Determining when and where to fish: Linking scallop spawning, settlement, size and condition to collaborative spatial harvest and industry in-season management strategies

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Contents

List of Tables

List of Figures

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Abbreviations

BSCZSF Commonwealth Bass Strait Central Zone Scallop Fishery

GW Gonad weight

MW Adductor muscle weight

OSF Victorian Ocean Scallop Fishery

SH Shell height

SL Shell length

SW Shell width (depth)

TSF Tasmanian Scallop Fishery

TRSF Tasmanian Recreational Scallop Fishery

Executive Summary

Commercial scallop (*Pecten fumatus*) fisheries were overfished in southeast Australia from their inception in the 1920s right up until the late 1980s, when there were no productive scallop grounds left in the region. Because of this historical overfishing, current management of the harvest faces the significant challenge of trying to rebuild the stock and recruitment. The present study, undertaken by University of Tasmania's Institute for Marine and Antarctic Studies, was developed to critically examine spatial harvest strategies employed in the southeast Australian commercial scallop fisheries, which aim to buffer against recruitment variation to increase both production and continuity between seasons. As part of the Commonwealth Bass Strait Central Zone Scallop Fishery (BSCZSF) harvest strategy and the Tasmanian Scallop Fishery (TSF) Management Plan, pre-season surveys determine areas to be opened/or closed during the upcoming season. Known areas with >20% discard rate are closed to fishing, regardless of scallop quality and potential for opening during the season. A detailed characterization of morphometric relationships across different locations would permit greater confidence in the use of the relationships that exist between various measurements used. Additionally, scallops in the areas opened can be unsuitable for harvest due to poor condition when the season opens. This means the areas are opened then rapidly closed to fishing again, causing disruption to fishing/processing businesses, and marketing problems. Delayed opening while scallops gain condition can also prevent the total catch being taken because there is a fixed, pre-determined finish date. The fixed finish dates have been established to protect settling scallop spat, which traditionally occurs between September and December following spawning between August and October. The problem with poor condition at the start of the season has arisen because scallops are increasingly reaching spawning condition between December and February, particularly in the BSCZSF. As well as potentially putting settling scallops at risk through impacts upon opening the fishery, this late development is also contributing to difficulty in providing well-conditioned scallops throughout the season. This study aimed to better define timing of scallop spawning based on gonad condition, and hence potential settlement of recruits across the different populations/beds of the fishery and determine any differences in spawning potential among scallop beds/locations. Additionally, this project aimed to define differences in spawning potential between scallops ranging from 80 to 90 mm shell length (SL) and assess the size limits used to define a bed as commercially viable across the three southeast Australian jurisdictions. Furthering our understanding of growth rate in several fishing locations across all three jurisdictions may also allow better management of individual beds and in addition to scallop condition will be used to inform current season openings and closings. An overall aim was to also provide information that will allow the jurisdictions greater capacity to work together to facilitate effective management for the fishery as a whole.

Objectives

Specifically, this study aimed to: 1) better define the timing of spawning and settlement of commercial scallops across the three fisheries; 2) better define differences in spawning potential between scallops

ranging from 80 to 90 mm and gain an understanding of growth rate in this size range; 3) define agreed operational measures of spawning condition for use in the scallop fisheries; 4) establish season openings and closings that are more responsive to annual changes in spawning condition and timing of settlement; 5) define an agreed use of the minimum size limit and 20% discard rule to open/close individual beds; and 6) incorporate spawning condition and a more focused use of the 20% discard rule into cooperative spatial harvest and industry in-season management strategies to enhance the operation and profitability of the fisheries.

Methods

Biological data was collected via specific sampling for this project, along with collating data from previous FRDC projects and dredge surveys in the BSCZSF and TSF. This allowed for data from 2004 to 2017 and across multiple beds in the BSCZSF, TSF, the Victorian Ocean Scallop Fishery (OSF), as well as the Tasmanian Recreational Scallop Fishery (TRSF), to be compiled and analysed. Shell length (SL)-shell height (SH) and SL-shell width (SW, also referred to as shell depth) relationships were examined at each location. Size (SL) frequency data was examined for growth analysis. Identifying cohorts of scallops (those animals that settled at the same time) and tracking each cohort through time enabled the growth trajectory to be estimated at each site. The relationship between the initial mean size of the identified cohorts and their growth increments over the time was described. The effect of year and season on muscle, gonad and meat recovery weight (muscle and gonad weight combined) were evaluated. Muscle and gonad weight indices were calculated as the muscle or gonad weight divided by the shell length and multiplied by 100. Scallop gonads were categorized according to the existing macroscopic (visual) staging scheme for commercial scallops and compared to histological observations to assess the accuracy of the macroscopic technique to identify reproductive stages. Gonad volume and mean oocyte (egg) count determined from histology were used to estimate fecundity (total number of eggs) and compare it across different scallop sizes.

Key Findings

As we expected from their biology, changes in muscle weight, gonad weight and meat recovery weight (combined meat and gonad weight) in the commercial scallop are influenced by season, as both muscle and gonad weight are influenced by the gametogenic cycle, but this relationship is affected by year. In fact, there is no common trend in changes in muscle, gonad and combined weight across areas, instead the changes are area-specific and year-specific and can vary considerably. The difference in muscle, gonad and combined weight is at such a magnitude that economically, it warrants increased investigation prior to or at the start of the fishery. This is particularly relevant in the TSF, when only relatively small areas of the fishery are opened at any one time and the remainder of the fishery is closed, although the adaptive in-season management model in this fishery (i.e., open area boundaries can be changed during the season) can overcome this issue in some circumstances. In the BSCZSF and OSF, given only relatively small areas of the fishery are closed during the fishing season or the entire fishery is opened, respectively, there may be a greater opportunity for scallop fishers to find beds with higher muscle, gonad and combined weights, although this is of course dependant on the number of different beds available, with limited to no scallop beds available for harvest in the OSF for over two decades. Furthermore, without adaptive in-season management, which is the case in the BSCZSF (i.e., spatial closures are not adjusted during the fishing season), there is the potential for the best quality scallops to be 'locked-up' in spatial closures for the entire season.

Maturity stages identified macroscopically did not consistently match the maturity stages identified by histological sampling. Apart from macroscopic stage 2, which comprised scallops with predominantly gonads in the developing stage, the other macroscopic stages showed a mixture of reproductive stages. Therefore, while the macroscopic staging scheme is useful to derive a general indication of gonad condition, it does not accurately reflect the maturity stage in the ovary.

Based on microscopic observations compared to macroscopic examination of gonads, three visual stages are described based on the morphological appearance of the gonad to the naked eye: Developing or spent; maturing or atretic (reabsorbing eggs as spawning is delayed); and partially spawned. Fishing in the Commonwealth predominately takes place in the beds or regions surveyed before the season commences. Similarly, the TSF only opens to fishing surveyed areas that meet the management plan. While the OSF does not use surveys to determine open areas, as it is not a spatially managed fishery, fishing generally occurs in traditional areas, which will have variable gonad development and spawning timings within and between them. As such, the simple three stage visual classification system developed in this project is useful to both scallop resource managers and industry, as part of in-season management strategies, to define the overall reproductive stage of scallops and predict timing of spawning, thus assisting in the best condition scallop beds being fished sequentially throughout the season.

Collection of data on scallop condition, reproductive stages and settlement rates collectively can help inform best timing for season opening and closing dates in each location. The information available from this study and previous studies, suggest that the Lakes Entrance region, which comprises the majority of the OSF, would profit from an early start during winter. However, note that the OSF is currently considered depleted and has not had significant catches in over two decades. This in part may be attributable to the fact that the fishery has historically been open continuously throughout the year, including the settlement period. At White Rock in the TSF, starting the fishery in September would appear more beneficial in terms of harvesting the best product, although this may not fit best with protecting newly settled scallops, and may in part explain why this area has not supported a fishery in recent years and is now classified as depleted. At the Bass Strait site in the eastern section of the BSCZSF, the best time to fish appears to be spring and summer/autumn. Fishing up to the closing date of December 31 may not fit best with protecting newly settled scallops, with the major settlement period occurring in spring, and again may in part explain why this area has not been viable in recent years. At King Island, in the BSCZSF, the best time to fish appears to be spring and summer, however, settlement occurs from approximately November to January.

Fecundity increased exponentially with SL and modelling predicted that a scallop measuring 90 mm in shell length would be 13 and 25% more fecund than an 85 and 80 mm scallop, respectively. Furthermore, an 80 mm scallop would be 44% more fecund that a scallop measuring 70 mm in SL. Scallops measuring 100 mm in SL would produce 32% more eggs than a scallop measuring 90 mm. These differences are less dramatic than previous findings where 3+ years old scallops measuring ~90 mm SL shed (3.5 million eggs on average) compared to 2 million eggs shed by scallop measuring ~ 83 mm SL (a 57% difference compared to 19% estimated in this study). This result of the current study showing a much smaller difference in fecundity in scallops of various sizes compared to previous findings, is a very important finding in relation to the decision rules around scallop harvest, particularly the under-sized discard rate rule and the two spawnings criteria which states that scallops should be allowed a minimum of two major spawning events before being harvested. Scallops that are 85-95 mm SL are 3+years old and have had two major spawning and thus contributed significantly to potential recruitment. However, given the relationship between fecundity and SL demonstrated in this study, which shows a 3-fold decline in the difference between fecundity of an 83 and 90 mm SL scallop compared to the previous research, the size limits are very conservative. As such, the use of 85 mm SL still allows the scallops to have produced two major spawnings before harvest, with relatively little difference between the fecundity of 85 and 90 mm SL scallops (13%). However, it should be noted that in regions that have very low biomass or are recovering from being depleted (e.g. TSF), this additional 13% could be significant, and a highly conservative approach may be warranted. Furthermore, it should be noted that the 80 mm SL size limit used for the decision rules in the OSF is likely not appropriate, as it is outside of the size range for the two major spawnings criteria and should be revisited, with this low size limit perhaps contributing to the long history of limited biomass and recruitment in the fishery.

Differences in shell morphology were evident among regions, with significant differences between the standardised height for a standard scallop measuring 90 mm SL. However, differences in morphology were more evident among locations when comparing shell widths for standard scallops measuring 90 mm SL. North West Tasmania (TSF) and Great Bay (TRSF) had comparatively thinner individuals, followed by King Island (BSCZSF), Banks Strait (TSF), Marion Bay (TSF) and White Rock (TSF). Scallops from Babel Island (TSF and BSCZSF) showed no significant differences in shell width with Eddystone (TSF) or the Bass Strait (BSCZSF) site. Scallops located in Victoria (OSF) had the thickest scallops. For fisheries management purposes it is interesting to determine if scallops with greater SW also have greater muscle and/or gonad weights. Indeed, the Victorian (OSF) site had the thickest (deepest) scallops and these scallops generally had the heaviest muscles, gonads and combined weights in winter of all the regions. Additionally, other thick scallop regions, Isthmus Bay (TRSF) and Eddystone Point (TSF), also had heavy muscles, gonads and combined weights in winter. Furthermore, the relatively thick scallops from the Bass Strait (BSCZSF) site had heavy muscles, gonads and combined weights in autumn. Fishing these areas (when opened) in the seasons noted could increase commercial yields.

Scallops at different sites showed variable mean growth increments depending on initial mean size of cohorts. There was no obvious growth pattern on the latitudinal gradient. For instance, sites at the extreme north (North Flinders and King Island, both in the BSCZSF) and south (Great Bay, TRSF) of Tasmania showed average mean growth increments. Low and high values of growth were observed in sites that are close to each other in the BSCZSF (1.9 and 9.20 mm/year for King Island Middle and King Island 2 respectively). Therefore, growth variations seem to be associated with local factors rather than factors linked with large spatial scale change, which has also been observed for other species of scallop. This growth analysis has shown that there is great variation in growth rates of commercial scallop across the traditional fishing areas within the south east of Australia, with great variation even prevalent between beds in the same area, e.g. King Island (BSCZSF) and East Flinders Island (TSF). Importantly, however, this analysis has shown that the fishing areas examined can be generally grouped into three general groups: rapid growers; moderate growers; and slow growers.

Rapid growers will be younger than their shell length indicates, so those scallops may not be 3+ at 85-95 mm SL and may not have had three major spawnings. As such, despite the relationship between size and fecundity showing that the 90 mm size limit is generally conservative for the fishery as a whole, it may not be for these rapidly growing scallops, and perhaps a more conservative approach is needed, particularly as the size limit used in the BSCZSF, where the two North Flinders fishing areas are located, is 85 mm SL. Alternatively, if a validated aging technique can be developed for commercial scallops, this should be adopted to ensure scallops are only fished from the 3+ age class onwards. It is interesting to note that three rapid growing areas are North and North West Flinders (BSCZSF) and White Rock (TSF), all areas that have had large reductions in biomass, with little or no recruitment in recent years. The TSF also plans to use an 85 mm SL from 2020 onwards, so a conservative approach may need to be adopted for the White Rock region of that fishery.

As previously mentioned, there is great variability with areas, with Flinders Island 1 (BSCZSF), which like North and North West Flinders is also situated north of Flinders Island, showing slow growth. Two other slow growing areas are at King Island (KI 2 and KI New, BSCZSF), with King Island Mid (BSCZSF) showing moderate growth. The slow growing scallops will be older than their shell length indicates, and as such 90 mm SL minimum size is likely to be very conservative. The King Island sites are in the BSCZSF, and as such currently managed under an 85 mm SL size limit, which would appear appropriate and conservative. This may be a factor in the maintenance of high biomass in this region despite the fishery operating in the region since 2014 and ~12500 t coming out of the area (west of 147 degrees east) in that time. Although note that the North West region in Tasmania is fished with an 85 mm SL size limit rule, as fishers nominated this area as a slow growing scallop area, however it has undergone a large decline in biomass, following no recruitment in recent seasons.

In those areas with slow growing scallops, closing beds based on the 20% discard rule may mean that some beds that have 80% or greater of the scallops within it having reached 3+ and having had at least two major spawnings may be closed, and as such this rule will be very conservative in these areas. Conversely, the opposite will apply in fast growing areas, with beds that have less than 80% of the scallops within it having reached 3+ and having had at least two major spawnings being opened, and as such this rule not be met in these beds, which could have an impact on the sustainability of fisheries in these areas. As such, defined use of the minimum size limit and 20% discard rule is not appropriate, and instead they should be used in conjunction with the known attributes of the beds within region to be fished and applied in an informed and sensible manner such that recruitment potential is not impacted. If a validated aging method can be developed for commercial scallops, the 20% discard rule will be able to be applied with greater confidence.

Keywords

Commercial scallop, *Pecten fumatus*, spatial fisheries management, in-season industry management, Bass Strait Central Zone Scallop Fishery, Tasmanian Scallop Fishery, Ocean Scallop Fishery, discard rate, fecundity, condition, growth rate

Introduction

This project builds upon three FRDC scallop projects previously conducted by the applicants:

- 2003/017 “Juvenile scallop trashing rates and bed dynamics: testing the management rules for scallops in Bass Strait”;
- 2005/027 “Facilitating industry self-management for spatially managed stocks: a scallop case study”, and
- 2008/022 “Establishing fine-scale industry based spatial management and harvest strategies for the commercial scallop fishery in south east Australia”.

The major conclusion of FRDC 2003/017 was that spatial closures in the management of commercial scallop (*Pecten fumatus*) stocks offers a real prospect for providing continuity and sustainability for the fishery (Haddon et al., 2006), especially when compared to conventional management. Importantly, FRDC 2003/017 also identified the very extensive data/stock information requirements of closed area spatial management (Haddon et al. 2006; Harrington et al. 2007). If this extensive level of data can be obtained to enable their use, spatial closures can be used as a management tool to provide:

(1) increased protection from fishing and consequent increased abundance and mean size of exploited species;
(2) enhanced local reproductive potential as a consequence of greater synchronization of spawning events (Mendo et al., 2014) ; and
(3) protection of associated benthic communities and habitats (Halpern, 2003; Beukers-Stewart et al., 2005).

FRDC 2005/027 established the capacity for industry to organise and implement surveys at both the scale of the fishery, and the scale of individual scallop beds (Harrington et al., 2008). The population structure and abundance data that industry obtains during such surveys can be used by management to meet decision rules allowing the successful implementation of detailed spatial management strategies within the fishery. Furthermore, the development and use of electronic measuring and recording devices both simplifies and adds a level of credibility to the process of data collection, storage and analysis. The inclusion of industry in the data collection process of management also creates a sense of industry ownership. In general, this improves the relationship and communications between all stakeholders in the fishery (industry, managers and research), and creates both an acceptance and level of understanding of the biological and economic benefits of detailed spatial management. This belief in the benefits of spatial management has directly led to industry empowerment, with much greater roles and responsibilities in the management of their fishery.

FRDC 2008/022 examined scallop stock structure, spawner biomass density/recruitment relationships, and the impacts of intensive fine spatial scale fishing on scallop communities with the aim of refining detailed spatial management/industry fine-scale management harvest strategies, such that they promote recruitment and minimise impacts on the broader environment. The project also demonstrated that overall genetic exchange appears to be limited when distances exceed 300 km and the finest scale at which we found genetic subdivision was around 100km (Semmens et al., 2015). Currents are likely to be playing a major role in dispersal, as locations within embayments (Port Phillip Bay and D'Entrecasteaux Channel) are genetically more distinct from those in open water. Currents are also responsible for the gene pool of commercial scallops not being uniformly homogenous in Bass Strait and Tasmania, with biophysical modelling highlighting different patterns of propagule dispersal, self-recruitment and significant propagule loss to non-suitable settlement habitat, depending on the location of the spawning stock and the year (Ovenden et al. 2016). As an example, Lakes Entrance scallop beds (VI in Figure 1), which comprise the majority of the Victorian Ocean Scallop Fishery (OSF, see Figure 2), showed subtle genetic distinctiveness from other beds in Bass Strait and eastern Tasmania, making the Lakes Entrance region somewhat of an anomaly (Ovenden et al. 2016), particularly given the fact that biophysical modelling demonstrated limited self-recruitment in this region. Importantly, the 2008/022 study demonstrates that appropriate scales of management should consider both long established patterns of dispersal and recruitment as indicated by population genetic structure as well as short term patterns due to demographic heterogeneity. The genetic evidence indicates that stock structuring can occur within 100 km implying that yearly stock-recruitment dynamics are likely to exist on even smaller spatial scales. In other words, recovery of depleted scallop beds in the short term will be heavily influenced by recruitment from adjacent scallop beds rather than from distant beds. The current 'most area open, little area closed' spatial management harvest strategy employed in the Commonwealth Bass Strait Central Zone Fishery (BSCZSF, see Figure 2), where some of the scallop beds surveyed in the pre-season survey must be closed to fishing if the season is to have a total allowable catch (TAC) higher than the 150 t default opening, the TAC is set using a tiered approach based on the combined biomass of beds closed to fishing, and closed beds must be present in the region being fished (Marton and Mobsby, 2018), would seem appropriate given the evidence available, as 'adjacent' beds are maintained in each fished region. Conversely, the 'most area closed, little area open' spatial management plan employed in the Tasmania Scallop Fishery (TSF, see Figure 2), where only beds surveyed in the pre-season surveys are open to fishing if they have commercial quantities of scallops and meet the relevant decision rules (see below) and the remainder of the fishery is closed, beds of scallops are not closed to fishing in the regions that are being fished. Instead, protection of potential scallop habitat is afforded through a ban on scallop dredging in waters less than 20 m and a network of dredge-prohibited areas around the state, with some of these areas none to be traditional scallop grounds. While this strategy has the potential to still provide for the protection of adjacent scallop beds that can contribute to recruitment in the areas that are being fished, unlike the BSCZSF harvest strategy, there is no guarantee of this, with the presence or absence of beds in these areas largely unknown as these protected areas are rarely surveyed. Unlike the BSCZSF and TSF, the OSF is not spatially managed and thus offers no protection of 'adjacent' beds in fished regions.

In general, FRDC 2003/017, 2005/027 and 2008/022 have provided a compelling argument for the detailed spatial management of scallop fisheries in southeast Australia. Spatially explicit harvest strategies employed in the southeast Australian commercial scallop fisheries aim to buffer against recruitment variation to increase both production and continuity between seasons. At present, one of the decision rules used to decide whether a scallop bed is suitable for harvesting is the under-sized discard rate rule, which states that a scallop bed should not be fished if the discard rate of undersized (< 90 mm shell length (SL; see Figure 3) in TSF Management Plan; < 85 mm SL in the BSCZSF Harvest Strategy; < 80 mm SL in OSF) scallops is greater than 20%. The origin of this decision rule stems from the notion that all scallops on a scallop bed, including those under the minimum size limit, are either harvested or incidentally killed, damaged, or disturbed by the physical nature of dredging. This relates to the second major management decision rule: the 'two spawnings criteria' which states that scallops should be allowed a minimum of two major spawning events, based on size class of the scallops, before being harvested (McLoughlin, 1994; Zacharin, 1994). The size range currently used to define a bed as commercially viable was based on research conducted by CSIRO during the 1980s which suggested that scallops that were 3+ years old gave rise to 3-5 time as many eggs as younger scallops through at least two major spawnings and that scallops would grow to 75-85 mm shell height (SH; see Figure 3) in that time (Martin et al., 1988; McLoughlin, 1994). Based on predictions from linear regression models, 75-85 mm SH is equivalent to approximately 85-95 mm SL (Haddon et al., 2006). To maximise spawning potential, in 2003 and 2005 respectively, the TSF and BSCZSF both adopted a conservative 90 mm SL size limit to define a bed as commercially viable in place of 80 mm SL, which had been used since the 1980's in both jurisdictions, while the OSF maintained the 80 mm SL limit. In April 2014, the BSCZSF Harvest Strategy was amended to adopt an 85 mm SL size limit for the criteria, noting that it was less precautionary, however, it was still in the lower range of 85-95 mm SL for 3+ year old scallops and two major spawning events. Subsequently, in November 2018, the Tasmanian Scallop Fishery Advisory Committee (ScFAC) also recommended that the size limit used to define a bed as commercially viable be changed to 85 mm in the TSF Management Plan, to better align with the BSCZSF, with the change to commence in March 2020.

Although a generalised morphometric relationship between SL and SH has been established for commercial scallops (Haddon et al., 2006), morphometric relationships vary among locations in bivalves (Newell and Hidu, 1982; Schick et al., 1992). These morphometric differences between populations do occur in commercial scallop, for example, relatively larger SH for a given SL within the BSCZSF compared to the TSF have been previously reported for commercial scallop in FRDC report 2003/017 (Haddon et al., 2006) and industry members have long suggested there may be morphometric, and growth rate differences between populations around south eastern Australia, e.g. scallops in the north west of Tasmania are thought to grow slower. Again, growth rates in pectinids have been found to vary greatly among locations in other species (e.g. great Atlantic scallop (*Pecten maximus)* (Mason, 1957) and queen scallop (*Aequipecten opercularis)* (Taylor and Venn, 1978)). In Port Phillip Bay, Victoria, a two-year-old commercial scallop is estimated to grow to ~71-87 mm in SH (Sause et al., 1987a) while in Jervis Bay, NSW, a scallop of the same age is reported to reach 70 mm (Hamer and Jacobs, 1987). There may be similar differences between populations in the TSF, OSF and BSCZSF. Differences in growth rates in commercial scallop occur at the scale of beds and have been shown to be density-dependent (Haddon et al., 2006). During the FRDC 2003/017 project, most scallop beds on the east coast of Flinders Island in the TSF (see Figure 35) were in relatively dense beds and showed lower growth rates than in less dense beds of adjacent BSCZSF waters (Haddon et al., 2006). These variations imply there are spatial differences in the relative growth of scallops, a result which may have important implications for fisheries management with respect to management decision rules. In other words, if some areas have slower growing scallops, then the relationship between SL and age may not be appropriate for determining the two major spawning and under-sized discard rate rules.

As well as spatial variation in shell shape and growth rates, fecundity can vary across locations in marine invertebrates, e.g. blacklip abalone, *Haliotis rubra* (Saunders and Mayfield, 2008) and the wavy turban snail, *Megastraea undosa* (Martone and Micheli, 2012). An initial analysis of fecundity of commercial scallop at different locations showed that the average fecundity in one area could be three times that of scallops in another location (Martin et al., 1988), however, these variations might be the result of different sizes, density or environmental conditions present in each location at the time of spawning. A more comprehensive study of fecundity is needed to generate greater confidence of industry in the application of the two spawnings criteria.

Despite the positive effects of spatial management, currently the harvest strategies do not consider scallop condition. A commonly held perception among the scallop industry is that scallops of the same size from different areas can generate different meat yields. Martin et al. (1988) demonstrated differences in meat yields from standard scallops of 80 mm SH from around Bass Strait, with the meat weights in some areas being double the meat weight of other areas. In contrast, Haddon et al, (2006), showed no obvious differences in meat weight, except for scallops originating from a deeper bed (80 m) which had the smallest weight for a given shell length. These authors also hypothesised that there may be some relationship between latitude and meat condition and showed that a scallop of 80 mm SL in the BSCZSF contained meat of similar weight to a scallop over 90mm SL in the TSF. Conclusions from this study were only tentative because in March when the scallops were collected, very few scallops were in prime condition (i.e. with roe in optimal condition). These authors recommended sampling in May or June to allow scallops to come into better condition and allow for more applicable comparisons related to the period when fishery begins.

As part of the BSCZSF harvest strategy and the TSF Management Plan, pre-season surveys determine areas to be opened/or closed during the upcoming season. Known areas with >20% discard rate are closed to fishing, regardless of scallop quality and potential for opening during the season. A detailed characterization of morphometric relationships across different locations would permit greater confidence in the use of the relationships that exist between various measurements used. Additionally, scallops in the areas opened can be unsuitable for harvest due to poor condition when the season opens. This means the areas are opened then rapidly closed to fishing again, causing disruption to fishing/processing businesses, and marketing problems. Delayed opening while scallops gain condition can also prevent the total catch being taken because there is a fixed, pre-determined finish date. The fixed finish dates have been established to protect settling scallop spat, which traditionally occurs between September and December following spawning between August and October. The problem with poor condition at the start of the season has arisen because scallops are increasingly reaching spawning condition between December and February. As well as potentially putting settling scallops at risk through impacts upon opening the fishery, this late development is also contributing to difficulty in providing well-conditioned scallops throughout the season.

The current project aims to better define timing of scallop spawning based on gonad condition, and hence potential settlement of recruits across the different populations/beds of the fishery and determine any differences in spawning potential among scallop beds/locations. Additionally, this project aims to define differences in spawning potential between scallops ranging from 80 to 90 mm SL and assess the size limits used to define a bed as commercially viable across the three southeast Australian jurisdictions. Furthering our understanding of growth rate in several fishing locations across all three jurisdictions may also allow better management of individual beds and in addition to scallop condition will be used to inform current season openings and closings. The overall aim is also to provide information that will allow the jurisdictions greater capacity to work together to facilitate effective management for the fishery as a whole.

Objectives

1) To better define the timing of spawning and settlement of commercial scallops across the three fisheries.

2) To better define differences in spawning potential between scallops ranging from 80 to 90 mm and gain an understanding of growth rate in this size range.

3) To define agreed operational measures of spawning condition for use in the scallop fisheries.

4) To establish season openings and closings that are more responsive to annual changes in spawning condition and timing of settlement.

5) To define an agreed use of the minimum size limit and 20% discard rule to open/close individual beds.

6) To incorporate spawning condition and a more focused use of the 20% discard rule into cooperative spatial harvest and industry in-season management strategies to enhance the operation and profitability of the fisheries.

Methods

Sample and data collection

Data was collected via specific sampling for this project as well as collated from previous FRDC projects and dredge surveys in the BSCZSF and TSF. Scallops (n > 50 per sampling occasion) were collected between 2012-2014 in locations across the TSF, OSF and BSCZSF (Figure 1, Table 1, see also Figure 2), as well as recreational only fishing areas in Tasmania (TRSF). These scientific dredge or diving surveys were conducted on-board of several commercial or research vessels for the diving surveys. Scallops were kept alive in plastic containers (40x40x30 cm) until processing in the laboratory (IMAS Taroona facilities). Each scallop was measured for shell length (SL, greatest distance from the anterior to the posterior end of the shell), shell height (SH, maximum distance between the dorsal and ventral edges of the shell), and shell width (SW, maximum distance between the furthest expansion of the left and right valve; also referred to as shell depth) (to the nearest 1 mm, Figure 3). Additional size (SL) frequency data for growth analysis was obtained from pre-season surveys in the BSCZSF and TSF from 2015 to 2017 (see Table 10). Total weight, gonad weight (GW), adductor muscle weight (MW), meat recovery weight (muscle + gonad weight), shell weight, and digestive gland weight (to the nearest 0.1 g) were also recorded. Additionally, morphometric data from previous studies: FRDC 2003/017; FRDC 2005/027; FRDC 2008/022 (Figure 1, Table 1). In 2012, due to the outbreak of the the Paralytic Shellfish Toxin and subsequent closure of the TSF and very low levels of participation in the BSCZSF, sample collections were limited (Table 1).

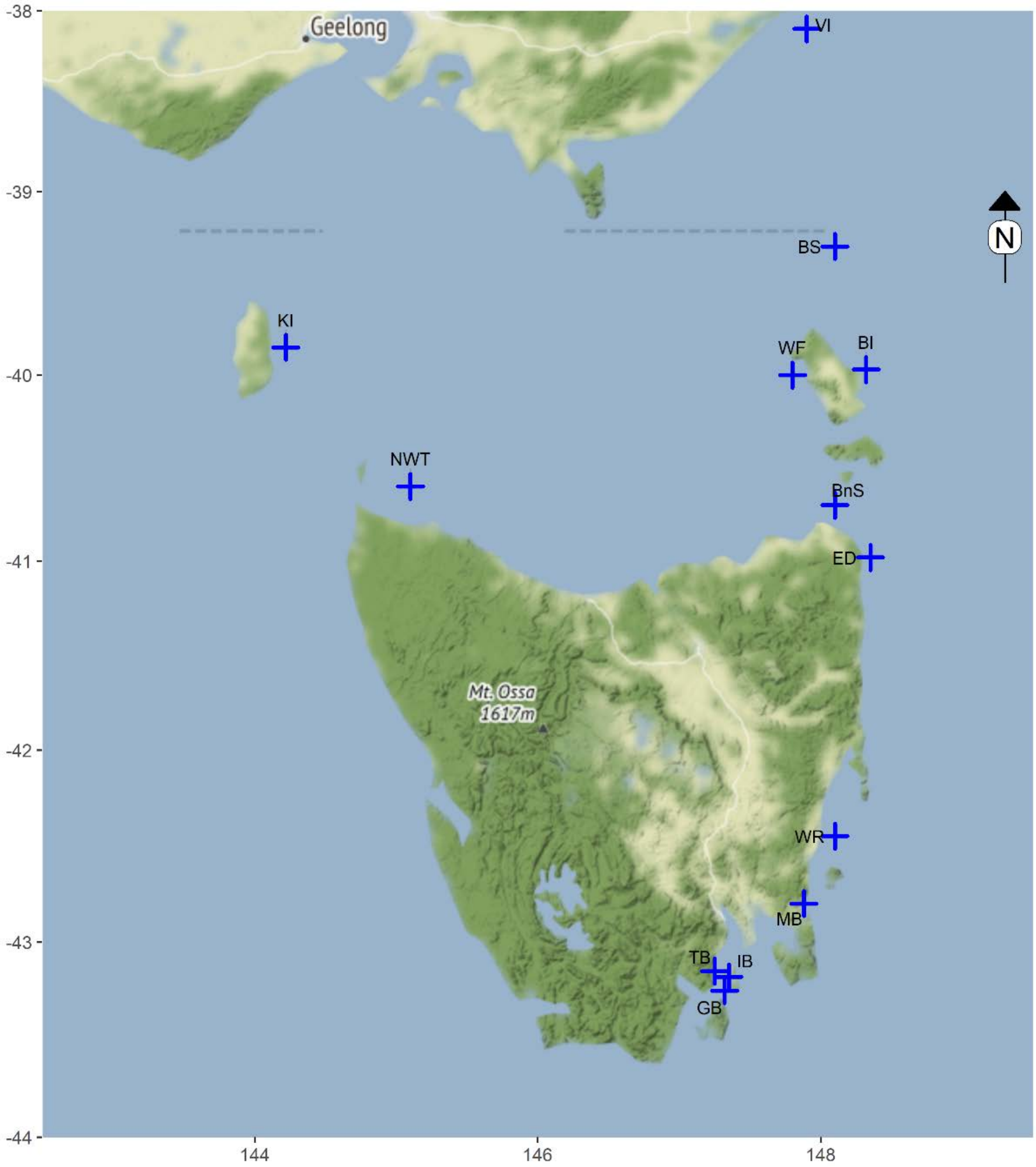


Figure 1. Sampling locations around Tasmania, the Commonwealth and Victoria. IB=Isthmus Bay (TRSF), GB= Great Bay (TRSF), TB=Trial Bay (TRSF), MB= Marion Bay (TSF), WR= White Rock (TSF), ED=Eddystone (TSF), BnS= Banks Strait (TSF), BI= Babel Island (TSF & BSCZSF), WF= West Flinders (TSF), BS= Bass Strait (BSCZSF), NWT= North West Tasmania (TSF), KI= King Island (BSCZSF), VI= Victoria (OSF).

