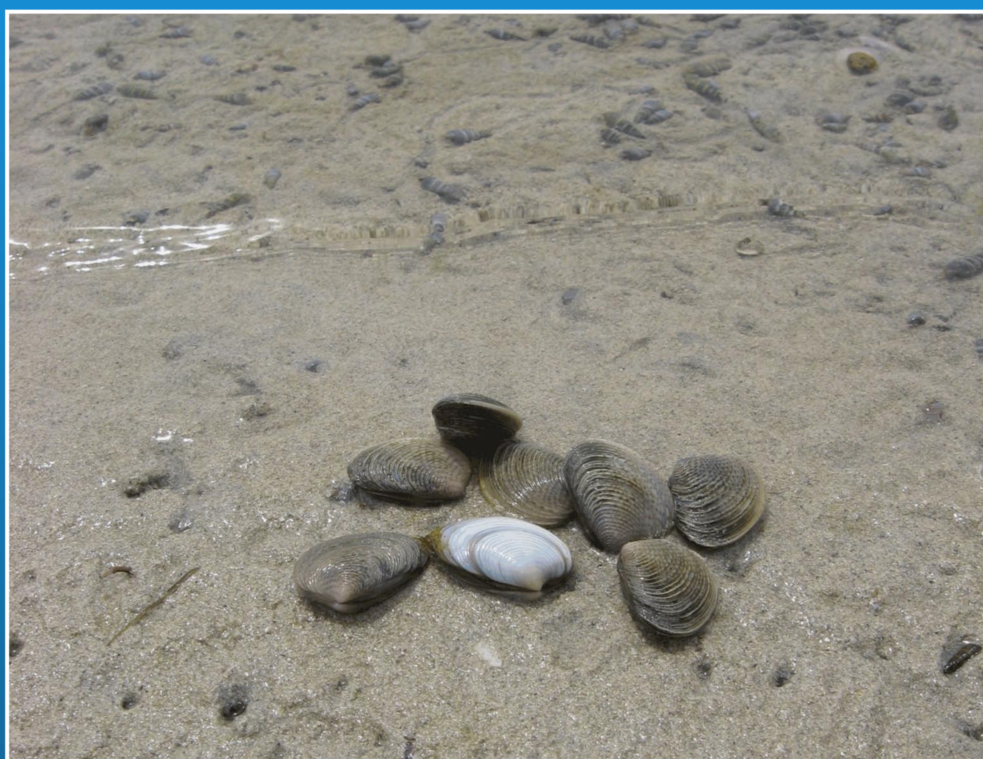
Wild Fisheries

Distribution, harvestable biomass and fisheries biology of *Katelysia spp.* in the South Australian commercial mud cockle fishery



SARDI Aquatic Sciences Publication No F2010/000263-1
SARDI Research Report Series No 442

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Government of South Australia

May 2010

Report for PIRSA Fisheries

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This Publication may be cited as:
Gorman, D., Mayfield, S., Burch, P. and Ward, T.M (2010). Distribution, harvestable biomass and fisheries biology of *Katelysia* spp. in the South Australian commercial mud cockle fishery. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000263-1. SARDI Research Report Series No. 442. 36p.

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Printed in Adelaide: May 2010

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Date: 5 May 2010

Distribution: SAASC Library, University of Adelaide Library

Circulation: Public Domain

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ACKNOWLEDGMENTS

Funds for this research were provided by PIRSA, obtained through licence fees. SARDI Aquatic Sciences provided substantial in-kind support. The willingness of commercial cockle fishers from all zones to identify productive fishing grounds is gratefully acknowledged. Cockle biomass surveys were conducted by Mark Hocking, Kevin O'Brien, David (Jumbo) Backen, David Sherry, Reece Gynell and David Corston. We thank Lianos Triantafillos (PIRSA) and Nicholas Payne and Damian Mathews (SARDI Aquatic Sciences) for assistance with fieldwork. Collections for size at first maturity analysis were done by Kevin O'Brien, David (Jumbo) Backen and David Sherry. We are thankful for the support of Paul Tretheway (PIRSA Spatial Information Services) for GIS spatial analysis and mapping. Ian Carlson created Figure 1. This report was formally reviewed by Dr Shane Roberts and Greg Ferguson (SARDI Aquatic Sciences) and Dr Craig Noell (PIRSA Fisheries). It was formally approved for release by Dr Stephen Madigan, Key Program Manager, MISA, SARDI Aquatic Sciences.

EXECUTIVE SUMMARY

1. This report provides information on the distribution, abundance, harvestable biomass and fisheries biology of mud cockles (*Katelysia* spp.) in the South Australian fishery. The information will be used to evaluate the suitability of current management arrangements, especially total allowable commercial catches (TACCs) and size limits.
2. Rapid increases in catch led to implementation of a quota-management system across the three commercial fishing zones in October 2008. The TACCs in the West Coast, Coffin Bay and Port River in 2009/10 are 15 t, 56 t and 22.6 t, respectively. The minimum legal size (MLS) in the West Coast and Port River is 30 mm shell length (SL). In Coffin Bay the MLS is 38 mm SL.
3. Setting a TACC in each fishing zone is complicated by differences in the distribution, relative biomass and size-at-first-maturity (L_{50}) of each of the three species: *K. scalarina* ('greys'), *K. peroni* ('peroni') and *K. rhytiphora* ('yellows').
4. Estimates of L_{50} for *K. scalarina* and *K. rhytiphora* were obtained from Coffin Bay only and were 26.1 and 31.1 mm shell length (SL), respectively. L_{50} may vary among fishing zones.
5. In the Port River, the median estimates of harvestable biomass were 124 t for *K. peroni*, 13 t for *K. rhytiphora* and 106 t for *K. scalarina*. Collectively, these represent a median harvestable biomass of 243 t. The TACC for the Port River is 22.6 t which was determined using the "80/10" rule (i.e. 10% harvest fraction from the 80% confidence limit of biomass). Assuming the same L_{50} value as in Coffin Bay, the 30 mm MLS is relatively conservative for *K. scalarina* (i.e. above L_{50}) which comprises ~44% of the fishable biomass. However, L_{50} is poorly understood for *K. peroni* which comprises over 50% of the biomass. Therefore, more robust estimates of this measure are required.
6. In Coffin Bay, median estimates of harvestable biomass were 657 t and 45 t for *K. rhytiphora* and *K. scalarina*, respectively. In combination, these provide a median harvestable biomass of 702 t. Application of the "80/10" rule would result in a TACC of 55 t, which is similar to the current TACC of 56 t. The MLS (38 mm) is well above L_{50} for both *K. scalarina* and *K. rhytiphora*. As only 5% of *K. scalarina* exceeded the MLS and *K. peroni* are rare, the Coffin Bay fishery is focused almost entirely on *K. rhytiphora*. This suggests the size limits in this fishing zone need to be reviewed.
7. Estimates of the harvestable biomass of mud cockles from the West Coast were 28 t for *K. peroni*, 54 t for *K. rhytiphora* and 806 t for *K. scalarina*, which collectively provide a median harvestable biomass of 888 t. As the fishable biomass was dominated by *K. scalarina* (>90%), the MLS of 30 mm SL is relatively conservative. Application of the "80/10" rule would result in a TACC of ~64 t. Consequently, the current TACC of 15 t represents a conservative harvest strategy (i.e. "80/2.5") in comparison to the Port River and Coffin Bay.
8. The low abundance of small mud cockles confirms that recruitment occurs periodically and provided no evidence of recent recruitment events. In combination with recent, spatially-consistent reductions in CPUE, this suggests existing adult stocks need to be managed using conservative harvest strategies. Surveys should also be undertaken regularly (e.g. biennially) to measure harvestable biomass and identify recruitment events.

