Resurvey of the Longspined Sea Urchin (*Centrostephanus rodgersii*) and associated barren reef in Tasmania

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This report details the 2016/17 re-survey of the Longspined Sea Urchin *Centrostephanus rodgersii* and associated barrens in eastern Tasmania relative to baselines established in 2001/02 via the Fisheries Research and Development Corporation project no. 2001/044 "*Establishment of the long-spined sea urchin (Centrostephanus rodgersii) in Tasmania: first assessment of potential threats to fisheries*" (Johnson et al. 2005).

The following staff/ students of the Institute for Marine & Antarctic Studies contributed to the re-survey: Sarah-Jane Pyke, Edward Forbes, Jane Ruckert, Olivia Johnson, Simon Talbot, Laurel Johnston, Martin Filleul, Elizabeth Oh, Vallorie Hodges, Kate Fraser, Ellie Paine, Amy Nau.

NON-TECHNICAL SUMMARY

The abundance of *Centrostephanus* and the extent of its impact on kelp beds in eastern Tasmania was re-surveyed by divers and underwater towed-video in 2016/17 and assessed relative to baselines established in 2001/02.

The re-survey involved 156 diver transects spanning 13 eastern Tasmanian sites spaced ~20 km from Eddystone Point to Recherche Bay (Fig. 1). From these transects, the abundance of *Centrostephanus* on reefs within the 4 to 18 m depth range increased from an average density of 1,036 to 1,818 urchins per hectare between 2001/02 and 2016/17. The increase in *C. rodgersii* has not occurred evenly across the coast and there are many sites in southern Tasmania (Bruny Bioregion) where *Centrostephanus* remains rare, occurring at densities less than ~20 individuals per hectare. Conversely, across the Freycinet Bioregion to Tasman Island (sites 1 to 9, Fig. 1), *C. rodgersii* increased from an average density of 1,495 to 2,623 urchins per hectare between 2001/02 and 2016/17. This represents a 75% increase in *C. rodgersii* density over 15 years in this region, equating to a population increase of 3.8% per annum.

Multiplying observed *C. rodgersii* densities across available rocky reef habitat within the 4 to 18 m depth range leads to an estimated increase in the *C. rodgersii* population from ~6.7 million to 9.9 million individuals between 2001/02 and 2016/17 (a 48% increase over the 15 year period or an average of ~200,000 urchins per year). Factoring by the average individual weight of urchins in each survey period, this equates to an estimated biomass increase from ~1,850 to ~3,000 tonnes, or an average increase of ~80 tonnes per year. Scaling urchin densities across the full width of available reef (4 to 40m depth), the population of *C. rodgersii* is estimated to have grown from ~11 million to more than 18 million over the 15-year period (a 60% increase over the 15 year period or an average of ~460,000 urchins per year); equating to a biomass increase from ~3,000 to ~5,500 tonnes, or an average increase of 170 t per year. Inclusive of the sizeable population on Kent Group reefs in Bass Strait, the population of *C. rodgersii* in Tasmanian State Waters is estimated to have exceeded 20 million individuals by ~2017.

Diver assessment of urchin grazing within the 4 to 18 m depth range for all eastern Tasmanian sites, revealed an increase in urchin barrens cover from 1.6% to 6.3% during the 2001/02 to 2016/17 period. Considering only the eastern Tasmanian sites north of Tasman Island to Eddystone Point where *C. rodgersii* is now common, diver assessment of barrens within the 4 to 18 m depth range revealed an increase in barrens from 2.3% to 9.0% cover of reef. Using towed underwater video to sample the full width of reefs (from 4-40m depth), the percentage of reef as barrens across sites 1-9 in eastern Tasmania was observed to grow from 3.4% to 15.2% from 2001/02 to 2016/17, equating to a ~10.5% increase per annum over the 15-year period.

Increase in the density of *C. rodgersii* and expansion of associated barrens over the 15-year period was greatest on boulder-dominated reef between 18 to 30 m. Across the eastern Tasmanian coastline, greatest variability in *C. rodgersii* and barrens occurred from site to site (i.e. at scale of ~20 km), with relatively lower variation in urchin abundance and cover of barrens at finer kilometre (sub-site) or sub-kilometre (transect) scales. Notably, beyond increasing barrens cover, changes to the structure of kelp beds were also apparent between survey periods, with some algal species increasing in cover while others declined. The kelp *Ecklonia radiata*, which, is an algal type heavily grazed by *C. rodgersii*, showed increase in cover. That is, while barrens cover generally increased, remaining kelp beds appeared to become

thicker as indicated by overall increase in macroalgal cover. This seemingly unintuitive result is likely an ongoing response to widespread decline of giant kelp *Macrocystis pyrifera*, which historically dominated eastern Tasmania reefs where it outcompeted smaller understorey kelps such as *E. radiata*. However, giant kelp as assessed by divers measuring coverage of the seafloor was observed to decline by 42% across eastern Tasmania, disappearing from 7 of the 10 sites where it was present in 2001/02.

Re-confirming findings of the original 2001/02 baseline survey, low density of both abalone and rock lobster were observed on urchin barrens. Continued proactive management of urchin overgrazing is critical given that removing sufficient urchins to reverse barren grounds becomes increasingly difficult. The observed annual increase in tonnage of urchins has been of a scale that control, such as by rebuilding of predators and upscaling of culling and/ or harvesting would appear plausible. The spatial information on barrens coverage and locations at greatest risk of overgrazing as obtained during this survey will assist further targeted interventions.

BACKGROUND

Global climate change is a mechanism that has already resulted in and is predicted to further lead to widespread re-distribution of marine species ranges (Harley et al. 2006; Pecl et al. 2017). In the southern hemisphere, the southeastern coast of Australia has been identified as a climate change hotspot (Ridgway 2007; Oliver et al. 2018). Here the East Australian Current (EAC) has strengthened resulting in greater poleward penetration of warm water over the past 60 years and an approximate quadrupling of ocean warming rates compared to the global ocean average (Ridgway 2007). This pronounced change in the physical oceanography of the region represents an approximate 350 km southward shift in this major current system, which corroborates with an increased number of recent poleward range-extensions (Johnson et al. 2011; Last et al. 2011).

Of the range-extending species recently documented to have undergone extension to Tasmania from further north (e.g. http://www.redmap.org.au/), the sea urchin *Centrostephanus rodgersii* (Agassiz) is a most conspicuous and ecologically important arrival due to its ability to overgraze kelp beds and maintain an alternative and stable barrens habitat (Andrew and Byrne 2001; Hill et al. 2003; Ling 2008; Ling et al. 2009a; Ling et al. 2015b). In central and southern New South Wales, *C. rodgersii* maintains barrens habitat over ~50% of shallow reef (Andrew and O'Neill 2000) and similar levels of intensive overgrazing impact on kelp beds are also now observable at some sites in northeastern Tasmania. The flow-on impacts of kelp bed overgrazing by *C. rodgersii* is profound with a demonstrable local loss of over 150 species that live amongst Tasmanian kelp beds (Ling 2008). The arrival of *C. rodgersii* therefore poses a major threat to the structure and functioning of Tasmanian reef systems including impacting the productivity of lucrative reef-based fisheries for abalone and southern rock lobster that depend on kelp bed habitat (Andrew and Underwood 1992; Andrew et al. 1998; Johnson et al. 2005; Strain and Johnson 2009; Johnson et al. 2011).

Based on thermal conditions suitable for successful development of *C. rodgersii* larvae, continued warming of eastern Tasmanian coastal waters appears to have favoured ongoing recruitment and population expansion of the sea urchin within Tasmania (Ling et al. 2008; 2009b). Importantly, collapse of productive kelp beds to nil-value 'barren grounds' is ensured if *Centrostephanus* reaches high abundance (approx. >2 urchins m^{-2}), and recovery of kelp beds is very difficult once urchin barrens have formed given that removal of almost every sea urchin from the barrens is required (Ling et al. 2009a; Ling et al. 2015a).

In 2001/02, a baseline survey of *Centrostephanus* in Tasmania was achieved via the Fisheries Research and Development Corporation (FRDC) funded project #2001/044 "*Establishment of the long-spined sea urchin (Centrostephanus rodgersii) in Tasmania: first assessment of potential threats to fisheries*" (Johnson et al. 2005). A partial re-survey of some sites was achieved in 2008/09 via a Tasmanian Community Fund grant to recreational divers, which indicated increases in urchin abundance, and coverage of barrens on eastern Tasmanian reefs (Ling and Jacques 2009). In addition to that partial re-survey, increasing *Centrostephanus* abundance and overgrazing in Tasmania were also indicated during monitoring of control sites as part of a predator intervention experiment commencing in 2008/09 (Johnson et al. 2013; *see also* Redd et al. 2014).

Project aims & objectives

The current report provides an assessment of the current status and population trend of *C. rodgersii* and its impact on eastern Tasmanian reefs over the recent 15-year period from 2001/02 to 2016/17. The assessment involved the complete re-survey of urchins (*C. rodgersii* and the native *Heliocidaris erythrogramma*), blacklip abalone (*Haliotis rubra*) and lobster (*Jasus edwardsii*) abundances and coverage of barrens and macroalgae for a total of 156 diver transects ranging 4 to 18 m depth across 13 sites spread every ~20 km along the east coast of Tasmania from Eddystone Point to Recherche Bay (Fig. 1). Additionally, barrens were assessed across the entire reef-scapes (from 4 to 40+ m), using towed underwater video systematically repeating transects totalling >80 km in total across the 13 sites. Identifying those reef sites showing largest increase in *C. rodgersii* over the past decade and a half, and those approaching or now exceeding the critical point of overgrazing, assists targeted tactical control of the sea urchin.

METHODS

Spatial & temporal change in *Centrostephanus*, commercial invertebrates & macroalgal habitat

Scientific divers repeated the same methods used to survey 13 sites (156 transects within 39 sub-sites) as originally performed during the 2001/02 baseline survey (Johnson et al. 2005) across eastern Tasmania (Fig. 1). GPS was used to locate both the start and end positions of the previously surveyed sites. Using this method, belt transects were set perpendicular to the shore, extending from ~4 m depth to a maximum depth of 18 m or a maximum total length of 100 m if the maximum seaward depth was less than 18 m. Based on reef topography across all sites, transects were on average ~50 m in length during both 2001/02 and 2016/17 survey periods. On each transect line, a pair of buddy divers surveyed a 1 m swath each side of the line, and for each 5 m section of the transect, recorded the depth and abundance of sea urchins (*Centrostephanus rodgersii* and *Heliocidaris erythrogramma*), rock lobster (*Jasus edwardsii*) and abalone (*Haliotis rubra*). Each diver used a 1 m pole to define the 1 m swath width along the transect line and held a slate with printed data sheet on which all data were systematically recorded.

To examine potential changes in the distribution of *C. rodgersii* (plus other invertebrates) across different substratum types, the percentage planar cover of substratum types within each contiguous 5 by 1 m quadrat was estimated to the nearest 5 %, i.e. resolved to a 0.5 by 0.5 m area. The substratum within each quadrat was classified as either flat rock (>5 m effective diameter), large boulders (>1 m and < 5 m diameter), small boulders (>0.2 m and <1 m diameter), cobble (>0.1 m and < 0.20 m diameter), pebble (>0.01 m and < 0.10 m diameter), gravel (< 0.01 diameter), or sand. The percentage cover of macroalgae was also estimated for each contiguous quadrat using the same planar percentage cover method to the nearest 5%. Algal taxa were resolved to species-level for large brown macroalgae where possible, noting that species belonging to *Sargassum* and *Cystophora* genera were pooled due to difficulty in ascribing individual species), *see* Appendix I for list of algal taxa assessed.

Spatial & temporal dynamics of urchin barrens

As per the baseline survey conducted in 2001/02 (Johnson et al. 2005), the spatial distribution of urchin barren cover was assessed by two methods:

1. *In situ* SCUBA diver assessment along the same transects where urchin and invertebrate counts were recorded;

2. Towed underwater video enabling depths greater than 18 m to be surveyed and allowing broader kilometre-scale assessment of barrens cover across sites.

Diver transect estimation of barrens cover

As per the assessment of percentage cover of substratum types within each 5 by 1 m quadrat, each diver also estimated the percentage cover of sea urchin barrens and macroalgal species to the nearest 5%. Reef classified as “urchin barrens” was characterised as intensively grazed by locally abundant sea urchins, which was discernible from reef lacking foliose macroalgae for other reasons, e.g. scour, and/ or dominance of sessile invertebrates such as mussels, sponges, bryozoans or ascidians.

Towed-video estimation of barrens cover

The spatial extent of *C. rodgersii* ‘barrens’ was estimated by surveying rocky reef with a towed underwater video camera system. The sampling design for the video tows included the same overall spatial design as per the diver-based surveys, i.e. 13 sites, 39 sub-sites and 4 transects per sub-site. However, at the sub-site level, two video transects were run perpendicular (i.e. normal) to the shore and two transects run parallel with (i.e. along) the shore. The perpendicular transects covered depths from 1 to 45 m, while parallel transects were focused on the 15 m depth contour where *C. rodgersii* densities were observed to reach high levels as noted during original baseline dive surveys prior to towed-video deployments. Generally, perpendicular towed-video transects spanned the width of available reef from the shore to the reef fringe/sand edge. Parallel tows were typically 1 km in length in straight-line distance from start to end. Therefore, the total distance surveyed using towed-video across all sites was >80 km of reef in each survey period.

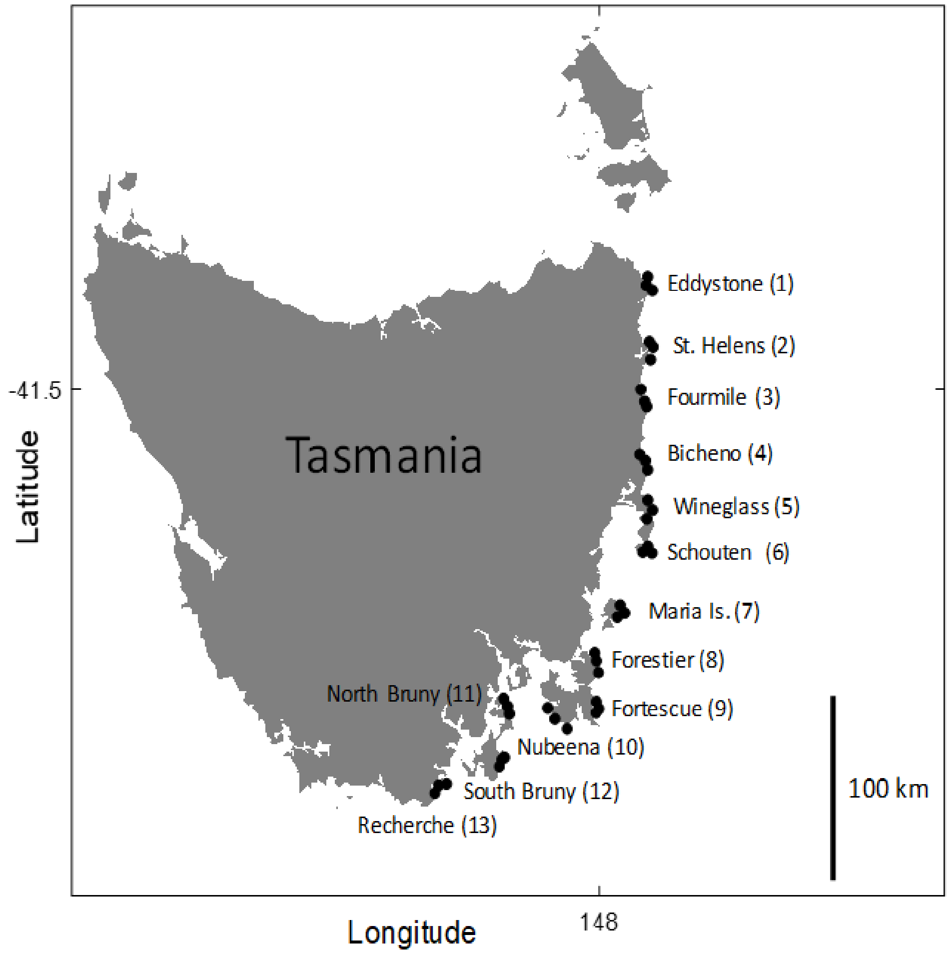

Figure 1. Sites in eastern Tasmania surveyed in 2001/02 and 2016/17. Within each of the 13 sites, which were spaced at ~20 km, there were three sub-sites spread by ~ 2 km. At each sub-site, four transects (~500 m -1 km apart) were surveyed by SCUBA divers and towed-video.

The towed-video system was 'flown' approximately 1-2 m above the seafloor and/or algal canopy, which provided a swath width of ~3-4 m. The recorded video footage was linked by time stamp to an onboard laptop computer dually capturing the time, date, GPS position and depth via depth sounder. Note that positional information related to the boat, while the camera was offset on a tow-line ~20 - 30 m behind the boat which varied depending on depth and speed which in turn was determined by calmness of sea state. In the laboratory, the video footage was examined in detail to classify habitat types for each interval between contiguous ~10 m intervals along each transect (using *Transect Measure*© software) which were then summed and converted to percentages of the total transect length for each variable.

