Assessment of reef condition in the southern D'Entrecasteaux Channel

Camille White, Jaime McAllister, Olivia Johnson, Craig Mundy and Jeff Ross

March 2021

Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 49,
Hobart TAS 7001

Enquires should be directed to:
Dr Camille White
Institute for Marine and Antarctic Studies
University of Tasmania
Private Bag 49, Hobart, Tasmania 7001, Australia
Camille.White@utas.edu.au
Ph. (03) 6226 8377
Fax (03) 6226 8035

Executive summary

Data collected through the Rapid Reefs project enabled us to better understand the functional health of reefs in the southern D'Entrecasteaux Channel, as well as establish a baseline in this region for future monitoring. This project also allowed us to establish new reference sites of importance to the abalone industry, namely Mouldies, Black Reef, Middle Ground and George III. From a functional perspective, these sites were very similar to pre-existing survey sites within the southern D'Entrecasteaux Channel. When combined with the data from FRDC 2015-024, rapid visual assessment (RVA) as a monitoring technique was found to perform well in the detection of low-moderate levels of organic enrichment across the survey area. Ongoing monitoring of these sites could be used to provide greater resolution of natural variability and aid in the development of indicator thresholds for a loss of ecosystem function.

Abalone recruitment modules (ARMs) continue to provide a functional indicator of abalone recruitment at monitoring sites throughout the D'Entrecasteaux Channel. Because some ARMs may still be undergoing a period of conditioning, and the limited number of sites established, results should not be scaled up to represent the broader patterns of recruitment in the Channel, but rather interpreted in the context of site-specific changes in abundance. The performance of the ARMs at the current sites in the Channel suggests they are best suited to detecting large changes in abundance (i.e. >100% increase). Whilst a longer-term deployment may improve the ability of ARMs to detect smaller changes in abundance such as the case at George III and Black Reef, it is important to consider the level of change that would warrant a management response when determining the required duration and frequency of monitoring.

Both the RVA method and ARM modules provide important insight into different aspects of reef function. For a more integrated assessment of reef health the RVA method is most suitable. Monitoring the recruitment of a commercially important species in abalone using ARM’s on the other hand addresses an industry focus. The overall choice of methods used in any ongoing reef monitoring program will ultimately depend on the management question of interest.

Table of contents

Introduction **9**

Aims & Objectives **12**

Methods **13**

Study Sites 13

RVA Methods 14

ARM Resurvey Methods 19

Results & Discussion **21**

Rapid visual assessment surveys 21

Resurvey of temperate reefs in the lower D'Entrecasteaux Channel using rapid visual assessment 21

Detecting organic enrichment using rapid visual assessment 25

Assessing significance of organic enrichment on reef function 28

ARM Resurvey 39

Abalone size structure 39

Abalone density 44

ARM ability to detect change 47

Conclusions **49**

References **52**

Appendix I: **55**

List of Figures

Figure 1. Map of southern D'Entrecasteaux Channel with the fifteen sites surveyed. Double circles indicate Abalone Recruitment Module (ARM) assessment sites, red dots indicate the four new Rapid Visual Assessment (RVA) sites established for this project. 14

Figure 2. Principal coordinates analysis (PCO) on RVA parameter values across sites during 2019 sampling events. Each data-point represents an individual quadrat. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with $r \geqslant 0.3$. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0. 22

Figure 3. Principle coordinates analysis (PCO) on RVA parameter averages across sites during 2019 sampling events, a) including the Actaeons, b) without the Actaeons. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with $r \geqslant 0.5$. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0. 24

Figure 4. Principle coordinates analysis (PCO) on RVA parameter averages across sites during Spring 2018 and Summer and Spring 2019 sampling events a) including the Actaeons and b) without the Actaeons. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with $r \geqslant 0.5$. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0. 26

Figure 5. Site average cluster analysis of the group average for each site based on site similarity for Spring of 2018 and both 2019 survey periods. 28

Figure 6. Average canopy cover at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only. 30

Figure 7. Average cover of a) understorey red and b) understorey green at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only. 31

Figure 8. Average cover of a) epiphytic algae and b) filamentous algae at all sites across 2018 and 2019 surveys. Note that data was collected at GIII, Black Reef, Middle Ground and Mouldies Hole in 2019 only. 32

Figure 9. Average cover of a) nuisance green algae and b) nuisance red algae at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only. 33

Figure 10. Average cover of turfing algae at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only. 34

Figure 11. Boxplot of size distributions for abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 D'Entrecasteaux Channel monitoring sites (site strings pooled). Red dot indicates mean shell length. Hashed red line represents a shell length of 25 mm as a reference to denote approximately the first 12-months of abalone growth. Total number of abalone measured within each season given above each boxplot. BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. 41

Figure 12. Boxplot of size distributions for abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 Storm Bay monitoring sites (site strings pooled). Red dot indicates mean shell length. Hashed red line represents a shell length of 25 mm as a reference to denote approximately the first 12-months of abalone growth. Total number of abalone measured within each season given above each boxplot. BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North. 42

Figure 13. Size frequency of abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 monitoring sites (site strings pooled). Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. Total number of abalone measured during each sampling period are also given. 43

Figure 14. Mean abalone density (no. $m^{-2} \pm$ SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 D'Entrecasteaux Channel monitoring sites. Each ARM had a planer surface area of 0.126 m^2. Replicate strings (sub-sites) denoted by line type. BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. Note difference in density scale between sites. 45

Figure 15. Mean abalone density (no. $m^{-2} \pm$ SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 Storm Bay monitoring sites. Each ARM had a planer surface area of 0.126 m^2. Replicate strings (sub-sites) denoted by line type. BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North. Note difference in density scale between sites. 46

Figure 16. Mean abalone density (no. $m^{-2} \pm$ SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 monitoring sites (site strings pooled). Each ARM had a planer surface area of 0.126 m^2. Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. 47

List of Tables

Table 1. Functional parameters for rapid visual assessment of temperate reef ecosystems in south-east Tasmania 17

Table 2. PERMDISP analysis examining the deviation of data from a centroid for each site. Note that the higher the average deviation the more dispersed the data. 22

Table 3. Pairwise comparison of function parameters across sampling events using PERMANOVA on site averaged dataset. Asterisk denotes significant difference. 27

Table 4. Average values for key functional parameters at all sites across 2018 and 2019 surveys. Note the blank cells indicate that no data was collected for that parameter during that survey. 35

Table 5. Sample means and effect size (Cohen's D) by site and string (1 or 2). Sample size was set at n = 20. MDD = Minimum detectable Difference between sample means. % change = change in mean density from Autumn 2019 required for MDD and n = 20. Prob of Sig T = probability of a significant difference in density between 2017 and 2019 sampling periods (bold denotes significant differences where p < 0.01). Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. 48

Introduction

Temperate reef ecosystems are inherently complex in nature, as they are multi-dimensional habitats with multi-trophic linkages, often combined with a high degree of regional endemism, all of which can affect the response to organic enrichment (Connell & Irving 2008, Gorman et al. 2009). While kelp forests are foundation habitats and thought to be relatively resilient to anthropogenic stressors, sustained organic enrichment has also led to loss of macroalgae and phase shifts in ecosystem function (Graham 2004, Connell et al. 2008, Teagle et al. 2017). The ability to identify when temperate reef ecosystems are under stress and therefore at risk of collapse represents a considerable challenge for management.

Whilst determining the trigger points for phase shifts is difficult, there are several common ecological responses of temperate reef ecosystems to organic enrichment. The most extreme is loss of canopy forming kelp and a proliferation of turfing algae (Eriksson et al. 2002, Connell et al. 2008). Other opportunistic algal types with fast growth rates, rapid reproduction and high demand for nitrogen also respond positively to organic enrichment (Oh et al. 2015). These include opportunistic green algae species from the genera *Ulva*, *Cladophora* and *Chaetomorpha* (Lavery & Mccomb 1991, Nelson et al. 2008), red algae such as *Asparagopsis armata* (Paul et al. 2006, Mata et al. 2010), and several filamentous and epiphytic algal species (Oh et al. 2015). While rapid growth algae can initially act as a nutrient sink, effectively buffering the ecosystem from the effects of organic enrichment, under eutrophic conditions, these algae can form dense blooms, significantly altering ecosystem structure and function (Nelson et al. 2008).

Intensification of human activity in the lower D'Entrecasteaux Channel has led to increased concern regarding the effects of sustained low-level organic enrichment on the health and function of rocky reef ecosystems in this region. Temperate reef ecosystems in south-eastern Tasmania support high value commercial fisheries, such as abalone (*Haliotis rubra*) and rock lobster (*Jasus edwardsii*). They are also important to the tourism and recreational sectors and have intrinsic natural biodiversity and conservation value. Through a large FRDC project (FRDC 2015-024), IMAS has been developing and trialling methodology aimed at detection of impacts of organic enrichment on reef ecosystems in regions of salmon aquaculture expansion. One of the methods developed through FRDC 2015-024 includes a targeted reef assessment technique for detection of organic enrichment on reef ecosystems – the "Rapid Visual Assessment" method (RVA). This method was developed throughout the lifespan of FRDC 2015-024, with validation occurring on a broadscale organic enrichment gradient in the southern D'Entrecasteaux Channel.

Fieldwork for FRDC 2015-024 finished in 2018; however, human activities within the lower Channel region continue to intensify. Eastern Zone abalone fishing blocks 13 and 14 (Lower D'Entrecasteaux Channel and Actaeons) are currently and historically highly valuable abalone fishing grounds. Industry is concerned that increasing organic enrichment in these environments may lead to a detrimental effect on abalone population productivity. The only method of detecting the effects of sustained low-level organic enrichment on reef ecosystems is through regular monitoring of key functional indicator groups. Through FRDC 2015-024, we have developed techniques that are tailored for this purpose; however, as method development occurred throughout the project, the establishment of a true baseline with multiple time points was not possible. The method still needs validation over a longer time series and questions remain over what design is best for long term monitoring (i.e. fixed vs random). This project allowed for a further year of data collection to aid in method evaluation, which included an assessment of the robustness of a fixed vs random design. To provide further information to stakeholders (DPIPWE, Tasmanian Abalone Council), the juvenile abalone collector modules deployed through FRDC 2015-024 at Sisters Bay and Scott Point were also monitored for the duration of project to assess their effectiveness at detecting population fluctuations.

Aims & Objectives

The aim of this project was to extend the rapid reef assessment program established in FRDC project 2015-024, to obtain sufficient baseline data for the area.

Specific objectives include:

1. An annual assessment of the condition of reef ecosystems in the lower D'Entrecasteaux Channel at sites established through FRDC 2015-024.
2. Establishment of four new reef monitoring sites at Black Reef, George III, Middle Ground and Mouldies that correspond to high value abalone sites.
3. Evaluation of the effectiveness of abalone recruitment modules (ARMs) in the lower D'Entrecasteaux Channel at detecting change in abalone recruitment, particularly in relation to time of establishment.

Methods

Study Sites

Salmonid farming has been active in the south-east D'Entrecasteaux Channel region (Tasmania, Australia) (SE Channel) since 1985, with the most southern lease (East of Lippies MF78) active since 2016. While aquaculture of Atlantic salmon (*Salmo salar*) is now the dominant industry in this region, the SE Channel is a multi-use area, subject to commercial and recreational fishing efforts, forestry and other industry inputs from the catchment, as well as localised urbanisation from several small townships. The Huon river is the largest freshwater input into this region, with smaller rivers such as the Esperance and the Lune also providing freshwater input.

Fifteen sites within the SE Channel region were surveyed as part of this study in 2019 (Figure 1). Rapid Visual Assessment (RVA) surveys were undertaken at all fifteen sites in February and September, with eleven of these sites previously established through FRDC project 2015-024 and a further four RVA sites (George III, Black Reef, Middle Ground, Mouldies) established solely for this project (Figure 1). Abalone Recruitment Modules (ARM) were surveyed at Lippies Point, Sisters Bay, George III and Black Reef. ARM sites were established at Lippies Point and Sisters Bay in May 2017 as part of FRDC 2015-024, whereas Black Reef and George III were established much earlier in May 2015 as part of FRDC 2014-10. Collectively these were classed as D'Entrecasteaux sites. ARM sites installed in Storm Bay since June 2016 as part of the aforementioned FRDC projects were also included to provide additional context across a larger spatial scale.

Figure 1. *Map of southern D'Entrecasteaux Channel with the fifteen sites surveyed. Double circles indicate Abalone Recruitment Module (ARM) assessment sites.*

RVA Methods

The assessment methods developed under FRDC 2015-024 and repeated here included 15 functional parameters assessed within a 1m^2 quadrat with photos also taken for archival purposes. Of the 15 parameters, 10 assessed broad structural parameters associated with reef function (four assessed the condition of the macroalgal canopy, four assessed the condition of the substrate and two related to trophic effects), while five related solely to enrichment responses (Table 1). The 15 parameters were incorporated into a scorecard, with all parameters assessed in each quadrat. Broad functional parameters included percentage total canopy cover, sub-canopy brown, green and red algal cover, turfing algal cover, pink and red encrusting algal cover, sponge cover, levels of encrusting fauna, and numbers of the dominant major mobile invertebrates. In addition, canopy cover was also characterised into species and the dominant species of subcanopy algae and invertebrates were also recorded where possible, except for red algae due to the level of training required to consistently identify correctly. Enrichment parameters included percentage cover of epiphytic and filamentous algae, cover of nuisance or opportunistic green (characterised by *Ulva, Cladophera* and *Chaetomorpha* in our sampling region) and nuisance or opportunistic red species (characterised by *Asparagopsis armata* in our sampling region), along with the level of "dust" (sedimentation) covering the algae.

This survey technique was designed using fixed quadrats with the aim of limiting the confounding effects of small-scale spatial variability when assessing change through time. The infrastructure required for this method was already in place at the eleven sites established under the FRDC 2015-024 project. The George III, Black Reef, Middle Ground and Mouldies sites were established as part of this project, with site layout identical to sites already established previously in the southern D'Entrecasteaux Channel. At each site 12 fixed quadrat locations were established at 5m depth using eyebolts drilled and anchored into the substrate. These were located around three separate central locator poles that were bolted to the substrate using drilled anchors. Diving on SCUBA, at each site the two divers located the first quadrat and commenced visual assessment. Diver 1 assessed all 12 quadrats using a $1m^2$ quadrat sub-divided into four smaller $0.5m^2$ subsections to increase scoring accuracy.

