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# Harvestable biomass of *Katelysia* spp. in the South Australian commercial Mud Cockle Fishery

**J. Dent, S. Mayfield and J. Carroll**

SARDI Publication No. F2014/000191-2
SARDI Research Report Series No. 898

SARDI Aquatics Sciences
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May 2016

Report to PIRSA Fisheries and Aquaculture

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Cover photo: *Katelysia sp.* J. Dent

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## EXECUTIVE SUMMARY

This is the fourth report to provide estimates of harvestable biomass of mud cockles (*Katelysia* spp.) across the South Australian commercial fishery. Along with the harvest strategy in the Management Plan and previous estimates of size at maturity, these provide the most robust information for determining appropriate total allowable commercial catches (TACCs).

The Mud Cockle Fishery consists of three fishing zones and is based on three species: *Katelysia scalarina* ("greys"), *K. rhytiphora* ("yellows"), and *K. peronii* ("whites"). The current (2015/16) TACCs in Coffin Bay and the West Coast cockle fishing zones are 50.0 t and 16.0 t, respectively. These correspond to harvest fractions of 6.2% and 3.2% from the 2013 survey, respectively.

Best estimates (from the 50% quantile) of harvestable biomass from the Coffin Bay fishing zone in 2015 were 990.2 t for *K. rhytiphora* (≥35 mm shell length (SL)), 158.6 t for *K. scalarina* (≥30 mm SL) and 0.0 t for *K. peronii* (≥35 mm SL). Collectively, this provided a total best estimate of harvestable biomass of 1148.8 t. There was an 80% probability that the estimate was at least 867.7 t.

The combined best estimate of harvestable biomass (≥30 mm SL) from the West Coast fishing zone in October and November 2015 was 603.5 t, most of which was in Streaky Bay (50%). The best estimates of harvestable biomass were 335.7 t for *K. scalarina,* 188.5 t for *K. rhytiphora* and 79.3 t for *K. peronii.* There was an 80% probability that the total harvestable biomass was at least 478.1 t.

The harvest strategy for the fishery allows a maximum harvest fraction of 7.5% (at the 80% quantile) permitting a maximum TACC in the Coffin Bay fishing zone of 65.1 t and 35.9 t for the West Coast fishing zone. Maintaining the 2015/16 TACC in the Coffin Bay (50.0 t) and West Coast (16.0 t) cockle fishing zones, would translate to harvest fractions of 5.8% and 3.3%, respectively.

The collective evidence of high harvestable biomass, low current exploitation rates and recent evidence of recruitment indicates that the stocks in the Coffin Bay and West Coast mud cockle fisheries are unlikely to be recruitment overfished and that current levels of fishing pressure are unlikely to cause these to become recruitment overfished. Using the national framework for stock status reporting (Flood *et al*. 2014), the Coffin Bay and West Coast mud cockle fisheries are classified as '**sustainable**'.

# 1. INTRODUCTION

## 1.1 Background

This is the fourth report on the harvestable biomass of mud cockles in South Australia and follows from Gorman *et al.* (2010) and Dent *et al.* (2012, 2014). The objective of this report is to provide an estimate of harvestable biomass of mud cockles in the Coffin Bay and West Coast fishing zones (hereafter referred to as Coffin Bay and West Coast, respectively). Information on changes in mud cockle density and population structure through time, as well as catch history, is also provided. Collectively, this information will be used in conjunction with the harvest strategy to establish TACCs for the 2016/17 fishing season.

The genus *Katelysia* (Family Veneridae), commonly known as mud cockles or vongole, is a group of commercially important bivalves that comprise a major faunal component of shallow estuarine and marine embayments (Roberts 1984). In Australia, the genus is represented by three species – *Katelysia scalarina* (Lamarck 1818) known as “greys”, *K. rhytiphora* (Lamy 1835) known as “yellows” and *K. peronii* (Lamarck 1818) known as “whites” – all of which are broadly distributed around the temperate coastline from Augusta, Western Australia to Port Jackson, New South Wales (Roberts 1984).

Mud cockles have been harvested in South Australia since the early 1960s, with management arrangements changing throughout that 55-year period (see Table 1). Prior to 1985, most of the catch was obtained from the Port River and Kangaroo Island for use as bait. Since then, mud cockles have largely been used for human consumption, particularly in Melbourne. Despite increasing demand, the fishery remained lightly exploited until 1995/96, when the State-wide annual catch first exceeded 50 t. From 1996/97, catches increased rapidly to a peak of 375 t in 2005/06. Most of the catch during this period was obtained from the Port River and Coffin Bay. Given the large number of licenses (>600) with access to the resource and the rapid increases in catch, concerns for the sustainability of the fishery were raised, which led to implementation of a quota management system across the three cockle fishing zones (Port River, Coffin Bay and West Coast; Figure 1) in October 2008.

The initial total allowable commercial catch (TACC) in 2008/09 was based primarily on catch history. The combined TACC for all zones in 2008/09 was 195 t. Of this, 171 t (including the catch used as bait and berley) was landed with a value of AU$1.28M (Knight and Tsolos 2012). In 2009/10, advice from fishers (West Coast and Coffin Bay) and survey estimates of biomass (Port River fishing zone) led to concerns over fishing sustainability and TACCs were reduced in all three cockle fishing zones (Table 1).

Following the first assessment of harvestable biomass (Gorman *et al.* 2010), TACCs for 2010/11 were set at 11.3 t for the Port River, 48.1 t for Coffin Bay and 21.0 t for the West Coast (total 80.4 t). In response to further concerns around sustainability, the Mud Cockle Fishery in the Port River was closed from 1 July 2011, while the TACC for the West Coast was reduced for the 2011/12 season (Table 1). In the 2015/16 fishing season, the TACC for Coffin Bay was increased to 50 t (6.2% harvest fraction), while the TACC for the West Coast was 16.0 t (3.2% harvest fraction) for the 2014/15 and 2015/16 fishing seasons. In Coffin Bay, the MLLs for *K. scalarina* and *K. rhytiphora* were reduced in 2012 and 2015, respectively (Table 1), following a re-analysis of size at maturity.

**Table 1.** Management milestones in the South Australian Mud Cockle Fishery

| Date | Milestone |
|---|---|
| 1960 | Fishery started |
| | Minimum legal length (MLL) set at 30 mm shell length (SL) state wide |
| 1990 | MLL at Coffin Bay increased to 38 mm SL for all three *Katelysia* species |
| 2005 | State wide catches peaked at 375 t |
| 2008 | TACCs introduced; 100.0 t Port River, 70.0 t Coffin Bay and 25.0 t West Coast |
| 2009 | TACCs reduced to 22.6 t Port River, 56.0 t Coffin Bay and 15.0 t West Coast |
| 2010 | MLL at Coffin Bay reduced to 33 mm SL for all three species by ministerial exemption (ME) |
| 2010 | TACCs amended to 11.3 t Port River, 48.1 t Coffin Bay and 21.0 t West Coast |
| 2010 | Trial to harvest cockles at Coffin Bay in the ratio they exist (yellow to grey cockles 2:1) |
| 2011 | Port River mud-cockle fishery closed due to concerns over sustainability |
| 2011 | TACCs amended to 48.1 t Coffin Bay and 18.0 t for West Coast |
| 2012 | TACCs increased to 50.0 t Coffin Bay and 18.5 t West Coast |
| 2012 | MLL for *K. scalarina* at Coffin Bay reduced to 30 mm SL by ME |
| 2012 | MLLs for *K. rhytiphora* and *K. peronii* at Coffin Bay returned to legislated 38 mm SL |
| 2013 | New Management Plan for SA commercial marine scalefish fishery (PIRSA 2013) |
| 2014 | TACCs reduced to 46.0 t Coffin Bay and 16.0 t West Coast |
| 2015 | TACC for Coffin Bay increased to 50.0 t |
| 2015 | MLL for *K. rhytiphora* and *K. peronii* at Coffin Bay amended to 35 mm SL by ME |