1. INTRODUCTION

The genus *Katelysia* (Family Veneridae), commonly known as mud cockles, is a group of commercially important bivalves that often represents a major faunal component of shallow estuarine and marine embayments (Roberts 1984). The three Australian species are *K. peroni* (Lamarck, 1818), *K. rhytiphora* (Lamy, 1835) and *K. scalarina* (Lamarck, 1818). All are broadly distributed around Australia's temperate coastline from Augusta, Western Australia to Port Jackson, New South Wales (Roberts 1984), where they commonly co-exist.

In South Australia, harvesting of mud cockles began in the early 1960's. Initially, they were harvested for use as bait or berley when fishing for King George Whiting, with most of the catch obtained from Section Bank and Kangaroo Island. Historical records suggest fishers first supplied the human consumption market in Melbourne in 1986. Despite a recognition that this market was expanding, the fishery remained lightly exploited until 1995/96 when the State-wide annual catch first exceeded 50 t. Catches increased rapidly thereafter, peaking at 375 t in 2005/06. Most of the catch was obtained from Section Bank and Coffin Bay. The rapid increases in catch led to implementation of a quota management system in the three fishing zones (Port River, Coffin Bay and West Coast; Figure 1) in October 2008.

Initial (2008/09) total allowable commercial catches (TACCs) were based primarily on catch history. The TACCs for 2008/09 were 25 t in the West Coast, 70 t in Coffin Bay and 100 t in the Port River. The combined TACCs of 195 t had a value of approximately AU$1.3M (Cantin et al. 2008; Knight and Tsolos 2010). Advice from fishers (West Coast and Coffin Bay) and preliminary survey estimates of biomass (Port River) led to TACCs in all three Zones being reduced substantially for 2009/10. TACCs for the West Coast, Coffin Bay and Port River fishing Zones in 2009/10 were 15 t, 56 t and 22.6 t, respectively.

The objectives of this study were to (1) estimate the biomass of mud cockles in each commercial fishing zone, and (2) determine the size-at-first-maturity (L_{50}) for *K. rhytiphora* and *K. scalarina* in Coffin Bay. This information will inform discussions regarding the suitability of the current management arrangements for the fishery, particularly the TACCs and size limits.

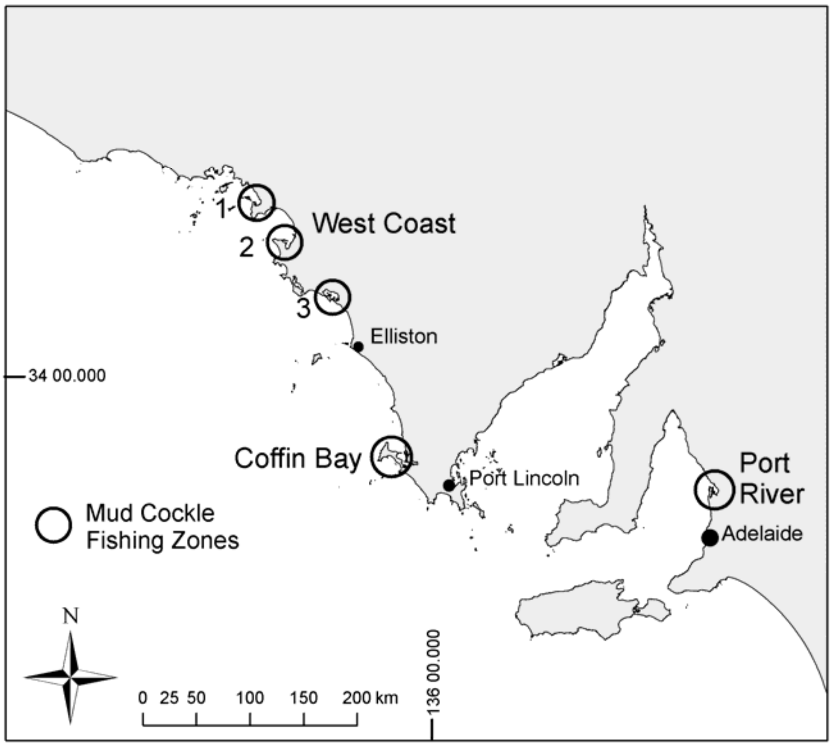

Figure 1. Map showing location of the three commercial mud cockle fishing zones in South Australia: Port River, Coffin Bay and the West Coast. The West Coast zone comprises Smoky Bay (1), Streaky Bay (2) and Venus Bay (3).

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2. METHODS

This study required the integration of data from three sources. These were (1) commercial catch and effort data, (2) fishery-independent surveys in the three commercial fishing zones, and (3) estimates of L_{50} for *K. rhytiphora* and *K. scalarina* in Coffin Bay.

2.1 Fishery statistics

Commercial catch and effort data for the period 1 July 1983 to 30 June 2009 were obtained from the commercial Marine Scalefish catch and effort database, which contains data from the catch returns that are submitted on a monthly basis by the commercial fishers. Data were aggregated by financial year at two spatial scales. These were (1) the entire commercial fishery, and (2) each of the three commercial fishing zones separately (i.e. Port River, Coffin Bay and West Coast). Catch-per-unit-effort (CPUE) was determined as total catch (kg) divided by total effort (man days).

2.2 Fishery-independent surveys

2.2.1 Study sites and survey design

The focus of the study was to provide estimates of the density and total biomass of mud cockles in bounded, stratified survey regions within the commercial fishing zones –- Port River, Coffin Bay and West Coast –- that comprise the South Australian mud cockle fishery (Figure 1). The West Coast fishery comprises Venus Bay, Streaky Bay and Smoky Bay.

