial variability in settlement and recruitment of *C. rodgersii* and whether such variability shows any consistent patterns.

Competition for food is a major factor limiting growth of *C. rodgersii*, with variations in density resulting in pronounced differences in growth rate (and gonad mass) in both experimental and natural settings (Byrne and Andrew 2013). Growth and size of urchins in barrens habitats is less than in habitats with ample algal cover (Ling et al. 2009c), and changes in algal density of as little as 33% have produced a doubling of growth rate (Blount and Worthington 2002). Due to their dependency on shelter, particularly at small sizes, *C. rodgersii* may also compete for shelter space, potentially creating bottlenecks in populations when smaller urchins cannot access suitable shelters (Byrne and Andrew 2013). Evidence of such bottlenecks may exist in the form of population structures lacking small individuals, although such populations may also be the result of episodic settlement, or even simple asymptotic growth of long-lived individuals.

The average density of *C. rodgersii* in barrens habitat in NSW has been reported as approximately 6 m^{-2} but densities of up to 60 m^{-2} have been recorded in some barrens (Andrew et al. 1998a, Johnson et al. 2005, Ling and Johnson 2009). Barrens in Tasmania commonly support urchin densities of 1.9 – 2.3 m^{-2} (Johnson et al. 2005, Johnson et al. 2011). Because of the reliance of *C. rodgersii* on shelter, distribution is rarely uniform and, consequently, reducing measures of population density to a single figure is an oversimplification of a complex set of factors that may influence distribution and limit urchin growth and reproductive output, as well as modifying kelp forest habitat (see below).

2.4.3 **Habitat preferences**

Wave exposed marine coastlines with rocky substrates are preferred by *C. rodgersii* over more sheltered and estuarine habitats, which are subjected to higher rates of sediment accumulation and periodic freshwater inundation (Andrew and Byrne 2007). The upper depths inhabited by *C. rodgersii* are generally delimited by the subtidal algal fringe habitat dominated by a mixture of fucoid algae down to depths of approximately 5m (Underwood et al. 1991). Within this fringe, the higher wave activity and associated sweeping of algal fronds restricts the movement and feeding of urchins. Consequently, the actual depth of the shallow fringe habitat varies according to wave action and the topography of the shore in terms of what shelter it may provide. Below these depths, *Ecklonia* begins to become the dominant algae and urchins are able to move more freely to feed and, given the opportunity, to create barrens habitat. Habitats at these depths form a mosaic of kelp forests and other algae, and urchin dominated barrens of varying sizes, ranging from small cleared areas around shelter to extensive full urchin barrens (Andrew 1994).

Within their current range, the extent to which urchins dominate and form barrens is largely determined by the amount of shelter present. *C. rodgersii* is most abundant in depths of between 10 and 20-25m (Byrne and Andrew 2013, Ling and Keane 2018), although it is present at depths of up to 50m (Beaman et al. 2005), and where light and algal growth permit it is reported to form barrens even at these depths. Barrens at depths of 40m are common on the Tasmanian east coast (Ling and Keane 2018). Urchin densities measured on Tasmanian east coast reefs in 2016-17 peaked in the 12-18m depth strata, declining gradually to less than 10% of those values at 40m (Figure 1) (Ling and Keane 2018). The formation of barrens at these depths is presumably due to the lack of light and reduced algal growth meaning that fewer urchins are necessary to overgraze the algae. *Centrostephanus rodgersii* barrens could ultimately account for 50% of all rocky reef in eastern Tasmania (Johnson et al. 2005, Johnson et al. 2011), as observed in New South Wales (Andrew and O'Neill 2000).

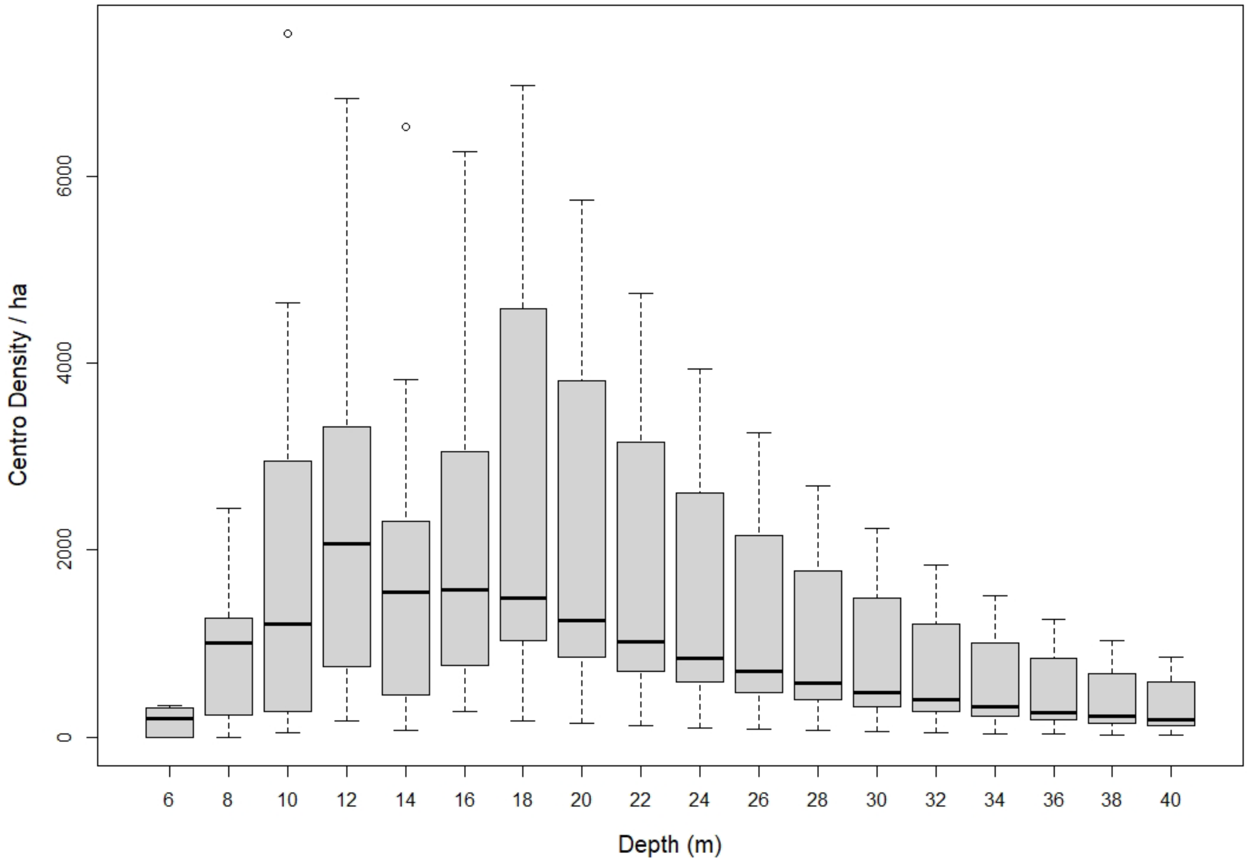


Figure 1 Distribution of *C. rodgersii* densities across the depth profile at 21 sites surveyed by Ling and Keane (2018). The plots show the median density (dark bar), quartiles (boxes), outliers (whiskers) and extreme values (circles).

2.4.4 Drivers of barren formation / ecological dynamics

The creation of urchin barrens in Tasmania has been closely associated with the recent warming trends in sea surface temperature experienced globally, but more particularly with the accelerating extension of the East Australian Current (EAC) south along the Australian east coast (Ling et al. 2009c). This has created larval supply conditions necessary for establishing large urchin populations in Tasmania. Despite the presence of large urchin populations along the Tasmanian coast, it is likely that temperatures are often too cool during the spawning period for successful larval development and that the Tasmanian populations may continue to be largely seeded by populations in the Bass Strait or even further north (Ling 2008a). Despite this, it is highly likely that large populations of urchins would not have become established, and barrens would not have developed, without the presence of other factors that allowed them to flourish. The principal factor among these is the reduction in the number of natural predators, particularly lobsters (Ling et al. 2009a).

Lobsters in general are known predators of urchins, and the southern rock lobster, *Jasus edwardsii, is* an effective predator of *C. rodgersii*. Significant ecological research and management practice has been invested in lobster protection and translocation measures in Tasmania in recent years (Johnson et al. 2013, Marzloff et al. 2013, Wild Fisheries Management Branch 2018, Ling and Keane 2021a). Large lobsters (>140mm carapace length - CL) are able to overcome and consume even emergent urchins >60mm TD (Ling et al. 2009b). However, research suggests that C. rodgersii are not the preferred prey of lobster when alternatives exist (Smith et al. 2022), and the population of *J. edwardsii* in fished areas of Tasmania contains few lobsters above the minimum legal size of 105mm CL for females and 110mm CL for males (Ling et al. 2009a). Modelling of kelp-urchin-lobster interactions indicates that lobster predation by populations with a more natural (unfished) size structure could prevent barrens formation (Marzloff et al. 2013). However, modelling also shows that even significant rebuilding of lobster populations can take many decades to generate meaningful seaweed bed restoration in established barrens (Johnson et al. 2013, Marzloff et al. 2013), and the chances of recovering from extensive barrens solely through rebuilding lobster stocks are relatively low (Marzloff et al. 2013).

The lengthy period of time estimated for Tasmanian reef recovery from the barrens state to kelp forest is a characteristic of observations in other urchin dominated kelp ecosystems globally (Filbee-Dexter and Scheibling 2014, Ling et al. 2015). Kelp-Urchin dynamics display a high level of hysteresis or asymmetry in the densities at which state transitions occur, and urchin densities must be far lower in order for kelp to recover than those that are required to create barrens (Ling et al. 2015). Determining precise estimates for the densities of urchins required to trigger transitions between barrens and kelp dominates states is difficult because they will, in general, depend on the productivity of kelp forests, and the size distribution of urchins. However, for the Tasmanian system, urchin densities required to create barrens reported in the literature range from 4 – 10 m^{-2} (Filbee-Dexter and Scheibling 2014, and references therein), are maintained at approximately 0.8 - 1.6 m^{-2} within barrens (Flukes et al. 2012, Johnson et al. 2013), and must be reduced to by roughly an order of magnitude to as low as 0.2 – 1.2 m^{-2} for kelp to return (Filbee-Dexter and Scheibling 2014). Furthermore, predator populations may take a time to recover (Babcock et al. 2010), although this could be accelerated with stock rebuilding and targeted translocation efforts, such as those occurring for lobster (Wild Fisheries Management Branch 2018). There may also be effects relating to facilitation of kelp recruitment, whereby kelp propagules require the presence of other kelp or macroalgae in order to successfully recruit (Layton et al. 2019).

3 General principles for Centrostephanus management

In Section 2 we outlined the background ecology and biology of both *C. rodgersii,* its impact on rocky reef communities and our current understanding of the drivers of urchin-kelp interactions. This information provides us with much of the key background systems information required in designing an effective control program. In this Section, we outline some of the key guiding principles that underpin an adaptive and ecologically-based approach to pest management and, in the light of our understanding of *C. rodgersii* and current and likely future options for its management, we develop recommendations for what are essentially a set of guiding principles for the operation of a Centrostephanus Control Program. These principles outline the broad characteristics of the Control Program's approach, rather than going into the specifics of how particular actions are done. These specifics are considered in more detail in Section 4 for overarching decisions and in Section 5 for the operations of the program.

3.1 Control Program objectives

Defining the objective of a Control Program is a fundamental step in developing an implementation strategy, and prioritising research that will, in turn, inform further strategy development (Canessa et al. 2015). Identifying explicit objectives is important to establish clear and common goals for all stakeholders and in determining what the Program outcomes will look like.

In specifying Program objectives it is important that consideration be given to the natural scales of management implied by the ecological processes driving the system (Fletcher and Westcott 2013). It is these scales which determine what is feasible in any given context and, hence, what realistic objectives might actually be. At the start of a new Control Program, the specifics of the relevant processes will often not be well known, however, many of the processes are known in broad terms, can be inferred, or can be estimated from similar systems elsewhere. Even this coarse understanding will be sufficient to develop an initial ecologically-informed system understanding and will enable identification of reasonable initial program objectives. If the program is designed with adaptive management principles, it can then itself collect the information required to refine the system understanding and review and refine Control Program objectives over time.

In the case of Centrostephanus, the overall objective is to reduce and maintain *C. rodgersii* densities to below barren-forming densities across Tasmanian waters to protect:

- the biodiversity values of rocky reef habitat, and,
- the social and economic values of existing fisheries that are dependent on rocky reef habitat, including abalone fisheries, lobster fisheries, and urchin fisheries.

This overarching objective requires that the strategy serves to achieve the following subsidiary objectives:

- Prevent formation of new barrens;
- Reduce the size and number of existing barrens to less than 5% of rocky reef habitat on the east coast;
- Prevent growth of existing barrens;
- Maintain and enhance the existing values of rocky reef habitat.

3.2 Type of strategy

Pest control programs can pursue pest management strategies of several types, including eradication, containment, asset protection, or ongoing density reduction (Hulme 2006, Panetta and Cacho 2012, Fletcher et al. 2015). Some of these strategies can, if successful, provide a permanent solution to a pest problem. Others require ongoing management but are still strategically useful because they continuously deliver greater benefits than the costs they incur. One of the most important steps in designing an ecologically-informed pest management strategy is selecting a type of strategy that can be realistically achieved given the dispersal capability of the pest and the management resources available (Fletcher and Westcott 2013).

In the case of *C. rodgersii*, even without knowing the specific details of larval dispersal distances, we do know that *C. rodgersii* are a pelagic spawner and fecund at the individual and population level (Byrne et al. 1998). Their larvae also have a relatively long larval competency period (Andrew and Byrne 2007, Byrne and Andrew 2013). Consequently, *C. rodgersii* larval are capable of:

1) dispersing across Bass Strait, and
2) dispersing long distances along the Tasmanian coast relative to the scale of existing management.

The first of these points suggests that our aspiration should not be to eradicate because re-infestation and recruitment from the mainland cannot be controlled (Fletcher and Westcott 2013). The second point recommends that we should not aim to contain (prevent further spread) (Fletcher *et al.* 2015) because larval competency periods, and the potential dispersal distances these indicate, are of sufficient magnitude that all locations can be reached by larvae given permissive currents and temperatures (Andrew and Byrne 2007, Byrne and Andrew 2013).

We also know that the aspirations of the Centrostephanus Control Program (CCP) are extensive, as the abalone and lobster fisheries are distributed along the full length of the Tasmanian coast. This need to protect large areas suggests that, in the medium to long term, the objective is not a geographically constrained asset protection program.

Finally, recent reports suggest that controlled *C. rodgersii* populations recover relatively slowly post-control, e.g., from the Munro Bight, Block 22A pilot study (Huddlestone 2020). This suggests that *C. rodgersii* density reductions at particular sites could be achieved and maintained with less frequent control visits. This would allow management of a larger number of individual sites, potentially covering a significant area. Further work will be required to ascertain the scope of the area coverable and the costs and benefits of such a strategy.

Recommendation: The CCP's short term objective should be to establish a program with a geographically constrained asset protection-based strategy. This would get control happening immediately and provide an opportunity for learning how best to operate any subsequent, larger-scale program. The CCP's long-term strategy should be to establish an ongoing widespread *C. rodgersii* density reduction strategy, because eradication and containment are infeasible, we expect the ongoing benefits to outweigh the ongoing costs, and our interest is in protecting broad geographic areas from urchin impacts. This is consistent with the *a priori* objectives for the CCP (section 3.1).

3.3 Methods of control

A pest management strategy of any type is achieved through implementing specific control methods. In general, there will be a range of control options available to managers, with different levels of field readiness, efficacy, and efficiency, and with different spatial and temporal scales at which they can be implemented. In refining an existing program with practically implementable approaches matched to ecologically-informed principles, the first step is ensuring the current methods of control are implemented at spatial and temporal scales that allow them to achieve ecologically meaningful outcomes. The ecological and management merits of incorporating alternative or complementary methods of control can then be identified and assessed based on the objectives and type of strategy being pursued.

There are a range of possible methods of urchin control that can be considered by the CCP in the medium- and long-terms (these are reviewed in detail in Section 4.2). However, in the short term there are a much smaller number of options available and ready to implement on-water; these being culling and commercial harvest for roe and possibly fertilizer production, augmented by lobster translocation occurring at certain locations along the Tasmanian coast. In the first instance, the CCP should refine the implementation of these two methods by focusing the location and timing with which these control actions occur, while establishing the appropriate monitoring and data collection systems to better understand control operations and outcomes and urchin population responses. Such systems will eventually allow assessment of the likely benefit of potential future control methods. In the longer term, novel control methods should be assessed against their expense, simplicity of on-water implementation, availability, ability to be targeted to areas of need at the relevant spatial scales, and possible complementarity with other control methods.

Recommendation: In the short term, the CCP should aim to ensure that culling and commercial harvest are implemented at the locations and times that can best achieve and maintain an ecologically-meaningful reduction in urchin density. In doing so, it should collect the data necessary to inform current decisions about i) when, where and what type of control operation should be implemented (see Monitoring Section 4.3), ii) potential future adaptive refinements to the CCP approach (see Adaptive Management section 3.7), and iii) potential novel control methods (see Monitoring Section 4.3).

3.4 Ecological thresholds

The goal of ecologically-informed pest management is to structure control actions such that they achieve ecologically-meaningful outcomes over the long term. If eradication or containment are not feasible, ecologically-meaningful outcomes can still be achieved if key assets are protected, or if pest density can be maintained below a threshold level that prevents or reduces ecological damage. Meaningful "ecological threshold" targets include pest densities below which the normal functioning of an ecosystem can be maintained, densities below which an ecosystem state change is prevented, or which allow for some degree of ecosystem recovery.

The concern that underpins the CCP is the role of *C. rodgersii* in driving barrens formation, not simply its occurrence in Tasmanian waters. As a consequence, the goal of the CCP should be to maximise the reduction of barrens formation. Doing this efficiently requires removing the urchins that contribute the most to barren formation, rather than simply removing the most urchins. This is a fundamentally important distinction in the light of the program's objectives.

Furthermore, the transition from kelp-dominated rocky reefs to barrens habitat through the action of urchins exhibits significant hysteresis to urchin density. That is, the density of urchins capable of converting an area of kelp habitat to an area of barrens habitat is much higher than the density that same population of urchins would have to be reduced to in order to allow the barrens to re-transition to kelp-dominated habitat (Ling et al. 2009b). Where possible, therefore, the goal of the CCP should be to prevent the creation of barrens before they are formed, in preference to recovering barrens after they are formed. However, as some priority locations are already significantly affected by barrens, in these locations the objective of the Control Program will need to be recovery of existing barrens.

In general, pest management programs exhibit decreasing-marginal-returns on investment because, as pest densities drop, control staff must spend more time searching for individuals before controlling them. *Centrostephanus rodgersii* in barrens habitat are easily located, but less is known about the detectability of *C. rodgersii* in non-barrens habitat. Nevertheless, the maximum efficiency of the program will be achieved by reducing *C. rodgersii* densities to the point at which they are unlikely to form barrens but not necessarily further than this key threshold density.

The goal of control cannot be the complete eradication of *C. rodgersii.* Once the population at a site has been controlled, normal population processes such as immigration, growth of individuals and growth of the population through reproduction, as well as management-related processes such as imperfect detectability leading to missed individuals during control, will cause the measured population at a site begin to increase.

Consequently, the goal of the Strategy must be to keep the density of urchins below the barrens-forming density until the next time the site is controlled.

Recommendation: where possible, the Control Program should aim to prevent barren formation by urchins by reducing their density to the barren-formation density, plus a buffer as required due to site revisitation schedules. Where barrens have already formed, or incipient barrens are present, the Control Program should aim to reverse barren formation by reducing urchin density to at least the barren-recovery density.

3.5 Spatial scales of the Control Program

An important principle of ecologically-informed pest management is that the resources available should be distributed across the space to be managed such that where management takes place it achieves ecologically meaningful outcomes (Fletcher et al. 2020). Spreading effort over the entire area to be managed may remove a lot of individual pests, but it is rare that removing the most individual pests results in the greatest improvement in ecological outcomes (e.g, Westcott et al. 2021). Instead, once clear objectives are established, the area that can be controlled in an ecologically-meaningful manner should be calculated based on the total resourcing available and the objectives to be achieved. Where this isn't possible the program should be designed such that its activities achieve the desired outcomes at a site before they expand. If resource constraints limit the controllable area to less than the total distribution of the pest, then natural spatial scales in the ecological processes driving the pest population should be used to target the investment within areas where the difference it makes can be maintained. These spatial scales are often either defined by the movement potential of the adult pest, the dispersal potential of the larval phase in marine systems, and natural breaks in suitable habitat in the landscape. The most relevant spatial scale will depend on the goal of the Control Program, the relative importance of each process in impacting that goal, and control logistics and resourcing.

Considering the extent of the entire CCP, and given limited resources, the goal should not be to try to manage everywhere. Rather, the scale at which the CCP will operate should be determined based on its funding and the effort required to reduce urchin densities to the point where barrens are avoided, or existing barrens can recover. Operating at scales greater than this will mean that control efforts will not achieve ecologically-meaningful outcomes despite removing *C. rodgersii*, potentially in great numbers. In the short-term, while total resourcing and CCP efficacy are not yet well known, control actions should be targeted around priority assets so that: 1) they are protected immediately; and 2) the information required to better understand how to set the overall extent of the CCP can be collected. The availability of complementary conservation efforts, as well as regions that should be left uncontrolled, from other management programs, such as lobster translocation or Marine Protected Areas, can be incorporated in the prioritisation of locations for control, but should not alter the fundamental principle that scale is limited to the area that can be controlled in an ecologically effective manner.

With limited resources, the CCP should structure the spatial scale of its local operations to clusters of sites of roughly the spatial scale of the ecological processes driving population recovery after control. For instance, if *C. rodgersii* recovery after control is driven primarily by immigration of urchins from surrounding uncontrolled regions, then the scale of local control should be larger than the movement capacity of individual *C. rodgersii* in the time between control visits. If, instead, *C. rodgersii* recovery after control is driven by detectability or recruitment of settled juveniles, processes with little spatial component, then the scale of local control should be set by management requirements. The scale of these ecological processes is not yet fully known, although urchins appear to have relatively low mobility, relatively slow dynamics, and are relatively easy to detect and manage. In the short term, while these processes have not yet been parameterised, control actions should be targeted consistent with the requirements expressed above, but monitoring protocols and data collection methods should be established to answer these ecological questions so that the next phase of the Control Program can be structure accordingly.

While this report focuses on laying out the design for a pragmatic and implementable control program with the resources presently available, it is useful to keep in mind the larger context. Because *C. rodgersii* are present in NSW, Victorian and Tasmanian waters and can disperse long distances on ocean currents, providing an ecological link between independent state control programs, significant value is likely to be realised in the long term if an integrated, range-wide state and federal program can be established. This aspiration is beyond the scope of current report, so is not considered in detail in the strategies outlined below, but could be important in the longer term.

The other spatial scale of interest is the depth of control operations relative to the distribution of *C. rodgersii*. *Centrostephanus rodgersii* have been recorded to depths of 50m (Beaman et al. 2005) while control activities become much more constrained and expensive below 25 m. There is little evidence that significant numbers of *C. rodgersii* move from deep water to shallow water, so in the short-term distinct control strategies and operations can be used to control *C. rodgersii* above and below 25 m, and control actions in these two depth zones can be considered separately. At the same time, suitable monitoring should be established to verify whether this approach is valid and whether it adversely impacts other Values (e.g. lobster recruitment and habitat) to support potential future refinements to the CCP.