Diver 2 located the next quadrat pin in the sequence, installed a second quadrat frame and photographed it for archive, working in sequence across the 12 quadrats. All parameters were assessed in the full $1m^2$ quadrat, except for substrate parameters, which were sub-sampled using the $0.5m^2$ subsection of the quadrat closest to the adjacent locator pole. Quadrats 1 & 2 at all sites were visually assessed by both divers as a calibration and data QA/QC check. Quadrats 3-12 were assessed by Diver 1 only.

Table 1. *Functional parameters for rapid visual assessment of temperate reef ecosystems in south-east Tasmania*

Functional parameter	***Expected response to increased organic enrichment***	***Reference***
Total canopy cover (including breakdown of species)	Decline	Connell et al. (2008), Eriksson et al. (2002), Benedetti-Cecchi et al. (2001)
Sub-canopy brown cover	Likely to decline as per canopy	
Sub-canopy green cover	Potential increase due to increased nutrient availability	Oh et al. (2015), Nelson et al. (2008)
Sub-canopy red cover	Potential increase due to higher sedimentation in water column. Overall increase in red+green:brown algae ratio expected in enhanced nutrient conditions	Stuart-Smith et al. (2008)
Turfing algal cover	Increase	Connell et al. (2008), Eriksson et al. (2002), Benedetti-Cecchi et al. (2001)
Pink encrusting algae cover	Potential decline and replacement by turfing or opportunistic algae, if canopy is lost	Burkepile and Hay (2006)
Red encrusting algae cover	Could decline as per pink encrusting, or increase due to changes in predation pressure or light conditions	Burkepile and Hay (2006)
Sponge cover (including breakdown of encrusting vs branching)	Likely to increase under mild organic enrichment.	
Encrusting & epibiotic fauna	Potential increases with increases in opportunistic algae cover likely	Russell and Connell (2005), Burkepile and Hay (2006)
Species and number of dominant mobile invertebrate	Unknown	
Epiphytic algae cover	Increase	Oh et al. (2015)
Filamentous algae cover	Increase	Oh et al. (2015), Lavery and Mccomb (1991)
Opportunistic green algae cover	Increase	Oh et al. (2015), Nelson et al. (2008)
Opportunistic red algae cover	Increase	Anecdotal
“Dust” on algae	Increase (a reflection of sedimentation)	Anecdotal

Analysis of data was undertaken in three sections. Section 1 examined the data from this project only, the February 2019 and September 2019 surveys. The aim of this section was to assess reef function across all fifteen sites, exploring both within site and between site variation. Patterns in functional parameters were investigated using the multivariate software package PRIMER v7 (Plymouth Routines in Multivariate Research; Clarke and Warwick 2001) and its complementary software package PERMANOVA+(v7) (Anderson et al. 2008). A Bray-Curtis dissimilarity matrix was calculated and principal coordinates analysis (PCO) undertaken to visualise patterns in the data. Vector overlays using a Pearson correlation were used to identify key parameters driving trends in data. A PERMANOVA was undertaken to test the effect of site on the data and a PERMDISP undertaken to explore variability within site. Data were also analysed to explore spatial and temporal patterns, with site means calculated and differences across site and sampling event examined through PCO analysis.

In section 2 we tested the capacity of the RVA method to detect effects of organic enrichment at the survey sites. For this we incorporated data from the final survey undertaken through FRDC 2015-024 in September 2018. As FRDC 2015-024 focused on method development, this was the only survey where the final version of the method was used, and thus the only survey that could be effectively incorporated into a multivariate analysis with data collected for this project. As there were no data collected prior to 2019 for Mouldies, Black Reef, Middle Ground and George III, these sites were omitted from analysis for this section. We used site averaged data to examine temporal patterns in the data. A Bray-Curtis dissimilarity matrix was calculated and principal coordinates analysis (PCO) undertaken, along with cluster analysis to visualise patterns in data. Vector overlays using a Pearson correlation were used to identify key parameters driving trends in data, with particular note taken of parameters associated with organic enrichment. A PERMANOVA was undertaken to test the effect of time of sampling on the data.

In section 3 we examined the magnitude of any differences found through multivariate analysis. In this section, we added data collected through FRDC 2015-024 from February 2018, with means and standard errors calculated for each site and sampling event.

ARM Resurvey Methods

Abalone Recruitment Module (ARM) resurveys consisted of three divers working either individually or in buddy pairs to count and measure all abalone present underneath the ARMs to the nearest mm using plastic callipers. In summary, each site consists of 20 replicate ARMs secured to the substrate with a single central pin while three adjustable risers are located on the perimeter to control the gap between the ARM and the substrate. For a more detailed description of the ARM design see FRDC 2014-010 (Mundy et al. 2018) and ARM Standard Operating Procedures Manual (Pyke et al. 2018). Storm Bay ARMs were resurveyed periodically since winter 2016 and Lippies Point and Sisters Bay since autumn 2017. ARMs at George III and Black Reef were serviced biannually since autumn 2015.

Data collected from all sampling periods were used to describe seasonal trends in the abundance and size composition of abalone underneath ARMs across sites. Abundance of abalone underneath ARMs were converted to abalone m^{-2} to explore trends in mean density through time. Size frequency distributions (pooled across replicate strings at each site) were used to examine the size composition of abalone found underneath ARMs. All data analyses were conducted using R (R-Core-Team 2017), and data summaries and figures prepared using dplyr (Wickham and Francois 2016) and ggplot2 (Wickham 2009) packages.

The power of the sampling design to detect change in abalone recruitment density was determined using Cohen's D to provide a comparison across sampling sites. The Minimum Detectable Difference (MDD) was used to determine the effect of changing sample size *n* on the capacity to detect difference between the means of the sampling events. Given the long time-series of sampling events and the complexity of interpreting multiple combinations of factors, pairwise comparisons in density were only made between the same seasons for the two most recent sampling years in each region (i.e. D'Entrecasteaux – Autumn 2018 and 2019; Storm Bay – Autumn 2017 and 2019). Cohen's D effects or the difference between two groups' means (i.e. sampling events) were interpreted as small (<0.2), medium (0.2 – 0.5) or large (>0.8). For example, if two groups' means do not differ by 0.2 standard deviations or more, the difference is trivial, even if it is statistically significant. Cohen's D were calculated using the effsize package (Torchiano 2017) in R.

Results & Discussion

Rapid visual assessment surveys

Resurvey of temperate reefs in the lower D'Entrecasteaux Channel using rapid visual assessment

Spatial trends were initially examined across all fifteen sites using the data collected for this project (i.e. only the 2019 data collected as part of the SMRCA "Rapid Reefs" project). There was significant spatial variability in reef function (PERMANOVA, $F_{14,359} = 11.47$, P(perm) = 0.0001), with our analysis suggesting that canopy cover was a key parameter in driving site-level differences (Figure 2). Canopy cover tended to be inversely correlated with understorey green and red algal cover. For example, sites such as the Actaeons which scored lower for canopy cover had comparatively greater understorey cover of red and green algae (Figure 2). Sites with greater between-quadrat variability (i.e. more highly dispersed through PCO and PERMDISP analysis) such as the Actaeons, Zuidpool or Penguin tended also to have lower overall canopy cover (Table 2; Table 3). Of note, all new sites (George III, Black Reef, Middle Grounds, Mouldies) clustered with most other sites surveyed in 2019 and also had similar dispersions (Figure 2; Table 2). This indicated that from a functional perspective, these four sites were typical of those found within this region.

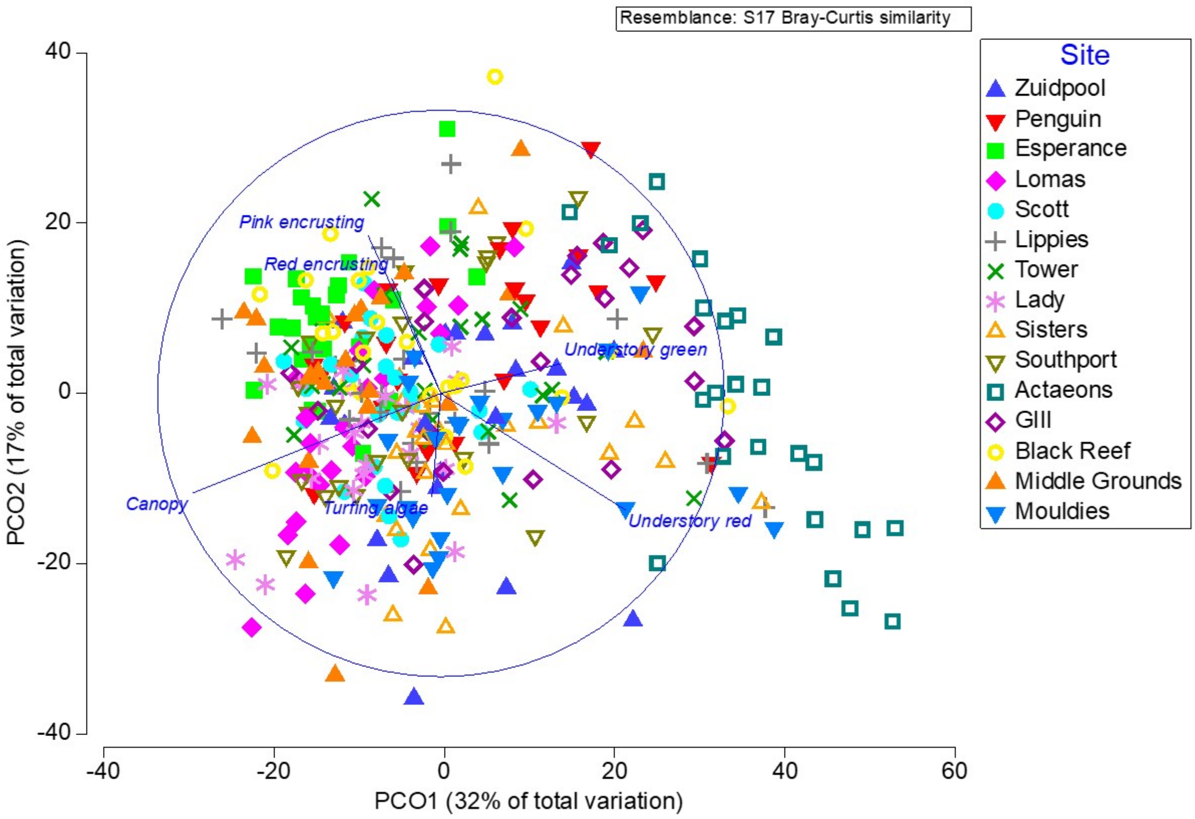


Figure 2. *Principal coordinates analysis (PCO) on RVA parameter values across sites during 2019 sampling events. Each data-point represents an individual quadrat. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with r ⩾ 0.3. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0.*

Table 2. *PERMDISP analysis examining the deviation of data from a centroid for each site. Note that the higher the average deviation the more dispersed the data.*

Site	Number of samples	Mean distance from centroid	Standard Error
Zuidpool	24	25.183	1.2222
Penguin	24	23.229	1.95
Esperance	24	17.075	1.1278
Lomas	24	21.308	1.1614
Scott	24	18.68	1.7527
Lippies	24	21.811	2.0505
Tower	24	21.183	1.5247
Lady	24	17.515	0.8948
Sisters	24	21.084	1.8153
Southport	24	23.662	1.66
Actaeons	24	31.293	1.6119
GIII	24	21.992	1.2244
Black Reef	24	19.741	1.7739
Middle Grounds	24	19.775	1.6908
Mouldies	24	20.41	1.5289

NB: $F_{14,345}$ = 4.8993 P(perm) = 0.0001

The influence of canopy cover in shaping reef function was not surprising, given the role that the canopy plays in shaping the reef environment. A lower canopy cover allows greater light penetration and water movement through to the substrate (Layton et al. 2019), alters reef structure and habitat (Teagle et al. 2017), decreases abrasion by adult plants and increases settlement space available for juvenile canopy and understorey species (Kennelly 1987; Flukes et al. 2014; Shelamoff et al. 2019). These factors contribute to settlement and growth of understorey species.

There was a clear difference between the two survey events based on site averaged data (Figure 3), with summer surveys correlating to increasing values for canopy cover, as well as pink and red encrusting algae (Figure 3a). Of note, the Actaeons was an outlier for both sampling events (Figure 3a) and was distinct within the survey area for being the only site dominated by the giant kelp, *Macrocystis pyrifera*. As *M. pyrifera* forms canopies on the surface, it is not possible to accurately assess cover of this species using benthic quadrats. While quadrat results (Figure 3a) suggested the Actaeons had a depleted canopy, in reality the *M. pyrifera* canopy was regularly so dense at the surface as to be impenetrable by boat (C. White pers obs). Thus, while the Actaeons consistently scored low for canopy cover, the RVA canopy score only reflected the abundance of macroalgal stipes within each quadrat.

Given the limitations of the RVA design for capturing giant kelp cover using benthic quadrats, spatial structure among sites were also examined after excluding the Actaeons site (Figure 3b). This again indicated differences between survey events, based largely on changes to canopy cover. Several vectors relating to enrichment parameters, such as nuisance red algae, turfing algae and filamentous algal cover were also shown to have high correlations with site. Lomas in both spring and summer clustered with the vector for nuisance red algae and turfing algae, as did Zuidpool in summer (Figure 3b), indicating some form of noticeable enrichment at those sites and sampling events.