The survey design involved an integration of commercial fisher knowledge with fishery-independent research sampling, similar to that undertaken elsewhere for abalone (Mayfield et al. 2008, 2009). Fishers within each zone identified commercial fishing grounds, with high and low mud cockle densities, on large-scale aerial photographs. Information on the location of commercial grounds from returned maps were uploaded into ArcGIS V9.3. Boundaries were drawn around common commercial grounds, showing the locations of high and low mud cockle densities (termed strata). Fishing grounds identified by a single commercial fisher were excluded. The resultant maps were returned to fishers to confirm the location of the fishing grounds. Once confirmed, point sampling locations were systematically distributed within the bounded survey areas that collectively comprised each survey region. Sampling intensity was greater in those areas with expected high mud cockle densities. Incorporating fisher knowledge greatly improved the overall survey efficiency and precision.

Two low-density strata and one high-density stratum, collectively constituting a single survey area, were identified across Section Bank in the Port River commercial fishing ground (Figure 2). The Coffin Bay survey region comprised six survey areas (Figure 3). Three of these survey areas comprised both high and low density strata (Figures 4-6). The West Coast survey region comprised 10 survey areas: four in Smoky Bay (Figure 7), two in Streaky Bay (Figure 8) and four in Venus Bay (Figure 9).

2.2.2 Survey methodology

The fishery-independent surveys were conducted by SARDI in conjunction with commercial fishers. GPS positions of each numbered sampling location were provided to the survey teams. At each predetermined sampling site, a commercial mud cockle rake (~41 cm wide × 20 cm height; 2 cm diagonal mesh size), with a small-mesh insert, was used to collect mud cockles along a 2 m belt transect. Mesh selectivity was not examined.

Collections obtained from each site were bagged, labelled and returned to the laboratory. Each sample was sorted by species (after Edwards 1999) before being separated into the legal-sized (≥ 30 mm SL for Port River and West Coast; ≥ 38 mm SL for Coffin Bay) and sub-legal-sized components. For Coffin Bay, the sub-legal-sized component was further subdivided (≥ 30 mm SL and < 30 mm SL). Each size category was counted and weighed. All cockles obtained from Section Bank and the West Coast were measured to the nearest 0.1 mm along the longest posterior-anterior axis (shell length) using Vernier callipers. The high number of mud cockles obtained in samples from Coffin Bay (>11,000) necessitated sub sampling, which was achieved by randomly selecting five sites from each of the six areas.

2.2.3 Estimates of density and harvestable biomass

Surveys were undertaken in May (Port River) and November (West Coast and Coffin Bay) 2009. Count data from all surveyed sampling locations within each stratum and survey area were averaged to generate a weighted mean number density (no.m^{-2}) for each mud cockle species. Similarly, the weight data were averaged to determine a weighted mean biomass density (kg.m^{-2}). Total, legal-sized, biomass (i.e. harvestable biomass) in each survey area was calculated as the weighted mean biomass density multiplied by its area (m^{2}). Total harvestable biomass in each survey area and, subsequently, the stratified total harvestable biomass for each of the three survey regions were calculated as the sum of the totals from the strata and survey areas in each of these survey regions, respectively.

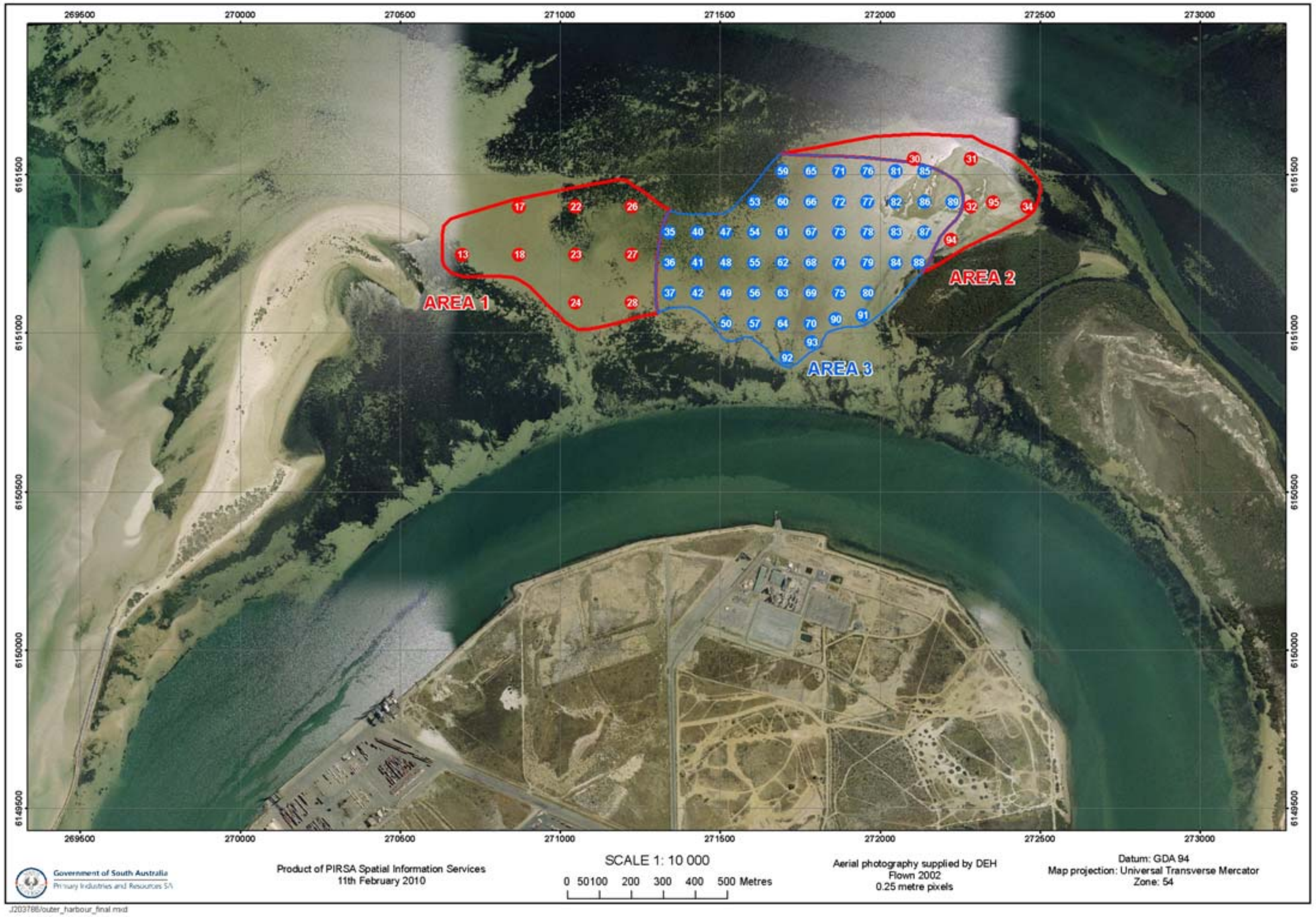


Figure 2. Map showing the stratified sampling design and location of survey points on Section Bank, Port River. The survey area comprised two strata: (1) low-density (areas 1 and 2; red polygons and red sampling locations) and (2) high-density (area 3; blue polygon and blue sampling locations).