Where possible, existing spatial units of management should be leveraged where they match or complement the spatial scales of ecological drivers.

Recommendation: In the short term, the CCP should target a small number of key assets to: 1) ensure that efforts are implemented at an intensity sufficient to generate an ecologically meaningful outcome; and 2) establish the monitoring and data collection required to: a) better determine the level of resourcing required to create and sustain ecologically-meaningful outcomes at a location; and b) understand which ecological processes primarily drive urchin population recovery following control, and the spatial scales over which they operate (see Monitoring section below). In the medium term, this data should be used to refine the Control Program structure to match the overall extent and the local scale of Control actions to the ecological processes driving urchin population growth and spread (see Adaptive Management section below).

3.6 Temporal scales of the Control Program

In practice, achieving an ecologically-meaningful outcome in a pest management program requires multiple visits to specific sites being managed over time (e.g. Westcott et al. 2020). The period between control visitation to a site should be determined by the ecological processes driving population recovery at a site. In general, this is driven by a few ecological-management processes: individuals missed during pest control actions due to imperfect detection and immigration of pest individuals from surrounding unmanaged areas over the short term, and individual recruitment and population growth at a site over medium and longer terms. Additionally, when the goal of a Control Program is continuous density suppression, there is a trade-off between how frequently sites are visited and how far below the relevant ecological threshold they are controlled: a site visited every week could be controlled to just below the relevant ecological threshold; a site visited once a year would have to be controlled much lower to ensure that population growth over the subsequent year did not allow densities to rise above the Ecological Threshold.

The Centrostephanus Control Program should structure the temporal scale of site revisitation based on the rate at which urchin populations at a site recover. This is necessary because if control crews visit too infrequently barrens will begin to form, but if they visit too frequently they will control urchins inefficiently, reducing the availability of resources for other locations. Actual population recovery at a Site will be driven by immigration of settled juveniles and adults from surrounding areas, larval input and recruitment of on-site juveniles to adults, i.e. to detectable and controllable individuals. Apparent population recovery will also be driven by imperfect detection of individuals during control. The precise scale of the ecological processes influencing actual and apparent population recovery is not well known. Urchins exhibit relatively slow growth rates, taking 8 years to reach maximum size, but the management relevance of this time scale must be compared against the age-size at which urchins are first detectable and controllable, and the age-size at which they become reproductive.

Initially, a short revisitation interval should be selected and data collection methods should be established so that sufficient data is collected to clearly identify the relevant *C. rodgersii* recovery rates. Analysis of this data should then be used to adaptively refine site revisitation rates for the next phase of the Control Program.

As well as the frequency of site control, in the case of *C. rodgersii* in Tasmania there are also issues of absolute timing: in the case of culling, in relation to spawning; and in the case of harvest, in relation to roe quality and quantity. The optimal structure of control actions through time for a hybrid system involving culling and harvesting is not yet known, but possible options should be investigated using ecosystem-management modelling systems, and good monitoring and data collection established to allow further assessment of the relative performance of different strategies at different points in time, to be incorporated into the next refinement of the CCP.

Recommendation: The CCP should aim to revisit control Sites at short intervals initially, in order to sample frequently enough to ascertain rates of population recovery given control. Data collection should be structured to inform better understanding of detection, urchin immigration, recruitment and growth rates (see Monitoring section 3.10). As further data becomes available, the Site revisitation frequency should be refined (see Adaptive management section 3.7). Preliminary modelling studies should be used to investigate the potential benefits of sequencing the timing and distribution of cull and harvest actions.

3.7 Adaptive management

The goal of refining a pest control program using ecologically-informed principles is to make the most ecologically impactful decisions at each moment in time, given current knowledge of the ecological and management processes driving the system. This approach does not require perfect knowledge of the system at the outset, but instead aims to: 1) make good decisions today based on current information; while 2) simultaneously collecting the information required to make better decisions tomorrow. Achieving both of these aims requires strategic effort: simple goals like culling the greatest number of individual pests rarely provide the best ecological performance; and the necessary data is unlikely to be collected without a concerted monitoring program to do so. However, both goals can often be achieved with minor but considered refinements to current management strategies.

In the short-term, the Centrostephanus Control Program should be structured to:

1) reflect the underlying ecological processes that we know, or can infer, are driving population growth and spread of *C. rodgersii*;
2) monitor and collect the data required to estimate the relative scale of ecological processes to further refine the next phase of the CCP, and
3) inform on the performance of the control program.

The first of these goals will be achieved by the structure laid out in the sections above: specific objectives consistent with the ecology of the system; overall CCP extent limited to an area over which ecologically-meaningful outcomes, specifically the prevention or recovery of barrens, can be achieved; and local sites managed at the spatial and temporal scales of population recovery processes. The second and third goals will be achieved through the design and implementation of appropriate data collection and monitoring.

In the medium-term, the CCP should fine-tune each of the key parameters of the Program: extent, precise urchin density leading to barrens formation and recovery, spatial scale of local areas managed together, and frequency and timing of revisitation to controlled sites. Refining these parameters will increase both the effectiveness and efficiency of the CCP wherever it is implemented. Additionally, modelling studies should be used to identify the key components and combinations of components that will yield the greatest efficiency improvements, and those results used to target the highest priority refinements for the CCP.

Recommendation: The CCP should be structured using the ecologically-informed extents, ecological thresholds, and spatial and temporal scales outlined in the sections above, with appropriate data collection and monitoring components put in place to capture the data needed to refine the CCP in future.

3.8 Scalability

A well-designed pest control program will scale to ensure that ecologically meaningful outcomes are achievable at different levels of resourcing. In the first instance, this is vital to ensure that effort is not spread so thinly over the entire management region that no ecological impact is achieved. However, as the Control Program demonstrates success at specific locations, it will both free up resources to start managing new locations, and provide evidence for the success of the Control Program and thereby increase the likelihood that additional funding will be become available to expand it. It is important to ensure that the scales at which the Control Program are targeted are adjusted through time to respond to changes in available resources. Additionally, because *C. rodgersii* are present in NSW, Victorian and Tasmanian waters and can disperse long distances on ocean currents, there will be an ecological link between independent state control programs. This suggests that while in the short-term the CCP should focus efforts at the scale of individual priority locations where ecologically meaningful outcomes can be achieved and maintained, in the longer-term, an integrated, range-wide state and federal program is likely to deliver significant value.

To generate ecologically-meaningful outcomes, the extent, location and timing of the Centrostephanus Control Program must be scaled to the resources available. However, resourcing can be uncertain, may vary over time, and can also be influenced by the successful demonstration of an effective strategy, so the strategy must be designed such that it can be scaled to achieve meaningful outcomes against the program objectives for a range of levels of investment. One important method of achieving scalability is by triggering decisions to expand the extent of management only once ecological objectives are achieved at the locations currently being controlled. This approach ensures that control at a location is continued until it generates ecologically-meaningful outcomes, and the overall extent of the CCP scales naturally to the amount of resources available. In the case of *C. rodgersii*, the key ecological outcome being sought is the avoidance or recovery of barrens through the reduction of *C. rodgersii* density. This implies that the CCP should work at a Site until *C. rodgersii* is reduced below the density required to form barrens, or the density to allow barren recovery, plus an appropriate operational buffer, before new locations are added.

Additionally, the CCP should begin monitoring and collecting the data required to demonstrate the success of operations at the locations that control is being implemented. This data should be used to support the case for continuing and expanded investment to increase the scale of the CCP over time.

Recommendation: The CCP should be structured around rules that scale its operation to the resources available by ensuring that control continues at a location until the relevant ecological outcome is achieved. Monitoring should be implemented to ensure that the ecological outcome is maintained and to trigger additional control should densities rebound. The relevant ecological outcome will be either avoidance or recovery of barrens, and so control should continue until the urchin densities relevant to those outcomes are achieved. Appropriate data collection and monitoring frameworks should be put in place to capture the data needed to demonstrate the effective operation of the CCP and support its future expansion.

3.9 Decisions

An ecologically-informed pest management program drives real-world impact by informing key decisions made by decision-makers at different points in the pest management process. To be effective, the ecological understanding has to be collated and analysed at the specific scales relevant to each decision that needs to be informed. On the one hand, this requires up-to-date ecological information, e.g. daily decisions about where to control pests should be based on surveillance data collected recently relative to the speed with which the pest can move in the landscape. On the other hand, an effective program does not require perfect ecological information. Rather, it only requires that the overall design of the program reflects the broad ecological processes, rates and logistical constraints driving the pest-control system interaction, and that ecological information is collected with sufficient resolution to discriminate between the two or three options that a decision maker faces at each decision point. For example, surveillance doesn't have to be perfect, but it does have to be collected at the ecologically-relevant time and place, and it has to be accurate enough to inform where pest control should occur. An ecologically-informed pest management strategy will collect the information required to inform decision making at the scales and accuracies required to make the right decision.

The key decisions that need to be made in a *C. rodgersii* CCP are:

1) the overall extent of the CCP for a given level of resources;
2) the relative proportion of the management resources that should be invested in control versus monitoring;
3) the methods that will be used to control urchins;
4) where and
5) how frequently local control actions should take place; and
6) when urchin density is low enough to achieve the ecological goals of no new barrens formed and recovery of existing barrens.

The first of these decisions will be scaled automatically using the principles in the Scalability section above. In the very short term, the second will likely be determined by establishing control and associated monitoring at a small number of sites while the CCP is tested, but in the medium term a formal value-of-information approach should be used to optimise the split. In the short term, the third will be determined by the methods currently in use; cull and harvest, augmented by efforts taking place in related programs, such as lobster translocation. In answering the final three questions, we only need information of sufficient accuracy and precision to choose between the realistic alternatives, although we should keep in mind data quality considerations related to adaptive management and demonstration of CCP success. Because we have limited information on the most important locations, speed with which populations recover, and the precise density at which barrens form and recover, we should use the best available estimates from the literature, and then establish the required monitoring and data collection frameworks to refine these estimates using adaptive management in future.

Recommendation: The decisions required to structure the CCP in the short term do not require perfect knowledge, understanding or parameterisation of urchin population dynamics. In the short term, the CCP should be set up to scale automatically to the resources available, employing currently available techniques, and choosing locations, revisitation frequencies and target *C. rodgersii* density thresholds informed by the best currently available information, while establishing monitoring and data collection frameworks with sufficient accuracy to improve these parameters of the CCP in future.

3.10 Monitoring

An ecologically-informed pest management strategy requires monitoring for three key purposes: 1) to inform decisions directly; 2) to refine the program through adaptive management; and 3) to independently verify the performance of the program. Each of these goals will have its own relevant spatial and temporal scales, but with forethought each form of monitoring can contribute to the others, increasing program efficiency. Monitoring to inform decision making should, generally, be targeted at the exact spatial and temporal scale related to the decision, and with sufficient accuracy to discriminate between the alternative decisions available (Fletcher and Westcott 2016). Monitoring to refine the program through adaptive management should be targeted at the knowledge gaps that are preventing improved decision making over medium time scales. In many cases, this information can be analysed from compilations of the same data collected to inform short-term decision making, as long as the data has been collected with sufficient care. Monitoring to verify performance needs to be conducted over the longer term. Again, to some degree this information can be analysed from compilations of the same data collected to inform short-term decision making, but to do so good experimental design needs to be established and detail of appropriate covariates collected at the beginning of the program.

In the Centrostephanus Control Program, monitoring will be used to:

1) Inform decision decisions directly. This requires describing the current status of the system at the time a decision needs to be made, e.g., surveying the distribution and abundance of *C. rodgersii* or

of kelp to inform selection of priority sites and polygons. This enables informed decision making in order to achieve objectives.

2) Refine the program through adaptive management. This requires sufficient information be collected and compiled over long enough time periods that the consequences of management decisions can be detected. To some degree, this can be understood from longitudinal control data, but often the collection of associated covariables can significantly improve the process, e.g. regular surveys of kelp loss or recovery, age-size class data for controlled *C. rodgersii*. This underpins the program's ability to perform optimally given current knowledge.
3) Independently verify the performance of the program. This requires assessing the performance of control over longer periods, e.g. long-term age-size class control catches, and with some independence from the control actions themselves, e.g. post-control non-removal surveys at key sites, and comparison with control data collected at unmanaged sites. This allows for refinement but, critically, is fundamental to reporting and external assessment of the program.

In addition, monitoring data from control programs provide fundamentally important information on the ecological processes and system dynamics, e.g. recruitment and immigration rates, that improve our understanding of the system and lay the foundation for significant future improvements to the CCP.

Recommendation: Because monitoring comes at a cost and takes time it is important to prioritise monitoring activities so that the overall chance of achieving the objective is maximised. In the first instance, the key monitoring tasks should be:

1) Distribution of kelp habitat on rocky reefs
2) Distribution and dynamics of Barrens
3) Distribution and dynamics of *C. rodgersii*
4) Control operations and performance data

This will require a focused and strategic monitoring program to provide information for points 1-3 and for the implementation of standardized data collection protocols and tools for control activities.

3.11 Values

Where a control program aims to achieve multiple objectives simultaneously, it is important to identify how the value of different outcomes can be recognised. In some cases, control actions can be structured such that mutually beneficial outcomes can be achieved (win-win); in many cases there must be some trade-off between outcomes that generate different values. Multiple objectives can occur in any system, but they are especially important when systems involve multiple stakeholders. There are many formal and informal methods of multi-criteria analysis, from quantitative to qualitative, however they all benefit from a clear articulation of what value different outcomes of a Control Program can create. To achieve this, it is important that a Control Program: 1) clearly identifies the value of various outcomes to different stakeholder groups; 2) provides a transparent management approach that can be responsive to changes in the values and in their relative priority, 3) seeks solutions that maximise the return to all stakeholders, 4) develops strategies that serve to identify issues and establish solutions early.

The Centrostephanus Control Program in Tasmania covers a particularly wide set of stakeholders and their values. *Centrostephanus rodgersii* is a pest that affects the financial performance of traditional fisheries and the socio-economic health of the communities that depend on them, but it is also a fishery in its own right. *C. rodgersii* is also an ecosystem engineer that fundamentally changes Tasmanian marine ecosystems, affecting conservation values and other environmental management efforts, and likely reducing the resilience of these systems to future climate threats (Ling et al. 2009c, Pecl et al. 2009, Johnson et al. 2011). Engaging key stakeholders and communities to enumerate these values, building an understanding of them and how they interact, and estimating their relative importance to different stakeholder groups will be a vital part of creating a long-term socio-ecologically sustainable CCP. Completing the first task collegiately and effectively will require stakeholder workshops and advanced facilitation and elicitation skills. The second task needs to leverage socio-ecological modelling to understand how outcomes and values interact across different parts of the socio-ecological system. The final part will require multi-objective optimisation approaches that leverage complementarity in order to identify the outcomes, techniques, locations and times that generate the greatest benefits for the most people.

Recommendation: In the short term, the CCP should establish capability to run facilitated workshops to elicit and collate objectives, desired outcomes and values from key stakeholders right across the social, ecological and economic systems that are affected by or depend on *C. rodgersii*. Socio-ecological modelling should be used to identify the most important interactions and trade-offs between broad control options for *C. rodgersii* in Tasmania. Capability should be established in employing multi-objective optimisation leveraging complementarity to identify outcomes, techniques, locations and times that generate the greatest widespread benefits.

4 Some key decisions and definitions

At the outset of the program there are a number of decisions that have to be made and processes that have to be defined. These are all central to the Control Program and its operation but at the same time are either decisions that are best made, or options that need to be defined, outside the operational decision framework itself (outlined in detail in Section 5). In this section we outline these underpinning decisions and definitions and either make recommendations as to the best choice, where sufficient information exists, or outline how a decision should be arrived at. While in some cases we make quite specific recommendations, and in some cases the decisions underpin key aspects of how the program will operate, it must be remembered that these decisions are not necessarily fixed. Decisions are made with the best information currently available but if information improves or circumstances change, then so to must the Control Program.

4.1 Defining and prioritising values

Identifying and prioritizing the values that are being protected by the Control Program is an important early step, as the nature of these values should be a significant determinant of many of the fundamental decisions that are to be made in the program, from the foundational objectives to how it is that urchins are controlled. The objectives of the program and the values that are being protected should ultimately be refined through an elicitation process with stakeholders (Section 3.11). In an ideal scenario, the CCP would contribute positively to all relevant values. However, win-win scenarios may not be possible for all combinations of values. It is therefore important to clarify expectations surrounding the values the CCP should aim to report on. To do this, we need to define suitable indicators that are measurable and which will reflect how the CCP contributes to these values. As an example, Table 1 provides a list of indicators for a selection of values for discussion and refinement. For each value, we provide a preliminary list of indicators to build on in the following subsections. Input should be sought from stakeholders on i) additional values that should be considered and ii) for each value, which indicators would be most suitable to monitor.

Part of the concern associated with *C. rodgersii*'s range expansion and its impact on kelp and rocky reef habitat are the resulting economic consequences for the abalone and lobster fisheries. There are, however, also concerns about the consequences for communities of any downturn in these and other *C. rodgersii*-impacted industries, e.g. tourism, fin fisheries. The dollar value of a fishery can be a poor measure of the social values of an economic activity. These social values might include the number of jobs generated, where those jobs are generated and the contribution they make to overall employment in those communities. We use the term Social Return Investment (SRI) as a temporary catchall for these additional direct and indirect benefits of an activity.

Once values and indicators have been clarified, the allocation of control effort across space and time will aim to achieve the objectives of the CCP while maximising the outcomes for values of interest. While it is unclear whether all values will benefit from the CCP, clarifying expectations and exploring alternatives will allow stakeholders to discuss alternative strategies and reach consensus if needed.

Prioritising the allocation of resources spatially and under limited budget is a difficult optimisation problem that can be formulated mathematically to provide transparency to decision-makers and stakeholders. The aim of the prioritisation exercise will be to provide guidance for decision-making accounting for the multiple values expressed and offer the means to adaptively manage the system as we learn how to increase the efficiency of the CCP.

Table 1 Example of indicators that will help designing the CCP. These values will help design and measure progress towards the stated objectives of the CCP.

	VALUES								
	Kelp	Barrens	Control Logistics	Centro Risk	Abalone Fishery	Lobster Fishery	Tourism	Community	Centro Fishery
INDICATORS OF VALUES	% coverage	% coverage	Distance to harbour	Population density	Biomass	Biomass	Biomass	Employment	Biomass
	Kelp community	Average size of barren	Vessel requirements	Size structure	Quality	Quality	Quality	Income	Quality
	% vs depth	Spatial structure	Exposure	Site or Polygon Status	Cost of harvest	Cost of harvest	Cost of harvest	Community sizes	Cost of harvest
	Ranking	% loss in abalone production	Depth distributions	SRI Values	Catch value	Catch value	Catch value	Local jobs vs remote jobs	Catch value
		% loss in lobster production	Control type		SRI Values	SRI Values	SRI Values		SRI Values
		% loss in Centro fishery							

4.2 Assessment of methods of control

In this section, we review the different control options currently and potentially available for use in the Centrostephanus Control Program.

4.2.1 Culling

Manual culling is conducted with individual divers searching for and killing *C. rodgersii* by manually breaking the teste with a 'spear'. Diving is conducted from independent small vessels using methods that are standard in the existing commercial dive, abalone and lobster fisheries. In some instances, e.g. in the Block 22A pilot program, diving may be conducted from a mother ship using tenders and over multiple days at a site, i.e. an 'operation'. At the moment, most culling occurs as part of the activities of commercial divers, but evidence from other systems suggest that recreational fishers could provide an additional source of "citizen science" control effort at little or no cost. At the current time, the volume of catch due to recreational fishing is considered negligible relative to commercial harvesting (Cresswell et al. 2018, 2020, 2022), however similar initiatives by the Tasmanian starfish volunteer culling group (C. Gardner, pers. comm. 22 January 2022), and a program design being assessed for feasibility in Tasmania (NRM South 2022) suggest that they could form a significant resource if enabled.

Pros:

- Effective, affordable, and currently available
- Can be conducted in all contexts
- Suggested design scales resources for manual control to objectives at appropriate scales
- Can be tailored to different objectives
- Trained and skilled workforce available
- Social benefits – employment
- Economic benefit – indirect through enhanced recruitment of fisheries species, tourism
- Low collateral impact
- Bulk of *C. rodgersii* population within dive limits, remainder accessible with mixed gas diving
- Potentially cheap or free access to additional resources in the form of recreational fishers

Cons:

- Requires manual culling of each individual – slow, costly if run as a commercial system
- Cost increases with depth beyond 10m and becomes uneconomical beyond c. 25m
- Requires 100% subsidy
- Deprives industry of resource (roe, fertilizer)
- Requires verification of cull

Assessment:

- The foundational, if not necessarily the preferred, control method for the program.

4.2.2 Roe Harvest

Harvesting is conducted by divers bringing live *C. rodgersii* to the surface and transporting them ashore and to a central facility for processing for roe and potentially additional products, e.g. fertilizer. Diving is conducted from independent small vessels using methods that are standard in the existing commercial dive, abalone and lobster fisheries. Since the quality of the roe is influenced by post-harvest – pre-processing handling and exposure, harvesting is likely to be conducted where the urchins can reach the processing facility rapidly. Harvest for roe is restricted to the *C. rodgersii* reproductive season and economical for an urchin size of >85mm.

Pros:

- Simple technology, readily implemented, developed methods
- Effective in reducing densities of large *C. rodgersii*
- Can be combined with culling or other harvest operations
- Provides a financial incentive for control, effectively subsidizing the cost of a control program
- Contributes economically and consequently requires only partial subsidy
- Established processor and markets for roe, other products being investigated
- Harvest is verifiable through catch records provided to DPIPWE
- Waste can be used as inputs for fertilizer production

Cons:

- Roe harvest economical only for larger individuals, high density sites, and during the reproductive season.
- Roe quality is improved when pre-processing handling is minimised potentially restricting where harvest is viable.
- Potential for perverse outcomes - imperative to manage to sustain *C. rodgersii* stocks at a cost to abalone and kelp habitat

Assessment:

- An important method that should be deployed where the economics make it appropriate.

4.2.3 Removal - Grow out

"Removal" in this context refers to the live harvest of individuals of <85 mm teste diameter for growing out in aquaculture. The method is not currently used in Tasmania but has been implemented successfully in Canada and Norway. It is unclear whether it might be viable in Tasmania, but is worth considering as a complementary method alongside culling and harvesting. Alternatively, harvest for grow out could be viewed as part of an overall strategy around *C. rodgersii* harvest, augmenting the economics for harvest of individuals that are not viable candidates for roe harvest due to season, location or size.

Pros:

- Broadens the range of *C. rodgersii* taken for commercial purposes
- Promotes economic activity
- Subsidises the control program
- Could be combined with cull/harvest operations

Cons:

- Limited range of size classes removed
- Focus on <85mm teste individuals, though probably on individuals closer to 85mm rather than to juvenile size

Assessment:

- Potential candidate method that would require a commercial investor. Could be incorporated into the program if a commercial operation was established.