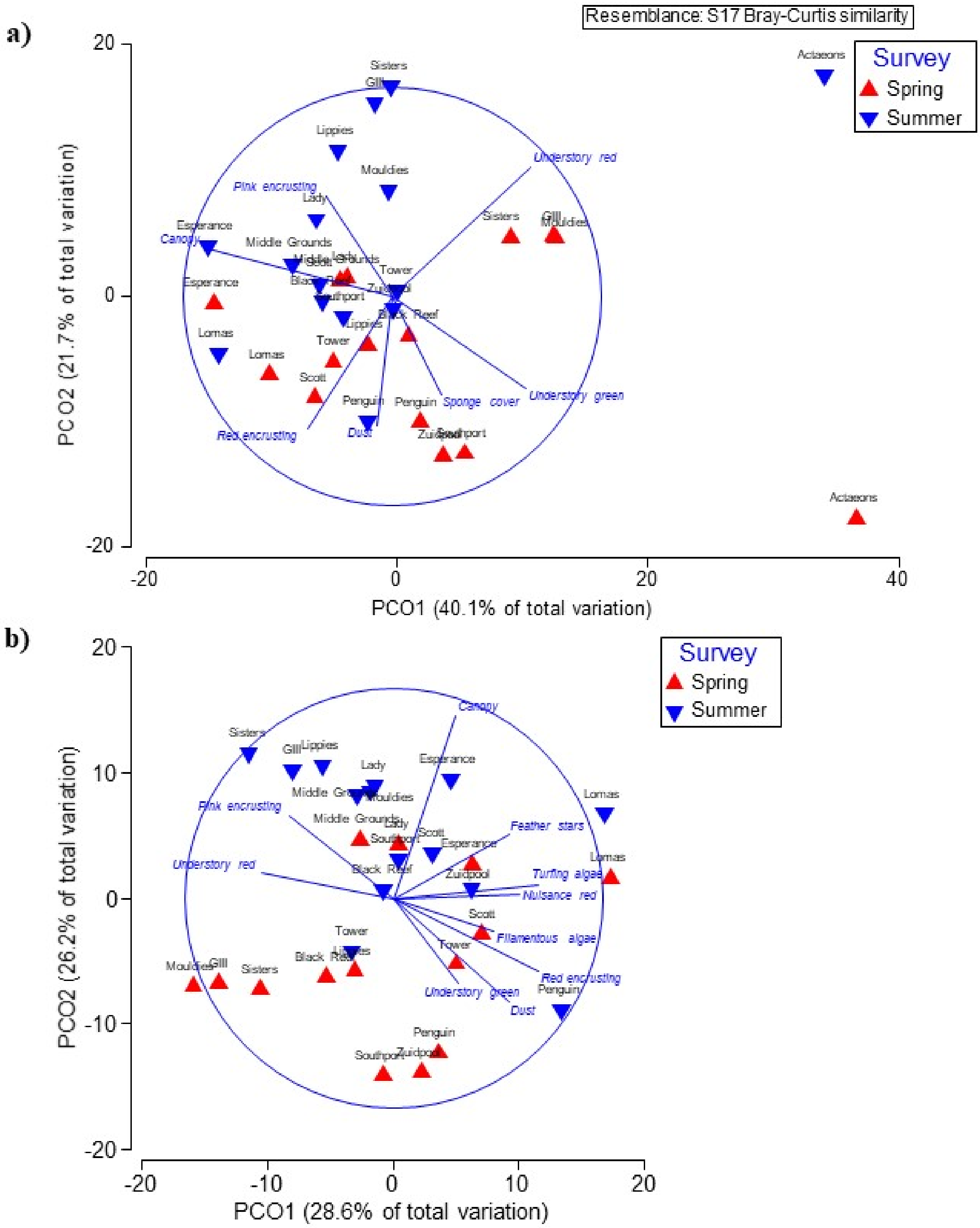


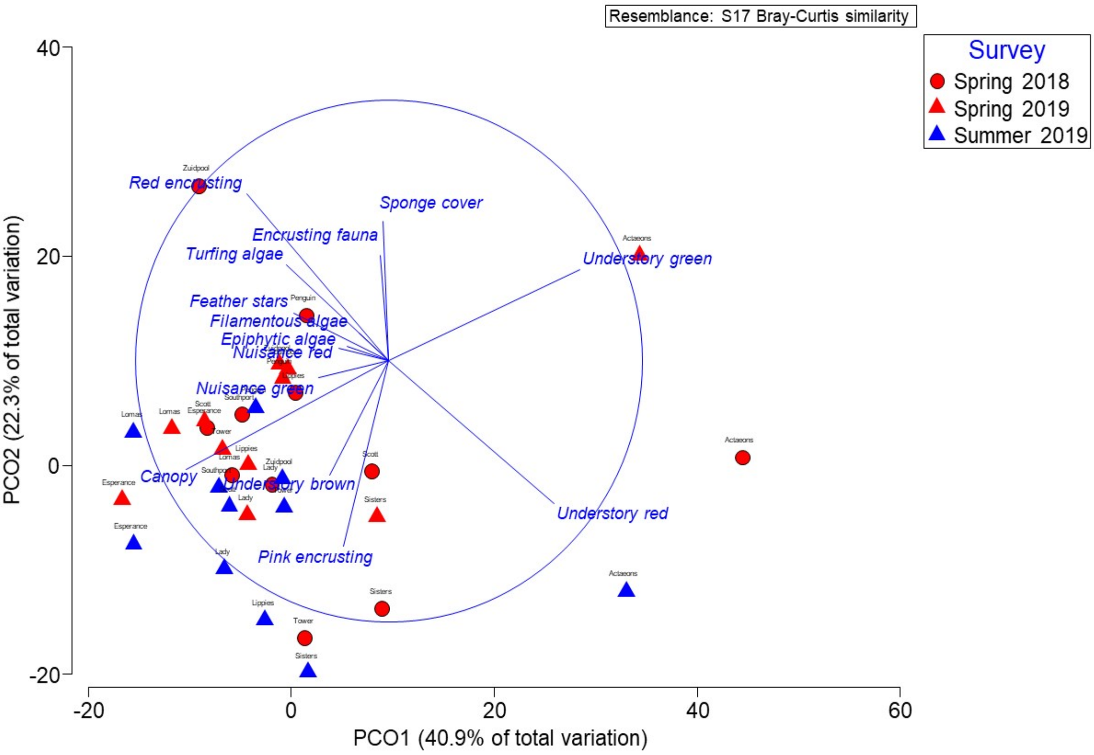
__Figure 3.__ Principle coordinates analysis (PCO) on RVA parameter values across sites during 2019 sampling events, a) including the Actaeons, b) without the Actaeons. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with r ⩾ 0.5. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0.

Detecting organic enrichment using rapid visual assessment

Data from Spring 2018, collected as part of FRDC 2015-024, were incorporated into the dataset to extend the analysis. This was done with the aim of a) evaluating how well the RVA method performed with a longer time series and b) examining if the method could be used to detect sites susceptible to organic enrichment. The new sites established through the current project (Mouldies, Black Reef, Middle Ground, George III) were removed from the dataset, as they were only sampled in 2019.

Site average data were used to compare results between the three sampling events: Spring 2018, Spring 2019, and Summer 2019, both with (Figure 4a) and without the Actaeons (Figure 4b) included in the data set. There were significant differences in the data across both site (PERMANOVA, $F_{10,32} = 4.14$, P(perm) = 0.0002) and sampling event (PERMANOVA, $F_{1,32} = 5.65$, P(perm) = 0.0033). Pairwise comparisons indicated differences between the summer and two spring sampling events; however, no significant differences were observed between Spring 2018 and Spring 2019 (Table 3). While a longer time series is required to fully evaluate how sensitive the RVA is to detecting seasonal changes in ecosystem function, this initial result shows some promise. These results also demonstrate the need to manage the timing of sampling programs (season) given the significant differences between Spring and Summer surveys.

a



b

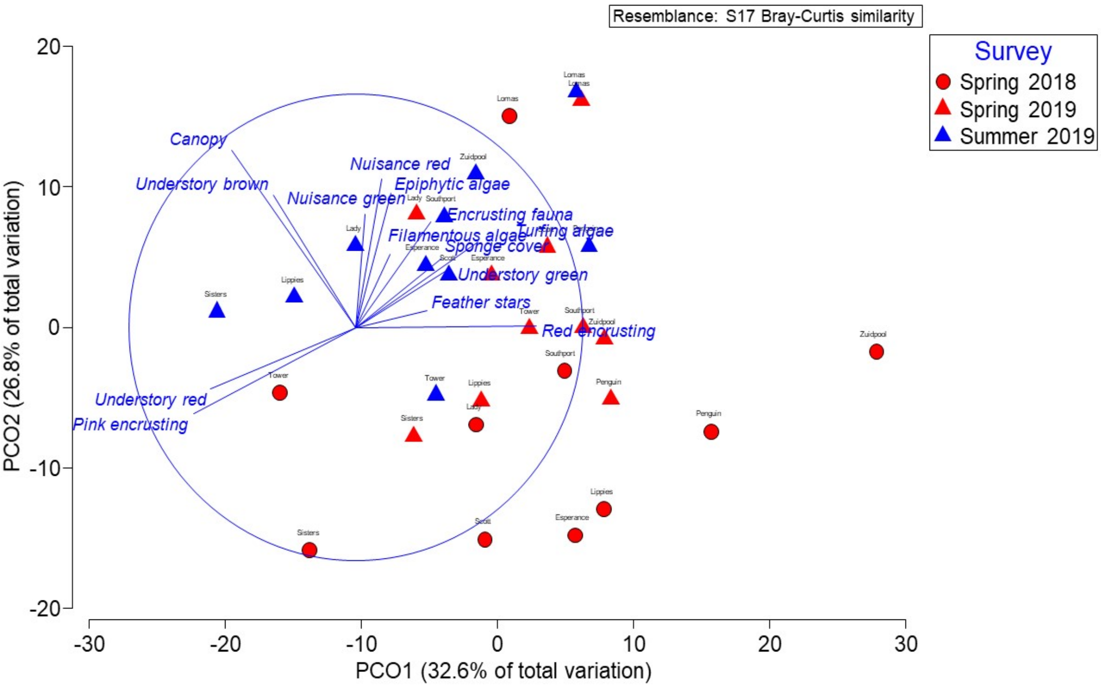


Figure 4. *Principle coordinates analysis (PCO) on RVA parameter values across sites during Spring 2018 and Summer and Spring 2019 sampling events a) including the Actaeons and b) without the Actaeons. Correlations between the first two principal coordinate axis and functional parameters are shown for parameters with r ⩾ 0.5. The length of the lines indicates the strength of the correlation, with the circle having a radius of 1.0.*

Table 3. *Pairwise comparison of function parameters across sampling events using PERMANOVA on the site averaged dataset. Asterisk denotes significant difference.*

Comparison	**t value**	**P(perm)**
Spring 2018 vs Spring 2019	1.4002	0.0969
Spring 2018 vs Summer 2019	1.6509	0.0197*
Spring 2019 vs Summer 2019	1.5723	0.0271*

Functional differences were largely due to differences in canopy cover in Summer 2019 compared to either of the spring sampling events, with variability in enrichment parameters between sampling events also observed (Figure 4). Both Zuidpool and Penguin were more likely to record high values for enrichment parameters in Summer 2019, but they clustered with the other sites in both spring sampling events, as indicated by vector correlations. In contrast, Lomas grouped with vectors for enrichment parameters, including epiphytic algae, nuisance red, encrusting fauna and filamentous algae, across all three sampling events, indicating that enrichment was generally higher at Lomas compared to all other sites (Figure 4).

Not surprisingly, cluster analysis indicated that the Actaeons (all sampling events) was different to all other sites (Figure 5). Zuidpool in Spring 2018 was also less similar (approximately 65%) than all other sites. Sites that tended to group around enrichment parameter vectors in the PCO analysis, Lomas (all sampling events), Zuidpool (Summer 19) and Penguin (Summer 19), formed a clear cluster at approximately 75% similarity to the remaining sites surveyed. The RVA surveys were successful in identifying sites that were subject to some degree of organic enrichment, although the effect of organic enrichment might be considered intermittent at some sites. For example, Lomas showed clear signs of enrichment across all three sampling events, whereas Zuidpool and Penguin showed characteristics of enrichment in Summer 2019 only.

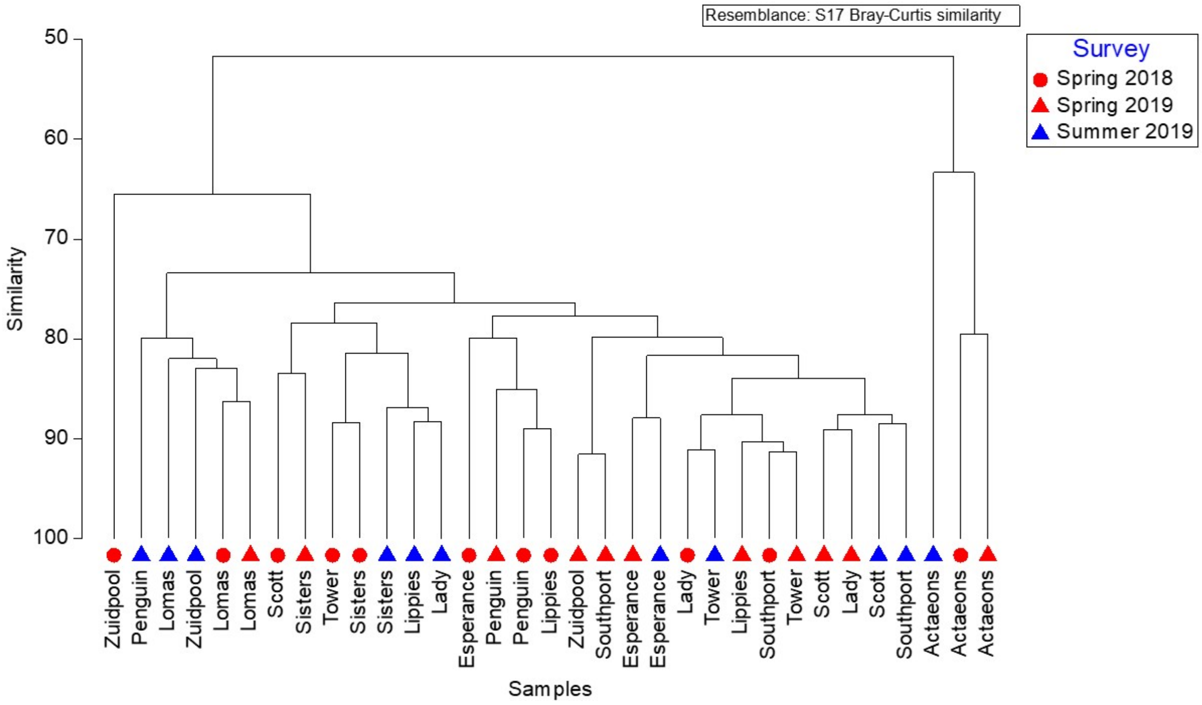


Figure 5. *Cluster analysis of the group average for each site based on site similarity for Spring of 2018 and both 2019 survey periods.*

Assessing the significance of organic enrichment on reef function

Multivariate analysis across three sampling events indicated that three sites (Lomas, Zuidpool and Penguin) are subject to organic enrichment. A strength of the RVA method is the capacity to detect concurrent shifts across multiple parameters using multivariate analysis. This is particularly useful in assessing organic enrichment, where several functional parameters would be expected to correlate strongly. For instance, in extreme cases of organic enrichment, losses of canopy might be expected along with increases in epiphytic, filamentous, opportunistic, as well as turfing algae (Russell et al. 2005, Connell et al. 2008, Oh et al. 2015). Assessing parameters in isolation limits the capacity to relate changes to organic enrichment. For example, loss of canopy could be due to environmental factors including storm events (e.g. Wernberg 2006), or overgrazing by pest species (e.g. Ling et al. 2015), whilst opportunistic species may respond to seasonal increases in light or nutrient availability (Smith et al. 2005, Krause-Jensen et al. 2007). By examining shifts in multiple parameters, we are using multiple lines of evidence to link cause and effect to organic enrichment. However, while multivariate analysis is valuable in indicating overall shifts across several parameters simultaneously, it does not define the magnitude of these shifts. Therefore, where multivariate analysis indicates there may be effects of organic enrichment seen in reef function, it is necessary to also examine the parameters individually. Data collected through FRDC 2015-024 for Summer 2018 (e.g. canopy cover, understory cover, epiphytic and filamentous algae) were also incorporated into the dataset to provide an additional point in the time series across these parameters.