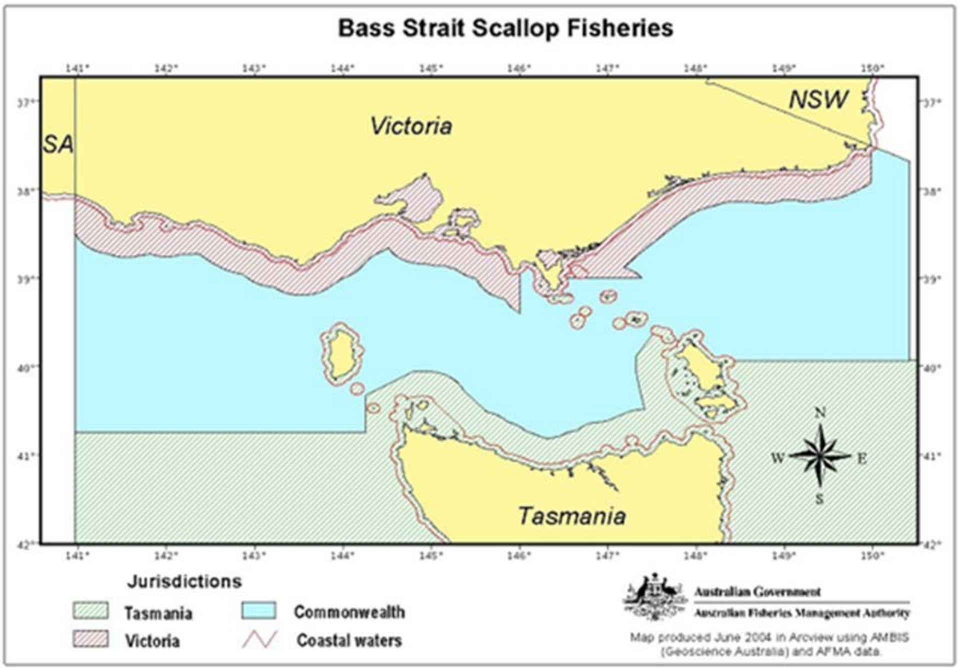


Figure 2. The boundaries of the three jurisdictions. Tasmania = Tasmanian Scallop Fishery (TSF, only Northern section shown; excludeswaters less than 20 m and a network of dredge-prohibited areas around the state), Victoria = Ocean Scallop Fishery (OSF, excludes the bays and inlets along the coast where commercial fishing for scallops is prohibited and Port Phillip Bay, which is a dive only fishery and is manged separately), Commonwealth = Bass Strait Central Zone Scallop Fishery (BSCZSF).

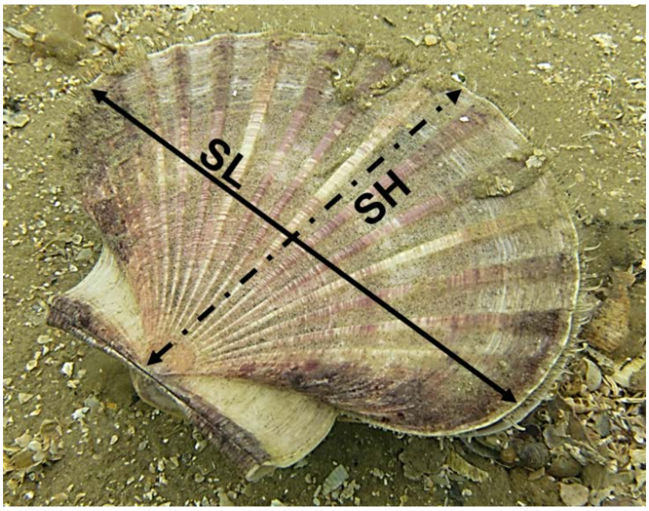


Figure 3. Image of commercial scallop, looking at the right shell and depicting the shell length (SL) and shell height (SH) measurements used for morphological assessments.

Condition of scallops

Muscle and gonad weights

Due to the patchiness of the data (Table 1), and the expected seasonal variation in muscle and gonad weight due to reproduction or food availability, the effect of year and season on muscle, gonad and meat recovery weight (muscle and gonad weight combined) were evaluated first in Great Bay, to assess whether it was feasible to compare data from different seasons in different locations across years. Great Bay was the location for which the most consistent sampling effort was conducted during 2009-2012 (Table 1). Due to the seasonal variations in gonad and muscle weights, which are related to reproduction, only sexually mature scallops could be compared. As scallops > 65 mm SL were consistently observed to have mature gonads, only scallops in this size range were examined. Muscle and gonad weight indices were calculated as the muscle or gonad weight divided by the shell length and multiplied by 100. Temporal patterns of muscle and gonad weights were examined using generalised least square models. We tested for autocorrelation of the residuals using the ACF function in R (R Development Core Team, 2015). When a clear violation of independence in the residuals was detected, we used an auto-regressive model of order 1 (corAR1), which models the residual at time s as a function of the residual at time s-1 (Zuur et al., 2009), or a corExp structure which fits data taken at irregular time intervals (Zuur et al., 2009). We incorporated the varIdent variance structure to deal with heterogeneity of variances when the spread of residuals differed per year or season (Zuur et al., 2009). Akaike's information criterion (AIC (Burnham and Anderson, 2002)) was used to select models. Analyses were performed in R (R Development Core Team, 2015).

Table 1. Main sampling locations and number of individuals measured each sampling period."-" denotes no data available. [1]BSCZSF; [2]TRSF; [3]TSF; [4]OSF. See Figure 1 for site locations.

Location	Date	Length (mm)	Height (mm)	Depth (mm)	Total weight (g)	Muscle weight (g)	Gonad weight (g)	Digestive gland weight (g)	Shell weight (g)	Gonad condition
Bass Strait[1]	Dec 2005	321	321	321	321	321	-	-	321	321
	May 2009	50	50	50	50	50	50	-	50	50
	May 2012	114	114	114	114	114	114	114	114	114
	Jun2012	46	46	46	46	46	46	46	46	46
	May 2013	150	150	150	150	150	150	150	150	150
	June 2013	152	152	152	152	152	152	152	152	152
King Island[1]	Dec 2014	191	101	76	166	166	76	76	75	191
Trial Bay[2]	Feb 2006	300	99	300	300	300	100	-	300	300
Great Bay[2]	June 2008	148	148	148	148	148	148	148	148	148
	May – Dec 2009	1006	84	84	463	829	863	-	84	863
	Feb 2010	102	-	-	102	102	102	-	-	102
	Aug 2010 – Mar 2011	1177	-	-	1202	1202	1202	1202	-	1202
	Oct 2011 – Jan 2013	1318	637	635	1318	1318	1318	1318	637	634
Marion Bay[3]	Nov 2012	143	143	143	143	143	143	143	143	143
Eddystone[3]	Mar 2004	292	292	292	292	292	-	-	292	292
	Jun – Nov 2006	644	437	642	640	640	640	-	640	246

	May 2008	100	100	100	100	100	100	-	100	100
Babel Island[1, 3]	Mar 2004	245	245	245	235	245	-	-	243	245
	May 2008	85	85	85	85	85	85	85	85	85
Banks Strait[3]	Jul 2006	100	100	100	100	100	100	-	100	20
	Sep 2006	116	116	116	116	116	116	116	116	116
	May 2008	97	97	97	97	97	72	-	97	97
NW Tasmania[3]	Oct 2013	300	300	300	300	300	300	300	300	300
	Dec 2013	124	124	124	124	124	124	124	124	124
White Rock[3]	May – Oct 2006	853	419	851	799	699	650	-	799	100
	Jun 2008	100	100	98	100	100	100	100	100	100
	Oct-Nov 2012	120	120	120	120	120	120	120	120	120
	May – Sep 2013	720	720	720	720	720	720	720	720	720
Victoria[4]	Jul 2008	114	114	114	114	114	114	114	114	114
Isthmus Bay[2]	Jul 2006	97	97	97	97	97	97	97	97	97
West Flinders[3]	May 2008	97	97	97	97	97	97	97	97	97
Total		**9422**	**5608**	**6417**	**8811**	**9087**	**7899**	**5222**	**6364**	**7389**

Gonad visual staging

During the morphometric measurements, each gonad was categorized according to the macroscopic staging scheme for commercial scallops (Harrison, 1961; Young et al., 1999) (Table 2). This scheme places emphasis on the colour and size of the gonad and incorporates gonad weight as well as condition. The scheme, however, is rather subjective in nature, with wide-ranging differences in the size and colour of stage 5 and stage 6 gonads. Subsequently, stage 5 individuals were subcategorized into three further stages, based on the size of the gonad relative to the size of the meat. These subcategories of gonad condition were developed by the authors after several years of observation of scallop gonad condition. According to this classification, prime gonad condition in this report is defined as the combination of stage 5.3 and stage 6 (Table 2, where gonads are larger than muscles). All data available was pooled, but only locations with more than one sampling occasion were included for analysis. These observations were also compared to histological observations to assess the accuracy of the macroscopic technique to identify reproductive stages.

Table 2. Gonad maturation scheme for macroscopic field staging of scallops.

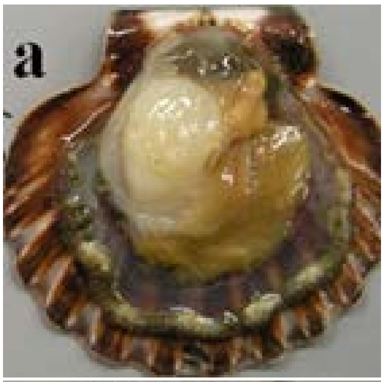
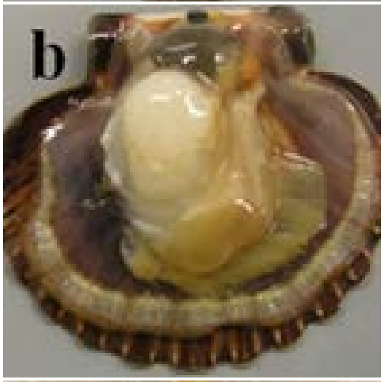
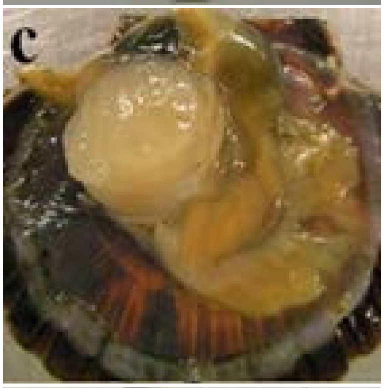
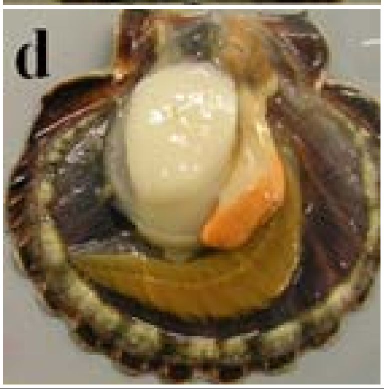
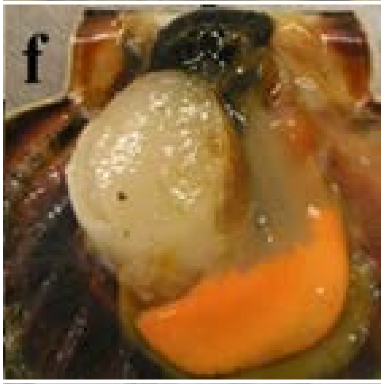
Stage	Description	Image
1	Immature. Small strap-like organ, transparent and with the intestine seen looping through it.	None identified
2	Like stage 1, but gonad larger. Completely spawned scallops may revert to this stage.	
3	Early developing. Gonad larger with male and female components distinguishable, but with the intestine visible through the wall of the testis and ovary. Ovary becoming orange.	
4	Gonad larger than stage 3. Intestine only in the male part of the gonad. Ovary becoming orange.	
5.1	Gonad larger than stage 4., intestine not visible Gonad smaller than size of meat.	

Table 2. *Continued*

Stage	Description	Image
5.2	Ovary orange. Intestine not visible. Gonad approximately equal to size of meat.	
5.3	Ovary orange. Intestine not visible. Gonad larger than size of meat	
6	Ripe. Gonad like stage 5 but larger and full, ovary bright orange.	

Histological examination and fecundity

Sexually mature scallops (defined as > 65 mm SL from observation) were collected from five locations across 2 years (Table 3). Scallops were kept alive in seawater filled plastic containers (40x40x30 cm) until processing in the laboratory. Each scallop was measured for shell length, height, and depth (to the nearest 1 mm), total weight, gonad weight, adductor muscle weight, shell weight, and digestive gland weight (to the nearest 0.1 g). For each gonad, volumes were estimated from density and wet weight. Densities were obtained by first washing individual gonads in water and patting them dry on blotting paper before placing them in liquids with known densities. Gonad volumes were then calculated as:

$$\text{Gonad volume} = \text{gonad mass} / \text{gonad density}.$$

The gonad was then fixed in FAACC (formalin, acetic acid and calcium chloride) (Winsor, 1994), then transferred to 70% ethanol, and stored for at least 48 hours, before being embedded in paraffin and sectioned to 6µm. Sections were stained with Haemotoxylin and Eosin and mounted with a mixture of distyrene, tricesyl phosphate and xylene (DPX synthetic resin mountant) (Kiernan, 2008).

Table 3. Description of samples used for fecundity analyses. [1]BSCZSF; [2]TRSF; [3]TSF. See Figure 1 for site locations.

Location	Sample date	Season	SL range (mm)	Average eggs per volume (range)	Median histo-logical Gonad stage (range)*	N	Day length
Bass Strait[1]	19/05/13	Autumn	79-103	44.9 (18.4-59.2)	2 (1-3)	30	9.7
	01/06/13	Winter	74.3–100.5	54.6 (31.4-70.6)	3 (1-3)	31	9.4
Great Bay[2]	11/10/12	Spring	96-124.5	50.5 (40.6-62.6)	3 - 4(2-4)	19	12.9
Marion Bay[3]	05/11/12	Spring	79.8-106	42.3 (18-59.8)	3 (2-4)	23	14
NW Tasmania[3]	08/10/13	Spring	68-96	51.4 (33.3-71.6)	3 (3-4)	30	12.7
	23/10/13	Spring	77-95.5	46.1 (34.6-58.4)	3 (2-3)	31	13.4
	13/12/13	Summer	68.5-98	54.4 (42.8-68.4)	3 (3)	34	14.9
White Rock[3]	31/10/12	Spring	84-104	48.6 (37.2-58.4)	3 (2-4)	22	13.8
	20/11/12	Spring	87-112.3	45.7 (28.4-61.4)	3 (2-4)	22	14.6
	01/05/13	Autumn	89-103	44.9 (29-76.2)	1 (1-2)	20	10.1
	20/06/13	Winter	64-115.5	48.7 (28.4-69)	1 (1-4)	25	8.9
	17/07/13	Winter	85-104	37.9 (14.2-62.4)	3 (1-4)	23	9.2
	16/09/13	Spring	85-108.8	46.3 (32.2-62)	3 (2-3)	27	11.7

*Gonad stages are defined in Table 4.

A photograph of the whole female gonad section was taken using a Nikon camera fitted with a Micro NIKKOR 60mm lens. Each gonad photograph was examined using the specialised software Corel Point Count with Excel extensions (CpCE v4.1, Nova Southeastern University). Using the overlay and feature counter software, five grids of 0.5 mm^2 were randomly placed over the ovary of the gonad. Total egg (oocyte) counts per area were then recorded; all eggs falling wholly within the boundary were counted as well as any eggs that were intersected by the top or left boundaries of the grid. All eggs intersected by the right or bottom edges of the grid were not counted. The five sets of total egg counts were then averaged to give a mean egg count for the section. This score was used to calculate a proxy for fecundity:

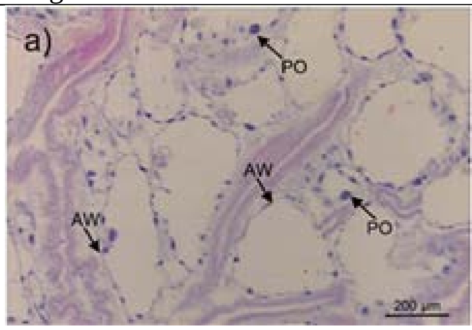
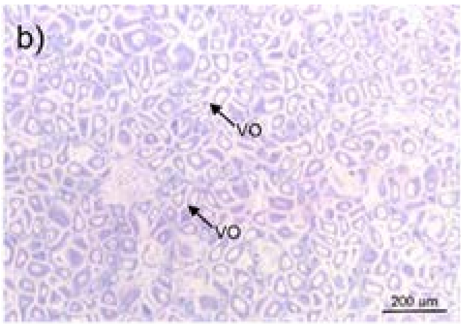
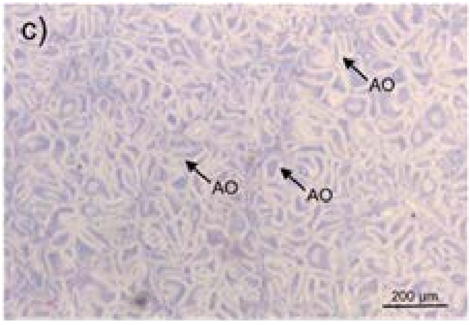
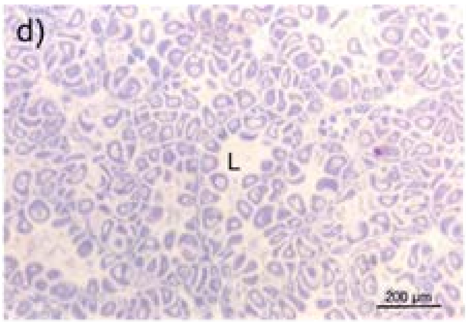
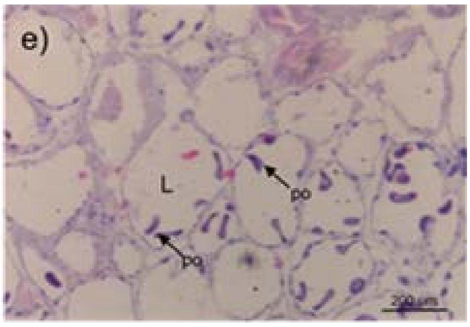
$$PF = V \times OO$$

Where PF= Proxy for fecundity, V= gonad volume, OO=mean oocyte count.

These proxies for fecundity were used to compare fecundity across different scallop sizes and to allow comparisons of egg counts without having to disregard irregularly shaped oocytes. Oocytes in either atretic (oocyte being reabsorbed, with the resultant energy recycled to fuel further oocyte production (Mendo et al., 2016)) or partially spawned stages cannot be easily counted in traditional fecundity analysis.

A decrease in the gonad mass index may be due to either spawning or resorption of gametes (egg and/or sperm cells), and this can only be determined histologically (Barber and Blake, 2006). The gonad contains many acini (saclike dilations), whose walls are composed of connective tissue and primary germ cells (embryonic cells with the potential of developing into gametes). The lumen (cavity) of the acini is filled with gametes in varying stages of gametogenesis, depending on the reproductive stage of the gonad (Table 4). Reproductive stages were identified for female gonads in each of the five sections following a modified scale from Sauce et al, (1987b), Mason (1958) and Cantillanez et al, (2005) (Table 4). When the acini structure was clear the reproductive stage was classified using the appearance of the acini (Table 4). When the acini structure had broken down and its wall was hard to observe, the appearance of the oocyte was assigned a reproductive stage (Table 4). For each area, the ovarian tissue was classified to the stage most prevalent in that area. For each gonad, the reproductive stage was assigned as the most frequently observed reproductive stage of the acini and oocytes. In addition to the gonads collected for fecundity analysis, histological analysis was conducted for scallops collected from Great Bay from August 2010 to March 2011 and from October and November 2012, as part of FRDC 2008/022 (Semmens et al., 2015).

Table 4. Descriptions of the reproductive stages of gonads based on the types of gamete stages present in commercial scallop from histological assessment. Images show histological sections of commercial scallop at each stage of oogenesis. AW: acinus wall; PO: previtellogenic oocyte; VO: vitellogenic oocyte; AO: Atretic oocyte; L: lumen; po: pedunculated oocyte.

Gonad stage	Description	Image
1. Developing	Previtellogenic oocytes (eggs with yolk yet to form) of various sizes adhering to acini wall. This stage includes the formation of oocytes in acini, but inter-acinal tissue is still present.	
2. Mature	Large gonadal acini, completely filling the gonadal space, with a predominance of fully developed vitellogenic oocytes (eggs with yolk).	
3. Atresia	Oocytes are being reabsorbed and are deformed (jigsaw-puzzle appearance) and staining affinities change.	
4. Partial spawning	Initiation of gamete release; decrease in number of free vitellogenic oocytes in the lumen.	
5. Fully spawned	Very few free vitellogenic oocytes in the lumen; most remaining oocytes are pedunculated (supported by a stalk).	

The logarithm of Proxy for Fecundity was modelled as a function of size using linear mixed effect models (nlme package, (R Development Core Team, 2015). Shell length (mm) and month of sampling were fitted as fixed effects and a random intercept (Location) was included to reflect the hierarchical nature of observations. Assumptions were assessed graphically.

Growth

Allometry and shell morphology

Major axis regressions were used to test whether the slope between log (SL) and log (SH) and between log (SL) and log (SW) were equal to +/- 1, which would indicate that growth is isometric (Warton et al., 2006), i.e. the scallop exhibits a constant shape regardless of size. In the case of allometric growth (where the scallop changes shape in response to size changes), the effect of size was removed by first calculating the parameters of the allometric ratios between total shell length (SL), taken as an independent variable, and shell height (SH), shell width (SW), muscle weight (MW), and gonad weight (GW) taken as dependent variables according to the allometric model:

$$Yij = ai\ SLj^{bi}$$

where: *SLj* is the shell length of the individual *j*, *Yij* is the *i* dependent variable of the individual *j* and *ai* and *bi* are the parameters of the allometric ratio between total length and variable *i* which were calculated by the previously log-linearized lineal regression of the allometric model. Only populations with a sample size greater than 100 individuals were used to assess allometry.

In order to eliminate the influence of size due to allometric growth, the data were transformed with the normalization of individuals of each group (sample location) proposed by Lleonart *et al*. (2000). This normalization is a theoretical generalization of the technique used by Thorpe (Thorpe, 1975) hence:

Zij = Yij (SL0 /SLj)bi

where: *Zij* is the value of the variable *Yij* once it has been transformed, SL0 represents a reference value of size to which all individuals are reduced. This normalization completely removes all the information related to size, not only scaling all individuals to the same size, but also adjusting their shape to the one they would have in the new size according to allometry (Lleonart et al., 2000). The SL0 used was 90.0 mm, which was the size limit used in the TSF Management Plan (to be changed to 85 mm SL in 2020) and the BSCZSF Harvest Strategy (changed to 85 mm SL in 2014), when the project commenced in 2012. Transformed SH and SD were compared among locations using an ANOVA, followed by a Tukey post-hoc test. Assumptions of normality and homogeneity of variances were assessed visually. If the homogeneity of variance assumption was violated, a generalised least squares (GLS) model was fitted (Zuur et al., 2009), using the varIdent variance structure to allow a different pattern of spread of residuals to vary per location (Zuur et al., 2009).

Growth analysis

Data on scallop size (SL) frequency obtained from dredge surveys conducted at multiple sites in the BSCZSF, TSF and OSF and dive surveys in the TRSF between 2000 and 2017 (see Figure 35) was collected for growth analysis. Exploratory analysis on raw SL frequencies and temporal coverage was carried out to ensure sufficient sample size to depict cohorts and continuity of data to determine the suitability of each site for growth analysis.

Samples may contain several cohorts and tracking each cohort through time enabled the growth trajectory to be estimated at each site. Mixtures of univariate normal distributions were fitted to the samples obtained in each day/location to identify cohorts from size frequencies. The number of cohorts present was identified by comparing the log likelihood of different numbers of fitted normal distributions and choosing the best fit by using the Akaike Information Criterion as a guideline (Macdonald and Pitcher, 1979). The parameters estimation of each cohort was carried out using the R package mixtools ((Benaglia et al., 2009; R Development Core Team, 2015).

Cohorts identified in the project FRDC 2003/17 (Haddon et al., 2006) were included here in addition to our estimations. In that project, the modal progression analysis was carried out separately for different scallop density strata in the East Flinders region, which highlighted variable size increment estimates according to density variations. These outputs were used as a reference for comparison purposes, as density influences wild scallop growth estimates for both asymptotic size and growth rate (Harris and Stokesbury 2006). Finally, we described the relationship between the initial mean size of the identified cohorts and their increments over the time.

Results and discussion

Condition of scallops

Standardized muscle weight

Scallop muscle weight data was pooled across years per season to give an overall view of condition during the whole sampling period (Figure 4). There was not a clear seasonal pattern of muscle weight ().

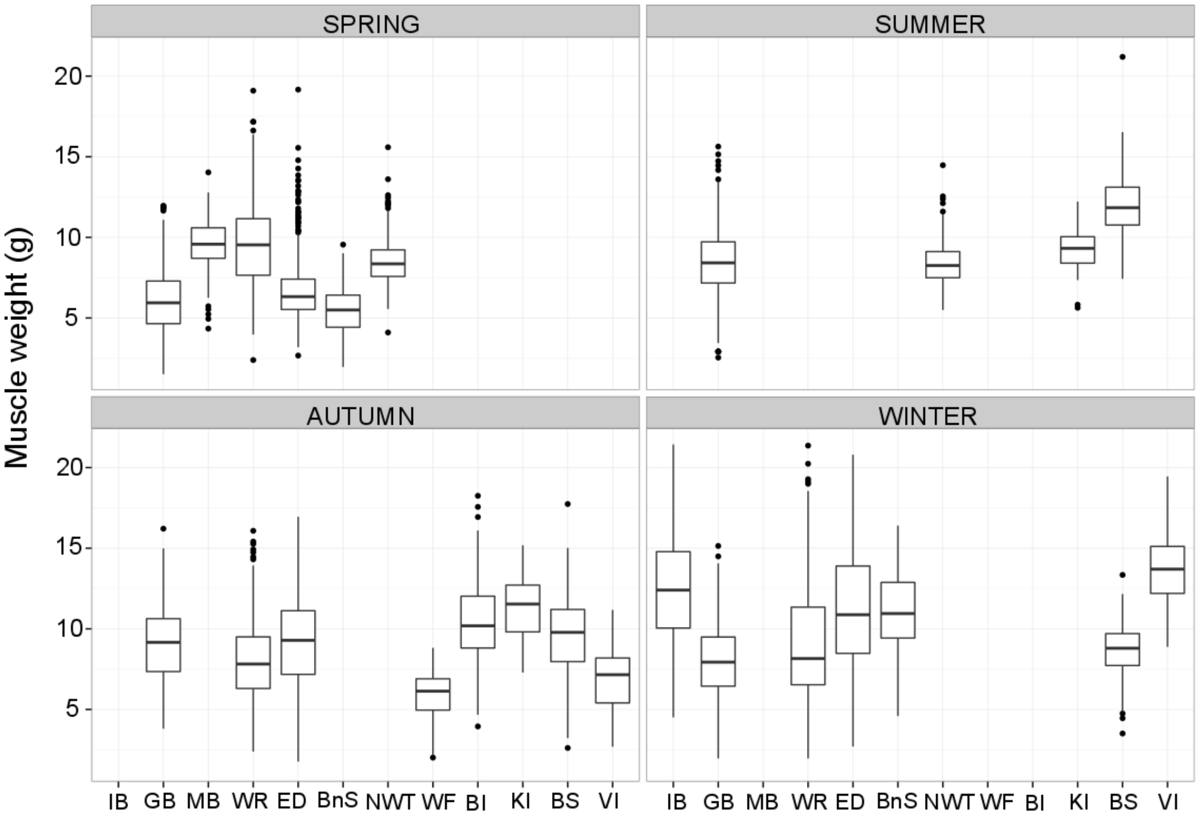


Figure 4. Mean muscle weight (g) for a standard scallop measuring 90 mm SL across different locations in spring, summer, autumn, and winter. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), MB= Marion Bay (TSF), WR=White Rock (TSF), ED= Eddystone (TSF), BnS=Banks Strait (TSF), NWT=North West Tasmania (TSF), WF= West Flinders (TSF), BI=Babel Island (TSF and BSCZSF), KI=King Island (BSCZSF), BS= Bass Strait (BSCZSF), VI=Victoria (OSF). See Figure 1 for site locations.

Due to the lack of continuous data across all seasons in each location, and the expected seasonal variation in muscle and gonad weight due to reproduction, the effect of year and season on muscle weight of scallops were evaluated first in Great Bay, to assess whether it was feasible to compare data from different seasons in different locations across years. In Great Bay, muscle weight for a standard scallop measuring 90 mm in SL was affected by the interaction between season and year ($F=5.10$, $df=3,2412$, $p=0.001$,Figure 5). This model shows, as we expected from their biology, that changes in muscle weight are influenced by season, but this relationship is affected by year. Seasonal meat weight variation is associated with food availability (Lodeiros, 2000) and the reproductive cycle in many scallop species. In commercial scallop, specifically, muscle weight is influenced by the gametogenic cycle, and in Great Bay, lowest values are found in spring, after energy stored in the muscle is used to fuel the initial peak of gametogenesis (Mendo et al, 2015).