4.2.4 Fertilizer Harvest

The feasibility of using *C. rodgersii* biomass as input to fertilizer production is currently being investigated by IMAS researchers (J. Keane, presentation). If implemented, harvesting would be conducted by divers bringing live *C. rodgersii* to the surface and transporting them ashore for processing as fertiliser. Diving would be conducted from independent small vessels using methods that are standard in the existing commercial dive industry and abalone and lobster fisheries. Conducted in isolation, harvest for fertilizer would be most economical for larger urchins and higher density populations due to the reduced effort required. Alternatively, harvest for fertilizer could be viewed as part of an overall strategy around *C. rodgersii* harvest, augmenting the economics for harvest of individuals that are not viable candidates for roe harvest due to season, location or size.

Pros:

- Simple, effective with established methods
- Provides an economic incentive/subsidy for control operations and potentially a useful supplement for harvest income.
- Harvest is verifiable
- Less sensitive to post-harvest degradation than roe harvest

Cons:

- Fertilizer harvest will be less restricted but will likely still be most profitable at high density sites and where average size is large
- Economic and processing viability yet to be established
- Potential for perverse outcomes – i.e. imperative to sustain *C. rodgersii* stocks at cost to abalone and kelp habitat

Assessment:

A potentially useful component of an overall control program.

4.2.5 Quicklime

Quicklime (CaO) is produced by heating limestone and has been used for urchin control in the context of kelp and mussel aquaculture since the mid-1900s. It is used either in a slurry or pellet form and is applied either directly to the urchin or distributed over the water surface and allowed to settle from there. The quicklime's reaction with water produces heat, causing epidermal lesions and allowing bacterial infection of the urchin's coelomic fluid. This results in death over a period of days to weeks with mortality rates reported to be in the vicinity of 70 to 100%. It has been shown to be effective in managing irruptive urchin populations in temperate marine habitats.

Pros:

- Results in high mortality
- Spreading of pellets from the surface is quick, cheap and relatively efficient in topographically simple and shallow habitats.
- May be possible to pair with ROVs for targeted application in deep water.

Cons:

- Indiscriminate - lethal to all echinoderms, abalone are vulnerable, other gastropods, lobsters, fish less so
- Difficult to apply directly to the urchin
- Abalone mortality can reach 70%
- Unacceptable to some stakeholders

Assessment:

- Compared with culling or harvesting, the directed use of liming is involved and relatively expensive. Greatest potential may lie in targeted use with ROVs at depth.

4.2.6 Robotics

Autonomous (AUVs) and Remotely Operated (ROVs) have potential roles in both monitoring and control activities. AUVs would be devices that are placed in the water and which independently survey transects as part of a monitoring program or locate *C. rodgersii* and cull them as part of the CCP. They would be capable of independently: i) navigating systematically through their habitat, ii) identifying and recording the presence, location and abundance of *C. rodgersii*, and in culling operations, iii) discriminating between *C. rodgersii* and similar species, iv) making decisions to cull or not, and v) effectively implementing those decisions. ROVS are similar except that they are operated from a vessel on a cable. Their decision processes are controlled fully or partially by a human operator (in which case any additional controls performed by the machine's systems, e.g. obstacle avoidance, *C. rodgersii* recognition, etc).

Pros:

- Once in operation AUVs, in theory, operate autonomously and at low cost and without supervision.
- Both ROV's and AUVs may have potential for monitoring and control in deeper waters where diver access becomes increasingly restricted.
- AUVs and ROVs could be developed for targeted liming at depth.

Cons:

- AUV technology is currently very primitive and current AUVs, e.g. COTSBOT, RangerBOT (QUT), are not capable of more than basic navigation, positioning, or manipulation abilities and do not operate unsupervised.
- ROVs are far more advanced, e.g., StarBugs (CSIRO), BlueROV (AIMS/QUT) and Vertigo3 (Babel-sbf/CSIRO/AIMS) but their operations are currently restricted to surveillance.
- Kelp habitats are likely to be particularly difficult for AUVs and because of their cables, particularly so for ROVs.
- The cost of moving these technologies from "Technology Readiness Level 6 - Technology demonstrated in relevant environment" to "TRL 9 – Actual system proven in operational

environment", is immense, requiring major focused investment. Without this development the technology is unreliable.

Assessment

- The promise of AUVs is unlikely to be realised on the budget of a CCP and will come from devices developed for other applications. ROVs have potential but whether investment is warranted would be determined by assessments of the need to control in waters deeper than 30m and their efficacy in the targeted delivery of quicklime. In the initial phases of a program this is not necessary.

4.2.7 Biological Control - Predator Enhancement

There is now abundant evidence of the strength of top-down control on the population dynamics of sea urchins. Urchin populations released from top-down (predator) control often irrupt, leading to kelp loss, the classic example of this being the loss of western Aleutian kelp forests to grazing by sea urchins (*Strongylocentrotus* spp.) following the decimation of sea otters (*Enhydra lutris*) and their subsequent recovery with sea otter population recovery (Estes & Palmisano 1974). Similarly, recent die-offs of the predatory sunflower seastar (*Pycnopodia helianthoides*) in the north-east Pacific due to the combined impact of global warming and sea-star wasting disease have resulted in elevated densities of green (*Strongylocentrotus droebachiensis*), red (*Mesocentrotus franciscanus*), and purple urchins (*Strongylocentrotus purpuratus*) across their range and the subsequent loss of kelp habitat (Harvell et al. 2019). Similarly, over-fishing of lobsters in Maine, USA, led to increased green urchin (*Strongylocentrotus droebachiensis)* densities that led to the loss of kelp habitat, which was then reversed by over-harvesting of the urchins for roe and resulted in a switch back to kelp dominated habitat (Steneck et al. 2013). Similar dynamics have been observed around the world, including in Tasmania, and this suggests that re-introduction or enhancement of natural top-down control may be an efficient component of urchin population control.

Current evidence suggests that lobster enhancement and protection has an important but targeted role to play in *C. rodgersii* control (Ling and Keane 2021a). Since 2013, significant ecological research and management practice has been invested in lobster protection and translocation measures in Tasmania through the East Coast Stock Rebuilding Strategy, which aims to rebuild lobster stocks to greater than 20% of unfished stock by 2023 (Wild Fisheries Management Branch 2018). Supporting lobster stocks plays a number of roles, including maintaining lobster fisheries stock, and supporting ecosystem health (Wild Fisheries Management Branch 2018), but in the context of *C. rodgersii* specifically, early results have indicated several important characteristics of leveraging lobsters as a management option. Ling and Keane (2021b) analysed the results of a 12-year experimental closure of lobster harvest that was combined with the enhancement of large (>140mm) lobsters. This work showed that locations with healthy lobster populations have shown an increased ability to avoid the formation of barrens (Ling and Keane 2021a). However, there was no detectable effect of lobster enhancement/protection on the coverage of already-existing extensive barrens, with these remaining at ~90% cover at both the experimental and the control sites. This is arguably not surprising given that modelling suggests that recovery of extensive barrens using lobster predation alone will yield little effect for 20 – 30 years (Johnson et al. 2013). In Ling and Keane's (2021a) analysis, incipient barrens with good kelp cover showed; i) significantly reduced *C. rodgersii* densities, ii) significantly reduced cover of incipient barrens, and, iii) a stable number of incipient barrens. In contrast, in control areas the number of incipient barrens doubled and their area tripled or quadrupled.

These results suggest that lobster protection is an effective tool for preventing barrens formation. It could be used over large areas at high value sites at risk of barrens formation where harvest can be controlled, including those where incipient barrens exist but where resourcing or logistics don't allow for other forms of control. Used in combination with other forms of control it should allow for more sustained recovery and potentially for a reduction in the number of incipient barrens. Finally, at extensive barrens sites, lobster protection will be most likely only be effective on relevant timeframes if implemented with some other form of direct urchin control, e.g. harvest for roe, fertilizer or grow out, or, culling, and potentially with some form of kelp replanting.

Pros:

- ‘System friendly’ with little local collateral impact
- Low direct or on-going cost of implementation
- Could be achieved in part by purchase of commercial licences

Cons:

- Evidence from other systems suggests that promoting predator recovery through MPAs alone moderate but do not prevent pest species irruptions
- Long timeframes required for recovery of extensive barrens without additional control
- Predators are subject to heavy exploitation and, as a consequence, protection from some parts of the fishery, e.g. the recreational fishery, may be difficult to implement

Assessment:

- An effective method particularly for prevention and management of incipient barrens and in combination with direct forms of control such as harvest or culling.

4.2.8 Biological Control - Traditional Biological Control

Traditional biological control would involve the identification and distribution of a naturally occurring or introduced pathogen. A range of pathogens and parasites are known for echinoderms, e.g. Vibro viruses, however, no candidate pathogens have been identified in the context of other echinoderm control programs (Hoj et al. 2020).

Pros:

- An effective pathogen is likely to be relatively simple to deploy

Cons:

- Unlikely to be sufficiently specific or containable – there are related urchins in the same habitat
- Huge research investment required with uncertain outcome.
- No examples of current viral diseases, gonadal parasites, etc being successfully harnessed for control of urchins or starfish.

Assessment:

- Unlikely to be a viable option

4.2.9 Biological Control - Gene-Technology based Biocontrol

Gene technology has long been touted as the ‘magical’ solution to pest species management issues, in medicine, in agriculture and in environmental management. Until recently, however, there has been little evidence of widespread potential in environmental management contexts. New gene technologies may be about to change this. CRISPR is a gene editing technology that allows for controlled and highly specific editing of specific locations in the genome (Jinek et al. 2012). Unlike previous genetic technologies, CRISPR generally edits existing gene sequences, rather than introducing new genes, and does so in order to modify their functioning (Hsu et al. 2014). Not only is CRISPR accurate in terms of identifying specific locations in the genome for editing, but by linking its function to genes found only in a species or population, it can be designed to be highly species- and population-specific (Esvelt et al. 2014). This is significant, as it points to an ability to limit spread to non-target species thereby conveying a higher degree of safety in field deployment than previous methods. Target genome sites might include sites that bias sex determination to one or the other sex, that influence the regulation and timing of sexual development, or that influence fecundity, growth or nutrient assimilation.

To be an effective technology in a biocontrol context, it is desirable that genetic modifications can spread rapidly within the population and become sufficiently represented so as to achieve the desired outcomes at a population level (Champer et al. 2016). However, most genetically-based modifications will have negative impacts on the fitness of carriers resulting in selection removing them from the population – indeed even neutral traits will eventually be eliminated. Gene drives are genetic mechanisms that cause a gene to spread rapidly through a population at rates far greater than would otherwise occur and irrespective of their fitness cost (Burt 2003). Such biased inheritance mechanisms occur naturally in a range of taxa, however gene-editing technologies such as CRISPR have made synthetic gene-drives relatively simple to engineer and, as a consequence, accessible for a broader range of systems and researchers. Pairing a population-suppressing genome edit with a gene-drive mechanism would ensure spread within a population.

While there has been much fanfare around CRISPR and gene-drive technologies, there are no examples of their combined application outside laboratory settings. This is not surprising given the very major regulatory and ethics hurdles they face. In the context of an environmental pest and a native species, it is likely that approaches that result in population suppression rather than control are more likely to ultimately be approved. There are also significant biological and technological knowledge gaps that must first be filled. In the light of these considerations we recommend not considering these technologies at this juncture but remaining alert to development in this very rapidly progressing area.

Pros:

- Population specific so theoretically no collateral impacts
- Focuses on specific genetic pathways
- Spread can theoretically be engineered to very fine degrees
- Technology could be used to improve the fishery product

Cons:

- Legally, ethically, and socially unacceptable at the moment even if focus is on population suppression.
- While the gene editing technologies are proven most aspects of the gene-drive are yet to be demonstrated even in the lab.
- Currently blue-sky, unlikely to have field application in the next decade

Assessment:

- Attractive but attainable only in the long-term.

4.2.10 **Summary**

The preceding consideration of the potential control methods suggest that at this point in time manual culling and roe harvesting are the most appropriate methods for deployment in a Program designed to provide short-term reduction in *C. rodgersii* impacts at a reasonably large scale, and, that they will likely remain so in the medium term at least. These methods are currently available, they are familiar, they utilize current resources and infrastructure, are effective in reducing densities and achieving outcomes, can scale to the extent of the problem, and, are economically viable. In short, they are a solid foundation for a program. Other methods may provide useful complements to these control efforts, but are likely to deliver results at negligible levels compared to commercial efforts, e.g. Citizen Science (Cresswell et al. 2018, 2020, 2022), or over too long a time, e.g. lobster translocation, to be considered as core control methods for the Program. Understanding where and how we can harness these other methods to complement manual control efforts, as well as the overlap of control with other conservation management efforts, like Marine Protected Areas, is likely to be central to the long-term success of the program.

When the two methods, culling and harvest, are compared, they present slightly different advantages. Manual culling has broader utility, being suitable for use in all seasons and at all sites, while roe harvest is more restricted in terms of its seasonality, the targeted size range, and the preference for sites closer to processing facilities. The addition of harvest for fertilizer or aquaculture may in the future lessen these constraints on commercial harvest but the extent to which this is the case remains to be seen. Overall, the relative benefits of the two approaches suggest that in contexts where the *C. rodgersii* harvest is of low priority culling will be the preferred method. However, where harvest has value, e.g. for defraying costs or as part of a viable *C. rodgersii* fishery, then developing a set of decision rules for the optimal deployment of the two methods in time and space will be appropriate.

A simple decision rule for optimising deployment of culling and harvest for roe would combine i) the seasonal deployment of the methods, ii) sequencing of sites relative to the harvest season given their *C. rodgersii* population structure, and iii) sequencing the use of the methods at individual sites. An initial and qualitative decision process might be as follows:

1. Prioritize sites for control, incorporating information about current distribution of lobster translocation programs and Marine Protected Areas
2. In the roe harvest season focus effort on high priority sites with known or assumed economically viable *C. rodgersii* populations, e.g. high density, large individuals, close to processing, previously uncontrolled sites
3. Harvest during the initial operation/s at a site
4. Switch to cull, contract or subsidised harvest when population structure drops below economically-viable average size
5. Cull to no remaining individuals available for control during a dive, and to below the threshold density for an operation.
6. Outside the roe harvest season focus effort on sites with less economically viable populations, e.g., distant or previously controlled sites
7. Should harvest for fertilizer or aquaculture become viable, they should be used where profitable
8. Cull is used elsewhere, sites are culled to no individuals available on a dive.

Steps 4 and 5 are important. Whether a harvest or cull method is initially used at a site, the goal of control must be to reduce *C. rodgersii* density to the relevant target ecological threshold before moving operations to the next site.

Successful development of alternative products, e.g., fertilizer, may reduce geographic and seasonal constraints on harvest but would likely still focus on larger individuals and high-density populations to remain economically viable. The economics of fertilizer harvest are as yet unclear but will determine where and when it can be deployed. Even where it is not independently viable it should at least subsidize the costs of control.

Other methods, such as Citizen Science culling or lobster translocation, may be useful complements to these control efforts, but are not considered as core components of the CCP described below because they are likely to be too limited in scale, in the case of citizen science culling, or to generate reduced impacts from *C. rodgersii* over longer timescales than targeted by the CCP, in the case of lobster translocations. Positive impacts due to Marine Protected Areas are likely to be realised over even longer timeframes. Both are likely to be useful contributors to a larger, longer scale program, and data on the interactions between culling, harvest and these other strategies should be collected during the initial phases of a new program.

We do not recommend that significant resources are invested in developing new, high-tech approaches to culling in the initial phases of the program. Early in the development of the CCP it is most important to ensure that the program has an effective strategy and an efficient implementation of that strategy. This is important, because collecting data to improve our ecological knowledge and developing the underlying principles that will guide the spatial and temporal distribution of culling or harvesting approaches will also be relevant to the efficient application of new technologies, which can be incorporated as they become available or economical. In saying this, we are not suggesting that new technologies are not desirable, particularly given the depth and bottom time limitations associated with diving, however they are not a high priority at the outset and can be the subject of a 'watching brief'. The candidate technology most likely to see investment would be ROVs and possibly targeted liming may have application at depth, a potentially critical gap in the coverage provided by manual control methods.

4.3 Operationalising monitoring

In Section 3.10 we identified the key monitoring tasks as:

1) Distribution of kelp-dominated habitat
2) Distribution and dynamics of Barrens
3) Distribution and dynamics of *C. rodgersii*
4) Control operations data

Data of the first three types currently come primarily from informants in the different fisheries and limited and infrequent research surveys. This latter approach is expensive and does not provide data with sufficient temporal or spatial resolution to reliably guide decision making in the CCP. As a consequence, in the interim we recommend that there should be a formal reporting process developed to source information from the different Departmental and Industry sources with app-based data collection and upload. A similar system for the public and recreational divers should also be developed.

Ultimately, comprehensive and regular surveys are required to inform decisions about how to distribute effort. To this end, the UTas sonar surveys, like those reported in Lucieer et al. (2021), should be assessed for their potential for providing monitoring at the required spatial and temporal scales for operational use in the Active Management Region and adjacent areas of the Monitoring Region. Since the sonar monitoring may not be able to discriminate individual *C. rodgersii*, consideration should be given to exploring the potential of video surveys mounted on similar towed gliders to be conducted in tandem or instead of the sonar surveys.

App-based data collection and upload tools should also be developed to ensure standardized and high-quality data is collected on the outcomes of each dive and of each operation (defined below). Again, tools currently being developed by IMAS are likely to be appropriate for the task.

4.4 Ecological threshold versus economic threshold

Urchin barrens form when urchin densities exceed thresholds at which kelp recruitment can keep pace with urchin grazing (Filbee-Dexter and Scheibling 2014). Conversely, recovery of existing barrens occurs when urchin densities drop below the threshold at which kelp recruitment can outpace their grazing. Typically, the recovery threshold is considered to be significantly lower than the formation threshold and in the Tasmanian context these thresholds are estimated to be on the order of 0.8 - 1.6 urchins / m^2 for barren formation and 0 - 0.5 urchins / m^2 for recovery (Flukes et al. 2012, Johnson et al. 2013, Filbee-Dexter and Scheibling 2014, Ling et al. 2015). These two thresholds, the barren formation and recovery densities, are the critical metrics for assessing the performance of CCP activities. To be effective, it is imperative that at the locations where CCP invests in control actions, divers achieved these densities. While in reality both these thresholds will vary depending on local conditions, we currently do not have sufficient information to estimate site specific thresholds and so will need to use general estimates.

Commercial divers, however, will make decisions about when, where, and for how long to dive based on a number of factors other than ecological thresholds, such as the densities of Centro that determine the economic viability of their operations. In theory they should choose to dive sites above their economic viability threshold and avoid sites where urchin densities are below their economic viability threshold. This threshold will be a function of the fixed costs of their operations (e.g. base salaries, insurance, etc) and the variable costs associated with diving a particular site (e.g. fuel, additional dive time, etc). In some cases, such as harvest for roe, the timing of activities will also be important to the economic benefits derived from management.

For each location that is targeted by the CCP a key issue will be whether, when control actions begin or as control actions reduce the density of urchins, the location falls below the “economic threshold” and becomes unprofitable or less profitable than nearby alternatives before the ecological threshold required to prevent the formation or foster the recovery of barrens is reached.

In the happy eventuality that the economic urchin density threshold is lower than the relevant ecological threshold for the location (formation or recovery), then we might expect that divers will continue returning to sites even after the ecological threshold has been reached and passed, and so the program’s objectives at the site will be achieved without intervention. If, however, the economic threshold at which a location becomes unprofitable occurs at a higher urchin density than the relevant ecological threshold, then we would expect that divers will leave a site before the ecological threshold is achieved in order to avoid losing money. In this circumstance, commercial harvest may reduce *C. rodgersii* grazing pressure, but will not be sufficient to achieve the desired ecological outcome, i.e. to prevent barren formation or to allow recovery. In this case, achieving program objectives will require some means of incentivising divers to return to a site to a degree that ensures their operations remain economically viable.

Similarly, when urchin densities at previously harvested sites that remain above the ecological threshold result in lower profitability than can be achieved at alternative sites, economically rational divers would choose to abandon those previously harvested sites and favour the higher viability sites. This will result in the CCP objectives not being achieved while higher viability sites remain available. Again, avoiding this situation will require that re-visitation of previously harvested sites be incentivised.

4.5 Program Type

Where the ecological thresholds lie relative to the economic threshold will have a strong influence on how divers invest their effort, and this, in concert with environmental and social factors, will influence how a control program should best be structured and managed in order to influence divers’ decisions to achieve those goals. There are a range of tools, financial and management, that can be used to focus the attention of divers on achieving thresholds at particular locations. The simplest and cheapest of these is the management action of closing areas to harvest in order to focus effort on other areas. This can be used to change how harvest is distributed, to produce greater harvest pressure at open sites. Financial tools include contracting divers to work particular sites, auctioning rights to access sites, and paying subsidies designed to achieve thresholds (Cresswell et al. 2019). Each of these approaches will be most effective under particular circumstances and imply different modes of operation for the Program. The key attributes of the different Program Types that are likely to be relevant in the context of control of *C. rodgersii* in the Tasmanian context and the general conditions under which they are likely to be appropriate are described below. The decision processes leading to each of these Program Types are identified in Section 5.2.3. The Program Types are as follows:

1) Commercial Harvest – used where harvest to the Economic Threshold is sufficient to achieve the Program’s objectives, i.e. it reduces *C. rodgersii* density to below the relevant Ecological Threshold, in the necessary locations. This is a Passive Program and relies entirely on Operators choosing where to work and how hard to harvest a site.
2) Spatially Targeted Harvest – used where harvest is sufficient to achieve the Program’s objectives, i.e., a reduction to below Ecological Thresholds, but requires targeting to particular locations. This is an Active Program, in that Control Program managers make decisions that affect control effort. It allows Operators to determine how hard to harvest a site but influences their choice of site by setting catch limits at some spatial scale in order to focus effort on key areas. The strategy is not responsive to market conditions.
3) Fixed Subsidy Harvest – used where Commercial Harvest generates insufficient return to motivate Operators to harvest Centro to the Ecological Threshold. A single rate of subsidy is applied across

the Control Program, and Operators choose where and how intensely to harvest, but how much effort they invest, and hence what *C. rodgersii* density is achieved, is influenced by the additional return provided by the subsidy. This is an Active Program, in that Control Program managers make decisions that affect control effort. The strategy is not responsive to market conditions.

4) Spatially Targeted Subsidised Harvest – combines facets of a Fixed Subsidy Harvest and a Spatially-Targeted Harvest using subsidies and potentially catch limits to motivate Operators to harvest Centro to the Ecological Threshold at certain locations. Operators choose where and how intensely to harvest, but their choice of both where to harvest and how much effort they invest, and hence what *C. rodgersii* density is achieved, is influenced by the additional return provided by the spatially-varying subsidy. This is an Active Program, in that Control Program managers make decisions that affect control effort. The strategy is not responsive to market conditions.
5) Auction / Tender – This approach allows Operators to bid on the right to control certain locations. The successful Operator is paid to control those locations, providing additional motivation to engage in control. By rewarding low bids at a specific location, the Auction / Tender process ensures that spatially varying costs of operation and general market conditions are factored into the subsidy paid to Operators. Operators choose what locations to bid on, but Control Program managers determine the successful bid and hence which Operator is assigned to a location. This is an Active management "market supplemented" approach that is designed to respond to market conditions. It requires a competitive marketplace amongst Operators to function efficiently.
6) Adaptive Subsidy – This approach calculates a subsidy that varies in different locations and at different times based on the costs of operating in different locations, the current harvest rate from that location, and the current market prices for *C. rodgersii*. This method uses varying subsidies to efficiently target effort to particular locations and to ensure that Operators have a sufficient economic incentive to control a site beyond the Economic Threshold all the way to the relevant Ecological Threshold. The approach is adaptive in that it supplements processor payments in a manner that is responsive to market and other drivers to ensure that Operators are guaranteed a minimum and attractive profit when a site is below the Economic Threshold but above the Ecological Threshold. Control Program managers set and publicise the subsidy, and Operators choose where to operate based on the additional incentive they receive.
7) Contract – This is an active management approach where Operators are employed as contractors and are directed to control at specific locations to a particular density. This approach is most likely to be employed when the control method is a cull. A similar arrangement may be used with citizen scientist divers and community groups. This method may or may not be market supplemented.