Although the effect of season should be treated with caution given we only have two summer and two spring sampling events, the data indicated that canopy cover was higher in summer than spring (Figure 6, Table 4); average canopy cover across the region was ~ 75% in summer and ~ 53% in spring (Table 4). Typically, neither *Phyllospora comosa* nor *Ecklonia radiata*, the two dominant canopy-forming species found in the southern D'Entrecasteaux Channel, experience large-scale seasonal dieback or necrosis associated with change in water temperatures (Sanderson 1992, Bearham et al. 2013, Flukes et al. 2015, Coleman & Wernberg 2017). While both species have elevated growth rates as light and temperature increase, canopy dieback and recovery of the magnitude observed are more likely to be due to mechanistic rather than physiological processes (Wernberg & Goldberg 2008). Pruning via abrasion or wave disturbance can account for up to 50% biomass loss in *E. radiata*, with increased swells and lower light levels over winter in the southern D'Entrecasteaux Channel likely to exacerbate the noticeable effect of these processes (Kirkman 1984, Wernberg & Goldberg 2008). While a longer time series is necessary to properly evaluate natural fluctuations in canopy cover, our results indicate that changes of approximately 20-30% are within the natural variability of the system across this survey area (Figure 6, Table 4).

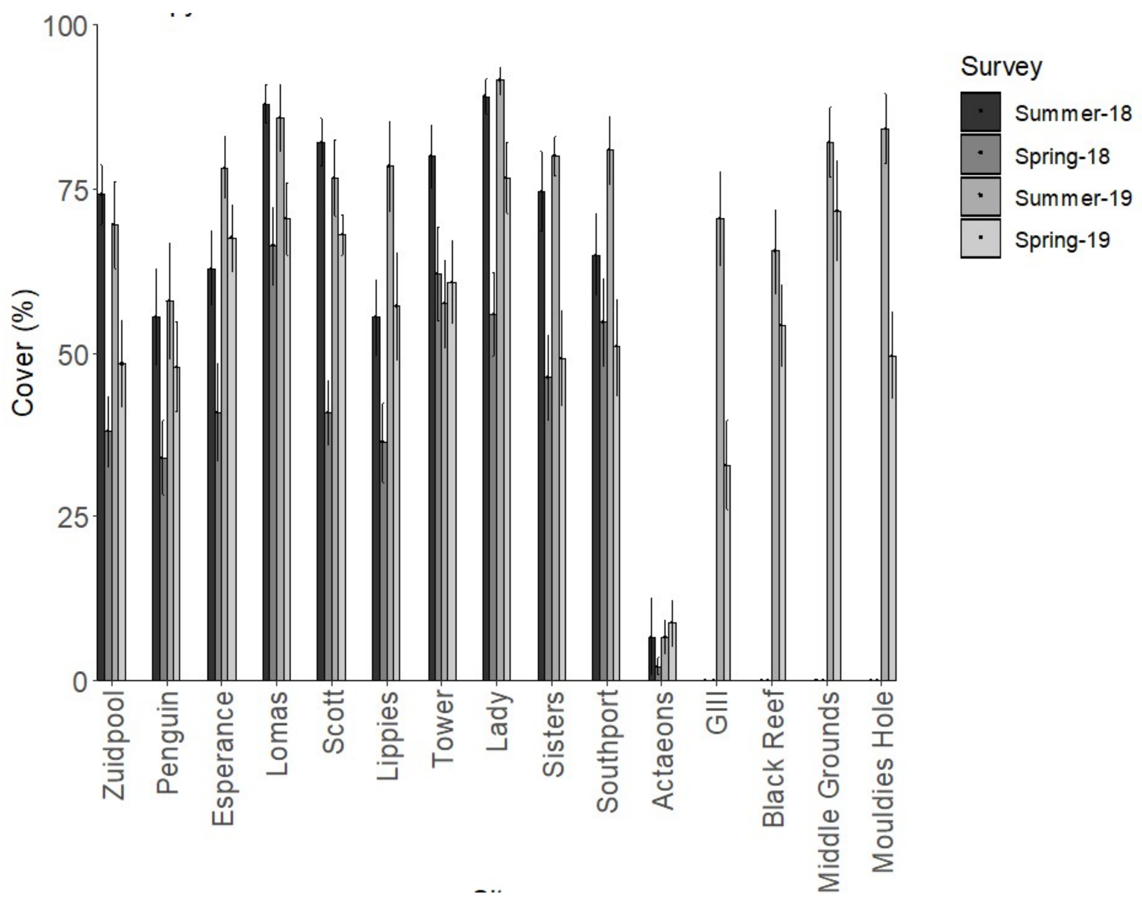


Figure 6. *Average canopy cover at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only.*

The exception was the Actaeons, which recorded much lower canopy than all other sites. However, as discussed above, the Actaeons was dominated by giant kelp, which tends to form canopies on the surface, rendering it unscorable using this method. Instead, RVA indicated that the Actaeons was dominated by green and red algae (Figure 7, Table 4). This is not surprising, as the giant kelp canopy is metres above the substrate, providing space subsidies to the understory with no mechanical abrasion to remove sporophytes (Breda & Foster 1985, Wernberg & Goldberg 2008). Lower light levels beneath the *Macrocystis* canopy were also likely to prohibit growth of a secondary brown algae canopy or understory.

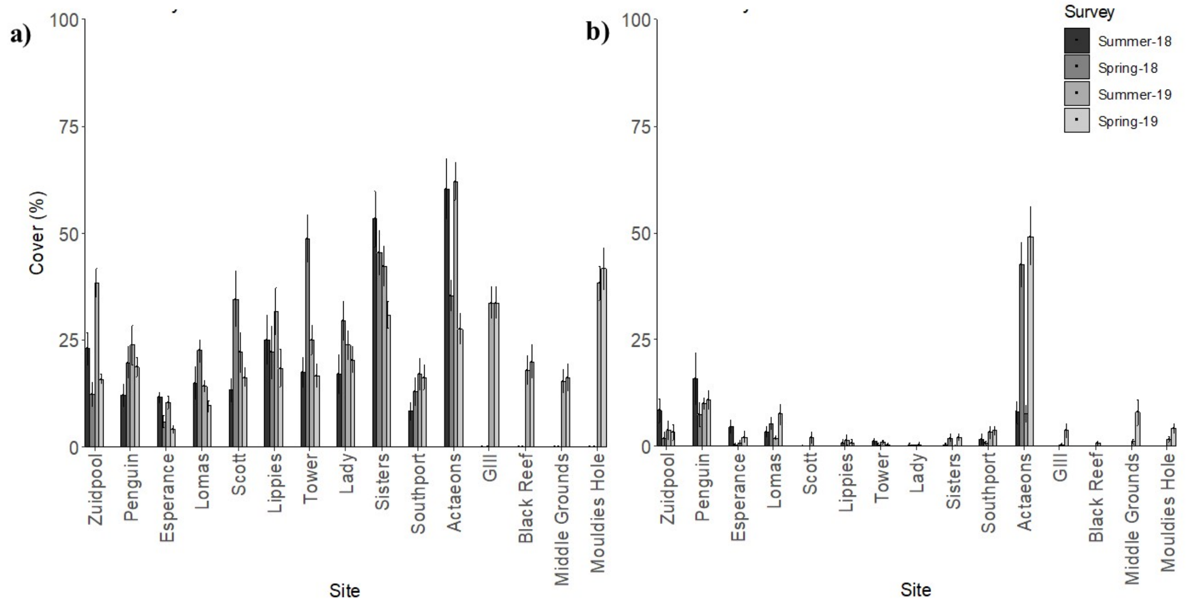


Figure 7. *Average cover of a) understorey red and b) understorey green at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only.*

Multivariate analysis indicated that the enrichment parameters likely to be occurring in higher levels at Lomas, Zuidpool and Penguin included epiphytic algae, filamentous algae, nuisance green algae, nuisance red algae and turfing algae. These parameters were therefore examined further to determine the extent of organic enrichment occurring at these sites. Overall, values for epiphytic algae tended to be higher at these three sites compared to all others, although average values were generally low, and only exceeded 25% cover once throughout the survey period (Spring 2018, Lomas) (Figure 8a). At sites where epiphyte exceeded 5% cover, there tended to be a seasonal trend, with higher values recorded in summer at Zuidpool and Penguin, although the reverse was true for Lomas (Figure 8). Similarly, filamentous algae were higher at Zuidpool, Penguin and Lomas than all other sites; however, they were only recorded in Summer 2019 in any notable cover (6%, 12% and 4% respectively) (Figure 8b).

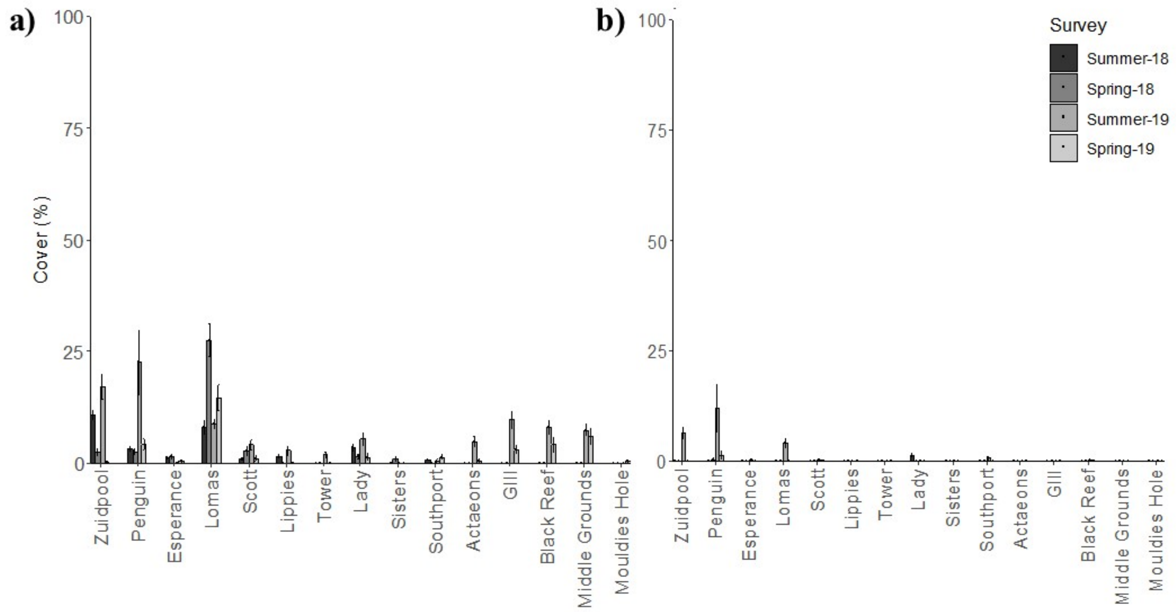


Figure 8. *Average cover of a) epiphytic algae and b) filamentous algae at all sites across 2018 and 2019 surveys. Note that data was collected at GIII, Black Reef, Middle Ground and Mouldies Hole in 2019 only.*

The RVA surveys also detected low levels of nuisance green algae including species such as *Chaetomorpha billiardeirii*, *Ulva/Enteromorpha* and *Cladophora* spp. While multivariate analysis indicated that this functional group was a key parameter characterising organic enrichment, the average cover for nuisance green algae was always less than 2.5% (Figure 9a, Table 4). Nuisance greens were recorded in negligible levels across the entire northern range of the study area and largely absent from the southern range of the study area (Figure 9a, Table 4). In contrast, nuisance red algae, typified in the southern D'Entrecasteaux Channel by *Asparagopsis armata*, were only found at Zuidpool, Penguin and Lomas (Figure 9b). At Zuidpool (7.5%) and Penguin (3.9%) they were only recorded in Summer 2019; however, at Lomas they were recorded in all of the four surveys (Table 4). At these value ranges, nuisance algae were unlikely to be playing a key role in driving shifts in reef function due to organic enrichment. However, in the case of Lomas, the consistent presence of nuisance species with their rapid growth life-history patterns does suggest a sustained source of nutrients.