Generally, heavier muscles were observed in summer than in spring in Great Bay, but mean muscle weights in the same season were significantly different among years (Figure 5). Therefore, sampling locations could not be compared among different seasons in different years. Comparing locations in the same season and year showed that mean muscle weights differed significantly (i.e. in autumn 2009 $F=51.4$, $df=2,147$, $p<0.001$; Figure 6a), however, this trend was not consistent in different years (i.e. autumn 2012, $F= 0.61$, $df=1,229$, $p=0.43$; Figure 6b). Additionally, comparing muscle weights in the same location and season showed that in White Rock, mean muscle weight in winter significantly differed among years (Figure 7a; $F=26.6$, $df=2,606$; $p<0.001$) with heavier muscles in winter 2006, followed by 2008 and the lowest muscle weights recorded in 2013 (Figure 7a). In spring, muscle weight varied among years ($F=17.33$, $df=2,617$; $p<0.001$), and smaller muscle weights were recorded in 2013, compared to 2006 and 2012 (Figure 7b). In autumn, muscle weights differed markedly between year 2006 and year 2013 (Figure 7c, $F=53.73$, $df=1,514$, $p<0.001$). While in White Rock, the smallest muscle weights were consistently found in 2013, this was not applicable to other locations, i.e. Bass Strait site, where the greatest meat weight in autumn was registered in 2013, compared to 2009 and 2012 (Figure 7d; $F=94.58$, $df=2,311$, $p<0.001$). This strongly implies that there is no common trend in changes in muscle weight across areas, but that the changes are area-specific and year-specific. Water depth has been found to be an important predictor of muscle weight in the American sea scallop, *Placopecten magellanicus* (Hennen and Hart, 2012), mostly associated with food availability in the water column (Macdonald and Thompson, 1985; Schick et al., 1992). As such, depth should be considered for any future attempts to understand muscle weight dynamics in commercial scallop, however, it should be noted that there is less variation in depth at which commercial scallop are harvested compared to the American sea scallop.

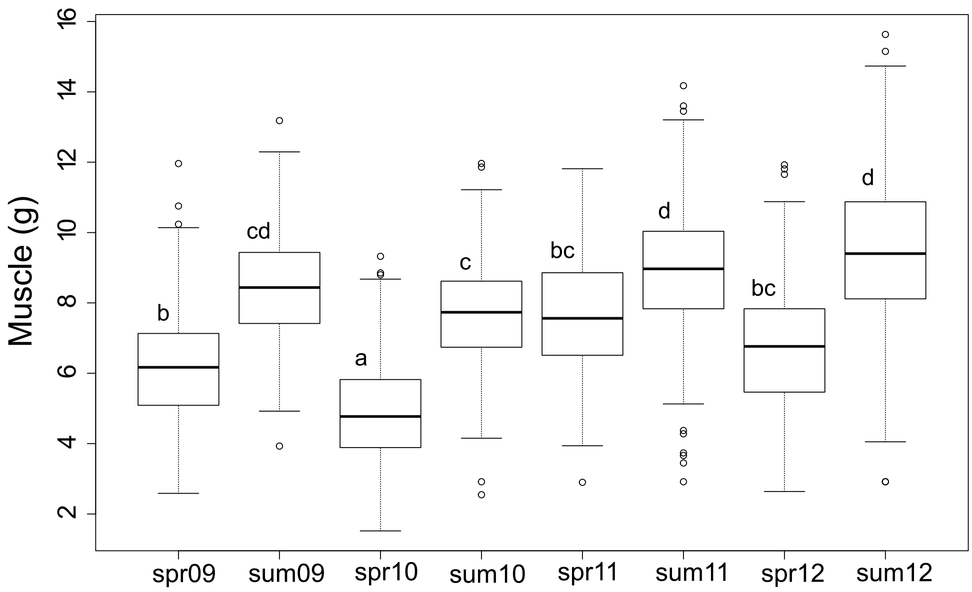


Figure 5. Muscle weight (g) for standardized scallop measuring 90 mm SL in Great Bay (TRSF) in summer (sum) and spring (spr) from 2009-2012. See Figure 1 for site location.

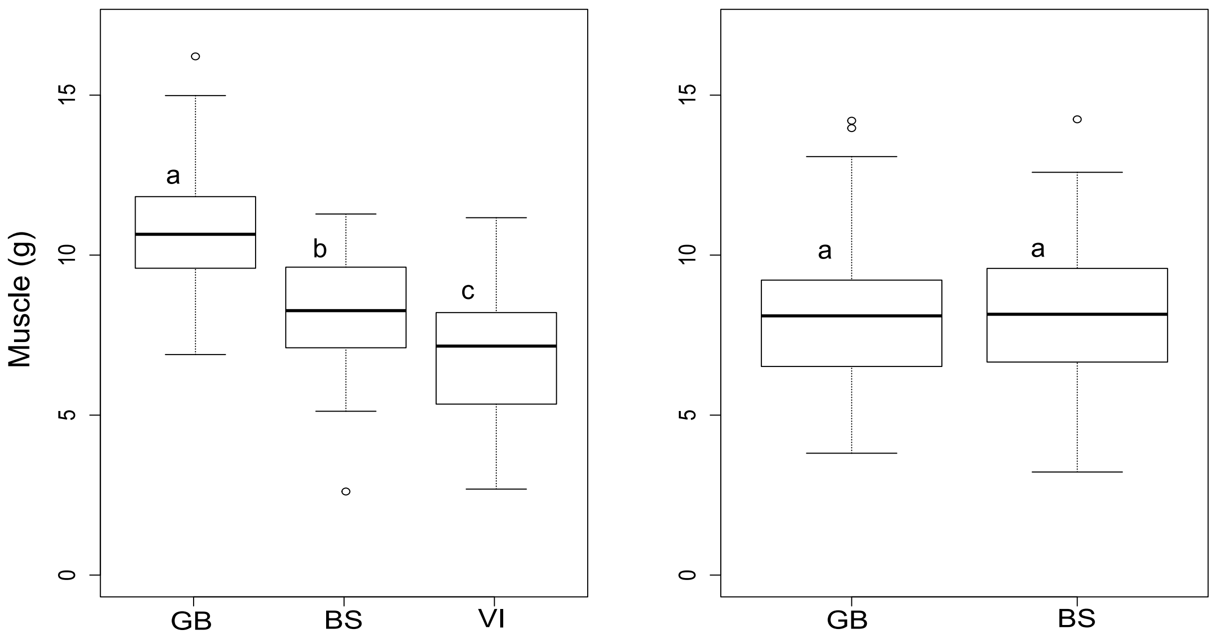


Figure 6. Muscle weight (g) for a standard scallop measuring 90 mm SL in a) autumn 2009 and b) autumn 2012. GB=Great Bay (TRSF), BS= Bass Strait (BSCZSF), VI=Victoria (OSF). See Figure 1 for site locations.

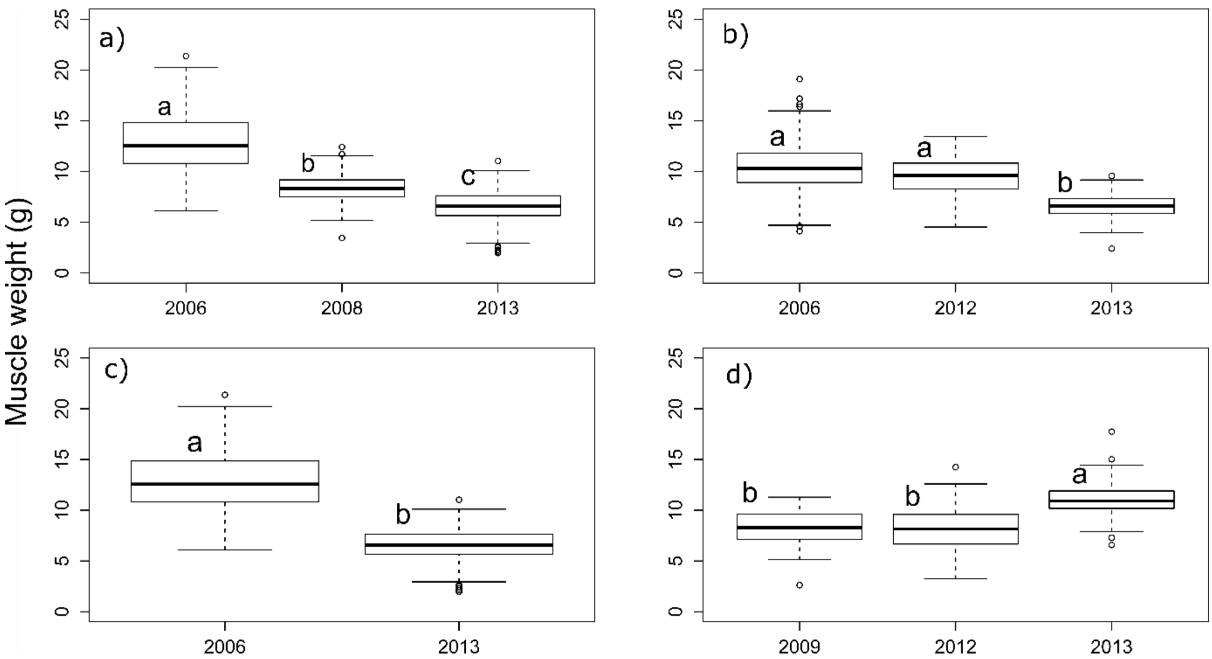


Figure 7. Muscle weight (g) for a standard scallop measuring 90 mm SL in White Rock (TSF) during a) winter 2006, 2008 and 2013; b) spring 2006, 2012 and 2013; c) Autumn 2006 and 2013 and d) at the Bass Strait site (BSCZSF) for autumn 2009, 2012, and 2013. See Figure 1 for site locations.

Differences in mean muscle weight in Great Bay, varied between 10.7 g, recorded both in May 2009 (autumn) and January 2012 (summer), and 4.3 g in September 2010 (spring, Figure 8). This suggests that mean muscle weight can vary up to 2.5 times (or ~60%, MW variation = 1-(4.3÷10.7)*100) in the same location across different seasons, highlighting the importance of fishing in the appropriate season (typically summer/autumn) to maximise muscle yields. However, mean muscle weight varied up to 1.8 times among locations during the same season in a particular year, which stresses the importance of conducting preliminary investigations in different fishing locations (where available) each year to obtain best yields. Mean muscle weights can vary considerably (up to 3.6 times, or 70%) across locations and sampling occasions (Figure 8). During the whole study period, the greatest mean muscle weight recorded in a sampling occasion was 14.5 g in White Rock in July (winter) 2006 followed by 13.7 at the Victorian site in July (winter) 2008. The lowest mean muscle weight recorded was 4.3 g in Great Bay in September (spring) 2010. This difference in mean muscle weight is greater than the one reported for the American sea scallop in Georges Bank, United States (~50%; [MW variation = 1-(22.8÷43.4)*100, for a standard scallop measuring 120 mm SL], (Sarro and Stokesbury, 2009)). The difference in muscle weight might be in such magnitude that economically, it may warrant increased investigation prior to or at the start of the fishery, especially when considering that the average difference in muscle weight between two consecutive months in a location is ~10%. This is particularly relevant in the TSF, when only relatively small areas of the fishery are opened at any one time and the remainder of the fishery is closed, although the adaptive in-season management model in this fishery (i.e., open area boundaries can be changed during the season) can overcome this issue in some circumstances. In the BSCZSF and OSF, given only relatively small areas of the fishery are closed during the fishing season and the entire fishery is opened, respectively, there may be a greater opportunity for scallop fishers to find beds with higher muscle weights, although this is of course dependant on the number of different beds available, with limited to no scallop beds available for harvest in the OSF for over two decades (https://vfa.vic.gov.au/commercial-fishing/scallop). Furthermore, without adaptive in-season management, which is the case in the BSCZSF (i.e., spatial closures are not adjusted during the fishing season), there is the potential for the best quality scallops to be 'locked-up' in spatial closures for the entire season.

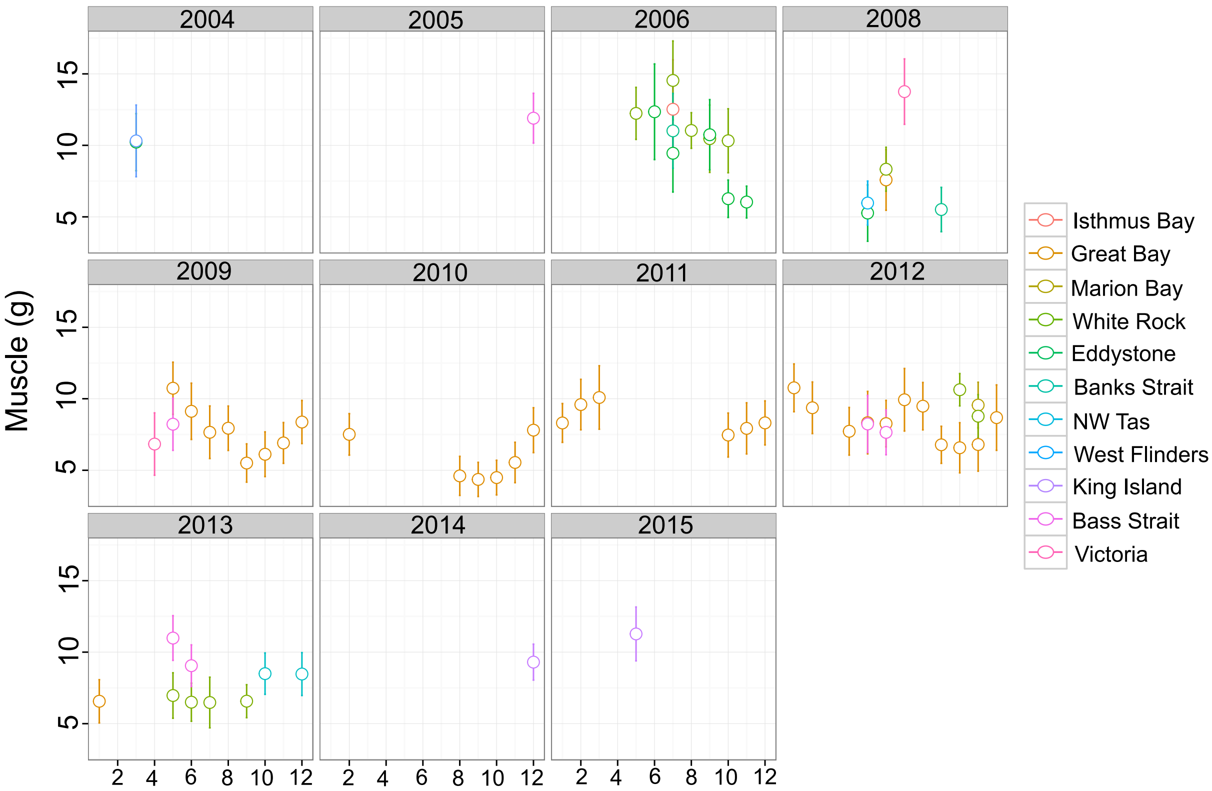


Figure 8. Mean muscle weight (+- SD) for a standard scallop measuring 90 mm SL. See Figure 1 for site locations.

Muscle weight Index

Muscle weight index (MW divided by SL and multiplied by 100) increased proportionally to scallop SL (Figure 9). Mean muscle weight index was affected by sampling location and size class. Significant differences were observed between the muscle weight index of scallops measuring 80 – 90 mm compared to scallops measuring 90 – 100 mm in SL (e.g. autumn 2009: White Rock; Figure 10) and between scallops measuring 80 – 90 and 100-110 mm in SL (e.g. autumn 2009: Victorian site and White Rock; Figure 10) in some locations. Significant differences in the muscle weight index were found among scallops originating from different locations in the same season and year (Figure 10). This further highlights large muscle weight variation and the need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in spatial management regimes where not all of the fishery is opened for fishing during the fishing season, as is the case in BSCZSF and TSF.

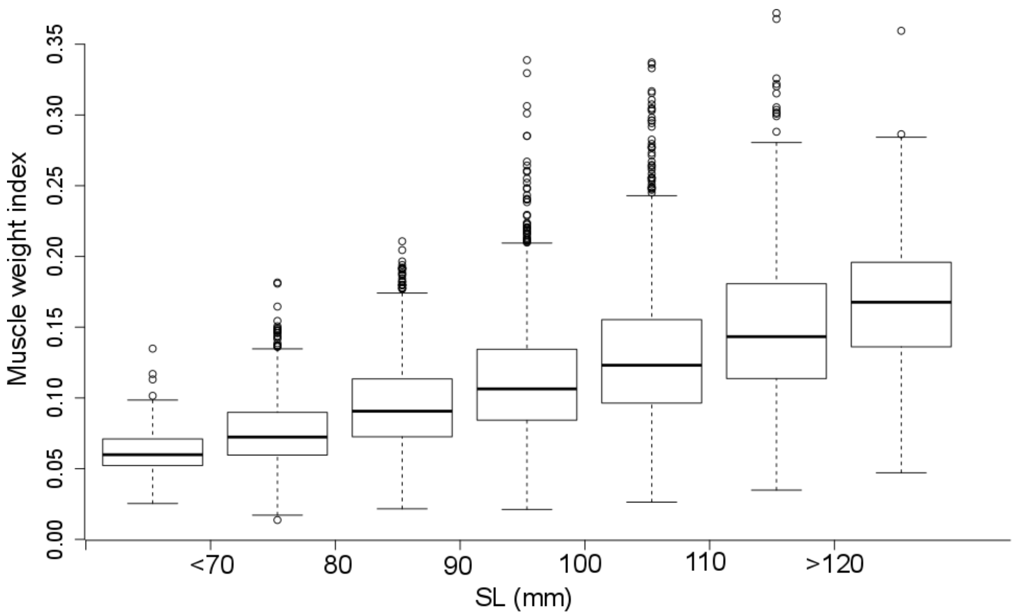


Figure 9. Mean muscle weight index for different size classes of scallop SL.

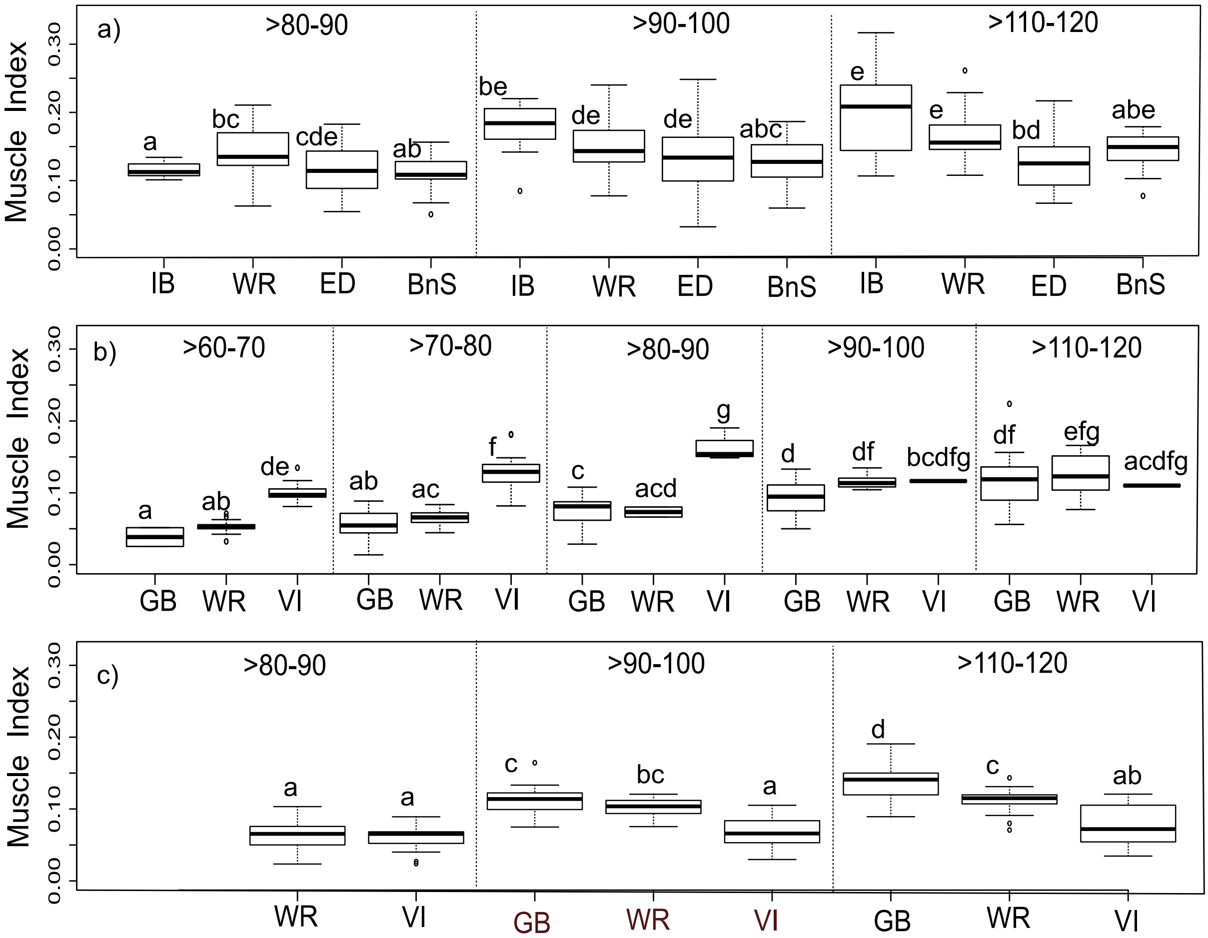


Figure 10. Muscle weight Index in a) winter 2006, b) winter 2008 and c) autumn 2009 divided per size class. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), WR=White Rock (TSF), ED= Eddystone (TSF), BnS=Banks Strait (TSF), VI=Victoria (OSF). See Figure 1 for site locations.

Standardized gonad weight

Pooled data of gonad weight across years per season showed that in general, mean gonad weight was lower in autumn and greater in winter and spring, with insufficient data to compare summer (Figure 11).

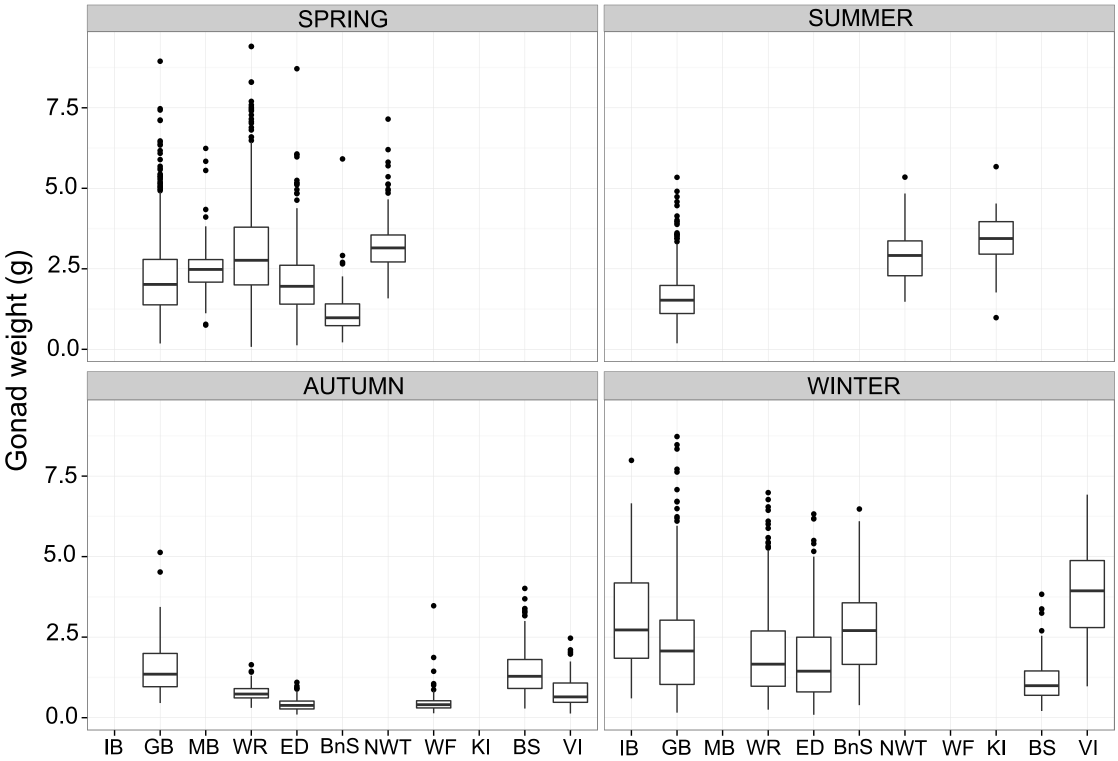


Figure 11. Mean gonad weight (g) for a standard scallop measuring 90 mm SL across different locations in a) spring, b) summer, c) autumn, and d) winter. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), MB= Marion Bay (TSF), WR=White Rock (TSF), ED=Eddystone (TSF), BnS=Banks Strait (TSF), NWT=North West Tasmania (TSF), WF=West Flinders (TSF), KI=King Island (BSCZSF), BS= Bass Strait (BSCZSF), VI=Victoria (OSF). See Figure 1 for site locations.

In Great Bay, gonad weight for a standard scallop measuring 90 mm in SL was affected by the interaction between season and year ($F=4.38$, $df=3,2441$, $p=0.004$ $p<0.001$; Figure 12), however, this trend was not consistent in different years (i.e. autumn 2012, $F= 0.39$, $df=1,229$, $p=0.27$; Figure 13). These results agree with previous studies on the great Atlantic scallop, where differences in gonad weights from different sites were not consistent between years (Hold et al., 2013). Weights in the same location and season showed that in White Rock, mean gonad weight in winter significantly differed among years (Figure 14; $F=26.6$, $df=2,606$; $p<0.001$), with heavier gonads in winter 2006, followed by 2008 and the lowest gonad weights recorded in 2013. In spring, gonad weight was not significantly different among years ($F=1.91$, $df=2,617$; $p=0.15$;). At the Bass Strait site, the greatest gonad weight in autumn was registered in 2013, compared to 2009 and 2012 (; $F=30.49$, $df=2,311$, $p<0.001$).

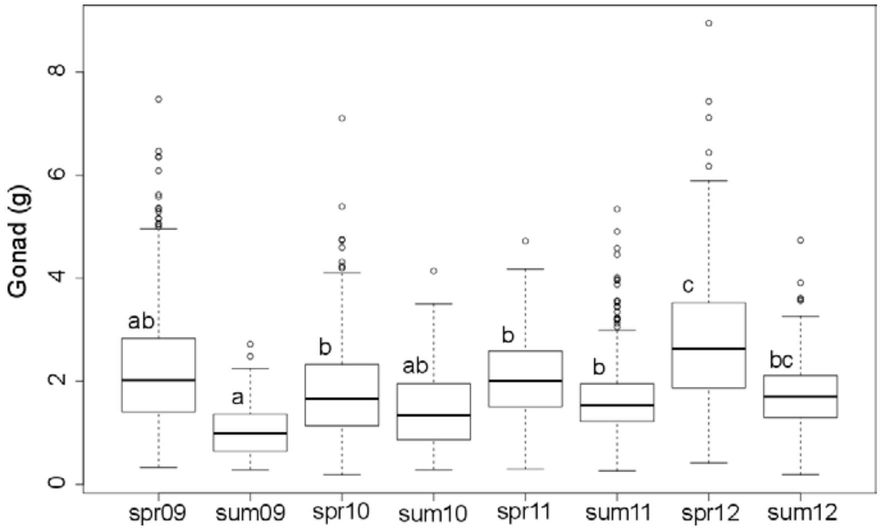


Figure 12. Gonad weight (g) for standardized scallop measuring 90 mm SL in Great Bay (TRSF) in summer (sum) and spring (spr) from 2009-2012. See Figure 1 for site location.

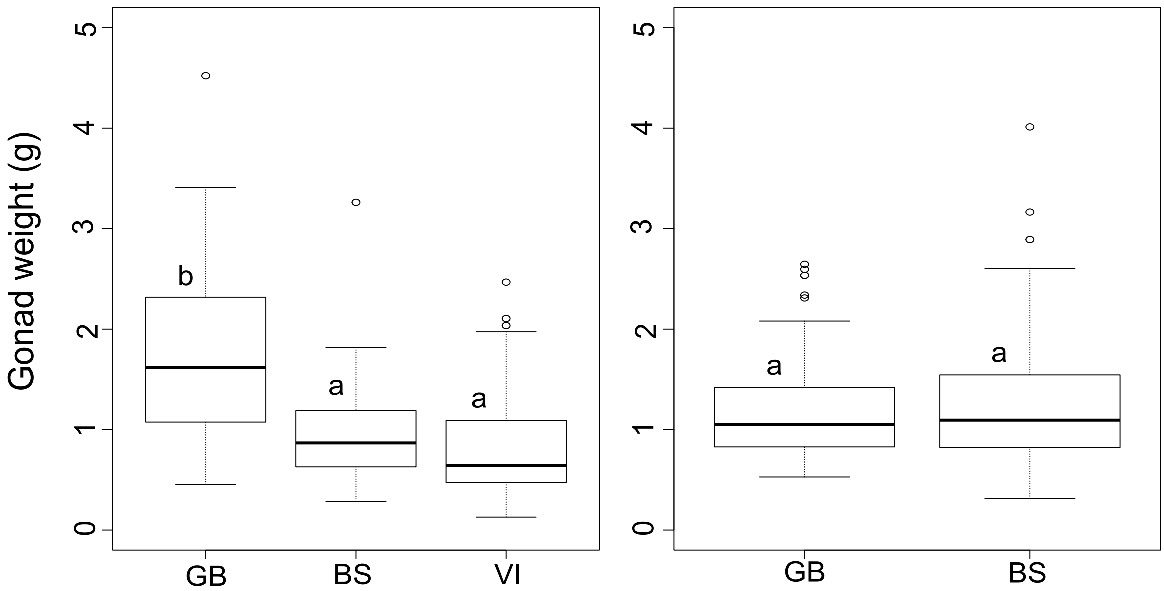


Figure 13. Gonad weight (g) for a standard scallop measuring 90 mm SL in a) autumn 2009 and b) autumn 2012. GB=Great Bay (TRSF), BS= Bass Strait (BSCZSF), VI=Victoria (OSF). See Figure 1 for site locations.

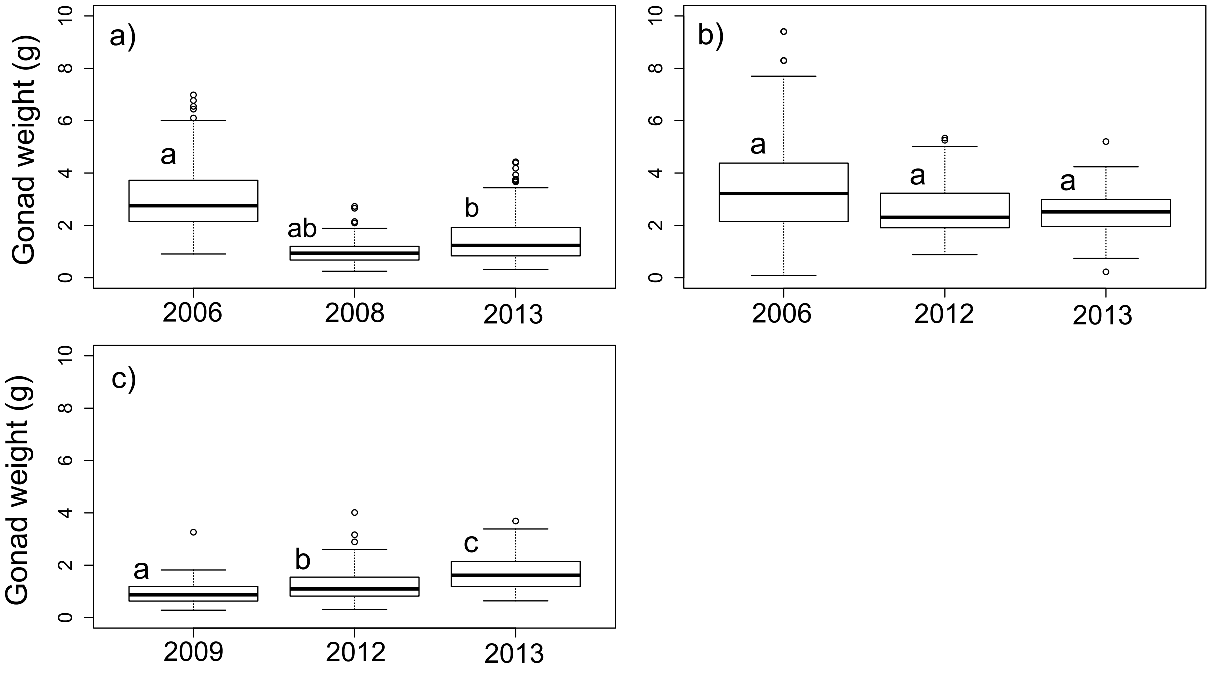


Figure 14. Gonad weight (g) for a standard scallop measuring 90 mm SL in White Rock (TSF) during a) winter 2006, 2008 and 2013; b) spring 2006, 2012 and 2013; and c) in Bass Strait (BSCZSF) for autumn 2009, 2012, and 2013. See Figure 1 for site locations.