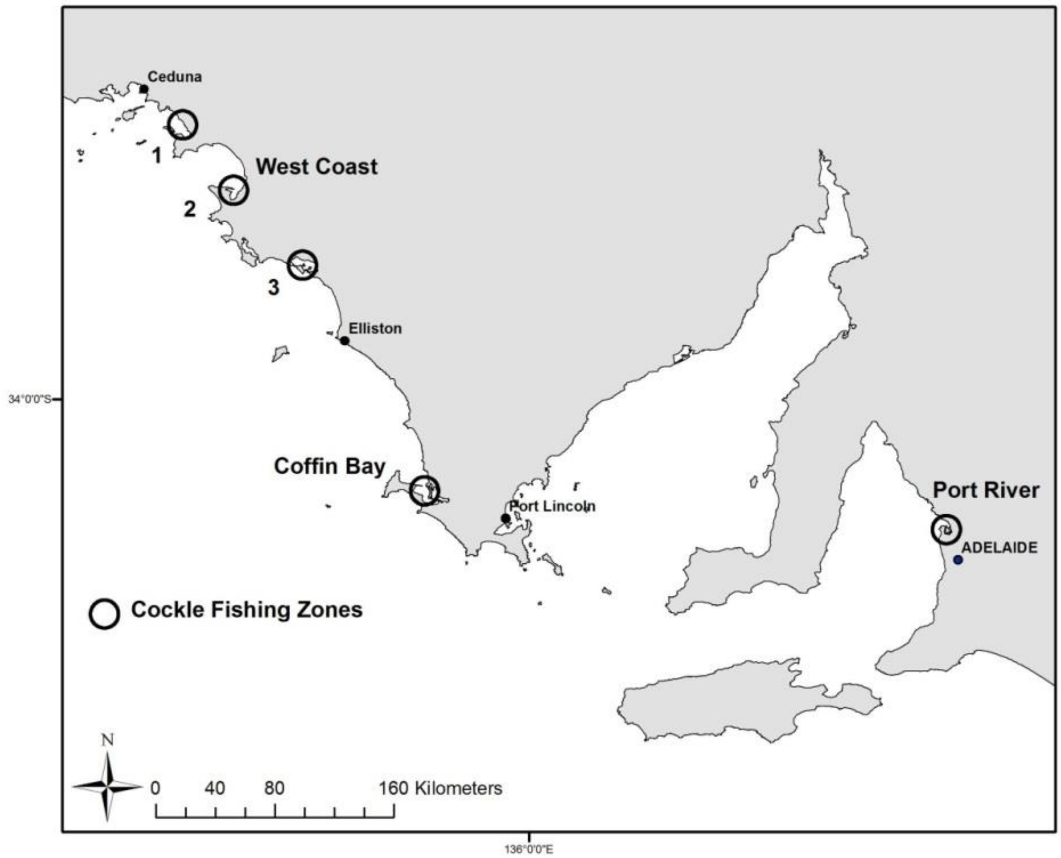


**Figure 1**. Map showing locations of commercial cockle fishing zones in South Australia: Port River, Coffin Bay and the West Coast. The West Coast zone comprises Smoky Bay (1), Streaky Bay (2) and Venus Bay (3).

## 2. METHODS

The focus of the study was to provide estimates of the harvestable biomass of mud cockles (*i.e.* ≥ MLL) within two of the three commercial mud cockle fishing zones: Coffin Bay and the West Coast. The West Coast comprises Smoky Bay, Streaky Bay and Venus Bay (Figure 1). Surveys of mud cockles were undertaken in bounded, stratified survey regions of Coffin Bay in October and November 2015, and January and February 2016. These data were pooled and are referred to as 2015. For the West Coast, surveys were undertaken in October and November 2015.

### 2.1 Catch statistics

Commercial fishers provide daily data on catch, effort and fishing location. Since 2010/11, Coffin Bay fishers have also been able to voluntarily report the catch by species. Using all available records, the daily catch data were aggregated within financial year, by species and location. These data were used to determine the percentage of the catch between species (Coffin Bay) and among fishing grounds (West Coast).

### 2.2 Survey design and transect location

The overall survey design was consistent with previous assessments of the mud cockle resource in South Australia (Gorman *et al.* 2010; 2011; Dent *et al.* 2012; 2014) and integrated design principles of fishery-independent research with knowledge obtained from commercial fishers. This approach is similar to that undertaken for the South Australian Abalone Fishery (Mayfield *et al.* 2008; 2009). Within each cockle fishing zone, fishers identified areas of high and low productivity in the fishing grounds on large-scale aerial photographs. This information was digitized using a Geographic Information System package (ArcGIS V10.3.1) and used to identify areas of high and low density strata. Maps depicting areas of varying mud cockle density were generated and returned to fishers for confirmation. Point sampling locations (transects) were then distributed systematically within the high and low density strata comprising each survey region. To improve survey precision, sampling intensity was greater in areas with expected high densities of mud cockles (high density strata, transects separated by 30-100 m) than those of expected low densities of mud cockles (low density strata, transects separated by 250-360 m).

Surveys of the mud cockle resource are undertaken biennially. In 2015, the Coffin Bay survey comprised twelve strata, while that for the West Coast survey comprised 23 strata: nine in Smoky Bay, three in Streaky Bay and sixteen in Venus Bay. In Coffin Bay, there have been several changes to the survey design since the first survey in 2009. These include (1) exclusion of several previously surveyed areas, resulting in a reduction in area of the low density strata; and (2) incorporation of additional survey areas, notably near to "Dead Man's Corner" in the north-western part of Coffin Bay. Collectively, these changes were made to exclude/include areas on the basis of their perceived status as commercial viability. This approach increased the efficiency of the survey.

Several changes to the West Coast survey areas have also been implemented over time. These include (1) incorporation of additional areas at Smoky Bay in 2013 and 2015; and (2) incorporation of additional and removal of one area at Streaky Bay in 2013. The Venus Bay survey design has had the most substantial changes in recent years with areas both removed and added in 2011 and 2013, and several areas added in 2015 to capture fishing grounds for *K. peronii* and *K. rhytiphora*. The latter changes were implemented following advice from fishers that cockles without clean shells were now highly marketable and commonly targeted.

## 2.3 Survey methods

The fishery-independent surveys were conducted by survey teams which included a South Australian Research and Development Institute (SARDI) observer and a commercial fisher. Sampling was done at fixed sites selected prior to the commencement of surveys and located using coordinates (latitude, longitude) stored in handheld global positioning system (GPS) units. At each sampling site a commercial fisher used a cockle rake (~40 cm in width by ~20 cm in height) with a mesh bag insert (2 cm diagonal mesh size) to collect mud cockles along a transect length of 2 m (*i.e.* ~0.8 $m^2$). Samples were sieved through 7 mm square mesh in the base of a plastic crate to remove sand. Live and dead mud cockles were bagged, labelled and frozen for subsequent processing in the laboratory.

In the laboratory, each sample was sorted to remove dead shells and identify mud cockles to species (after Edwards 1999). For the West Coast, samples were separated into legal (≥30 mm shell length (SL)) and sublegal-sized (<30 mm SL) components using digital calipers. For Coffin Bay, all species were split into legal and sublegal-sized components (*K. scalarina* <30 mm SL and ≥30 mm SL; *K. rhytiphora* and *K. peronii* <35 mm SL and ≥35 mm SL). Mud cockles in each size category were counted and weighed to the nearest gram.

## 2.4 Estimates of harvestable biomass

Total harvestable biomass for each survey area was estimated as the weighted-mean (by stratum area) biomass density multiplied by the survey area ($m^2$). Total harvestable biomass for each survey area and stratified total harvestable biomass for each of the survey regions were calculated as the sum of the totals from the strata and survey areas in each region.

A non-parametric bootstrap method (after McGarvey *et al.* 2008) was used to determine quantiles of the estimates of legal-sized biomass for each species, in each survey region, using R (version 3.2.0). All strata and survey areas within each sampled survey region were included in the analysis. The bootstrap procedure accounted for the random variation at the sampled level of the survey design (*i.e.* the sampling locations in each survey block). The 50,000 bootstrap iterations of estimated biomass were ranked and the 10%, 20% to 90% quantiles extracted. The 'best estimate' harvestable biomass values presented in this report are the 50% (median) quantiles from this bootstrap.

Decision tables were formulated based on the nine quantile levels of lower-bound, survey-estimated biomass in the survey sub-region (Mayfield *et al.* 2008). Each table corresponded to a bootstrap cumulative probability from 10% to 90%, to provide a risk assessment framework for determining the TACCs. In the decision tables, the quantiles (10%, 20%, …, 90%) are used to identify harvestable biomass estimates from the stratified bootstrap. They specify the cumulative confidence probability that the actual harvestable mud cockle biomass is greater than or equal to the estimated biomass values. An assumption of this method was that the sampling gear was 100% efficient. As this assumption is unlikely to be true, estimates of harvestable biomass are considered conservative.

## 2.5 Temporal change in mud cockle density and stock structure

Changes in the estimates of harvestable biomass among years reflect changes in the area surveyed, MLLs and mud cockle density. To evaluate temporal changes in legal and sublegal-sized mud cockle density in Coffin Bay and for each of the bays comprising the West Coast, historical density estimates were re-calculated using (1) only those transects sampled in all years; and (2) current size limits for each species. The numbers of consistent transects used in this analysis were 209 at Coffin Bay, 10 at Smoky Bay, 20 at Streaky Bay and 31 at Venus Bay. Due to historical sub-sampling and multiple changes in the MLL for *K. rhytiphora* over time at Coffin Bay, estimates of density for 2009 could not be calculated. In all other years, *K. rhytiphora* density estimates were calculated using length frequency data to allow comparisons among years. For Streaky Bay, the November 2013 survey data were ignored and the February 2014 data were used. This was done because Streaky Bay was re-surveyed in February 2014 following a mortality event in January 2014 (Dent *et al.* 2014). Data presented are mean ± SE. Following data transformation (SQRT(X+1)) one-way ANOVA outputs from PERMANOVA followed by testing of pairwise outcomes using uncorrected SNK was used to evaluate statistically significant differences in densities between years.

Digital calipers were used to measure all individuals to the nearest 0.1 mm along the longest axis (SL) following previous methods (Gorman *et al.* 2010; Dent *et al.* 2012; 2014). Historically, large sample sizes from Coffin Bay necessitated sub-sampling. However, in 2015, all mud cockles from Coffin Bay were measured to facilitate sample processing and provide robust comparisons among years. Similarly to the estimates of density, the length-frequency data from only those transects sampled in all years for the West Coast and from 2011 to 2015 for Coffin Bay were used to evaluate changes in population size composition among surveys (Gorman *et al.* 2010; Dent *et al.* 2012; 2014). For *K. rhytiphora* at Coffin Bay, data from 2009 were excluded because of sampling methodology changes between 2009 and 2011. As above for Streaky Bay, the November 2013 survey data were ignored and the February 2014 data were used.