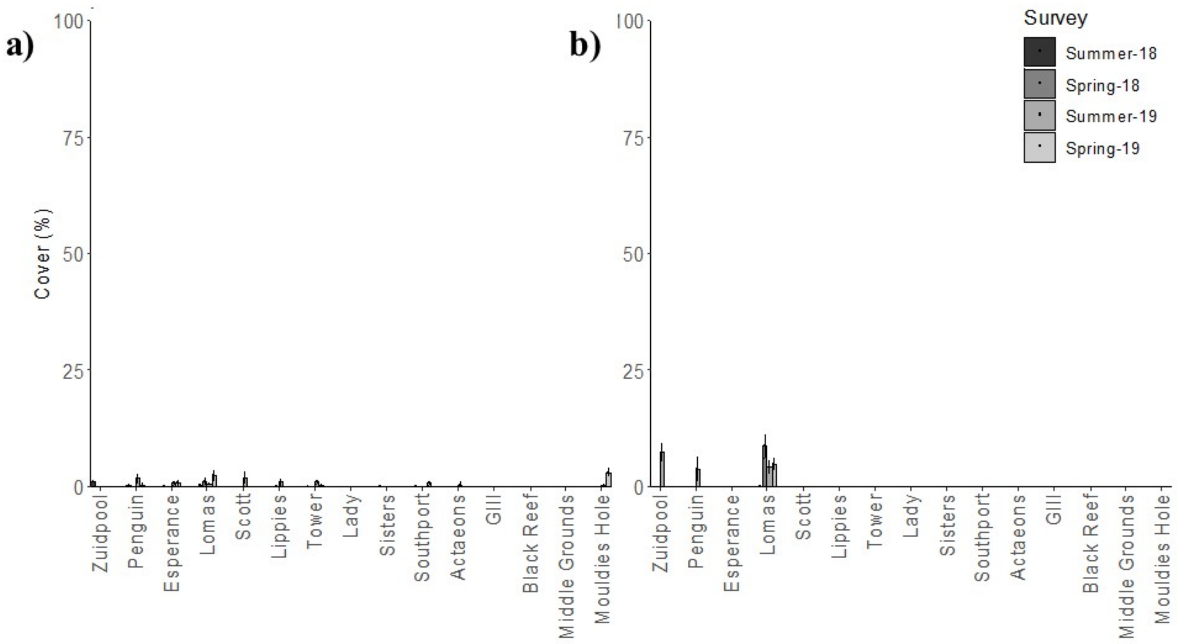


Figure 9. *Average cover of a) nuisance green algae and b) nuisance red algae at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only.*

Turfing algae were recorded at all sites and sampling events, although tended to have much higher cover at Zuidpool, Penguin and Lomas (Figure 10, Table 4). While turfing algae are flagged as inhibiting re-growth of canopy following dieback or clearance (Connell et al. 2008), Zuidpool, Penguin and Lomas all had healthy canopy cover. Thus, it is unlikely that turf algae have a large impact on reef function at the scale of this study.

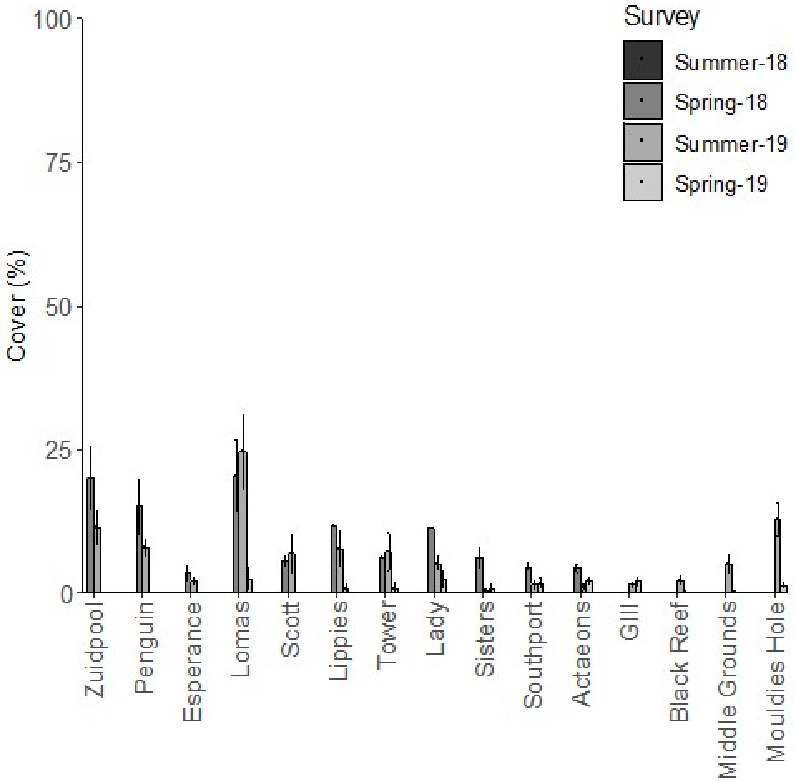


Figure 10*. Average cover of turfing algae at all sites across 2018 and 2019 surveys. Note that data were collected at George III, Black Reef, Middle Ground and Mouldies Hole in 2019 only.*

Table 4. *Average values for key functional parameters at all sites across 2018 and 2019 surveys. Note the blank cells indicate that no data was collected for that parameter during that survey.*

			Zuidpool	**Penguin**	**Esperance**	**Lomas**	**Scott**	**Lippies**	**Tower**	**Lady**	**Sisters**	**Southport**	**Actaeons**	**GIII**	**Black Reef**	**Middle Grounds**	**Mouldies**	**Yearly Ave**	**Seasonal Ave***
% Canopy	2018	Summer	74.2	55.4	62.9	87.9	82.1	55.4	80.0	89.2	74.6	65.0	6.7					55.0	74.4
		Spring	37.9	33.9	40.8	66.3	40.8	36.3	62.1	55.8	46.3	54.6	2.1						53.3
	2019	Summer	69.6	57.9	78.3	85.8	76.7	78.5	57.5	91.5	80.0	80.8	6.67	70.4	65.4	82.1	84.2	62.6	
		Spring	48.3	47.9	67.5	70.4	67.9	57.1	60.8	76.7	49.2	50.8	8.75	32.9	54.2	71.7	49.6		
% Understorey brown	2018	Summer	15.0	14.2	20.8	30.8	12.9	12.5	11.3	15.8	7.50	16.3	8.75					13.4	15.2
		Spring	10.8	5.75	11.7	21.7	6.50	8.33	19.2	9.67	13.3	10.8	11.3						13.4
	2019	Summer	12.5	5.92	20.0	16.7	11.7	15.4	13.8	17.1	14.2	17.9	18.8	23.8	10.6	11.4	20.0	14.9	
		Spring	16.3	11.3	21.7	20.4	12.9	10.0	14.6	16.3	15.4	15.0	10.8	16.3	12.9	10.8	13.5		
% Understorey green	2018	Summer	8.33	15.8	4.58	3.33	0.00	0.00	1.25	0.42	0.42	1.67	7.92					4.78	3.10
		Spring	1.75	7.42	0.42	5.25	0.00	0.83	0.42	0.17	1.92	0.83	42.5						6.04
	2019	Summer	3.75	10.0	0.83	1.92	2.08	1.50	1.08	0.50	0.08	3.33	7.67	0.42	0.83	1.17	1.58	4.41	
		Spring	3.33	10.8	2.08	7.50	0.00	0.83	0.42	0.00	2.08	3.67	49.2	3.75	0.00	7.92	4.08		
% Understorey red	2018	Summer	22.9	12.1	11.7	15.0	13.3	25.0	17.5	17.1	53.3	8.33	60.4					24.8	25.9
		Spring	12.3	19.8	6.00	22.5	34.6	22.1	48.8	29.6	45.4	12.9	35.4						22.9
	2019	Summer	38.3	23.8	10.4	14.2	22.1	31.7	25.0	23.8	42.3	17.1	62.1	33.8	17.9	15.4	38.3	24.1	
		Spring	15.8	18.8	4.17	9.58	16.3	18.3	16.7	20.4	30.8	16.3	27.5	33.8	20.0	16.3	41.7		
% Epiphytic algae	2018	Summer	10.7	3.08	1.17	7.92	0.83	1.50	0.00	3.50	0.00	0.67	0.00					3.09	4.67
		Spring	2.42	2.50	1.33	27.5	2.67	0.00	0.00	1.33	0.83	0.00	0.00						2.90
	2019	Summer	17.1	22.5	0.00	8.75	4.00	2.83	1.75	5.25	0.00	0.42	4.75	9.58	7.92	7.25	0.00	4.29	
		Spring	0.17	4.17	0.42	14.6	1.00	0.00	0.00	1.25	0.00	1.25	0.42	2.92	4.17	6.00	0.42		
% Filamentous algae	2018	Summer	0.00	0.08	0.00	0.08	0.08	0.00	0.00	1.42	0.00	0.00	0.00					0.10	1.00
		Spring	0.00	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00						0.07
	2019	Summer	6.42	12.1	0.42	4.00	0.33	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.33	0.00	0.00	0.86	

		Spring	0.00	1.42	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		
% Nuisance green	2018	Summer	1.17	0.42	0.25	0.33	0.00	0.00	0.25	0.08	0.17	0.25	0.00					0.20	0.43
		Spring	0.00	0.00	0.00	1.25	0.00	0.17	0.00	0.00	0.00	0.00	0.00						0.36
	2019	Summer	0.00	1.83	0.75	0.58	2.00	1.08	1.08	0.08	0.08	0.00	0.50	0.00	0.00	0.00	0.33	0.54	
		Spring	0.00	0.42	0.83	2.50	0.00	0.00	0.42	0.00	0.00	0.75	0.00	0.00	0.00	0.00	3.08		
% Nuisance Red	2018	Summer	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00					0.41	0.61
		Spring	0.00	0.00	0.00	8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00						0.53
	2019	Summer	7.50	3.92	0.00	4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.69	
		Spring	0.00	0.00	0.00	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
% Pink encrusting	2018	Summer																31.3	34.2
		Spring	10.2	28.8	38.8	21.3	29.2	32.9	54.2	38.3	45.4	23.8	22.1						31.3
	2019	Summer	22.9	24.6	39.2	23.8	30.8	51.3	34.2	39.2	37.1	30.8	25.6	40.0	43.3	45.0	25.8	32.7	
		Spring	23.8	33.8	40.4	21.3	23.8	36.7	27.1	25.0	27.1	21.7	17.5	41.7	38.8	55.4	35.0		
% Red encrusting	2018	Summer																26.0	20.7
		Spring	49.2	32.1	30.4	19.6	21.7	32.1	21.7	28.8	13.5	26.3	11.1						24.7
	2019	Summer	22.7	31.7	31.3	30.8	25.0	16.3	21.7	20.0	11.4	24.2	11.7	10.8	24.8	14.8	15.4	22.2	
		Spring	22.1	37.1	35.8	28.3	26.7	24.6	30.8	13.8	11.7	23.8	20.8	22.9	24.2	17.5	15.4		
% Sponge	2018	Summer	4.17	1.83	1.25	1.17	0.92	2.08	0.67	1.42	0.67	2.00	1.75					3.84	6.47
		Spring	17.7	9.08	2.67	5.33	4.58	5.33	2.67	5.50	2.67	7.25	3.83						10.8
	2019	Summer	14.1	6.83	3.58	11.0	6.67	6.42	3.67	10.4	8.00	18.8	6.08	6.42	9.75	24.2	14.6	12.2	
		Spring	24.2	12.1	7.50	7.92	14.6	10.4	7.92	14.6	7.92	27.1	21.3	9.58	15.0	14.6	19.6		
% Turfing algae	2018	Summer																9.90	6.49
		Spring	20.0	15.0	3.50	20.4	5.50	11.8	6.25	11.3	6.17	4.58	4.48						7.29
	2019	Summer	11.4	7.92	2.08	24.6	6.92	7.67	7.25	5.17	0.42	1.42	1.00	1.33	2.25	5.17	12.8	5.93	
		Spring	11.3	8.33	9.83	13.3	11.4	4.00	6.00	6.33	4.25	0.42	0.42	3.42	0.75	0.00	0.75		

* Seasonal average includes both 2018 and 2019 data

Overall, we recorded low to moderate values for enrichment parameters such as epiphytic and filamentous algae, along with nuisance red, nuisance green and turfing algae. At all sites except Lomas, these parameters tended to be seasonal and associated with summer sampling events. At Lomas, many of these parameters were sustained, albeit in low levels, across both survey periods. Sustained low to moderate cover of enrichment parameters, but an intact macroalgal canopy, may indicate low to moderate organic enrichment at that site (Connell et al. 2008, Oh et al. 2015). Losses of canopy, along with increases in opportunistic species may be more indicative of high or extreme organic enrichment, a scenario that was not observed as part of this study. While this might indicate that the method needs to be further tested in an environment subject to more extreme organic enrichment, it also highlights the potential of this method to be used to scale the effects of organic enrichment. A reef monitoring program that can produce a scale or index of organic enrichment for each site would be an invaluable tool for management (van Beusekom et al 2019).

Management of other environments in relation to salmon farming, such as soft sediment or pelagic systems, is dependent on identifying critical ecosystem changes or tipping points and their thresholds. The value at which a particular parameter exceeds a known compliance point (Macleod et al. 2004a, Macleod et al. 2004b, Ross & Macleod 2013, Keeley et al. 2015) becomes a key management value. The maximum cover of epiphytic or opportunistic species that a temperate reef can sustain without causing functional loss to an ecosystem is currently unknown. However, due to the inherent complexity in temperate reef ecosystems, it is likely to be dependent on a range of factors, including seasonality in wave energy and nutrient inputs.

In this study, loadings of epiphytic and filamentous species were negligible at most sites and only exceeded 25% once. With values for canopy cover generally greater than 50%, it is unlikely that the detected level of epiphytic growth was causing stress to the canopy. Oh et al. (2015) noted that where reef systems were 100 m or closer to active salmon farms at sheltered sites, epiphytic and filamentous species cover could be greater than 50%, however, even at these higher opportunistic species loadings, canopy brown algae appeared relatively stable at approximately 50% cover. If a large storm event removed the macroalgae from sites where there were simultaneously high epiphyte loads, it is unknown if the re-establishment of the canopy would be prevented by higher nutrient loadings and proliferation of opportunistic species, including sediment trapping algal turfs (Eriksson et al. 2002, Connell 2005, Connell et al. 2008). While a temperate reef may be resilient to relatively high loadings of epiphytic and opportunistic species, the sustained presence of these species may indicate ongoing vulnerability should disturbance lead to the clearance of the canopy.