Mean gonad weight in winter 2012 in Great Bay varied between 0.7 g in June and 4.5 g in August (Figure 15). This suggests that mean gonad weight can vary up to 6.5 times (or ~85%, GW variation = 1-(0.7÷4.5)*100) in the same location across different months, highlighting the importance of fishing in the appropriate period to maximise gonad yields. Mean gonad weight varied up to 4.3 times among locations during the same season in a particular year (winter 2008, 0.9 g mean gonad weight in White Rock compared to 3.9 g at the Victorian site). Mean gonad weights can also vary considerably (up to 11 times or ~90%) across locations and sampling occasions (Figure 15). During the whole study period, the greatest mean gonad weight recorded in a sampling occasion was 4.5 g in Great Bay in August (winter) 2012, followed by 3.9 g at the Victorian site in July (winter) 2008 and 3.7 g in Eddystone in September (spring) 2006. The lowest mean gonad weight recorded was 0.4 g in Eddystone in May (autumn) 2008, followed by 0.5 g in West Flinders in May (autumn) 2008.

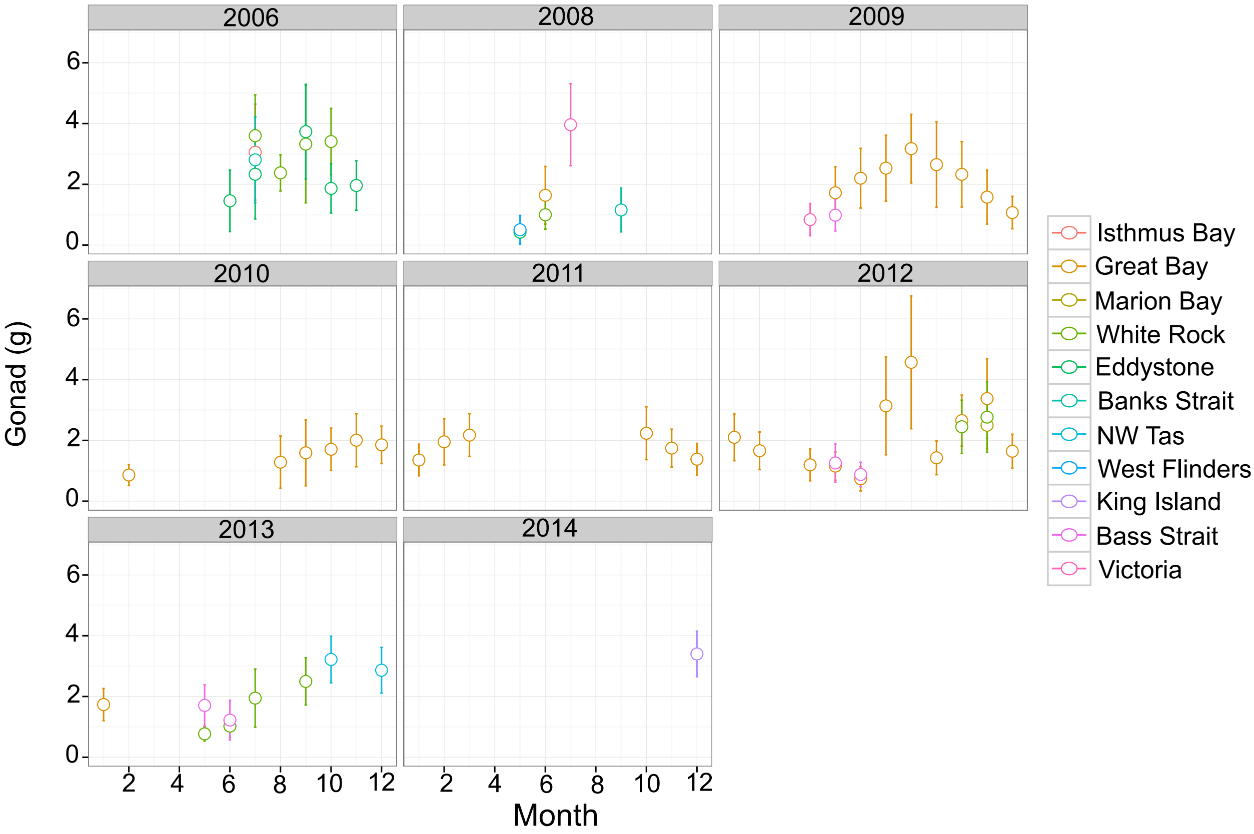


Figure 15. Mean gonad weight (+- SD) for a standard scallop measuring 90 mm SL. See Figure 1 for site locations.

Gonad weight Index

Gonad weight index (GW divided by SL and multiplied by 100) increased proportionally to scallop shell length (Figure 16). Mean gonad weight index was affected by sampling location and size class. While no significant differences were observed between gonad weight indices of scallops measuring 80 – 90 mm compared to scallops measuring 90 – 100 mm in SL in the same location, significant differences were found between scallops measuring 80 – 90 and 100-110 mm in SL in some locations (i.e. winter 2006, Eddystone; Figure 17). Again, this confirms that different locations can have very different gonad weights for similar-sized scallops.

The results for both gonad weight and gonad weight index highlight large gonad weight variation, and like that for muscle weight variation, the need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in the BSCZSF and TSF, where not all the fishery is opened for fishing during a fishing season.

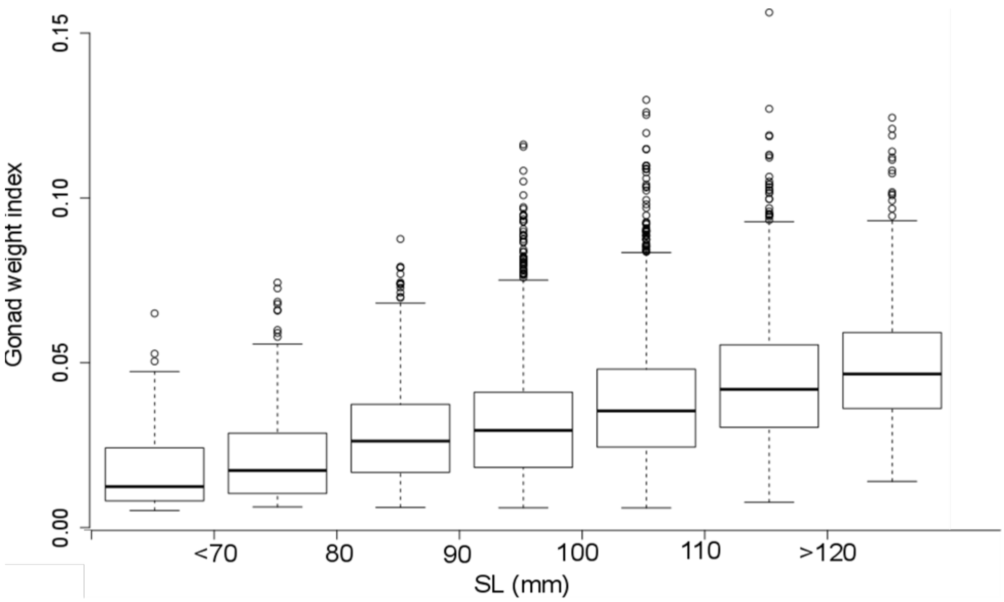


Figure 16. Mean gonad weight index for different size classes of scallop SL.

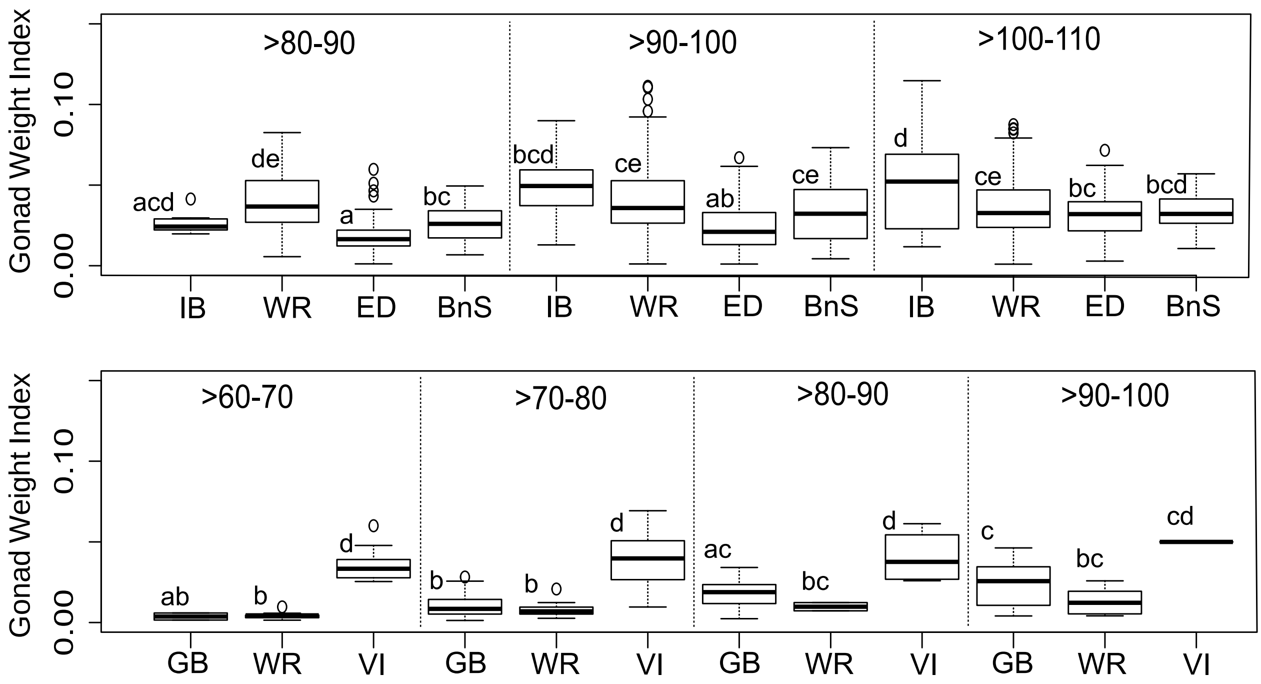


Figure 17. Gonad weight Index in a) winter 2006, and b) winter 2008 divided per size class. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), WR=White Rock (TSF), ED= Eddystone (TSF), BnS=Banks Strait (TSF), VI=Victoria (OSF). See Figure 1 for site locations.

Meat recovery weight (muscle and gonad weight combined)

Pooled data of meat recovery weight across years per season showed that in general, mean weight was lower in autumn and greater in winter and spring, with insufficient data to compare summer (Figure 18). Differences in meat recovery weight in autumn in Great Bay varied between 5.7 g in August 2010 and 14.0 g in August 2012 (Figure 19). This suggests that mean meat recovery can vary up to 2.5 times in the same location and season across different years, while mean meat recovery varied up to 1.9 times among locations during the same season in a particular year (winter 2008, 9.2 g mean meat recovery in Great Bay compared to 17.7 g at the Victorian site). Mean meat recovery also varied considerably (up to 11 times) across locations and sampling occasions (Figure 20). During the whole study period, the greatest mean meat recovery recorded in a sampling occasion was 18.1 g in White Rock in July (winter) 2004, followed by 17.7 g at the Victorian site in July (winter) 2008, and 15.5 g in Isthmus Bay in July (winter) 2004. The lowest mean meat recovery recorded was 5.7 g in Eddystone in May (autumn) 2008 and 5.7 g in Great Bay in August (winter) 2010. This confirms that meat recovery weight can vary significantly across years, area and season and therefore further highlights the need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in the BSCZSF and TSF, where not all the fishery is opened for fishing during a fishing season.

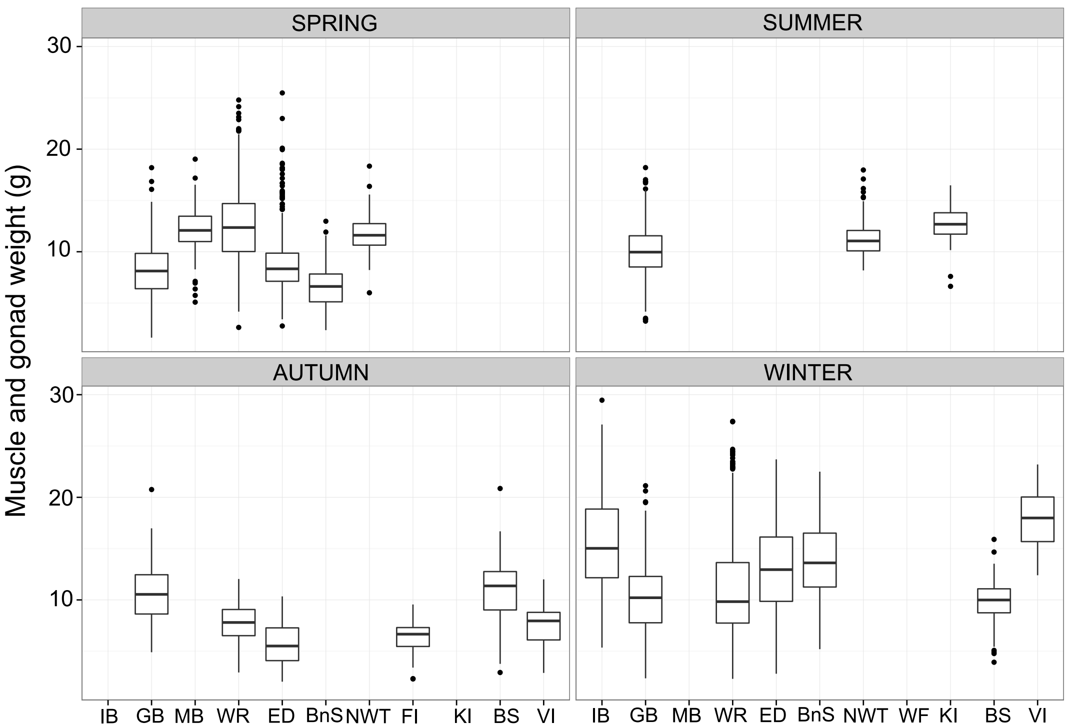


Figure 18. Mean meat recovery weight (muscle and gonad weight combined) (g) for a standard scallop measuring 90 mm SL across different locations in a) spring, b) summer, c) autumn, and d) winter. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), MB= Marion Bay (TSF), WR=White Rock (TSF), ED= Eddystone (TSF), BnS=Banks Strait (TSF), NWT=North West Tasmania (TSF), WF= West Flinders (TSF), KI=King Island (BSCZSF), BS= Bass

Strait (BSCZSF), VI=Victoria (OSF). Interquartile range (boxes), median (middle lines), 95% CI (bars), outliers (points). See Figure 1 for site locations.

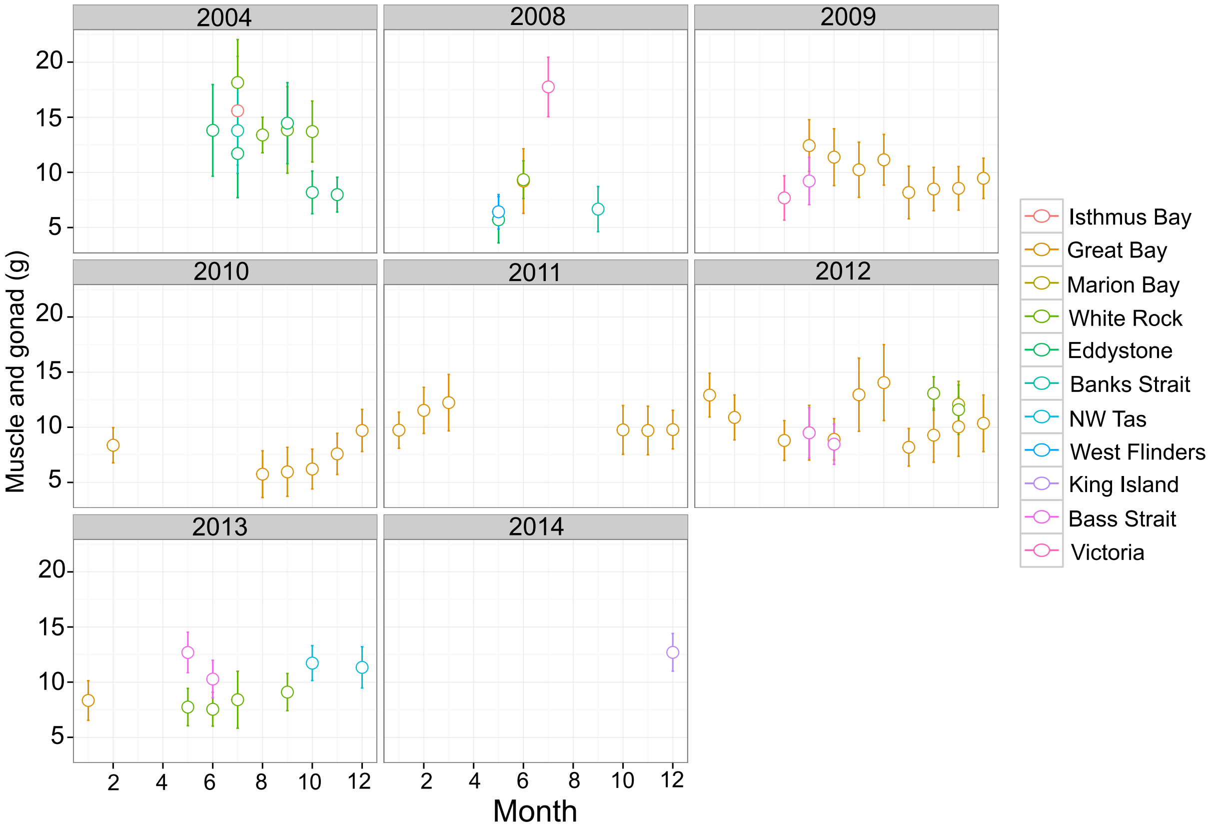


Figure 19. Mean meat recovery (muscle and gonad weight combined) (± SD g) for a standard scallop measuring 90 mm SL. See Figure 1for site locations.

Visual staging of gonads

Pooled data of gonad macroscopic staging combined across years per season showed that only scallops greater than 70 mm in SL presented gonads in prime condition (scallops in which gonads were larger than muscles) and larger scallops showed a greater proportion of gonads in prime condition. In general, gonad condition was worst in autumn (Figure 20). In winter, gonad condition was increasing, although White Rock seemed to have worse condition than the other locations in this season. While in spring most scallops were in primer condition, this trend differed for Banks Strait, for which a greater proportion of developing gonads were identified (Figure 20). These data suggest that, in terms of gonad condition, Banks Strait (TSF) and possibly the Victorian site (OSF) might benefit from harvesting early in winter while Great Bay (TRSF), White Rock (TSF) and Eddystone (TSF) might benefit from harvesting later in the season. There is insufficient macroscopic data to make an assessment about the Bass Strait site (BSCZSF).

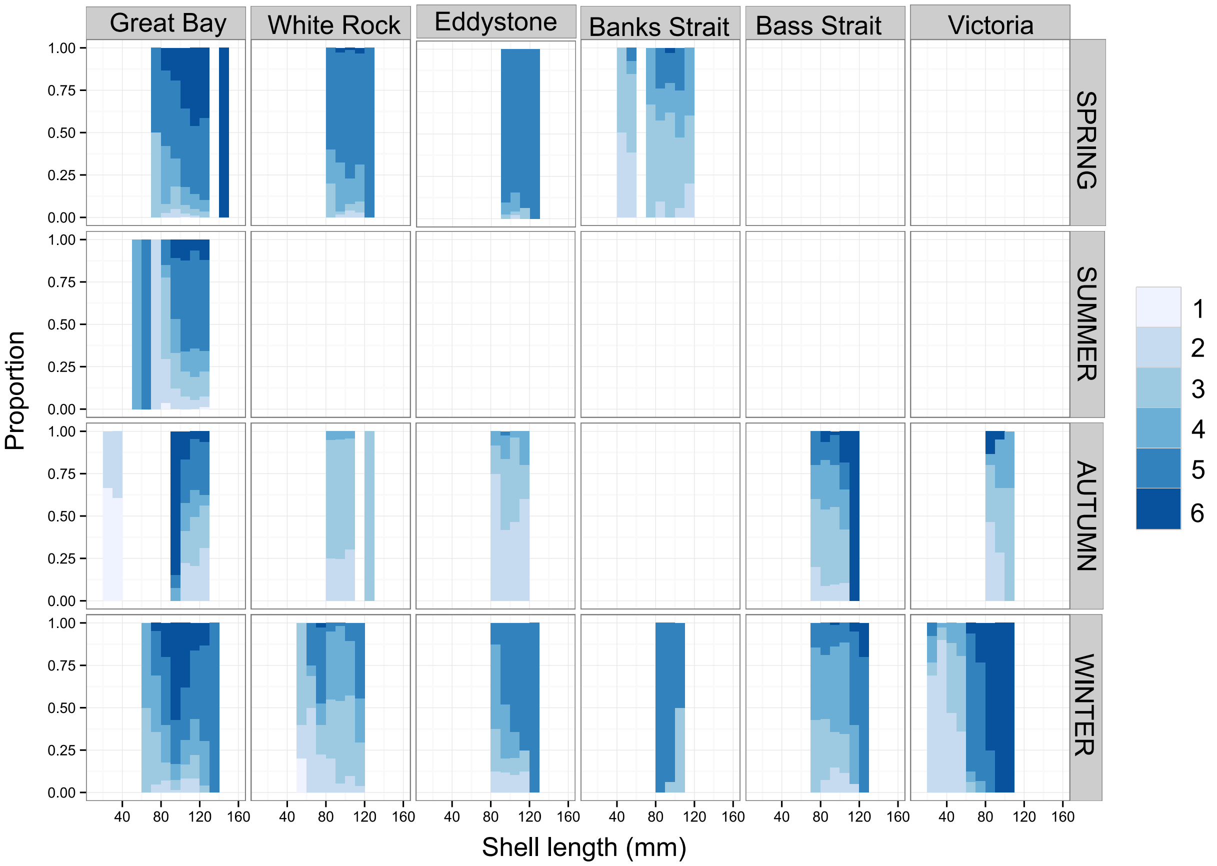


Figure 20. Proportion of gonads in each stage determined macroscopically in different locations during the sampling period 2006-2013. See Figure 1 for site locations.

Macro vs. microscopic assessment in commercial scallop

Maturity stages identified macroscopically did not consistently match the maturity stages identified by histological sampling (Figure 21). Apart from macroscopic stage 2, which comprised scallops with predominantly gonads in the developing stage, the other macroscopic stages showed a mixture of reproductive stages (Figure 21). Therefore, while the macroscopic staging scheme is useful to derive an indication of gonad condition, as provided above, it does not accurately reflect the maturity stage in the ovary.

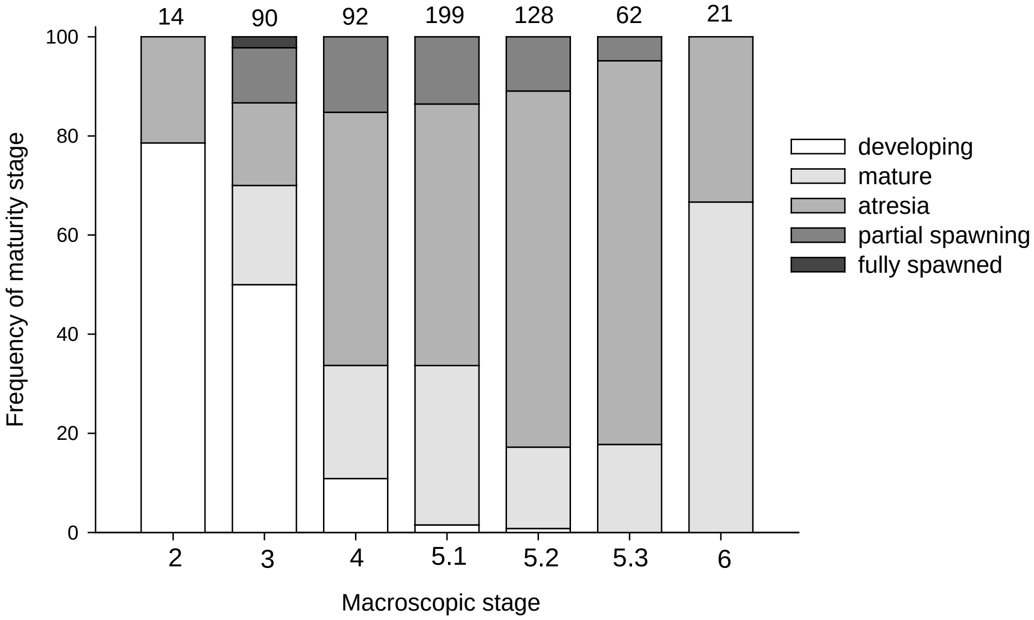
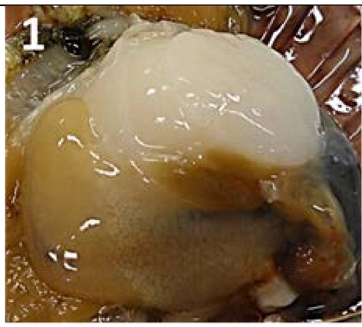
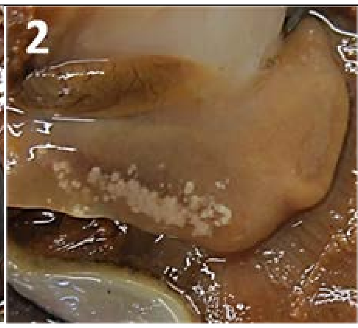


Figure 21. Macroscopic stages vs. microscopic staging in commercial scallop. Numbers above bars indicate samples size per stage.

Proposed macroscopic visual staging to incorporate reproductive stage and define operational measures of spawning condition for use in the scallop fisheries

Based on microscopic observations compared to macroscopic examination of gonads, three visual stages are described based on the morphological appearance of the gonad to the naked eye (Table 5).

Table 5. Proposed visual staging system to identify spawning events in commercial scallop.

Reproductive stage	Description	Images
Developing or spent	Gonad is small, thin, translucent, brownish colour. Intestinal loop usually visible. Ovarian and testicular tissues difficult to differentiate.	 
Maturing or atretic (reabsorbing eggs as spawning is delayed)	Separate acini clearly visible, male (white) and female (orange) part of gonad distinguishable. Gonad increases in turgor (rigidity) and becomes less granular in appearance as acini begin to fill until ovarian tissue appears uniform in colour.	 
Partially spawned	Gonad reduced in size compared to previous stage. Ovary appears mottled, presumably due to some acini being voided. Intestinal loop usually visible, ovarian tissue uniform in colour, but interspersed with isolated specs of translucent (void) acini. Testicular tissues turn paler in colour.	 

When the application for this FRDC project was submitted (2011), the BSCZSF harvest strategy dictated that most of the fishery was closed, with a relatively small defined area opened for fishing. Therefore, scallops in the areas opened could be unsuitable for harvest due to poor condition when the season opened. This meant the areas were sometimes opened then rapidly closed to fishing again, causing disruption to fishing/processing businesses, and marketing problems. Delayed opening while scallops gained condition could also prevent the total catch being taken because there is a fixed, pre-determined finish date to the fishing season. Given these issues, operational measures of spawning condition for use in the scallop fisheries were an objective of this project. However, the BSCZSF moved to a relatively small area closed, remainder of the fishery open harvest strategy in April 2014 to help alleviate these problems. Despite this, fishing in the Commonwealth still predominately takes place in the beds or regions surveyed before the season commences. Similarly, the TSF only opens to fishing surveyed areas that meet the management plan. While the OSF does not use surveys to determine open areas, as it is not a spatially managed fishery, fishing generally occurs in traditional areas, which will have variable gonad development and spawning timings within and between them. As such, the simple three stage visual staging system developed in this project is useful to both scallop resource managers and industry, as part of in-season management strategies, to define the overall reproductive stage of scallops and predict timing of spawning, thus assisting in the best condition scallop beds being fished sequentially through out the season. This has the potential to enhance the operation and profitability of the fisheries. The benefit of the scheme is there are only three stages, so classification is relatively simple. Additionally, photos of opened scallops could be taken by fishers, fisheries observers, scallop processers, etc., and sent to other parties to examine and confirm, as a method of validating the reproductive condition of the bed or area. For example, as part of in-season industry management, photos of the gonad staging could be sent to fishers to validate decisions made by industry representatives on which scallop beds to fish at any particular time and which beds need measures such as volentary closures.

A further example of using this gonad staging scheme could be in relation to the season end date in the BSCZSF, which is Decmber 31 each year (also 31 December in TSF; noting that OSF is open continually throughout the year) to protect potential scallop larval settlement. Fishers are currently interested in trialling fishing past December 31, in order to keep established markets going, with a proposal that they would stop fishing once spawning begins and thus in theory before settlement starts. If this proposal went ahead, this simple gonad staging system could be used to quickly assess all the beds in the region to determine if spawning has commenced and quickly relay the information to AFMA managers. While separate to determining the utility of the gonad staging system, it should be noted, however, that the recruits may not come from the known King Island beds, with the current fished area occurring in a region that was surveyed in 2009 and only seven individual scallops found (Harrington and Semmens, 2010), suggesting that recruits came from another region.

Timing of spawning and settlement; season openings and closings that are more responsive to this timing; and incorporation into harvest strategies and industry in-season management

Timing of spawning was estimated for Great Bay (TRSF) and White Rock (TSF), both locations with the greatest number of sampling occasions. Pictures taken of scallops collected in Great Bay during FRDC 2008/022 were staged using the proposed macroscopic visual staging (described above). The greatest proportion of developing or spent gonads occurred in April and May in Great Bay (Figure 22). In 2010 the population underwent partial spawning that lasted for several months and occurred mainly in November, December and again in February and March 2011. In 2012, spawning occurred mainly in January, June, July, August, December, and then January 2013. This suggests that in Great Bay, September and October might be sensible months to open the TRSF season when in operation. Again, this data corroborates previous studies showing that a protracted spawning strategy, i.e. where gametes are shed during several consecutive months, is used by this species (Sause et al., 1987b; Fuentes, 1994; Mendo et al., 2014).