Sea urchin barrens were classified in four types (*after* Johnson et al. 2005). Type I barrens denotes continuous barrens where the understorey was completely denuded and overstorey occupied <15% cover in the camera field of view for approx. >10 m in length of the video transect. The other three categories of barrens corresponded to increasingly 'patchy' incipient barrens, where a patch was defined as a section of reef that was not continuously barren for 10 m in length of the video transect. Type II barrens was defined as incipient barrens where barrens covered >40% of the bottom; Type III barrens defined patchy barrens in which barrens occupied between 20 - 40% cover; while Type IV barrens referred to patchy barren where barren cover was <20% cover. To obtain an overall planar estimate of barrens cover across barrens

Types I-IV, the proportion of each barrens type for each transect was multiplied by the mid-point of barrens cover as defined for that barrens type. That is, the proportion of Type I barrens on a transect was multiplied by 0.925 (i.e. the mid-point of barren cover between 85 and 100% barrens is 92.5% for this barrens type). Likewise, barrens Types II-IV were multiplied by their respective mid-points of 0.625, 0.30 and 0.10 respectively (i.e. mid-point barrens cover of each Type of 62.5%, 30% and 10% respectively).

Data analysis

Densities (no. individuals m^{-2}) of sea urchins, other benthic invertebrates and cover of substratum and macroalgal taxa, plus depth, were averaged across adjacent 5 by 1 m quadrats on either side of the transect line (i.e. by combining data from each buddy pair as assessed in 5 by 1 m quadrats on either side of the transect line). To ensure densities and percentage covers were robust estimates per unit area of reef, abundances where converted to densities once the area of sand in each diver quadrat or interval of video had been removed. To ensure temporal consistency in the depths sampled during each sampling period, diver and video transects were individually matched by depth and overall length of transect between 2001/02 and 2016/17 sampling periods.

Data were analysed using analysis of variance (ANOVA) using a 2-factor mixed effects model testing the effects of "Time" (i.e. fixed effect, 2001/02 *versus* 2016/17) and "Site" (i.e. random effect of 13 eastern Tasmanian sites), plus the interactive term of "Time" by "Site", (i.e. variability in the "Time" effect across "Sites"). The analysis of variance in *C. rodgersii* density and barrens cover at the site level (for both dive and towed-video estimates of barrens), within each time-period, was based on means of n=3 sub-sites, with sub-site estimates themselves generated from the mean of n=4 transects. All statistical analyses were undertaken using *R* (R Development Core Team 2018) and appropriate transformations of response variables were determined using the "boxcox" routine available in the *MASS* package in *R*.

Distribution of *C. rodgersii* density and barrens cover across depth, as assessed *in situ* by divers, was analysed by defining 2 m depth strata; ranging 4 to 6 m, 6 to 8 m, 8 to 10 m, 10 to 12 m, 12 to 14 m, 14 to 16 m and 16 to 18 m. The influence of reef substratum type on *C. rodgersii* density and barrens cover was explored by assigning averaged neighbouring quadrats to a dominant substratum type, i.e. the substratum type constituting >50% cover. In cases where substratum types were equally dominant, the dominant substratum was assigned as the smaller diameter category, i.e. where large and small boulders were equally dominant, the quadrat would be assigned to small boulders. Effects of depth and substratum were analysed through time using a 3-way fixed effects ANOVA on data averaged across sites.

Abiotic and biotic explanatory variables of *C. rodgersii* density, barrens cover, plus abalone, lobster, and native urchin *Heliocidaris erythrogramma* density were explored using linear regression. Relative importance metrics for each explanatory variable were determined using the "*Relaimpo*" package available in *R*. The "*Relaimpo*" package (https://cran.r-roject.org/web/ packages/relaimpo/relaimpo.pdf) partitions the contribution of each explanatory variable to the overall R^2 of each model fit. Univariate linear regression models predicting *C. rodgersii* density, barrens cover and other invertebrates, where appropriate, included a subset of the following list of explanatory variables: Time (categorical), Site (categorical), Subsite (categorical), Transect (categorical), *Centrostephanus* density (continuous), Barren cover (continuous), *Heliocidaris* density (continuous), *Haliotis* density (continuous), *Jasus* density (continuous), Depth (continuous), *Ecklonia* cover (continuous), *Phyllospora* cover (continuous), Flat rock cover (continuous), Large boulder cover (continuous), Small boulder cover (continuous).

Algal community data were analysed by generating a multivariate similarity matrix of square-root transformed mean percentage cover data of each algal species/ taxonomic group for each sub-site at each site for each sampling period and was analysed using PRIMER 6.1.12 software, specifically using the nMDS, SIMPER, and PERMANOVA (v. 1.0.2) routines (further detail presented in the results).

Finally, *C. rodgersii* abundance and biomass spanning eastern Tasmanian sites 1 to 9 was estimated by scaling observed depth-specific densities by reef area contained within each site as available from Sea Map Australia (http://seamapaustralia.org/) (see Appendix II). As reef areas for each site were broadly resolvable by Seamap Australia, mean density estimates for all hard-reef (across flat rock, large boulders, small boulders, cobble and pebble) were scaled within each 2 m depth strata for each site to obtain overall estimates of abundance. For depths in excess of 18 m, *C. rodgersii* density was modelled using an exponential decline function as observed in deeper water at St. Helens (Site 2) (Ling et al. 2016). Biomass of *C. rodgersii* for each site and eastern Tasmania as a whole was then estimated using allometric conversions between test diameter and total wet weight [biomass (g) = 4.7293 *Test Diam. - 153.22], which was calculated on mean test diameter for each site, or group of sites (see results), from a minimum of n=300 test diameters in each survey period. For the 2001/02 period, mean test diameters measured across sites in 2005 were used (Ling et al. 2009b), while for 2016/17 mean test diameters measured in 2015 were used (Ling & Keane, *unpub. data*).

RESULTS

Spatial & temporal change in *Centrostephanus* & associated barrens: diver re-survey

Diver surveys revealed the abundance of *C. rodgersii* between 4 and 18 m depth across all 13 eastern Tasmanian sites increased from an average density of 0.104 individuals m^{-2} in 2001/02 to 0.182 individuals m^{-2} in 2016/17 (Fig. 2a). This represents a 1.75 times increase in density or an increase of 75% over 15 years, equating to a 3.8% increase per annum over this period. Analysis of variance at the site-level (using sub-site means as replicates), revealed significant increase in *C. rodgersii* density over the 15-year period (Table 1a). Analysis of variance also detected a strong effect of site on *C. rodgersii* abundance, but consistency in the effect of time across sites (Table 1a). As discovered during the 2001/02 baseline survey, the highest densities of *C. rodgersii* were again recorded at St. Helens (Site 2) in north east Tasmania and lowest densities south west of the Tasman Peninsula where only a total of 7 individuals were recorded across Nubeena, North Bruny, South Bruny, and Recherche Bay sites (Fig. 2a).

Diver surveys revealed the average cover of urchin barrens between 4 to 18 m depth increased from an average of 1.59% in 2001/02 to 6.31% in 2016/17 (Fig. 2b). This represents a 3.97 times increase or an increase of 297% over 15 years, equating to a ~10% increase per annum over this period. Analysis of variance revealed a statistically significant increase in barrens cover as determined by divers between sampling periods (Table 1b). Analysis of variance also revealed significant variability in barrens cover between sites (Table 1b), with highest cover of barrens found at St. Helens and nil barrens cover observed during formal surveys at the four southernmost sites, i.e. Nubeena, North Bruny, South Bruny and Recherche Bay (Fig. 2b). Demonstrating consistency in the increase in barrens through time across sites, there was also a lack of significant variability for the “Time by Site” interaction term (Table 1b).

Change by depth & reef type

For eastern Tasmanian sites 1-9, urchin density showed general increase with depth in both survey periods and increased within each depth category through time (Fig 3a). The depth distribution of barrens over the range 4 to 18 m depth, as assessed *in situ* by divers, also broadly reflected the distribution of *C. rodgersii* density (Fig. 3b; for change in *C. rodgersii* and barrens by depth at specific sites and sub-sites *see* Appendices III-V). Notably however, in deeper water (>14 m), higher percentage barren cover appeared to occur at relatively low urchin density (compare Fig. 3a & 3b).

In addition to depth, substratum type was also a key determinant of *C. rodgersii* abundance and barrens cover through time (Fig. 4). Analysis of variance of *C. rodgersii* density, pooled across sites 1-9, revealed significant effects of substratum type, depth and time (Table 2a); with large boulders in deep water containing highest urchin densities (Fig. 4). While patterns of significance were similar for cover of barrens, in terms of the main effect of substratum type, depth and time, a significant interactive effect between substratum type and time was evident for barrens cover (Table 2b). Explaining this interactive effect, the increase in barrens cover through time was significantly greater for large boulder substratum compared to either flat rock or small boulder reef habitat (Fig. 4ii).

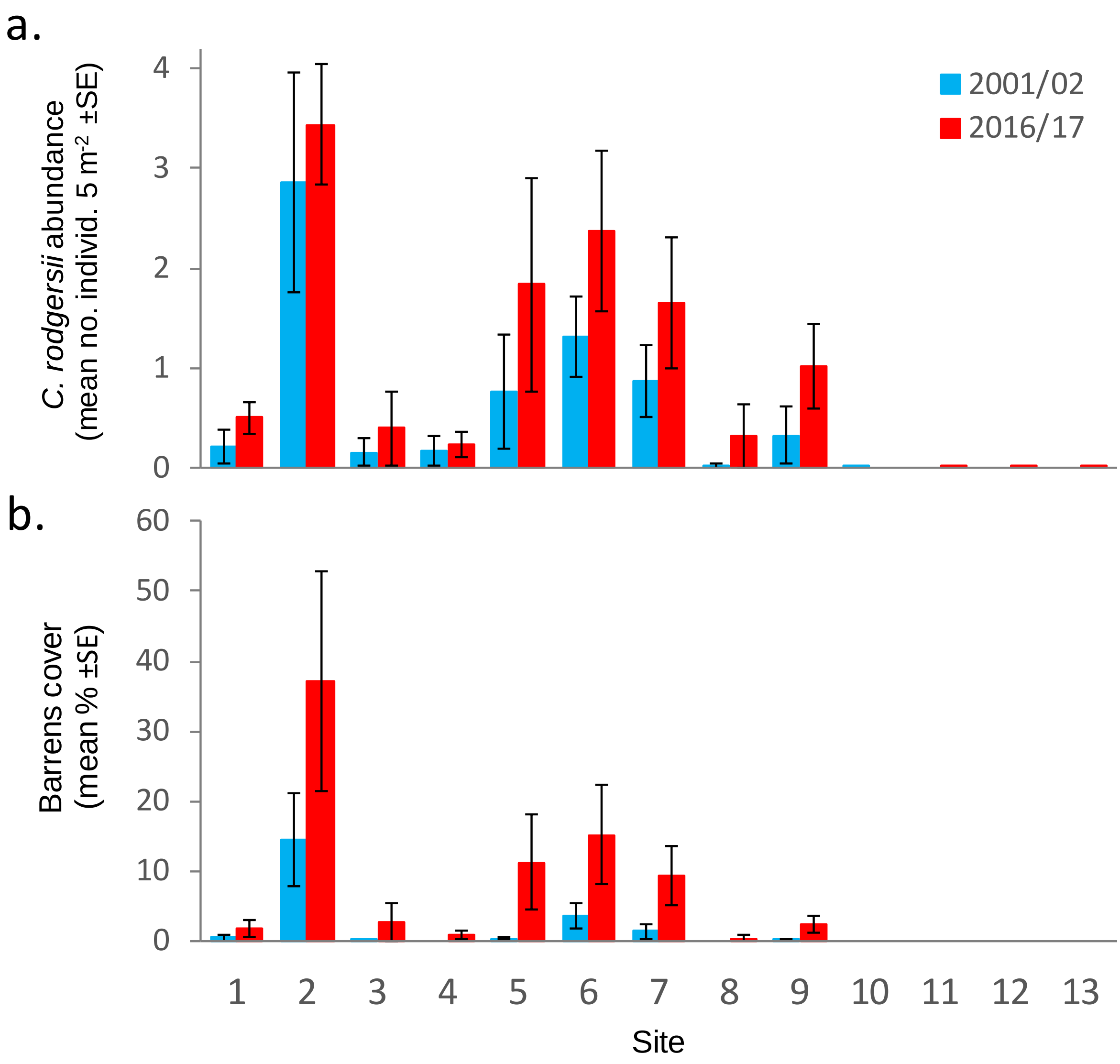

Figure 2. Spatial and temporal patterns in (a.) *Centrostephanus rodgersii* abundance and (b.) barrens coverage assessed *in situ* by SCUBA divers across eastern Tasmania in 2001/02 (blue) and 2016/17 (red) sampling periods. Means and standard errors for each site were generated from n=3 sub-sites, with sub-site values generated from the mean of n=4 transects within each sub-site. Sites are arranged from north to south with the northernmost site of Eddystone Point (1) to the southernmost site of Recherche Bay (13).

Spatial & temporal change in barrens across reefs: towed-video re-survey

Assessed by underwater towed-video to depths of >40 metres, urchin barrens of all types (I-IV) were observed to increase from 2001/02 to 2016/17 (Fig. 5). While all barren Types demonstrated consistent and significant increase through time (Table 3), increase was greatest for incipient barrens Types II-IV (Fig. 5b-d). Continuous barrens and incipient barrens Types II & III showed consistent increase across space and time (Fig. a.-c.), while Type IV barrens showed greater increase at some sites compared to others (Fig. 5d) as indicated by the significant Time by Site interaction (Table 3d). Estimation of planar barrens cover to depths of 40 m, as obtained by summing barrens proportions across Types I-IV as scored from towed-video, revealed similar quantitative patterns in cover across sites and through time to that of *in situ* diver estimates in shallower (4-18 m) depths (cf. Fig. 2b and 6a).

Considering all barrens types for sites 1-9, the percentage of video transects containing barrens of some variety showed clear increase through time (Fig. 6b). For these sites, barrens patches were present on >30% of video transects and the presence of barrens of any type occurred on >60% of video transects at St. Helens, Schouten and Maria sites (Fig. 6b; Table 4). Overall the increase in planar barrens cover (as derived by summing proportions of each barrens type as determined from towed-video) across sites 1-9 in eastern Tasmania more than quadrupled, from 3.4% to 15.2%, during the 2001/02 to 2016/17 period (Table 4); equating to an increase of ~350% and a 10.5% increase per annum over this period. This increase was however uneven across depth with the largest increase occurring at depths between 18 and 30 m and less increase either deeper or shallower than this range (Fig. 7; Table 4).

Table 1. Analysis of variance table for 2-factor ANOVA testing the effects of "Time", i.e. fixed effect, 2001/02 *versus* 2016/17; and "Site" (i.e. random effect, sites 1-13), plus the interactive term of "Time" by "Site" on the response of (a.) *Centrostephanus rodgersii* abundance and (b.) barrens cover. Note to meet the assumption of homogeneity of variances the *C. rodgersii* abundance, estimated as density of individuals per 5 m^{-2}, and barrens cover required log transformation, i.e. log(*Y*+0.001). Density and cover estimates at the site level were based on means of n=3 sub-sites, with sub-site estimates themselves generated from the mean of n=4 transects. Tests highlighted in bold indicate significance at the α=0.05 level; significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

a. *Centrostephanus* density

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)	
Time	**1,12**	**16.1**	**16.14**	**15.82**	**0.0018**	**
Site	**12,52**	**573.7**	**47.81**	**14.36**	**<0.0001**	***
Time*Site	12,52	12.2	1.02	0.305	0.99	
Residuals	52	173.2	3.33			

b. Barrens cover

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)	
Time	**1,12**	**108.9**	**108.93**	**14.841**	**0.0023**	**
Site	**12,52**	**1761.7**	**146.81**	**17.099**	**<0.0001**	***
Time*Site	12,52	88.1	7.34	1.755	0.082	
Residuals	52	217.6	4.18			

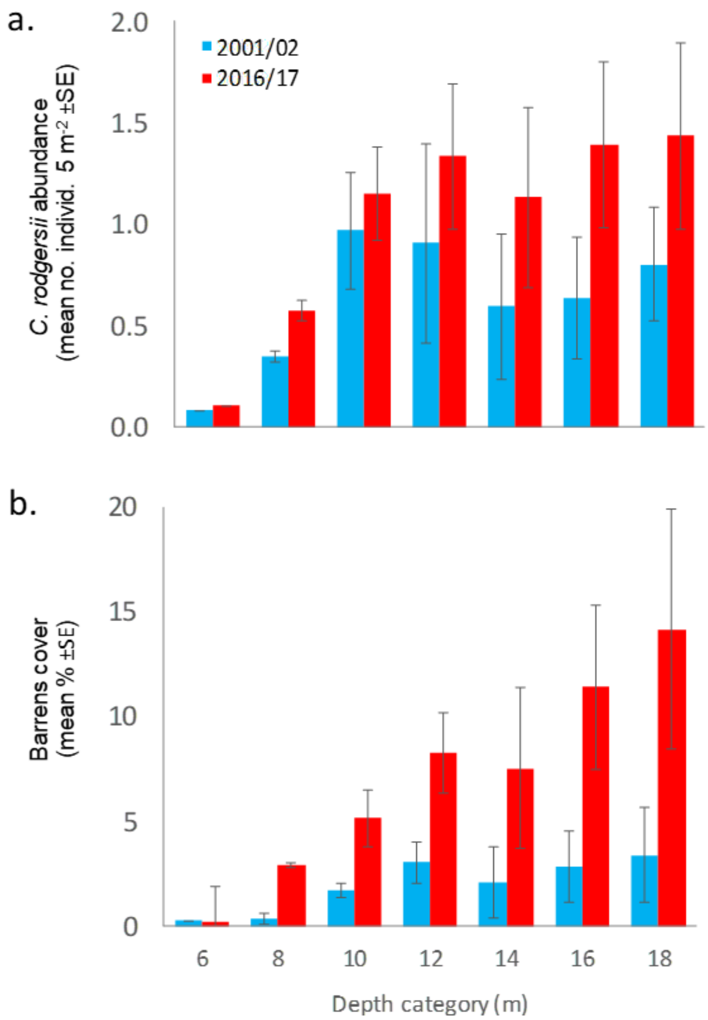

Figure 3. Overall depth distribution of (a.) *Centrostephanus rodgersii* abundance, and (b.) barrens cover in eastern Tasmania as assessed by *in situ* diver transects in 2001/02 and in 2016/17 as shown in blue and red bars respectively. Data are means per 5 m^2 as pooled within each depth bin for sites from Eddystone Point to Fortescue Bay (i.e. sites 1-9). Note that depth values shown represent the ceilings of each depth category.