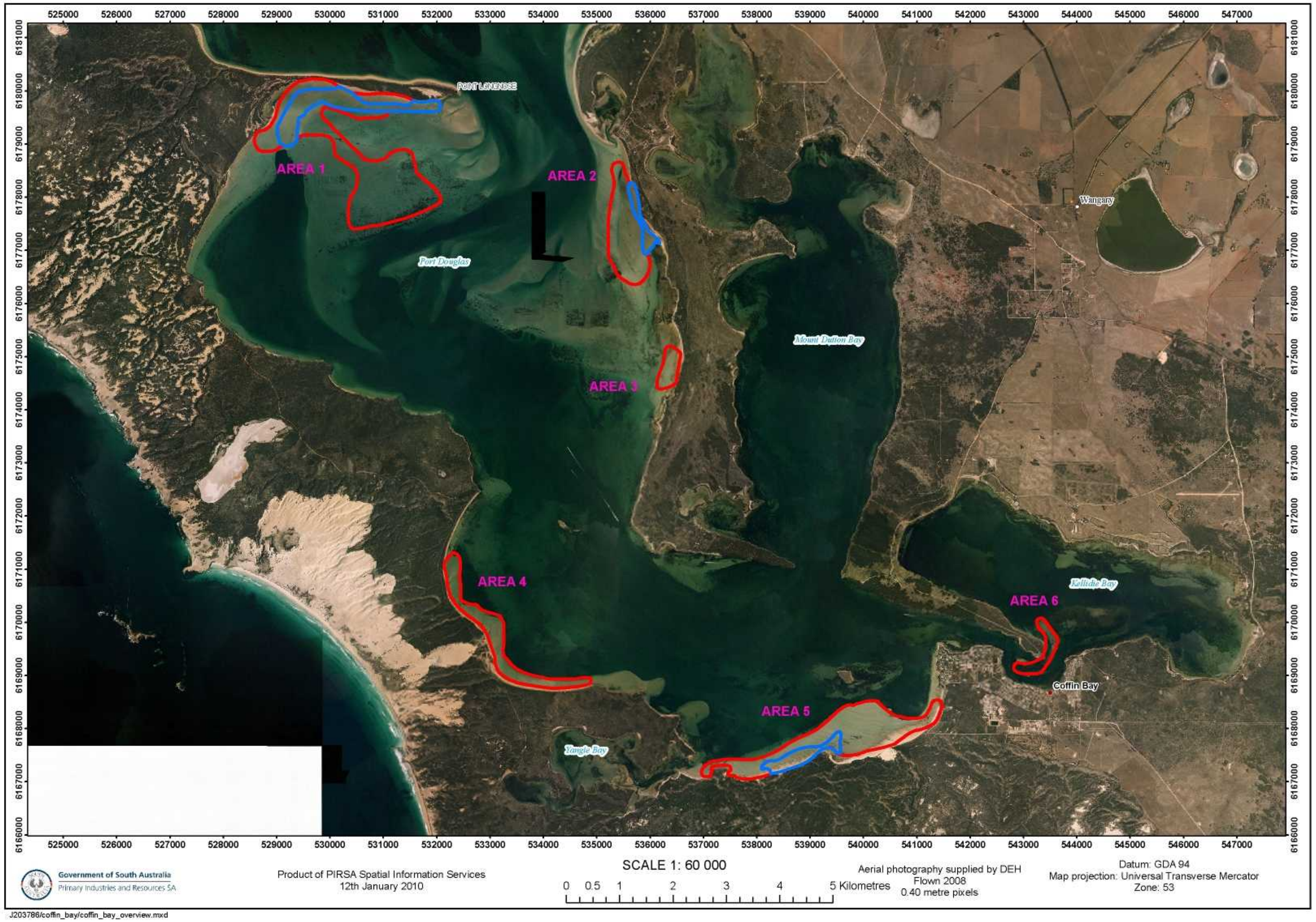
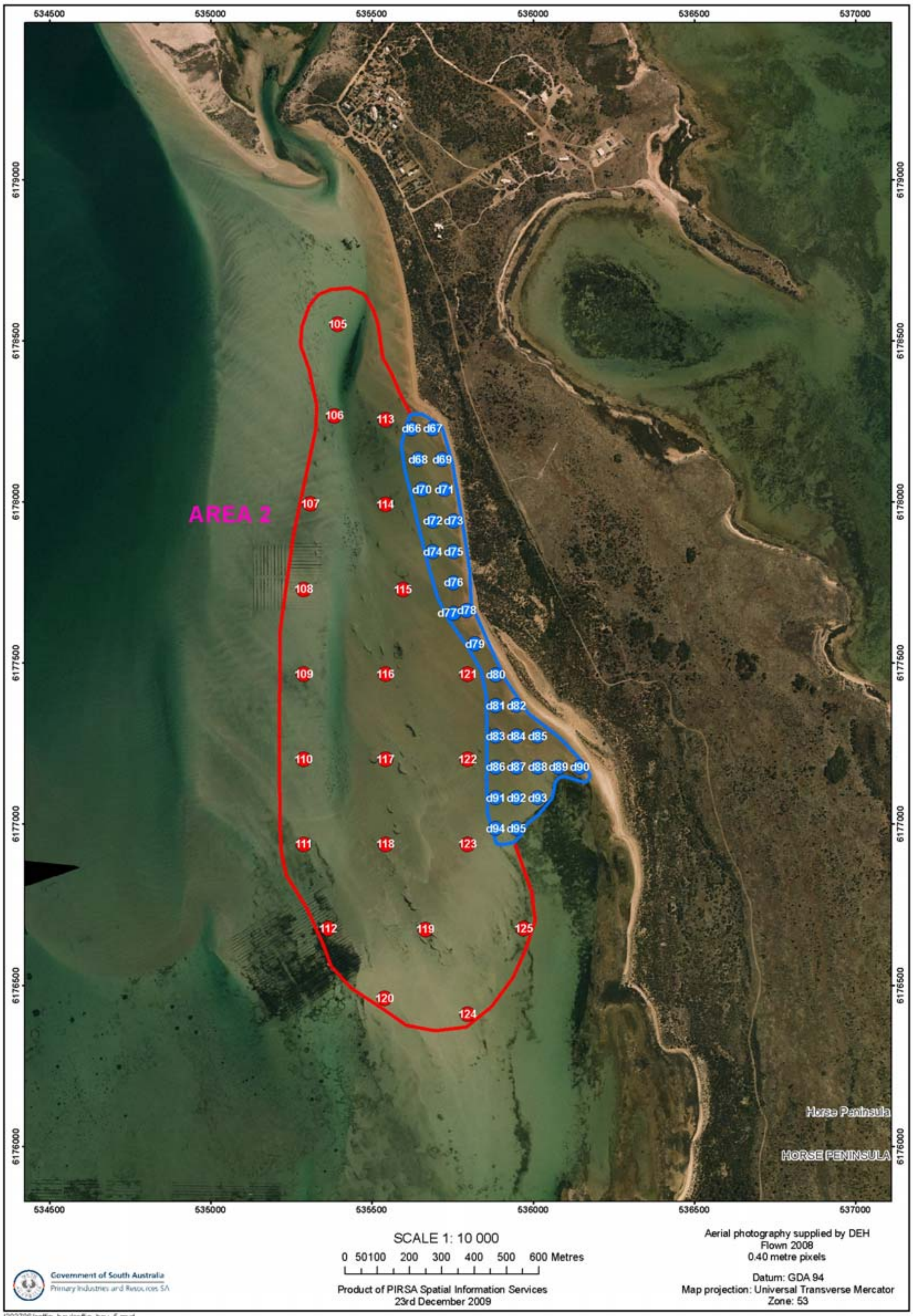