There are a number of details around how an Adaptive Subsidy could be implemented. Appendix A provides a worked example demonstrating payments sufficient to make harvest to the Ecological Threshold economic for divers.

4.6 Depth of Operations

There are three approximate depth ranges that are of interest to the CCP, and these are defined by their accessibility to divers (Table 2). In short, as depth increases, so too do the logistical difficulties and the cost of control operations. As a consequence, how deep diver-based control operations are extended and how much is invested into control at any particular depth, will be a function of the value of the habitat at any particular depth, the extent of the threat to that habitat or coming from that depth range, and the cost of operating in that depth range. If, for example, rocky reefs below 30m are the source of significant rock lobster, abalone or *C. rodgersii* recruitment to shallower depths, then investment in control below 30m may be warranted if the costs are low relative to the benefit.

Data on the extent of rocky reef habitat below 40m is limited, but what is available suggests that deep habitat may be significant (J. Keane, pers. comm. 1 June 2021, reporting on initial results of IMAS acoustic surveys) and consequently may be valuable as source habitat for shallower waters. Whether *C. rodgersii* and barrens are abundant in these deep habitats, however, is less clear. The 2018 resurvey of barrens on the east coast indicated that *C. rodgersii* densities peak at ~20m and decline steadily with depth thereafter (Figure 1; Ling and Keane 2018), while earlier surveys suggested that barrens peak in coverage at c. 20-25m (Johnson et al. 2005, Johnson et al. 2011). Despite this, barrens and *C. rodgersii* are reported to 60m and are considered by some to be extensive and abundant below 25m (C. Johnston, pers. comm. 2nd June 2021). Initial reports on acoustic mapping work by IMAS researchers (J. Keane, pers. comm. 1 June 2021) suggest that barrens are likely to be more extensive than suggested by Ling and Keane (2018)'s results.

The value of deeper rocky reefs is likely to vary across the fisheries. Approximately ≥70% of effort in the abalone fishery occurs in ≤10m, though CPUE (kg/hour) increases with depth in some locations (Mundy and McAllister 2019). That the majority of barrens formation occurs between 15 and 30m might at first glance be interpreted as suggesting limited impact on the abalone fishery. However, the negative relationship between abalone and *C. rodgersii* (Johnson et al. 2005) and experimental evidence from NSW that removal of *C. rodgersii* can result in as much as a 10-fold increase in abalone densities (Andrew et al. 1998b) suggest that, if the commercial fishery is dependent on recruitment from deeper water, depths beyond 30m may be of high value and deserving of control effort. Rock Lobster are fished throughout, and beyond (to 110m), the depth distribution of *C. rodgersii* and of barrens (Johnson et al. 2005). The negative relationship between lobster and *C. rodgersii* densities (Johnson et al. 2005) point to a clear impact but this will be a function of the proportion of the fished lobster habitat that is in the 20-60m depth range. Finally, deeper water habitats may have high negative values associated with them because they are sources of *C. rodgersii* recruitment. Whether this is the case is unclear.

Table 2 Depth ranges and potential management options and factors influencing this. Dive-based control refers to culling or harvest for Roe, Fertilizer or Grow-out.

Depth Range	Dive Viability	Value	Potential Management Options
0-20m	Viable with air	High	i) Dive-based control ii) Protect rock lobsters
		Low	i) Dive-based control ii) Protect rock lobsters
20-~27m	Viable with mixed gas	High	i) Dive-based control ii) Protect rock lobsters
		Low	i) Protect rock lobsters ii) Do nothing
~27-60m	Not viable	High	i) Purchase commercial rock lobster licences ii) Encourage investment in non-dive technologies; a) Private if value is moderate-high, b) Public if value is very high
		Low	i) Purchase commercial rock lobster licences ii) Do nothing

4.7 Lobster Strategy

Significant ecological research and management practice has been invested in lobster protection and translocation measures in Tasmania in recent years (Johnson et al. 2013, Marzloff et al. 2013, Wild Fisheries Management Branch 2018, Ling and Keane 2021a). Since 2013, the East Coast Stock Rebuilding Strategy has been working to rebuild lobster stocks to greater than 20% of unfished stock by 2023, through a combination of catch caps and, since 2015, targeted translocation (Wild Fisheries Management Branch 2018). Whether stocks are more effectively supported through catch caps or translocation is largely determined by economic conditions and may vary across locations and through time – a catch price above $40/kg supports translocation, whereas lower prices support catch limits (C. Gardner, pers. comm. 22 January 2022). Supporting lobster stocks plays a number of roles, including maintaining lobster fisheries stock, supporting ecosystem health, and, potentially, reducing the impacts of *C. rodgersii* as a key predator (Wild Fisheries Management Branch 2018).

In the context of *C. rodgersii* specifically, early results have indicated several important characteristics of leveraging lobsters as a management option. Based on both global experience and the results of Ling and Keane (2021b)'s experiment, locations with healthy lobster populations have shown an increased ability to avoid the formation of barrens (Johnson et al. 2013, Marzloff et al. 2013, Ling and Keane 2021a). They have also, potentially, shown an ability to foster recovery of established barrens, albeit very slowly (Johnson et al. 2013, Marzloff et al. 2013). This could be due to the long timescales associated with ecological recovery, however recent studies have suggested that while lobsters will predate *C. rodgersii*, they are not the preferred prey (Smith et al. 2022).

Centrostephanus rodgersii barrens could ultimately account for 50% of all rocky reef in eastern Tasmania (Johnson et al. 2005, Johnson et al. 2011), as observed in New South Wales (Andrew and O'Neill 2000). Impacts of this magnitude would have significant flow-on effects reducing future lobster recruitment and populations (Johnson et al. 2013). Bolstering lobster stocks was recommended as a method of both supporting the ongoing productivity of lobster fisheries, and reducing the impacts of barrens formation through increased predation on *C. rodgersii* by lobsters (Johnson et al. 2013, Wild Fisheries Management Branch 2018). However, results from field trials (Ling and Keane 2021a), and uncertainty around the strength of interaction between lobsters and urchins (Smith et al. 2022) and hence barrens formation, make it difficult to estimate precisely how specific lobster targets will impact likely future trajectories for barrens formation. Even significant rebuilding of lobster populations can take many decades to generate meaningful seaweed bed restoration in established barrens (Johnson et al. 2013, Marzloff et al. 2013), and modelling suggests that the chances of recovering from extensive barrens solely through rebuilding lobster stocks are relatively low (Marzloff et al. 2013).

Due to the fact that the lobster rebuilding efforts run for multiple reasons outside of the presence of *C. rodgersii*, and the long lead time and uncertainty associated with achieving an observable reduction in the formation or recovery of barrens, the Centrostephanus Control Program outlined below, which is focussed on initially delivering near-term reduction in *C. rodergsii* impacts, does not explicitly incorporate lobster rebuilding as part of the management structure. However, it assumes that lobster rebuilding efforts will continue, and the CCP should work with them in future to coordinate activities as the benefits are better understood. From a *C. rodgersii* perspective, the greatest benefits are likely to come where lobster rebuilding efforts are targeted at sites where i) extensive barrens are not yet formed, and ii) where lobster densities are low, and iii) can be effectively protected (Ling and Keane 2021b).

4.8 Kelp Rehabilitation Strategy

In contexts other than extensive barrens, kelp recovery post-control appears to be rapid (Huddlestone 2020, Larby 2020). In extensive barrens, however, recovery is estimated to take up to 50 years and was not observed even during Ling and Keane (2021b)'s 12-year lobster experiment. Kelp rehabilitation is an effective means of increasing the rate of barrens recovery (Eger et al. 2020, Layton et al. 2020). It is however expensive and logistically intensive. These factors means that kelp rehabilitation would likely only be used in the context of barrens at high value locations.

5 Proposed Strategy

The principles described in the preceding sections outline the structure of an ecologically-informed pest management strategy, how those principles would apply in the specific case of *C. rodgersii*, the control methods available and the values the CCP aims to protect. In this section, we describe two strategies for implementing a *C. rodgersii* control program on Tasmania's east coast. These strategies seek to incorporate the pest control principles of Sections 3 and 4 with the objectives, tools, and constraints specific to the context of *C. rodgersii* control. The two strategies reflect two different levels of resourcing and centralised planning and control.

The first, an Initial Implementation Strategy, builds on current *C. rodgersii* control arrangements, providing a framework to ensure that control is targeted at priority locations, and that where control investment is made it achieves ecologically meaningful outcomes. It is designed based on the current state of knowledge of the distribution of *C. rodgersii* and of the assets being protected, the structure of the fishery and dive operations, and the general scale of funding. Implementing the program would incur some additional costs and require some changes to current operations, but these would not be dramatic.

The second strategy outlines a Full-Scale Program managed and implemented at a state-wide scale and potentially linked to an even larger coordinated multi-state program – clearly a longer-term prospect. The Full-Scale Program operates similarly to the Initial Implementation Strategy at the scale of individual Sites, but structures control decisions at larger spatial and temporal scales in response to the underlying ecological drivers of *C. rodgersii* population dynamics and spread.

Importantly, although the two strategies could be implemented independently, they are also designed to be implemented sequentially; instituting the Initial Implementation Strategy in the short-term would both make significant progress in controlling *C. rodgersii* at key locations, while simultaneously building vital experience and collating information on a range of key parameters important to the effective implementation of a Full-Scale Program.

Before outlining these strategies, however, it is necessary to define a number of parameters and thresholds that are used in the Strategies. Below, we establish a number of key definitions around the objectives of the program, the scales over which it will be run, and the thresholds it will target, before defining the Initial Implementation Strategy and the Full-Scale Program.

5.1 Outline of a Centrostephanus Control Strategy

The goal of any Centrostephanus Control Strategy must be to achieve a lasting ecologically-meaningful reduction in the impacts of *C. rodgersii* at locations along the Tasmanian coast. The Initial Implementation Strategy assumes that we will have the resources and knowledge to control only a relatively small fraction of locations, and so proposes a framework capable of: 1) identifying and then protecting priority locations that are considered valuable, either intrinsically or in relation to complementary conservation efforts along the Tasmanian coast, such as lobster translocation or Marine Protected Areas; 2) managing *C. rodgersii* at a priority location until an ecologically-meaningful reduction is achieved; 3) scaling the program to available resources by only controlling a new priority location once previous locations have achieved ecologically-meaningful outcomes; and 4) ensuring that those hard-won ecologically-meaningful outcomes are maintained over time. The Full-Scale Program aims to achieve these same objectives at individual Sites, but instead of selecting locations based on their short-term intrinsic value, looks to select groups of locations that can disrupt the large-scale ecological drivers of *C. rodgersii* population dynamics and spread and then control them in an efficient and effective order, again, taking into account the location of complementary conservation efforts, and potentially coordinating control efforts between states. Identifying which locations are most important to these large-scale ecological processes requires a detailed understanding of both Centrostephanus ecology and their current distribution, as well as the distribution of other species and ecosystems affected by Centrostephanus and social and economic factors.

Under either Strategy, we need to successfully implement a similar sequence of steps:

1. Identify objectives of the Program with representative stakeholders
2. Use those goals to prioritise locations for management
    a. In the Initial Implementation Strategy this is done based on the value of a location, intrinsic and in the context of other management programs, but independent of larger ecological concerns
    b. In the Full-Scale Strategy, this is done based on the value of a location in the broad-scale context of its long-term contribution to *C. rodgersii* impacts along the Tasmanian coast, taking into account the location of other management and conservation programs.
3. Direct on-water managers to the highest priority locations by some method, either contractual, or market-based, or diver-selected
4. Ensure that any location that is controlled achieves an ecologically-meaningful outcome by reducing *C. rodgersii* numbers below an appropriate threshold density
5. Monitor and ensure outcomes are maintained
6. Potentially implement supplementary management efforts, such as kelp rehabilitation

To actually implement these steps, we need to identify or define key scales at which management should take place: the size of a location to be targeted for control, how frequently each location should be visited, the *C. rodgersii* density threshold to be targeted in order to achieve an "ecologically-meaningful outcome", or how control crews will be directed to the next priority location etc.

Below, we relate the key components that will be required in the CCP to the requisite ecological and management drivers.

5.1.1 **Objectives – what are we trying to achieve through the investment in the CCP?**

In order to understand which locations should be prioritised for control, and what outcomes control should target, we must define the objectives of the control program. The broad objectives targeted by DPIPWE and the AIRF are described in section 3.1. For the purposes of defining an implementable strategy these objectives can be summarised as:

1. Protect kelp-dominated sites
2. Stop development of incipient barrens
3. Recover existing barrens

5.1.2 **Scales and units of management**

Identifying spatial management units is a fundamentally important step in implementing an ecologically-informed strategy. Having spatially-defined management areas allows assignment of values, identification of priority sites, and rigorous assessment of control performance and strategy, which is vital for tracking progress over time to build ecological understanding that can further refine future control efforts.

Units of management must be defined at a range of relevant scales, spatial, temporal, and scales of management intensity or effort, reflecting both ecological processes and the way management is structured.

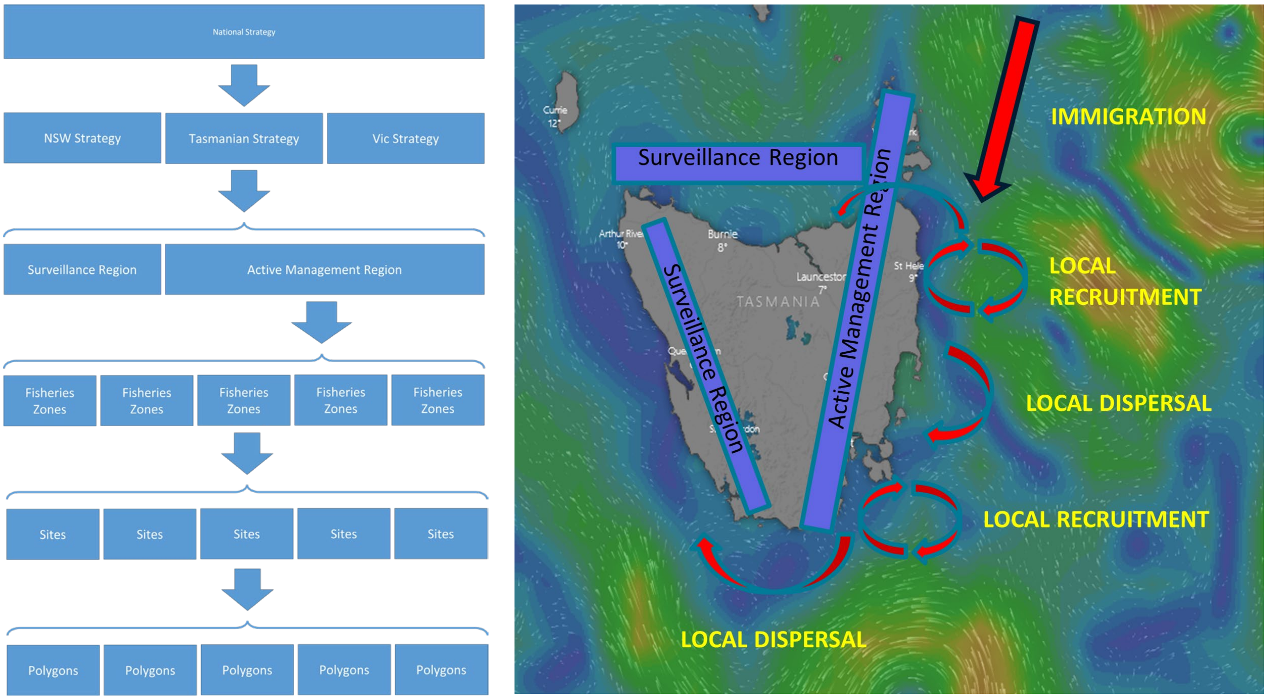


Figure 2 a): Spatial scales of management; and b) processes driving population dynamics of C. rodgersii in Tasmania and the approximate distribution of management activities.

Spatial Scales:

Spatial scales define areas over which management decisions are made and actions implemented. In practice, multiple scales are needed – the scale of an individual control action such as a dive, the scale at which a group of dives are conducted on a single voyage or group of voyages, the scale over which individual operators operate, and larger scales to structure regional prioritisation and decision making. In the case of the *C. rodgersii* fishery there are already a number of spatial scales well established for the management of abalone, urchin, and lobster fisheries licenses and, where possible, it makes sense to structure the proposed Centrostephanus Control Program consistent with these scales. Relevant scales (Figure 2) include:

i. National – *C. rodgersii* are present in NSW, Victorian and Tasmanian waters. Eventually, a coordinated approach may be possible across the species' range. An integrated, range-wide program is likely to deliver significant value because *C. rodgersii* can disperse long distances on ocean currents, providing an ecological link between independent state control programs
ii. State – Currently, C. rodgersii management decisions are made independently by State fisheries bodies; in the context of the current report the relevant state coordinating bodies include NRE.
iii. Regions – From a management perspective, the Tasmanian coastline can be divided into two regions, approximately shown in Figure 3, in which different management activities are conducted which define the nature of activities conducted there: a) Monitoring Regions - areas where *C. rodgersii* barrens are not yet recorded or where there are low levels of concern over their impact; and Management Regions – areas where barrens are recorded and are of concern. Additionally, *C. rodgersii* control or reporting could be linked to other existing regional or sub-regional management efforts (e.g. Bass Strait, parts of the east coast to the southwest corner of Tasmania).
iv. Zones – based on commercial dive fishery zones (Figure 3) and used in the fishery generally to identify general areas for management focus. Efforts could also be coordinated at or analysed against Abalone blocks or aggregations of blocks to communicate links to that sector.

v. Sites – A geographically defined, and ideally distinct, patch of rocky reef habitat (see Figure 3). This represents the minimum scale at which individual control "Operations" (see below) would be focused. A site would generally be comprised of a number of control "polygons".

vi. Polygons - A standardized and geolocated area that is the focus of a control dive (Figure 3). This area should be standardized on what can be accomplished by a standard dive team in a standard dive. Geo-referenced standardized polygons might be, e.g. 100x100m = 1 ha (based on Huddlestone (2020) and Larby (2020)), and distributed across all relevant habitat along the coast in a regular and numbered grid.

Depth Scales

There are a range of depth scales relevant to both *C. rodgersii* ecology and management, as described in detail in Section 4.6. For the purposes of the current strategy, we focus primarily on those depths that can be visited using current control methods, namely 0 – 20m on air and 20 – 27m on mixed gas. It will be important to establish reliable monitoring to assess both the likely distribution of *C. rodgersii* at depths beyond this, and the importance of these deeper populations to management efforts in accessible areas.

Key Temporal Scales and influence on revisitation intervals

Temporal scales relate the frequency of management actions, most importantly the rate at which controlled sites are revisited, to the ecological processes that allow Centrostephanus populations to recover or move following control actions, such as emergence of cryptic populations, immigration from outside controlled areas, and population dynamics.

i. Minimum revisitation interval – revisitation should not be more frequent than this, or management will be inefficient – defined by behavioural cycling of urchins between "available for control" and "hidden" (not available for control); probably on the order of days

ii. Asset protection revisitation interval – revisitation should be this frequent to protect key habitat from being damaged by *C. rodgersii* individuals that immigrate from uncontrolled regions – defined by *C. rodgersii* immigration rates from adjacent polygons – will vary across sites; probably on the order of weeks to months, depending on density targets and control efficacy

iii. Maximum revisitation interval - revisitation must be more frequent than this to reduce reproduction and invasion spread – *C. rodgersii* minimum reproduction age; probably on the order of a year, depending on density targets and control efficacy

iv. Timeframe for success - Kelp recovery rate; probably on the order of years to decades dependent on status (Healthy, Kelp, Incipient, Barren)

Scales of Management Effort

To be effective, the scale of management effort should match the ecological scales driving population dynamics and spread. To make decisions about how and where to invest management effort, it is useful to define units of management corresponding to pragmatic management structures. The smallest unit of management is a single control dive by the smallest viable dive team. This is important because it defines the granularity with which control actions can be targeted. A Dive takes place as part of an Operation, which consists of many Dives in a cluster of nearby Sites. This is important because it is logistically efficient to manage areas close together at one time. Relevant scales of Management Effort include:

i. Dive Team – based on the standard for the industry – Two divers and a boat person is assumed.

ii. Dive – fundamental unit of management investment comprising a dive of standard bottom time by a standard dive team at a polygon.

iii. Operation – a defined investment of dive days focused on controlling one or several nearby sites that can be visited during a voyage, and that typically would form a natural geographic grouping, e.g., recent operations at Block 22A, and the Fortescue Bay Complete Cull (Huddlestone 2020, Larby

2020). An Operation represents the minimum unit of revisitation to a site or polygon, i.e., a vessel travels to a Site and institutes a number of Dives. During an Operation, each polygon actioned would be Dived as many times as necessary until no further *C. rodgersii* were available for control. A polygon or site that had been controlled to zero available *C. rodgersii* in Operation 1 would only be revisited in subsequent operations and would not be revisited during Operation 1.