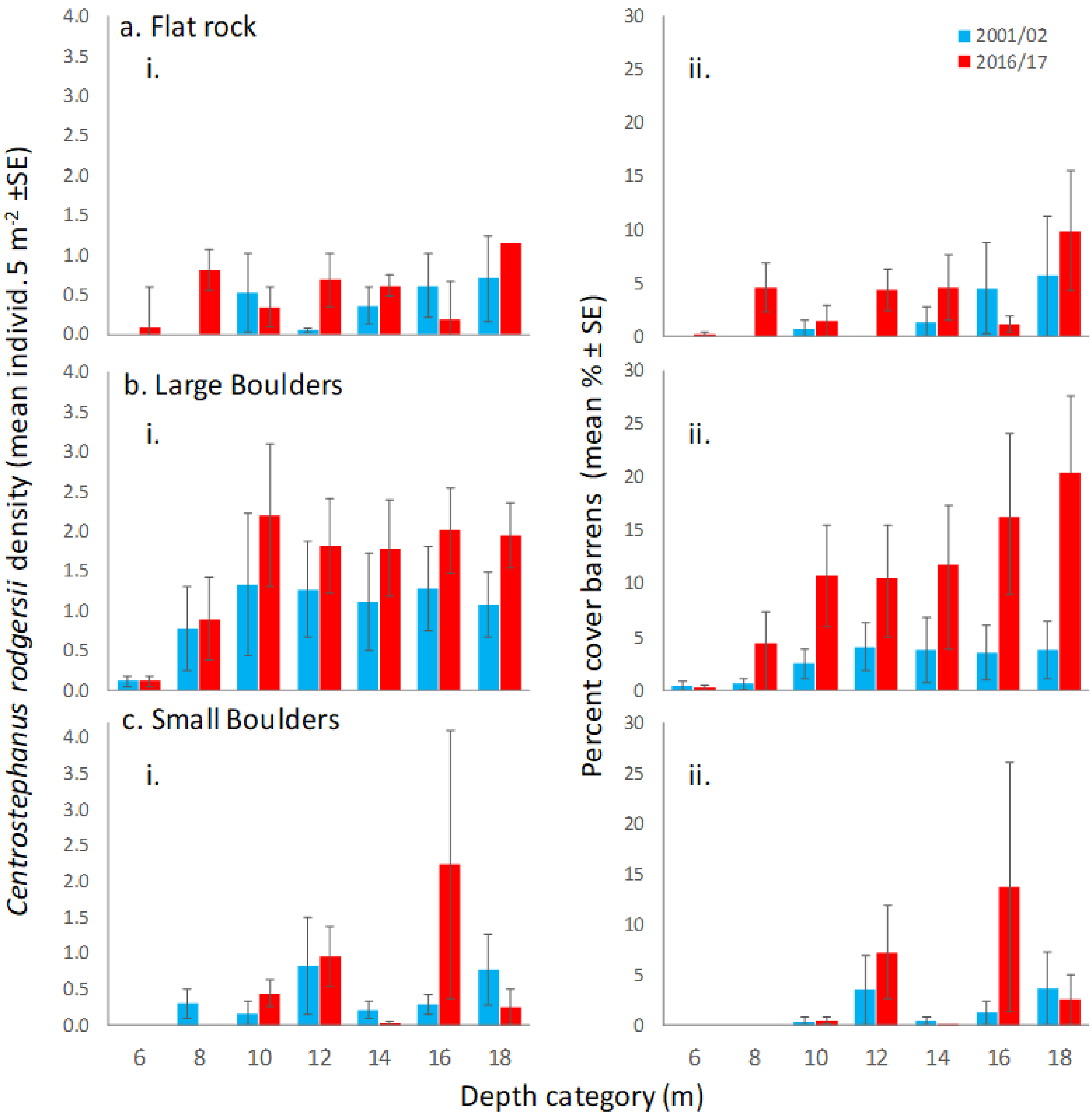

Figure. 4. Change in *Centrostephanus rodgersii* abundance (i.), and barrens cover (ii.) by substratum type (a. – c.) across depth categories (4 to 18 m depth) pooled for sites 1-9 from 2001/02 (blue) to 2016/17 (red) time periods. Data are means derived from 5 m^2 quadrats assessed *in situ* by divers and averaged for quadrats dominated by a particular substratum type within each 2 m depth category. Note that depth values shown represent the ceilings of each depth category.

Table 2. Analysis of variance table for 3-factor ANOVA testing the effects of “Depth”, i.e. fixed effect of depth strata (i.e. 4-6m, 6-8m, 8-10m, 10-12m, 12-14m, 14-16m, 16-18m), “Substratum” (i.e. fixed effect, Flat Rock, Large Boulders, Small Boulders) and “Time” (i.e. fixed effect, 2001/02 *versus* 2016/17), plus all interactive terms on the response of (a.) *Centrostephanus rodgersii* density and (b.) barrens cover as assessed *in situ* by divers, for sites 1-9 in eastern Tasmania where barrens were recorded during both survey periods. Data are means across sites 1-9. Note to meet the assumption of homogeneity of variances *C. rodgersii* density and barrens cover required transformations of $Y^{0.25}$ and sqrt(*Y*) respectively. Tests highlighted in bold indicate significance at the α=0.05 level.

a. *Centrostephanus* density

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Substratum	**2**	**15.11**	**7.55**	**32.34**	**<0.0001**	***
Depth	**6**	**3.04**	**0.51**	**2.17**	**0.046**	*
Time	**1**	**2.03**	**2.03**	**8.71**	**0.003**	**
Substratum*Depth	11	2.54	0.23	0.99	0.459	
Substratum*Time	2	1.07	0.54	2.3	0.103	
Depth*Time	6	1.87	0.31	1.337	0.243	
Substratum*Depth*Time	10	2.03	0.2	0.87	0.564	
Residuals	240	56.06	0.23			

b. Barrens cover

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Substratum	**2**	**83.06**	**41.53**	**13.52**	**<0.0001**	***
Depth	**6**	**42.65**	**7.11**	**2.31**	**0.034**	*
Time	**1**	**83.47**	**83.47**	**27.17**	**<0.0001**	***
Substratum*Depth	11	16.51	1.5	0.49	0.909	
Substratum*Time	**2**	**27.56**	**13.78**	**4.49**	**0.012**	*
Depth*Time	6	14.31	2.39	0.78	0.589	
Substratum*Depth*Time	10	20.02	2	0.65	0.768	
Residuals	240	737.29	3.07			

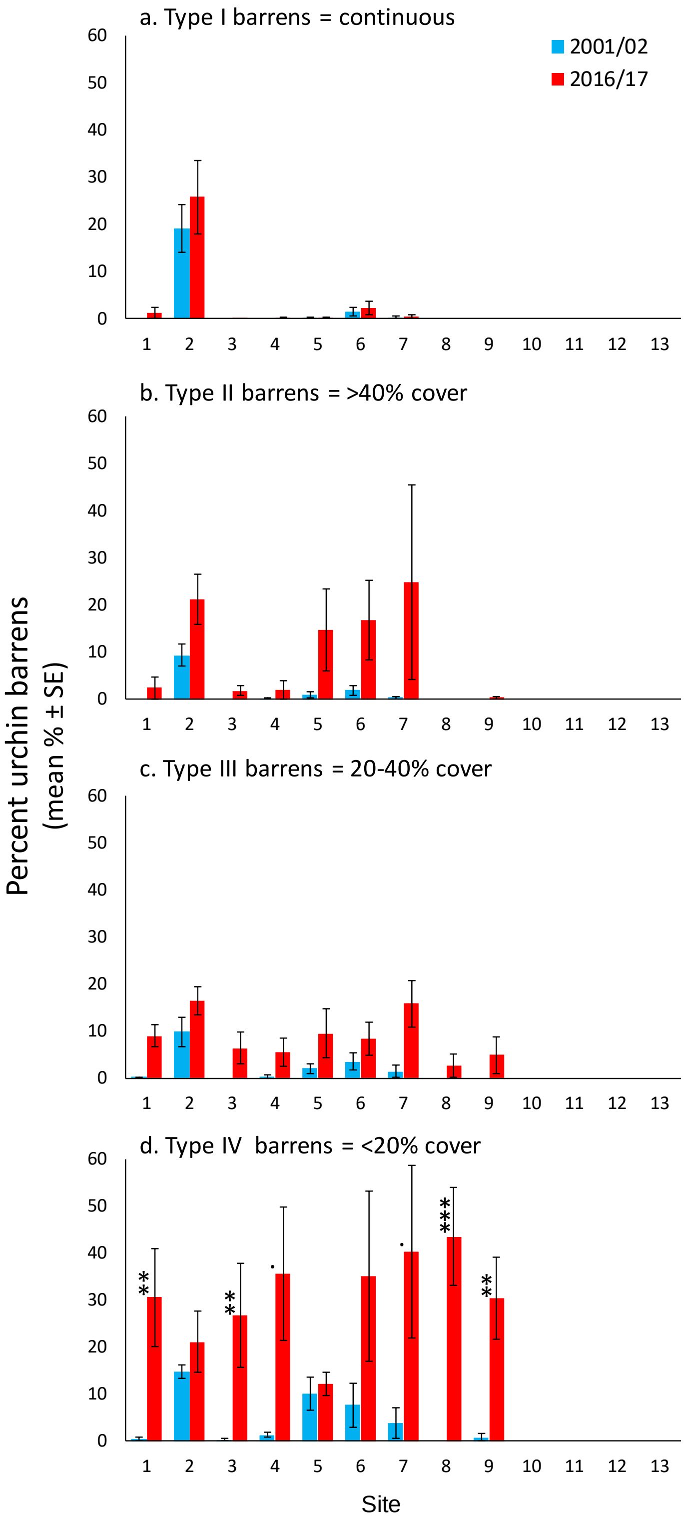

Figure 5. Spatial and temporal patterns of barrens Types I-IV (a.-d.) as assessed by towed-video across eastern Tasmania in 2001/02 (blue) and 2016/17 (red) sampling periods. Means and standard errors for each site were generated from n=3 sub-sites, with sub-site values generated from the mean of n=4 transects within each sub-site. Sites are arranged from north to south with the northernmost site of Eddystone Point (1) to the southernmost site of Recherche Bay (13). For d., significant "Time by Site" effects (see Table 3d) are partitioned across sites, with significant time effects for particular sites highlighted by asterisks, significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

Table 3. Analysis of variance table for 2-factor ANOVA testing the effects of "Time", i.e. fixed effect of 2001/02 versus 2016/17; and "Site" (sites 1-9, i.e. random effect), plus the interactive term of "Time" by "Site" on the response of percentage of reef containing barrens of Types I-IV (a.-d.) as assessed by towed-video. Estimates at the site level were based on means of n=3 sub-sites. Tests highlighted in bold indicate significance at the α=0.05 level; significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

a. Type I barrens (log(*Y*+0.001)

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1,8**	10.50	10.50	**6.18**	**0.038***
Site	**8,36**	503.5	62.94	8.12	**<0.0001*** **
Time*Site	8,36	13.6	1.70	0.22	0.99
Residuals	36	279.0	7.75		

b. Type II barrens ($Y^{0.25}$)

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1,8**	**5.12**	**5.12**	**16.06**	**<0.001 ** **
Site	**8,36**	**19.79**	**2.47**	**6.30**	**<0.001 ** **
Time*Site	8,36	2.56	0.32	0.81	0.60
Residuals	36	14.130	0.39		

c. Type III barrens ($Y^{0.25}$)

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1,8**	**10.84**	**10.84**	**56.75**	**<0.0001*** **
Site	**8,36**	**11.42**	**1.43**	**4.96**	**<0.0001*** **
Time*Site	8,36	1.53	0.19	0.66	0.72
Residuals	36	10.37	0.29		

d. Type IV barrens ($Y^{0.25}$)

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1,8**	**20.65**	**20.65**	**48.02**	**<0.001 ** **
Site	**8,36**	**3.44**	**0.43**	**2.36**	**0.038 ***
Time*Site	**8,36**	**7.27**	**0.91**	**4.99**	**0.0003*** **
Residuals	36				

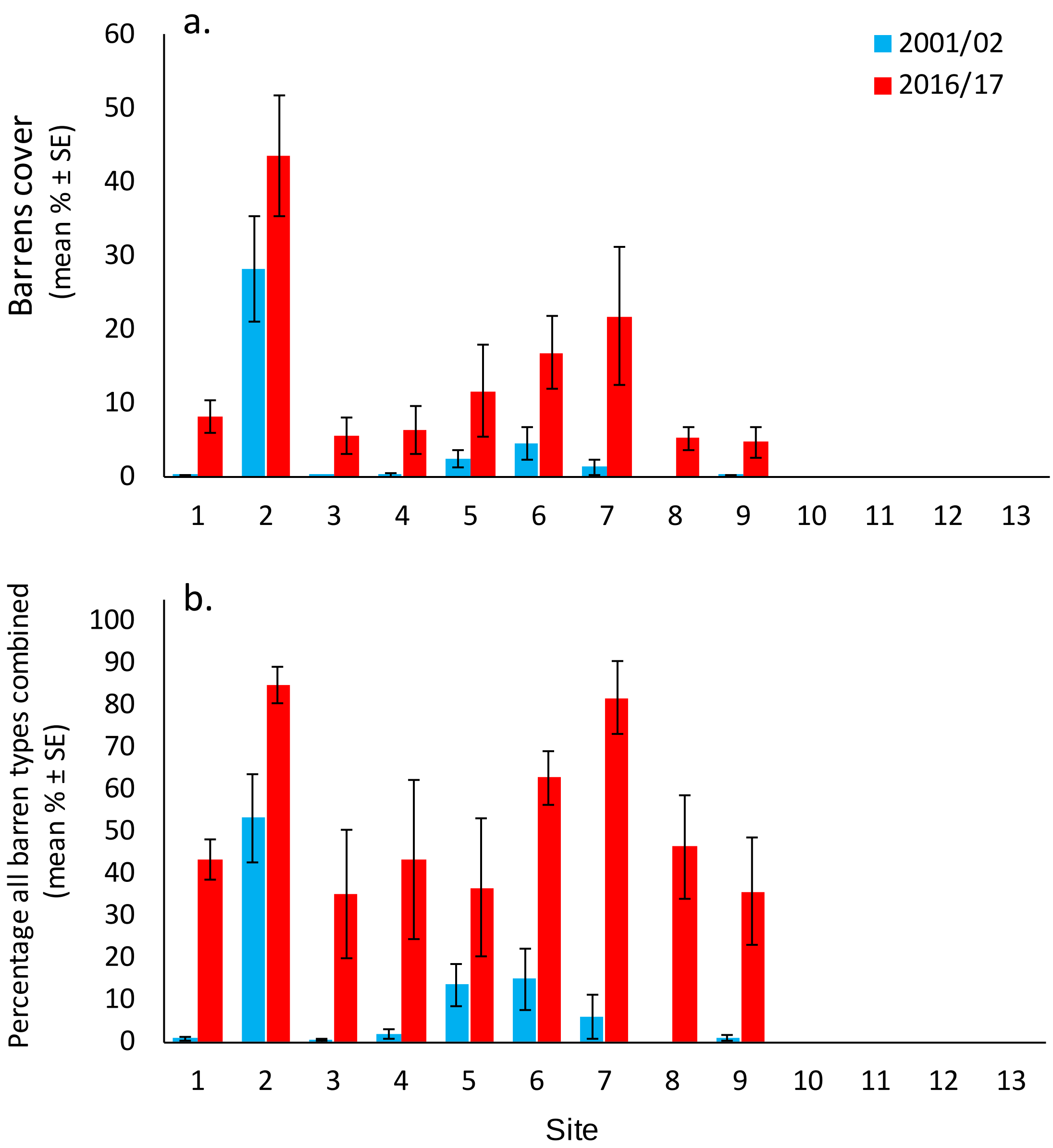

Figure 6. Spatial and temporal patterns in (a.) planar barrens cover and (b.) percentage of all barrens types (I-IV summed) as assessed by underwater towed-video across eastern Tasmania in 2001/02 (blue) and 2016/17 (red) sampling periods. Means and standard errors for each site were generated from n=3 sub-sites, with sub-site values generated from the mean of n=4 transects within each sub-site. Sites are arranged from north to south with the northernmost site of Eddystone Point (1) to the southernmost site of Recherche Bay (13).