The 2019 RVA resurvey of the southern D'Entrecasteaux Channel provided the means to a) establish a more comprehensive baseline for reef systems in this region and b) assess the performance of the RVA method over a longer timeframe than allowed through FRDC 2015-024. The RVA method performed well over the longer time series in the detection of low-moderate levels of organic enrichment across the survey area. However, to adequately manage temperate reef ecosystems there needs to be a much clearer understanding of the level of change that will lead to a significant alteration to ecosystem function. The RVA method is clearly a robust monitoring tool with potential to trigger more intensive and detailed investigation when the data analysis indicates a site is subject to enrichment (i.e. when enrichment indicators start to drive cluster separation through multivariate analysis). There also needs to be better understanding regarding the amount of epiphytic, filamentous or opportunist algal growth that indicates a reef ecosystem is vulnerable. Sustained presence of epiphytic and filamentous algae is a sign of an ecosystem under nutrient stress, and as the presence of these species increases, the potential for canopy loss also becomes more likely (Moy & Christie 2012, Norderhaug et al. 2015). While none of the sites in this study appeared to be under severe nutrient stress, ideally mitigation strategies would occur before a site reached this point. This study indicates that the RVA technique provides a potentially powerful tool for tracking functional change in reef function over time. To further validate this technique, it would be ideal to evaluate performance across acute enrichment gradients. In conjunction with ongoing monitoring using RVA, this will aid in determining thresholds for ecosystem function within the context of natural variability of the system.

ARM Resurvey

Abalone size structure

Abalone recorded underneath Abalone Recruitment Modules (ARMs) at Lippies Point and Sisters Bay were mostly <100 mm shell length (Figure 11; Figure 13) representing several age cohorts less than approximately four years of age. Similarly, established D'Entrecasteaux sites (Black Reef and George III) were comprised of abalone across a broad size range <100 mm SL but were generally dominated by abalone centred around 50 mm SL in all sampling periods. Regardless of the reason for the differences in size structure these observations clearly demonstrate that recruitment continued to occur across all sites.

In Autumn 2018, ARMs at Lippies were dominated by abalone centred around 40 mm SL compared to a bi-modal size structure in Autumn 2019 with a cohort of smaller individuals centred around 25 mm SL (Figure 11; Figure 13). Except for Trumpeter Bay North (TBN) which appears to have experienced a recent recruitment event given 75% of abalone were <50 mm SL during Autumn 2019, larger abalone centred around 40-50 mm SL also dominated the more established sites in Storm Bay (Figure 12; Figure 13). In contrast, size structures at Sisters Bay were dominated by smaller individuals <25 mm SL in Autumn 2018 followed by slightly larger abalone around 25-30 mm SL in Autumn 2019, a pattern consistent with earlier sampling periods. There are two possible explanations for these different patterns of size structure observed. Firstly, survival of juvenile abalone at established D'Entrecasteaux sites may be higher resulting in larger abalone being observed underneath ARMs. Alternatively, there may be a lack of suitable habitat at established D'Entrecasteaux sites and thus ARMs provide a more suitable refuge compared to Sisters Bay where available natural habitat may encourage juveniles to emigrate away from the ARMs. Establishing a longer time-series of observation and more experimental work will provide further insight to these observed differences.

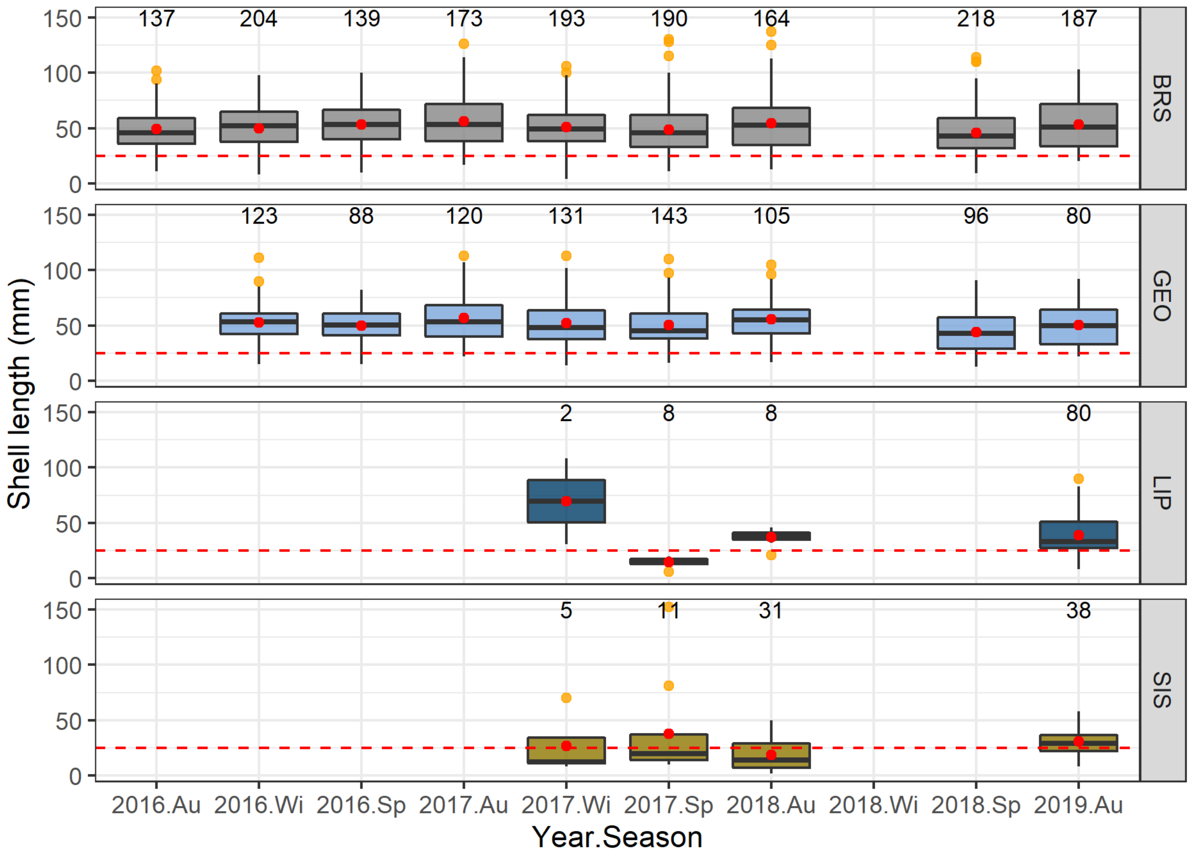


Figure 11. *Boxplot of size distributions for abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 D'Entrecasteaux Channel monitoring sites (site strings pooled). Red dot indicates mean shell length. Hashed red line represents a shell length of 25 mm as a reference to denote approximately the first 12-months of abalone growth. Total number of abalone measured within each season given above each boxplot. BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay.*

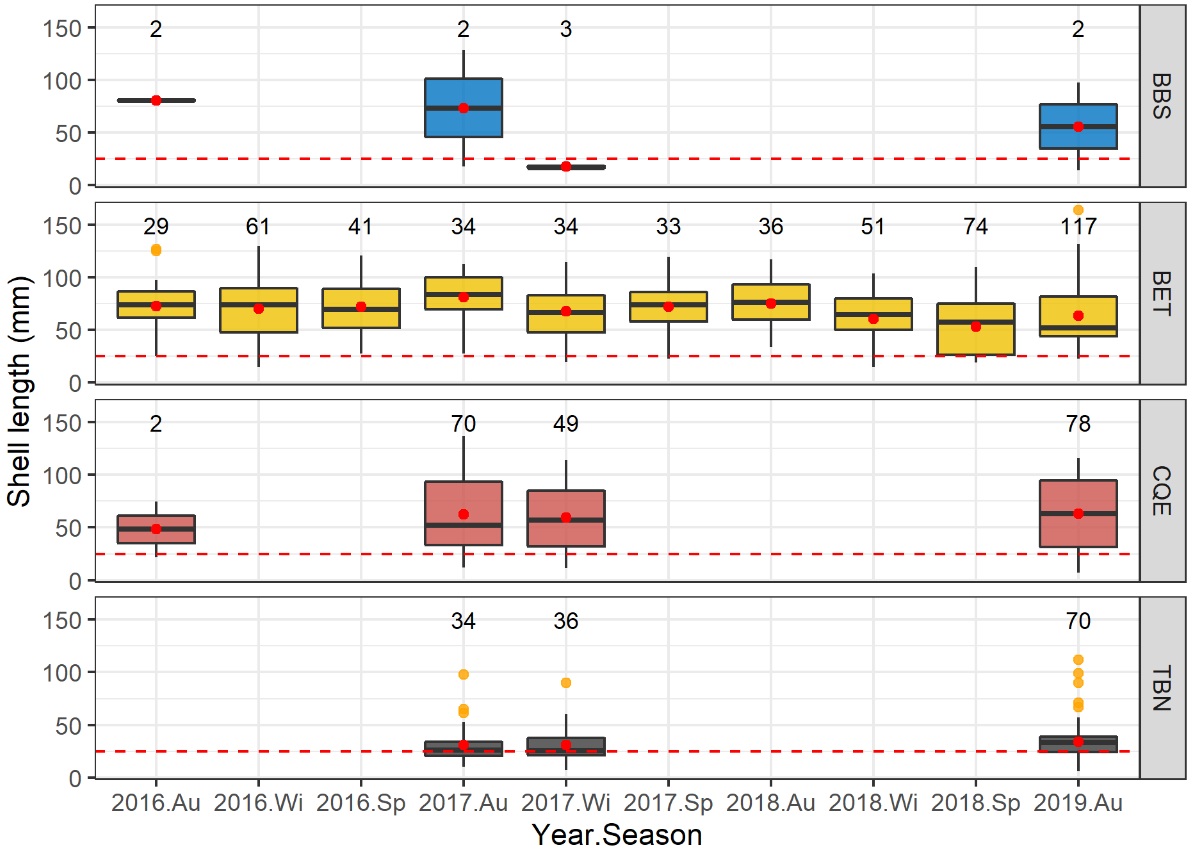


Figure 12. *Boxplot of size distributions for abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 Storm Bay monitoring sites (site strings pooled). Red dot indicates mean shell length. Hashed red line represents a shell length of 25 mm as a reference to denote approximately the first 12-months of abalone growth. Total number of abalone measured within each season given above each boxplot. BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North.*

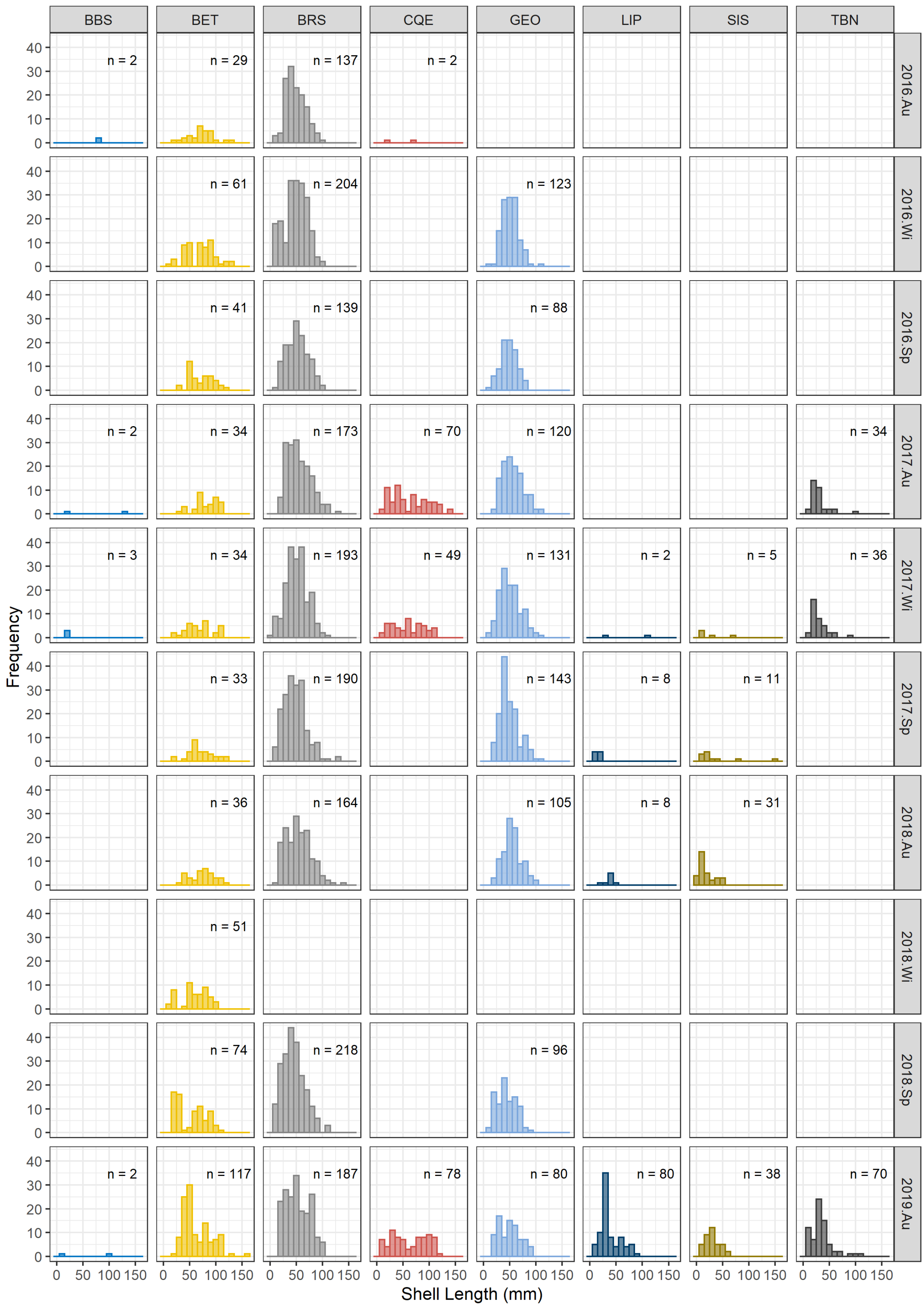


Figure 13. *Size frequency of abalone recorded underneath ARMs across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 monitoring sites (site strings pooled). Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. Total number of abalone measured during each sampling period are also given.*

Abalone density

Abalone density was negligible on ARM strings at Lippies Point in 2017 and 2018; however in Autumn 2019 (Figure 14; Figure 16) juvenile abalone density was 15 abalone m^{-2}, a substantial increase from the previous levels of ~ 2.5 abalone m^{-2} in Autumn 2018. In contrast, abalone density at Sisters Bay varied between strings across seasons but stabilised at around 5 and 10 abalone m^{-2} at strings two and one, respectively, between Autumn 2018 and 2019 (Figure 14; Figure 16). Similarly, densities at the control sites George III and Black Reef remained relatively stable but were much higher (George III: 25-30 abalone m^{-2}; Black Reef: 40-45 abalone m^{-2}; Figure 14, Figure 16). These site differences in density were not surprising and conformed to a fishery dependent catch history of supporting increasing catches from Lippies Point in a southward direction to Black Reef (Actaeon Islands).