Figure 3. Map showing the stratified sampling design in Coffin Bay. The survey region comprised six survey areas. Areas 3, 4 and 6 were comprised of a single low-density stratum (red polygons), while areas 1, 2 and 5 were comprised of both low (red polygons) and high-density (blue polygons) strata.

Figure 4. Map showing the stratified sampling design and location of survey points in survey area 1 in Coffin Bay. The survey area comprised two strata: (1) low-density (red polygon and red sampling locations) and (2) high-density (blue polygon and blue sampling locations).



J203786/coffin_bay/coffin_bay_5.mxd

Figure 5. Map showing the stratified sampling design and location of survey points in survey area 2 in Coffin Bay. The survey area comprised two strata: (1) low-density (red polygon and red sampling locations) and (2) high-density (blue polygon and blue sampling locations).

Figure 6. Map showing the stratified sampling design and location of survey points in survey area 5 in Coffin Bay. The survey area comprised two strata: (1) low-density (red polygon and red sampling locations) and (2) high-density (blue polygon and blue sampling locations).

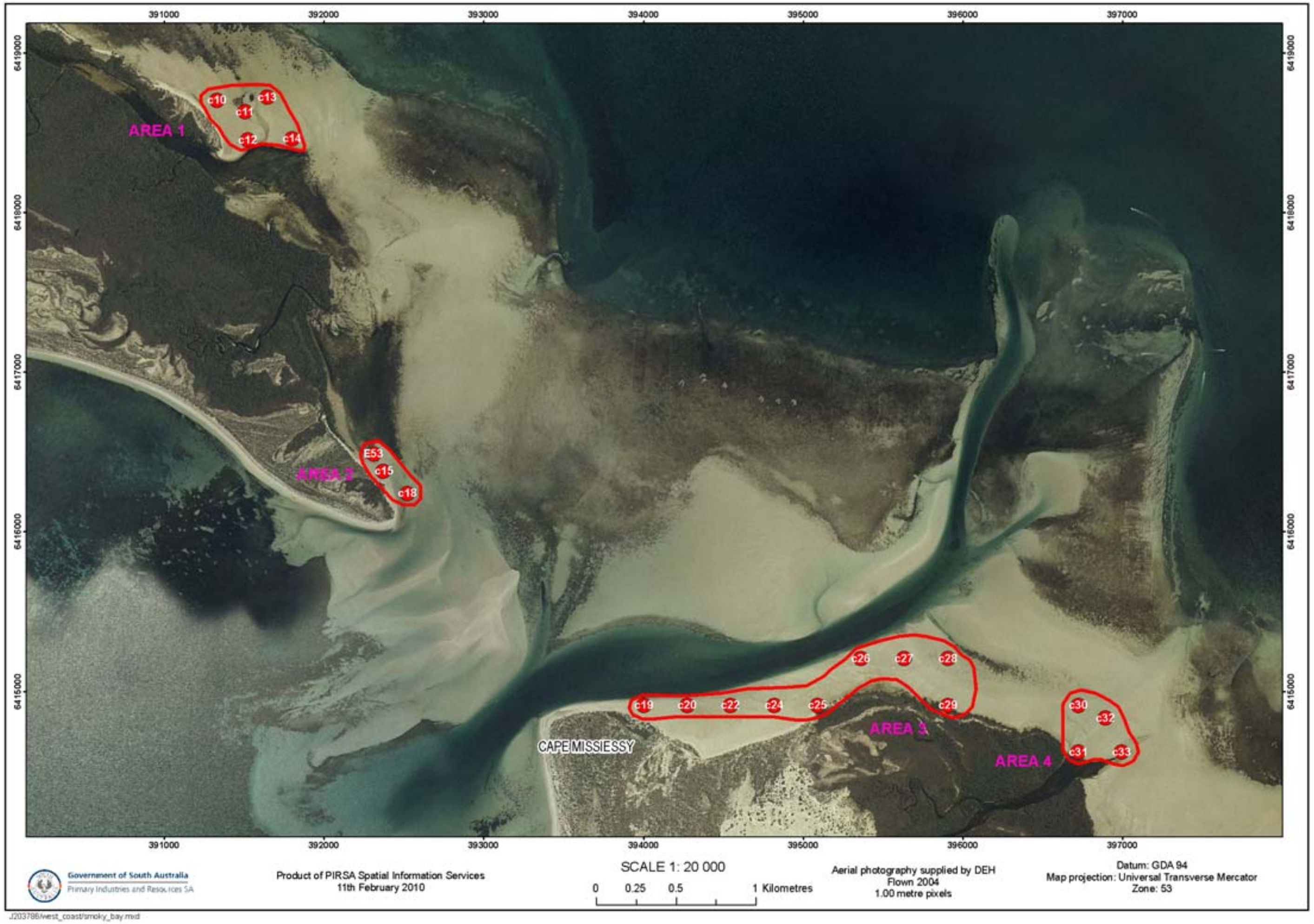


Figure 7. Map showing the stratified sampling design and location of survey points in Smoky Bay. The survey region comprised four survey areas, all of which consisted of a single, low-density stratum (red polygons and red sampling locations).