Table 4. Spatial and temporal trends in planar urchin barren cover, as assessed by towed-video, by site and depth strata for eastern Tasmania (sites 1-9) in (a.) 2001/02 and (b.) 2016/17. Data are mean planar percentage cover derived by summing planar cover across the four barrens types after multiplying by approx. proportion of planar barrens per type, i.e. Type I = 0.925 barren; Type II=0.625 barren; Type III= 0.30 barren; Type IV = 0.10 barren), with means by depth strata (ceiling of each 2 m depth strata shown) and by site shown in last row and columns of each table respectively. Means obtained by averaging across each depth strata by site are emboldened in last row and columns of each table respectively. Overall increase in barren cover, factor of increase, and percentage increase between the 20-01/02 and 2016/17 periods are summarised at bottom right hand side of b.

a. 2001/02

	Depth strata (m)																			**Means**	
	Site	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**	**4-18**	**4-40**
1	Eddystone	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.8	0.0	0.0									0.0	0.1
2	St Helens	0.0	8.7	12.1	17.6	23.9	34.8	29.8	32.1	28.6	32.6	28.1	20.7	2.8	2.9	10.0				18.1	19.0
3	Four Mile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0										0.0	0.1
4	Bicheno	0.0	0.0	0.4	0.0	0.0	0.1	0.7	1.4	0.1	0.7	0.4	0.3	0.0	0.6	3.1	0.0			0.2	0.5
5	Wineglass	0.0	1.7	3.2	1.8	0.7	2.0	2.9	2.9	2.3	1.8	1.5	5.9	2.8	15.4	9.6	0.0	0.0	0.0	1.7	3.0
6	Schouten	0.0	3.0	5.5	4.4	6.1	10.8	5.9	3.8	3.1	2.9	6.7	2.6	2.3	7.9	19.7	0.0			5.1	5.3
7	Maria	0.0	0.0	0.5	0.5	0.5	0.8	1.2	1.0	0.8	2.1	1.4	0.2	5.4	3.9	10.9	5.7	6.0	0.0	0.5	2.3
8	Forestier	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0							0.0	0.0
9	Fortescue	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Means	**0.0**	**1.5**	**2.4**	**2.7**	**3.5**	**5.4**	**4.5**	**4.7**	**3.9**	**5.0**	**5.4**	**4.2**	**2.2**	**5.1**	**8.9**	**1.1**	**2.0**	**0.0**	**2.9**	**3.4**

b. 2016/17

	Site	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**	**38**	**40**	**4-18**	**4-40**
1	Eddystone	0.0	1.1	2.1	2.5	3.0	7.3	11.7	12.2	24.9	38.7	28.3	4.9	0.0						4.0	10.5
2	St Helens	4.1	12.6	14.4	22.8	43.3	48.4	56.9	70.9	71.4	62.1	37.1	36.3	41.1	0.0					28.9	37.2
3	Four Mile	13.1	0.9	3.2	7.5	6.4	10.7	11.8	29.3	18.0										7.6	11.2
4	Bicheno	0.0	2.9	3.6	6.2	3.5	3.7	3.9	7.9	10.2	17.7	21.7	31.9	62.5						3.4	13.5
5	Wineglass	12.4	4.4	11.2	4.7	7.5	15.2	11.2	13.2	18.0	22.2	24.3	25.9	22.3	14.5					9.5	14.8
6	Schouten	19.3	24.1	30.1	18.7	23.0	21.7	18.1	14.0	10.1	21.8	20.5	11.1	8.6	15.4	17.6	34.2	36.0		22.2	20.3
7	Maria			11.5	18.9	34.2	25.1	25.1	20.9	26.6	23.6	23.8	38.6	35.4	27.3	3.8	22.8	13.6	0.0	23.0	22.0
8	Forestier	0.4	3.4	4.0	6.0	5.9	5.0	6.7	7.3	3.0	7.9	12.7	0.0	0.0	0.0					4.5	4.5
9	Fortescue	0.0	1.4	0.6	8.6	5.8	4.1	5.4	9.7	4.2	3.0	1.3	0.0	0.0	0.0	0.0	0.0			3.7	2.7
	Means	**6.2**	**6.4**	**9.0**	**10.6**	**14.7**	**15.7**	**16.8**	**20.6**	**20.7**	**24.6**	**21.2**	**18.6**	**21.3**	**9.5**	**7.1**	**19.0**	**24.8**	**0.0**	**11.9**	**15.2**
	Increase 2001/02 to 2016/17																			**9.0**	**12**
	Times increase																			**4.15**	**4.52**
	% Increase																			**315**	**352**

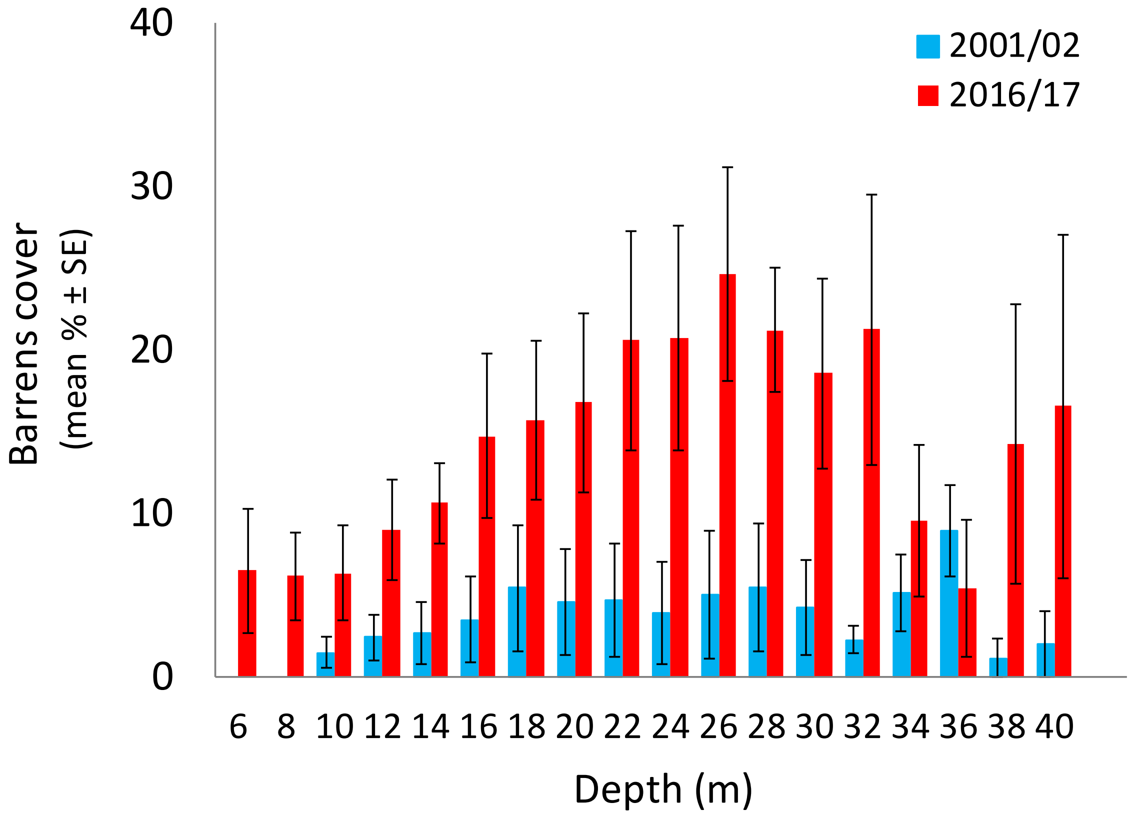

Figure 7. Temporal patterns in barrens cover as assessed by underwater towed-video across eastern Tasmanian sites 1-9 in 2001/02 (blue) and 2016/17 (red). Means and standard errors were generated using site means as replicates. Note that depth values shown represent the ceilings of each category.

Abiotic & biotic explanatory variables of *Centrostephanus* & barrens

Examination of abiotic and biotic explanatory variables of *C. rodgersii* abundance revealed "Site" to be the largest contributor to the variance (i.e. 37.87% of model variance, with *C. rodgersii* density declining with increasing site number southward along eastern Tasmania; *see* Table 5a). The next most important explanatory variable of *C. rodgersii* was the positive effect of increasing cover of large boulders (19.37% of observed model variance), followed by a negative effect of increasing cover of the macroalga *Phyllospora* (11.41% of model variance; Table 5a). The significant positive effects of Time, *Heliocidaris* density and *Ecklonia* cover all contributed less than 10% of observed model variance (Table 5a). Increasing cover of Flat Rock was observed to have a significant negative effect on *C. rodgersii* density, contributing 7.26% to model variance (Table 5a). Other than the major influence of Site, there was negligible contribution to model variance by the finer-scale spatial factors of either Sub-site (0.58%) or Transect (0.02%) on *C. rodgersii* density (Table 5a).

Examination of abiotic and biotic explanatory variables of urchin barrens across eastern Tasmanian revealed the density of *C. rodgersii* as the overwhelming positive contributor to barrens cover by accounting for 83.25% of model variance (Table 5b; *see also* scatter plot Fig. 8a). The effect of "Site" was the second largest contributor to variance in barrens cover (6.45%, again a negative effect as per *C. rodgersii* density above), followed by positive significant effects of Time and Large Boulders, followed by negative significant effects, but low contribution to variance of Flat Rock (Table 5b). Other than Site, again there was negligible contribution to model variance by the finer-scale spatial factors of either Sub-site (0.13%) or Transect (0.02%) on barrens cover (Table 5b).

Notably, the effect of the native urchin *Heliocidaris erythrogramma* on barrens cover across the eastern Tasmanian sites was negligible with only a 0.72% contribution to overall model variance (Table 5b, *see* Fig. 8b). Of further note, although the effect of *H. erythrogramma* on *C. rodgersii* appears negative Table 5a, scatter plot between the two urchin species revealed evidence for a factor-ceiling type distribution (Fig. 8c). Evidence of such negative distributions were also apparent between *C. rodgersii* and blacklip abalone (*Haliotis rubra*) (Fig. 9a), plus abalone *versus* barrens (Fig. 9b), and rock lobster (*Jasus edwardsii*) *versus C. rodgersii* (Fig. 9c) and rock lobster *versus* barrens (Fig. 9d). That is, higher densities of abalone and rock lobster were not associated with higher densities of *C. rodgersii* or overgrazed barren grounds.

Table 5. Linear regression of (a.) *Centrostephanus* abundance and (b.) barrens cover against potential abiotic and biotic explanatory variables for eastern Tasmania. Data is that assessed *in situ* by divers and at the 5 m^2 quadrat scale, n= 3,200 quadrat-level estimates. Metrics have not been normalised and significant effects highlighted in bold.

a. ***C. rodgersii*** **abundance** [transformation= *Y*^0.75]

(Total response variance= 1.33; Proportion of variance explained by model: 18.91%)

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)		effect	% model explained
Time	**1**	**27.50**	**27.54**	**25.45**	**<0.001**	***	**positive**	**4.29%**
Site	**1**	**304.20**	**304.23**	**281.20**	**<0.001**	***	**negative**	**37.87%**
Subsite	1	1.60	1.60	1.48	0.225		positive	0.58%
Transect	1	0.00	0.04	0.03	0.857		positive	0.02%
Depth	1	0.10	0.12	0.11	0.737		positive	3.15%
Jasus	1	1.80	1.76	1.63	0.202		negative	0.98%
Haliotis	1	0.10	0.10	0.09	0.760		positive	0.14%
Heliocidaris	**1**	**76.60**	**76.62**	**70.82**	**<0.001**	***	**positive**	**8.49%**
Ecklonia	**1**	**9.70**	**9.73**	**9.00**	**<0.01**	**	**positive**	**3.24%**
Phyllospora	**1**	**182.60**	**182.62**	**168.80**	**<0.001**	***	**negative**	**11.41%**
Flat rock	**1**	**61.20**	**61.18**	**56.55**	**<0.001**	***	**negative**	**7.26%**
Large boulders	**1**	**137.60**	**137.60**	**127.18**	**<0.001**	***	**positive**	**19.37%**
Small boulders	1	0.60	0.61	0.57	0.451		negative	3.21%
Residuals	3185	3446.9	1.1					

b. **Barrens cover** [transformation= log(*Y*+0.001)]

(Total response variance= 9.62; proportion of variance explained by model=61.74%)

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)		effect	% model explained
Time	**1**	**943.10**	**943.10**	**255.44**	**<0.001**	***	**positive**	**3.58%**
Site	**1**	**2348.60**	**2348.60**	**636.16**	**<0.001**	***	**negative**	**6.45%**
Subsite	**1**	**17.00**	**17.00**	**4.59**	**0.032**	*	**negative**	**0.13%**
Transect	1	2.60	2.60	0.70	0.404		negative	0.02%
Centrostephanus	**1**	**15564.80**	**15564.80**	**4215.94**	**<0.001**	***	**positive**	**83.25%**
Heliocidaris	1	0.00	0.00	0.01	0.909		positive	0.72%
Depth	1	5.90	5.90	1.61	0.205		positive	0.45%
Flat rock	**1**	**16.30**	**16.30**	**4.41**	**0.036**	*	**negative**	**1.14%**
Large boulders	**1**	**104.10**	**104.10**	**28.19**	**<0.001**	***	**positive**	**3.51%**
Small boulders	1	0.20	0.20	0.06	0.809		negative	0.76%
Residuals	3188	11773.50	3.70					

Spatial and temporal change in commercial invertebrates and macroalgal habitat

In contrast to *C. rodgersii* and barrens cover which were both observed to increase through time, the native urchin *H. erythrogramma* was observed to show significant decline (56% decline) from 2001/02 to 2016/17 (Table 6, 7a; Fig. 10a;). For abalone and rock lobsters, abundances showed significant variability across sites (Table 7b,c; Fig. 10b,c) and an interaction between Time and Site was observed for abalone, i.e. at two sites abundances decreased while at other sites abundances did not show significant change though time (Table 7b; Fig. 10b). While lobster abundance varied across sites, variability in lobster abundance between sampling periods was non-significant (Table 7b; Fig. 10b).

Abiotic and biotic predictors of commercial invertebrates

Examination of the relative importance of abiotic and biotic explanatory variables on density of abalone, lobster and the native urchin *H. erythrogramma* revealed contrasting patterns among these invertebrates. While the effect of Time was negative in all cases and explained up to 15.64% of model variance, Site contributed a high proportion of model variance for lobsters and *H. erythrogramma* but not abalone (Table 8a-c). In contrast, sub-site was the most important explanatory variable of abalone density (Table 5a). Transect explained negligible model variance for abalone and *H. erythrogramma* (<0.40%) but had a significant effect and contributed a small amount to model variance (~3%) in lobster abundance (Table 5a-c).

In terms of biotic explanatory variables, *C. rodgersii* contributed an apparent positive effect on *H. erythrogramma* (29.75% of model variance, i.e. the most important variable for *H. erythrogramma*), and a smaller apparent positive effect for abalone (6.44%), while a negative effect of *C. rodgersii* on lobsters (accounting for 4.11% of model variance) was observed (Table 8). Barrens were observed to have negative effects on abalone and lobster density but were positive for *H. erythrogramma* (Table 8). Depth had an important negative effect on abalone, explaining ~11% of model variance, but contributed little to lobster and *H. erythrogramma* density (Table 8). For lobsters, the density of *H. erythrogramma* had a positive effect, explaining 11.38% of model variance (Table 8b). All three invertebrates were positively correlated with increasing cover of large boulders, which was particularly important for lobsters, while all three invertebrates were negatively associated with increasing cover of flat rock (Table 8).

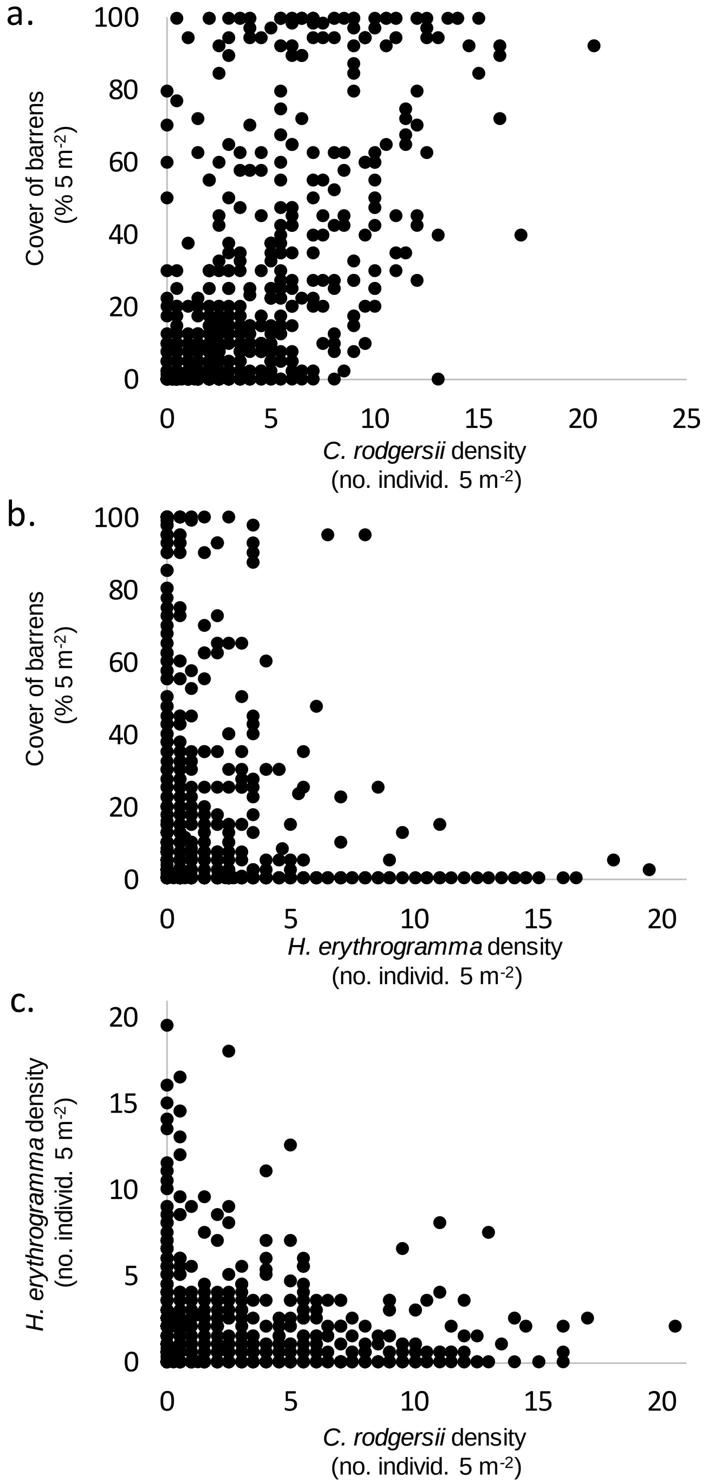

Figure 8. Relationships between sea urchins and cover of sea urchin barrens on eastern Tasmanian reefs as assessed by diver transects. (a.) Relationship between *Centrostephanus rodgersii* and barrens habitat. (b.) Relationship between *Heliocidaris erythrogramma* and barrens habitat. (c.) Relationship between *H. erythrogramma* and *C. rodgersii*. Data are for 4,214 individual 5 m^2 quadrats pooled across all eastern Tasmanian sites surveyed across both 2001/02 and 2016/17.