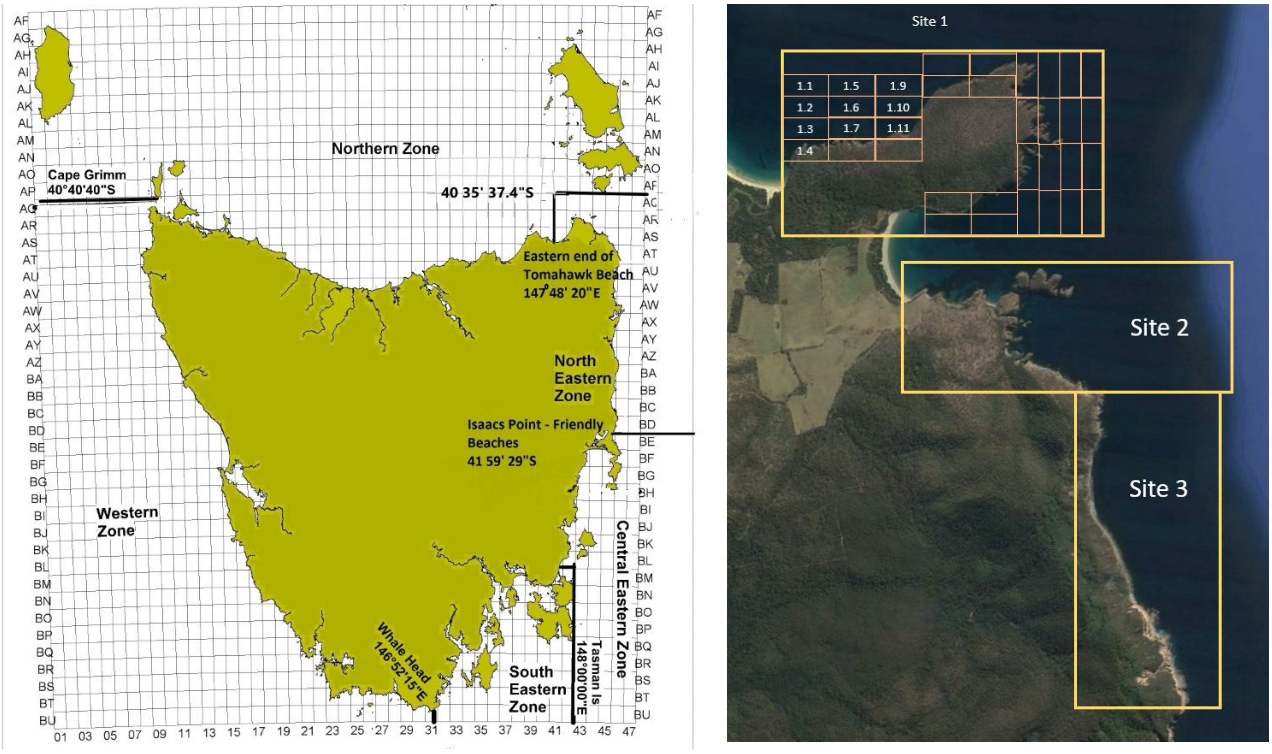


Figure 3: a) Commercial dive fishery management Zones (Black text) for Tasmania; and b) Sites and polygons

5.1.3 Performance Metrics – what state are the urchins in?

To understand when control is needed at a given location, when it is complete, and when and where it is working across larger scales, it is important to clearly define metrics of performance based on the ecological process related to the management objectives. In the case of *C. rodgersii*, the relevant metric is density because it is the density of *C. rodgersii* that determines the relevant ecological impact, i.e. the formation of barrens (Filbee-Dexter and Scheibling 2014, Ling et al. 2015). Density is the fundamental metric for documenting *C. rodgersii* population dynamics and monitoring control performance.

In practise, *C. rodgersii* density will be measured as “control density” and defined as the number or mass of *C. rodgersii* controlled per hectare (or m^2) at the end of a control operation, i.e. when there are no more *C. rodgersii* available to control. This density should be estimated at the polygon scale for each size class and as a total number controlled for each polygon across all dives during an operation. These estimates at the end of an operation represent the current state of the polygon.

Note that while many fisheries commonly report catch-per-unit-effort (CPUE) as a performance metric, it should not be considered a primary performance metric for a control program because it is not directly related to ecological progress of the CCP. CPUE data reflects fishery performance as number of *C. rodgersii* controlled per minute invested. The density data collected for informing control program decisions can be interpreted as CPUE for use in assessments of harvest economics.

5.1.4 Polygon and Site Status – what is ecological state?

To simplify the communication of management decision making, it is useful to assign each management unit a "status" reflecting its ecological condition, and determining the management strategy to be applied:

a. Barrens – polygons or sites with established urchin barrens of any size
b. Incipient – polygons or sites with kelp thinning or patchiness
c. Kelp – polygons or sites with healthy kelp communities but elevated *C. rodgersii* densities
d. Healthy – polygons or sites with healthy kelp communities and no-to-low *C. rodgersii* densities

Polygons and sites are assigned a status based on the most degraded area, e.g. a site that is mostly incipient but with a small area of barren should be assigned barren status. Polygons and sites determined not to have suitable substrate are excluded from the program area.

5.1.5 Key Thresholds – what density must *C. rodgersii* be controlled to?

Polygons and Sites are assigned a status, or moved from one status to another, based on the *C. rodgersii* density thresholds at which important ecological processes change, requiring a different management response. There are two key ecological thresholds, and two control thresholds, each of which apply to polygons within certain statuses (barrens, incipient, kelp or healthy):

Ecological Thresholds:

a. Ecological Barren Formation threshold – this is the critical *C. rodgersii* density at which action becomes a priority at non-barren sites (i.e. "kelp" or "healthy" sites). In the first instance, the threshold is defined as a conservative proportion (e.g. 0.5) of the estimated *C. rodgersii* "barren formation density" to provide a buffer to account for uncertainty in the estimate of this critical parameter. As new data on densities is obtained and uncertainties reduced this conservative proportion can be increased. We use the minimum threshold density reported by Filbee-Dexter and Scheibling (2014) for Tasmanian waters as our working estimate of the target density required to prevent barren formation, i.e. 4 individuals / m^2 or 900 g / m^2. Applying a buffer proportion of 0.5 to this yields a Formation Density of 2 individuals / m^2.
b. Ecological Barren Recovery threshold – minimum *C. rodgersii* density to be achieved at locations with barrens (i.e. "incipient" or "barrens" sites). This is also initially defined as a conservative proportion, e.g. 0.5, of the lowest density identified in Filbee-Dexter and Scheibling (2014), i.e. 0.2 individuals / m^2 or 50 g / m^2, but can be refined as data is collated by the program. Applying a buffer proportion of 0.5 to this threshold yields a target Recovery Density of 0.1 *C. rodgersii* / m^2, which in practice would be very close to zero caught over a polygon.

Control Thresholds:

c. Control Stopping threshold – *C. rodgersii* density below Barren Formation or Recovery Threshold at which control ceases. In its simplest form, this is the relevant Ecological Threshold for each site. However, the Control Stopping Threshold may be reduced below the Ecological Threshold to: 1) provide a buffer for population recovery when the time between control revisits is long; or 2) make operations advice simpler. For instance, even though the Barrens Recovery Threshold is 0.1 individuals / m^2, in practice it may be simpler to express the Control Stopping threshold as "zero *C. rodgersii* caught at a polygon during an operation". For the purposes of the strategies outlined here, we do not distinguish between the "Control Stopping" and "Ecological" thresholds.
d. Control Action thresholds – *C. rodgersii* density and site / polygon values (e.g. kelp status, season, *C. rodgersii* size structure) assessments that determine when different management actions, such as Roe Harvest, Grow-out, Fertilizer, Culling or combinations of these control methods are chosen. In theory Action thresholds could vary between sites at any point in time and for a site over time. In the current strategy, these thresholds are not used, but in future they could be implemented as part of a more complex control program structure.

The principles in Sections 5.1.4 and 5.1.5 are illustrated in the Decision Tree in Figure 4.

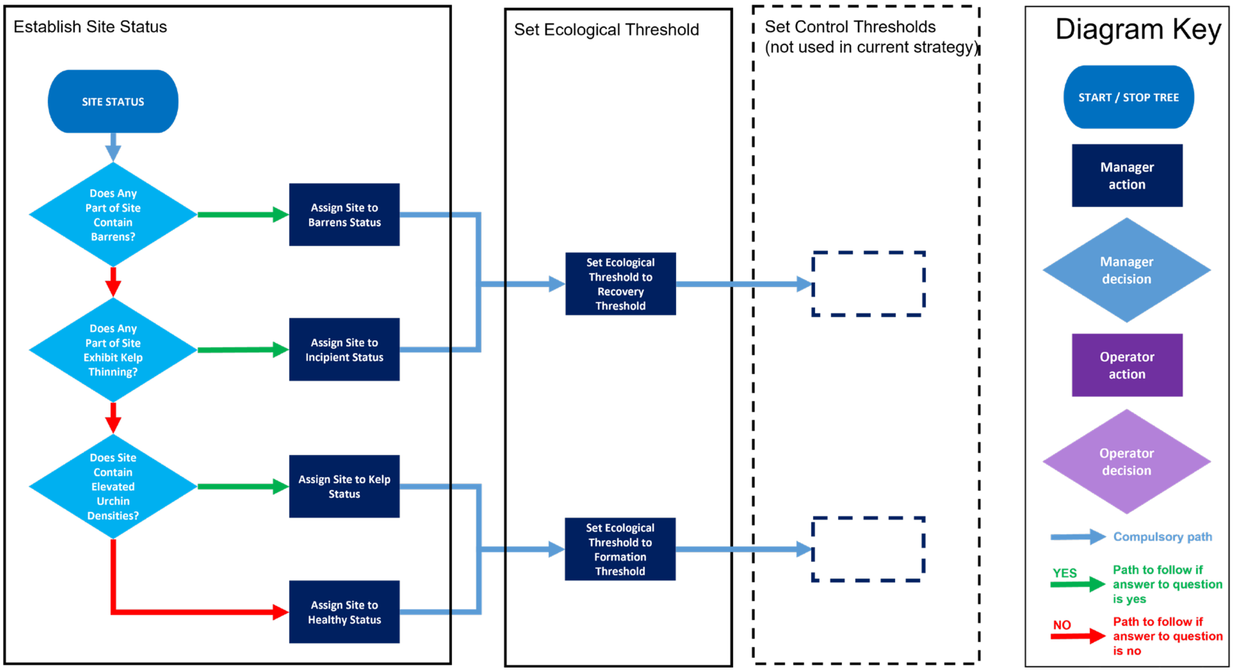


Figure 4 - Decision Tree for Site Status and Determining Ecological Threshold

5.1.6 Control Modes and Revisitation – different responses to different ecological states

The status of a Site and the density of *C. rodgersii* relative to the corresponding threshold allow it to be allocated to one of three management categories: Intensive; Maintenance; or Monitoring. These categories define the control activity and priority of a site and the revisitation interval for sites, and are illustrated in Figure 5:

Intensive Mode: site or polygon exceeds its status' threshold and requires management.

i. Control Objective – to reduce *C. rodgersii* densities to below relevant thresholds.
ii. Revisitation Interval - short-interval repeat visits. Control revisitation intervals will be a function of the detectability of *C. rodgersii*, which will be a function of i) the proportion of *C. rodgersii* that are exposed and available to control, ii) how they cycle between exposed and hidden, as well as immigration rates from adjacent areas. In the first instance, Intensive Revisitation might be set at a minimum of 1 week (sufficient time for animals to re-emerge) and revised as data on population recovery is generated by the control program.
iii. Dives would be 'Control Dives' where the intent would be to harvest or cull.
iv. Revisitation should continue until the target threshold is achieved this may take multiple Operations over a period of weeks to months. The goal should be to achieve thresholds in the minimum time possible as this results in the least loss of kelp cover.

Maintenance Mode: management has achieved its target *C. rodgersii* density.

i. Control Objective – to ensure that *C. rodgersii* densities remain below the relevant Site / Polygon Status Threshold until kelp recovery has been achieved.
ii. Revisitation Interval – medium interval revisitation. The frequency of revisitation will be a function of local *C. rodgersii* recruitment and immigration rates and the site's status. Recovering barrens may require more frequent maintenance revisitation due to the much lower recovery threshold.
iii. Revisitation could take the form of a 'Check Dive' where an efficient monitoring method such as transect or plot survey was deployed rather than an intensive 'Control Dive' to remove animals.

iv. In the first instance, Maintenance Interval might be set to 6-month intervals and should be revised as data on population recovery is obtained. Maintenance visitation should be continued until the site is returned to Healthy status

Monitoring Mode revisitation: site has recovered to Healthy status or has always been Healthy.

i. Control Objective – early detection of increased *C. rodgersii* densities that could lead to a state change
ii. Revisitation Interval - medium-to-long interval revisitation to detect and quickly eliminate any recovery or increase in *C. rodgersii* densities that could lead to a transition to a new State. The frequency of monitoring revisitation will be a function of local *C. rodgersii* recruitment and immigration rates, as well as detectability of *C. rodgersii* in kelp habitats, and program resources.
iii. Revisitation would take the form of a 'Check' dive, i.e. a standardized transect or plot survey.
iv. In the first instance, Monitoring Revisitation is set to 1 year.

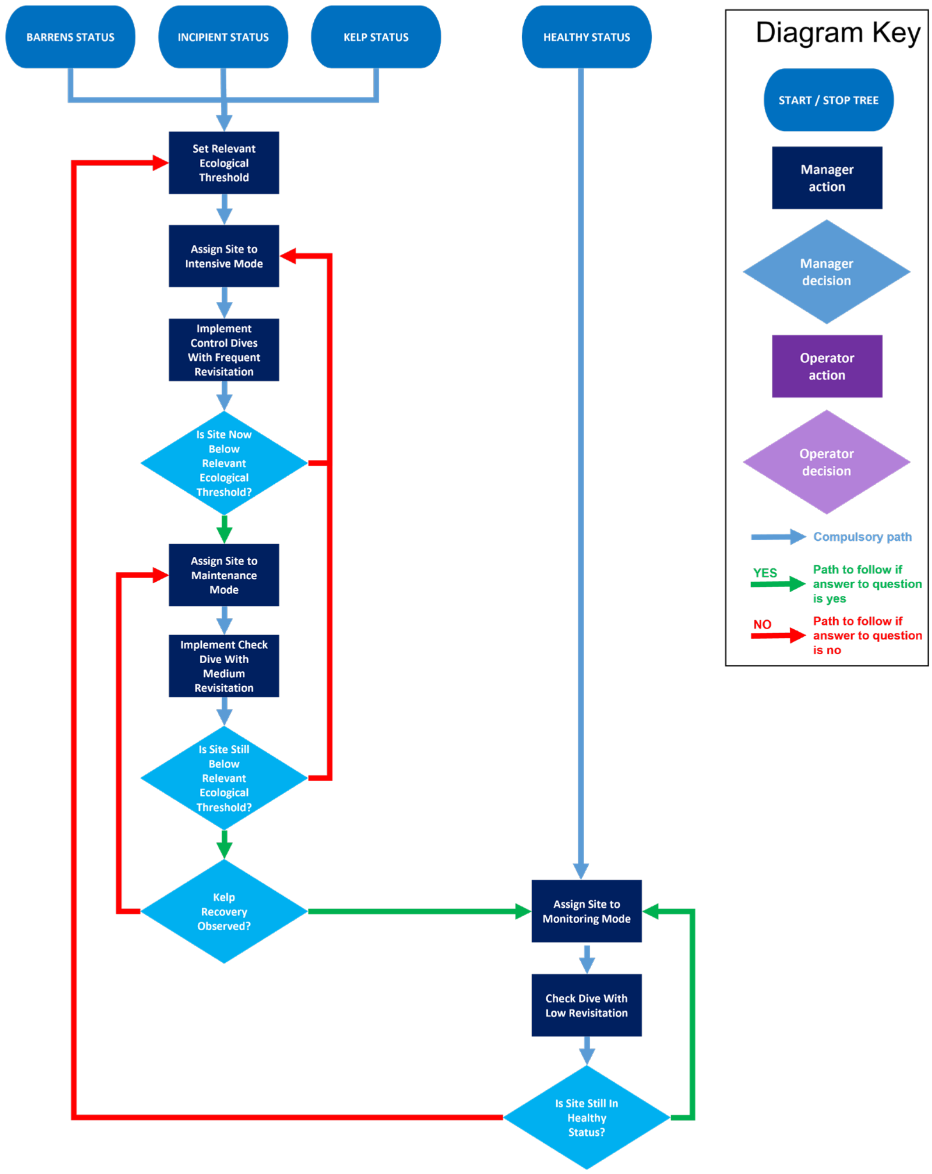


Figure 5 – Decision Tree for Control Modes

5.2 Design for an Initial Implementation

We base this Initial Implementation Strategy on the assumption that there is both limited resourcing available to support *C. rodgersii* control, and that the limited experience to date means that there is insufficient data to immediately underpin the roll out of a larger scale strategy. It is focused primarily on active control measures such as harvest for various purposes or culling, because these methods can provide immediate response to *C. rodgersii* impacts. It does not explicitly consider citizen science culling as an overall Program strategy, because current estimates suggest that the volume of catch due to recreational fishing of all forms is negligible relative to commercial efforts (Cresswell et al. 2018, 2020, 2022); however, it should be considered as a supplementary option for control at locations where it is available. In the longer term, it will also be important to consider how these control methods interact with other conservation efforts such as marine parks or lobster translocation.

The goal of this strategy to enact *C. rodgersii* control at a range of priority locations, in a manner that ensures that everywhere control effort is invested, it achieves ecologically-meaningful outcomes. It is designed based on the current state of knowledge of the distribution of *C. rodgersii* and of the assets being protected, the structure of the fishery and dive operations, and the general scale of funding.

This means that the overall goal isn't to reduce *C. rodgersii* densities in some structured manner across the entire east coast. Instead, the goal is to achieve meaningful ecological outcomes at particular locations, i.e. sites are chosen primarily for their inherent values rather than for their contribution to a larger strategic goal. Similarly, the presence of other conservation measures such as marine parks or lobster translations at a Site may influence whether it is targeted, but larger and longer-term interactions between conservation programs are not considered. Working at this scale is consistent with available funding and current operational capacity.

At each site that is controlled, we assume that the goal is to reduce polygon and site level densities to below the relevant ecological threshold given polygon status (Healthy, Kelp, Incipient, Barrens). This requires changes from the current approach, including repeated visits to control at sites and polygons until they are reduced to below relevant thresholds. If paired with appropriately structured subsidies, repeated visitation would have the additional benefit of ensuring that the program is properly scaled to its resources as it focuses effort incentivising achieving objectives before abandoning a polygon or site.

Below, we run through the sequence of steps required to successfully implement the Strategy, linking them to the ecological drivers outlined in section 5.1:

1. Planning - Identify objectives of the Program with representative stakeholders
2. Site Ranking and Selection - Use those goals to prioritise locations for management
3. Determine Program Type – Define Program method to be used, and then for the selected type:
    a. Direct on-water managers to the highest priority locations
    b. Ensure that any location that is controlled achieves an ecologically-meaningful outcome
    c. Monitor and ensure outcomes are maintained

5.2.1 **Planning**

1) Define specific Program Objectives and the Values they imply: This should be done from the perspective of the process owner, in this case DPIPWE. This initial step will identify the fundamentals of the program and these values will guide choices about sites, methods, etc.
2) Identify Stakeholders and the degree and nature of their relevance to the Program. Those with direct involvement will become Program Participants, others may be consulted as necessary.
3) Identify and engage Program Participants:
    a. Steering Committee – responsible for oversight and strategic decisions (e.g. priority Blocks, sites, etc). Comprised of key Stakeholders
    b. Program Managers – responsible for operational oversight (including site selection, assignment and data management) and feeding information back to Steering Committee

c. Control Divers – responsible for on-water operations and pushing their assigned/chosen sites to below the relevant thresholds
d. Confirmation divers (optional) – check sites have been reduced to below thresholds once reported as such.

4) Define scope of project
5) Refine Objectives and Values based on input from Stakeholders & Participants
6) Determine Depth Range of the Program
7) Determine conditions for different kelp rehabilitation strategies

5.2.2 Zone and Site Ranking and Selection

1) Prioritize zones based on values, stakeholder input, other relevant factors. At these large scales, and while resources are sufficient only for a part of the coastline, such decisions are likely to be qualitative and responsive to information from the field.
2) Prioritize sites based on values, stakeholder input, and other relevant factors if this is appropriate (see below) and this information exists.
   a. Exactly how sites are selected for control will be a function of the Program Type selected (as indicated in Figure 7 and the following section). However, it is anticipated that even under a fully Commercial Harvest there may be some desire to ensure that priority sites are at least identified in order to assess whether the harvest is indeed achieving the Program's objectives. If not, then this phase can be skipped.
   b. Where there are conflicting or complex trade-offs to be made, approaches such as Multi-Criteria Decision Analysis and expert elicitation processes might be employed.
3) Prioritize Zone*Site combinations (optional): adjust site rankings based on the ranking of the zone.

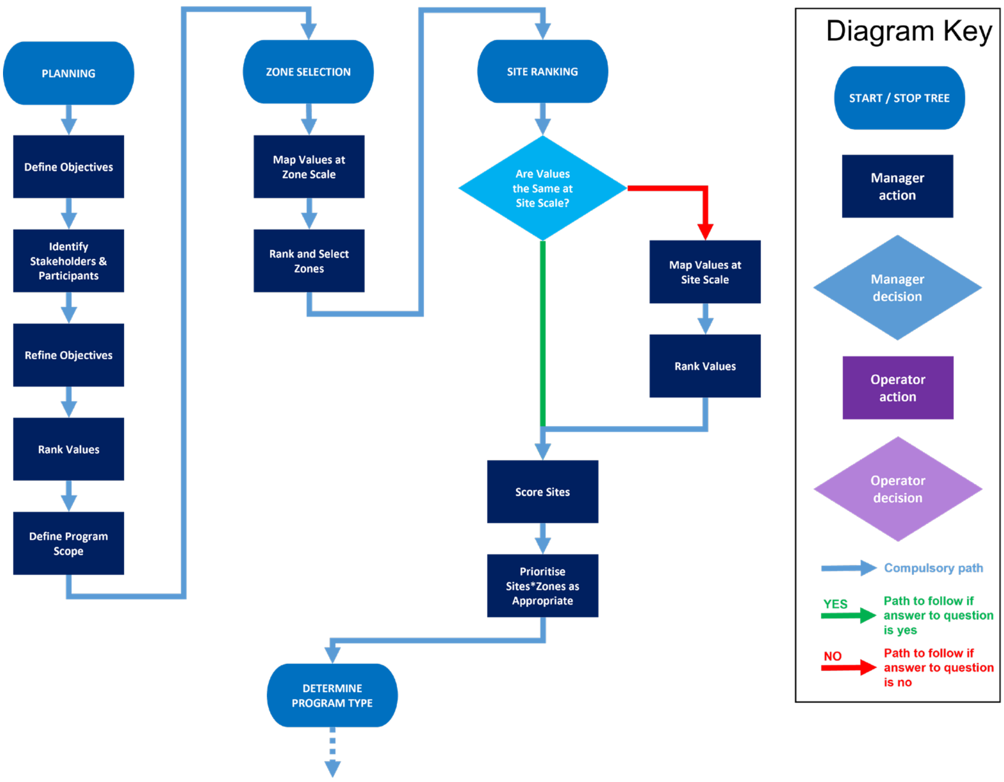


Figure 6 - Planning and Zone and Site Ranking and Selection Decision Tree

5.2.3 **Determine Program Type**

At this point in the process the main task is to determine which Program Type is to be implemented. This decision will be based on an assessment of the adequacy of Commercial Harvests to achieve the desired thresholds, whether they can be focused to improve performance through the use of Catch Limits or Subsidies, or, whether a targeted funding approach is required. Each of the seven options implies a slightly different decision process, different financial costs, and different levels of complexity. In the short term, this decision process could be applied across the entire control program coverage area encompassing multiple Zones, or the optimal type of strategy could be determined separately in several different Zones. In the long run, different optimal Strategies could be determined at finer scales, even individual Sites. However, at fine scales of optimisation the sheer number of different strategies to be coordinated and managed will become unwieldy and require simultaneous optimisation to avoid perverse outcomes between regions, so fine scale program design is unlikely to be used initially. Independent of the scale at which the type of control program is being selected, the overall process is illustrated in Figure 7, and would operate as outlined below:

1) Determine "Is the Economic Threshold that allows operators to generate a profit is lower than the Ecological Threshold across the management region being considered?"
    a. If the answer to 1 is "Yes", then determine "Do economic or other drivers in the region sufficiently focus on-water operators' efforts at the priority locations the Control Program seeks to protect?"
        i. If the answer to 1.a is "Yes", then a Commercial Harvest (i.e. one that is fully commercially funded and without spatial focus) can achieve program objectives, i.e. adequate density reductions, at priority sites. Under this Program Type divers choose their sites and harvest intensities, while Control Program managers define program targets and monitor to ensure program objectives are being achieved.
        ii. If the answer to 1.a is "No", then the Control Program needs to spatially focus operators' efforts, but not subsidise them, so the appropriate Strategy is a Spatially Targeted Harvest. This Strategy imposes Catch Limits on non-priority Sites to encourage operators to focus on Priority Sites.
    b. If the answer to 1 is "No", then the Control Program needs to provide a financial incentive so that operators that engage in the program can achieve a profit. There are several options with different levels of financial intervention, cost and complexity. We work our way from least complex and / or costly to most, starting by determining "Does the harvest market for Centro across the Control Program region being considered provide an economically significant motivation for operators, even if it doesn't cover all costs?"
        i. If the answer to 1.b is "Yes", then we can leverage the harvest market to offset some costs of running the Control Program. Next, we determine "Is variation in the market over time, through market prices for catch, likely to cause significant variation in economic motivation to operators to engage in harvest?"
            1. If the answer to 1.b.i is "No", then there is little benefit in designing a complex subsidy, so the appropriate Strategy is a type of Fixed Subsidy. Next, we determine "Do, given the Fixed Subsidy, economic or other drivers in the region sufficiently focus on-water operators' efforts at the priority locations the Control Program seeks to protect?"
                a. If the answer to 1.b.i.1 is "Yes", then apply a single Fixed Subsidy across the entire region
                b. If the answer to 1.b.i.1 is "No", then apply several different Fixed Subsidies across different zones in the program and / or Catch Limits on non-priority Sites or Zones

2. If the answer to 1.b.i is "Yes", then there is there is a benefit to making the subsidy respond to variable market conditions, such as catch prices, changing competition, or seasonal variation. There are two ways to do this, an operator-driven Auction / Tender process by Site, or a program-driven Adaptive Subsidy. We determine "Is the market is competitive enough to make an Auction / Tender process efficient?"
    a. If the answer to 1.b.i.2 is "Yes", the appropriate Strategy is an Auction / Tender
    b. If the answer to 1.b.i.2 is "No", the appropriate Strategy is an Adaptive Subsidy

ii. If the answer to 1.b. is "No", then all costs of control must be borne by the Control Program to achieve objectives at Priority Sites, and the appropriate Strategy is based on a Contract to provide control services across the management region being considered. In this case, Control Program managers would provide specific direction about where and how control actions were to occur, and Operators would follow that guidance, rather than incorporating harvest considerations into their decisions.