Figure 8. Map showing the stratified sampling design and location of survey points in Streaky Bay. The survey region comprised two survey areas, both of which consisted of a single, low-density stratum (red polygons and red sampling locations).

Figure 9. Map showing the stratified sampling design and location of survey points in Venus Bay. The survey region comprised four survey areas. Areas 1, 2 and 3 were comprised of a single, low-density stratum (red polygons and red sampling locations), while area 4 comprised a single, high-density stratum (blue polygon; blue sampling locations).

A non-parametric bootstrap (see Appendix B in McGarvey et al. 2008) was used to determine the confidence range around the estimates of legal-sized biomass for each species in each survey region. This approach included all strata and survey areas within each sampled survey region. The bootstrap accounted for the random variation at the sampled level of the survey design, which was the sampling locations in each survey block. The 200,000 bootstrap iterations of legal-sized, mud cockle biomass were ranked, and the 10%, 20%, . . . , 90% quantile confidence intervals (CI's) extracted. The bootstrap was implemented in R 2.10.1.

2.3 Reproductive physiology

Mud cockle samples were collected monthly by commercial fishers between November 2008 and October 2009 at six sites distributed across Coffin Bay (Figure 10). At each site for each month, approximately 50 individuals were collected using a commercial cockle rake. Samples were immediately fixed using formaldehyde (10 % in seawater). Preserved samples were subsequently transferred into an ethanol solution (70 % in seawater) prior to assessment of reproductive physiology.

2.3.1 Size at first maturity

In the laboratory, samples were separated by species and each specimen was measured to the nearest 0.1 mm as described above. Only one specimen of *K. peroni* was collected and hence this species was excluded from further analyses. For each *K. rhytiphora* and *K. scalarina* obtained, the whole gonad (and attached tissue) was removed from the shell and dissected along a transverse line running between the top of the digestive gland and foot margin (Figure 11). Individual specimens were examined under a dissecting microscope (up to 10 X magnification) and were assigned a gonad score, defined using a categorical scale from 1 – 5, modified from Edwards (1999). This scale describes a qualitative series of developmental stages (Figure 11; Table 1). Mature gonads were observed in all individuals assigned a gonad score of 3 or greater. The proportion of mature individuals of each species was plotted for each 1-mm length class, and a logistic curve – $y = 1/(1+\exp(-(a+bx))$ – fitted to the data by maximum likelihood. The length at which 50% of individuals were mature (i.e. size-at-first-maturity (L_{50})) was extracted from the logistic curve equation parameters.

Assignment of gonad scores were validated through histological analysis of gonads obtained from fresh *K. rhytiphora* and *K. scalarina* samples. The whole gonad (and attached tissue) was removed from replicate individuals within each gonad class and fixed in 10% formalin for 48 hr, where after they were transferred into 70% ethanol for preservation. Routine histology was undertaken by the University of Adelaide. Transverse sections (6-7 µm thick) of each gonad were mounted on a microscope slide and stained with haematoxylin and eosin. Examination of the developmental stage of each section under a high-powered microscope allowed direct comparison with the staging undertaken using the dissecting microscope (see Eglinton 2001).

Table 1. Criteria used to stage the gonad development of mud cockles from Coffin Bay. Modified from Edwards (1999).

Stage Number	Condition of Gonad
1	No gonad material visible (includes immature individuals)
2	Poorly developed A small amount of gonad material is evident on margins of the viscera Digestive gland completely uncovered upon external observation
3	Moderately developed Gonad material does not cover an extended area A portion of digestive gland still visible upon external observation
4	Well developed Gonad material covers large area extending into the foot Digestive gland completely covered upon external observation Gonad material 'oozes' out with the release of pressure when body wall is broken Gonad appears 'grainy'; white to cream in colour
5	Fully developed Digestive gland completely covered upon external observation Gonad material covers an extended area extending into the apex of the foot Very tightly packed and body wall hard to touch Gonad appears 'grainy' throughout; white to cream in colour

2.3.2 Temporal variation in reproductive condition

Gonad scores obtained for *K. rhytiphora* and *K. scalarina* specimens from Coffin Bay (see 2.3.1 above) were used to evaluate temporal variation in the reproductive condition of mud cockles. This was done by calculating a mean gonad index (i.e. percentage of mature individuals greater than the estimated L_{50}) for each species, by month, between November 2008 and October 2009.

2.4 Statistical analysis

Differences in the relative density among areas and reproductive condition among months were tested using Analysis of Variance (ANOVA). The data were tested for homogeneity of variance using Cochran's C test. Following determination of significant differences ($\alpha < 0.05$), post hoc analyses were undertaken using Student-Newman-Keuls tests (SNK-tests). Length-frequency distributions were compared using the non-parametric Kolmogorov-Smirnov or Kruskal-Wallis tests.