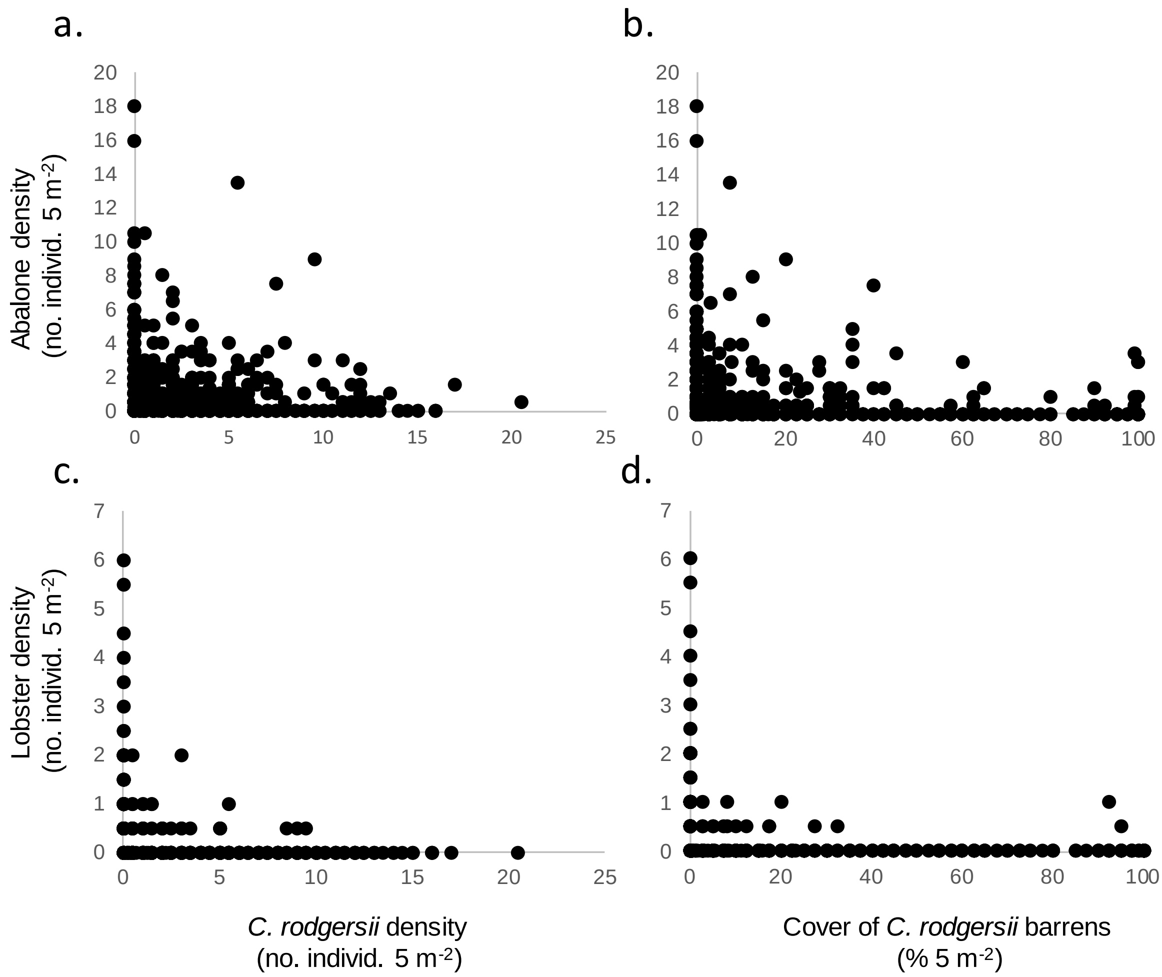

Figure 9. Relationships between black-lipped abalone (*Haliotis rubra*) and *Centrostephanus rodgersii* (a.), plus barrens habitat (b.); Southern rock lobster (*Jasus edwardsii*) and *Centrostephanus rodgersii* (c.), plus barrens habitat (d.) at a scale of 5 m^2. Data are for 4,214 individual 5 m^2 quadrats pooled across all eastern Tasmanian sites surveyed across both 2001/02 and 2016/17.

Change in macroalgal communities

Spatial trends in the macroalgae revealed clear separation of communities between sites 1-9 and sites 10-13 in nMDS space, which were broadly consistent through time (Fig. 11a). Macroalgal communities present at Sites 1-9 overlapped with high densities of *C. rodgersii*, whereas *C. rodgersii* was rare amongst macroalgal communities found at Sites 10-13 (Fig. 11a). Barrens cover increased across sites where the kelp *Ecklonia radiata* was a major contributor to the macroalgal community (see vector diagram inset, Fig. 11a). Conversely, *C. rodgersii* and associated barrens were less common among the macroalgae of *Durvillea potatorum*, *Macrocystis pyrifera*, *Lessonia corrugata, Phyllospora comosa* and red algae, which all dominated macroalgal communities across site 10-13 (Fig. 11a inset). Permutational multivariate analysis of variance revealed significant effects of Time and Site on macroalgal communities and a marginally non-significant interaction between Time and Site (Table 9a; see SIMPER results in Appendix VI for contributions of specific macroalgal taxa to community differences through time).

Individual macroalgal taxa showed variable responses through time, with species such as the dominant *Ecklonia radiata* and *Phyllospora comosa* showing slight increases in percentage cover through time of 16% and 13% respectively, while others such as kelps *Lessonia corrugata* and *Macrocystsis pyrifera* declined by more than 40% (Table 6). Overall, macroalgal richness showed significant decline at Site 4 (Bicheno) and slight but non-significant decline through time at 10 of the other 12 sites (Fig. 11b; see Table 9b for patterns of significance). Macroalgal richness also showed significant variability among sites (Table 9b) with a general increase in macroalgal richness from north to south, but with the northernmost site of Eddystone Point (Site 1) showing unusually high macroalgal richness (Fig. 11b).

Estimated change in *Centrostephanu*s population size and biomass

Interpolating site, time and depth specific urchin density by available reef area within the depth range of 4 to 40 m spanning eastern Tasmanian sites 1-9 (Table 10a), the population of *C. rodgersii* is estimated to have increased from 11.2 million individuals in 2001/02 to 18.1 million in 2016/17 (Table 10b-c) or a 60% increase over the total 15 year period. This equates to an average increase of ~460,000 emergent urchins per annum.

Scaling by reef area within the 4 to 18 m depth range only, where density information was directly assessed by divers, the population of *C. rodgersii* spanning sites 1-9 increased from 6.7 million in 2001/02 to 9.9 million in 2016/17 (Table 10b,c) or a 48% increase over the total 15 year period. This equates to an average increase of ~210,000 emergent urchins per annum.

Multiplying urchin abundance by the mean individual wet weight by site for each period, the total biomass of *C. rodgersii* in the depth range of 4 to 40 m for eastern Tasmanian sites 1-9 is estimated to have increased from ~3,082 tonnes in 2001/02 to ~5,526 tonnes in 2016/17 (Table 11b-c). Restricting estimates to the 4 to 18 m depth range for the same region, the biomass of *C. rodgersii* across reef spanning sites 1 to 9 is estimated to have increased from ~1,840 to ~3,017 tonnes. This equates to an increase in biomass from 2001/02 to 2016/17 by ~79% and ~64% for the 4-40 m and 4-18 m depth ranges respectively over the total 15 year period. Average annual increase in tonnage was approximately 80 and 170 tonnes respectively.

Table 6. Summary of change in density of sea urchins and cover of 15 macroalgal taxa (ranked in decreasing occurrence) in eastern Tasmania, averaged across all sites (1-13) as assessed by SCUBA divers, from 2001/02 to 2016/17. Data is mean density per m^2 for urchins (top-two rows) and mean percent cover for barrens and macroalgae using sub-sites as replicates, n=39. "Difference" is the 2016/17 value minus 2001/02; "Percent change" is the "Difference" divided by 2001/02 value multiplied by 100.

	Mean			Percent
Taxa	2001/02	2016/17	Difference	change
Centrostephanus rodgersii	0.104	0.182	0.078	+75%
Heliocidaris erythrogramma	0.124	0.054	-0.070	-56%
Barrens	1.59	6.31	4.72	+297%
Phyllospora comosa	29.43	33.24	3.81	+13%
Ecklonia radiata	28.84	33.33	4.49	+16%
Rhodophyta (all species pooled)	19.00	20.57	1.58	+8%
Caulerpa flexilis	3.30	2.13	-1.17	-35%
Lessonia corrugata	2.82	1.68	-1.14	-41%
Carpoglossum	2.20	3.25	1.05	+48%
Durvillea potatorum	2.16	2.12	-0.04	-2%
Acrocarpia paniculata	1.14	1.57	0.43	+38%
Halopteris paniculata	0.84	1.99	1.14	+136%
Zonaria sp.	0.79	1.76	0.97	+123%
Cystophora sp.	0.73	1.28	0.55	+75%
Sargassum sp.	0.67	1.43	0.76	+114%
Xiphophora	0.65	0.57	-0.09	-13%
Carpomitra costata	0.59	0.72	0.13	+22%
Macrocystis pyrifera	0.41	0.24	-0.17	-42%

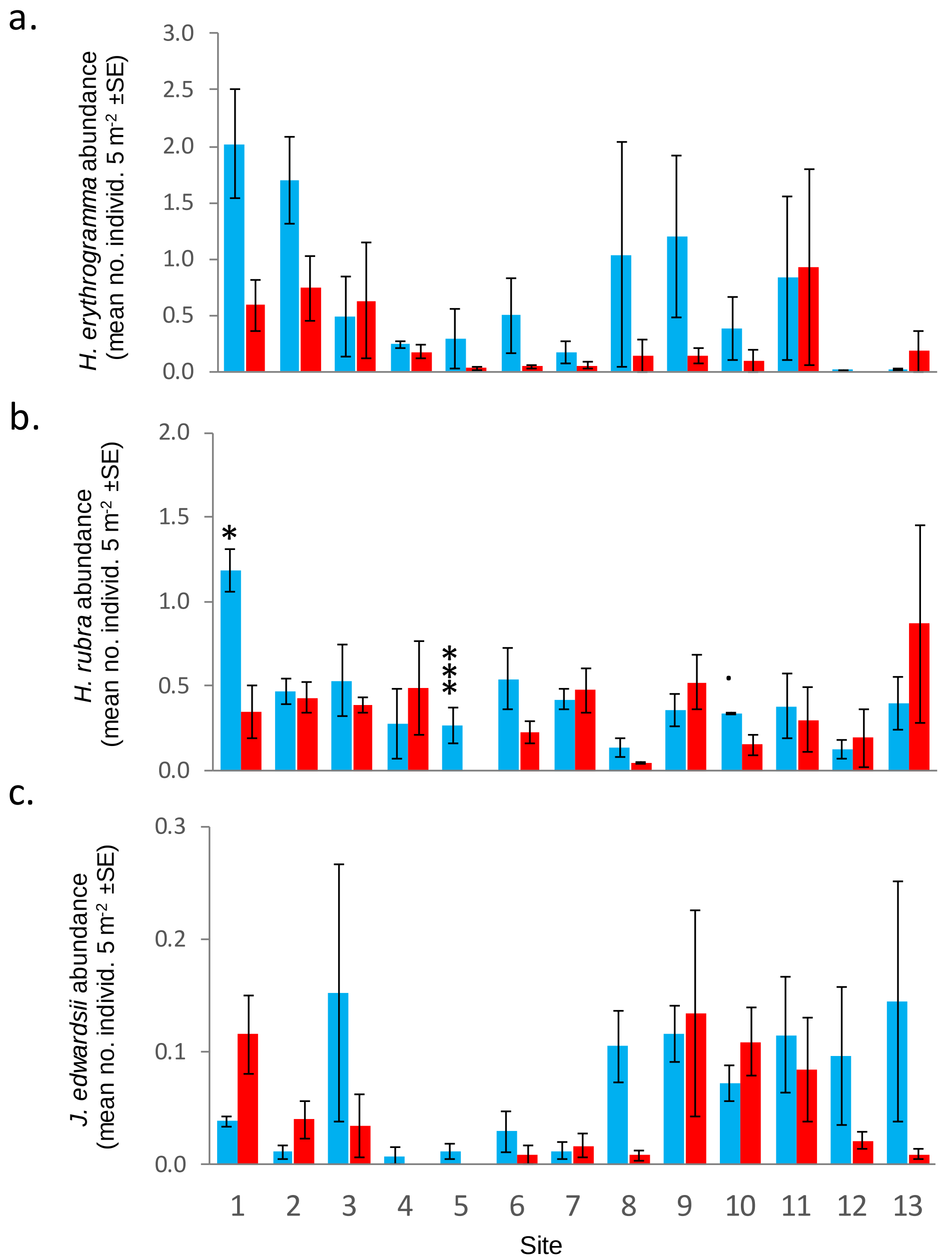

Figure 10. Spatial and temporal patterns in (a.) native sea urchin (*H. erythrogramma*), (b.) blacklip abalone (*Haliotis rubra*), and (c.) southern rock lobster (*Jasus edwardsii*) across eastern Tasmania in 2001/02 (blue) and 2016/17 (red) sampling periods. Means and standard errors for each site were generated from n=3 sub-sites, with sub-site values generated from the mean of n=4 transects within each sub-site. Sites are arranged from north to south with the northernmost site of Eddystone Point (1) to the southernmost site of Recherche Bay (13). For b., the significant "Time by Site" effect (see Table 7b) is partitioned across sites, with significant time effects for particular sites highlighted by asterisks, significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

Table 7. Analysis of variance table for 2-factor ANOVA testing the effects of "Time", i.e. fixed effect of 2001/02 versus 2016/17; and "Site" (i.e. random effect), plus the interactive term of "Time" by "Site" on the density of commercially fished reef invertebrates (a.) native sea urchin (*Heliocidaris erythrogramma*), (b) black-lip abalone (*Haliotis rubra*), (c.) southern rock lobster (*Jasus edwardsii*). Note to meet the assumption of homogeneity of variances the abundance of commercial invertebrates, estimated as density of individuals per 5 m^{-2}, a required log transformation, i.e. log(*Y*+0.001). Density and cover estimates at the site level were based on means of n=3 sub-sites, with sub-site estimates themselves generated from the mean of n=4 transects. Tests highlighted in bold indicate significance at the α=0.05 level, significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

a. *Heliocidaris erytrhrogramma*

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1,12**	**21.1**	**21.12**	**16.03**	**0.0018****
Site	**12,52**	**209.6**	**17.46**	**2.73**	**<0.001****
Time*Site	12,52	15.8	1.32	0.21	0.99
Residuals	52	332.6	6.39		

b. *Haliotis rubra*

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	1,12	10.98	10.977	3.12	0.103
Site	**12,52**	**72.89**	**6.074**	**7.465**	**<0.0001*****
Time*Site	**12,52**	**42.25**	**3.521**	**4.327**	**<0.0001*****
Residuals	52	173.2	3.33		

c. *Jasus edwardsii*

	Df of F-test	Sum Sq	Mean Sq	F value	Pr(>F)
Time	1,12	11.90	11.90	4.34	0.06.
Site	**12,52**	**122.50**	**10.21**	**5.70**	**<0.0001*****
Time*Site	12,52	32.91	2.74	1.53	0.1432
Residuals	52	93.16	1.79		

Table 8. Linear regression of (a.) *Haliotis rubra*, (b.) *Jasus edwardsii*, and *Heliocidaris erythrogramma* abundance against abiotic and biotic predictor variables for eastern Tasmania. Data is that assessed *in situ* by divers and at the 5 m^2 quadrat scale for all quadrats, n= 3200 quadrat-level estimates, across all eastern Tasmanian sites for both 2001/02 and 2016/17 time periods. Metrics have not been normalised and significant effects highlighted in bold, significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

a. *Haliotis rubra* abundance [transformation= log(Y + 0.001]
(Total response variance= 9.69; Proportion of variance explained by model: 5.22%)