Other control options, such as citizen science enabled culls, may be considered at specific locations where they are available, but they are not considered explicitly here because they are unlikely to be of sufficient scale to structure an entire Program around.

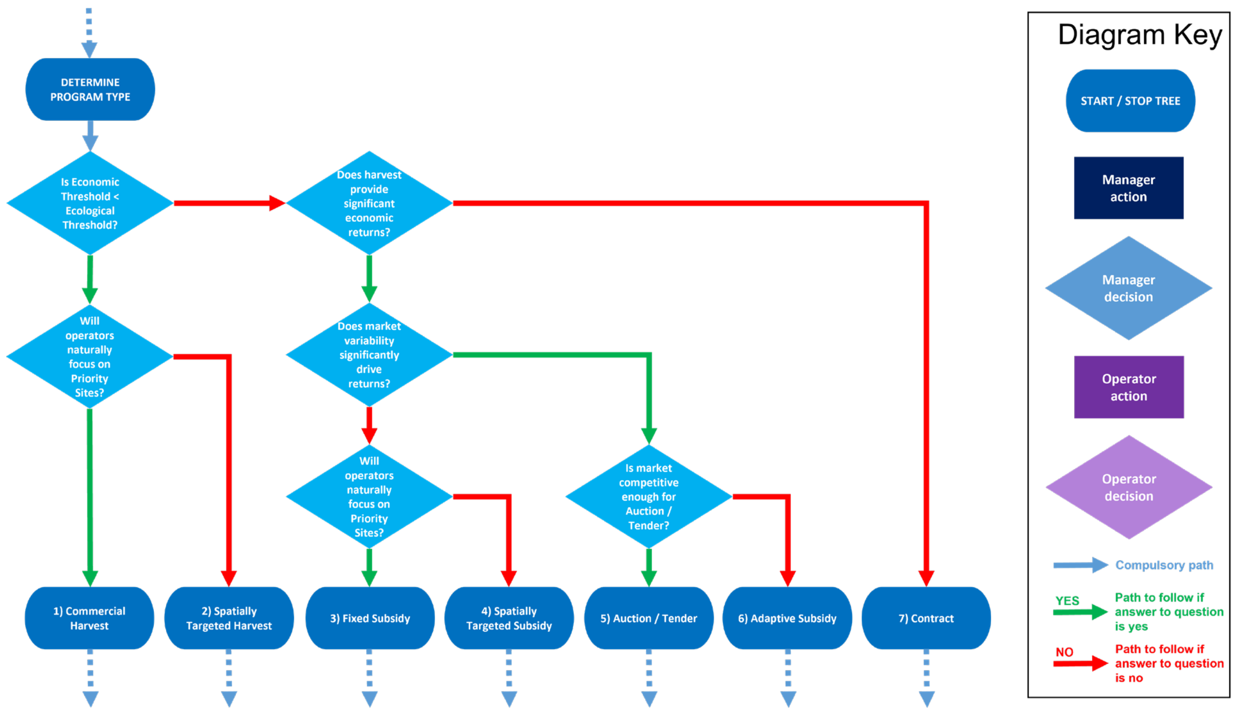


Figure 7 – Determine Program Type Decision Tree

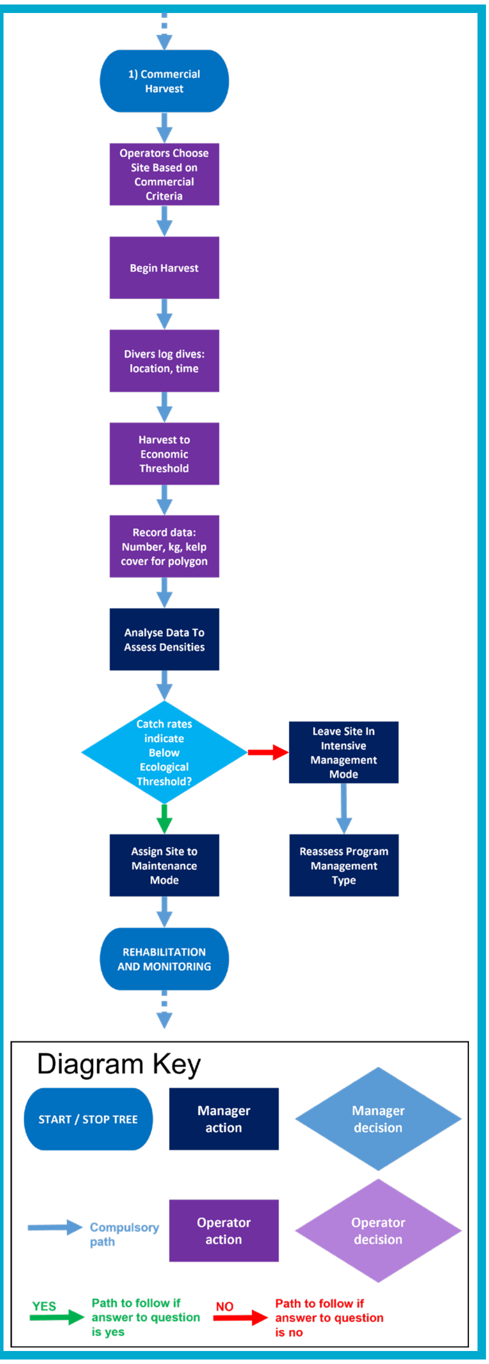
5.2.4 **Implementation**

The different Program Types have different modes of operation, as outlined in the Table below:

Implementation – 1) Commercial Harvest

If the recommended Program Type is Commercial Harvest, then the following implementation is required, as illustrated in the figure to the right:

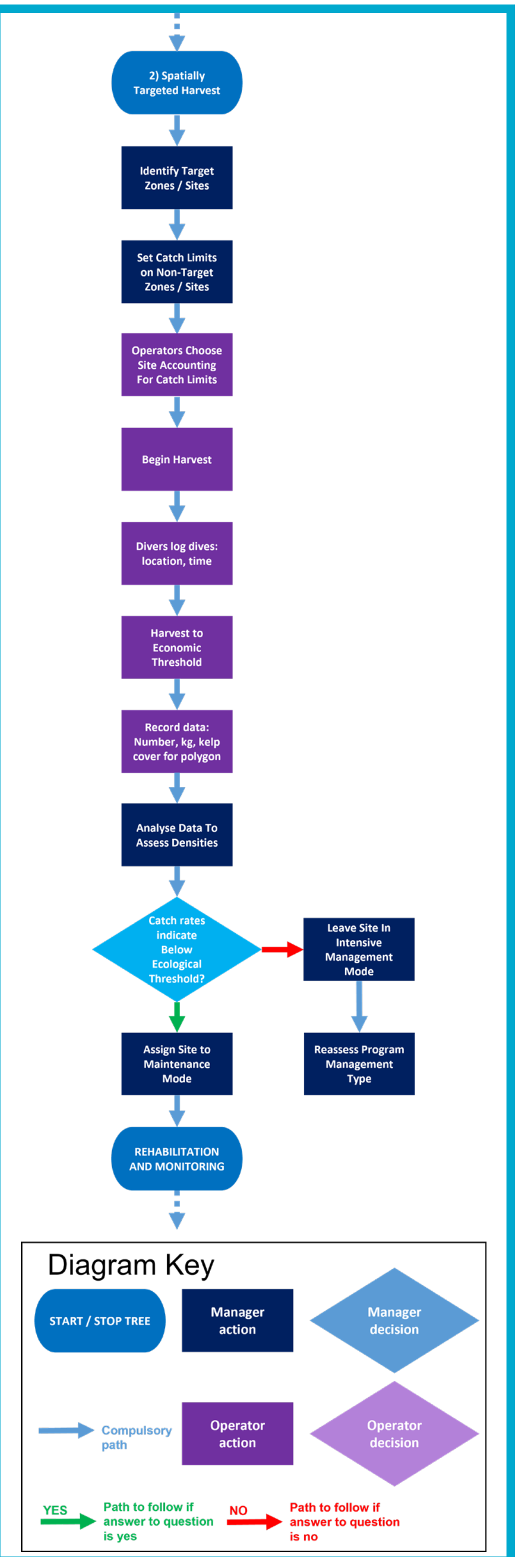
1) Operators choose Sites based on their commercial criteria.
2) Operators Dive each polygon at a Site to harvest *C. rodgersii*.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing.
3) Operators repeat the previous step at appropriate intervals until Economic Threshold is achieved.
4) Control Program managers analyse data reported by Operators, using kelp cover data to ascertain the Site Status and appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery), and catch data to assess whether catch rates are consistent with Centro densities below the Ecological Threshold.
    a. If so, they move the Site to Maintenance Mode, after which the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.
    b. If not, the Site is left in Intensive Management Mode, and a different Program Type is considered to achieve Program objectives.



Implementation – 2) Spatially Targeted Harvest

If the recommended Program Type is Spatially Targeted Harvest, then the following implementation is required, as illustrated in the figure to the right:

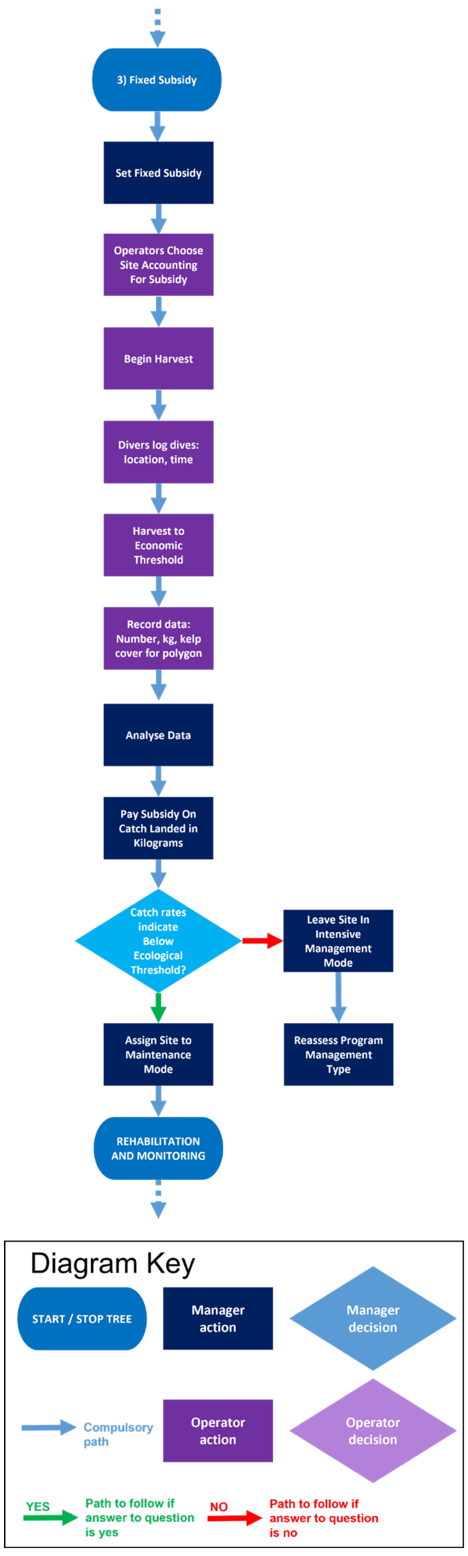
1) Control Program managers identify Target Zones / Sites.
2) Sites where Catch Limits are to be imposed are chosen such that the limits displace harvest to the Priority Zones / Sites.
3) Operators choose from non-limited Sites based on their commercial criteria.
4) Operators Dive each polygon at a site to harvest *C. rodgersii*.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing.
5) Operators repeat the previous step at appropriate intervals until Economic Threshold is achieved.
6) Control Program managers analyse data reported by Operators, using kelp cover data to ascertain the Site Status and appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery), and catch data to assess whether catch rates are consistent with Centro densities below the Ecological Threshold.
    a. If so, they move the Site to Maintenance Mode, after which the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.
    b. If not, the Site is left in Intensive Management Mode, and a different Program Type is considered to achieve Program objectives.



Implementation – 3) Fixed Subsidy Harvest

If the recommended Program Type is Fixed Subsidy Harvest, to ensure harvest is profitable so Operators are motivated to engage in harvest, then the following implementation is required, as illustrated in the figure to the right:

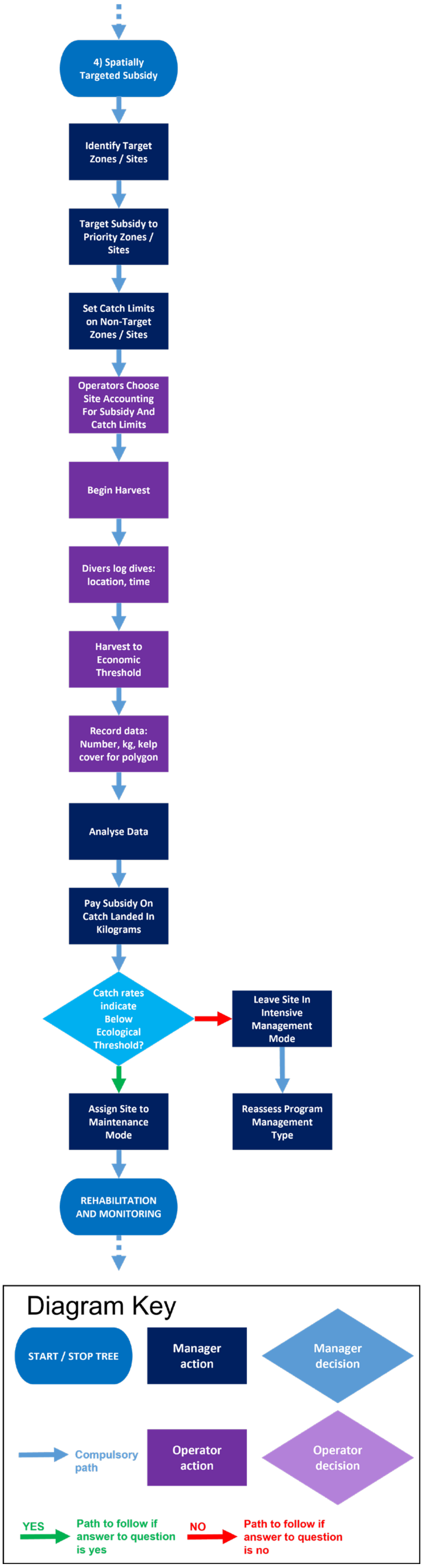
1) Control Program managers determine a Fixed Subsidy sufficient to motivate Operators to engage in harvest. The process is similar to a Commercial Harvest, with the fixed subsidy being paid based on catch landed in kg.
2) Operators choose Sites based on their commercial criteria.
3) Operators Dive each polygon at a Site to harvest *C. rodgersii*
   a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing.
4) Operators repeat the previous step at appropriate intervals until Economic Threshold, including the Fixed Subsidy, is achieved.
5) Control Program managers analyse catch data reported by Operators and pay subsidy as required.
6) Control Program managers analyse data reported by Operators, using kelp cover data to ascertain the Site Status and appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery), and catch data to assess whether catch rates are consistent with Centro densities below the Ecological Threshold.
   a. If so, they move the Site to Maintenance Mode, after which the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.
   b. If not, the Site is left in Intensive Management Mode, and a different Program Type is considered to achieve Program objectives.



Implementation – 4) Spatially Targeted Subsidised Harvest

If the recommended Program Type is Spatially Targeted Subsidised Harvest, to both ensure harvest is profitable so Operators are motivated to engage in harvest, and increase geographic focus over and above that achieved with Catch Limits, then the following implementation is required, as illustrated in the figure to the right:

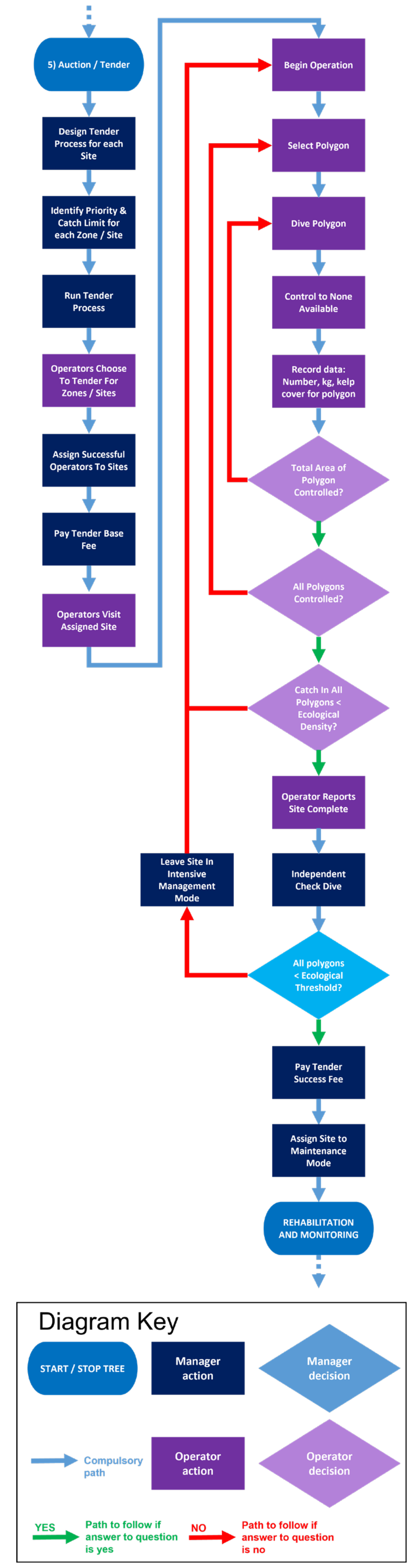
1) Control Program managers identify Target Zones / Sites.
2) Control Program managers decide whether to employ Spatially Targeted Subsidies, Catch Limits or both. If no Catch Limits are imposed, the process is similar to the Commercial Harvest. If Catch Limits are imposed, the process is similar to the Spatially Targeted Harvest. The subsidy is paid on catch landed in kg.
3) Operators choose Sites based on their commercial criteria, accounting for Spatially Targeted Subsidy and Catch Limits.
4) Operators Dive each polygon at a Site to harvest *C. rodgersii*.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing.
5) Operators repeat the previous step at appropriate intervals until Economic Threshold is achieved.
6) Control Program managers analyse catch data and pay subsidy as required.
7) Control Program managers analyse data reported by Operators, using kelp cover data to ascertain the Site Status and appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery), and catch data to assess whether catch rates are consistent with Centro densities below the Ecological Threshold.
    a. If so, they move the Site to Maintenance Mode, after which the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.
    b. If not, the Site is left in Intensive Management Mode, and a different Program Type is considered to achieve Program objectives.



Implementation – 5) Auction / Tender

This is the first of the Market subsidized strategies. It is assumed that Divers are paid by the processor for their costs and that competition for access to sites will ensure that Tenders take this processor payment into account. Limiting Catch at non-Priority Sites may enhance this competition.

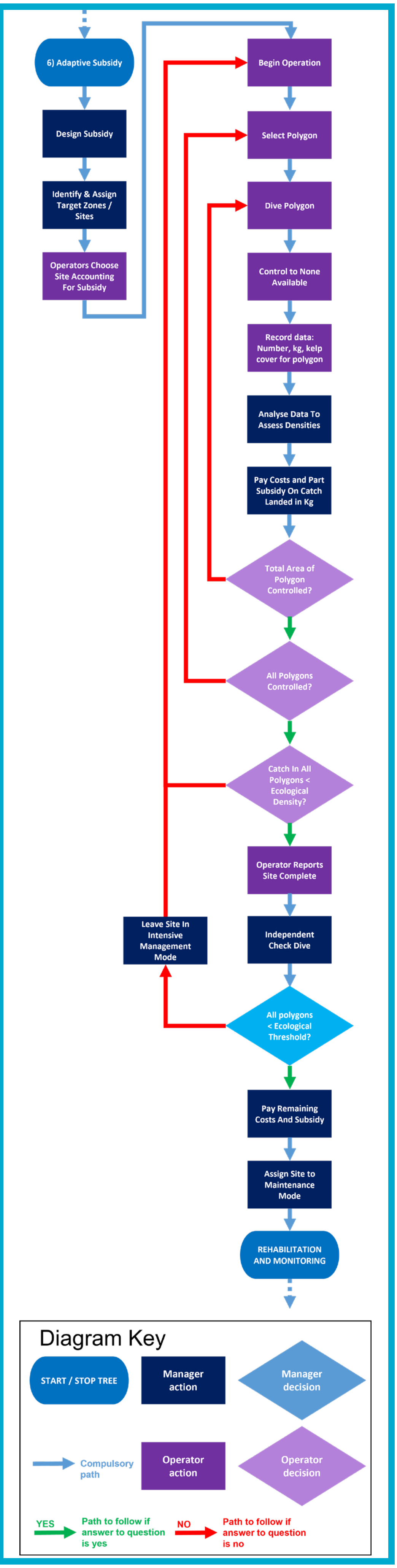
1) Control Program managers design tender process. This process could take a number of forms, e.g. a Reverse Auction, where Operators provide their lowest bid for the right to work a site to the Ecological Threshold
2) Control Program managers determine Priority Sites and if necessary, Catch Limit Sites
3) Control Program managers run Tender process
4) Operators bid on right to control Sites
5) Control Program managers assign successful Operators to Sites
6) Operators begin operations at their assigned Site
7) Operators Dive each polygon at a site to remove *C. rodgersii* to the Ecological Threshold.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing.
8) Because the goal is cull rather than harvest, Operators keep Diving a Polygon until it has been completely covered, then move to the next Polygon until every Polygon has been covered.
9) Operators repeat the previous steps until their catch data indicates that the appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery based on Site Status) has been achieved at all polygons, then notify Control Program managers that the Site is complete.
10) Control Program managers organise an independent check dive.
    a. If any Polygons are above the threshold, control begins again.
    b. If all Polygons are below the threshold, payment is made, Site is assigned to Maintenance Mode, and the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.