# 3. RESULTS

## 3.1 Fishery Statistics

The total catch over the past five seasons has been stable at ~50 t, reflecting the annual TACC. Since 2010/11, the relative proportions of *K. scalarina* and *K. rhytiphora* in the catch from Coffin Bay have varied among years with, respectively, a general reduction and increase in the relative proportions of these two species. However, as a high proportion of the catch is recorded as ‘mud cockle’ (e.g. 37.5% in 2014/15) rather than by species, the species composition of the catch remains poorly understood.

For catches from Coffin Bay where the species of mud cockle was also reported, the proportional contribution by each species to the catch did not correspond with results from the fishery independent surveys (Figure 2). For example in the 2010/11 and 2011/12 fishing seasons, ~30% of the reported catch consisted of *K. scalarina,* while the harvestable biomass contribution from this species was estimated at ~10%. Since 2012/13, the proportion of *K. scalarina* in the harvestable biomass has exceeded its proportion on the catch. The opposite trend was evident for *K. rhytiphora*.

The total catches from the West Coast since 2010/11 have been relatively stable at approximately 20 $t.yr^{-1}$, reflecting the TACC. The spatial distribution of catch among the three bays comprising the West Coast has varied among years, particularly between Venus Bay and Streaky Bay. For Smoky Bay, catches have been consistently low (range: 0% to 14% of West Coast catch). The distribution of catches was poorly correlated with the levels of harvestable biomass among the three bays (Figure 3.) Notably, harvests at Smoky Bay have been much lower than the percentage contribution to the harvestable biomass from this area, with the reverse trend evident for Streaky Bay and Venus Bay.

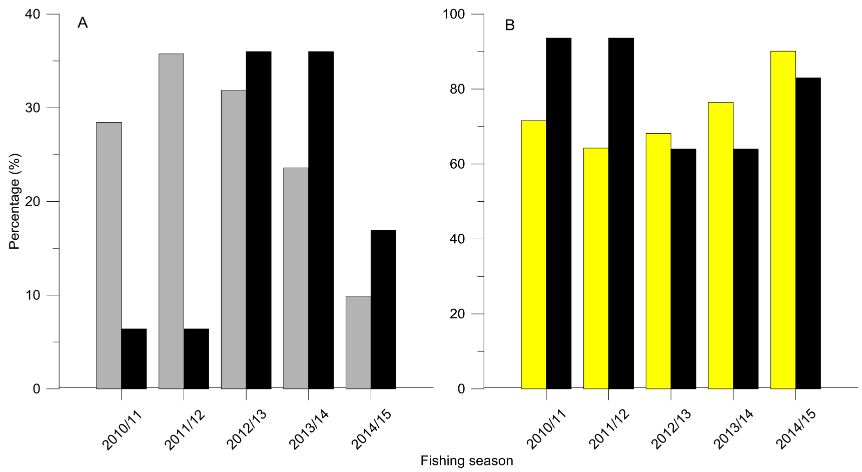


**Figure 2.** Percentage (%) of catch comprising *K. scalarina* (A; grey bars) and *K. rhytiphora* (B; yellow bars) and percentage of harvestable biomass (black bars) from previous biomass assessments from 2010/11 to 2014/15 fishing seasons in Coffin Bay. Note scales on y-axes vary.

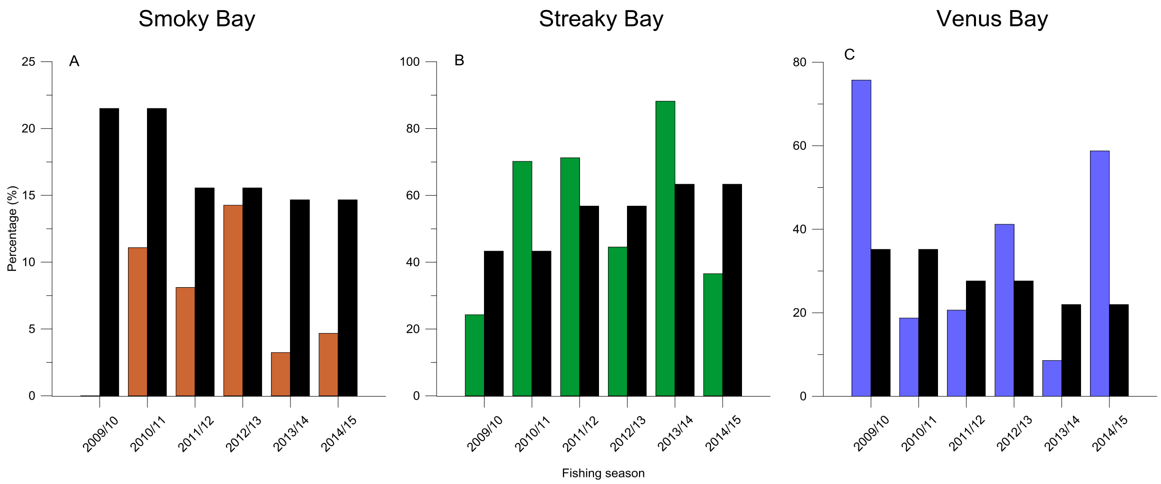


**Figure 3.** Percentage (%) of catch harvested from Smoky Bay (A; brown bars), Streaky Bay (B; green bars) and Venus Bay (C; blue bars), and percentage of harvestable biomass (black bars) from previous biomass assessments from  2009/10 to 2014/15 fishing seasons for the West Coast. Note scales on y-axes vary.

## 3.2 Coffin Bay

A total of 5,375 mud cockles were obtained from 223 transects in Coffin Bay. The dominant species was *K. scalarina* (number of cockles (n) = 3,244; ~60%), followed by *K. rhytiphora* (n=2,113; ~39%) and *K. peronii* (n=18; ~1%). Legal-sized *K. rhytiphora* (≥35 mm SL) and *K. scalarina* (≥30 mm SL) individuals were observed in eight of the twelve strata. Sublegal-sized individuals of *K. rhytiphora* and *K. scalarina* were collected from ten and nine of the twelve strata, respectively. Sublegal-sized (<35 mm SL) *K. peronii* were observed in two of the twelve strata surveyed, but no legal-sized individuals were sampled from Coffin Bay.

In 2015, the mean estimates of density for legal and sublegal-sized *K. scalarina* in 2015, from the 209 transects consistently sampled since 2009, were 8.2±1.6 and 12.0±2.3 mud cockles.$m^{-2}$, respectively (Figure 4). These were similar to 2013 values (legal-sized: 9.5±1.8; sub-legal-sized: 11.7±1.7), but significantly lower, than the mean density estimates in 2009 (legal-sized: 19.2±3.3; sublegal-sized: 23.7±4.3; $F = 5.5$, $P < 0.01$ and $F = 2.8$, $P < 0.05$, respectively). For legal-sized and sublegal-sized *K. rhytiphora*, the mean estimates of density in 2015 were 3.2±0.9 and 4.4±0.8 mud cockles.$m^{-2}$, respectively. Aside from elevated mean densities in 2013, there were no obvious temporal trends in the densities of either legal-sized or sublegal-sized *K. rhytiphora* in Coffin Bay.

The best estimate (50% probability) of total harvestable biomass for all species in Coffin Bay was 1,148.8 t. The majority of the biomass comprised *K. rhytiphora* (990.2 t, ~86%; MLL ≥35 mm SL) with a smaller contribution from *K. scalarina* (158.6 t, ~14%; MLL ≥30 mm SL). No legal-sized individuals (MLL ≥35 mm SL) of *K. peronii* were observed, therefore, the biomass estimate was 0 t (Table 2).

In 2015, legal-sized (≥ 30 mm SL) *K. scalarina* comprised 55% of the sample. This was similar to the values observed in 2011 and 2013 (Figure 5) and indicates some recruitment has occurred for this species. Length frequency data for both 2011 (22-28 mm SL) and 2015 (16-18 mm SL) indicate the presence of pre-recruits (sublegal-sized mud cockles) in the population in these years. Legal-sized (>35 mm SL) *K. rhytiphora* comprised 53% of the sample collected in 2015, which was similar to that in 2011 and 2013 (Figure 5). Length frequency data in 2011 (18-24 mm SL) and 2015 (20-25 mm SL) also support the presence of pre-recruits in the population.