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)		effect	% model explained
Time	**1**	**291.90**	**291.87**	**31.64**	**<0.001**	***	**negative**	**15.64%**
Site	1	15.70	15.74	1.71	0.192		negative	3.50%
Subsite	**1**	**458.60**	**458.63**	**49.72**	**<0.001**	***	**negative**	**27.08%**
Transect	1	5.30	5.33	0.58	0.447		negative	0.39%
Centrostephanus	1	25.90	25.87	2.80	0.094	.	positive	6.44%
Barren	**1**	**201.60**	**201.60**	**21.86**	**<0.001**	***	**negative**	**7.61%**
Heliocidaris	**1**	**44.70**	**44.72**	**4.85**	**0.028**	*	**positive**	**4.88%**
Jasus	**1**	**38.50**	**38.52**	**4.18**	**0.041**	*	**negative**	**2.14%**
Depth	**1**	**214.80**	**214.84**	**23.29**	**<0.001**	***	**negative**	**11.20%**
Ecklonia	**1**	**155.80**	**155.78**	**16.89**	**<0.001**	***	**negative**	**6.90%**
Phyllospora	1	18.4	18.39	1.9939	0.158		positive	4.56%
Flat rock	**1**	**103.3**	**103.26**	**11.1946**	**<0.001**	***	**negative**	**5.05%**
Large boulders	**1**	**39.4**	**39.43**	**4.2741**	**<0.001**	*	**positive**	**1.11%**
Small boulders	1	2.9	2.86	0.31	0.578		positive	3.50%
Residuals	3185	29379.6	9.22					

b. *Jasus edwardsii* abundance [transformation= log(Y + 0.001]
(Total response variance= 2.53; Proportion of variance explained by model: 3.57%)

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)		effect	% model explained
Time	**1**	**26.10**	**26.10**	**10.63**	**0.01**	**	**negative**	**7.65%**
Site	**1**	**42.70**	**42.66**	**17.39**	**<0.001**	***	**positive**	**12.05%**
Subsite	1	4.80	4.75	1.94	0.164		negative	1.19%
Transect	**1**	**11.50**	**11.51**	**4.69**	**0.030**	*	**positive**	**2.97%**
Centrostephanus	1	1.20	1.16	0.47	0.491		negative	4.11%
Barren	1	0.00	0.03	0.01	0.918		negative	1.85%
Heliocidaris	**1**	**51.00**	**51.04**	**20.80**	**<0.001**	***	**positive**	**11.38%**
Haliotis	1	1.70	1.69	0.69	0.407		negative	0.49%
Depth	1	0.90	0.90	0.37	0.545		negative	1.39%
Ecklonia	**1**	**33.90**	**33.88**	**13.81**	**<0.001**	***	**positive**	**3.42%**
Phyllospora	**1**	**11.70**	**11.66**	**4.75**	**0.029**	*	**negative**	**9.96%**
Flat rock	**1**	**72.70**	**72.69**	**29.62**	**<0.001**	***	**negative**	**17.93%**
Large boulders	**1**	**11.20**	**11.19**	**4.56**	**0.033**	*	**positive**	**18.11%**
Small boulders	**1**	**19.90**	**19.92**	**8.12**	**0.004**	**	**positive**	**7.50%**
Residuals	3185	7815.3	2.45					

Table 8. Continued... Linear regression of (c.) *Heliocidaris erythrogramma* abundance against abiotic and biotic predictor variables for eastern Tasmania.

c. *Heliocidaris erythrogramma* abundance [transformation= log(Y + 0.001]
(Total response variance= 9.095; Proportion of variance explained by model: 18.34%)

Source	Df	Sum Sq	Mean Sq	F value	Pr(>F)		effect	% model explained
Time	**1**	**298.40**	**298.37**	**39.19**	**<0.001**	***	**negative**	**6.26%**
Site	**1**	**866.40**	**866.35**	**113.81**	**<0.001**	***	**negative**	**15.30%**
Subsite	**1**	**165.80**	**165.82**	**21.78**	**<0.001**	***	**negative**	**2.92%**
Transect	1	3.70	3.70	0.49	0.486		negative	0.34%
Centrostephanus	**1**	**1551.80**	**1551.79**	**203.85**	**<0.001**	***	**positive**	**29.75%**
Barren	**1**	**277.60**	**277.59**	**36.46**	**<0.001**	***	**positive**	**7.20%**
Haliotis	**1**	**56.10**	**56.12**	**7.37**	**0.007**	**	**positive**	**1.73%**
Jasus	**1**	**57.30**	**57.31**	**7.53**	**0.006**	**	**positive**	**0.49%**
Depth	**1**	**91.60**	**91.57**	**12.03**	**<0.001**	***	**negative**	**1.37%**
Ecklonia	**1**	**32.80**	**32.77**	**4.30**	**0.038**	*	**positive**	**1.66%**
Phyllospora	**1**	**435.20**	**435.21**	**57.17**	**<0.001**	***	**negative**	**6.58%**
Flat rock	**1**	**719.80**	**719.81**	**94.56**	**<0.001**	***	**negative**	**11.74%**
Large boulders	**1**	**78.70**	**78.73**	**10.34**	**<0.01**	**	**positive**	**5.59%**
Small boulders	**1**	**214.90**	**214.86**	**28.22**	**<0.001**	***	**positive**	**9.08%**
Residuals	3185	24245.9	7.61					

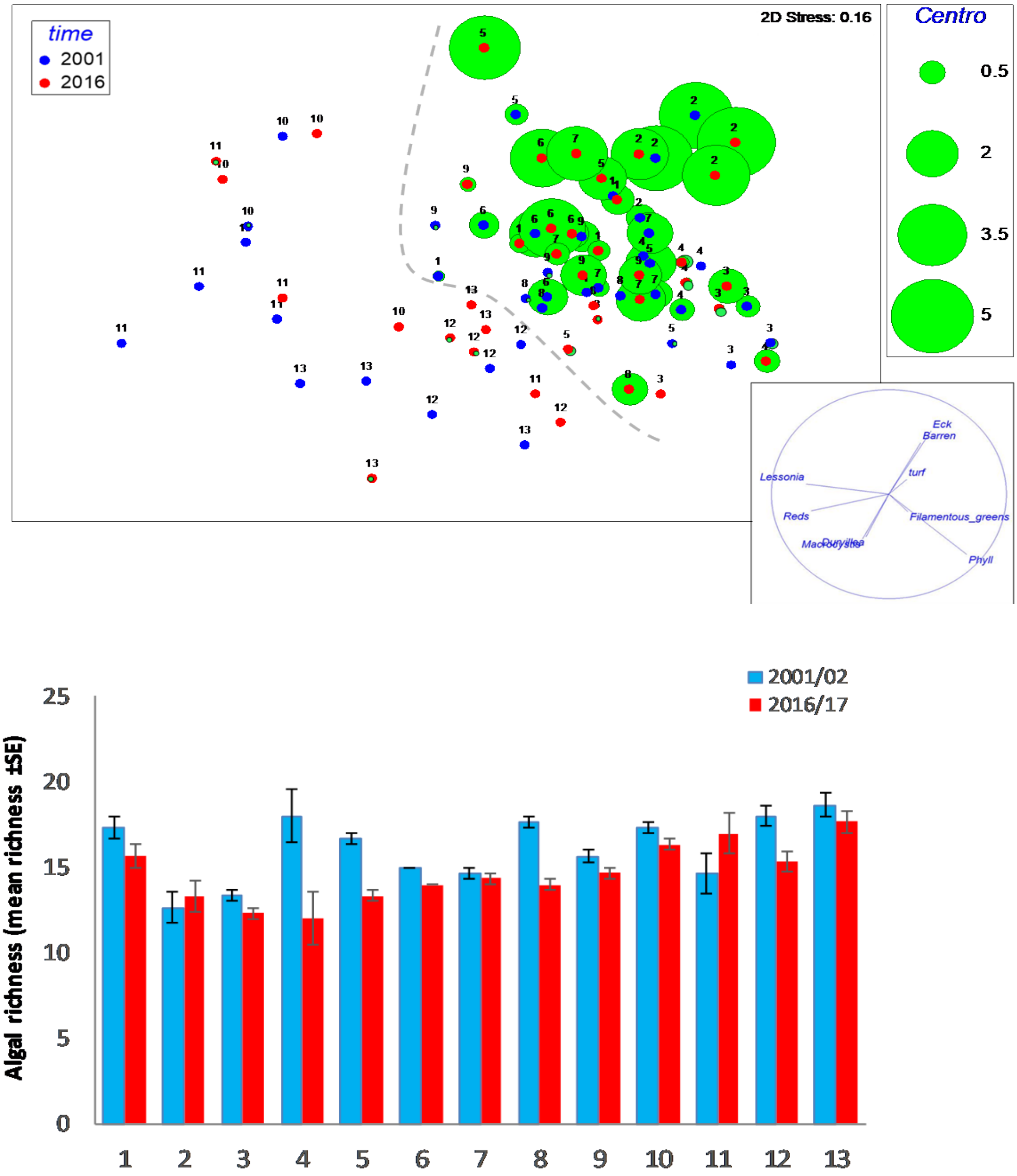

Figure 11. (a.) Non-metric multidimensional scale (MDS) of algal communities present at each of 3 sub-sites within each of the 13 sites across eastern Tasmania sampling during 2001/02 and 2016/17. MDS based on sqrt transformation and Bray Curtis similarity matrix. Overlaid bubbles correspond to density of *C. rodgersii* (i.e. no. individuals 5 m^{-2}). Dashed grey line approximates distinct community shift between sites 1-9 (RHS of dashed line) and sites 10-13 (LHS of dashed line). Vector diagram shows influence of most important algal types on community patterns (note that “Eck” = *Ecklonia radiata*; “Phyll”= *Phyllospora comosa*; “Durvillea” = *D. potatorum*; “Macrocystis” = *M. pyrifera*). Note that percentage of barrens cover “Barren” is included as a covariate to the vector diagram, however was not included in derivation of algal community patterns. (b.) Spatial and temporal patterns in algal species richness across eastern Tasmania as assessed in 2001/02 and 2016/17; significance codes are ‘***’ <0.001, ‘**’ <0.01, ‘*’ <0.05, ‘.’ 0.1.

Table 9. Analysis of variance of algal communities. (a.) PERMANOVA table of results testing effects of time (fixed) and site (random) on macroalgal community response. Resemblance Matrix based on Bray-Curtis Similarity, Square root transformation, Type III (partial), fixed effects sum to zero for mixed terms. 9999 unrestricted permutations of raw data; Monte Carlo (MC) P values were used. (b.) 2-way ANOVA testing response of algal richness (transformation=log(*Y*)) by time and site. Tests highlighted in bold indicate significance at the α=0.05 level, significance codes are '***' <0.001, '**' <0.01, '*' <0.05, '.' 0.1.

a.

		Df	SS	MS	P(perm)	Unique perms	P(MC)
Time	**1**	**1695.3**	**1695.3**	**4.7006**	**0.0038**	**9944**	**0.0026**
Site	**12**	**27311**	**2275.9**	**8.7207**	**0.0001**	**9847**	**0.0001**
Time*Site	12	4328	360.66	1.382	0.0501	9849	0.0535
residuals	52	13571	260.98				
total	77	46905					

b.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Time	**1**	**0.2114**	**0.21143**	**6.70**	**0.023 ***
Site	**12**	**0.7227**	**0.06022**	**3.895**	**<0.0001 *****
Time*Site	**12**	**0.3788**	**0.03156**	**2.041**	**0.039 ***
Residuals	52	0.8041	0.01546		

Table 10. Reef area in hectares (a.), and *C. rodgersii* abundance by site and depth strata for eastern Tasmania (sites 1-9) in (b.) 2001/02 and (c.) 2016/17. Abundances were calculated by multiplying reef area by density of *C. rodgersii* for each depth strata at each site. Reef area derived from Seamap Australia (http://seamapaustralia.org). Note that abundances deeper than 18 m, as shown in grey (b.-c.), have been extrapolated using the exponential decay of the abundance observed in the 16-18 m depth strata at each site (see Appendix VII for derivation of exponential decay function as observed in deep water at St. Helens). Means by depth strata and by site plus overall increases are emboldened as per previous.

a. Reef area (ha)

Depth strata (m)

	Site	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	4-18	4-40
1	Eddystone	138	180	216	272	266	220	163	135	115	109	110	75	67	64	52	53	48	5	1456	2290
2	St Helens	61	73	90	98	96	99	96	78	86	87	78	74	58	43	35	19	12	10	613	1194
3	Four Mile	106	71	47	63	57	58	55	102	105	77	64	62	43	25	22	19	18	4	455	996
4	Bicheno	186	197	250	273	290	279	281	312	267	264	130	68	62	55	44	26	13	10	1756	3006
5	Wineglass	42	58	79	89	102	99	103	101	106	106	100	96	114	132	112	103	107	85	573	1733
6	Schouten	35	33	42	42	38	36	34	37	40	38	38	50	81	74	149	106	51	46	260	970
7	Maria Is.	91	92	89	86	83	78	77	84	84	72	67	69	78	85	111	126	204	192	596	1766
8	Forestier	76	90	88	86	74	75	75	75	77	78	62	62	66	65	60	49	37	23	563	1218
9	Fortescue	59	66	58	55	58	59	56	56	56	57	62	67	71	78	74	78	64	54	412	1130
	Totals	**795**	**860**	**959**	**1,064**	**1,063**	**1,002**	**941**	**981**	**936**	**888**	**711**	**623**	**640**	**620**	**659**	**579**	**552**	**429**	**6,685**	**14,304**

b. *C. rodgersii* density 2001/02

	Site	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	4-18	4-40
1	Eddystone	0	0	216,241	419,705	49,966	45,012	10,201	6,992	4,900	3,856	3,218	1,824	1,343	1,057	714	604	446	37	741,126	766,118
2	St Helens	0	385,707	752,605	636,415	511,505	523,531	548,475	370,284	337,231	282,638	209,444	163,322	106,992	65,002	43,714	19,824	10,222	7,406	3,358,23	4,974,319
3	Four Mile	0	0	4,074	12,570	16,682	31,039	13,659	21,139	17,903	10,895	7,495	6,012	3,399	1,670	1,215	849	666	122	78,023	149,388
4	Bicheno	0	0	83,359	0	0	114,839	241,197	221,229	156,754	127,907	51,935	22,547	16,971	12,418	8,219	4,067	1,647	1,010	439,394	1,064,098
5	Wineglass	0	0	39,718	152,050	123,318	59,737	116,018	93,907	81,361	67,447	52,613	41,704	41,082	39,221	27,478	20,949	17,954	11,791	490,842	986,351
6	Schouten	7,843	9,573	262,206	120,949	40,859	96,285	133,932	120,161	107,418	85,246	70,639	75,324	102,033	76,795	128,540	75,271	29,783	22,536	671,648	1,565,396
7	Maria Is.	15,141	18,371	44,318	197,370	203,289	131,439	77,398	69,446	57,343	40,659	31,419	26,580	24,796	22,410	24,261	22,735	30,459	23,757	687,326	1,061,194
8	Forestier	6,931	8,149	0	9,506	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24,586	24,586
9	Fortescue	9,882	8,304	53,440	19,568	15,735	22,135	84,083	69,465	57,505	48,122	43,433	38,980	34,105	31,120	24,412	21,251	14,302	9,943	213,147	605,785
		39,797	**430,104**	**1,455,961**	**1,568,135**	**961,354**	**1,024,017**	**1,224,963**	**972,624**	**820,415**	**666,772**	**470,197**	**376,294**	**330,722**	**249,694**	**258,554**	**165,550**	**105,478**	**76,603**	**6,704,331**	**11,197,235**

c. *C. rodgersii* density 2016/17

	Site	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	4-18	4-40
1	Eddystone		180,412	262,578	206,914	183,210	203,959	28,803	19,743	13,836	10,888	9,086	5,150	3,793	2,984	2,017	1,704	1,259	106	1,065,87	1,136,441
2	St Helens	20,360	178,814	677,431	669,808	626,779	620,422	440,521	297,403	270,856	227,008	168,220	131,176	85,933	52,208	35,110	15,922	8,210	5,948	3,234,13	4,532,131
3	Four Mile	0	0	2,231	10,836	9,453	42,624	81,952	126,834	107,416	65,372	44,967	36,070	20,394	10,023	7,293	5,095	3,994	731	147,096	575,285
4	Bicheno	0	13,135	216,732	263,990	21,508	75,465	291,099	267,000	189,186	154,371	62,681	27,212	20,482	14,988	9,919	4,909	1,988	1,219	881,930	1,635,884
5	Wineglass		66,787	233,013	187,401	223,885	156,553	717,765	580,972	503,352	417,274	325,502	258,011	254,161	242,649	169,999	129,605	111,075	72,949	1,585,40	4,650,952
6	Schouten	0	48,825	195,116	139,448	145,242	120,875	187,278	168,022	150,203	119,200	98,775	105,327	142,674	107,383	179,738	105,252	41,645	31,512	836,784	2,086,517
7	Maria Is.	18,170	84,790	221,592	477,275	192,061	238,113	111,260	99,829	82,431	58,448	45,165	38,209	35,645	32,214	34,876	32,682	43,785	34,151	1,343,26	1,880,696
8	Forestier	22,872	21,092	7,674	16,559	33,706	57,960	19,823	16,359	13,895	11,633	7,617	6,337	5,547	4,508	3,434	2,336	1,465	754	179,688	253,572
9	Fortescue	19,764	83,910	15,696	113,659	89,745	167,758	154,153	127,352	105,426	88,224	79,627	71,464	62,527	57,053	44,755	38,959	26,220	18,230	644,685	1,364,520
		81,166	**677,765**	**1,832,065**	**2,085,890**	**1,525,589**	**1,683,729**	**2,032,655**	**1,703,514**	**1,436,601**	**1,152,418**	**841,640**	**678,956**	**631,156**	**524,009**	**487,140**	**336,464**	**239,641**	**165,600**	**1,703,515**	**18,115,997**
																			Increase	**3,214,52**	**6,918,762**
																			Increase factor	**1.48**	**1.62**
																			% Increase	**47.95**	**61.79**