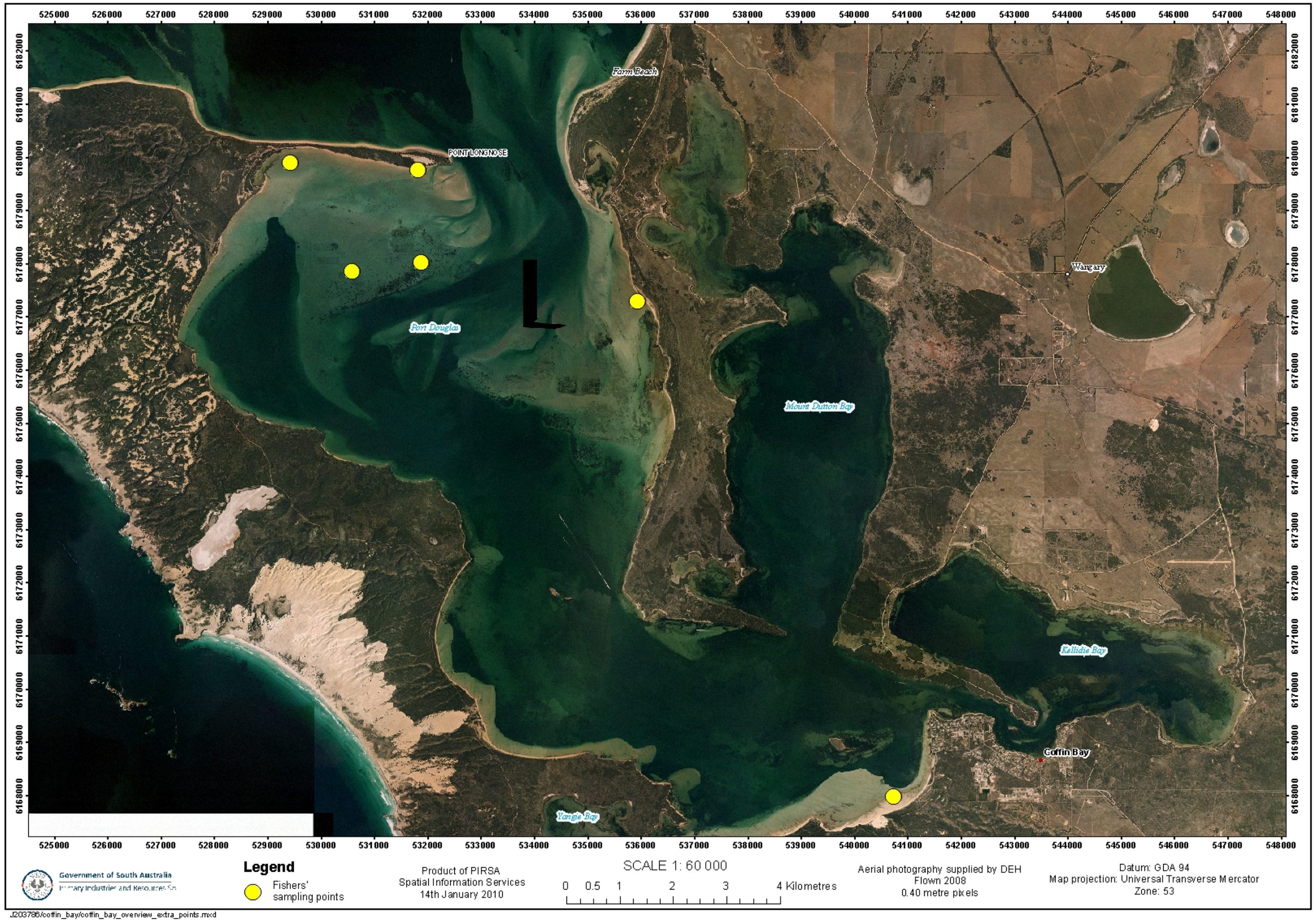


Figure 10. Map showing locations (yellow circles) of monthly mud cockle collections within Coffin Bay.

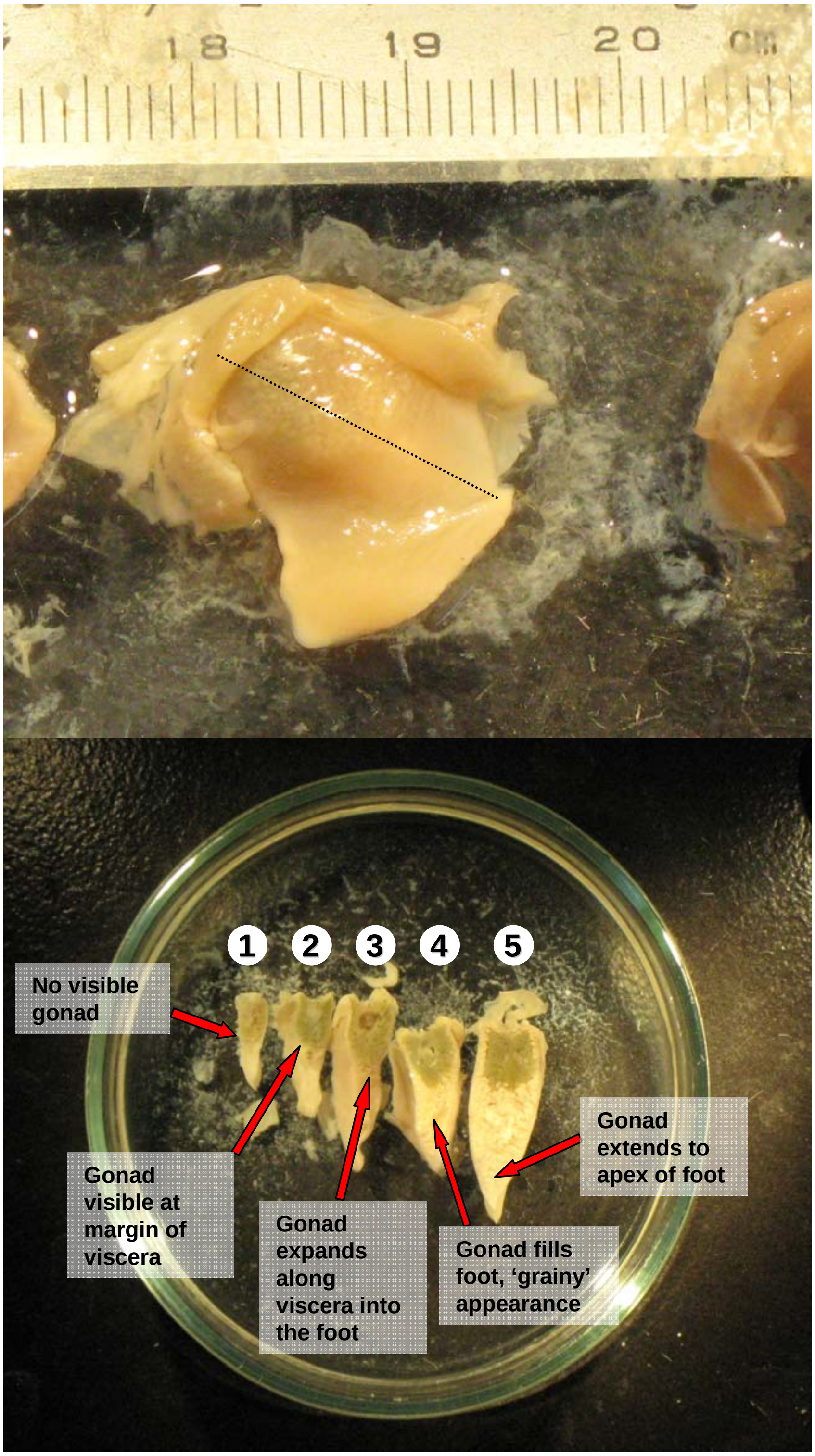


Figure 11. Photographs depicting the line of dissection (top) and gonad stage attributed to the variation in mud cockles (bottom).