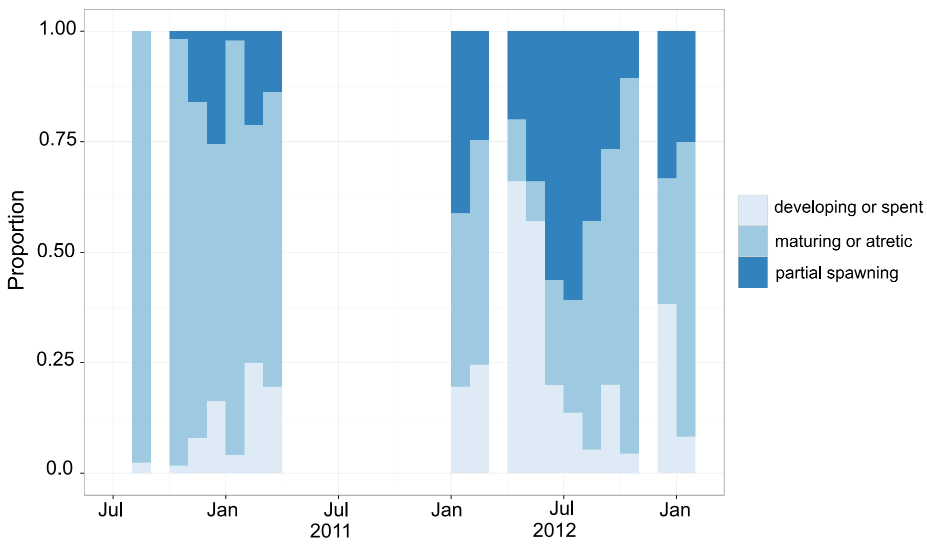


Figure 22. Proportion of ovaries in each reproductive stage in Great Bay (TRSF). See Figure 1 for site location.

At White Rock, gonads were staged histologically (allowing all five histological stages to be used, unlike the three that can be used for the visual staging system), with data showing that in May gonads of scallops were developing, and still showing a great proportion of developing gonads during June (about 40%) and July (~25%). Interestingly, June and July also showed scallops with partially spawned and fully spawned gonads (~30 and 20% of all scallops, respectively). Only during September, October and

November did scallops have mainly mature or atretic gonads (Figure 23). The histological analysis, combined with the analysis of gonad condition (Figure 23) suggest that in White Rock spawning might be more prevalent in June and July than in spring (September, October and November), although further studies are needed to corroborate this and to determine the proportion of scallops spawning in summer months. Even though the proportion of partially spawned gonads was very low in October and November, this shows that a protracted, "dribble" spawning strategy might be used by scallops in White Rock. These observations also agree with records of spat settlement in Mercury Passage (a few kilometres away from White Rock), where a major settlement was recorded in mid-late September (possibly from spawning in winter months), but small irregular settlements were observed in late spring and early summer (Hortle and Cropp, 1987).

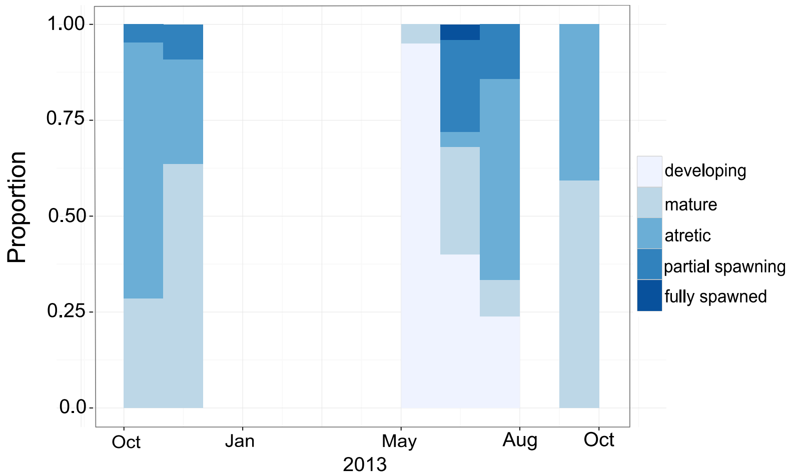


Figure 23. Proportion of ovaries in each reproductive stage in White Rock (TSF). See Figure 1 for site locations.

Collection of data on scallop condition, reproductive stages and settlement rates collectively can help inform best timing for season opening and closing dates in each location (Table 6). The information available from this study and previous studies, while still limited, suggest that the Lakes Entrance region, which comprises the majority of the OSF, would profit from an early start during winter. However, note that the OSF is currently considered depleted (Semmens et al., 2019) and has not had significant catches in over two decades. This is part may be attributable to the fact that the fishery has historically been open continuously throughout the year, including the settlement period. In Great Bay (TRSF), while gonad weight is greatest in winter, actual gonad condition is greatest in spring, therefore harvesting late winter, beginning of spring would seem appropriate when this area is open. However, it should be noted that the D'Entrecasteaux Channel where Great Bay is located is currently considered depleted and is closed to recreational fishing (Ewing and Lyle, 2017). At White Rock in the TSF, starting the fishery in September would appear more beneficial in terms of harvesting the best product, although this may not fit best with protecting newly settled scallops, and may in part explain why this area has not supported a fishery in recent years and is now classified as depleted (Semmens et al., 2018; Semmens et al., 2019). North of Flinders Island (‘Bass Strait’ site, see Figure 1 and Figure 35) in the eastern section of the BSCZSF, the best time to fish appears to be summer/autumn and most likely spring (currently lacking data for this period), noting that the fishery currently closes December 31. Like White Rock, fishing up to this closure date may not fit best with protecting newly settled scallops, with the major settlement period occurring in spring, and again may in part explain why this area has not been viable in recent years (Patterson et al., 2017). At King Island, in the BSCZSF, the best time to fish appears to be spring and summer, however, settlement is from approximately November to January. As previously noted, fishers are currently interested in trialling fishing in the BSCZSF past December 31, in order to keep established markets going. From a perspective of harvesting the best product, this would seem to be a sensible approach at least for the King Island portion of the fishery, which has significant biomass currently over a relatively large area. However, as previously discussed this has to be balanced with the important need of ensuring settlement is not distruped, given that peak settlement is in the summer months and there is no way of knowing where recruits will come from (i.e. King Island beds or beds in another area). However, given the large biomass currently available (i.e. large potential area for recruits to settle) and the fisher proposal to stop fishing once spawning begins in the area, it may be possible to oporationally limit the risk to settelement of fishing past December 31, e.g. spatially restrict any post December 31 portion of the fishery.

Table 6. Combination of different condition indicators, histology and settlement information from this study and previous studies for Great Bay (TRSF)[1], White Rock (TSF)[2,3,4], Victoria (OSF)[5,6,7], Bass Strait (BSCZSF)[6] and King Island (BSCZSF)[6]. Grey areas denote best condition of scallops for fishing. See Figure 1 for site locations.

		Summer		Autumn			Winter			Spring			Summer
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Great Bay	Histology		partial		developing			mature and spawning			mature	partial	
	Muscle weight									←	lowest	→	
	Gonad weight						←	greatest	→				
	Muscle and gonad									←	lowest	→	
	Gonad condition									←	greatest	→	
	Settlement	---- yes →										← yes	----
White Rock	Histology					developing		developing & spawning		←	mature	→	
	Muscle weight												
	Gonad weight									←	greatest	→	
	Muscle and gonad									←	greatest	→	
	Gonad condition				lowest					←	greatest	→	
	Settlement	- yes →								Yes	←	yes (minor)	---
Victoria	Histology	spawning	spent								←	spawning	-----
	Muscle weight						←	greatest	→				
	Gonad weight						←	greatest	→				
	Muscle and gonad						←	greatest	→				
	Gonad condition				lowest		←	greatest	→				
	Settlement	------	yes →									← yes	----
Bass Strait	Histology					developing & mature							
	Muscle weight	--- greatest →					←	lowest	→				greatest -
	Gonad weight			greatest	←		low	→					
	Muscle and gonad			greatest	←		low	→					
	Gonad condition			←	greatest →		←	lowest	→				
	Settlement									←	yes	→	
King Island	Histology	mature & spawning						atretic			mature & spawning		
	Muscle weight			←	greatest →								
	Gonad weight	---- high →											high --
	Muscle and gonad	---- high →											high --
	Gonad condition	- greatest ←				lowest	→		←		greatest	------	------
	Settlement	-- yes →										← yes	----

[1]Semmens et al. (2015), [2]Hortle and Cropp (1987), [3]Cropp (1989), [4]Dix (1981), [5]Suase et al. (1987b), [6]Young et al. (1999), [7]Coleman (1989)

Spawning potential between scallops ranging from 80 to 90 mm

Proxy for fecundity

Fecundity was positively related to shell length, and this relationship varied according to month of sampling (Table 7, Figure 24). Post-hoc comparisons showed that fecundity in May, June and July (autumn and winter) was significantly lower than in September, October, November and December (spring and autumn). As an example, fecundity estimated for a scallop measuring 90 mm in November was 2.5 times greater than in June (Figure 25). Fecundity increased exponentially with SL and the model predicted that a scallop measuring 90 mm in shell length would be 13 and 25% more fecund than an 85 and 80 mm scallop, respectively. Furthermore, an 80 mm scallop would be 44% more fecund that a scallop measuring 70 mm in SL (Figure 26a and b). Scallops measuring 100 mm in SL would produce 32% more eggs than a scallop measuring 90 mm (Figure 26). These differences are less dramatic than previous findings (Martin et al., 1988) where 3+ years old scallops measuring ~90 mm SL shed (3.5 million eggs on average) compared to 2 million eggs shed by scallop measuring ~ 83 mm SL (a 57%

difference compared to 19% estimated in this study). However, the Martin et al. (1988) estimates of fecundity were driven by high fecundity counts from scallops located in Banks Strait, a location that was not included in this study. Scallops in Banks Strait had almost twice as many eggs as scallops of similar sizes located in King Island (Martin et al., 1988). If we remove Banks Strait as a study location from Martin et al (1988) the difference in fecundity between scallops measuring 90 mm compared to 80 mm is 25%, very similar to the findings in this study.

This result of the current study showing a much smaller difference in fecundity in scallops of various sizes compared to previous findings (Martin et al., 1988), is a very important finding in relation to the decision rules around scallop harvest, particularly the under-sized discard rate rule and the two spawnings criteria which states that scallops should be allowed a minimum of two major spawning events before being harvested (McLoughlin 1994; Zacharin 1994). As previously described, scallops that are 85-95 mm SL (adapted from 75-85 mm SH, Martin et al. 1988; McLoughlin 1994) are 3+years old and have had two major spawning and thus contributed significantly to potential recruitment. However, given the relationship between fecundity and SL demonstrated in this study, which shows a 3-fold decline in the difference between fecundity of an 83 and 90 mm SL scallop compared to the previous research (Martin et al. 1988; McLoughlin 1994), the size limits are very conservative. As such, the use of 85 mm SL, as now used in the BSCZSF and to be adopted by the TSF in 2020, still allows the scallops to have produced two major spawnings before harvest, with relatively little difference between the fecundity of 85 and 90 mm SL scallops (13%). However, it should be noted that in regions that have very low biomass or are recovering from being depleted (e.g. TSF; Semmens et al. 2018), this additional 13% could be significant, and a highly conservative approach may be warranted. Furthermore, it should be noted that the 80 mm SL size limit used for the decision rules in the OSF is likely not appropriate, as it is outside of the size range for the two major spawnings criteria and should be revisited, with this low size limit perhaps contributing to the long history of limited biomass and recruitment in the fishery.

Along with the fished scallops having greater fecundity in relation to larger scallops, our finding also means that those scallops that are not retained as they are undersized also have a greater fecundity than previously thought. For example, in both the BSCZSF and the TSF 83 mm SL scallops are not retained, as they are undersized. We now know that these scallops are only approximately 19% less fecund than a 90 mm SL scallop, compared to the previously thought difference of 57% (Martin et al. 1988). As such, undersized scallops have the potential to contribute much more significantly to recruitment than previously thought.

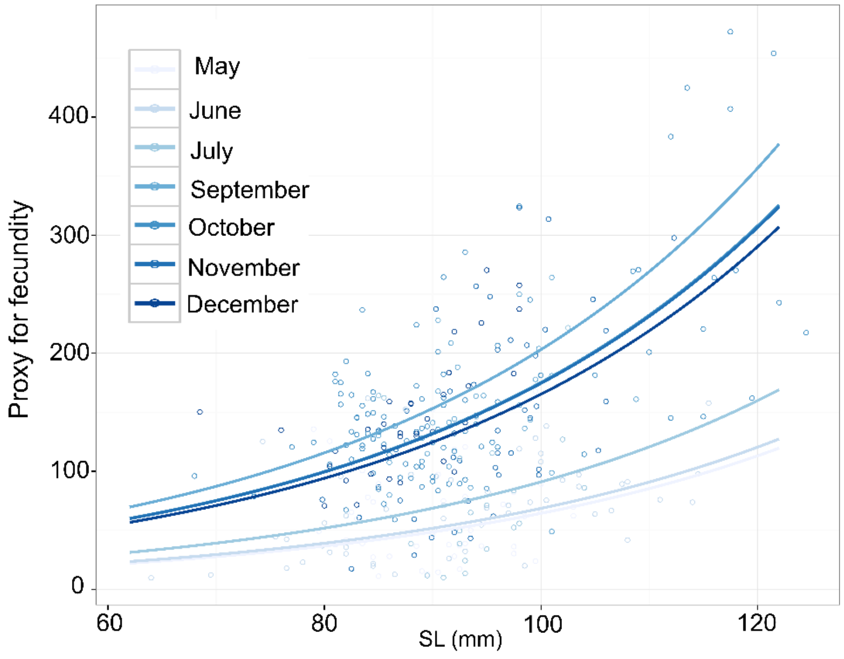


Figure 24. Relationship between shell length, month and proxy for fecundity.

Table 7. Parameter estimates for the generalized mixed effect model describing variation in fecundity.

Fixed effect	Estimate (SE)	df	p value
Intercept	3.93 (0.15)	325	<0.001
CLength	0.028 (0.003)	325	<0.001
June	0.062 (0.115)	325	0.587
July	0.346 (0.214)	325	0.106
September	1.149 (0.129)	325	<0.001
October	1.001 (0.123)	325	<0.001
November	0.997 (0.152)	325	<0.001
December	0.942 (0.136)	325	<0.001

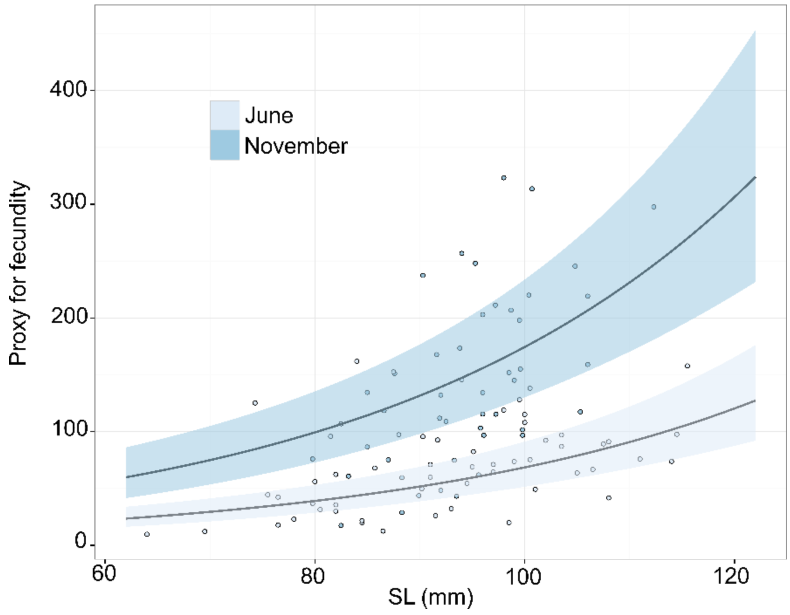


Figure 25. Predicted fecundity (solid line) and 95% confidence intervals for June and November.

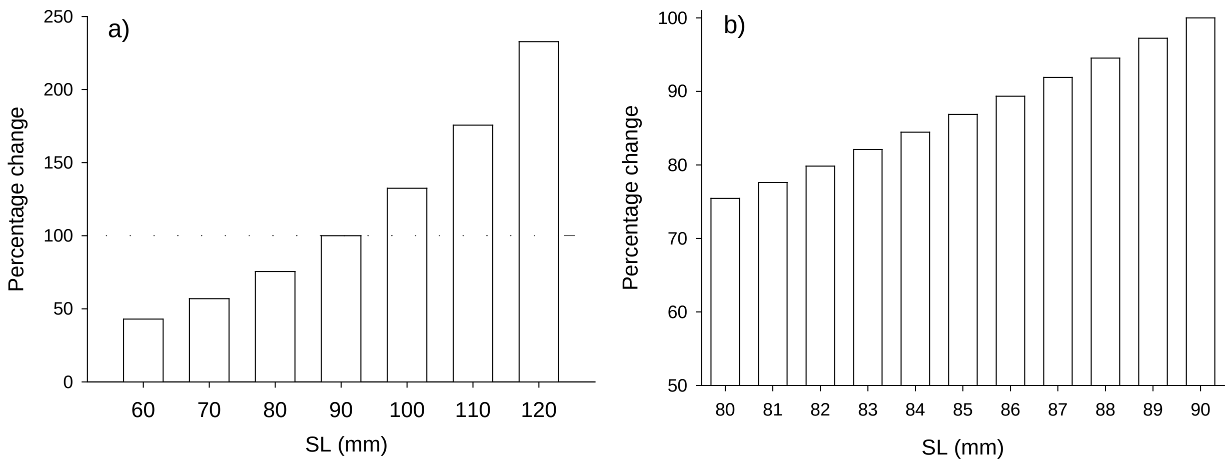


Figure 26. a) Percentage change of scallop fecundity compared to reference level (90 mm SL) for scallops measuring 60 – 120 mm SL. b) Percentage change of scallop fecundity between 80- 90 mm SL.

Comparing fecundity among locations

For a standard scallop measuring 90 mm in SL, an almost two-fold difference in fecundity of scallops was evident between the Bass Strait site (BSCZSF) and White Rock (TSF) in May (Figure 27a, F=12.7, df=1, p<0.001), but this was not significant in June (Figure 27b, F=2.65, df=1, p=0.11). Histological examination showed a greater percentage of gonads in developing stage in May in White Rock. This may have affected the number of eggs counted in these gonads, as the average number of eggs was lower in developing gonads than in mature or atretic ones ($F=5.03$, $df=4,317$, $p<0.001$). In October 2012, significant differences in fecundity were found between Great Bay and White Rock (c, $F=14.32$, $df=1$, $p<0.001$), however, these differences did not seem to be explained by the reproductive stages in the ovaries. Differences between Marion Bay (TSF) and White Rock were not evident in November 2012 (Figure 27d, $F=0.06$, $df=1$, $p<0.81$). Variations in fecundity among locations was previously shown for scallops in different locations in the Bass Strait region, with almost three-fold differences between Ninth Island and Stoney Head (< 30 km apart) for same aged individuals (Martin et al., 1988). Likewise, for the bay scallop, *Argopecten irradians*, fecundity was shown to vary up to 39% between scallops just 1.5 km apart (Bricelj et al., 1987).

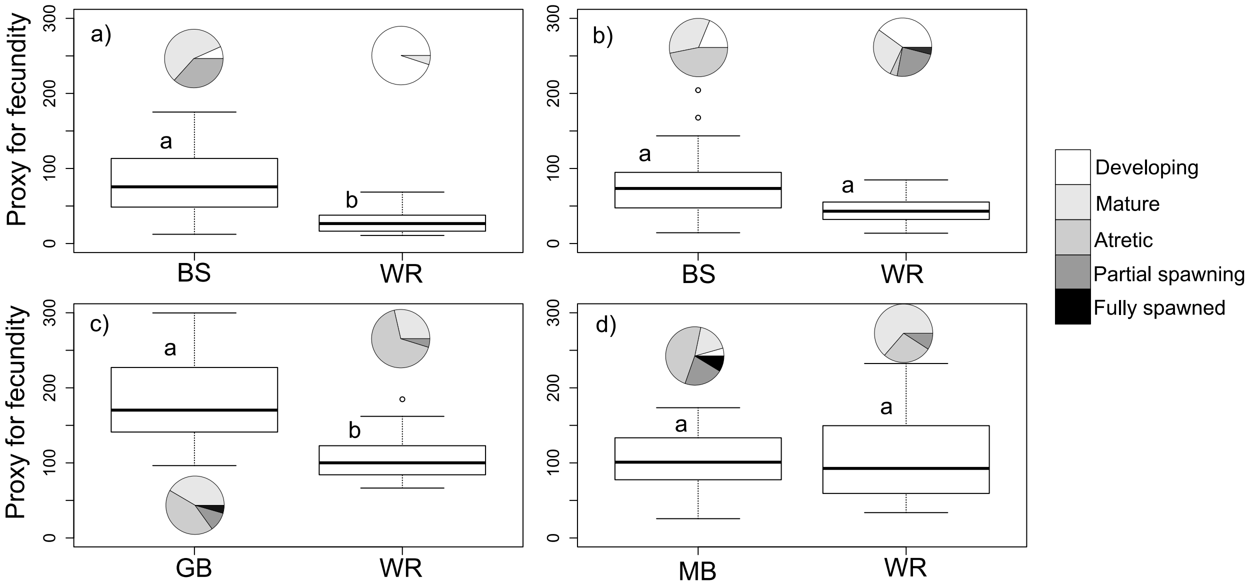


Figure 27. Proxy for fecundity for a standard scallop measuring 90 mm in SL in a) May 2013, b) June 2013, c) October 2012, and d) November 2012. Pie charts indicate the percentage of each reproductive stage (histological staging) in the population. GB=Great Bay (TRSF), MB= Marion Bay (TSF), WR=White Rock (TSF), BS= Bass Strait (BSCZSF). Interquartile range (boxes), median (middle lines), 95% CI (bars), outliers (points). See Figure 1 for site locations.

Growth Analysis

Allometry

During 2004-2015, 9322, 5509 and 6317 scallops were measured for shell length (SL), shell height (SH), and shell width (SW; also referred to as shell depth), respectively (Table 8). Length-height and length-width showed linear relationships at each location (Figure 28 and Figure 29, respectively).

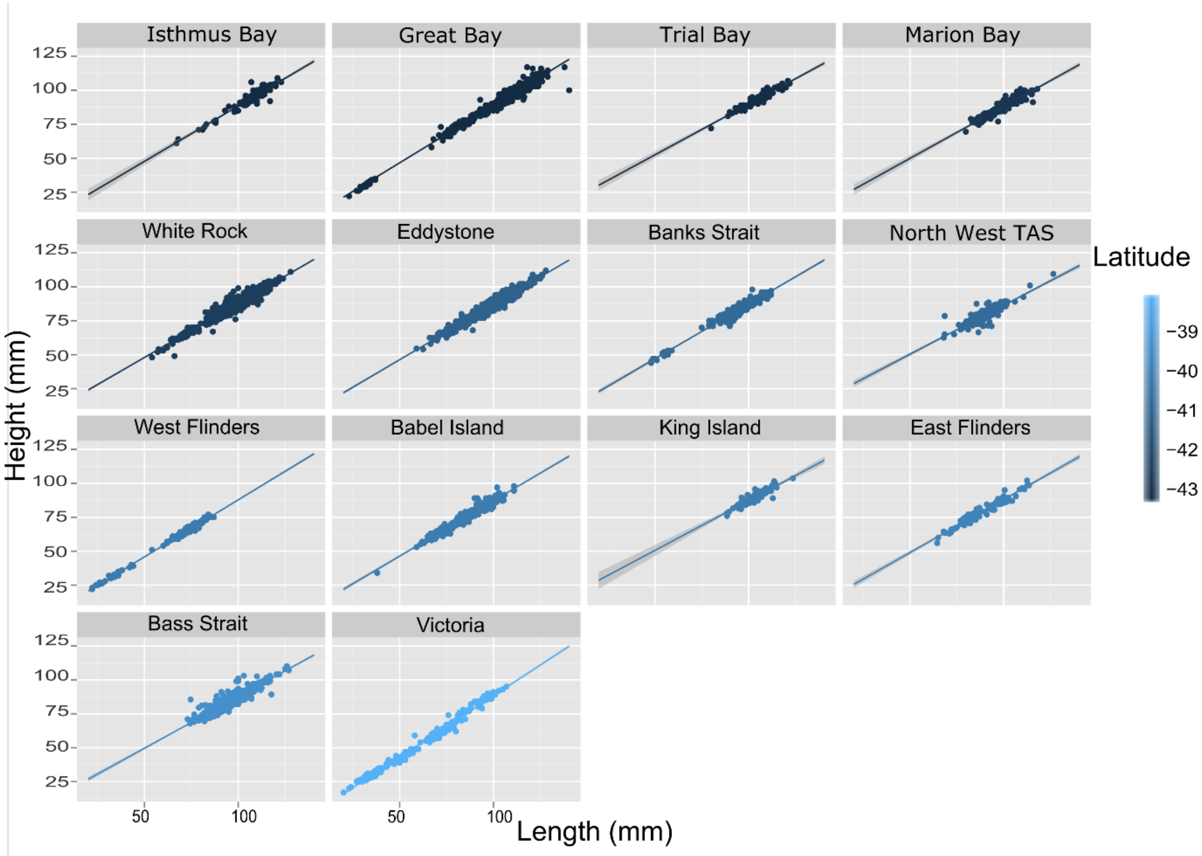


Figure 28. Relationship between shell length (SL) and shell height (SH) in different locations around Tasmania (TRSF and TSF), the BSCZSF and in Victoria (OSF). Grey shading shows the 95% confidence interval on the linear model between SL and SH. See Figure 1 for site locations.

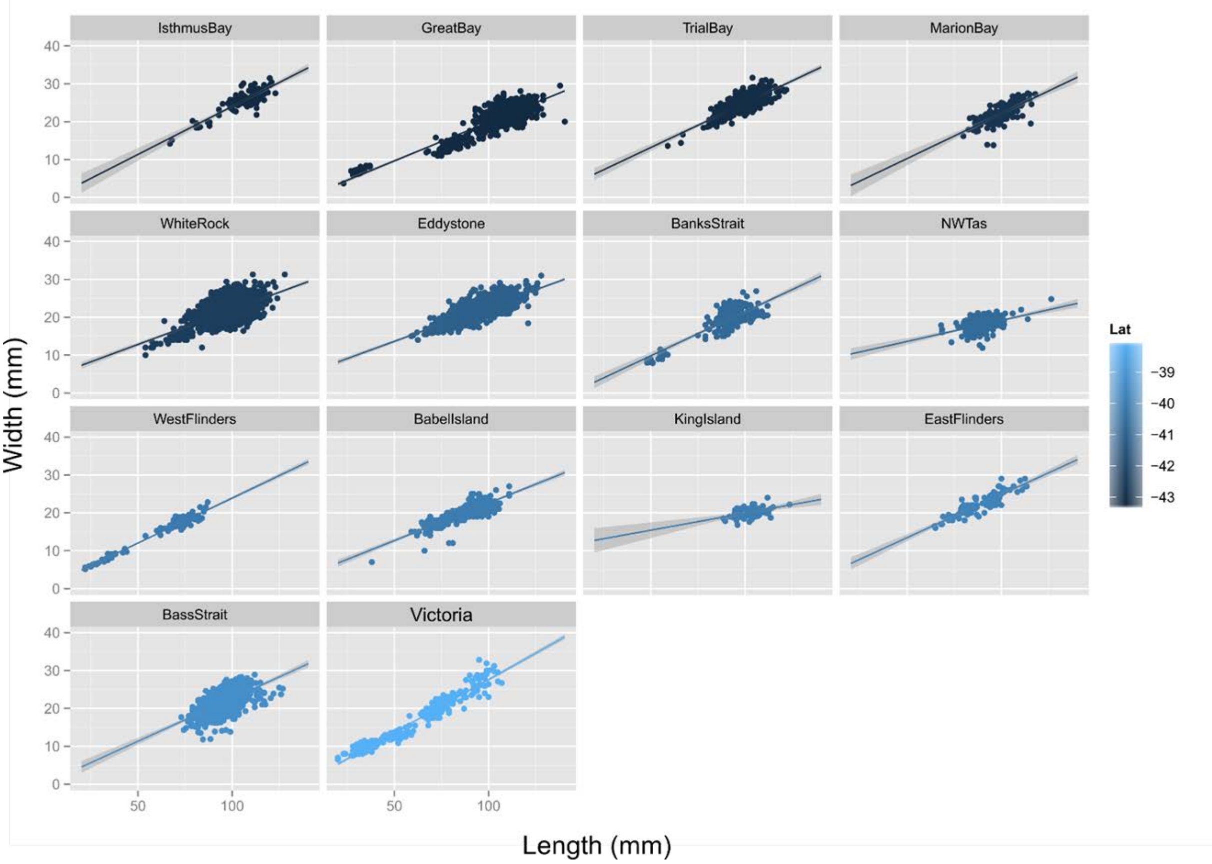


Figure 29. Relationship between shell length (SL) and shell width (SW) in different locations around Tasmania (TRSF and TSF), the BSCZSF and in Victoria (OSF). Grey shading shows the 95% confidence interval on the linear model between SL and SW. See Figure 1 for site locations.

The common slope of the relationship between SL and SH was significantly different from 1, indicating allometric growth (Figure 30a; W=270.2, df=9, $p<0.001$), which is differential growth in which parts of the same animal grow at different rates. Negative allometry ($b<1$) was observed between SL and SH (average ± SD slope = 0.97 ± 0.01), meaning scallops grow relatively longer than higher with increasing size, with significant differences in the slope between populations (W=78.19, df=8, $p<0.001$, Table 8, Figure 31a). Only scallops located at the Victorian site (OSF) showed positive allometry (average ± SD slope = 1.14 ± 0.04), meaning scallops grow relatively higher than longer with increasing size, and had a significantly steeper slope than the rest of the populations (Figure 31a). Most animals change shape as they change size in order to keep metabolism (which increases with body volume) in balance with respiration and excretion (which only increase with surface area) (Gould, 1966). In animals with allometric growth, different selection pressures are acting upon each of the measured traits (Gould, 1966). This study shows that in most of the studied populations of commercial scallop, an increase in SL will lead to a relatively smaller increase in SH, that is, shells become relatively broader as scallops grow. This change in scallop morphology increases the aspect ratio (the ratio between SL and SH) which augments the lift-drag ratio and therefore makes swimming more efficient than it would be for a scallop with isometric growth (the parts of the animal grow at the same rate) between SL and SH (Stanley, 1970; Gould, 1971).

There was a positive allometry (b>1) between shell length and width (depth) (Figure 30b, average ± SD slope = 1.20± 0.02), meaning scallops grow relatively wider (deeper) than longer with increasing size, with statistically significant differences among populations (W=391.5, df=8, p<0.001). Scallops located in the Bass Strait (BSCZSF), Banks Strait (TSF) and Marion Bay (TSF) sites had significantly greater slopes than the rest of the populations, while the Eddystone (TSF) and Babel Island (TSF and BSCZSF) populations had the smallest slopes that did not differ from 1 (isometric growth, Table 8, Figure 31b). This shows that in most of the studied populations of commercial scallop, an increase in SL will lead to a relatively greater increase in SW, that is, shells become relatively wider (deeper) as scallops grow, except for the Eddystone and Babel Island populations.