Table 11. Biomass of *C. rodgersii* by site and depth strata for eastern Tasmania (sites 1-9) in (a.) 2001/02, and (b.) 2016/17. Data is tonnes (1,000' kg) per hectare. Asterisks indicates where mean weights (*wt.* in kg) of n=300 individual *C. rodgersii* were obtained in either 2005 or 2015/16 and multiplied by 2001/02 and 2016/17 densities respectively (weight data, Ling & Keane *unpub. data*). Where weights were not measured at a particular site, mean weight of the nearest neighbouring site was assigned. Note that biomass deeper than 18 m, as shown in grey (a.-b.), has been extrapolated using the exponential decay of the abundance observed in the 16-18 m depth strata at each site (see Appendix VII for derivation of exponential decay function as observed in deep water at St. Helens). Means by depth strata and by site plus overall increases are shown as per previous.

a. 2001/02

			Depth strata (m)																	Totals	
	Site	*Wt.* (kg)	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	4-18	4-40
1	Eddystone	0.27	0	0	59	114	14	12	3	2	1	1	1	0	0	0	0	0	0	0	201	208
2	St Helens*	0.27	0	105	205	173	139	142	149	101	92	77	57	44	29	18	12	5	3	2	913	1,352
3	Four Mile	0.27	0	0	1	3	5	8	4	6	5	3	2	2	1	0	0	0	0	0	21	41
4	Bicheno	0.28	0	0	24	0	0	33	69	64	45	37	15	6	5	4	2	1	0	0	127	307
5	Wineglass*	0.28	0	0	11	44	36	17	33	27	23	19	15	12	12	11	8	6	5	3	141	284
6	Schouten Is.	0.28	2	3	76	35	12	28	39	35	31	25	20	22	29	22	37	22	9	6	193	451
7	Maria Is.*	0.26	4	5	12	53	55	35	21	19	15	11	8	7	7	6	7	6	8	6	185	285
8	Forestier	0.24	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	6
9	Fortescue*	0.24	2	2	13	5	4	5	21	17	14	12	11	10	8	8	6	5	4	2	52	148
			10	**117**	**401**	**429**	**263**	**282**	**338**	**269**	**227**	**184**	**129**	**103**	**92**	**69**	**72**	**46**	**29**	**21**	**1,840**	**3,082**

b. 2016/17

	Site	*Wt.* (kg)	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	4-18	4-40
1	Eddystone	0.29		53	78	61	54	60	9	6	4	3	3	2	1	1	1	1	0	0	316	337
2	St Helens*	0.29	6	53	201	198	186	184	131	88	80	67	50	39	25	15	10	5	2	2	958	1,343
3	Four Mile	0.29	0	0	1	3	3	13	24	38	32	19	13	11	6	3	2	2	1	0	44	170
4	Bicheno	0.31	0	4	68	83	7	24	91	84	59	48	20	9	6	5	3	2	1	0	276	512
5	Wineglass*	0.31		21	73	59	70	49	225	182	158	131	102	81	80	76	53	41	35	23	496	1,456
6	Schouten Is.	0.31	0	15	61	44	45	38	59	53	47	37	31	33	45	34	56	33	13	10	262	653
7	Maria Is.*	0.33	6	28	74	158	64	79	37	33	27	19	15	13	12	11	12	11	15	11	446	624
8	Forestier	0.26	6	6	2	4	9	15	5	4	4	3	2	2	1	1	1	1	0	0	48	67
9	Fortescue*	0.26	5	22	4	30	24	45	41	34	28	23	21	19	17	15	12	10	7	5	172	363
	Totals		**23**	**203**	**561**	**641**	**462**	**506**	**621**	**521**	**439**	**352**	**256**	**207**	**193**	**161**	**150**	**104**	**74**	**51**	**3,017**	**5,526**

DISCUSSION

Spatial and temporal change in *Centrostephanus* density & barrens cover

The re-survey of dive and towed-video transects across eastern Tasmania revealed clear increase in the abundance of *C. rodgersii* and even greater increase in the coverage of associated urchin barrens over the period 2001/02 to 2016/17. For dive transects where urchin abundance and barrens cover were co-recorded within the same quadrats over the depth range of 4 to 18 m depth, the average density of urchins was observed to increase from 0.104 to 0.182 individuals m^{-2}, an increase of ~75%; while the coverage of urchin barrens increased from 1.59 to 6.31%, an increase of ~400%, thus representing a rate of increase of barrens more than twice that of the increase in urchin abundance.

The disproportionately large increase in barrens relative to increase in urchin abundance is consistent with the non-linear 'tipping-point' behaviour of urchin grazing systems globally, whereby gradual increase in urchin populations within kelp beds can suddenly lead to kelp bed collapse when a critical threshold in grazing capacity is exceeded (Ling et al. 2015a). Notably, during the 2001/02 baseline survey, many of the now overgrazed reefs occurred as largely intact kelp beds but contained urchins occurring beneath closed kelp canopies (S. Ling *pers. obs.*). Given that *Centrostephanus* is long-lived (individual longevity >20 years, (Ling et al. 2009b)), population increase over the recent 15 year period appears to have compounded with latent grazing capacity present in kelp beds during the early 2000's and led to local exceedance of the overgrazing tipping-point across an increasingly broad extent of the eastern Tasmanian coastline (Fig. 2b, Fig. 6&7).

The increase in *C. rodgersii* has however not occurred evenly across eastern Tasmania coastline. The greatest variability in *C. rodgersii* and barrens occurred from site to site (i.e. at scale of ~20 km), with relatively little variation in urchin abundance and barrens cover occurring at finer kilometre (sub-site) or sub-kilometre (transect) scales. In southern Tasmania, i.e. sites 10-13 in the Bruny Bioregion, *C. rodgersii* remains rare, occurring at densities less than ~20 individuals per hectare. Although not observed as part of the formal resurvey, incipient *C. rodgersii* barrens have now been reported as far south as Recherche Bay (B. Denny, *pers. obs.* 2015). This southernmost observation of an incipient *C. rodgersii* barren is notable and forewarns of possible increase in frequency of incipient barrens in the Bruny Bioregion, which could ultimately threaten rocky reefs in this region, as is apparent further north in eastern Tasmania.

Notably, the only detectable decline in urchin abundance at any site was observed in shallow water at St Helens (Appendix IIIa), where a developing commercial fishery has harvested in excess of 350 tonnes since 2009 (J. Keane, *unpub. data* - FRDC project 2013/026). In waters of 6 – 10 m depth, mean abundance of urchins declined from 0.7 to 0.3 m^{-2} from 2001/02 to 2016/17 (Appendix IIIa). This result indicates that a sustained commercial harvest fishery could have a significant negative impact on urchin populations in diver-harvestable depths. Of further note, commercial fishing effort has progressively moved to reefs deeper than 10 m in recent years, with some fishers now opting to use nitrox gas mixes to facilitate the effective harvest of *C. rodgersii* at such depths (J. Keane *unpub. data* - FRDC project no. 2013/026).

Change by depth and reef type

In eastern Tasmania, the greatest increase in *C. rodgersii* density and barrens cover was observed to occur on reef dominated by large boulders (>1 to 5 m in diam.), particularly between 18 and 30 m depth. This observation is consistent with mechanistic understanding of barrens formation gained from experiments in NSW (Andrew 1993), plus monitoring of patches as part of natural experiments in eastern Tasmania (Ling 2008; Flukes et al 2012; Johnson et al. 2013). That is, *C. rodgersii* barrens are observed to first appear as incipient barrens patches (1-10s m^2) typically centred on high-relief boulder reef where predation risk is relatively low (Ling and Johnson 2012). Notably, the increase in *C. rodgersii* abundance not only appeared greater on boulder reef, but also appeared greatest on boulder reef already occurring as incipient barrens. That is, the suggested mode that barrens form as a result of coalescence of smaller scale incipient barrens patches (Flukes et al. 2012) appears supported based on longer-term observations of patch coalescence as urchins become more numerous within patches and as individual urchins grow in size, dually increasing grazing capacity within the incipient patch (S. Ling, *unpub. data*).

As consistently observed over the 2001/02 to 2016/17 period, the depth-distribution of *C. rodgersii* barrens in Tasmania is generally deeper than that observed within the native range of *C. rodgersii* in NSW (Johnson et al. 2005; Perkins et al. 2015). However, over the past 15 years barrens appear to now also be developing on reefs shallower than 10 m deep (see Fig. 3b & Fig. 7), as is commonly observable across the NSW coastline (Perkins et al. 2015). While the shallow water extent of *C. rodgersii* barrens in Tasmania appears constrained by the periodic whiplash-action of large kelps under the action of heavy ocean swell (Ling and Johnson 2009), sustained grazing pressure on the shallow margins of kelp beds plus dieback of mature kelps, appears poised to favour shallow-water advance of *C. rodgersii* and associated barrens. Notably, since 2012 individuals have been observed in sheltered waters <2 m depth and incipient barrens patches at 4 m depth in eastern Tasmania (Sites 2, 5, 8, 9), as per NSW (Authors, *pers. obs*.).

Predictions & observations of change

Based on the requirement of >12°C winter temperature for successful development of *C. rodgersii* larvae (Ling et al. 2008), predictions in late-2000's were that continued warming of eastern Tasmanian coastal waters would favour ongoing recruitment of the sea urchin (Ling et al. 2009b). This prediction appears well supported by the re-survey results, which show a sustained and ongoing increase of the *C. rodgersii* population in the now persistently warmer regime of water temperatures in eastern Tasmania (Ridgway 2007; Oliver et al. 2018). While the presence of *C. rodgersii* is of general interest as an indicator of ongoing regional warming, it is the occurrence of this urchin at high "barrens-forming" densities that is of major ecological consequence. As first projected during reporting of the baseline survey of *C. rodgersii* in Tasmania (Johnson et al. 2005), recent observations confirm that barrens expansion across eastern Tasmania could in time constitute half of all rocky reef from depths of ~4 m to the reef edge. That is recent trends of barrens expansion at St. Helens, Freycinet Peninsular and Maria Island (Sites 2, 5-7; Fig. 6) and experiences from the Kent Group (Johnson et al. 2005), plus large-scale patterns across NSW (Andrew and O'Neill 2000) suggest that an average level of 50% barrens could eventuate for eastern Tasmanian reefs in depth > 4 m.

Beyond clear increase in barrens cover, changes to the structure of kelp beds were also apparent between survey periods, with some species increasing in cover while some species showing decline. Notably, the kelp *Ecklonia radiata*, which, is an algal type heavily grazed by *C. rodgersii*, evidently increased in cover on reefs across eastern Tasmania. That is, while barrens cover increased, resulting in loss of areal extent of kelp beds, in the absence of grazing, kelp beds appeared to become thicker as indicated by overall increase in macroalgal cover. This seemingly counter-intuitive result is likely an ongoing response to widespread decline of the giant kelp *Macrocystis pyrifera* (Johnson et al. 2011), which previously formed dense-stands and outcompeted smaller kelps such as *E. radiata*. That is, *E. radiata* has been observed to become the dominant macroalga at several sites where remnant surface-canopies of giant kelp have recently collapsed (S. Ling, *pers. obs.*). As assessed by divers measuring percentage cover within the 5 m^{-2} quadrats on the seafloor, as opposed to aerial imagery, *M. pyrifera* was observed to decline by 42% across eastern Tasmania from 2001/02 to 2016/2017, with the kelp disappearing from 7 of the 10 sites where it was present during 2001/02.

Re-confirming findings of the baseline survey in 2001/02, negative relationships were observed between urchin barrens and blacklip abalone (*Haliotis rubra*) and southern rock lobster (*Jasus edwardsii*); with commercial quantities of both abalone and rock lobster not associated with high densities of *Centrostephanus* or extensive cover of urchin barrens. These results support experimental research demonstrating that barrens represent lost habitat for abalone (Johnson et al. 2005; Strain et al. 2013), native urchins (Strain and Johnson 2013) and lobsters (Johnson et al. 2013). Such lost habitat for commercial/ recreational fisheries will have the effect of displacing fishing effort to a diminishing area of available reef habitat, which will affect catch rates and in turn this leads to a lower total allowable catch (Haddon et al. 2002; Buxton et al. 2006).

Of further relevance to fishery dynamics and fisher behaviour, contrasting spatial scales of variability in abundance of fished invertebrates were observed. That is, lobsters and urchins (*H. erythrogramma* and *C. rodgersii)* varied most at the scale of sites (20 km scale), while Site was unimportant for abalone which varied most from sub-site to sub-site (~2 km) scale. Transects (~0.2 -0.5 km scale) explained negligible model variance for abalone, *H. erythrogramma* and *C. rodgersii* (<0.40% of model variance in all cases) but contributed a small (~3%) but significant amount to variance in lobster abundance.

Extension and Adoption

Results of this study assist with management planning for the control of *C. rodgersii* and associated barrens in Tasmania. In terms of integrated approaches of mitigation, the following measures have been enacted:

1. Ongoing subsidised development of a commercial harvest fishery (focused on shallow depths <15 m depth in the vicinity of kelp beds where roe quality and recovery is highest, Ling and Johnson 2009; J. Keane *unpub. data* - FRDC project 2013/026);

2. Diver-culling of *C. rodgersii* by abalone divers while they fish (Sanderson et al. 2016) and/ or systematic culling by the abalone industry on reefs containing incipient barrens (Tracey et al. 2015);

3. Catch reductions and rebuilding of lobster stocks within intact kelp beds to reduce risk of urchins building to the point of overgrazing (Ling et al. 2009a; Ling and Johnson 2012; Johnson et al. 2013).

4. Translocation of rock lobsters to the east coast to accelerate stock recovery targeting incipient barren areas identified through this study.

In addition to existing approaches, possible future approaches for upscaling mitigation include:

i. funded-culling of *C. rodgersii* on extensive barrens by commercial divers;

ii. diver-harvest of urchins from barrens for holding in cage and feeding to improve roe quality to the point that they're suitable for sale;

iii. recovery of extensive barrens via piping quicklime to the reef surface (e.g. Bernstein and Welsford 1982);

iv. enhancing local abundance of large eastern blue grouper (*Achoerodus viridis*) on extensive barrens given this specialist predator's high rates of *C. rodgersii* consumption[1];

v. automated culling of urchins using robotic technology.

To assess the effectiveness of current and novel mitigation methods, future surveys of urchin density and barren coverage would be required. Additionally, the effectiveness of fishing/ mitigation measures would benefit from fine-scale spatial mapping of effort via GPS and depth loggers and/ or mobile web-applications.

Conclusion

Since the first positive identification of an individual on the mainland coast of Tasmania at St. Helens in 1978, the population of *C. rodgersii* in eastern Tasmania has grown to an estimated 20 million individuals by 2017. Initial baselines surveys in the early 2000's identified the scope of potential threats of the urchin and its associated barrens to lucrative Tasmanian reef fisheries, while the recent resurvey in 2016/17 has confirmed ongoing population expansion and significant increase in unproductive barrens, which now constitutes 15% of reefs in the region from Eddystone Point to Tasman Island between 4-40 m. Furthermore, this report has contributed finer-scale information regarding the spatial distribution and rates of population increase for *C. rodgersii* in Tasmania to assist ongoing management responses.

In summary, *C. rodgersii* have increased in abundance and this had led to increase in barrens across eastern Tasmania. Research conducted over the past decade shows that effective management of the

[1] The eastern blue grouper has been observed to occur, albeit rarely, at St. Helens in eastern Tasmania (S. Ling/ T. Baulch, pers. obs.) and is highly susceptible to fishing. Recent work across NSW demonstrates high consumption of *C. rodgersii* by this wrasse species which is protected in NSW but not Tasmania (S. Ling, *unpub. data*). See also Bax et al. 2013 who explored managed translocation of eastern blue grouper to Tasmania

urchin problem requires proactive approaches due to the difficultly of removing sufficient urchins from barren grounds to allow kelp recovery once barrens are established at large-scales (Ling et al. 2009a; Johnson et al. 2013; Ling et al. 2015b). That is, given that '*an ounce of prevention is worth a ton of cure*', those reefs approaching the critical tipping-point in grazing capacity are logical targets for effective tactical intervention. Conversely, for reefs that have already collapsed to extensive barrens, a significant upscaling of yet to be trialed mitigation efforts will be required if their natural kelp bed cover and broader ecosystem is to be restored.

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APPENDICES

Appendix I. Algal species recorded by divers during transect surveys. Algae are listed from most to least common in terms of contribution to overall percentage cover on reefs across all 13 sites spanning eastern Tasmania.

Rank	Algal species/ taxonomic group
1	*Ecklonia radiata*
2	*Phyllospora comosa*
3	*Rhodophyta* (all red algal species pooled)
4	*Carpoglossum confluens*
5	*Caulerpa flexilis*
6	*Durvillea potatorum*
7	*Halopteris_paniculata*
8	*Zonaria sp.*
9	*Lessonia corrugata*
10	*Acrocarpia paniculata*
11	*Sargassum sp.*
12	*Cystophora sp.*
13	*Carpomitra costata*
14	*Xiphophora gladiata*
15	*Perithalia cordata*
16	*Macrocystis pyrifera*
17	*Caulerpa trifaria*
18	*Codium sp.*
19	*Ulva sp.*
20	*Sporochnus sp.*
21	*Caulerpa brownii*
22	Filamentous/ turf browns
23	*Cladophora feredayi*
24	*Codium pomoides*
25	*Chaetomorpha sp.*
26	*Seirococcus axillaris*
27	Filamentous greens
28	*Dictyopteris muelleri*
29	*Caulerpa hodgkinsoniae*
30	*Caulerpa scalpelliformis*
31	*Undaria pinnatifida*
32	Seagrass

Appendix II.

Figure. AII. Google Earth Map of Tasmania showing distribution of the east coast among sites 1-9 for purposes of calculating reef area from Seamap Australia data (http://seamapaustralia.org/).