Site appeared to have the most influence on density with those at the more established Black Reef and George III consistently higher than Lippies Point and Sisters Bay. Not surprisingly, the interaction between site and year indicated density at Lippies Point and Sisters Bay were considerably lower than established D'Entrecasteaux sites during the year they were installed (2017) but gradually started to record densities approaching those observed at George III. The most plausible explanation for the continued increase in density at Lippies Point and Sisters Bay is that these areas experienced some form of increased recruitment in recent times. Alternatively, ARMs could be undergoing a period of 'conditioning,' yet to attain a stable density baseline currently observed at the established D'Entrecasteaux sites. Although, the conditioning period at Black Reef, George III and Betsey Island appeared to be less than one year, suggesting that there may have been elevated recruitment in recent years. Interestingly, season appeared to have little effect on density, remaining relatively stable throughout the year and across sites. Thus, sampling is not sensitive to capturing seasonal trends in recruitment as part of an ongoing monitoring program.

The spatial and seasonal patterns observed in abalone abundance at the D'Entrecasteaux sites were comparable in Storm Bay (Figure 15; Figure 16). With the exception of Bull Bay South, all Storm Bay sites demonstrated a seasonal increase in density from Autumn 2017 to levels similar to those recorded at D'Entrecasteaux sites in Autumn 2019 (Figure 15; Figure 16). Site, year and season all appeared to influence density with site having the greatest effect, most likely the result of consistently low densities being recorded at Bull Bay South.

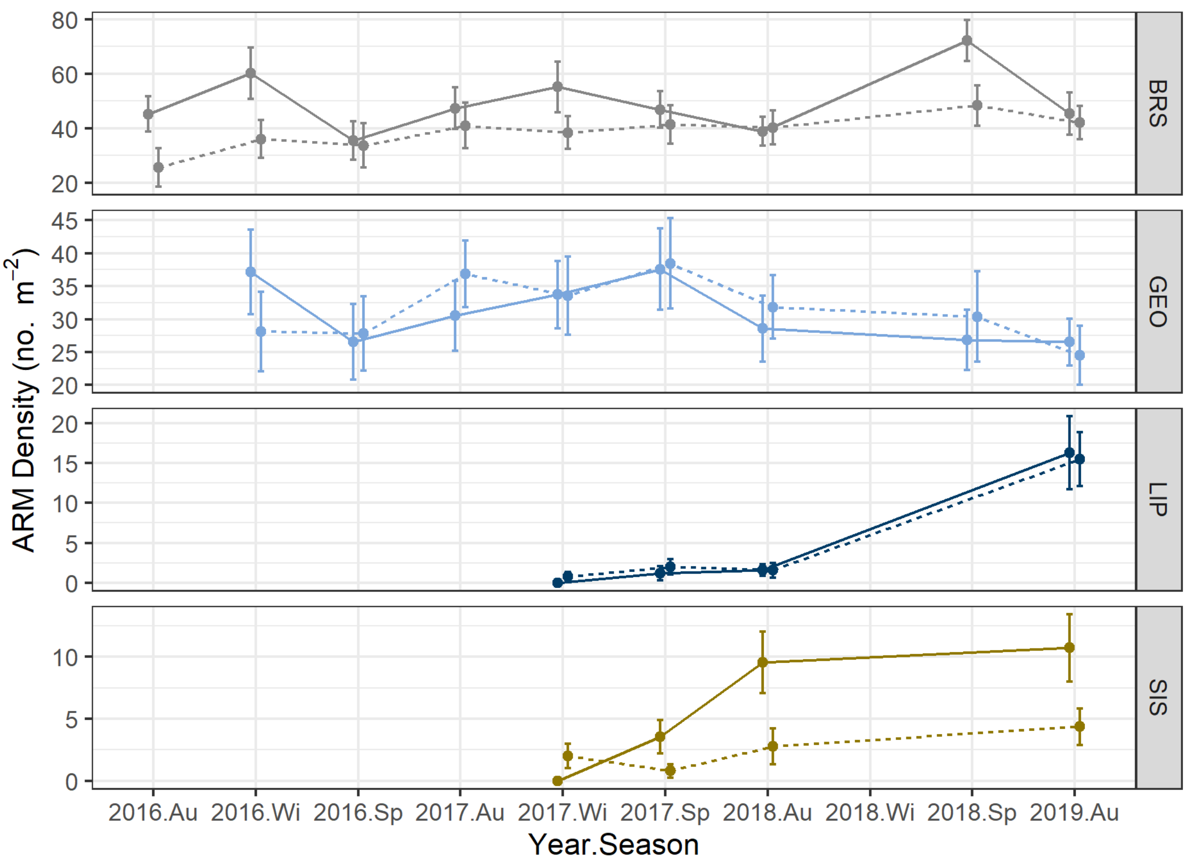


Figure 14. *Mean abalone density (no. m^{-2} ± SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 D'Entrecasteaux Channel monitoring sites. Each ARM had a planer surface area of 0.126 m^2. Replicate strings (sub-sites) denoted by line type. BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay. Note difference in density scale between sites.*

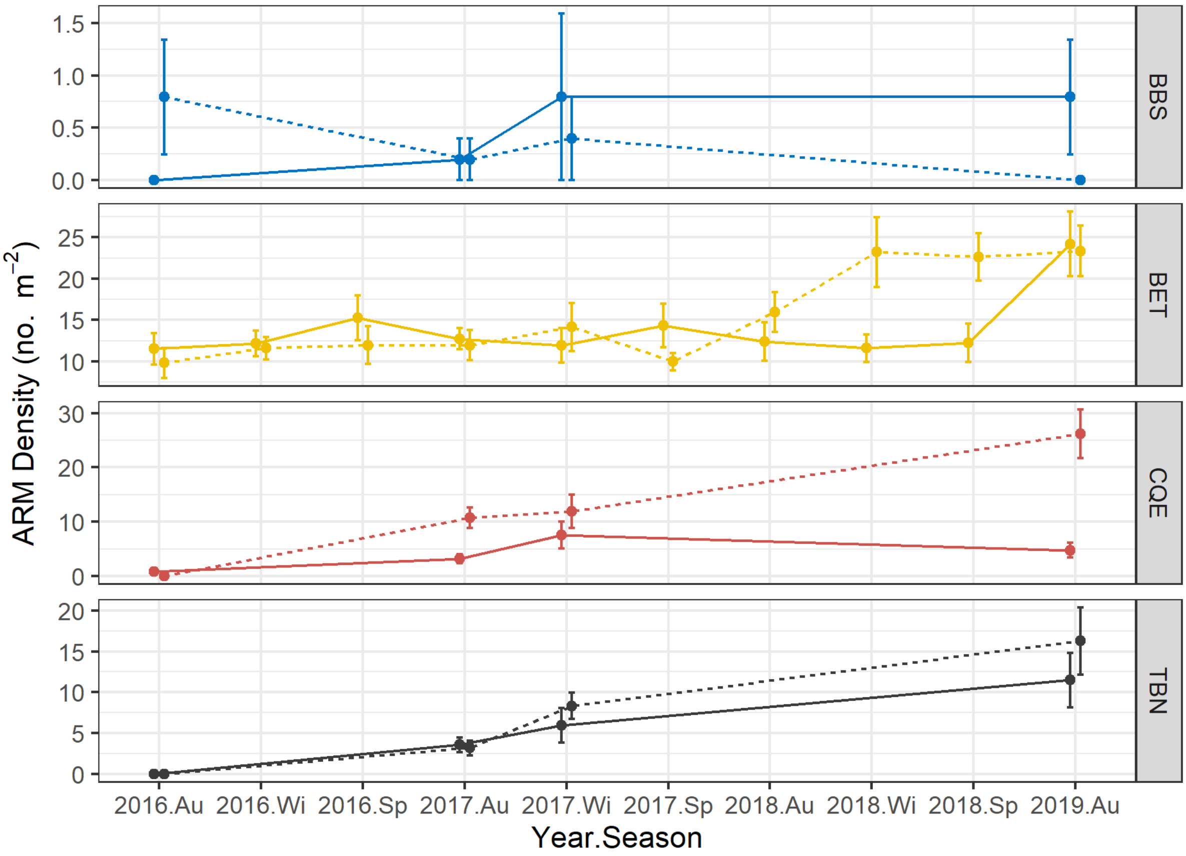


Figure 15. *Mean abalone density (no. m^{-2} ± SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 Storm Bay monitoring sites. Each ARM had a planer surface area of 0.126 m^2. Replicate strings (sub-sites) denoted by line type. BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North. Note difference in density scale between sites.*

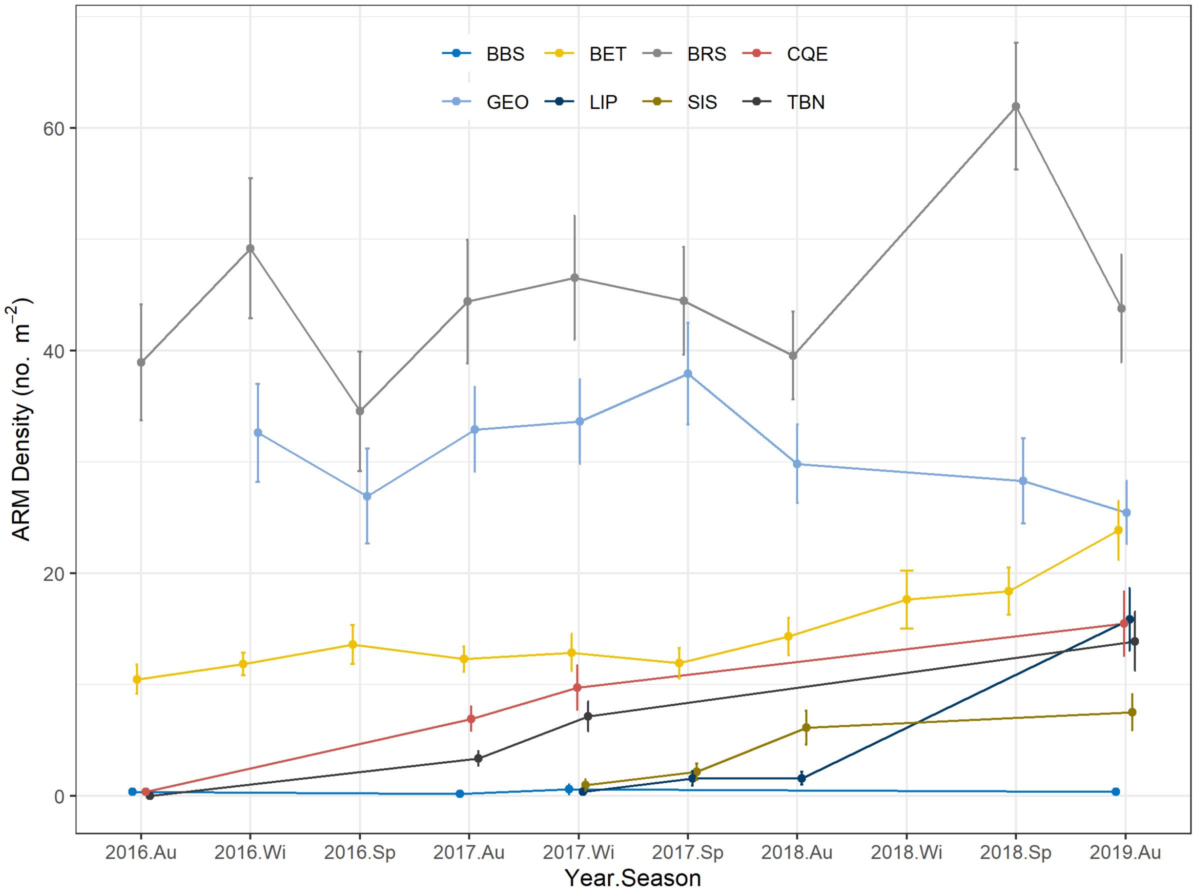


Figure 16. *Mean abalone density (no. m^{-2} ± SE) underneath ARMs recorded across the sampling period Autumn 2016 to Autumn 2019 at FRDC 2015-024 monitoring sites (site strings pooled). Each ARM had a planer surface area of 0.126 m^2. Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay.*

ARM ability to detect change

Cohen's D obtained from the D'Entrecasteaux sites from 2018 and 2019 Autumn ranged between 0.1 and 1.25, with 95% confidence intervals around D at all locations being relatively large (Table 5). Lippies Point was the only site to experience a significant increase in density between sampling periods which was supported by the relatively large Cohen's D (1.0-1.25). When translated to a Minimum Detectable Difference with a sample size of n = 20 individual ARM's at each location (i.e. a single transect), 84-106% and 127-174% change in density would be required to determine a significant change in density at Lippies Point and

Sisters Bay, respectively. In contrast, there was no significant change in density at the established sites between sampling events, potentially indicating that George III and Black Reef may be capable of detecting smaller changes in density (i.e. MDD = approx. 70%).

Although Cohen's D obtained from Storm Bay sites also ranged widely between 0.19 and 1.16 for the sampling period Autumn 2017, they generally appeared to have the ability to detect smaller changes in density. These observations possibly reflect the stabilisation in density at longer-established sites and suggests the ability of ARMs to detect smaller changes in density may improve with longer deployments and time-series of data.