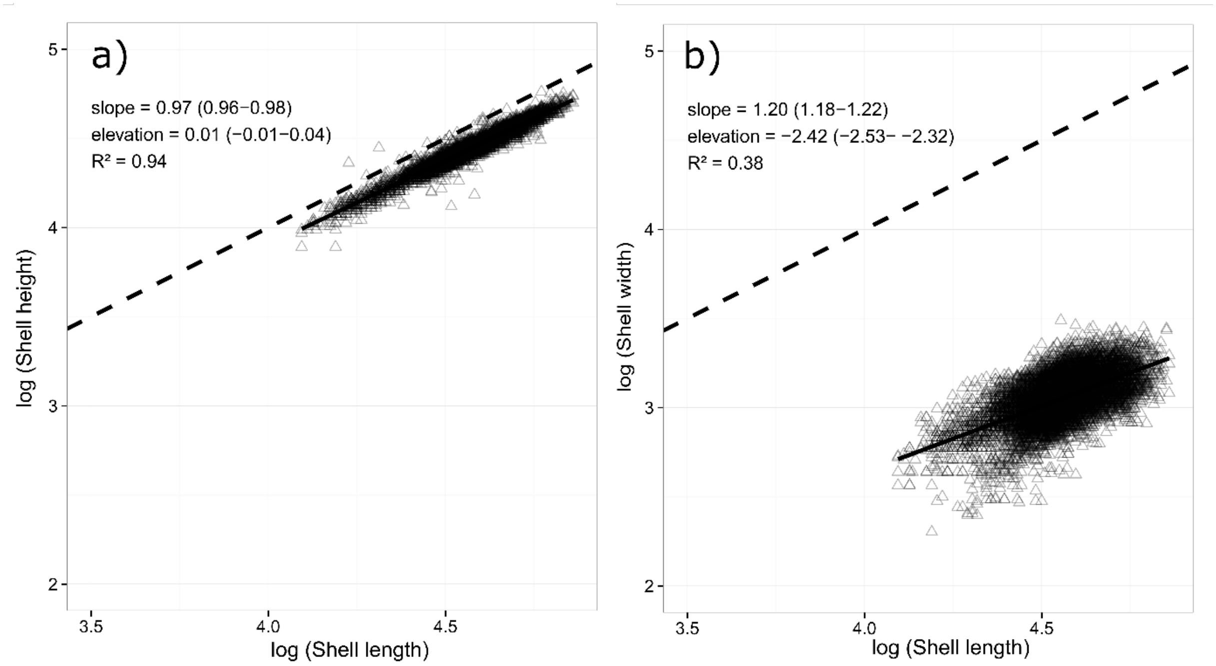


Figure 30. Allometric plots of a) shell length vs. shell height, b) shell length vs. shell width (depth). Dotted line shows a slope =1, which would indicate isometric growth

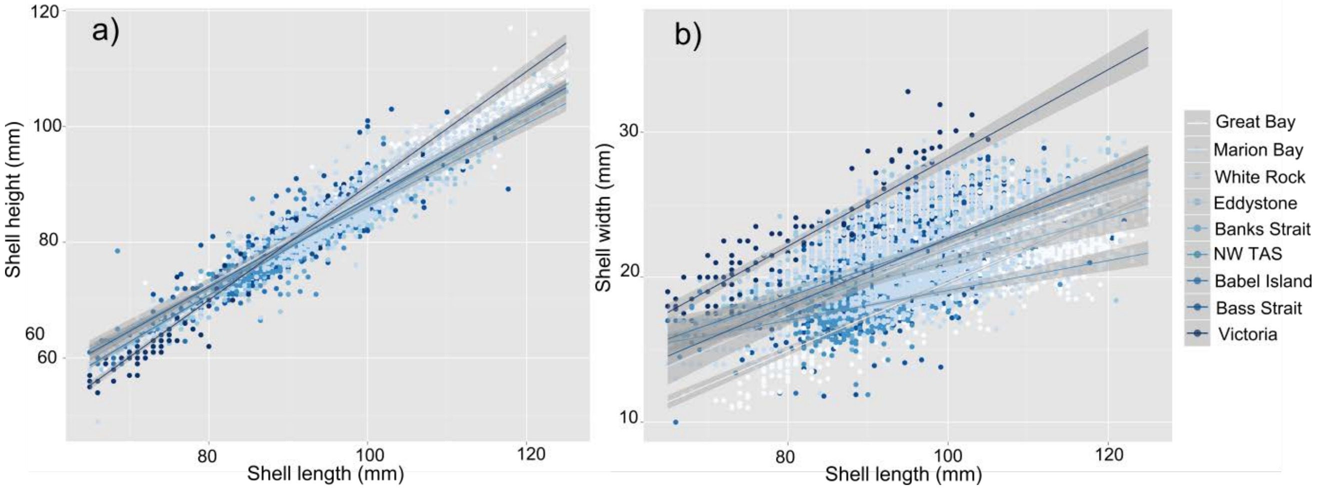


Figure 31. Relationship between a) shell length and shell height and b) shell length and shell width (depth) in different locations around Tasmania (TRSF and TSF) and in Victorina (OSF) and Commonwealth (BSCZSF) jurisdictions, showing different slopes for each sampling location. See Figure 1 for site locations.

Table 8. Test of isometry between shell length and shell height and shell length and shell width for each location. Non-significant tests indicate isometric growth and are presented in bold. Different letters indicate significant differences among sites. See Figure 1 for site locations.

Location	**Shell length (mm)**			**Latitude**	**Shell Height (mm)**			**Shell width (depth) (mm)**		
	mean	**SD**	**N**		**Slope (+-SD)**	**Elevation (+-SD)**	**Test isometry**	**Slope (+-SD)**	**Elevation (+-SD)**	**Test isometry**
Babel Island (TSF) and BSCZSF)	87.8	10.8	328	-39.96	0.94 (0.02)a	0.122 (0.11)	r = -0.239, df=322,p<0.001	1.043(0.06) de	-1.66 (0.21)	r = 0.073, df=321, **p=0.185**
Banks Strait (TSF)	94.6	7.2	199	-40.66	0.93 (0.05)a	0.18 (0.13)	r = -0.174, df=197,p=0.014	1.576 (0.21)ab	-4.163 (0.88)	r = 0.472, df=197, p<0.001
Bass Strait (BSCZSF)	94.21	7.7	833	-39.2	0.94 (0.03)a	0.147 (0.11)	r = -0.155, df=829,p<0.001	1.774 (0.09)a	-5.007 (0.44)	r = 0.603, df=829, p<0.001
Eddystone (TSF)	95.3	11.5	1032	-40.9	0.95 (0.02)a	0.102 (0.07)	r = -0.240, df=822,p<0.001	1.016 (0.03)e	-1.471 (0.18)	r = 0.025, df=1024, **p=0.412**
Great Bay (TRSF)	106.4	10.2	832	-43.2	0.95 (0.02)a	0.123 (0.06)	r = -0.264, df=820,p<0.001	1.496 (0.05)b	-3.937 (0.25)	r = 0.629, df= 818, p<0.001
Marion Bay (TSF)	99.2	8.0	142	-42.8	0.93 (0.05)a	0.204 (0.25)	r = -0.205, df=141,p<0.001	1.486 (0.16)abc	-3.74845 (0.79)	r = 504, df=141, p<0.001
NWTas (TSF)	89.4	5.7	424	-40.6	0.913 (0.04)a	0.262 (0.19)	r = -0.179, df=421, p<0.001	1.329 (0.11)bc	-3.08522 (0.52)	r = 0.298, df=421, p<0.001
White Rock (TSF)	95.9	9.4	1578	-42.4	0.94 (0.02)a	0.141 (0.07)	r = -0.205, df=1197,p<0.001	1.383 (0.05)bc	-3.259 (0.24)	r = 0.378, df=1577, p<0.001
Victoria (OSF)	82.12	11.6	111	-38.1	1.149 (0.04)b	-0.791 (0.19)	r = 0.578,df=110,p<0.001	1.226 (0.10)cd	-2.282 (0.50)	r = 0.416, df=110, p<0.001

Morphometric differences among regions

Differences in shell morphology were evident among regions, with significant differences between the standardised height ($F=59$, $df=13, 5613$, $p<0.001$) for a standard scallop measuring 90 mm in shell length. Scallops located in northern areas (Victoria (OSF), Babel Island (TSF and BSCZSF), West Flinders (TSF), NW Tasmania (TSF), Banks Strait (TSF) and Eddystone TSF) had relatively smaller heights for a standard scallop measuring 90 mm in SL, except for scallops located in the Bass Strait (BSCZSF) site (Figure 32a). This relatively larger shell height for a given SL within waters in the eastern region of the BSCZSF agrees with previous findings for the region (Haddon et al., 2006). On the other hand, scallops from southern populations (Isthmus Bay (TRSF), Great Bay (TRSF), Trial Bay (TRSF), Marion Bay (TSF), and White Rock (TSF)) showed relatively greater shell heights for a standard scallop (Figure 32a). Scallops from Trial Bay, in the D´Entrecasteaux Channel had the greatest heights for a standard scallop measuring 90 mm in shell length.

As mentioned in the previous section, variations in shape among scallops in different locations may affect swimming capabilities. For hydrodynamic considerations, the aspect ratio, which corresponds to the SL/SH ratio of scallops (aspect ratio), shows a positive correlation with the lift/drag ratio (Gould, 1971). Swimming intensity has also been associated with an increase in aspect ratio (Tremblay, 2014). This indicates that swimming becomes comparatively easier as aspect ratio increases and scallops with a smaller proportional height would be comparatively better shaped to overcome drag than scallops with comparatively greater heights. Therefore, scallops measuring 90 mm in SL in Eddystone (TSF), Banks Strait (TSF), North West Tasmania (TSF), West Flinders (TSF), Babel Island (TSF and BSCZSF) and Victoria (OSF) would be comparatively greater swimmers than scallops in the other locations studied. However, other characteristics such as position and area of muscles can also affect swimming performance (Gould, 1971) and still need to be tested. As scallops use two main predator escape mechanisms: a passive mechanism where they close their valves and remain recessed into the sediment or an active escape mechanism where they swim away from the potential threat (Barbeau and Scheibling, 1994), the relative use of each different escape tactic depending on shell morphology and location still needs to be investigated for different populations of commercial scallop.

Differences in morphology were more evident among locations when comparing shell widths for standard scallops measuring 90 mm in shell length ($F=380.0$, $df=13,6367$, $p<0.001$, Figure 32b). North West Tasmania (TSF) and Great Bay (TRSF) had comparatively thinner individuals, followed by King Island (BSCZSF), Banks Strait (TSF), Marion Bay (TSF) and White Rock (TSF). Scallops from Babel

Island (TSF and BSCZSF) showed no significant differences in shell width with Eddystone (TSF) or the Bass Strait (BSCZSF) site. Scallops located in Victoria (OSF) had the thickest scallops (Figure 32b). A variety of factors have been shown to influence shell width in many bivalve species. For example, differences in shell width were attributed to density of conspecifics and food availability in the blue mussel, *Mytilus edulis*, for which valves were narrower at high density and at low food concentration compared to low density and high food concentration (Alunno-Bruscia et al., 2001). For the soft-shell clam, *Mya arenaria*, shells were wider when reared in gravel than in sand or mud (Newell and Hidu, 1982). In scallops, differences in shell width have been attributed to depth for the American sea scallop, where individuals from shallow water were considerably wider than those from offshore, deep water populations (Schick et al., 1992). The factors influencing the differences in SW of commercial scallop among different locations still need to be explored.

However, for fisheries management purposes it is interesting to determine if scallops with greater SW also have greater muscle and/or gonad weights. Indeed, the Victorian (OSF) site had the thickest (deepest) scallops and these scallops generally had the heaviest muscles, gonads and combined weights in winter of all the regions (See Figures 4, 11 and 18). Additionally, other thick scallop regions, Isthmus Bay (TRSF) and Eddystone Point (TSF), also had heavy muscles, gonads and combined weights in winter. Furthermore, the relatively thick scallops from the Bass Strait (BSCZSF) site had heavy muscles, gonads and combined weights in autumn. Fishing these areas (when opened) in the seasons noted could increase commercial yields.

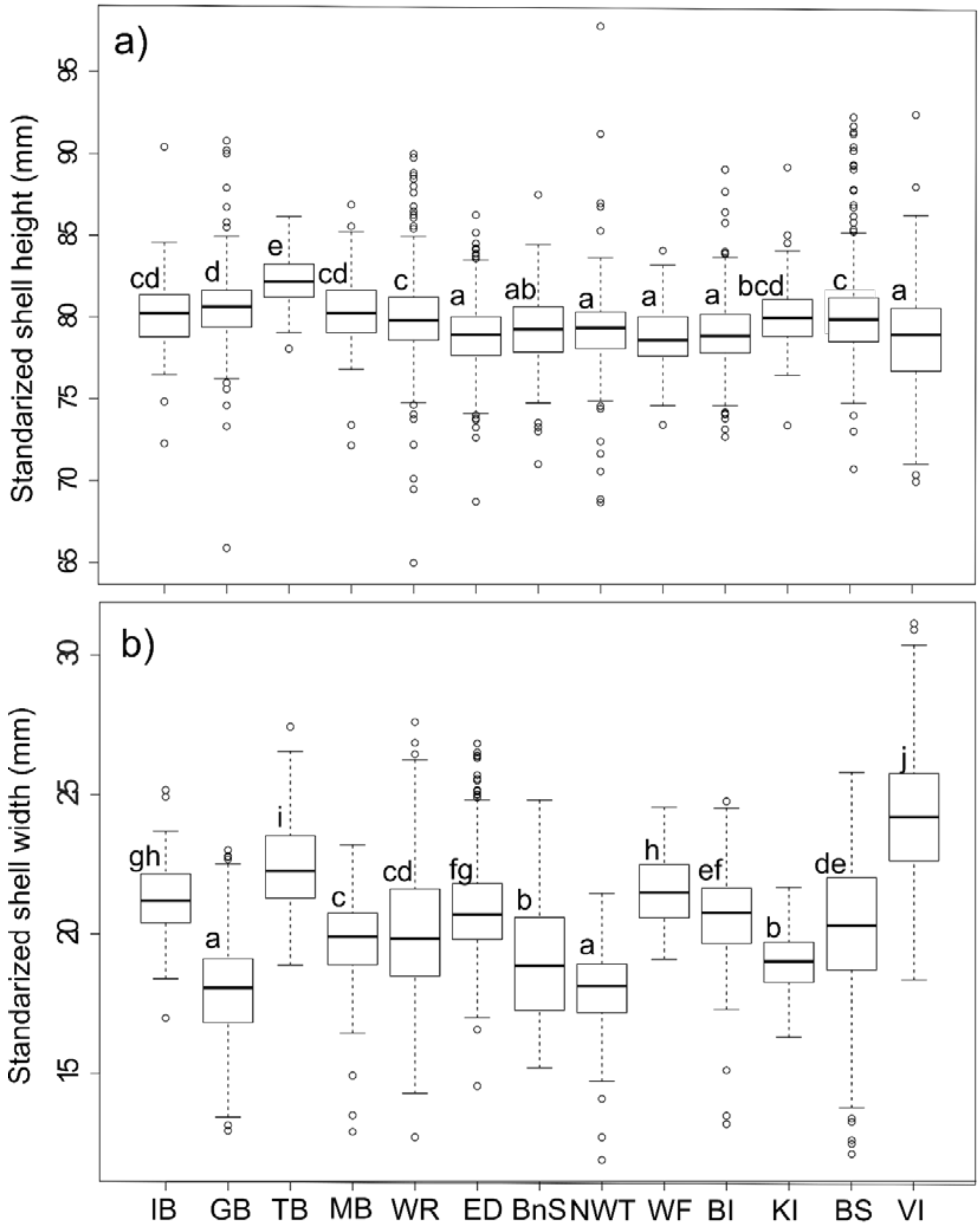


Figure 32. Boxplots showing ratios between a) standardized height and b) standardized width for a scallop measuring 90 mm SL across different sampling locations. The boxes enclose data falling between the 1st and 3rd quartile and the lines in bold represent the median in each location. The bars indicate the 95% confidence intervals of the median. Data points falling outside these ranges are plotted individually. Different letters above the boxes indicate significant differences among sites for each graph independently. IB=Isthmus Bay (TRSF), GB=Great Bay (TRSF), TB=Trial Bay (TRSF), MB= Marion Bay (TSF), WR=White Rock (TSF), ED= Eddystone (TSF), BnS=Banks Strait (TSF), NWT=North West Tasmania (TSF), WF= West Flinders (TSF), BI=Babel Island (TSF and BSCZSF), KI=King Island (BSCZSF), BS= Bass Strait (BSCZSF), VI=Victoria (OSF). See Figure 1 for site locations.

Site Suitability for growth analysis

The spatio-temporal distribution of samples highlighted sites having extensive temporal coverage suitable for growth analyses (e.g. East Flinders (TSF) between 2002 and 2005) while other sites have limited coverage (e.g. Long Point (TSF) and Maria Island (TSF)) (Figure 33). There are potentially several cohorts measured repeatedly at East Flinders, with an evident growth trend (Figure 34). In contrast, Banks Strait (TSF) was sampled five times in two close groupings and there is no clear indication of the growth of a single cohort because of a lack of repeated observation of the same cohort (Figure 34).

The suitability of each sample location for growth analysis was based on the initial exploratory examination described above. This examination was conservative and only dismissed those locations where a growth analysis would clearly yield no meaningful results. Table 9 shows the selected sites and the issues on those discarded. The site Eddystone (TSF) was spatially split into three sub-sites for a better resolution (i.e. Eddystone North, Central and South); therefore, data from a total of eight sites was used to carry out the modal progression analysis (Figure 35).

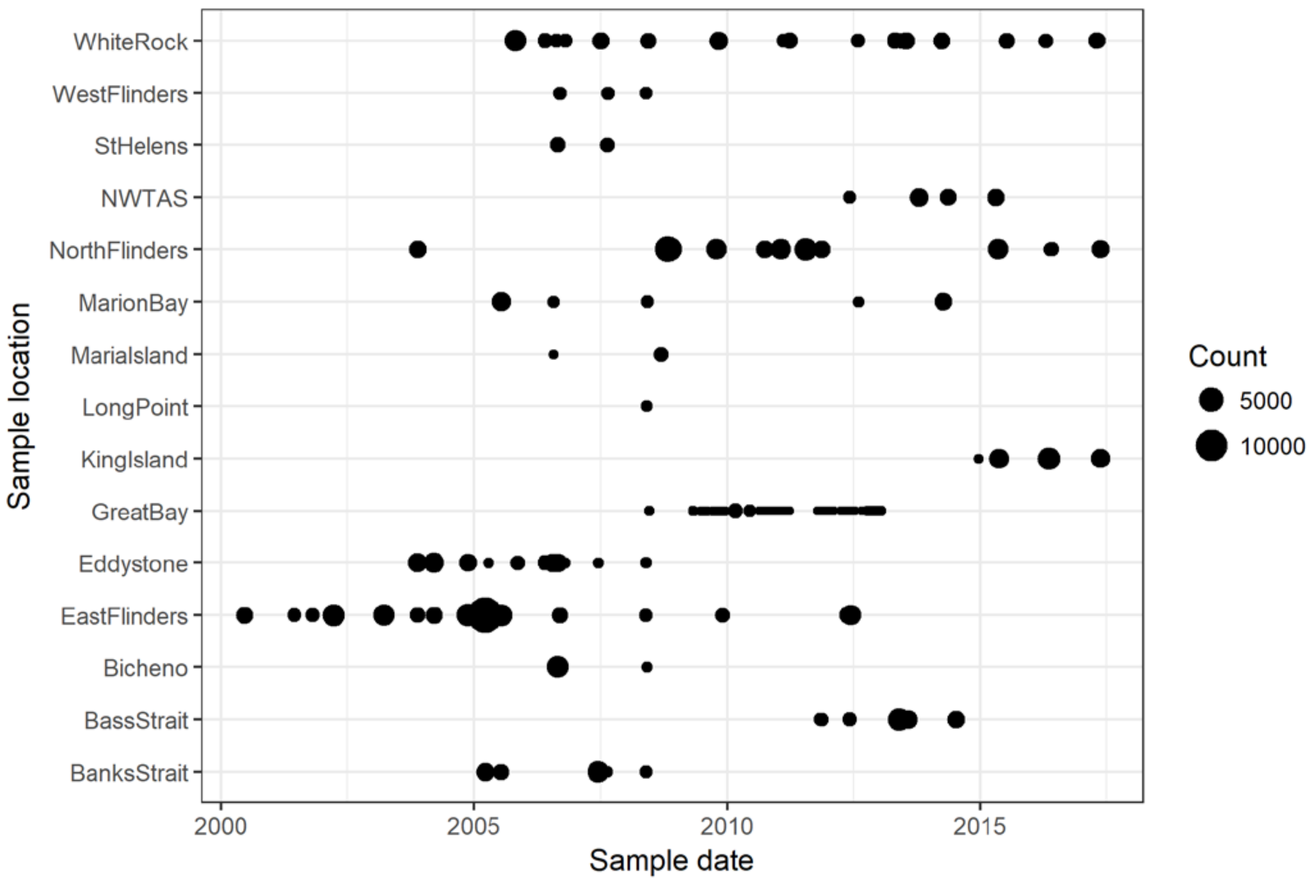


Figure 33. Sample dates for each location. The size of the point indicates the number of samples taken.

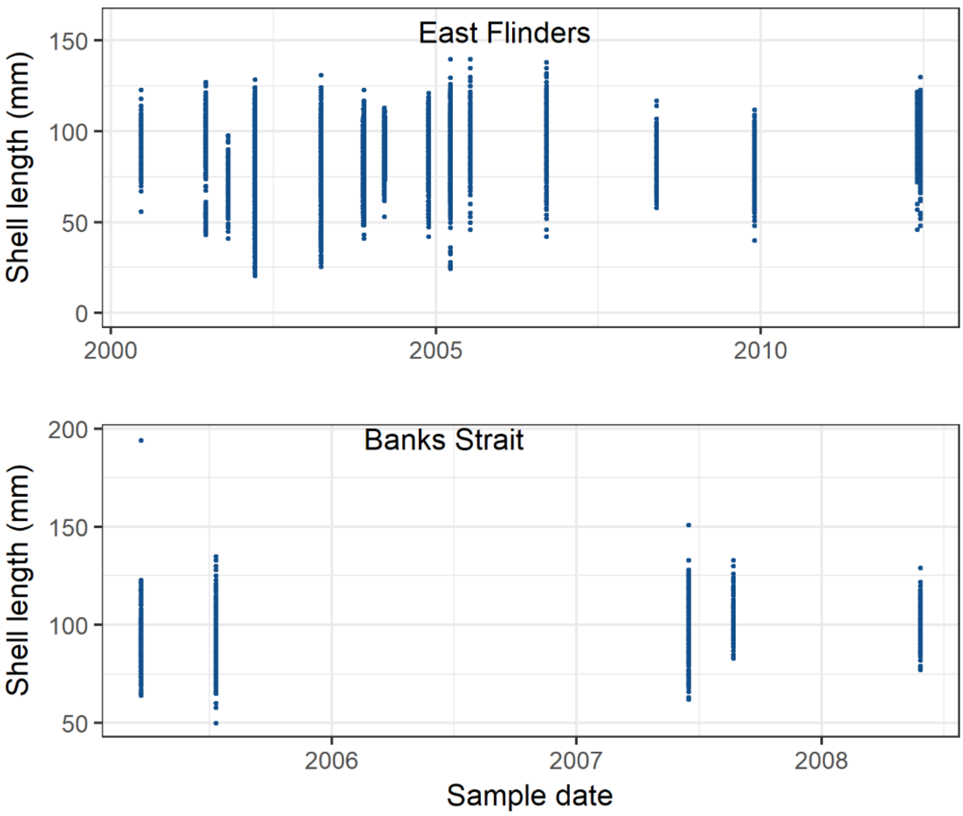


Figure 34. Temporal coverage scallops size change in two extreme sites, well sampled (East Flinders - TSF) and poorly sampled (Banks Strait - BSCZSF).

Table 9. Initial suitability assessment of each sample location for growth analysis.

Location	**Suitability**	**Rationale**
Banks Strait	✗	Two clustered sets of two dates and third one spatially clustered (one degree distant from each other)
Bass Strait	✗	Different cohorts sampled, subsequent observations of smaller scallops
Bicheno	✗	Only two dates
East Flinders	✓	
Eddystone	✓	
Great Bay	✓	
King Island	✓	
Long Point	✗	Only one date
Maria Island	✗	Only two dates
Marion Bay	✗	Different cohorts sampled
North Flinders	✓	
NW Tas	✗	Different cohorts sampled
St Helens	✗	Two sample dates, second date sampled smaller scallops
West Flinders	✓	
White Rock	✓	

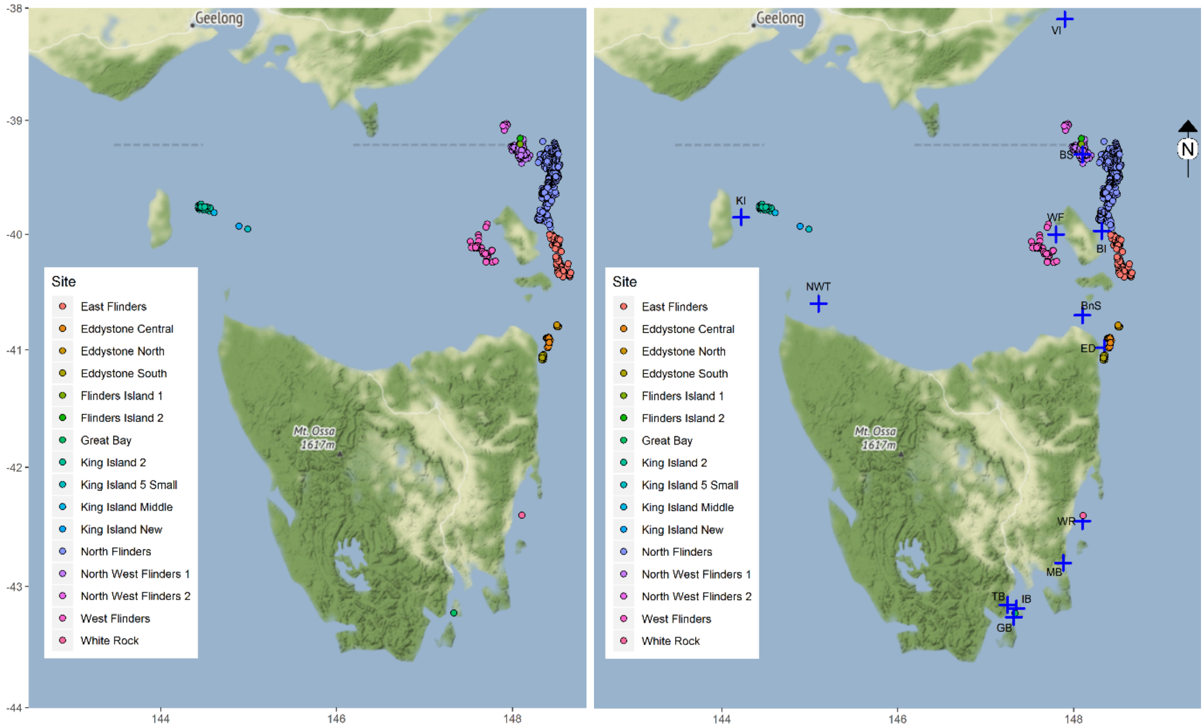


Figure 35. Geographical location of sites with suitable data for modal progression analysis (left), and the same map overlayed with morphometric sampling locations (Figure 1) for comparison (right). IB=Isthmus Bay (TRSF), GB= Great Bay (TRSF), TB=Trial Bay (TRSF), MB= Marion Bay (TSF), WR= White Rock (TSF), ED=Eddystone (TSF), BnS= Banks Strait (TSF), BI= Babel Island (TSF & BSCZSF), WF= West Flinders (TSF), BS= Bass Strait (BSCZSF), NWT= North West Tasmania (TSF), KI= King Island (BSCZSF), VI= Victoria (OSF).

Individual location analyses

The annual cohorts for each site and their size increments are represented in Figure 36 to Figure 46. The data enabled us to follow up to three different cohorts per site in periods of time ranging between two and six years. The interval of time between shell length measures was mostly 12 months, but this fluctuated between three and 18 months; therefore, the mean increase was corrected by these time intervals (Table 10).

The outputs of modal progression analysis carried out at East Flinders (TSF) by Haddon et al. (2006) are presented in Table 11. They are consistent with our estimations for East Flinders but are compiled at a smaller spatial scale in order to show growth variation within the region (Table 10, Table 11, Figure 47).

The studied sites showed variable mean growth increments depending on initial mean size of cohorts. For instance, in North West Flinders Island 1 (BSCZSF), a cohort with 61.5 mm of mean size grew 35.7 mm (58.0%) in one year; and in contrast, a similar mean size cohort (64.2 mm) in White Rock (TSF) grew 21.3 mm (33.2%) in one year (Table 10, Figure 38 and Figure 45). In Eddystone South (TSF), 79.6 and 105.8 mm scallops grew 21.3 and 9.1 mm (27.0 % and 8.6%) in one year respectively (Table 10, Figure 43). In comparison, in East Flinders (TSF) smaller individuals (75.5 and 94.2 mm), with higher expected growth, increased in size 12.4 and 3.8 mm (16.5 and 4.0%) in one year respectively (Table 10, Figure 39). This result is consistent with the fact that East Flinders (TSF) scallops have a lower mean growth increment than scallops in the Northern region (BSCZSF) of Flinders Island (Haddon et al. 2006).

There was no obvious growth pattern on the latitudinal gradient. For instance, sites at the extreme north (North Flinders and King Island, both in the BSCZSF) and south (Great Bay, TRSF) of Tasmania (Figure 35) showed average mean growth increments (Figure 48). Low and high values of growth were observed in sites that are close to each other in the BSCZSF (1.9 and 9.20 mm/year (1.8 and 10.8%) for King Island Middle and King Island 2 respectively, Figure 35 and Table 10). Therefore, growth variations seem to be associated with local factors rather than factors linked with large spatial scale change, which has also been observed for other species of scallop (Macdonald and Thompson 1988).