Implementation – 6) Adaptive Subsidy

This is the second Market Subsidized strategy. It uses a market-responsive and potentially spatially varying subsidy to efficiently supplement processor payments sufficient to ensure harvest is profitable and Operators are motivated to engage in harvest. It requires good data about market prices, harvest costs and catch rates.

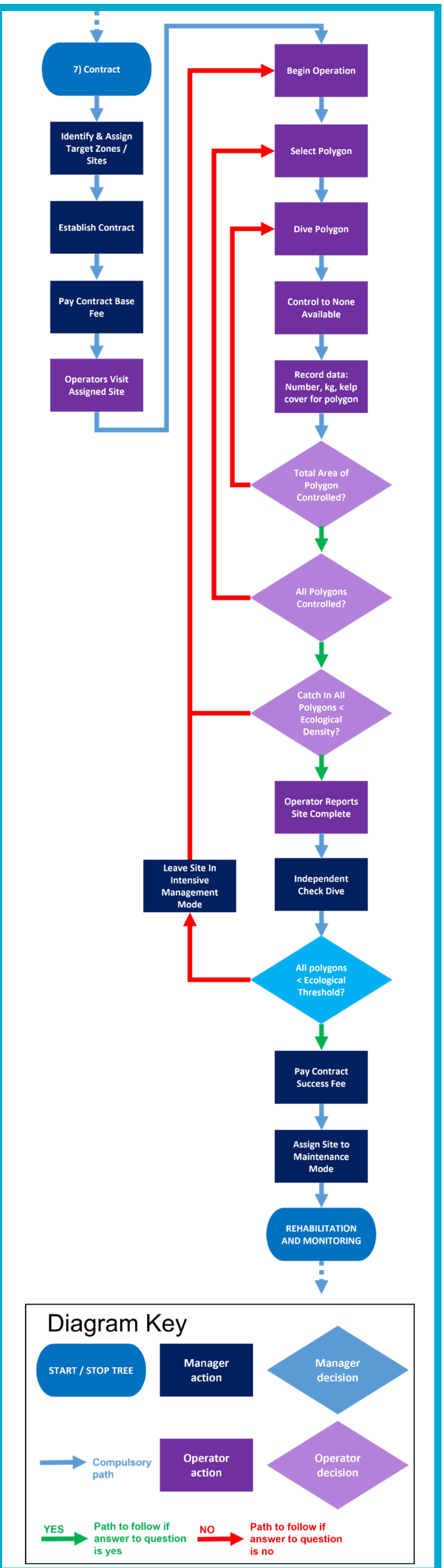
1) Control Program managers design Subsidy based on the quality of data available. The example provided in Appendix A would suit a situation where both processor payments and harvest are reliably documented.
2) Control Program managers determine Priority Sites and if necessary, Catch Limit Sites.
3) Operators choose Sites based on their commercial criteria, accounting for Adaptive Subsidy.
4) Operators Dive each polygon at a site to remove *C. rodgersii* to the Ecological Threshold.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing or at processor.
    b. Control Program managers may use harvest data to pay partial Subsidy on progress.
5) Because the goal is cull rather than harvest, Operators keep Diving a Polygon until it has been completely covered, then move to the next Polygon until every Polygon has been covered.
6) Operators repeat the previous steps until their catch data indicates that the appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery based on Site Status) has been achieved at all polygons, then notify Control Program managers that the Site is complete.
7) Control Program managers organise an independent check dive.
    a. If any Polygons are above the threshold, control begins again.
    b. If all Polygons are below the threshold, payment is made, Site is assigned to Maintenance Mode, and the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.



Implementation – 7) Contract

This strategy assumes that the Market provides no subsidy to the Control Program (though harvested *C. rodgersii* may still be provided to the processor, this would happen outside the Control Program) and that Control Program managers take on full control and responsibility for Control Activities.

1) Control Program managers determine Priority Sites and if necessary, Catch Limit Sites
2) Control Program managers define the necessary contract conditions
3) Control Program managers assign Operators to Sites
4) Operators begin operations at their assigned Site
5) Operators Dive each polygon at a site to remove *C. rodgersii* to the Ecological Threshold.
    a. Operators record site condition (kelp cover etc.) and tag urchins / crates to enable assignment to specific polygons to allow polygon metrics to be calculated (#, size, mass, status, etc) upon landing or at processor.
6) Because the goal is cull rather than harvest, Operators keep Diving a Polygon until it has been completely covered, then move to the next Polygon until every Polygon has been covered.
7) Operators repeat the previous steps until their catch data indicates that the appropriate Ecological Threshold (Barrens Prevention or Barrens Recovery based on Site Status) has been achieved at all polygons, then notify Control Program managers that the Site is complete.
8) Control Program managers organise an independent check dive.
    a. If any Polygons are above the threshold, control begins again.
    b. If all Polygons are below the threshold, payment is made, Site is assigned to Maintenance Mode, and the activities of the Program at this Site move to the Rehabilitation and Monitoring phase, where the performance of the program achieving and maintaining Program objectives is verified.



5.2.5 Rehabilitation and Monitoring

For all types of Program, once control activities are complete at a Site it is vital that: 1) any additional rehabilitation processes are put in place, and 2) the density of *C. rodgersii* at the Site is monitored over time. Sites that are successfully controlled will have been shifted to Maintenance Mode, after which they must be resurveyed with a Check Dive with a "medium" revisitation frequency, initially set at 6-monthly intervals. If those revisits show that urchin densities increase above the appropriate Ecological Threshold based on the Site Status, the management status should be shifted back to Intensive Mode, and reincorporated into control activities. If those revisits show that urchin density remains below the Ecological Threshold, then they should continue until signs of kelp recovery are observed. At this point, the management status can be moved to Monitoring Mode, and less frequent resurvey completed.

At all stages of this process, Control Program management staff should regularly review program data to: a) confirm that objectives are being achieved; b) if objectives are not being achieved, inform which alternative Program type to switch to; and c) ensure that *C. rodgersii* densities remain low, or rising densities are detected and controlled before they can cause additional long-term damage, i.e. barrens formation. This is especially important during the Initial Implementation Program when some assumptions have had to be made around facets of *C. rodgersii* ecology and management effectiveness.

For instance, if many Sites that have been moved out of intensive control to Maintenance Mode are found, once monitoring begins, to have *C. rodgersii* densities above the Ecological Threshold, then the appropriateness of the chosen Program Type should be reassessed using the data collected by the program to this point. If Sites that have been successfully controlled and moved to Maintenance Mode are found to experience rising urchin numbers shortly after intensive management is complete, then revisitation frequencies for Intensive Control and / or Maintenance Mode monitoring should be reassessed. If, over the longer term, Monitoring shows that the Control Program objectives are not being maintained, then underlying Program assumptions should be reassessed, refined using data collected to this point, and the Control Program tweaked in response. If Monitoring shows that the Control Program objectives are being maintained over the long term, then the Control Program should continue as designed, with the performance data and evidence collected communicated to key stakeholders.

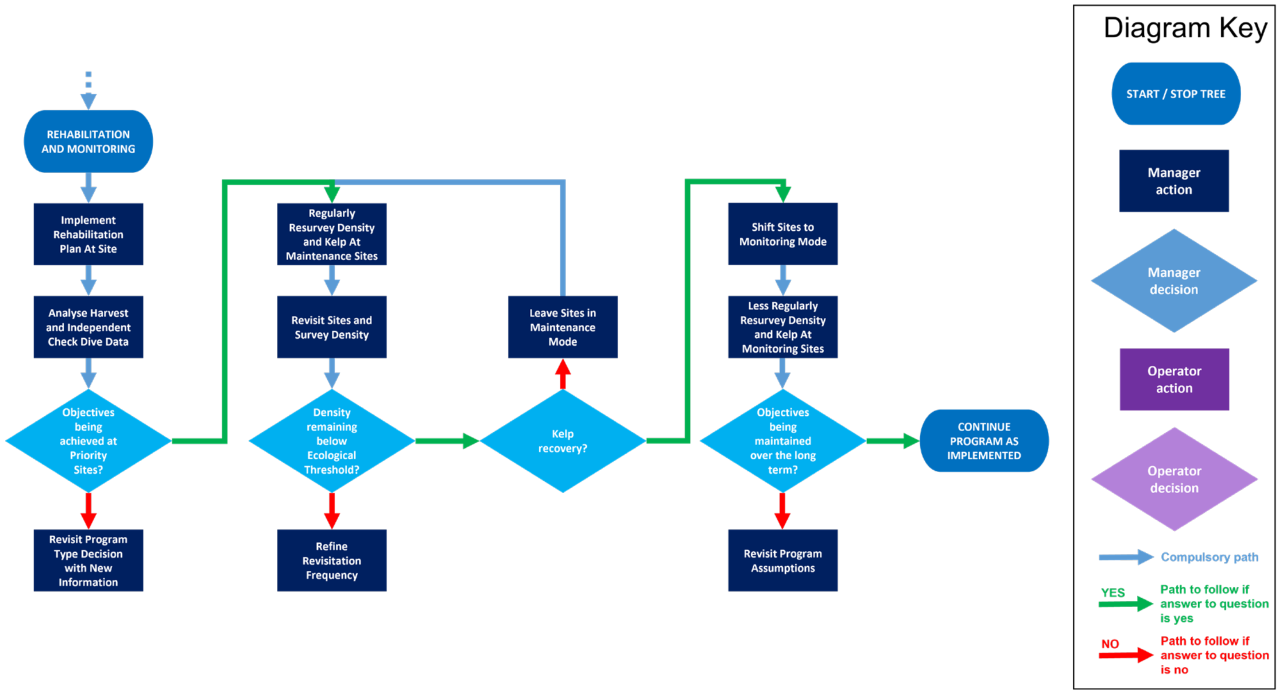


Figure 8 - Rehabilitation and Monitoring Decision Tree

5.3 Design for a Full-Scale Program

The Full-Scale Program is designed to be managed and implemented at larger spatial scales, e.g. the entire east coast, and to achieve ecological outcomes in the most effective manner at those scales. At the scale of individual Sites, the Full-Scale Program operates similarly to the Initial Implementation Strategy. However, it differs from the Initial Implementation Strategy in that it structures control decisions at larger spatial and temporal scales in response to the underlying ecological drivers of *C. rodgersii* population dynamics and spread and the distribution of relevant values at those scales. The focus of the Full-Scale Program remains active control measures that can provide short-term relief from *C. rodgersii* impacts, structured in a way that can contribute to longer-term and larger-scale goals. Similar to the Initial Implementation Program design, it does not explicitly consider citizen science culling, which although likely to be of use at specific locations, currently contributes negligible overall catch relative to commercial efforts, and therefore unlikely to match the scale of the *C. rodgersii* control program (Cresswell et al. 2018, 2020, 2022). Nor does it explicitly discuss longer-term conservation measures such as marine parks or lobster translocations as control methods, because their benefits are likely to accrue over longer timescales. However, for the Full-Scale Program it will be important to consider the interaction between the sites at which control is targeted and the locations of marine parks and lobster translations to harness ecological interactions and generate maximal ecological outcomes at large scales.

Additionally, the Full-Scale Program outlined here does not explicitly consider coordination efforts between control programs in different States or at a national scale. However, because *C. rodgersii* are present in NSW, Victorian and Tasmanian waters and can disperse long distances on ocean currents, there will be an ecological link between independent state control programs. This suggests that while initially the CCP should focus efforts at the scale accessible to managers, in this case Tasmanian waters, in the longer-term, an integrated, range-wide state and federal program is likely to deliver significant value.

Effectively implementing the Full-Scale Program would require both a significant increase in funding and improved knowledge of many ecological and management factors to well beyond what is currently available. Collecting the information to underpin this knowledge and make the case for increased investment and a larger coordinated approach could be provided by first employing the Initial Implementation Strategy before moving to the Full-Scale Program.

Below we outline the key steps in the decision process for a large-scale program for *C. rodgersii* Control, i.e. a program that seeks to manage the species at the scale of the East Coast of Tasmania (at least) and to do so in a comprehensive and coordinated fashion with a long term commitment. As with the Initial Implementation Strategy, we follow a similar sequence of steps required to successfully implement the Strategy: Planning; Zone and Site Ranking and Selection; Define Strategy for Control Method Selection; and Implementation, linking them to the ecological drivers outlined in section 5.1. However, while we outlined the Decision Tree for the Interim Program in some detail, we do not attempt to do that in the case of a Full-Scale Program, instead, we outline major decision points only. We do this for a number of reasons. First, and most importantly, at this point in time there is no commitment to a large-scale program and, without such a commitment, and an understanding of the latitude that commitment permits, it is impossible to identify what kind of a program should be considered. Second, much of the information that would contribute to the development of a large-scale program is yet to be collected. This ranges from key ecological inputs, e.g. recovery rates (used for determining revisitation times), operational inputs, e.g. types of vessels and dive teams, economic information, e.g. market information and subsidy structures, governance arrangements, Values and Value assessment processes, etc. Much of this information would be gained from the implementation of the Initial Implementation Strategy Interim Program.

5.3.1 **Planning**

1) Define Objectives and program success measures from the perspective of the overall program owner, in this case DPIPWE. This initial step will identify the fundamentals of the program and these values will guide choices about sites, methods, etc.
2) Identify Stakeholders and the degree and nature of their relevance to Program. Those with direct involvement will become Program Participants, others may be consulted as necessary.
3) Identify and engage Program Participants:
    a. Steering Committee – responsible for oversight and strategic decisions (e.g. priority Blocks, sites, etc). Comprised of key Stakeholders
    b. Program Managers – responsible for operational oversight (including site selection, assignment and data management) and feeding information back to Steering Committee. This role requires allocation.
    c. Control Divers – responsible for on-water operations and pushing their assigned/chose sites to below the relevant thresholds
    d. Confirmation divers (optional) – check sites have been reduced to below thresholds once reported as such.
4) Define scope of project
    a. Refine Objectives and Values based on input from Stakeholders & Participants
    b. Determine success measures
    c. Determine geographic scope of Program – East Coast, State, SE Australia
    d. Determine Depth Range of the Program
    e. Determine conditions for kelp rehabilitation
5) Design data collection methods, processing and feedback of data into the program decision making
    a. Divers – data collection underwater, primarily for control
    b. Dive boats – data and urchin processing that allows numbers, sizes and kilograms of urchins removed to be assigned to the relevant polygons
    c. Processors – processes that allow numbers, sizes and kilograms of urchins removed to be assigned to the relevant polygons

5.3.2 **Zone and Site Ranking and Selection**

6) Define and Assign values to the different management units
    a. Condition – Healthy, Kelp, Incipient Barren, Barren site
    b. *C. rodgersii* harvest value – predicted size distribution, season, access to processing
    c. Lobster Value
    d. Abalone Value
    e. Conservation Value
    f. Social Value
    g. Effort Distribution Weighting – e.g. current subsidy
7) Prioritize Zones, Blocks, Sites and Polygons – ultimately this will be based on a formal assessment of the CCP's objectives, the relevant values and thresholds at a site or polygon. In the initial phase this will likely be a relatively simple and possibly qualitative process based on assessments of key indicators, e.g. extent of kelp, barrens and the economic value of the site or polygon.
    a. Develop a means of assigning values based on incomplete information
    b. Develop process for assigning priority at each level

c. Develop means for determining if harvesting or culling are the priority action
d. Spatial and temporal strategies for maximising return relative to objectives
e. Consider location of and interaction with longer-term conservation strategies such as marine parks and lobster translocations
f. Give them an *a* priori ranking
    i. Polygons in the highest priority (may not be known, initially at least)
    ii. Sites, in the highest priority
    iii. Blocks, in the highest priority
    iv. Zones

5.3.3 Define Strategy for Control Method Selection

8) Define management options and the conditions under which they are used at each polygon. An initial and qualitatively-derived decision process might be as follows:
    a. In the harvest season, weight more highly high priority sites with known or assumed economically viable *C. rodgersii* populations, e.g. high density, large individuals, close to processing, previously uncontrolled sites:
        i. Roe harvest during the initial operation/s at a polygon when largest individuals are available
        ii. Grow-out when out of Roe season or when sizes below Roe viability
        iii. Fertiliser when sizes are small, e.g. during final dives
        iv. Switch to cull when population structure drops below economically viable average size for available harvest methods
        v. Polygons must be controlled to no individuals available
    b. Outside the harvest season in the prioritization process weight sites with less economically viable individuals, e.g., distant or previously controlled sites
        i. Cull is used, polygons are culled to no individuals available
        ii. Focus is on sites where Economic Harvest has low viability in the roe season

5.3.4 Implementation

1) Rank highest priority zones, blocks, sites, polygons
2) Choose zones and blocks for action based on *a priori* priority ranking.
3) Choose sites for action
    a. Initially this might done based on *a priori* ranking or other considerations, e.g. ease of conducting operations during a learning phase
    b. Ideally it would be based on surveillance data on Centro densities, presence and development of barrens,
4) Conduct surveillance to identify priority sites within Operation area and the priority polygons within them
    a. Field visits
    b. Aerial photography
    c. Manta/glider tows
    d. Reassessment of priority ranking based on field data*values*objectives
5) Select polygon with highest *C. rodgersii* density, set it to “Intensive” Mode and decide on type of action – harvest, cull, remove, both
6) Manage at polygon until there are no more *C. rodgersii* available, then move onto the next highest density polygon at the site. Repeat until all polygons at site have been dived once or no more dives are available for the Operation.

7) If more dives are possible and all polygons have been dived to zero *C. rodgersii* available, move to next highest priority site and begin there.
8) Next operation:
    a. if Intensive Mode Revisitation Interval at previous highest priority site has not elapsed – go to next highest Priority Site start/continue working there.
    b. if Intensive Mode Revisitation Interval at previous highest priority site has elapsed – return to previous highest priority site and go to step 5)
9) Repeat steps 5 to 8 until each polygon at the highest priority site is below the Stopping Threshold
    a. Place into "Maintenance" mode
10) Move to next priority site
11) Monitoring and Maintenance sites remain in these Modes until their relevant revisitation intervals elapse. When this occurs, they revert to Intensive Mode and high priority.

6 Research Priorities

Our ability to implement an effective *C. rodgersii* control program is constrained by a range of knowledge and technology gaps. These gaps range from a lack of information on fundamental aspects of the biology of *C. rodgersii* through to the development of simple tools to ensure that appropriate control data is accurately recorded. Below, we identify a number of the key knowledge or technology gaps and briefly describe the type of research required to fill these. These gaps are described in four general categories.

The first of these are gaps related to the fundamental biology and ecology of *C. rodgersii* and of rocky reef communities in Tasmania. The results of this work would provide important information on the context of control and on the key processes influenced by *C. rodgersii's* range expansion and control activities. The second category comprises questions related to the ecological consequences of control, with a focus on defining key thresholds and parameters, documenting control outcomes and effectiveness, and responses of species and community. The third category comprises research that would inform the management of the CCP, developing approaches to assessing values, developing incentive strategies, monitoring control effectiveness and most effectively deploying resources in the field. The final category identifies some of the key technologies that would enhance CCP operations, with a particular focus on data recording, management and reporting.

While the gaps we identify are relevant to both an Initial Implementation and a Full-Scale Program, the Initial Implementation is designed to have a lower information requirement and consequently not all of the research needs are necessarily relevant to this type of program, furthermore, even where the information is required, the scope of the data required may be smaller than would be the case for the Full-Scale implementation. In the final section we identify the gaps that are most important in the context of an Initial Implementation.

6.1 Fundamental Ecology of the *C. rodgersii* Control System

6.1.1 **The Ecological Context for Decision Making**

C. rodgersii control is essentially a spatial problem; *C. rodgersii* and the values we seek to protect are not distributed evenly along the east coast and we need to distribute our control investment across the distribution of the pest and of the values in the manner that is most effective and efficient in achieving our objectives. As a consequence, spatial information on the distribution and dynamics of the ecological entities and processes, i.e., kelp, barrens and *C. rodgersii*, is fundamental to strategic decision making. Just as important is an understanding of the spatial distribution of the social and economic values of the system, and of the capacity of potential control agents. An immediate research need is the 'best possible' estimates of these spatial parameters. Ideally these would be field validated estimates collected at the highest possible resolution. In reality, and especially at the outset, they are more likely to be estimates and extrapolations based on sparse data and to have large associated uncertainties. These uncertainties should, however, reduce over time. The relevant scales of assessment would be the Fishery Zone and the Site.

Spatial distribution, state and dynamics of kelp forests

The fundamental assets to be protected in this program are the kelp forests. Achieving this requires that we know i) where those kelp forests are, ii) their characteristics, iii) their trends at a site over time. Without this information to underpin strategic decision-making, management will inevitably be reactive.

- High resolution mapping of the distribution and trends in kelp forests based on monitoring or modelling

- Development of methods for mapping kelp bed distribution and dynamics. For example, using remote sensing, google earth or other satellite images:
  - Develop automated processes where appropriate
  - Where the method permits, develop an historical timeline
- Predictive models of the distribution of kelp:
  - based on ecological and environmental modelling e.g. i) depth, ii) substrate, iii) slope
  - predict presence and absence

Spatial distribution, state and dynamics of Barrens

Barrens are the physical representation of impact, consequently an understanding their distribution and dynamics is fundamental to strategic decision making. While barrens represent a key stage in the *C. rodgersii* impact, and have been the trigger for management action, barrens are not the starting point. Prior to the formation of barrens, kelp forests show marked changes in the density and the size of individual plants. Being able to detect incipient barrens as early as possible would allow for timely interventions.

- Remote sensing methods for mapping and monitoring of barrens at all stages of development, from areas of thinning to incipient, patch and extensive. Might be based on:
  - Imagery
  - Spectral data
  - Human reporting – technologies and systems for formal surveillance, industry, and Citizen Science reporting.
  - Response to management

Distribution and dynamics of *C. rodgersii*

Successfully managing a threat requires information on how that threat is distributed and how this distribution varies over time. In this program, this means the best quality information possible on *C. rodgersii* densities, size structure and distribution across habitat types, depth profiles and along the coast.

- Development of distribution maps based on all data sources, formal surveillance, Citizen Science, Industry reporting
- Tools that allow for updates on appropriate time frames.