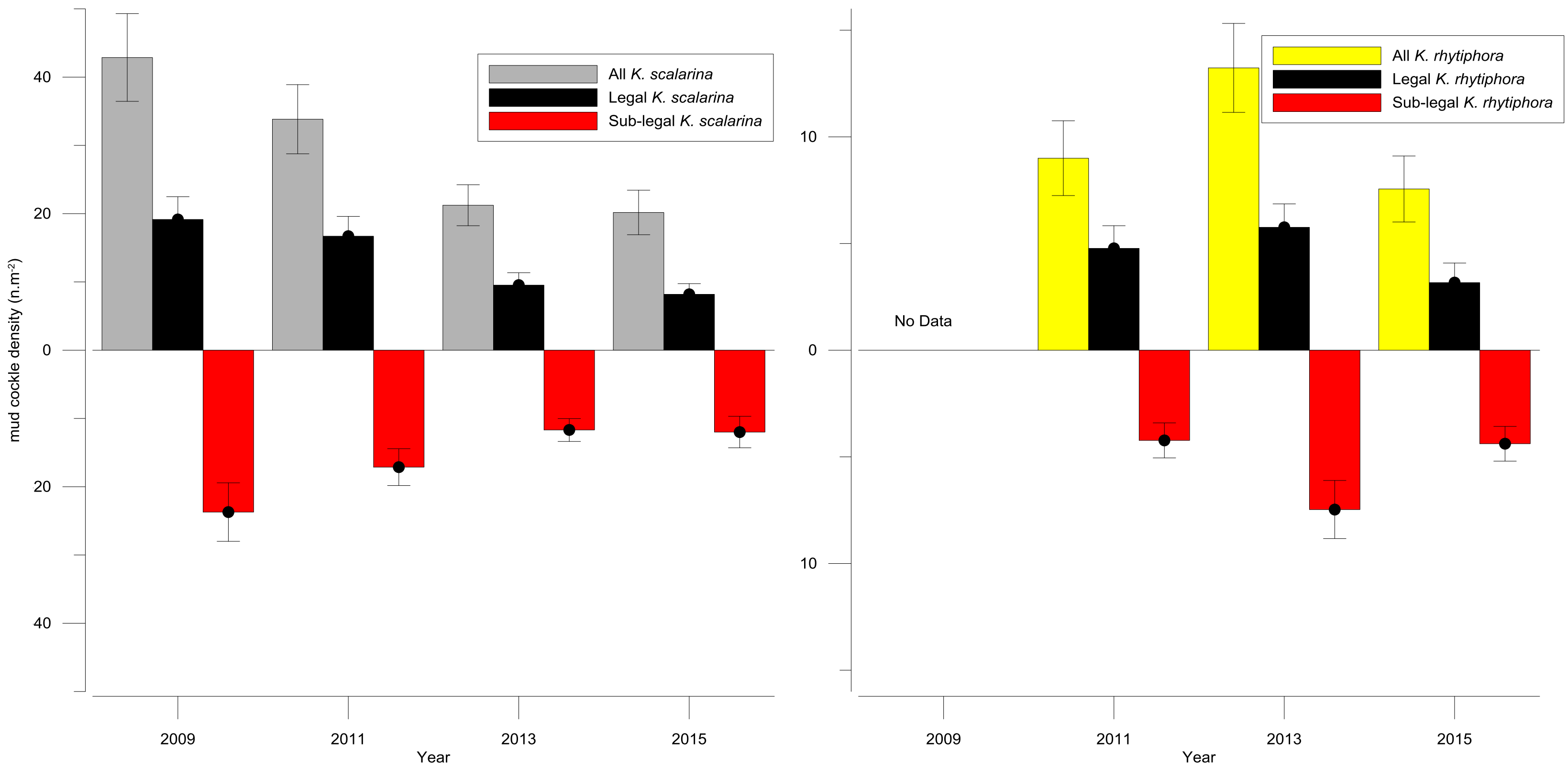


**Figure 4.** Mean ± se density estimate (mud cockles.m$^{-2}$) of all (grey bars), legal-sized (black bars) and sublegal-sized (red bars) *K. scalarina* from Coffin Bay in 2009, 2011, 2013 and 2015 and all (yellow bars), legal-sized (black bars) and sublegal-sized (red bars) *K. rhytiphora* from Coffin Bay in 2011, 2013 and 2015. Number of transects = 209 in all years. Note no data presented for 2009 for *K. rhytiphora* due to sub-sampling preventing estimation of density in that year. Note scales on y-axes vary between species.

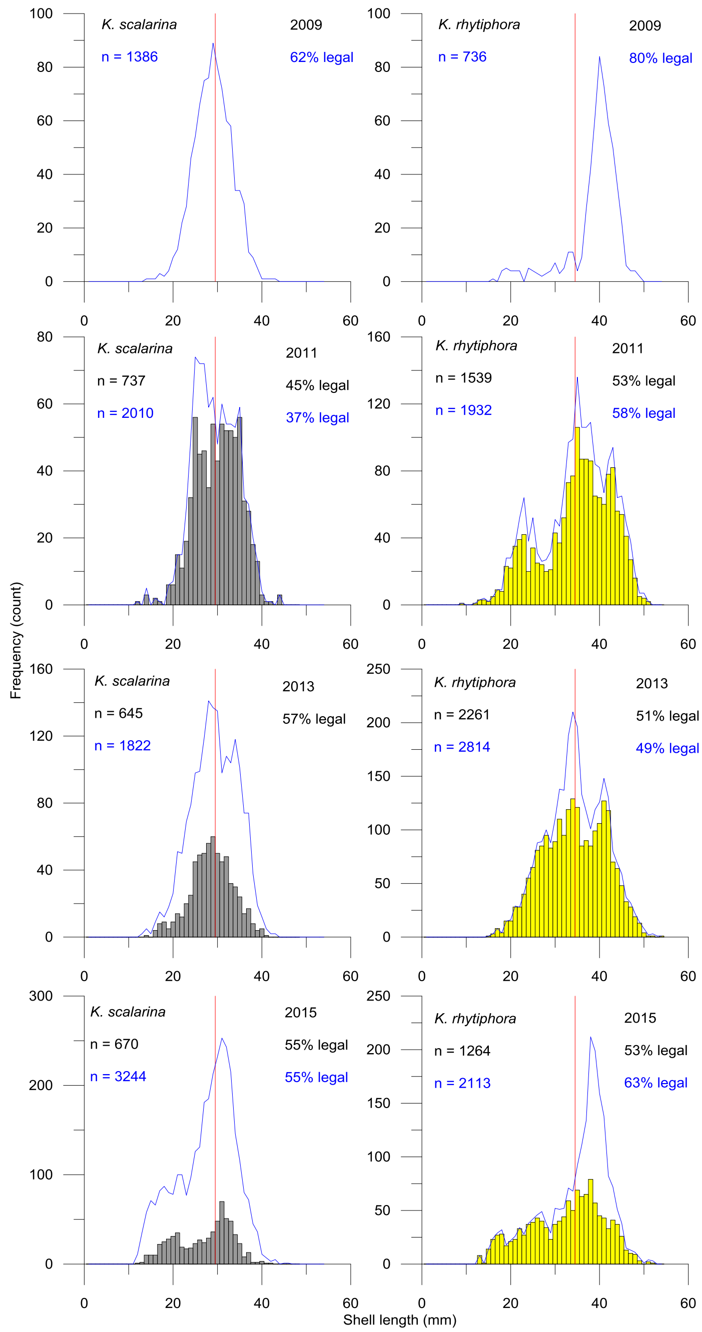


**Figure 5.** Length-frequency distributions for *K. scalarina* (grey bars) and *K. rhytiphora* (yellow bars) from Coffin Bay in 2009, 2011, 2013 and 2015. The red line indicates the current MLLs in place under a Ministerial exemption (*K. scalarina* 30 mm SL and *K. rhytiphora* 35 mm SL). Plots with blue lines represent all length data from that year, with n (number of cockles sampled) and percentage legal in blue text. Bars and black text indicate data from the consistently sampled transects (209 transects for *K. rhytiphora* and 33 transects for *K. scalarina*). Percent legal refers to the proportion of SLs ≥ MLL. Note scales on y-axes vary between species but not among years.

### 3.3 West Coast

A total of 10,307 mud cockles were collected from 193 transects. Overall, the numerically dominant species was *K. scalarina* (n=7,489; ~73%), followed by *K. peronii* (n=2,120; ~21%) and *K. rhytiphora* (n=698; ~7%). The greatest number of mud cockles was obtained from Venus Bay which yielded a total of 3,927 individuals (38.1%), followed by Streaky Bay (3,878 individuals; 37.6%) and Smoky Bay (2,502 individuals; 24.3%).

No *K. peronii* were observed at Smoky Bay (Figure 6). The estimates of mean density (61 transects, all years) of legal-sized *K. scalarina* (≥30 mm SL) in 2015 at Smoky, Streaky and Venus Bays were 11.5±6.7, 8.0±2.5 and 2.5±0.7 mud cockles.m$^{-2}$, respectively. The density estimates for legal-sized *K. scalarina* at Streaky and Venus Bays in 2015 were significantly lower than the estimates from these areas in 2009 and 2011 ($F = 3.7$, $P < 0.05$ and $F = 4.4$, $P < 0.01$, respectively). Temporal patterns in legal-sized mud cockle density were more variable for *K. rhytiphora* and *K. peronii* in all three West Coast fishing grounds and for *K. scalarina* in Smoky Bay. There were no significant differences in density among years for any of these areas-species combinations. Temporal patterns in sublegal-sized mud cockle density were also highly variable among species and bays (Figure 6). The only significant differences among years was for *K. scalarina* at Streaky Bay, where recent estimates of sublegal-sized mud cockle density were greater than those observed from 2009 and 2011 ($F = 3.5$, $P < 0.05$).

The best estimate of total harvestable biomass for all species in the West Coast was 603.5 t. The majority of the harvestable biomass was located at Streaky Bay which contributed 305.0 t (51%) to the total, whilst Venus Bay and Smoky Bay contributed 175.2 t (29%) and 123.3 t (20%), respectively (Table 2). The majority of the biomass comprised *K. scalarina* (335.7 t, 56%) with smaller contributions from *K. rhytiphora* (188.5 t, 31%) and *K. peronii* (79.3 t, 13%).