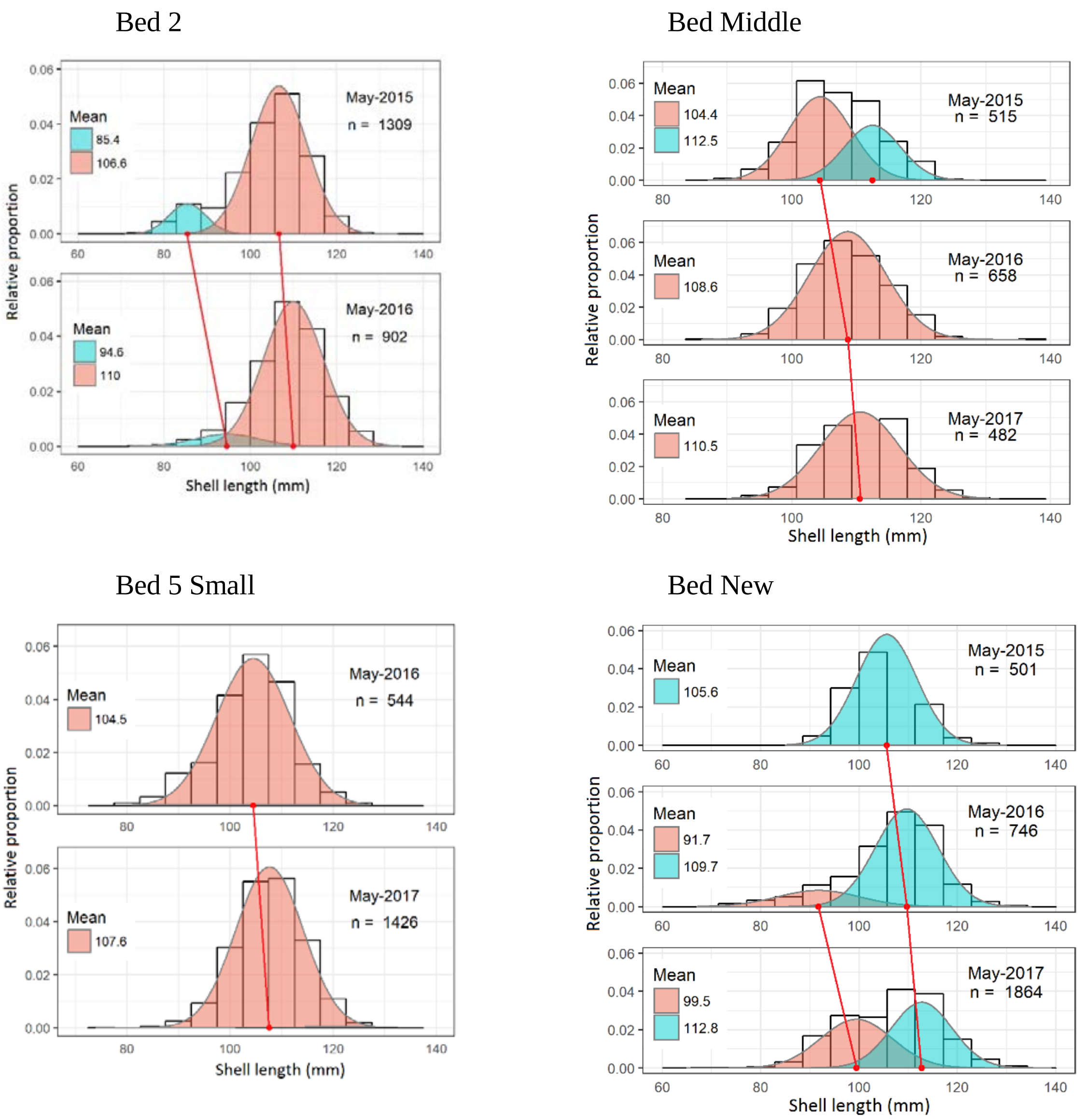


Figure 36. Length frequency distribution of scallops taken in different beds around King Island (BSCZSF) between May 2015 and May 2017, with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

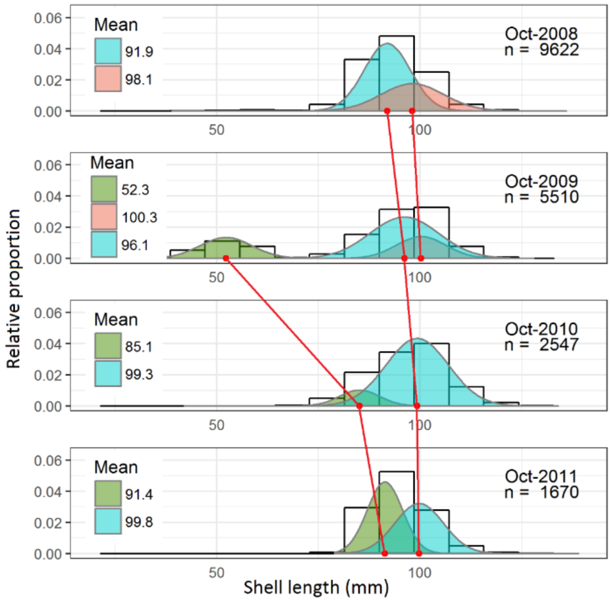


Figure 37. Length frequency distribution of scallops taken in North Flinders Island (BSCZSF) between October 2008 and October 2011 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

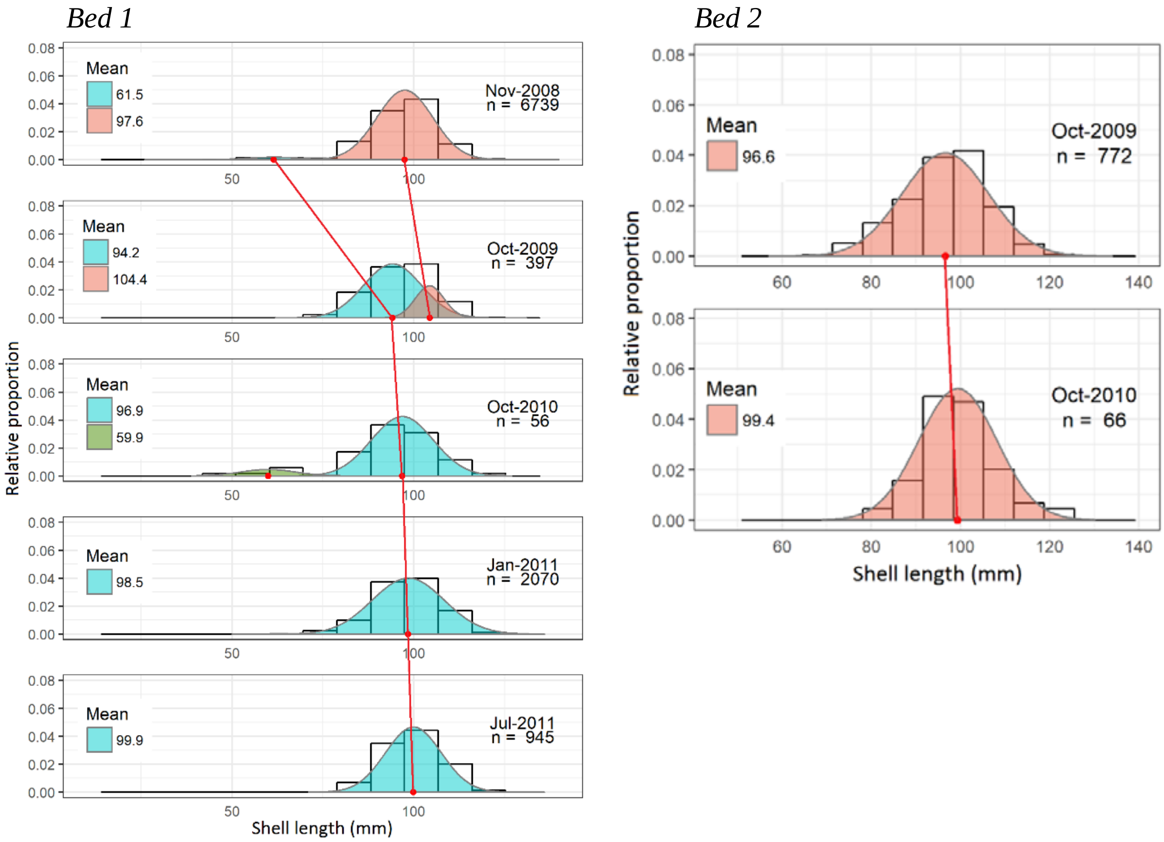


Figure 38. Length frequency distribution of scallops taken in two different beds in North West Flinders Island (BSCZSF) between November 2008 and July 2011 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

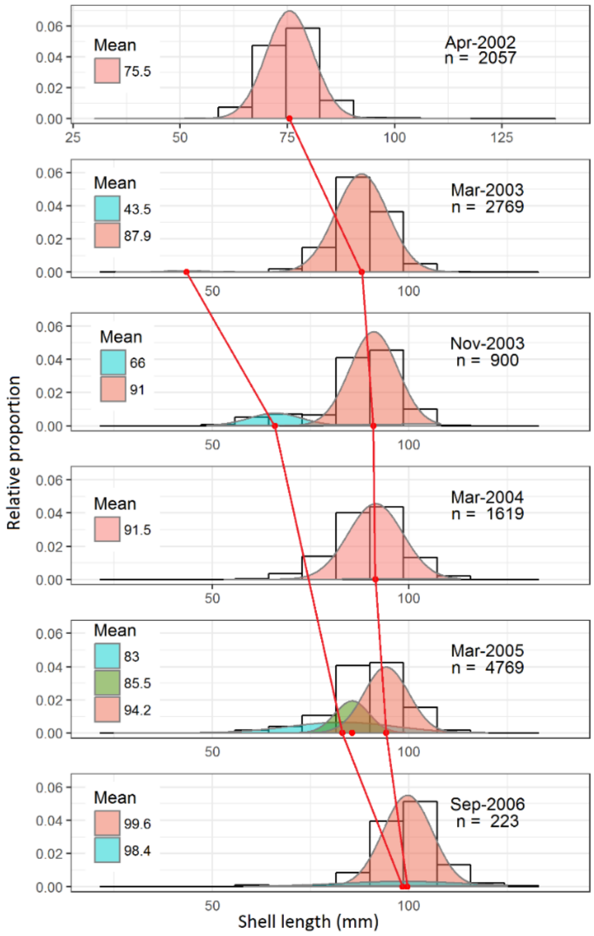


Figure 39. Length frequency distribution of scallops taken in East Flinders Island (TSF) between April 2002 and September 2006 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

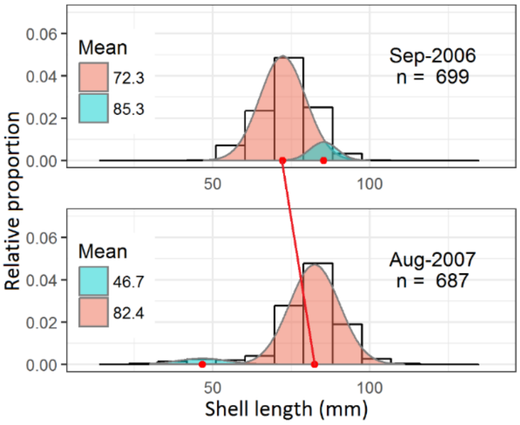


Figure 40. Length frequency distribution of scallops taken in West Flinders Island (TSF) between September 2006 and August 2007 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

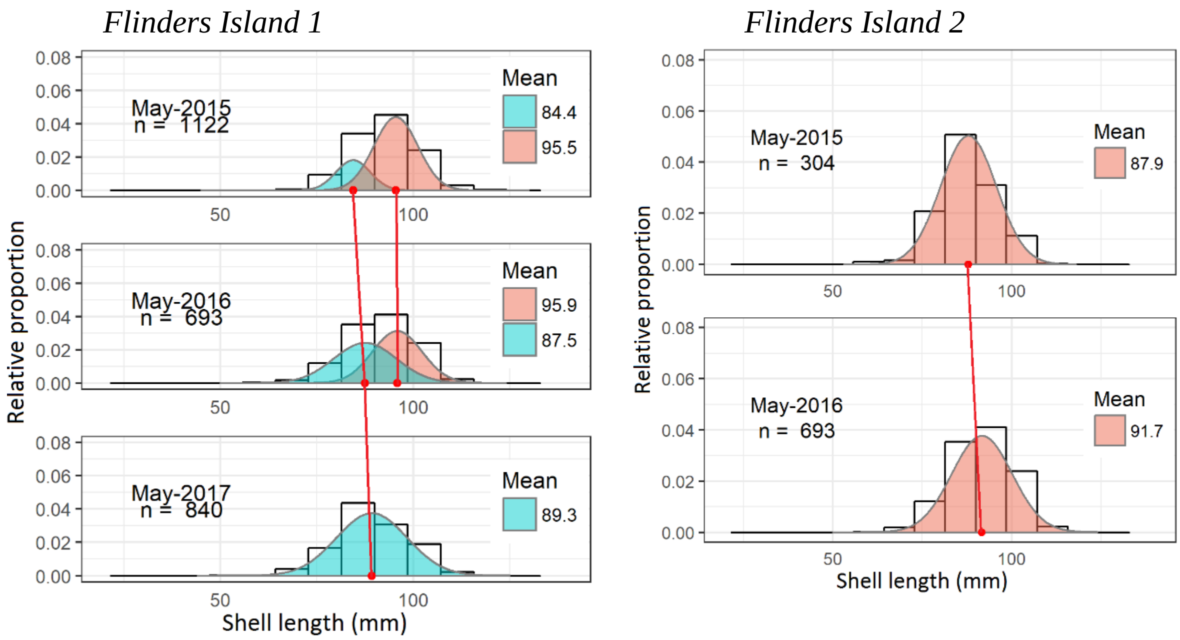


Figure 41. Length frequency distribution of scallops taken in Flinders Island beds 1 and 2 (BSCZSF) between May 2015 and May 2017 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

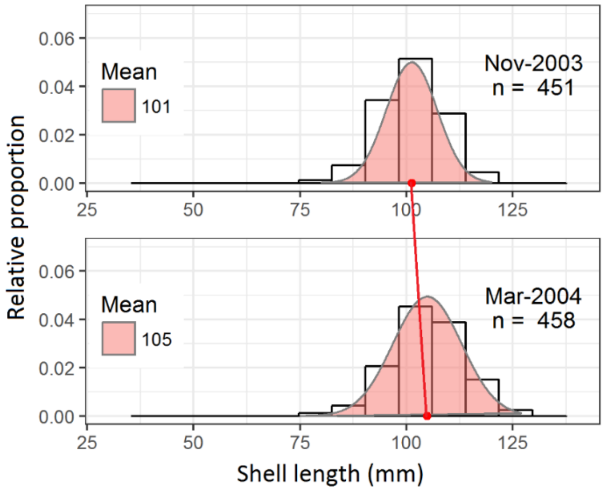


Figure 42. Length frequency distribution of scallops taken in Eddystone North (TSF) between November 2003 and March 2004 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

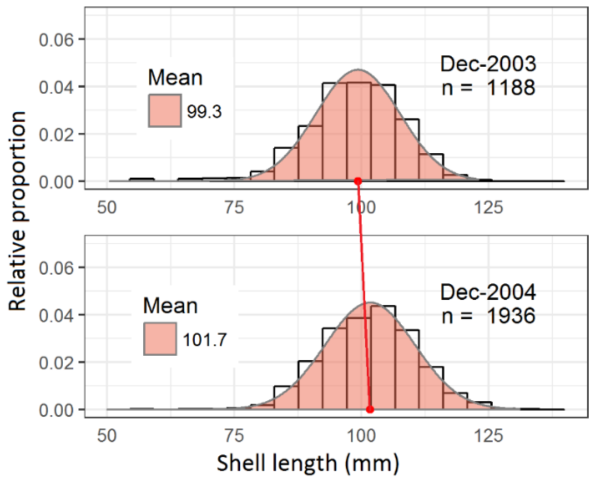


Figure 43. Length frequency distribution of scallops taken in Eddystone Central (TSF) between December 2003 and December 2004 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

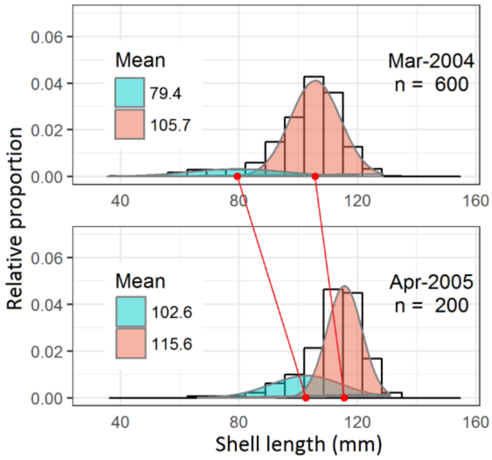


Figure 44. Length frequency distribution of scallops taken in Eddystone South (TSF) between March 2004 and April 2005 with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

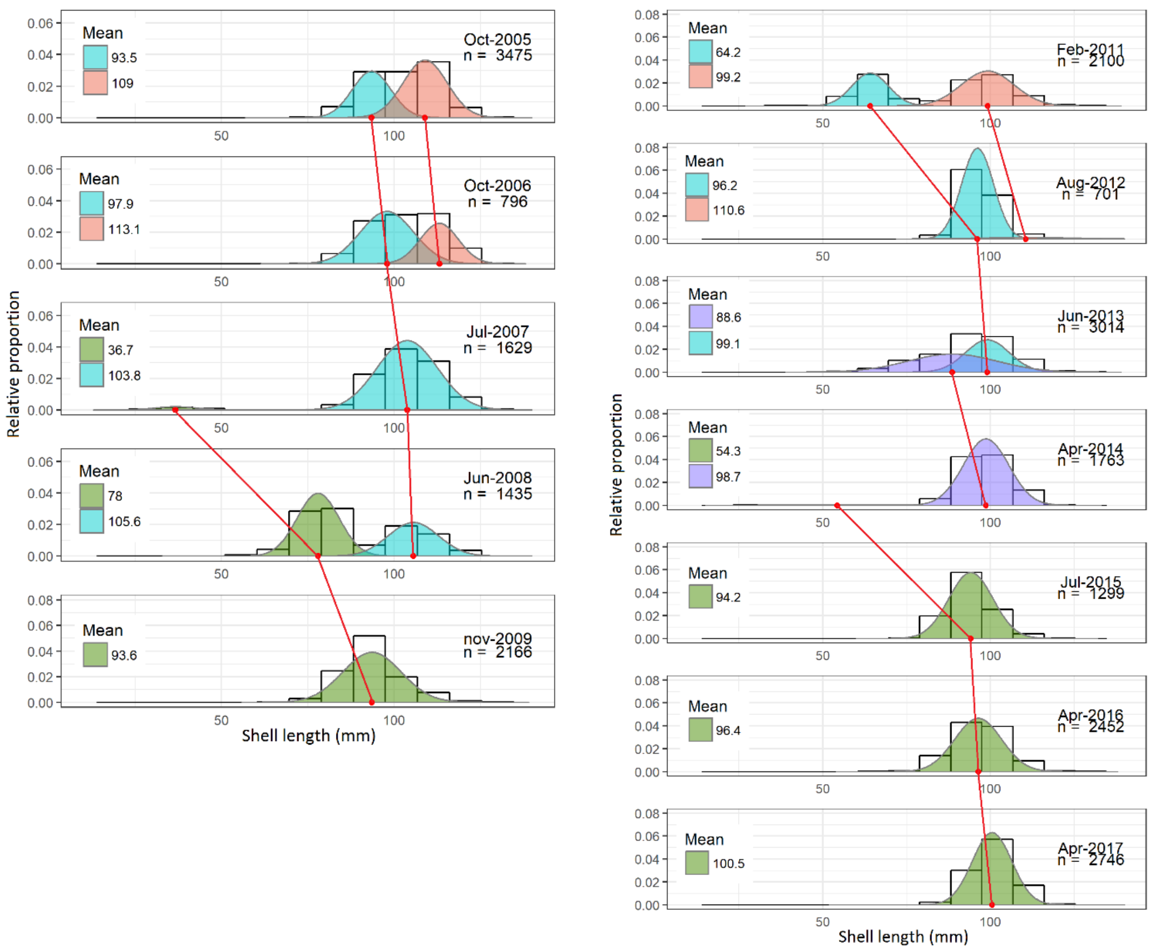


Figure 45. Length frequency distribution of scallops taken in White Rock (TSF) between October 2005 and November 2009, February 2011 and April 2017, with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

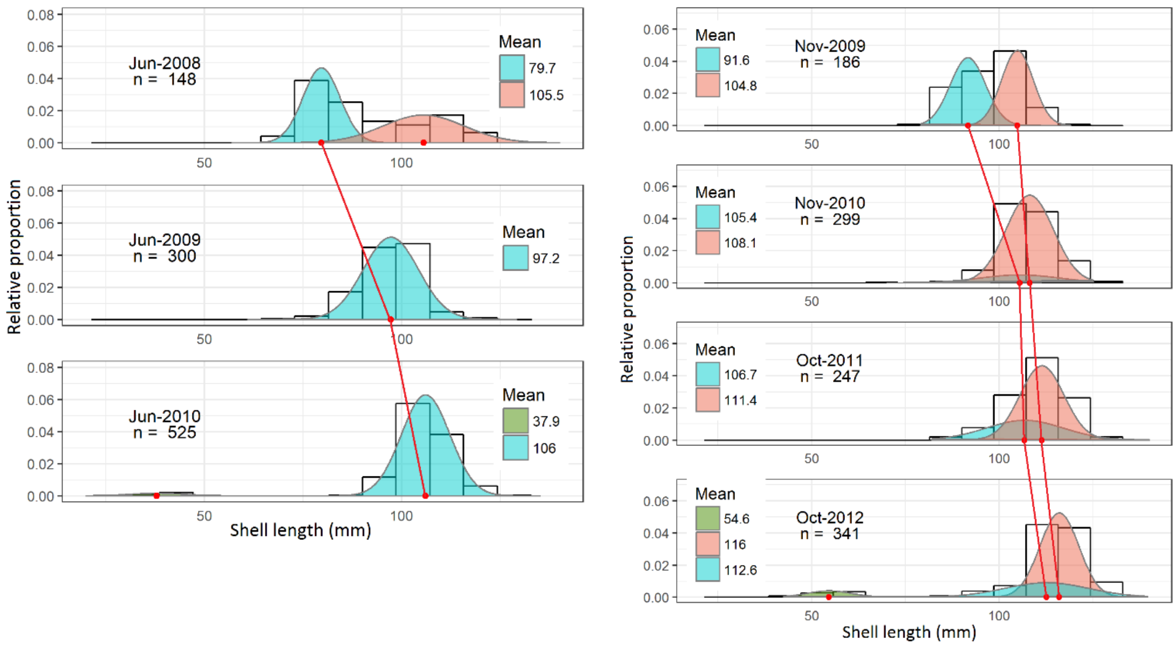


Figure 46. Length frequency distribution of scallops taken in Great Bay (TRSF) between June 2008 and June 2010, and between November 2009 and October 2012, with the fitted normal distribution defining cohorts. The red lines connect the estimated mean length for each cohort and represent the size increase over the time. See Figure 35 for site location.

Table 10. Modal progression observed at each site. See Figure 37 for site locations.

Site	Years	Δ Time (months)	Size: Initial	Increment	Increment/ Δt (mm/year)	Increment%	Change		
King Island 2 (BSCZSF)	15/16	12	85.40	9.20	9.20	10.77	85.4	-	94.6
	15/16	12	106.60	3.40	3.40	3.19	106.6	-	110.0
King Island 5 Small (BSCZSF)	16/17	12	104.50	3.10	3.10	2.97	104.5	-	107.6
King Island Middle (BSCZSF)	15/16	12	104.40	4.20	4.20	4.02	104.40	-	108.60
	16/17	12	108.60	1.90	1.90	1.75	108.60	-	110.50
King Island New (BSCZSF)	15/16	12	105.60	4.10	4.10	3.88	105.60	-	109.70
	16/17	12	109.70	3.10	3.10	2.83	109.70	-	112.80
	16/17	12	91.70	7.8	7.8	8.51	91.70	-	99.50
North Flinders Island (BSCZSF)	08/09	12	98.10	2.20	2.20	2.24	98.10	-	100.30
	08/09	12	91.90	4.20	4.20	4.57	91.90	-	96.10
	09/10	12	96.10	3.20	3.20	3.33	96.10	-	99.30
	10/11	12	99.30	0.50	0.50	0.50	99.30	-	99.80
	09/10	12	52.30	32.80	32.80	62.72	52.30	-	85.10
	10/11	12	85.10	6.30	6.30	7.40	85.10	-	91.40
North West Flinders Island 1 (BSCZSF)	08/09	11	97.60	6.80	7.42	7.60	97.60	-	104.40
	08/09	11	61.50	32.70	35.67	58.00	61.50	-	94.20
	09/10	12	94.20	2.70	2.70	2.87	94.20	-	96.90

	10/11	3	96.90	1.60	6.40	6.60	96.90	-	98.50
	11/11	6	98.50	1.40	2.80	2.84	98.50	-	99.90
North West Flinders Island 2 (BSCZSF)	09/10	12	96.60	2.78	2.78	2.88	96.60	-	99.38
Flinders Island 1 (BSCZSF)	15/16	12	95.50	0.36	0.36	0.38	95.50	-	95.86
	15/16	12	84.42	3.09	3.09	3.66	84.42	-	87.51
	16/17	12	87.51	1.76	1.76	2.01	87.51	-	89.27
Flinders Island 2 (BSCZSF)	15/16	12	87.93	3.79	3.79	4.31	87.93	-	91.72
East Flinders Island (TSF)	02/03	12	75.49	12.44	12.44	16.48	75.49	-	87.93
	03/04	12	87.93	3.57	3.57	4.06	87.93	-	91.50
	04/05	12	91.50	2.74	2.74	2.99	91.50	-	94.24
	05/06	17	94.24	5.4	3.81	4.04	94.24	-	99.64
West Flinders Island (TSF)	06/07	11	72.28	10.13	11.05	15.29	72.28	-	82.41
Eddystone North (TSF)	03/04	4	101.00	4.04	12.12	12.00	101.00	-	105.04
Eddystone Central (TSF)	03/04	12	99.28	2.37	2.37	2.39	99.28	-	101.65
Eddystone South (TSF)	04/05	13	105.75	9.81	9.06	8.57	105.75	-	115.56
	04/05	13	79.40	23.20	21.42	26.98	79.40	-	102.60
White Rock (TSF)	05/06	12	108.98	4.11	4.11	3.77	108.98	-	113.09
	05/06	12	93.48	4.45	4.45	4.76	93.48	-	97.93
	06/07	9	97.93	5.87	7.83	8.00	97.93	-	103.8
	07/08	11	103.80	1.79	1.95	1.88	103.8	-	105.59
	07/08	11	36.74	41.26	45.01	122.51	36.74	-	78.00
	08/09	17	78.00	15.60	11.01	14.12	78.00	-	93.60
	11/12	18	99.23	11.34	7.56	7.62	99.23	-	110.57
	11/12	18	64.17	32.00	21.33	33.24	64.17	-	96.17
	12/13	10	96.17	2.95	3.54	3.68	96.17	-	99.12
	13/14	10	88.65	10.11	12.13	13.68	88.60	-	98.71
	14/15	15	54.32	39.90	31.92	58.76	54.30	-	94.20
	15/16	9	94.20	2.19	2.92	3.10	94.20	-	96.39
	16/17	12	96.39	4.11	4.11	4.26	96.39	-	100.50
Great Bay (TRSF)	08/09	12	79.67	17.58	17.58	22.07	79.67	-	97.25
	09/10	12	97.25	8.75	8.75	9.00	97.25	-	106.00
	09/10	12	91.60	13.80	13.80	15.07	91.60	-	105.40
	10/11	11	105.40	1.30	1.42	1.35	105.40	-	106.70
	11/12	12	106.70	5.90	5.90	5.53	106.70	-	112.60
	09/10	12	104.80	3.30	3.30	3.15	104.80	-	108.10
	10/11	11	108.10	3.30	3.60	3.33	108.10	-	111.40
	11/12	12	111.40	4.60	4.60	4.13	111.40	-	116.00

Table 11. Modal progression observed in East Flinders (TSF). Result from FRDC 2003/17 project (Haddon et al. 2006).

			Size						
Site	Years	Δ Time (months)	Initial	Increment	Increment/ Δt (mm/year)	Increment %	Change		
T1N	02/03	12	75.00	12.42	12.42	16.56	75.00	-	87.42
T1N	03/04	13	90.00	3.75	3.46	3.84	90.00	-	93.75
T1N	03/04	13	43.50	30.59	28.24	64.92	43.50	-	74.09
T1N	04/05	11	77.00	12.16	13.27	17.23	77.00	-	89.16
T1S	02/03	12	79.39	10.10	10.10	12.72	79.39	-	89.49
T1S	03/04	13	90.40	5.24	4.84	5.35	90.40	-	95.64
T1S	04/05	11	95.01	3.10	3.38	3.56	95.01	-	98.11
T1S	03/04	13	43.00	31.97	29.51	68.63	43.00	-	74.97
T1S	04/05	11	84.00	9.03	9.85	11.73	84.00	-	93.03
T2	02/03	12	71.64	8.96	8.96	12.51	71.64	-	80.60
T2	03/04	13	80.60	7.48	6.90	8.56	80.60	-	88.08
T2	04/05	11	88.08	3.96	4.32	4.90	88.08	-	92.04
T3	02/03	12	72.75	12.20	12.20	16.77	72.75	-	84.95
T3	03/04	13	84.95	4.55	4.20	4.94	84.95	-	89.50
T3	04/05	11	89.50	4.72	5.15	5.75	89.50	-	94.22

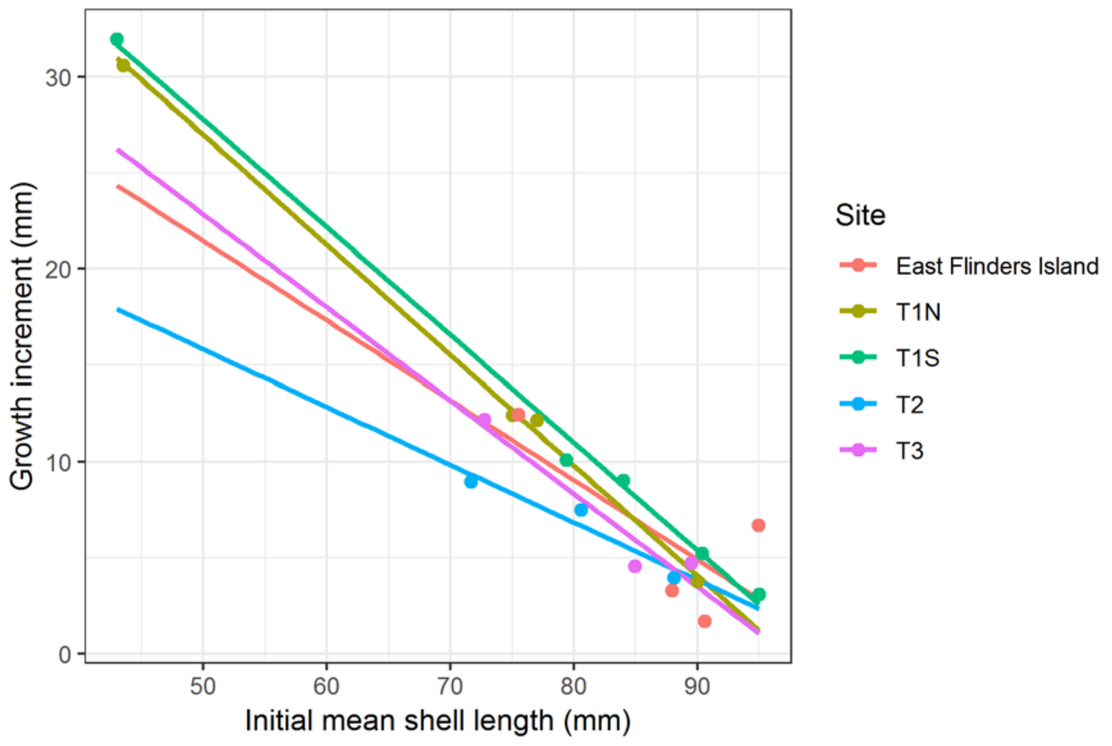


Figure 47. Annual growth increment (mm) based on an initial mean shell length of scallops from East Flinders Island (TSF) (Orange line - this study) compared to growth increments observed within the same region at smaller spatial scales in FRDC 2003/017 (T1N, T1S, T2 and T3).