***Table 5**. Sample means and effect size (Cohen's D) by site and string (1 or 2). Sample size was set at n = 20. MDD = Minimum Detectable Difference between sample means. % change = change in mean density from Autumn 2019 required for MDD and n = 20. Prob of Sig T = probability of a significant difference in density between 2017 and 2019 sampling periods (bold denotes significant differences where p < 0.01). Storm Bay sites: BBS = Bull Bay South, BET = Betsey Island, CQE = Cape Queen Elizabeth, and TBN = Trumpeter Bay North; D'Entrecasteaux Channel sites: BRS = Black Reef Slab, GEO = George III, LIP = Lippies Point, and SIS = Sisters Bay.*

Site	Mean abalone (no. m^{-2})	Prob of Sig T	Cohen's D 95% CI (Upper, Lower)	Pooled SD	MDD	% change
D'Entrecasteaux Channel (Autumn 2018 – Autumn 2019)						
BRS-1	38.9, 45.41	0.492	0.24 (-0.45 - 0.93)	27.47	32.14	71
BRS-2	40.32, 42.13	0.835	0.07 (-0.65 - 0.8)	24.38	28.52	68
GEO-1	28.55, 26.53	0.743	0.11 (-0.88 - 0.66)	16.93	19.81	75
GEO-2	31.83, 24.49	0.274	0.46 (-1.32 - 0.40)	15.99	18.71	76
SIS-1	9.52, 10.71	0.748	0.10 (-0.54 - 0.74)	11.64	13.62	127
SIS-2	2.78, 4.37	0.445	0.24 (-0.4 - 0.89)	6.50	7.61	174
LIP-1	1.59, 16.27	**0.005**	1.0 (0.32 - 1.68)	14.69	17.18	106
LIP-2	1.59, 15.48	**0.001**	1.25 (0.55 - 1.95)	11.09	12.97	84
Storm Bay (Autumn 2017 – Autumn 2019)						
TBN-1	3.57, 11.5	0.031	0.82 (0.25 - 1.39)	11.27	13.18	115
TBN-2	3.17, 16.3	**0.005**	1.14 (0.55 - 1.72)	13.66	15.98	102
CQE-1	3.17, 4.76	0.315	0.30 (-0.25 - 0.85)	5.52	6.46	136
CQE-2	10.71, 26.19	**0.004**	1.03 (0.45 - 1.61)	16.47	19.27	74
BBS-1	0.2, 0.79	0.316	0.34 (-0.21 - 0.89)	1.94	2.27	287
BBS-2	0.2, 0	0.324	0.19 (-0.74 - 0.36)	0.89	1.04	-
BET-1	12.73, 24.2	**0.010**	0.71 (-0.09 - 1.49)	13.84	16.19	67
BET-2	11.94, 23.34	**0.004**	1.16 (0.3 - 2.03)	9.49	11.11	48

Conclusions

Data collected through this project enabled us to better understand the functional health of reefs in the southern D'Entrecasteaux Channel and to establish a baseline in this region. The Rapid Visual Assessment (RVA) resurvey of the southern D'Entrecasteaux Channel provided the means to assess the performance of the method over a longer timeframe than allowed through FRDC 2015-024, which focused largely on method development rather than data collection. The resurvey also allowed us to establish data points at sites of importance to the abalone industry, such as Mouldies, Black Reef, Middle Ground and George III. From a functional perspective, these sites were very similar to established survey sites within the southern D'Entrecasteaux Channel.

RVA was found to perform well over the longer time series in the detection of low-moderate levels of organic enrichment across the survey area. Zuidpool, Penguin and Lomas showed signs of low-level organic enrichment. In Zuidpool and Penguin analysis indicated that enrichment effects were seasonal; at Lomas they appeared sustained throughout the survey period. To adequately manage activities of potential impact on temperate reef ecosystems there needs to be a much clearer understanding of the level of change that will result in a biologically significant alteration to ecosystem function. Ongoing monitoring of these sites could be conducted to provide greater resolution of natural variability and aid in the development of indicator thresholds for a loss of ecosystem function. This would help define the interaction between salmon aquaculture and reef health across the system.

Abalone Recruitment Modules (ARMs) provided a functional indication of abalone recruitment at monitoring sites throughout the D'Entrecasteaux Channel. Recruitment patterns largely conformed to trends in commercial catch productivity with higher recruitment at sites towards the southern Channel. For the period of the survey, recruitment appeared to remain stable or slowly increase at some sites such as Lippies Point. Low levels of juvenile abalone at Storm Bay sites is consistent with historically low levels of commercial catch over the past decade on North Bruny Island. Because some ARMs may still be undergoing a period of conditioning and the limited number of sites established, results should not be scaled up to represent the broader patterns of recruitment in the Channel, but rather only be interpreted in the context of site-specific changes in abundance.

The performance of the ARMs suggests they are best suited to detecting larger changes in abundance (i.e. >100% change) at the current sites in the Channel. Whilst a longer-term deployment may improve the ability of ARMs to detect smaller changes in abundance such as the case at George III and Black Reef Slab, an important consideration in continuing to monitor the ARMs will be understanding the level of change required before initiating a management response. Installing additional ARMs to track system wide change or to detect smaller magnitude changes in abundance would clearly come at significant cost. Therefore, ongoing monitoring program using ARMs may be better targeted at assessing specific sites of interest rather than attempting to provide detailed coverage of the whole region.

Both the RVA method and ARM modules provide important insight into different aspects of reef function. For a more integrated assessment of reef health the RVA method is most suitable. Monitoring the recruitment of a commercially important species in abalone using ARM's on the other hand addresses an industry focus, but they could be included in a broader program depending on priorities. The overall choice of methods used in any ongoing reef monitoring program will ultimately depend on the management question of interest.

References

Anderson,M.J., Gorley, R.N., Clarke, K.R., 2008. PERMANOVA+ for PRIMER: Guide to Software and Statistical Methods. PRIMER-E, Plymouth, UK.

Benedetti-Cecchi L, Pannacciulli F, Bulleri F, Moschella PS, Airoldi L, Relini G, Cinelli F (2001) Predicting the consequences of anthropogenic disturbance: large-scale effects of loss of canopy algae on rocky shores. Mar Ecol Prog Ser 214:137-150

Breda VA, Foster MS (1985) Composition, abundance, and phenology of foliose red algae associated with two central California kelp forests. J Exp Mar Biol Ecol 94:115e130

Burkepile DE, Hay ME (2006) Herbivore vs. nutrient control of marine primary producers: context-dependent effects. Ecology 87:3128-3139

Coleman MA, Wernberg T (2017) Forgotten underwater forests: The key role of fucoids on Australian temperate reefs. Ecol Evol 7:8406-8418

Connell SD (2005) Assembly and maintenance of subtidal habitat heterogeneity: synergistic effects of light penetration and sedimentation. Mar Ecol Prog Ser 289:53-61

Connell SD, Irving AD (2008) Integrating ecology with biogeography using landscape characteristics: a case study of subtidal habitat across continental Australia. J Biogeogr 35:1608-1621

Connell SD, Russell BD, Turner DJ, Shepherd SA, Kildea T, Miller D, Airoldi L, Cheshire A (2008) Recovering a lost baseline: missing kelp forests from a metropolitan coast. Mar Ecol Prog Ser 360:63-72

Eriksson BK, Johansson G, Snoeijs P (2002) Long-term changes in the macroalgal vegetation of the inner Gullmar Fjord, Swedish Skagerrak coast. J Phycol 38:284-296

Flukes EB, Johnson CR, Wright JT (2014) Thinning of kelp canopy modifies understory assemblages: the importance of canopy density. Mar Ecol Prog Ser 514:57-70

Flukes EB, Wright JT, Johnson CR, Wernberg T (2015) Phenotypic plasticity and biogeographic variation in physiology of habitat-forming seaweed: response to temperature and nitrate. J Phycol 51:896-909

Gorman D, Russell BD, Connell SD (2009) Land-to-sea connectivity: linking human-derived terrestrial subsidies to subtidal habitat change on open rocky coasts. Ecol Appl 19:1114-1126

Graham MH (2004) Effects of local deforestation on the diversity and structure of Southern California giant kelp forest food webs. Ecosystems 7:341-357

Keeley N, Gillard M, Broekhuizen N, Ford R, Schuckard R, Urlich SC (2015) Best-practice guidelines for salmon farm management in the Marlborough Sounds, Part 1: Benthic environmental quality standards and monitoring protocol. Benthic Standards Working Group, Wellington

Kirkman H (1984) Standing stock and production of Ecklonia radiata (C. Ag.) J. Agardh. J Exp Mar Biol Ecol 76:119e130

Krause-Jensen D, Middelboe AL, Carstensen J, Dahl K (2007) Spatial patterns of macroalgal abundance in relation to eutrophication. Mar Biol 152:25-36

Lavery PS, Mccomb AJ (1991) Macroalgal Sediment Nutrient Interactions and Their Importance to Macroalgal Nutrition in a Eutrophic Estuary. Estuar Coast Shelf S 32:281-295

Layton C, Shelamoff V, Cameron MJ, Tatsumi M, Wright JT, Johnson CR (2019) Resilience and stability of kelp forests: The importance of patch dynamics and environment-engineer feedbacks. Plos One 14:1-27

Ling SD, Scheibling RE, Rassweiler A, Johnson CR, Shears N, Connell SD, Salomon AK, Norderhaug KM, Pérez-Matus A, Hernández JC, Clemente S, Blamey LK, Hereu B, Ballesteros E, Sala E, Garrabou J, Cebrian E, Zabala M, Fujita D, Johnson LE (2015) Global regime shift dynamics of catastrophic sea urchin overgrazing. Philosophical Transactions of the Royal Society B: Biological Sciences 370

Macleod C, Bissett A, Burke C, Forbes S, Holdsworth D, Nichols P, Revill A, Volkman J (2004a) Development of Novel Methods for the Assessment of Sed Condition and determination of management protocols for sustainable finfish cage aquaculture operations. Aquafin CRC Project 41/ FRDC 2000/164. Tasmanian Aquaculture and Fisheries Institute, Hobart, Tasmania

Macleod CK, Crawford CM, Moltschaniwskyj NA (2004b) Assessment of long term change in sediment condition after organic enrichment: defining recovery. Mar Pollut Bull 49:79-88

Mata L, Schuenhoff A, Santos R (2010) A direct comparison of the performance of the seaweed biofilters, Asparagopsis armata and Ulva rigida. J Appl Phycol 22:639-644

Moy FE, Christie H (2012) Large-scale shift from sugar kelp (Saccharina latissima) to ephemeral algae along the south and west coast of Norway. Mar Biol Res 8:309-321

Mundy, C. N., Pyke, S., McAllister, J., & Jones, H. A. (2018). Development of a juvenile abalone monitoring method. Fisheries Research and Development Corporation Project 2014-10. Institute for Marine and Antarctic Studies, Hobart, Tasmania.

Nelson TA, Haberlin K, Nelson AV, Ribarich H, Hotchkiss R, Van Alstyne KL, Buckingham L, Simunds DJ, Fredrickson K (2008) Ecological and physiological controls of species composition in green macroalgal blooms. Ecology 89:1287-1298

Norderhaug KM, Gundersen H, Pedersen A, Moy F, Green N, Walday MG, Gitmark JK, Ledang AB, Bjerkeng B, Hjermann DO, Trannum HC (2015) Effects of climate and eutrophication on the diversity of hard bottom communities on the Skagerrak coast 1990-2010. Mar Ecol Prog Ser 530:29-46

Oh ES, Edgar GJ, Kirkpatrick JB, Stuart-Smith RD, Barrett NS (2015) Broad-scale impacts of salmon farms on temperate macroalgal assemblages on rocky reefs. Mar Pollut Bull 98:201-209

Paul NA, Nys Rd, Steinberg PD (2006) Seaweed–herbivore interactions at a small scale: direct tests of feeding deterrence by filamentous algae. Mar Ecol Prog Ser 323:1-9

Pyke, S.J., McAllister, J., Faloon, D., and Mundy, C.N. (2017). Abalone Recruitment Modules (ARMs): Installation and Servicing. Standard Operating Procedures including Underwater Drilling Equipment. Page 29. Institute for Marine and Antarctic Studies, Hobart, Tasmania.

Ross J, Macleod C (2013) Evaluation of Broadscale Environmental Monitoring Program (BEMP) data from 2009-2012. Book Technical Report Institute for Marine and Antarctic Studies, Hobart, Tasmania

Russell BD, Connell SD (2005) A novel interaction between nutrients and grazers alters relative dominance of marine habitats. Mar Ecol Prog Ser 289:5-11

Russell BD, Elsdon TS, Gillanders BM, Connell SD (2005) Nutrients increase epiphyte loads: broad-scale observations and an experimental assessment. Mar Biol 147:551-558

Sanderson CJ (1992) Subtidal macroalgal studies in east and south eastern Tasmanian coastal waters. MSc Thesis, University of Tasmania, Hobart. MSc Thesis, University of Tasmania, Hobart

Shelamoff V, Layton C, Tatsumi M, Cameron MJ, Wright JT, Johnson CR (2019) Patch size and density of canopy-forming kelp modify influences of ecosystem engineering on understorey algal and sessile invertebrate assemblages. Mar Ecol Prog Ser 632:59-79

Smith JE, Runcle JW, Smith CM (2005) Characterization of a large-scale ephemeral bloom of the green alga Cladophora sericea on the coral reefs of West Maui, Hawai'i. Mar Ecol Prog Ser 302:77-91

Stuart-Smith RD, Barrett NS, Crawford C, Edgar GJ, Frusher S (2008) Condition of rocky reef communities: A key marine habitat around Tasmania. NRM/NHT Final Report. Tasmanian Aquaculture & Fisheries Institute, Hobart, Tasmania

Teagle H, Hawkins SJ, Moore PJ, Smale DA (2017) The role of kelp species as biogenic habitat formers in coastal marine ecosystems. J Exp Mar Biol Ecol 492:81-98

Van Beusekom JEE, Carstensen J, Dolch T, Grage A, Hofmeister R, Lenhart H, Kerimoglu O, Kolbe K, Patsch J, Rick J, Ronn L Ruiter H (2019) Wadden Sea eutrophication: long-term trends and regional differences. Front Mar Sci 6:370

Wernberg T (2006) Scale of impact determines early post-disturbance assemblage structure in subtidal Fucus beds in the Baltic Sea (Bornholm, Denmark). Eur J Phycol 41:105-113

Wernberg T, Goldberg N (2008) Short-term temporal dynamics of algal species in a subtidal kelp bed in relation to changes in environmental conditions and canopy biomass. Estuar Coast Shelf Sci 76:265-272

Appendix I: Scorecard developed for assessing functional change on temperate reef ecosystems

Circle Quadrat #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Total % canopy												
Pcom / Sarg %												
Era / others %												
% Sub canopy brown + major spp.												
% Sub-canopy green + major spp.												
% Sub-canopy red												
% Epiphytic algae on kelp												
% Filamentous algae												
% *Ulva/ Chaetomorpha*												
% *Asparagopsis*												
Substrate characterisation												
% UALC & type Pink vs. Att. Red	P R	P R	P R	P R	P R	P R	P R	P R	P R	P R	P R	P R
% Sponge & type												
% Turfing algae												
# Feather stars												
MMI spp and #												
Dust on algae (H/M/L/N)?												
Enc. spp. on algae? (H/M/L/N)												