Appendix III.

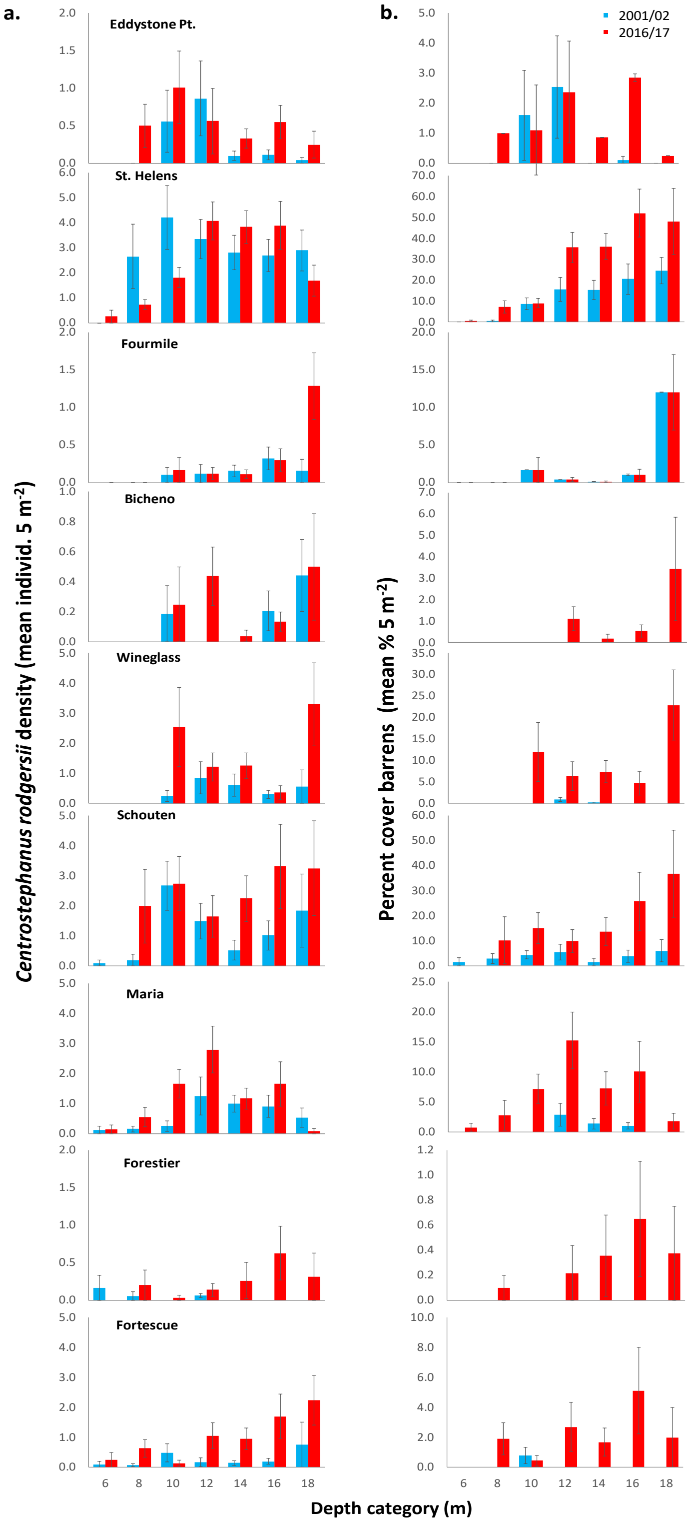

Figure. AIII. Spatial and temporal trends in (a.) *Centrostephanus rodgersii* abundance, and (b.) barrens cover across depth categories (4 to 18 m depth) within each site spanning sites 1-9 in eastern Tasmania where barrens have been recorded for 2001/02 (blue) and 2016/17 (red) time periods. Data are means derived from 5 m^2 quadrats assessed *in situ* by divers which have been pooled for all quadrats occurring within each 2 m depth category from 6 to 18 m. For details by sub-site within each site, see Appendices IV-V below.

Appendix IV. Spatial and temporal trends in *Centrostephanus rodgersii* density across depth categories as available within each site and sub-site spanning eastern Tasmania from 2001/02 to 2016/17 (4 to 18 m depth). Data are means derived from 5 m^2 quadrats assessed *in situ* by divers which have been pooled for all quadrats occurring within each 2 m depth category from 4 to 18 m; note that depth values represent the ceilings of each category. Totals for each period are shown as sub-table on RHS. Legends show categories of density or cover which refer to densities or cover greater than or equal to each category, i.e. category 0.25 ranges from ≥0.25 to <0.50.

Legend: *C. rodgersii* density (individ. 5 m^{-2})

0.00	0.1	0.25	0.50	0.75	1.00	2.50	5.00

		Period														Totals	
		2001/02 depth (m)							2016/17							2001/02	2016/17
Site	Subsite	6	8	10	12	14	16	18	6	8	10	12	14	16	18		
Eddystone	Georges Rocks		0.00	1.12	1.19	0.05	0.30	0.08		0.50	0.70	0.90	0.18	1.27	0.50	0.43	0.70
Eddystone	Purdon				0.00	0.21	0.09	0.00				0.00	0.54	0.21	0.00	0.12	0.29
Eddystone	Lighthouse		0.00	0.00	0.00	0.00	0.00	0.00			3.50		0.25	0.33	0.40	0.00	0.41
StHelens	Binalong	0.00	0.50	6.00	6.17	5.50	2.57	3.98		1.03	3.12	6.00	5.66	5.60	2.53	4.16	4.39
StHelens	St.Helens Point				0.04	0.86	0.65	0.00				2.47	2.08	2.00	0.00	0.60	1.98
StHelens	St. Helens Island		2.87	3.39	4.39	4.45	4.54		0.25	0.65	1.10	4.30	5.54	0.00		3.89	3.05
Fourmile	Falmouth		0.00	0.00	0.00	0.00	0.00		0.00	0.00		0.00	0.00	0.00		0.00	0.00
Fourmile	Ironhouse Pt				0.00	0.71	0.52	0.25			0.17	0.30	0.28	0.97	1.58	0.47	0.88
Fourmile	Saltwater Inlet			0.33	0.18	0.03	0.00	0.00				0.20	0.05	0.03	0.00	0.07	0.05
Bicheno	Porches						0.00						0.00	0.12		0.00	0.10
Bicheno	Governors		0.00	0.30	0.00	0.00	0.00	0.00			0.00	0.36	0.08	0.00	0.00	0.04	0.09
Bicheno	Cape Lodi			0.00	0.00	0.00	1.28	0.69			0.33	0.47	0.00	0.29	1.00	0.46	0.44
Wineglass	Boot Rock	0.00	0.00	0.00	0.00	0.09	0.00	0.00		0.00	0.06	0.20	0.00	0.00	0.00	0.02	0.07
Wineglass	Cape Tourville			0.00	2.25	1.63	0.88	1.50				0.00	0.95	0.50	5.25	1.32	1.23
Wineglass	Wineglass Bay			1.00	1.35	0.19	0.00	0.00			10.00	4.58	3.35	0.70	2.40	0.43	3.67
Schouten	Cape Baudin	0.00	0.00	2.75	3.38	0.50	3.00	2.50		2.50	6.21	1.70	3.17	2.78	1.58	2.07	3.30
Schouten	Cape Sonnerat	0.00	0.00	2.94	0.29	0.10	1.25	1.00	0.00	3.00	1.00	0.56	0.75	0.00		1.18	0.74
Schouten	Sarah-Anne Bay	0.25	1.00	1.50	2.00	0.92	0.00	0.00		0.00	0.17	3.75	3.33	4.42	5.50	0.52	3.04
Maria	Beaching Bay	0.00	0.00	0.00	0.00	0.35	0.44	0.25	0.00	0.00	0.67	4.00	0.00	0.04	0.00	0.29	0.46
Maria	Mistaken Cape	0.17	0.30	0.33	4.00	1.50	1.67		0.33	0.92	2.81	5.23	2.01	3.70	0.50	1.46	2.61
Maria	Bunker Bay	0.00	0.00	0.33	0.29	1.36	1.10	1.10	0.00	0.00	0.00	1.32	1.85	4.30	0.00	0.68	1.46
Forestier	Visscher Island	0.17	0.17	0.00	0.13	0.00	0.00	0.00	0.00	0.50	0.10	0.30	2.00	2.08	0.63	0.07	0.83
Forestier	High Yellow Bluff		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.01
Forestier	Sisters		0.00	0.00	0.04	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fortescue	Thumbs	0.00	0.25	0.00	0.00	0.00	0.03		0.00	2.00	0.50	1.50	0.25	1.79	2.75	0.03	1.29
Fortescue	Lanterns	0.25	0.13	1.59	0.75	0.50	0.83	1.50	0.50	0.57	0.83	2.32	2.13	1.50	3.50	0.68	1.35
Fortescue	Munro Bight	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.06	0.33	1.50	0.00	0.03	0.12
Nubeena	Cape Raoul	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nubeena	Salters Point	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nubeena	Wedge	0.00	0.14	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00		0.02	0.00
NthBruny	Patricks Bight	0.00	0.00	0.00	0.00	0.00			0.00	0.04	0.00	0.00	0.00			0.00	0.01
NthBruny	Yellow Bluff		0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NthBruny	Trumpeter Point	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
SthBruny	Cape Conella			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.01
SthBruny	Bay of Islands	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SthBruny	Mangana Bluff	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
Recherche	Actaeon	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.05	0.03			0.00	0.00	0.02
Recherche	Eliza Point			0.00	0.00	0.00					0.00	0.00	0.00	0.00		0.00	0.00
Recherche	Fisher Point				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix V. Spatial and temporal trends in barrens cover across depth categories (4 to 18 m depth) as available within each site and sub-site spanning eastern Tasmania from 2001/02 to 2016/17. Data are means derived from 5 m^2 quadrats assessed *in situ* by divers which have been pooled for all quadrats occurring within each 2 m depth category from 6 to 18 m. Sites and sub-sites are ordered from north to south along the coast. Totals across all depth strata for each period are shown as sub-table on RHS. Legends show categories of density or cover which refer to densities or cover greater than or equal to each category, i.e. category 2.5 ranges from ≥2.5 to <5.0.

Legend: Percent barrens

0	0.1	2.5	5	10	25	50

		Period: 2001/02 depth (m)								2016/17								Totals 2001/02	Totals 2016/17
Site	**Subsite**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**		
Eddystone	Georges Rocks			0.00	3.20	3.50	0.00	0.50	0.00			1.00	1.25	3.80	0.21	9.15	1.50	1.09	3.49
Eddystone	Purdon					0.00	0.00	0.00	0.00					0.00	2.00	0.36	0.00	0.00	0.92
Eddystone	Lighthouse			0.00	0.00	0.00	0.00	0.00	0.00				0.00		0.00	0.62	0.00	0.00	0.37
StHelens	Binalong	0.00	0.00	0.00	18.20	23.33	27.00	15.86	33.75			4.33	11.67	68.75	80.63	78.40	72.00	21.95	59.97
StHelens	St.Helens Point					0.00	2.00	0.00	0.00					6.86	10.04	20.20	0.00	1.15	10.00
StHelens	St. Helens Island	0.00		0.50	4.36	21.71	32.64	42.86			0.50	8.00	7.64	40.79	53.76	0.00		18.96	29.09
Fourmile	Falmouth			0.00	0.00	0.00	0.00	0.00			0.00	0.00		0.00	0.00	0.00		0.00	0.00
Fourmile	Ironhouse Pt					0.00	0.00	0.19	0.00				1.67	0.60	0.33	3.27	14.77	0.11	5.60
Fourmile	Saltwater Inlet				0.00	0.00	0.00	0.00	0.00					1.00	0.00	0.17	0.00	0.00	0.20
Bicheno	Porches							0.00							0.00	0.41		0.00	0.34
Bicheno	Governors			0.00	0.00	0.00	0.00	0.00	0.00				0.00	1.14	0.38	0.00	0.00	0.00	0.33
Bicheno	Cape Lodi				0.00	0.00	0.00	0.00	0.00				0.00	1.12	0.00	1.50	6.86	0.00	1.93
Wineglass	Boot Rock		0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	1.33	0.00	0.00	0.00	0.00	0.38
Wineglass	Cape Tourville				0.00	2.00	0.67	0.00	0.00					0.00	4.18	5.09	27.00	0.47	7.00
Wineglass	Wineglass Bay				0.00	1.67	0.00	0.00	0.00				47.67	23.17	21.20	12.20	24.20	0.34	23.31
Schouten	Cape Baudin		4.00	5.00	3.25	15.75	0.25	12.83	7.86			19.00	36.71	17.60	21.00	21.50	25.50	7.73	24.67
Schouten	Cape Sonnerat		0.00	0.00	6.00	0.71	0.00	0.00	5.00		0.00	3.00	1.00	0.75	1.88	0.00		2.32	1.16
Schouten	Sarah-Anne Bay		0.00	0.00	0.00	1.50	3.83	0.00	0.00			0.00	1.33	19.00	22.17	34.17	51.67	0.96	22.19
Maria	Beaching Bay		0.00	0.00	0.00	0.00	0.23	0.42	0.00		0.00	0.00	3.00	26.67	1.64	2.67	0.00	0.22	4.11
Maria	Mistaken Cape		0.00	0.00	0.00	10.50	4.78	1.33			0.00	4.67	12.13	33.00	18.57	32.00	3.00	3.26	16.71
Maria	Bunker Bay		0.00	0.00	0.00	0.00	0.00	2.00	0.00		1.67	0.00	0.00	3.86	5.50	14.60	2.67	0.25	4.88
Forestier	Visscher Island		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.25	0.00	0.56	2.75	2.17	0.75	0.00	0.97
Forestier	High Yellow Bluff			0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Forestier	Sisters			0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fortescue	Thumbs		0.00	0.00	0.00	0.00	0.00	0.00			0.00	7.50	0.00	3.00	0.38	6.45	0.00	0.00	3.49
Fortescue	Lanterns	0.00	0.00	0.00	2.57	0.00	0.00	0.00	0.00	3.33	0.00	0.86	3.67	7.20	3.88	2.67	8.00	0.55	3.33
Fortescue	Munro Bight	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.50	1.50	0.00	0.00	0.13
Nubeena	Cape Raoul		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nubeena	Salters Point	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nubeena	Wedge	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
NthBruny	Patricks Bight	0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00
NthBruny	Yellow Bluff			0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NthBruny	Trumpeter Point		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
SthBruny	Cape Conella				0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SthBruny	Bay of Islands		0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SthBruny	Mangana Bluff		0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
Recherche	Actaeon	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00	0.00
Recherche	Eliza Point				0.00	0.00	0.00						0.00	0.00	0.00	0.00		0.00	0.00
Recherche	Fisher Point					0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix VI. Similarity Percentages table of macroalgal taxa contributions to variability in macroalgal communities across eastern Tasmania (sites 1-13) between 2001/02 and 2016/17. Average dissimilarity between time periods was 23.33%.

Macroalgal taxa	Average Dissimilarity	Diss./SD	Contrib%	Cum.%
Phyllospora comosa	2.91	0.99	12.48	12.48
Ecklonia radiata	2.42	1.35	10.39	22.87
Caulerpa sp.	2.00	0.90	8.58	31.45
Rhodophyta (all red algae pooled)	2.00	1.19	8.58	40.03
Lessonia corrugata	1.37	1.04	5.86	45.88
Carpoglossum confluens	1.35	1.35	5.79	51.67
Durvillea potatorum	1.32	1.00	5.65	57.33
Zonaria sp.	1.09	1.17	4.68	62.01
Acrocarpia paniculata	1.05	1.08	4.48	66.49
Halopteris paniculata	1.01	1.01	4.33	70.82
Cystophora sp.	0.82	1.26	3.52	74.34
Sargassum sp.	0.78	0.91	3.33	77.67
Macrocystis pyrifera	0.68	0.70	2.91	80.59
Ulva sp.	0.65	0.70	2.81	83.40
Carpomitra costata	0.65	1.14	2.79	86.19
Xiphophora gladiata	0.54	0.99	2.32	88.51
Perithalia caudata	0.52	0.76	2.24	90.74
Codium sp.	0.50	1.06	2.14	92.88
Filamentous green algae	0.35	0.95	1.51	94.40
Sporochnus comosus	0.32	0.39	1.37	95.76
Cladophora feredayi	0.31	0.79	1.34	97.11
Chaetomorpha sp.	0.25	0.79	1.09	98.20
Dictyopteris muelleri	0.16	0.34	0.70	98.89
Filamentous brown algae	0.16	0.36	0.69	99.58
Seirococcus axillaris	0.06	0.25	0.24	99.82
Seagrass	0.02	0.22	0.09	99.91
Undaria pinnatifida	0.02	0.16	0.09	100.00

Appendix VII. Depth distribution of *C. rodgersii* from 4 - 30 m at St. Helens in 2009 as derived from counts obtained from Autonomous Underwater Vehicle imagery at night when *C. rodgersii* is emergent on the reef surface (*after* Ling et al. 2016). Density is multiplied by 1.19 to account for slightly lower sighting of *C. rodgersii* via AUV imagery at night as compared to SCUBA divers (Ling et al. 2016). (a.) mean density by depth, (b.) raw density data with percent cover of urchin barrens overlaid as determined during video surveys of St. Helens in 2017. Lower urchin density appears to maintain barrens in deeper water. Note that estimates of urchin abundance in depths shallower than ~12 m are underrepresented by urchin counts from AUV imagery given increasing obscuring of individuals by the kelp canopy (as detailed by Ling *et al.* 2016).