At Smoky Bay and Streaky Bay, the length frequency distribution of *K. scalarina* in 2015 was dominated by sublegal-sized individuals, suggesting strong recruitment (Figures 7 & 8). For Streaky Bay, length frequency data show a substantial proportion of the pre-recruits (~15 mm SL) observed in 2014 survived (Figure 8). For *K. rhytiphora* in Venus Bay, there was a consistent decline in the proportion of legal-sized individuals over time (Figure 9). In 2015, only 27% of the sampled population was of legal size (Figure 9). The estimates of legal-sized *K. peronii* density at Venus Bay have been similar since surveys began in 2009, however the sublegal-size density has been declining since the highest value in

2011. Evaluating temporal changes in the length frequency distributions of *K. rhytiphora* and *K. peronii* in the West Coast was impeded by small sample sizes in most years.

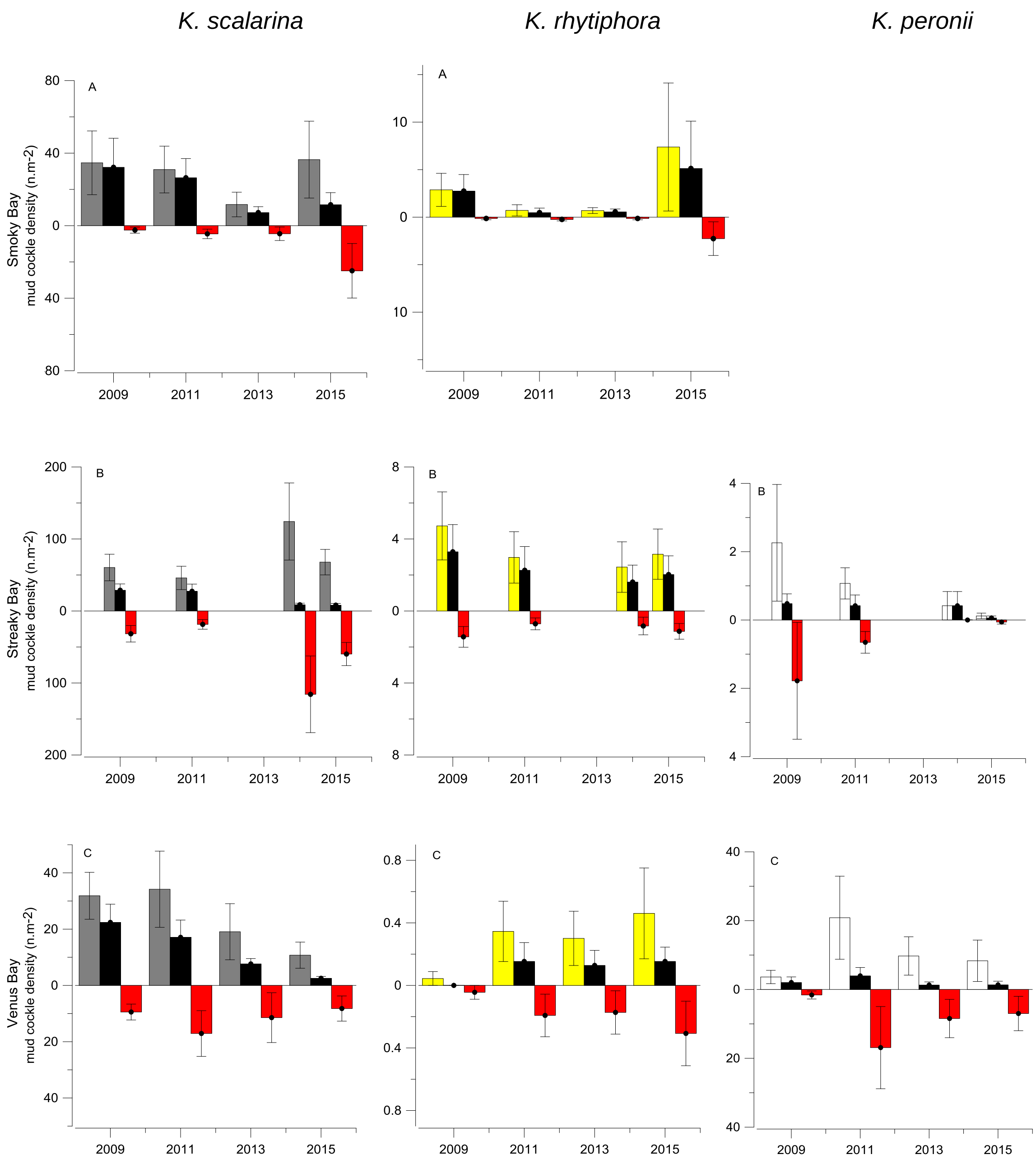


**Figure 6.** Mean ± se of density estimates (mud cockles.m$^{-2}$) of all, legal-sized (black bars) and sublegal-sized (red bars) mud cockles in the West Coast cockle fishing zone at Smoky Bay (A; n=10) and Venus Bay (C; n=31) for 2009, 2011, 2013 and 2015. For Streaky Bay (B; n=20) in 2009, 2011, 2014 and 2015. Denisty of all *K. scalarina* (grey bars), all *K. rhytiphora* (yellow bars) and all *K. peronii* (white bars). Note scales on y-axes vary between species and sites.

**Table 2.** Estimated harvestable biomass (t, whole weight; 10–90% quantiles) of *K. scalarina, K. rhytiphora and K. peronii* in Coffin Bay (A) and West Coast (B) comprised of Smoky Bay, Streaky Bay and Venus Bay between October 2015 and February 2016. Bold indicates total harvestable biomass estimates, by species, for each fishing zone.

**A Coffin Bay**

| **species** | **Probability (%) of legal biomass estimate (t)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **90%** | **80%** | **70%** | **60%** | **50%** | **40%** | **30%** | **20%** | **10%** |
| ***K. scalarina* (30 mm)** | **126.4** | **136.9** | **144.9** | **151.9** | **158.6** | **165.6** | **173.4** | **182.5** | **195.6** |
| ***K. rhytiphora* (35 mm)** | **603.4** | **730.8** | **825.3** | **909.5** | **990.2** | **1072.5** | **1163.8** | **1270.0** | **1427.8** |
| ***K. peronii* (35 mm)** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** |
| **Total** | **729.8** | **867.7** | **970.2** | **1061.3** | **1148.8** | **1238.1** | **1337.2** | **1452.5** | **1623.4** |

**B West Coast** **MLL 30 mm SL**

| **species** | **Probability (%) of legal biomass estimate (t)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **90%** | **80%** | **70%** | **60%** | **50%** | **40%** | **30%** | **20%** | **10%** |
| ***K. scalarina*** | **250.2** | **278.2** | **299.4** | **317.9** | **335.6** | **353.8** | **373.0** | **396.4** | **429.2** |
| ***K. rhytiphora*** | **119.6** | **141.8** | **159.1** | **174.0** | **188.5** | **202.9** | **218.7** | **237.4** | **263.3** |
| ***K. peronii*** | **48.4** | **58.1** | **65.8** | **72.4** | **79.3** | **85.3** | **93.2** | **102.3** | **115.2** |
| **Total** | **418.2** | **478.1** | **524.3** | **564.3** | **603.5** | **642.0** | **685.0** | **736.0** | **807.7** |

Smoky Bay MLL 30 mm SL

| species | Probability (%) of legal biomass estimate (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
| *K. scalarina* | 55.1 | 63.1 | 69.6 | 75.2 | 80.4 | 85.9 | 91.6 | 98.5 | 108.3 |
| *K. rhytiphora* | 26.2 | 31.6 | 35.7 | 39.3 | 42.9 | 46.5 | 50.6 | 55.3 | 61.8 |
| *K. peronii* | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Streaky Bay MLL 30 mm SL

| species | Probability (%) of legal biomass estimate (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
| *K. scalarina* | 125.0 | 140.2 | 151.6 | 161.6 | 171.1 | 180.8 | 191.2 | 203.9 | 221.6 |
| *K. rhytiphora* | 82.0 | 97.3 | 109.4 | 119.7 | 129.7 | 139.5 | 150.3 | 163.0 | 180.7 |
| *K. peronii* | 0.1 | 1.3 | 2.5 | 3.1 | 4.2 | 4.3 | 5.6 | 6.9 | 8.5 |

Venus Bay MLL 30 mm SL

| species | Probability (%) of legal biomass estimate (t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
| *K. scalarina* | 70.0 | 74.8 | 78.2 | 81.2 | 84.1 | 87.0 | 90.2 | 94.0 | 99.3 |
| *K. rhytiphora* | 11.4 | 12.9 | 14.0 | 15.0 | 15.9 | 16.9 | 17.9 | 19.1 | 20.9 |
| *K. peronii* | 48.3 | 56.8 | 63.3 | 69.3 | 75.1 | 81.0 | 87.7 | 95.4 | 106.7 |