Social, Economic and Biodiversity Values

An underpinning goal of the CCP is the protection of values associated with healthy kelp--dominated ecosystems. These values include a variety of commercial and recreational fisheries as well as tourism and biodiversity conservation. These values are not distributed evenly along the coast. For example, the value of a site to a particular fishery will be a function of factors that vary from location to location and in some instances over time. These factors include, but are not limited to, the distance to a harbour, the extent of suitable habitat, the biomass of the target species, fuel costs, operating depth, and the importance of the fishery to the community. Developing a framework for assessing the spatial distribution and dynamics of these values for each stakeholder group is a key task.

- With stakeholders, implement a process for identifying and assessing the spatial distribution of assets, values, costs and constraints associated with their sector (including the Social Return on Investment)
- Develop a method for assessing the relative priority of values and how that applies to the prioritization of sites, e.g., Multi-Criteria Decision Analysis or structured expert elicitation.

Significance of deep-water habitat

There is a mismatch between the depth distribution of *C. rodgersii* and that of control activities. Abalone and lobster are found at depths exceeding those available to control dive operations (which have operating limits c. <27m). It is unclear whether this depth mismatch should be of concern, and whether investment should be directed into extending control into deeper waters (e.g. through the use of AUVs). It is likely that the significance of *C. rodgersii* in deep-water habitat will depend of whether the processes operating in deep waters are i) significantly impacting on rocky reef habitat and processes at the dive-able depths, or, ii) are of concern in their own right.

- Extent of deep water rocky reef habitat and barrens
- Abundance of abalone, lobster and *C. rodgersii* in deep-water
- Contribution of deep-water populations to recruitment of all three species to shallower waters

6.1.2 *C. rodgersii* Biology and Ecology

Several aspects of *C. rodgersii* biology and ecology have a significant influence on processes that determine population spread, dynamics and impact. These have implications for the objectives of the program and for the strategies ultimately adopted.

Sources of Recruitment

In Tasmanian waters, *C. rodgersii* recruitment is comprised of two sources of larvae – those dispersing down from the mainland and those produced by the local population. The fact that Tasmanian water temperatures during the breeding and larval settlement period tend to be at or below the thermal limits for larval development has meant that historically recruits are likely to have predominantly been long-distance dispersers from the mainland. However, with increasing temperatures in Tasmanian water, the contribution of local populations to recruitment is likely to increase, shifting the balance between local and external contributions and potentially increasing. As the local contribution to recruitment increases the opportunity to strategically target key larval source populations will also increase.

- determination of the relative contribution of Tasmanian and Mainland sources to recruitment
- identification of key local source populations
- Identify and map conditions that result in a location becoming a key source population
- Integration into site prioritization

Dispersal

Describe dispersal kernels – mechanistic predictions of larval dispersal. Fine-scale modelling of ocean currents along the Tasmanian coast would enable estimation of physical connectivity between locations. Combined with network analyses this would allow for predictions of connectivity between populations and the identification of putative 'source' populations for targeting. At the 2019 Forum, the suggestion was made to link the TRITON ecosystem model (Sean Tracey) and the soon-to-be-developed larval dispersal model (Katie Cresswell) to provide mechanistic predictions of dispersal.

- Scale of Dispersal – Genetics provides a means of directly estimating the relatedness between individuals and populations. This makes it useful for measuring effective (or actual) dispersal distances. This might be done using traditional micro-satellite approaches but would be more usefully done through whole-of-genome approaches due to the fact that rapidly expanding populations of a fecund and mass spawning species are likely to exhibit low levels of genetic variation. As a consequence, the higher sensitivity of genomic approaches would ensure maximum probability of detecting sufficient variation.
- Larval Biology and Ecology - Using mechanistic models to estimate connectivity will require assessments of aspects of larval biology, including: i) larval competency and factors influencing this, ii) larval thermal tolerances, iii) environmental correlates of recruitment and their distribution along the Tasmanian east coast

Population Biology

Population biology and behavioural parameters provide important information for informing management action, including thresholds for control, frequency of revisitation, and risk of re-establishment. Relevant parameters include:

- Standard population and life-history parameters
  - Including age to detectability relative to age at first reproduction
- Influence of environmental factors on life history parameters, including:
  - Habitat
  - Time since population establishment
  - Population density
  - Water temperature (or latitude)
- Individual movement patterns
  - Daily and weekly patterns of ranging (detectability)
  - Movement frequency and distance between foraging sites
  - Movement frequency and distance across the depth profile
  - Movement in response to control, e.g. into barrens, into controlled areas, from deep water
- Age and habitat specific kelp consumption rates

6.2 Ecology of Control

6.2.1 Effectiveness of control in reducing C. rodgersii densities and promoting kelp recovery

Determination of the effectiveness of different control methods will help plan frequency of control visits and intensity. Important information include:

- Estimation of the proportion of *C. rodgersii* at a site that are removed during a control dive
- how this proportion varies with different control methods – commercial harvest, adaptive subsidies and auctions, take all contracts.
- how this proportion varies with *C. rodgersii* density and habitat complexity.
- Impact of control on population size structure

This information would inform choices about optimal control methods and the required frequency and interval of revisitation in any given situation

6.2.2 Estimation of ecological and economic threshold densities

Documentation of the response of kelp to control of *C. rodgersii* to different density thresholds and how this varies with ecological conditions. This work would allow for a more exact estimate of the thresholds that must be achieved and provide greater confidence in trade-offs between the investment made at any one site versus the number of sites at which control is conducted

6.2.3 *C. rodgersii* immigration and recruitment rates and sources post-control

Focused studies that would inform what factors contribute to re-establishment of *C. rodgersii* at a site (immigration, recruitment of settled juveniles, larval settlement), from which sources (the site, adjacent habitat, deep-water, distant sources) and how rapidly this occurs.

6.2.4 Kelp rehabilitation strategies

Development of cost-effective strategies for kelp rehabilitation post-control.

6.2.5 Lobster supplementation strategies

Experience of the formation of urchin barrens around the world suggests that urchin population dynamics are sensitive to top-down control by predators (Filbee-Dexter and Scheibling 2014). This conclusion is supported in the Tasmanian context by the results of Ling and Keane (2021b)'s lobster harvest exclusion experiment Significant ecological research and management practice has been invested in lobster protection and translocation measures in Tasmania in recent years (Johnson et al. 2013, Marzloff et al. 2013, Wild Fisheries Management Branch 2018, Ling and Keane 2021a). Since 2013, the East Coast Stock Rebuilding Strategy has been working to rebuild lobster stocks to greater than 20% of unfished stock by 2023, through a combination of catch caps and, since 2015, targeted translocation (Wild Fisheries Management Branch 2018). This has led to a number of recently published results, around the attractiveness of C. rodgersii as a food source for lobster (Smith et al. 2022), and the projected trajectory of barrens formation with and without lobsters (Johnson et al. 2013). Altogether, these results suggest that lobster protection may make a useful contribution to *C. rodgersii* control under appropriate conditions. As a consequence, we recommend that research be invested into:

i) Continue work on lobster management, with a focus on identifying the conditions under which lobster protection contributes to *C. rodgersii* control objectives, including relevant site characteristics, e.g. lobster densities, habitat status, as well as the perceived value of the site for commercial and recreational fisheries.

ii) Investigate strategies for formally incorporating lobster protection into the decision making processes of the *CCP,* including the types of sites (barrens, incipient barrens, healthy) that are chosen.

iii) Assessment of how such lobster management might be most effectively incorporated into the management of both the commercial and recreational fisheries.

6.3 Control Effectiveness and Efficiency

6.3.1 Identification, estimation and prioritization of program values

The consequences of the expansion of *C. rodgersii* into Tasmanian waters has been different for different stakeholders, with both positive and negative impacts. If the CCP is intended to address the needs of a range of stakeholders, from conservation groups through to commercial divers and urchin processors, the nature and magnitude of the values impacted, and the consequences of such impacts need to be identified and estimated to allow for considered trade-offs to be made.

- What are the range of values impacted by *C. rodgersii?*
- What are they worth? How best to evaluate them? How are they distributed across the management area?
- Development of tools to enable identification of the best balance of competing values and objectives, e.g. Multiple Criteria Prioritization Analysis
- Valuation process of Zones and Sites

6.3.2 Subsidy and auction strategies

Because the relevant *C. rodgersii* density target thresholds for control are likely to be below the densities that are economically viable to harvest in many locations, the development of incentives to ensure that divers persist in control at a site until target thresholds are achieved is required. This work might include:

- Adaptive subsidies – design of subsidy strategies that can accommodate varying amounts of information and varying degrees of cooperation in providing information
- Design of Auctions

- Strategies for implementing market-based tools into CCP operations
- Tools for automating up-to-date information into Adaptive Subsidy and Auction tools

6.3.3 **Check Dive Protocols**

Development of protocols for Check Dives that allow for rapid, efficient and reliable assessments of whether control has reduced densities at a polygon to below the relevant threshold.

6.3.4 **Monitoring control effort**

Standardised methods for collecting and reporting of data related to control effort, distribution, efficiency and effectiveness. Tailored for different stakeholders (recreational divers, cull divers and harvest divers) but reporting to a standardised database. By automating this through the use of apps, data quality can be maximised, submission automated, and the effort required for data management minimised. Automatic upload allows for near real time decision making.

6.3.5 **Economics of different program types**

Comparison of the cost effectiveness of each of the program types (commercial harvest, fixed subsidy, adaptive subsidy, auction, contract) and the factors influencing their effectiveness.

6.3.6 **Potential of citizen science in the CCP**

Citizen science provides a way of engaging with communities and collecting data that will help solve important science challenges, usually in collaboration with scientists and field experts. Citizen scientists work with scientists or the scientific framework to achieve scientific goals (see https://citizenscience.org.au/10-principles-of-citizen-science/). Recent research suggests that while Citizen Scientists can provide a valuable resource to conservation programs, the amount of effort available is negligible relative to commercial efforts, and therefore unlikely to match the scale of the *C. rodgersii* control program (Cresswell et al. 2018, 2020, 2022). Citizen science is a flexible concept that will need to be adapted to best suit the need of the CCP:

- What sorts of groups?
- How to deploy them?
- How to support their efforts to ensure effectiveness?
- Tools to support their efforts

6.4 Technology Needs

6.4.1 **Monitoring Tools**

Monitoring is one of the key tools for any effective species management program. In the CCP, monitoring is required in three contexts: i) monitoring the distribution of *C. rodgersii* and ecological variables across the management area, ii) monitoring the effectiveness of control in reducing *C. rodgersii* densities, and iii) monitoring of control activities themselves.

Deep Water Monitoring

- ROVs/AUVs – for rapid assessment of sites, particularly deep-water sites, to avoid unnecessary diving.

Broadscale Monitoring (*C. rodgersii,* barrens, other values)

- ROVs/AUVs – for surveillance and monitoring at larger spatial scales
- Image recognition and processing systems to automate data analysis
- Acoustic monitoring of barrens distribution and extent.

Monitoring of Control activities and outcomes

- Protocols for managing data collection, analysis and reporting from the CCP operations.

Data loggers and processing

- Dive data loggers (control) – designed to enable simple yet comprehensive and accurate data recording during dives and automated upload of data post dive. Data collected would include Date/time, GPS in/out, site, polygon, depth profile, dive time, urchins culled by size etc.
- Dive data logger (Check dive) – logger to automate Check Dive protocols, data entry and upload
- Tender loggers – logger and processing protocols that record urchins received from divers and track their size, #, and the polygon and site from which they are controlled. Automated data upload
- Landing/Processor logging – tools and processes for tracking #, size and weight of urchins landed and received by processors, site and polygon source, price paid. Automated upload
- Database, data management protocols, automated reporting tools.

6.5 Priority Research Issues for an Initial Implementation

The research needs of an Initial Implementation and a Full-Scale program are likely to be very different. Given that the Initial Implementation Program would be intended to operate as an effective contribution to *C. rodgersii* control in its own right, its smaller spatial and operational scale would not require as comprehensive an understanding of the *C. rodgersii* situation. Furthermore, given that it would represent the first steps in a coordinated and strategic program, an Initial Implementation program will inevitably be undertaken in the absence of some key background ecological and operational information. Given this, an Initial Implementation program should be viewed as a learning opportunity as much as a control program. Given the uncertainties and its limited scale, an Initial Implementation would be focused on a relatively small number of sites and would base many of its initial decisions on qualitative assessments and 'best available' information. The goal under this scenario is to do as well as possible given current knowledge and resources, and to use doing well now as a platform for doing better in future. However, there are a number of knowledge and technology gaps that, if filled, would allow for a more effective implementation. Here we list key research priorities for the Initial Implementation phase in the sequence of their appearance in the Decision Trees. Once a gap is identified it is not repeated in subsequent sections.

6.5.1 **Planning Phase:**

1) Describing the Values being managed for: At the outset any Initial Implementation Program is likely to select its Priority Zones and Sites in an arbitrary manner – the initial goal is to get experience in running a program, and, so long as the sites chosen are worth managing from the perspective of the program's objectives (i.e., have incipient barrens, economically viable *C. rodgersii* densities, etc) then their location or relative priority are less important. However, as the Initial Implementation matures the opportunity to use site selection more strategically will quickly

become apparent. Once this point is reached, identification, assessment and description of the spatial distribution of the values being protected will become important contributors to decision making about Zone and Site priority and selection.

2) Zone and Site Prioritization: Once values are identified and their distribution adequately defined, some means of prioritizing sites will be required if the number or sites is greater than the available control resources. In the Initial Implementation some form of qualitative expert elicitation is arguably all that is required, e.g. (Hemming et al. 2018). Understanding how control efforts interact with other management and conservation programs, such as lobster translocation or Marine Protected Areas, may enable improved prioritisation.
3) How are values distributed? In the first instance, decisions about where to act can be made subjectively, however, as the opportunity arises to operate strategically with respect to overall program objectives, the need to understand the distribution of each of the values along the coast will become important.

6.5.2 **Determining Program Type:**

4) What is the effectiveness of different levels and types of harvest on *C. rodgersii* density and kelp recovery and in achieving Program objectives? Do these different methods achieve the ecological threshold and are their outcomes sufficient?
    a. Commercial harvest
    b. Adaptive subsidy/auction
    c. Contract/take all
5) Design of subsidy and auction strategies that meet the specific needs of the control program
6) Role of citizen scientists in the CCP.

6.5.3 **Implementation Phase**

Commercial Harvest, Spatially Targeted Harvest:

7) Diver data loggers – tools for ensuring relevant dive data and catch/cull data are accurately and safely recorded and to reliably upload this data to the main database.
8) Vessel landing data processing and loggers – tools and processes to relate landed catch to polygons accurately and to reliably upload this data to the main database.
9) Data management and presentation tools for recording, interpreting and presenting data on harvest and control performance across the state

Auction/Tender:

10) Design of the Auction or Tender process to ensure greatest efficiencies
11) Design of Check Dive methods that are rapid, cost effective and reliable

Adaptive Subsidy:

12) Design of subsidy and payment strategy that is responsive to available market information, diver needs, and control program strategy.

Maintenance Mode:

13) Determination of the recovery rate of *C. rodgersii* populations post-control to determine Maintenance Mode revisitation period.

Monitoring Mode:

14) Recovery rate of *C. rodgersii* populations post-kelp recovery to determine Monitoring Mode revisitation period

Longer timeframes:

15) How significant is deep water for i) *C. rodgersii*, ii) lobster, iii) abalone, iv) kelp in terms of their dynamics at diveable depths.
16) Effectiveness of 'citizen scientist' divers.
    a. What sorts of groups
    b. How to deploy them
    c. How to support their efforts to ensure effectiveness
    d. Tools to support their efforts

7 Summary

The incursion of the long-spined sea urchin, *Centrostephanus rodgersii*, into Tasmanian waters constitutes a significant risk to the ecological balance of important Tasmanian rocky reef ecosystems. The formation of urchin barrens impacts not only the biodiversity of rocky reef habitats, but also has major and negative consequences for important recreational and commercial fisheries, including abalone and rock lobster.

Recent surveys and evidence from elsewhere in the world suggest that, without management intervention, the population density, range and impact of *C. rodgersii* will continue to expand, potentially encompassing much of Tasmania's east coast. This is an alarming prospect. Unfortunately, there is no simple permanent solution; *C. rodgersii* cannot be eradicated and its persistence in Tasmanian waters will be further reinforced with on-going ocean warming. Despite these difficulties, a well-designed ongoing control program will be able to reduce the impacts of *C. rodgersii* meaningfully at specific locations, or even across large regions with appropriate resourcing.

This report described how a Centrostephanus Control Program could achieve a lasting ecologically-meaningful reduction in the impacts of *C. rodgersii* at locations along the Tasmanian coast. It reviewed the current understanding of key biological and ecological processes driving the invasion in Tasmanian waters, as well as interactions between current marine industries. It summarised the fundamental principles of an ecologically-informed pest management strategy, how those principles would apply in the specific case of *C. rodgersii*, the control methods available and the values the CCP aims to protect. It identified key ecological drivers and the management thresholds that need to be targeted to achieve ecologically-meaningful outcomes.

Two strategies for implementing a *C. rodgersii* control program on Tasmania's east coast were then outlined. The two strategies reflect two different levels of resourcing and centralised planning and control. The first, an Initial Implementation Strategy, built on current *C. rodgersii* harvest and cull arrangements, provided a framework to ensure that control is targeted at priority locations, and that where control investment is made it achieves ecologically meaningful outcomes. Implementing the program would incur some additional costs and require some changes to current operations, but these would not be dramatic. The second strategy outlined a Full-Scale Program managed and implemented at a state-wide scale, clearly a longer-term prospect. Importantly, although the two strategies could be implemented independently, they were also designed to be implemented sequentially; instituting the Initial Implementation Strategy in the short-term would both make significant progress in controlling *C. rodgersii* at key locations, while simultaneously building vital experience and collating information on a range of key parameters important to the effective implementation of a Full-Scale Program.

Finally, the key research needed to underpin the successful application of these two strategies was identified and outlined.

The strategies presented form a comprehensive, integrated and action-oriented framework targeted to achieve the AIRF's three stated, strategic objectives: i) stop growth of existing barrens, ii) prevent establishment of new barrens, and, iii) promote recovery of full barrens.

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9 Appendix A - Using Subsidies to Incentivize Achieving Targets – a worked example

As noted in Section 4.5, subsidy payments provide a tool with which fisheries managers can influence how fishers distribute their effort. In the current program subsidies are used to support the industry during its establishment phase and to focus harvest effort in different zones on the east coast (Cresswell et al. 2019). This latter objective is achieved by offering larger subsidies in Fishery Zones deemed to require greater harvest effort. Overall, anecdotal reports from DPIPWE suggest that subsidies are viewed as having been successful in terms of achieving these objectives.

Subsidies may also be an effective tool for incentivising re-visitation to sites and, if structured appropriately, this could be achieved at the same time as using them to determine the geographic focus of the fishery. This could be achieved by i) varying the value of the subsidy by zone, or if greater resolution is required, by block, and ii) structuring the payment or scheduling of the subsidy to ensure repeat visitation. This might be achieved in a range of ways; we outline one example below.

The market price for abalone affects the price paid by processors to fishers, and an efficient subsidy design will account for this to ensure that operators can achieve the minimum profit required to motivate them to engage in harvest to the Ecological Threshold whether prices are high or low. When the price paid by processors is less than the total cost of the operations, then the subsidy has to be sufficient to make engaging in harvest worthwhile, i.e. cover costs and provide some minimum profit per Operation. When the price paid by processors is sufficient to make engaging in the harvest worthwhile then the intention of subsidy should be to pay a premium to the diver to ensure that their profit remains at levels that ensure re-visitation until the Ecological Threshold is achieved despite densities dropping to i) non-viable levels or ii) below the profitability of alternative sites. This might be achieved in a range of ways, for example:

$$\text{Subsidy} = (\text{Costs-Processor Payments}) + (\#\text{ Operations x Profit}_{\text{Operation}})$$

Where $\text{Profit}_{\text{Operation}}$ is the maximum profit recorded for an Operation at the site and set to a minimum to ensure that it remains attractive even when profit margins may not otherwise make it worth investing effort. Using this particular example, if processor payments were lower than costs then the subsidy would cover any difference between the cost of an operation and processor payments while the base minimum rate per operation would make it worth undertaking. Where costs were lower than processor payments this example would use the maximum profit to ensure re-visitation to the site. While structuring payments in this manner would make revisitation attractive, scheduling the payment of the cost component upon reporting of each Operation and the profit component once the harvest data indicates that the target threshold has been achieved would ensure that those targets are achieved.

Table 3 and Table 4 demonstrate two examples for subsidies designed in this manner. In the first example (Table 3) processor payments to the operator exceed their costs, and the goal is to incentivize re-visitation. In the second example (Table 4), processor payments to operators are lower than their costs and the goal is to make the harvest economically viable. In both cases, operations would continue until the harvest fell below the relevant Ecological Threshold. In this example we have used a Recovery threshold of 0.8 urchins / m2 or 34g/m2, which is achieved in Operation 4 in both examples. Area culled, catch, costs, and # of urchins/kg are based on averages for a single dive estimated from dive data as per Table 5.

Table 3. Worked example of a subsidy payment structured to incentivise revisitation when .

Operation	Catch (kg)	Processor $/kg	Processor Payment	Costs $	Profit $	# Urchins	density (#/m2)	density (g/m2)
1	487	2.75	1339.3	1037	303	1592	0.13	39.4
2	487	2.75	1339.3	1037	303	1592	0.13	39.4
3	487	2.75	1339.3	1037	303	1592	0.13	39.4
4	214	2.75	589.3	1037	-447	700	0.06	17.3
5	94	2.75	259.3	1037	-777	308	0.02	7.6
6	41	2.75	114.1	1037	-922	136	0.01	3.4
Total: 1-4	1675		4607	4146	461	5475	0.37	146.5

Subsidy = (Costs-Processor Payments) + (# Operations x $Profit_{Operationn}$)

Minimum Profit=$250

Subsidy = (4146-4607) + (4*303) = $751

Table 4. Worked example of a subsidy payment structured to make harvest economically viable.

Operation	Catch (kg)	Processor $/kg	Processor Payment	Costs $	Profit $	# Urchins	density (#/m2)	density (g/m2)
1	487	0.75	365.4	1037	-671	1592	0.13	39.4
2	487	0.75	365.3	1037	-671	1592	0.13	39.4
3	487	0.75	365.3	1037	-671	1592	0.13	39.4
4	214	0.75	160.7	1037	-876	700	0.06	17.3
5	94	0.75	70.7	1037	-966	308	0.02	7.6
6	41	0.75	31.1	1037	-1005	136	0.01	3.4

Subsidy = (Costs-Processor Payments) + (# Operations x $Profit_{Operationn}$)

Minimum Profit=$250

Subsidy = (4146-1257) + (4*250) = $3890

Table 5 Data for Table 2 calculations and derived from (Huddlestone 2020, Larby 2020).

Variable	Estimate
Mean dive time	3.53 hours
Mean area harvested/dive	1.24 ha/dive
Mean harvest/dive	487 kg
Mean. C.rodgersii mass	0.305 kg
Mean C. rodgersii/dive	1597
Density decline between dives	66%
Variable costs	$733
Fixed costs	$302
Mean subsidy/day	$1302
Mean Profit	$266

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