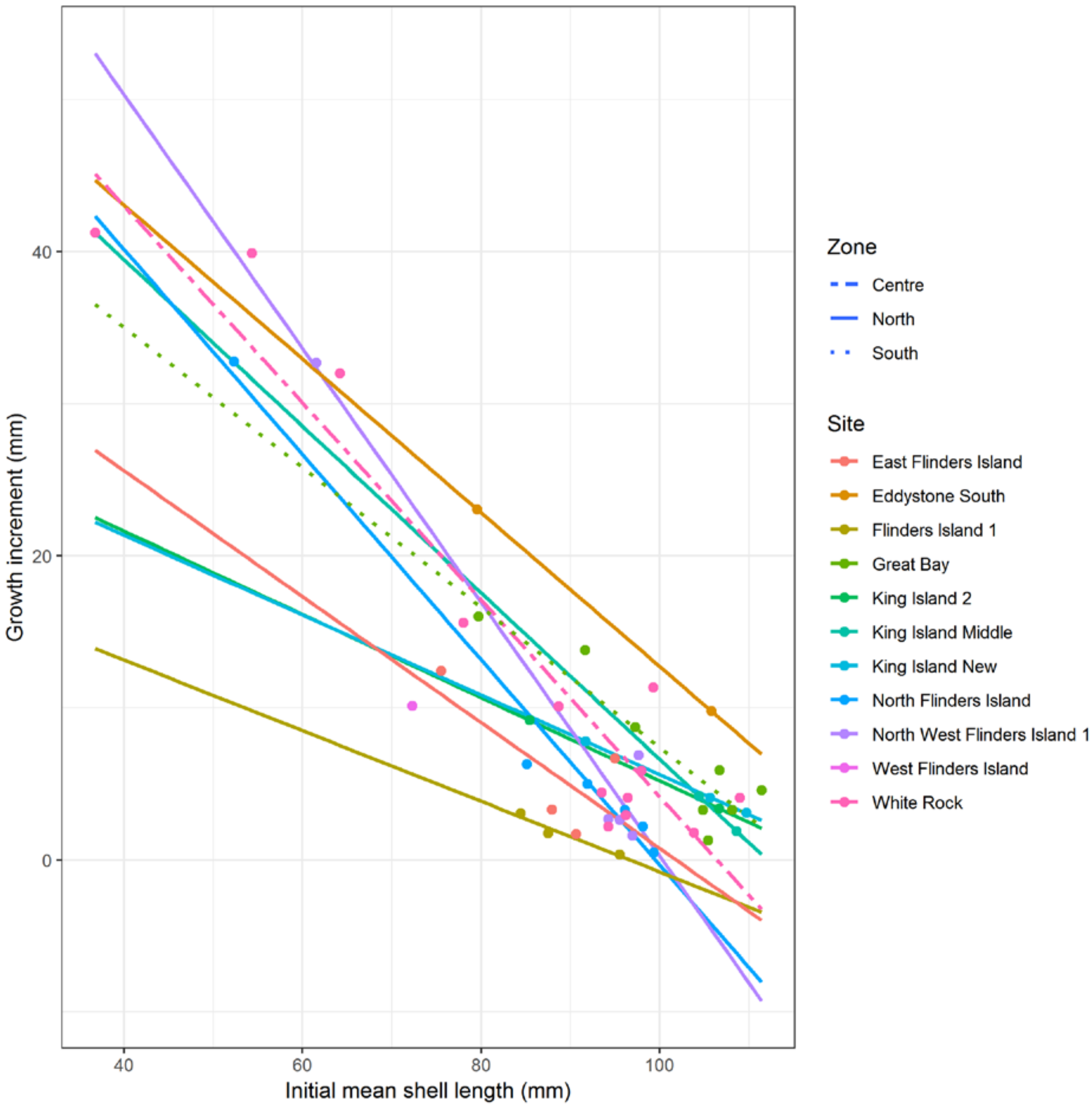


Figure 48. Annual growth increment (mm) based on an initial mean shell length (mm) of scallops from different locations and years.

This growth analysis has shown that there is great variation in growth rates of commercial scallop across the traditional fishing areas within the south east of Australia, with great variation even prevalent between beds in the same area, e.g. King Island (BSCZSF, Figure 48, Table 10) and East Flinders Island (TSF, Figure 47, Table 11). Importantly, however, this analysis has shown that the fishing areas examined can be generally grouped into three general groups: rapid growers; moderate growers; and slow growers. Rapid growers will be younger than their shell length indicates, so those scallops may not be 3+ at 85-95 mm SL and may not have had three major spawnings. As such, despite the relationship between size and fecundity showing that the 90 mm size limit is very conservative, it may not be for these rapidly growing scallops, and perhaps a more conservative approach is needed, particularly as the size limit used in the BSCZSF, where the two North Flinders fishing areas are located, is 85 mm SL. Alternatively, if a validated aging technique can be developed for commercial scallops, this should be adopted to ensure scallops are only fished from the 3+ age class onwards. It is interesting to note that three rapid growing areas are North and North West Flinders (BSCZSF) and White Rock (TSF), all areas that have shown large reductions in biomass, with little or no recruitment in recent years (Semmens et al. 2018; ABARES Fishery Status Report, 2017). The TSF also plans to use an 85 mm SL from 2020 onwards, so a conservative approach may need to be adopted for the White region of that fishery. Note that as previously mentioned, there is great variability with areas, with Flinders Island 1 (BSCZSF), which like North and North West Flinders is also situated north of Flinders Island, showing slow growth. Two other slow growing areas are at King Island (KI 2 and KI New, BSCZSF), with King Island Mid (BSCZSF) showing moderate growth. The slow growing scallops will be older than their shell length indicates, and as such 90 mm SL minimum size is likely to be very conservative. The King Island sites are in the BSCZSF, and as such currently managed under an 85 mm SL size limit, which would appear very appropriate, but likely to be highly conservative. This may be a key factor in the fact that this region has been maintaining very high biomasses despite the fishery operating in the region since 2014 and ~12,429 t coming out of the area in that time. Although note that the North West region in Tasmania is fished with an 85 mm SL size limit rule, as fishers nominated this area as a slow growing scallop area, however it has also undergone a large decline in biomass, following no recruitment in recent seasons (Semmens et al. 2018). In those areas with slow growing scallops, closing beds based on the 20% discard rule may mean that some beds that have 80% or greater of the scallops within it having reached 3+ and having had at least two major spawnings may be inadvertently closed, and as such this rule will be very conservative in these areas. Conversely, the opposite will apply in fast growing areas, with beds that have less than 80% of the scallops within it having reached 3+ and having had at least two major spawnings being inadvertently opened, and as such this rule not be met in these, which could have an impact on the sustainability of fisheries in these areas. As such, defined use of the minimum size limit and 20% discard rule is not appropriate, and instead they should be used in conjunction with the known attributes of the beds within region to be fished and applied in an informed and sensible manner such that recruitment potential is not impacted. If a validated aging method can be developed for commercial scallops, the 20% discard rule will be able to be applied with greater confidence.

Conclusion

As we expected from their biology, changes in muscle weight in the commercial scallop are influenced by season, as muscle weight is influenced by the gametogenic cycle, but this relationship is affected by year. In fact, there is no common trend in changes in muscle weight across areas, instead the changes are area-specific and year-specific. Mean muscle weight varied up to 1.8 times among locations during the same season in a given year, which stresses the importance of conducting preliminary investigations in different fishing locations (where available) each year to obtain best yields. Mean muscle weights can vary considerably (up to 3.6 times, or 70%) across locations and sampling occasions. This difference in mean muscle weight is greater than the ~50% reported for the American sea scallop in Georges Bank, United States. The difference in muscle weight might be at such a magnitude that economically, it may warrant increased investigation prior to or at the start of the fishery, especially when considering that the average difference in muscle weight between two consecutive months in a location is ~10%. This is particularly relevant in the TSF, when only relatively small areas of the fishery are opened at any one time and the remainder of the fishery is closed, although the adaptive in-season management model in this fishery (i.e., open area boundaries can be changed during the season) can overcome this issue in some circumstances. In the BSCZSF and OSF, given only relatively small areas of the fishery are closed during the fishing season or the entire fishery is opened, respectively, there may be a greater opportunity for scallop fishers to find beds with higher muscle weights, although this is of course dependant on the number of different beds available, with limited to no scallop beds available for harvest in the OSF for over two decades. Furthermore, without adaptive in-season management, which is the case in the BSCZSF (i.e., spatial closures are not adjusted during the fishing season), there is the potential for the best quality scallops to be ‘locked-up’ in spatial closures for the entire season.

Pooled data of gonad weight across years per season showed that in general, mean gonad weight was lower in autumn and greater in winter and spring, with insufficient data to compare summer. Mean gonad weight can vary up to 6.5 times (or ~85%) in the same location across different months, highlighting the importance of fishing in the appropriate period to maximise gonad yields. Mean gonad weight varied up to 4.3 times among locations during the same season in a given year. Mean gonad weights can also vary considerably (up to 11 times or ~90%) across locations and sampling occasions for similar-sized scallops. These results highlight large gonad weight variation, and like that for muscle weight variation, the need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in the BSCZSF and TSF, where not all the fishery is opened for fishing during a fishing season.

Pooled data of meat recovery weight across years per season showed that in general, mean weight was lower in autumn and greater in winter and spring, with insufficient data to compare summer. Mean meat recovery can vary up to 2.5 times in the same location and season across different years, while mean meat recovery varied up to 1.9 times among locations during the same season in a given year. Mean meat recovery also varied considerably (up to 11 times) across locations and sampling occasions. This confirms that meat recovery weight can vary significantly across years, area and season and therefore further highlights the need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in the BSCZSF and TSF.

Maturity stages identified macroscopically did not consistently match the maturity stages identified by histological sampling. Apart from macroscopic stage 2, which comprised scallops with predominantly gonads in the developing stage, the other macroscopic stages showed a mixture of reproductive stages. Therefore, while the macroscopic staging scheme is useful to derive a general indication of gonad condition, it does not accurately reflect the maturity stage in the ovary.

Based on microscopic observations compared to macroscopic examination of gonads, three visual stages are described based on the morphological appearance of the gonad to the naked eye: Developing or spent; maturing or atretic (reabsorbing eggs as spawning is delayed); and partially spawned. Fishing in the Commonwealth predominately takes place in the beds or regions surveyed before the season commences. Similarly, the TSF only opens to fishing surveyed areas that meet the management plan. While the OSF does not use surveys to determine open areas, as it is not a spatially managed fishery, fishing generally occurs in traditional areas, which will have variable gonad development and spawning timings within and between them. As such, the simple three stage visual classification system developed in this project is useful to both scallop resource managers and industry, as part of in-season management strategies, to define the overall reproductive stage of scallops and predict timing of spawning, thus assisting in the best condition scallop beds being fished sequentially throughout the season. This has the potential to enhance the operation and profitability of the fisheries. The benefit of the scheme is there are only three stages, so classification is relatively simple. Additionally, photos of opened scallops could be taken by fishers, fisheries observers, scallop processers, etc., and sent to other parties to examine and confirm, as a method of validating the reproductive condition of the bed or area. For example, as part of in-season industry management, photos of the gonad staging could be sent to fishers to validate decisions made by industry representatives on which scallop beds to fish at any given time and which beds need measures such as voluntary closures.

A further example of using this gonad staging scheme could be in relation to the season end date in the BSCZSF, which is December 31 (with a nominal start date of April 1) each year (also 31 December and April 1 (state wide survey period commences) in TSF; noting that OSF is open continually throughout the year) to protect potential scallop larval settlement. Fishers are currently interested in trialling fishing past December 31, to keep established markets going, with a proposal that they would stop fishing once spawning begins and thus in theory before settlement starts. If this proposal went ahead, this simple gonad staging system could be used to quickly assess all the beds in the region to determine if spawning has commenced and quickly relay the information to AFMA managers.

Collection of data on scallop condition, reproductive stages and settlement rates collectively can help inform best timing for season opening and closing dates in each location. The information available from this study and previous studies, suggest that the Lakes Entrance region, which comprises the majority of the OSF, would profit from an early start during winter. However, note that the OSF is currently considered depleted and has not had significant catches in over two decades. This in part may be attributable to the fact that the fishery has historically been open continuously throughout the year, including the settlement period. At White Rock in the TSF, starting the fishery in September would appear more beneficial in terms of harvesting the best product, although this may not fit best with protecting newly settled scallops, and may in part explain why this area has not supported a fishery in recent years and is now classified as depleted. North of Flinders Island, at the Bass Strait site (see Figure 1 and Figure 35) in the eastern section of the BSCZSF, the best time to fish appears to be summer/autumn and most likely spring (currently lacking data for this period), noting that the fishery currently closes December 31. Like White Rock, fishing up to this closure date may not fit best with protecting newly settled scallops, with the major settlement period occurring in spring, and again may in part explain why this area has not been viable in recent years.

At King Island, in the BSCZSF, the best time to fish appears to be spring and summer, noting that the fishery currently closes December 31, as settlement is from approximately November to January. As previously noted, fishers are currently interested in trialling fishing in the BSCZSF past December 31, to keep established markets going. From a perspective of harvesting the best product, this would seem to be a sensible approach at least for the King Island portion of the fishery, which has significant biomass currently over a relatively large area. However, this must be balanced with the important need of ensuring settlement is not disrupted, given that peak settlement is in the summer months and there is no way of knowing where recruits will come from (i.e. King Island beds or beds in another area). However, given the large biomass currently available (i.e. large potential area for recruits to settle) and the fisher proposal to stop fishing once spawning begins in the area, it may be possible to operationally limit the risk to settlement of fishing past December 31, e.g. spatially restrict any post December 31 portion of the fishery.

Fecundity was positively related to SL, and this relationship varied according to month of sampling. Fecundity in May, June and July (autumn and winter) was significantly lower than in September, October, November and December (spring and autumn). As an example, fecundity estimated for a scallop measuring 90 mm in November was 2.5 times greater than in June. Fecundity increased exponentially with SL and modelling predicted that a scallop measuring 90 mm in shell length would be 13 and 25% more fecund than an 85 and 80 mm scallop, respectively. Furthermore, an 80 mm scallop would be 44% more fecund that a scallop measuring 70 mm in SL. Scallops measuring 100 mm in SL would produce 32% more eggs than a scallop measuring 90 mm. These differences are less dramatic than previous findings where 3+ years old scallops measuring ~90 mm SL shed (3.5 million eggs on average) compared to 2 million eggs shed by scallop measuring ~ 83 mm SL (a 57% difference compared to 19% estimated in this study). This result of the current study showing a much smaller difference in fecundity in scallops of various sizes compared to previous findings, is a very important finding in relation to the decision rules around scallop harvest, particularly the under-sized discard rate rule and the two spawnings criteria which states that scallops should be allowed a minimum of two major spawning events before being harvested. Scallops that are 85-95 mm SL are 3+years old and have had two major spawning and thus contributed significantly to potential recruitment. However, given the relationship between fecundity and SL demonstrated in this study, which shows a 3-fold decline in the difference between fecundity of an 83 and 90 mm SL scallop compared to the previous research, the size limits are very conservative. As such, the use of 85 mm SL still allows the scallops to have produced two major spawnings before harvest, with relatively little difference between the fecundity of 85 and 90 mm SL scallops (13%). However, it should be noted that in regions that have very low biomass or are recovering from being depleted (e.g. TSF), this additional 13% could be significant, and a highly conservative approach may be warranted. Furthermore, it should be noted that the 80 mm SL size limit used for the decision rules in the OSF is likely not appropriate, as it is outside of the size range for the two major spawnings criteria and should be revisited, with this low size limit perhaps contributing to the long history of limited biomass and recruitment in the fishery. Along with the fished scallops having greater fecundity in relation to larger scallops, our finding also means that those scallops that are not retained as they are undersized also have a greater fecundity than previously thought. For example, in both the BSCZSF and the TSF 83 mm SL scallops are not retained, as they are undersized. We now know that these scallops are only approximately 19% less fecund than a 90 mm SL scallop, compared to the previously thought difference of 57%. As such, undersized scallops have the potential to contribute much more significantly to recruitment than previously thought.

Differences in shell morphology were evident among regions, with significant differences between the standardised height for a standard scallop measuring 90 mm in shell length. Scallops located in northern areas (Victoria (OSF), Babel Island (TSF and BSCZSF), West Flinders (TSF), NW Tasmania (TSF), Banks Strait (TSF) and Eddystone TSF) had relatively smaller heights for a standard scallop measuring 90 mm in SL, except for scallops located in the Bass Strait (BSCZSF) site. This relatively larger shell height for a given SL within waters in the eastern region of the BSCZSF agrees with previous findings for the region. On the other hand, scallops from southern populations (Isthmus Bay (TRSF), Great Bay (TRSF), Trial Bay (TRSF), Marion Bay (TSF), and White Rock (TSF)) showed relatively greater shell heights for a standard scallop. Variations in shape among scallops in different locations may affect swimming capabilities. For hydrodynamic considerations, the aspect ratio, which corresponds to the SL/SH ratio of scallops (aspect ratio), shows a positive correlation with the lift/drag ratio. Swimming intensity has also been associated with an increase in aspect ratio. This indicates that swimming becomes comparatively easier as aspect ratio increases and scallops with a smaller proportional height would be comparatively better shaped to overcome drag than scallops with comparatively greater heights. Therefore, scallops measuring 90 mm in SL in Eddystone (TSF), Banks Strait (TSF), North West Tasmania (TSF), West Flinders (TSF), Babel Island (TSF and BSCZSF) and Victoria (OSF) would be comparatively greater swimmers than scallops in the other locations studied. However, other characteristics such as position and area of muscles can also affect swimming performance and still need to be tested. As scallops use two main predator escape mechanisms: a passive mechanism where they close their valves and remain recessed into the sediment or an active escape mechanism where they swim away from the potential threat (Barbeau and Scheibling, 1994), the relative use of each different escape tactic depending on shell morphology and location still needs to be investigated for different populations of commercial scallop.

Differences in morphology were more evident among locations when comparing shell widths for standard scallops measuring 90 mm in shell length. North West Tasmania (TSF) and Great Bay (TRSF) had comparatively thinner individuals, followed by King Island (BSCZSF), Banks Strait (TSF), Marion Bay (TSF) and White Rock (TSF). Scallops from Babel Island (TSF and BSCZSF) showed no significant differences in shell width with Eddystone (TSF) or the Bass Strait (BSCZSF) site. Scallops located in Victoria (OSF) had the thickest scallops. A variety of factors have been shown to influence shell width in many bivalve species. For example, differences in shell width were attributed to density of conspecifics and food availability in the blue mussel, *Mytilus edulis*, for which valves were narrower at high density and at low food concentration compared to low density and high food concentration. For the soft-shell clam, *Mya arenaria*, shells were wider when reared in gravel than in sand or mud. In scallops, differences in shell width have been attributed to depth for the American sea scallop, where individuals from shallow water were considerably wider than those from offshore, deep water populations. The factors influencing the differences in SW of commercial scallop among different locations still need to be explored. However, for fisheries management purposes it is interesting to determine if scallops with greater SW also have greater muscle and/or gonad weights. Indeed, the Victorian (OSF) site had the thickest (deepest) scallops and these scallops generally had the heaviest muscles, gonads and combined weights in winter of all the regions. Additionally, other thick scallop regions, Isthmus Bay (TRSF) and Eddystone Point (TSF), also had heavy muscles, gonads and combined weights in winter. Furthermore, the relatively thick scallops from the Bass Strait (BSCZSF) site had heavy muscles, gonads and combined weights in autumn. Fishing these areas (when opened) in the seasons noted could increase commercial yields.

Scallops at different sites showed variable mean growth increments depending on initial mean size of cohorts. For instance, in North West Flinders Island (BSCZSF), a cohort with 61.5 mm of mean size grew 35.7 mm in one year; and in contrast, a similar mean size cohort (64.2 mm) in White Rock (TSF) grew 21.3 mm in one year. In Eddystone South (TSF), 79.6 and 105.8 mm scallops grew 21.3 and 9.1 mm in one year respectively. In comparison, in East Flinders (TSF) smaller individuals (75.5 and 94.2 mm), with higher expected growth, increased in size 12.4 and 3.8 mm in one year respectively. This result is consistent with the fact that East Flinders (TSF) scallops have a lower mean growth increment than scallops in the Northern region (BSCZSF) of Flinders Island.

There was no obvious growth pattern on the latitudinal gradient. For instance, sites at the extreme north (North Flinders and King Island, both in the BSCZSF) and south (Great Bay, TRSF) of Tasmania showed average mean growth increments. Low and high values of growth were observed in sites that are close to each other in the BSCZSF (1.9 and 9.20 mm/year for King Island Middle and King Island 2 respectively). Therefore, growth variations seem to be associated with local factors rather than factors linked with large spatial scale change, which has also been observed for other species of scallop. This growth analysis has shown that there is great variation in growth rates of commercial scallop across the traditional fishing areas within the south east of Australia, with great variation even prevalent between beds in the same area, e.g. King Island (BSCZSF) and East Flinders Island (TSF). Importantly, however, this analysis has shown that the fishing areas examined can be generally grouped into three general groups: rapid growers; moderate growers; and slow growers. Rapid growers will be younger than their shell length indicates, so those scallops may not be 3+ at 85-95 mm SL and may not have had three major spawnings. As such, despite the relationship between size and fecundity showing that the 90 mm size limit is very conservative, it may not be for these rapidly growing scallops, and perhaps a more conservative approach is needed, particularly as the size limit used in the BSCZSF, where the two North Flinders fishing areas are located, is 85 mm SL. Alternatively, if a validated aging technique can be developed for commercial scallops, this should be adopted to ensure scallops are only fished from the 3+ age class onwards. It is interesting to note that three rapid growing areas are North and North West Flinders (BSCZSF) and White Rock (TSF), all areas that have shown large reductions in biomass, with little or no recruitment in recent years. The TSF also plans to use an 85 mm SL from 2020 onwards, so a conservative approach may need to be adopted for the White region of that fishery. Note that as previously mentioned, there is great variability with areas, with Flinders Island 1 (BSCZSF), which like North and North West Flinders is also situated north of Flinders Island, showing slow growth. Two other slow growing areas are at King Island (KI 2 and KI New, BSCZSF), with King Island Mid (BSCZSF) showing moderate growth. The slow growing scallops will be older than their shell length indicates, and as such 90 mm SL minimum size is likely to be very conservative. The King Island sites are in the BSCZSF, and as such currently managed under an 85 mm SL size limit, which would appear very appropriate, but likely to be highly conservative. This may be a key factor in the fact that this region has been maintaining very high biomasses despite the fishery operating in the region since 2014 and ~12500 t coming out of the area (west of 147 degrees east) in that time. Although note that the North West region in Tasmania is fished with an 85 mm SL size limit rule, as fishers nominated this area as a slow growing scallop area, however it has also undergone a large decline in biomass, following no recruitment in recent seasons. In those areas with slow growing scallops, closing beds based on the 20% discard rule may mean that some beds that have 80% or greater of the scallops within it having reached 3+ and having had at least two major spawnings may be inadvertently closed, and as such this rule will be very conservative in these areas. Conversely, the opposite will apply in fast growing areas, with beds that have less than 80% of the scallops within it having reached 3+ and having had at least two major spawnings being inadvertently opened, and as such this rule not be met in these, which could have an impact on the sustainability of fisheries in these areas. As such, defined use of the minimum size limit and 20% discard rule is not appropriate, and instead they should be used in conjunction with the known attributes of the beds within region to be fished and applied in an informed and sensible manner such that recruitment potential is not impacted. If a validated aging method can be developed for commercial scallops, the 20% discard rule will be able to be applied with greater confidence.

Recommendations

Given that there are no common trends in changes in muscle, gonad and combined muscle and gonad (meat recovery) weight across areas, and instead the changes are area-specific and year-specific and can vary considerably, there is a clear need for pre-season or start of season surveys/investigations and/or adaptive in-season management, to maximise yields and fisheries profitability in the BSCZSF and TSF, where not all the fishery is opened for fishing during a fishing season. Without such ‘instruments’ there is the potential for the best quality scallops to be ‘locked-up’ in spatial closures for the entire season.

Maturity stages identified using the macroscopic staging scheme for commercial scallops (Harrison 1961; Young et al. 1999) do not consistently match the maturity stages identified by histological sampling. Therefore, while the macroscopic staging scheme is useful to derive a general indication of gonad condition, it should not be used to determine reproductive maturity, as it does not accurately reflect the maturity stage in the ovary. Instead, we recommend the use of the three-stage visual classification system (developing or spent; maturing or atretic (reabsorbing eggs as spawning is delayed); and partially spawned) we developed to assess the reproductive maturity stage of commercial scallops, as part of pre-season surveys, in-season management strategies, to define the overall reproductive stage of scallops and predict timing of spawning, thus assisting in the best condition scallop beds being fished sequentially throughout the season.

The OSF is currently considered depleted and has not had significant catches in over two decades. This in part may be attributable to the fact that the fishery has historically been open continuously throughout the year, including the settlement period. However, the most recent OSF fishing season commenced on 1 April and we recommend making this the earliest date the season can open, with a December 31 closing date at the latest. We recommend that the TSF and BSCZSF review the timing of fishing in the

White Rock region and Bass Strait (north of Flinders Island) sites (see Figure 1 and Figure 35 for area definition) to assist with protecting settlement of recruits.

At King Island, in the BSCZSF, the best time to fish appears to be spring and summer. However, we recommend that any change to fishing in this period is balanced with the important need of ensuring settlement is not disrupted, given that peak settlement is in the summer months and there is no way of knowing where recruits will come from (i.e. King Island beds or beds in another area).

Scallops that are 85-95 mm SL are 3+years old and have had two major spawning and thus contribute significantly to potential recruitment. However, given the relationship between fecundity and SL demonstrated in this study, which shows a 3-fold decline in the difference between fecundity of an 83 and 90 mm SL scallop compared to the previous research, the size limits are very conservative. As such, the use of 85 mm SL still allows the scallops to have produced two major spawnings before harvest, with relatively little difference between the fecundity of 85 and 90 mm SL scallops (13%). However, it should be noted that in regions that have very low biomass or are recovering from being depleted (e.g. TSF, BSCZSF Eastern Region), this additional 13% could be significant, and a highly conservative approach may be warranted. Furthermore, it should be noted that the 80 mm SL size limit used for the decision rules in the OSF is likely not appropriate, as it is outside of the size range for the two major spawnings criteria and we recommend that it be revisited, with this low size limit perhaps contributing to the long history of limited biomass and recruitment in the fishery.

The growth increment analysis demonstrated that the fishing areas examined can be generally grouped into three general groups: rapid growers; moderate growers; and slow growers. Rapid growers will be younger than their shell length indicates, so those scallops may not be 3+ at 85-95 mm SL and may not have had three major spawnings. As such, despite the relationship between size and fecundity showing that the 90 mm size limit is very conservative, it may not be for these rapidly growing scallops, and perhaps a more conservative approach is needed, particularly as the size limit used in the BSCZSF, where the two North Flinders fishing areas are located, is 85 mm SL. Alternatively, if a validated aging technique can be developed for commercial scallops, this should be adopted to ensure scallops are only fished from the 3+ age class onwards. It is interesting to note that three rapid growing areas are North and North West Flinders (BSCZSF) and White Rock (TSF), all areas that have shown large reductions in biomass, with little or no recruitment in recent years. The TSF also plans to use an 85 mm SL from 2020 onwards, so a conservative approach may need to be adopted for the White Rock region of that fishery, particularly as it is currently depleted and other recommendations have been made for this region (see above).

In those areas with slow growing scallops, closing beds based on the 20% discard rule may mean that some beds that have 80% or greater of the scallops within it having reached 3+ and having had at least two major spawnings may be inadvertently closed, and as such this rule will be very conservative in these areas. Conversely, the opposite will apply in fast growing areas, with beds that have less than 80% of the scallops within it having reached 3+ and having had at least two major spawnings being inadvertently opened, and as such this rule would not be met in these, which could have an impact on the sustainability of fisheries in these areas. As such, we recommend that a defined use of the minimum size limit and 20% discard rule is not appropriate, and instead they should be used in conjunction with the known attributes of the beds within region to be fished and applied in an informed and sensible manner such that recruitment potential is not impacted. If a validated aging method can be developed for commercial scallops, the 20% discard rule will be able to be applied with greater confidence.

While not a formal part of this project, given its close relationship to the objectives covered here, we recommend that the TSF and the OSF consider closing to fishing known beds (or portions of beds) in the regions open to fishing. This is based on the evidence available, which suggests that recovery of depleted scallop beds in the short term will be heavily influenced by recruitment from adjacent scallop beds rather than from distant beds. For the TSF, this may only entail relatively minor changes to their current policy of protecting potential scallop habitat, such that they have a means of identifying known beds of scallops in these areas. For the OSF, with no spatial management, this would be a larger change to the current management arrangements.

Extension and Adoption

Jayson Semmens presented the draft results to the AFMA Scallop Research Workshop on March 30 2017, which was attended by the members of the Commonwealth Scallop RAG and MAC, as well as representatives of the Scallop Fishermen's Association of Tasmania (SFAT - including the President and Executive Officer), along with independent fishers and processors from Victoria. All representatives were very interested in the findings. Of particular interest was our findings relating to the relationship between shell length and fecundity, given that they were significantly less dramatic than Martin et al. (1988), on which the current minimum size limits are based. In their study, 3+ year old scallops measuring 90 mm SL shed 3.5 million eggs compared to 2 million eggs shed by 83 mm SL scallops, this is a 57% difference. Conversely, our study estimated only a 25% difference in fecundity between an 83 and a 90 mm scallop. As a result, AFMA used our findings to better justify the change from a 90 mm size limit to an 85 mm limit in 2014, with the only reason given at the time being "Adopting 85mm compared to 90mm is less precautionary, however it is still the lower range of 3+ year old scallops and two major spawning events". They made the following recommendation from our results: "that the minimum size limit in the BSCZSF Harvest Strategy remain at 85 mm and that no further research in this area is required".

The main comment relating to additional work to come out of this meeting was in relation to our growth estimates for areas across the spatial and temporal extent of our data set. The growth curves for King and Flinders Islands looked like they were not representing the data as well as they should. As such, we suggested that we could look at the growth data from these areas at the bed level. We subsequently got the data from AFMA and undertook these analyses, which have improved the growth estimates.

On November 9 2017, Jayson Semmens also presented the draft results to the Tasmanian Scallop Fishery Advisory Committee (FAC), which includes representatives of SFAT (including the President and Executive Officer). Again, there was great interest in the fecundity at length estimates, with the Chair Ian Cartwright highlighting the significance of these results.

On May 15 2018, Jayson Semmens also presented the draft results at the SFAT AGM and General Meeting. Again, there was great interest in the fecundity at length estimates, with the members very happy that they can now demonstrate that a range of size limits could be introduced across the fishery where appropriate and still meet the two major spawnings rule. Additionally, the increased fecundity at smaller sizes gave them confidence that scallops under the minimum legal size could still contribute significantly to the spawning biomass. The members also found the growth analysis very important and informative, as it feeds into identifying those areas that could be fished at a lower minimum legal size, due to their slower relative growth. They also appreciated the ability to estimate how long scallops in different areas take to get to the minimum legal size, as this informs area closures and openings. As an example, at the time of the presentation SFAT were meeting with the Tasmanian minister responsible for fisheries to request that the Tasmanian Scallop Fishery was closed for two years to allow it to recover. SFAT presented our results to the minister and could show using the growth rates for the Tasmanian stocks that at the current size classes present in the fishery, it will take at least two years for any fishable biomass to be available. As such, it could be demonstrated that a two-year closure was a very sensible and defendable approach to ensuring the long-term future of the fishery. The minister subsequently closed the fishery until 2020.

On November 26 2018, the Tasmanian Scallop FAC discussed changing the size limit from 90 mm to 85 mm. Based on this study showing the difference in fecundity is only 13% between 85 mm and 90 mm scallops, the committee decided that given that biologically the difference is small, that it should not affect sustainability. As such, the proposal was supported, however, the existing provisions for different size limits for specific areas was retained to allow for more conservative limits to be employed if needed.

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