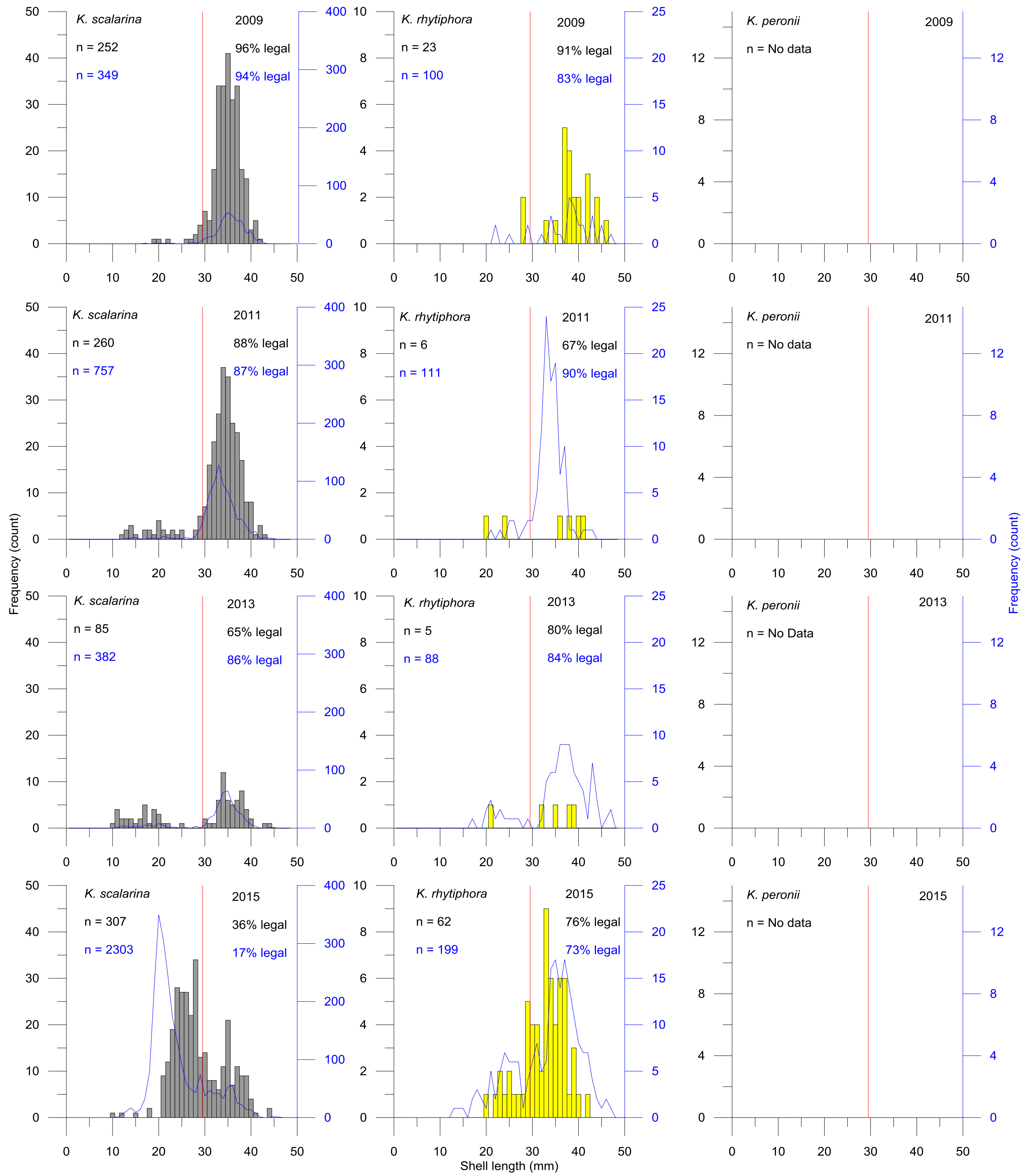


**Figure 7.** Length-frequency distributions for *K. scalarina*, *K. rhytiphora* and *K. peronii* obtained from Smoky Bay in 2009, 2011, 2013 and 2015. The red line indicates the MLL of 30 mm SL. Plots with blue lines (right-hand-side y axis) represent all length data from that year, with n (number of cockles sampled) and percentage legal in blue text. Bars (left-hand-side y axis) and black text indicate data from the consistently sampled transects (10 transects). Percent legal refers to the proportion of SLs ≥ MLL. Note scales on y-axes vary between species but not among years.

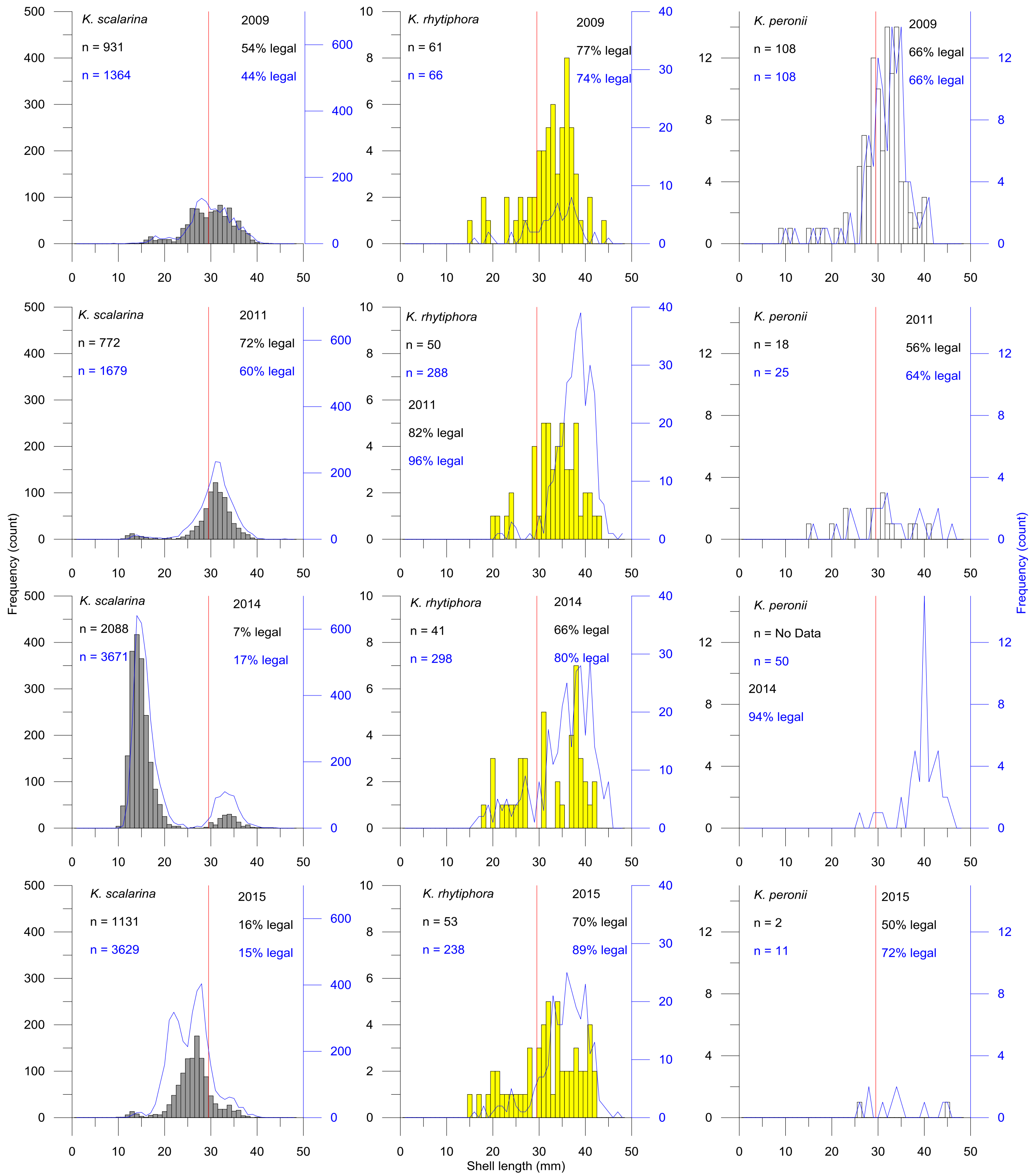


**Figure 8.** Length-frequency distributions for *K. scalarina*, *K. rhytiphora* and *K. peronii* obtained from Streaky Bay in 2009, 2011, 2014 and 2015. The red line indicates the MLL of 30 mm SL. Plots with blue lines (right-hand-side y axis) represent all length data from that year, with n (number of cockles sampled) and percentage legal in blue text. Bars (left-hand-side y axis) and black text indicate data from the consistently sampled transects (20 transects). Percent legal refers to the proportion of SLs ≥ MLL. Note scales on y-axes vary between species but not among years.

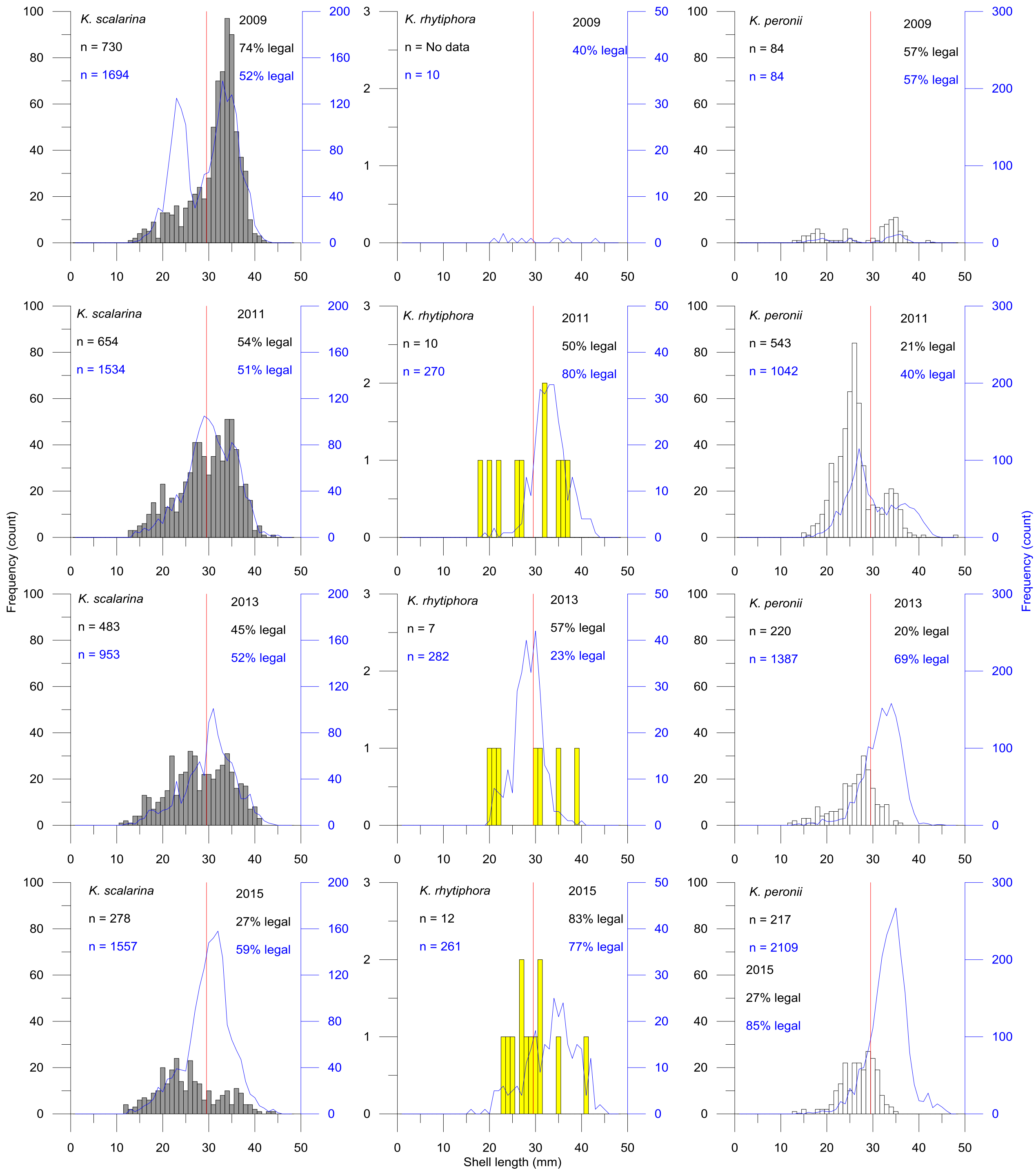


**Figure 9.** Length-frequency distributions for *K. scalarina*, *K. rhytiphora* and *K. peronii* obtained from Venus Bay in 2009, 2011, 2013 and 2015. The red line indicates the MLL of 30 mm SL. Plots with blue lines (right-hand-side y axis) represent all length data from that year, with n (number of cockles sampled) and percentage legal in blue text. Bars (left-hand-side y axis) and black text indicate data from the consistently sampled transects (31 transects). Percent legal refers to the proportion of SLs ≥ MLL. Note scales on y-axes vary between species but not among years.

## DISCUSSION

### 4.1 Status of the South Australian Mud Cockle Fishery

Optimising harvests in multi-species, spatially-structured fisheries is challenging and typically requires information on the composition, distribution, abundance, biomass and biology of the component species (Mangel *et al.* 1996; Haddon *et al.* 2006). The complexities in developing appropriate harvest strategies for the South Australian Mud Cockle Fishery was exhibited in the large reductions in TACCs first introduced in 2008/09 based on available catch history data, then modified following fishery independent surveys introduced in 2009 that provided the first estimates of harvestable biomass (Gorman *et al.* 2010; 2011).

The information presented in this report, which is the fourth to document the results of fishery independent surveys across the spatial extent of the fishery, remains the most suitable for informing management decisions relating to TACCs and MLLs (Mayfield *et al.* 2008; McGarvey *et al.* 2008; Gorman *et al.* 2010; 2011; Dent *et al.* 2012; 2014). The estimates of harvestable biomass and measures of size at maturity ($SAM_{50}$) obtained in these studies provide the most robust information for setting TACCs (Mayfield *et al.* 2008, 2009; McGarvey *et al.* 2008) because (1) the precision of the biomass estimates was optimised by targeting survey effort into productive fishing grounds identified by commercial fishers, with less sampling effort in less productive areas (Ault *et al.* 1999); and (2) measures of $SAM_{50}$ have been obtained from large sample sizes (>3,000 and >700 mud cockles) across Coffin Bay and the West Coast, respectively (Gorman *et al.* 2010; Dent *et al.* 2012). When applying this information for determining management arrangements for the fishery, consideration also needs to be made of the risk of depletion of populations in these fisheries (Ripley and Caswell 2006). Biomass declines have been shown to occur in cockle fisheries as a result of fluctuating abundance due to episodic recruitment (Warner and Chesson 1985; Sakurai *et al.* 1998; Ripley and Caswell 2006). For example, in Coffin Bay, modes of small individuals in size structures that indicated recruitment of *K. scalarina* in 2011 and 2015 were not observed in 2009 or 2013.

There is, however, some uncertainty in the assessment of harvestable biomass, population structure and stock status. First, transects are sampled by commercial fishers using cockle rakes of varying design, in addition to assumed differences in operator efficiency. Differences in rake-width among fishers are accounted for by standardising density results to an area of one square metre, but potential differences in operator efficiency are ignored. Second, the length-frequency distributions do not account for “stunting”. This is where animals do not achieve the average maximum size for that species, resulting in many individuals failing to reach the MLL, as has been observed for abalone (Saunders and Mayfield 2008). While this makes interpreting future recruitment levels difficult because ‘stunted’ and sublegal-sized cockles are indistinguishable, these ‘stunted’ cockles likely contribute to the spawning biomass. Third, the current Management Plan (PIRSA 2013) does not identify performance indicators or limit reference points below which the stock would be classified as ‘recruitment overfished’ under the national stock status framework (Flood *et al.* 2014). Future selection of appropriate performance indicators and reference points should consider estimates of density and biomass across species and fishing grounds. The absence of a definition for ‘recruitment overfished’ means this assessment uses a ‘weight-of-evidence’ approach to determine stock status.

The MLLs and TACCs are the primary tools used to manage exploitation of mud cockles in South Australia. The TACC is determined as a fraction of the harvestable biomass estimate (at the 80% quantile), up to a maximum of 7.5% (PIRSA 2013). Surveys are currently undertaken biennially, requiring annual TACC review using fisher information. The biennial surveys undertaken from 2009 to 2015 will be replaced with triennial surveys starting in 2016/17; approximately one third of Coffin Bay and the West Coast will be surveyed each year. This will result in additional uncertainty in the harvestable biomass and recruitment levels – known to be episodic – due to the increased time period between surveys.

The annual TACCs for the Mud Cockle Fishery have been determined from an aggregated estimate of legal-sized biomass for each species across all fishing grounds. Recent differences in the temporal trends in densities among species and fishing grounds and differing exploitation rates across these may compromise future sustainability of the fishery. Management arrangements that match harvest levels to species and/or area-specific productivity has the potential to mitigate localised high and/or unsustainable exploitation rates on species, fishing grounds or a combination of these.

### *4.1.1 Coffin Bay*

In the 2014/15 and 2015/16 fishing seasons, the TACC for Coffin Bay was 46.0 t and 50.0 t respectively, which represented a 5.7% and 6.2% harvest fraction, respectively, from the 80% quantile of the biomass estimate in 2013. Thus, recent total catches from Coffin Bay have been below the maximum harvest fraction of 7.5% (80% quantile), prescribed in the Management Plan (PIRSA 2013). Under the current MLLs, application of a 7.5% harvest fraction would yield a TACC of 65.1 t (10.3 t of *K. scalarina* ≥ 30 mm SL; 54.8 t of *K. rhytiphora* ≥ 35 mm SL). Maintaining the

TACC at 50.0 t would reflect an exploitation rate of 5.8%. Consequently, the TACC could be increased whilst remaining within the rules of the harvest strategy.

At Coffin Bay, changes in the estimates of harvestable biomass among years also reflect changes in the survey design, as well as changes in species-specific MLLs and mud cockle abundance. The survey design changes reflect refinement to areas of commercial importance. Notably, in 2015, a commercially important area for *K. rhytiphora* was added to the survey area and the harvestable biomass for this species estimated for a reduced MLL (35 mm SL vs 38 mm SL historically). To separate changes in harvestable biomass estimates among years from differences in stock abundance, density estimates of legal-sized and sub-legal-sized *K. scalarina* and *K. rhytiphora* were determined from those sampling locations surveyed in all years and standardised to the current MLLs. These data show that the density of legal-sized and sub-legal-sized *K. scalarina* in 2013 and 2015 were significantly lower (by approximately 50%) than the estimates from the first two surveys (*i.e.* 2009 and 2011). Although the density of *K. scalarina* has not declined between 2013 and 2015, the lower density estimates from 2013 suggest a conservative approach to TACC setting and regular monitoring in future years are warranted. In contrast, a consistent temporal trend in legal-sized abundance was not observed for *K. rhytiphora*. For both species, the length-frequency data show that a high proportion of the cockles sampled in 2015 were below the MLL and it is anticipated these will recruit into the fishable stock over the next 1-2 years.

In 2015, no legal-sized *K. peronii* were observed. Consequently, the contribution of this species to the total estimate of harvestable biomass was zero. The harvestable biomass in 2015 was dominated by *K. rhytiphora* (86%), with only a small contribution from *K. scalarina* (14%). This reflects the localised, higher densities of the larger *K. rhytiphora* compared with the more broadly distributed, less dense and smaller *K. scalarina*.

Historically, the relationships between the proportional contribution of each species to the harvestable biomass and catch have been inconsistent. While these differences reflect the higher market demand for *K. scalarina* during this period, they highlight the difficulty of optimising exploitation rates across species when a ‘global’ TACC is set on the combined harvestable biomass of all species. Although in more recent years at Coffin Bay there has been a closer relationship between the proportional contributions of each species to the harvestable biomass compared to the catch, these differences highlight the need to consider directly linking exploitation rates to species-specific productivity because productivity, and responses to being fished, inherently vary among species.

Despite the dynamics identified above, the exploitation rate in Coffin Bay is below the maximum of 7.5%, MLLs are set at a size that enable the majority of mud cockles to reproduce prior to being available for harvest and there is evidence of recent recruitment for both species. Given there is no evidence to indicate that the (1) stock is recruitment overfished; or (2) current fishing pressure is likely to result in the stock becoming recruitment overfished, the stock status of mud cockles in Coffin Bay is classified as '**sustainable**'.

### *4.1.2 West Coast*

The West Coast comprises three areas – Smoky Bay, Streaky Bay and Venus Bay. In 2014/15 and 2015/16, the TACC for the West Coast was set at 16.0 t. This reflected an exploitation rate (harvest fraction) of 3.2% at the 80% quantile of the 2013 biomass estimate. This relatively low TACC (and low harvest fraction) was set predominantly because commercial fishers identified that there was inadequate fishing capacity to harvest a larger TACC (Gorman *et al.* 2011), such as that permitted under the Management Plan's maximum 7.5% harvest fraction (*i.e.* 37.6 t). For 2016/17, the maximum available TACC permitted for the West Coast by the harvest strategy in the Management Plan is 35.9 t. If the TACC in 2016/17 was set at the same level as in 2015/16 (*i.e.* 16.0 t) this would reflect a harvest fraction of 3.3% (at 80% quantile).

On the West Coast, similar to Coffin Bay, changes in the estimates of harvestable biomass among years are affected by differences in survey design and abundance – the survey design changes again reflect refinement to areas of commercial importance. Notably, additional survey areas have potentially contributed to substantial increases in the median estimates of legal-size biomass at Venus Bay (32.0 t increase) and Smoky Bay (28.0 t increase) between 2013 (Dent *et al.* 2014) and 2015 (Table 2), contrasting with the 107.0 t (34%) decrease in the median estimate of legal biomass of *K. scalarina* at Streaky Bay over the same time period.

As with Coffin Bay, mud cockle density estimates were determined from only those transects surveyed in all years, to more robustly assess temporal changes in harvestable biomass estimates by eliminating the potential bias caused by changes in the areas included in survey design. These data show that the abundance of legal-sized *K. scalarina* in Streaky Bay and Venus Bay in 2015 were significantly lower when compared with 2009 and 2011, but the densities of sublegal-sized *K. scalarina* in recent years in Streaky Bay were substantially (approximately double) and significantly higher in 2013 and 2015 when compared with older density estimates. Although these juveniles are likely to recruit into the fishable stock over the next 1-2 years, the spatially-consistent declines in the density of legal-sized *K. scalarina* (*i.e.* at Streaky Bay, Venus Bay and Coffin Bay) reinforce the need for a conservative approach to TACC setting and regular monitoring in future years. Temporal patterns in legal-sized mud cockle density were more variable for *K. rhytiphora* and *K. peronii* in all three West Coast fishing grounds and for *K. scalarina* in Smoky Bay, with no significant differences among years identified.

Length-frequency distributions for Smoky Bay and Streaky Bay indicate a large cohort of individuals just below the MLL at the time of survey, which will likely recruit to the harvestable biomass in the next few years. The length frequency distributions between 2014 and 2015 for *K. scalarina* at Streaky Bay also provide some insight into the growth rate of juveniles of this species. Between February 2014 and November 2015 (20 months or 1.7 years), the dominant bin class (14 mm SL) was replaced by the 27 mm SL size class, suggesting a growth rate of ~7.5 $mm.y^{-1}$. It should be noted that this period includes two winters but only one summer so it is possible that this is an underestimate of growth, particularly if growth occurs seasonally during the warmer months.

The median estimate of total harvestable biomass in 2015 was dominated by *K. scalarina* (56%) and *K. rhytiphora* (31%), with only a small contribution from *K. peronii* (13%). Most of the biomass was in Streaky Bay (51%), followed by Venus Bay (29%) and Smoky Bay (20%).

Relationships between the proportional contribution of each bay to the harvestable biomass and catch have been historically inconsistent. For example, 80% of the catch in 2009/10 was harvested from Venus Bay, despite this area having about 38% of the total harvestable biomass. Similarly, in 2010/11, 2011/12 and 2013/14, the same patterns were observed for Streaky Bay. In contrast, Smoky Bay was relatively lightly fished in most years as the proportion of total catches reported as being from this area was substantially lower than the proportion of the harvestable biomass (e.g. 5% of catch vs 18% of harvestable biomass in 2012/13). These differences highlight the (1) difficulty of achieving consistent, optimal exploitation rates across fishing grounds when there is a ‘global’ TACC based on their combined harvestable biomass; and (2) opportunity for high (and highly variable) exploitation rates among fishing grounds, species and years. As the mud cockle populations in each of the three West Coast cockle fishing grounds likely comprise separate stocks, incorporation of this spatial structure into management of the fishery should be considered (Taylor and Dizon 1999; Lorenzen *et al.* 2010). While one way to achieve this would be to harvesting catches from areas in approximate proportion to the biomass available for harvest, this would likely require a greater level of spatial management for this fishery, that may be impeded because of a paucity of data and the necessary increases in research and management costs.

Overall, the exploitation rate in the West Coast is below the maximum of 7.5%, MLLs are in place that enable the majority of mud cockles to reproduce prior to being available for harvest and there is some evidence of recent recruitment across the fishery. Given there is no evidence to indicate that (1) the stock is recruitment overfished; or (2) current fishing pressure is likely to result in the stock becoming recruitment overfished, the stock status of mud cockles in the West Coast is classified as '**sustainable**'.

### 4.2 Future research needs

The most important component of future research is to standardise the survey sampling design for the West Coast and Coffin Bay for future surveys. This is required because, to inform sustainable management of the stock, it is essential to develop a robust time-series of harvestable biomass estimates that are unaffected by changes in survey design. If this was achieved, then changes in harvestable biomass would accurately reflect changes in population abundance, rather than a combination of changes in both abundance and survey design. This is particularly important for a species that has highly variable recruitment and is vulnerable to environmental mortality events.

Standardising the survey design requires several considerations. The first is to ensure that the survey design excludes areas that are unsuitable for commercial fishing, thereby preventing overestimation of the harvestable biomass. Areas (1) with low (*i.e.* commercially unviable) mud cockle density, (2) that are inaccessible (e.g. within private oyster leases), and/or (3) contain a high proportion of 'stunted mud cockles' requiring extensive catch measurement to ensure compliance with MLLs, should be considered for exclusion. Secondly, identification of a standard cockle rake for data collection would eliminate the need to correct for variable rake widths among operators, standardise gear efficiency and ensure that the population structure data are collected in a more consistent manner. Whilst this would eliminate several current aspects of uncertainty, it would not standardise across the capabilities of the commercial fishers undertaking the surveys. This could be achieved in future years using the method already established for pipi (Ferguson et al. 2015) where catch weights for each fisher are compared statistically and an efficiency correction applied where necessary.

Given the documented spatial variation in the biology of molluscs (Cranfield and Michael 2001) and other benthic marine invertebrates – at both local and regional scales as is the case for abalone populations (Saunders and Mayfield 2008), the lower estimate of $SAM_{50}$ obtained for *K. scalarina* in the West Coast (23.2 mm SL; Dent *et al.* 2012), whilst similar to previous estimates

(Fowler and Eglinton 2002), was smaller than that obtained from nearby Coffin Bay (26.1 mm SL; Gorman *et al.* 2011). However, the large increase in the proportion of *K. rhytiphora* comprising the harvestable biomass in the West Coast between surveys, and the lack of similar spatially-resolved data, suggests the need for more robust estimates of $SAM_{50}$ for this species.

Determining the proportion of each species in the catch is difficult because reporting of catch by species is voluntary. Few catch records contain this information for Coffin Bay (Figure 2) and there is almost no reporting by species from the West Coast. Mandatory reporting of catch, by species, in both cockle fishing zones would provide useful information to inform management aimed at protection of the harvestable/spawning biomass for each of the 10 stocks (three species by four bays with *K. peronii* absent from two bays).

Studies are underway to evaluate the potential for the estimate of biomass provided in these reports to be based on length, rather than weight. Currently, samples are split into sublegal and legal-sized components and then counted and weighed. A relationship between SL and weight could be used to estimate the weight of each cockle based on its shell length. This approach is similar to that used in the stock assessment of abalone in South Australia (Stobart *et al.* 2015) and provides several advantages including increased efficiency in sample processing and to enable more effective comparisons between years.

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