3. RESULTS

3.1 Fishery statistics

Total catches of mud cockles increased rapidly from <50 $t.yr^{-1}$ between 1983/84 and 1994/95 to >350 t in 2005/06 (Figure 12). Catches have since declined to 160 t in 2008/09. Most of the catch has been harvested from the Port River and Coffin Bay fishing zones. Catches from the West Coast have been <50 $t.yr^{-1}$, and no catches were reported from this area prior to 2002/03. CPUE in 2008/09 at all spatial scales is low compared to recent years, suggesting reductions in the abundance of legal-sized mud cockles in all fishing zones.

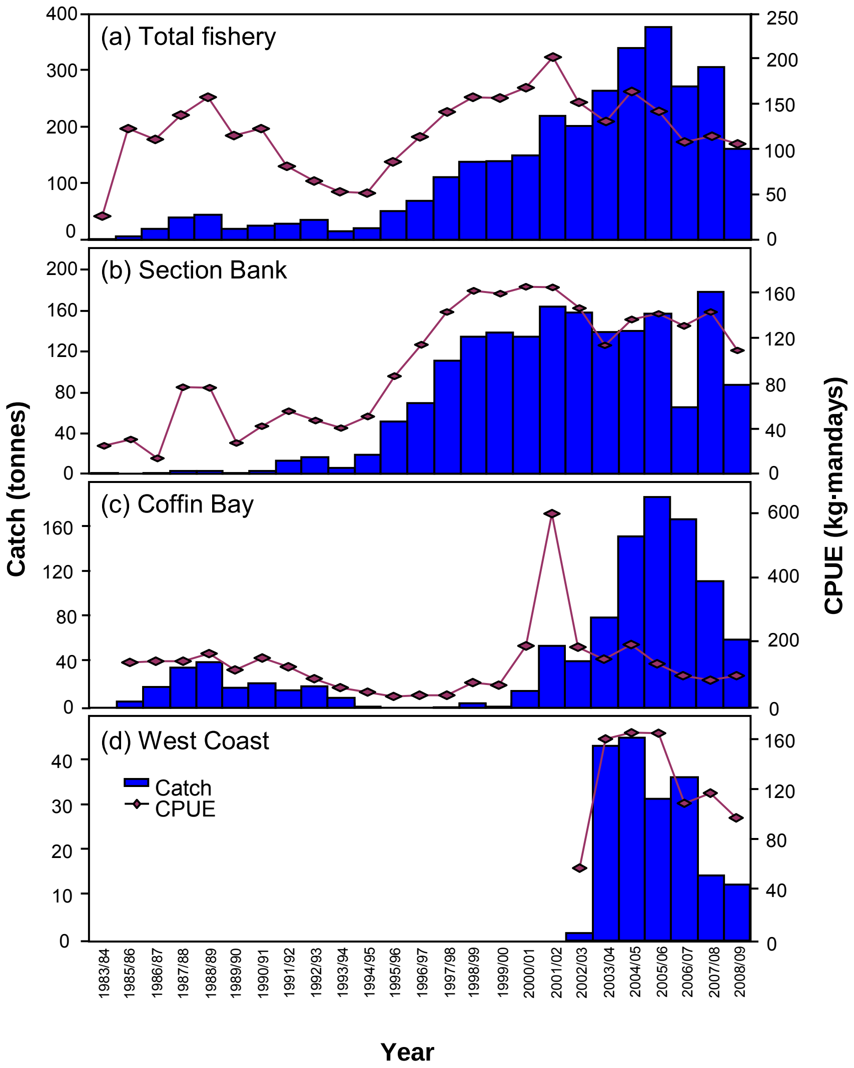


Figure 12. Total annual catch (bars) and mean annual CPUE (line) of mud cockles in all fishing zones comprising the South Australian fishery combined (a), and for the Port River (b), Coffin Bay (c) and West Coast (d) fishing zones separately. Note differences in y-axis scale among graphs.

3.2 Estimates of density and harvestable biomass

3.2.1 Port River

A total of 2,398 mud cockles were obtained from 65 sampling locations. *Katelysia scalarina* were the numerically dominant species (1,140; ~ 48%), followed by *K. peroni* (1,036; ~43%) and *K. rhytiphora* (222; ~9%).

Legal-sized individuals of each species were observed within all three surveyed areas, as were sub-legal-sized individuals of *K. rhytiphora* and *K. scalarina*. Sub-legal-sized *K. peroni* were not recorded from Area 1.

Density estimates (no.m^{-2}) varied among species and size classes (Figure 13). The density of legal-sized individuals (i.e. ≥ 30 mm SL) did not differ significantly among areas for any species (ANOVA: *K. peroni* $F_{2,62} = 1.99$, $P > 0.05$; *K. rhytiphora* $F_{2,62} = 2.65$, $P > 0.05$; *K. scalarina* $F_{2,62} = 1.61$, $P > 0.05$). The relative density of sub-legal-sized *K. peroni* and *K. rhytiphora* did not differ significantly among areas (ANOVA: $F_{2,62} = 0.428$, $P > 0.05$ and $F_{2,62} = 0.716$, $P > 0.05$, respectively), contrasting patterns of abundance for *K. scalarina* which were significantly greater in Area 2 which was closest to adjacent mangrove stands (ANOVA: $F_{2,62} = 4.66$, $P < 0.05$). Biomass estimates for each species were also different among areas and strata (Figure 14). Median estimates of total harvestable biomass for *K. peroni* (124 t) and *K. scalarina* (106 t) were substantially greater than those for *K. rhytiphora* (13 t; Table 2).

The mean size of all species exceeded the current size limit. For *K. peroni*, the difference was substantial at 34.8 mm SL. Mean sizes of *K. rhytiphora* and *K. scalarina* were 31.1 and 32.1 mm SL, respectively. Consequently, the population structure of all three species of *Katelysia* was dominated by legal-sized individuals (96%, 60% and 72%, respectively, for *K. peroni*, *K. rhytiphora* and *K. scalarina*; Figure 15), suggesting low and/or periodic recruitment. There was no significant difference in the length-frequency distributions among species (Kruskal Wallis test, $P > 0.05$).

3.2.2 Coffin Bay

A total of 11,111 mud cockles were obtained from the 251 sampling sites. *Katelysia scalarina* were the numerically dominant species (9,285; ~ 84%), followed by *K. rhytiphora* (1,766; ~ 16%) and *Katelysia peroni* (60; < 1%). The low relative abundance of *K. peroni* prevented the calculation of meaningful estimates of density and biomass for this species.

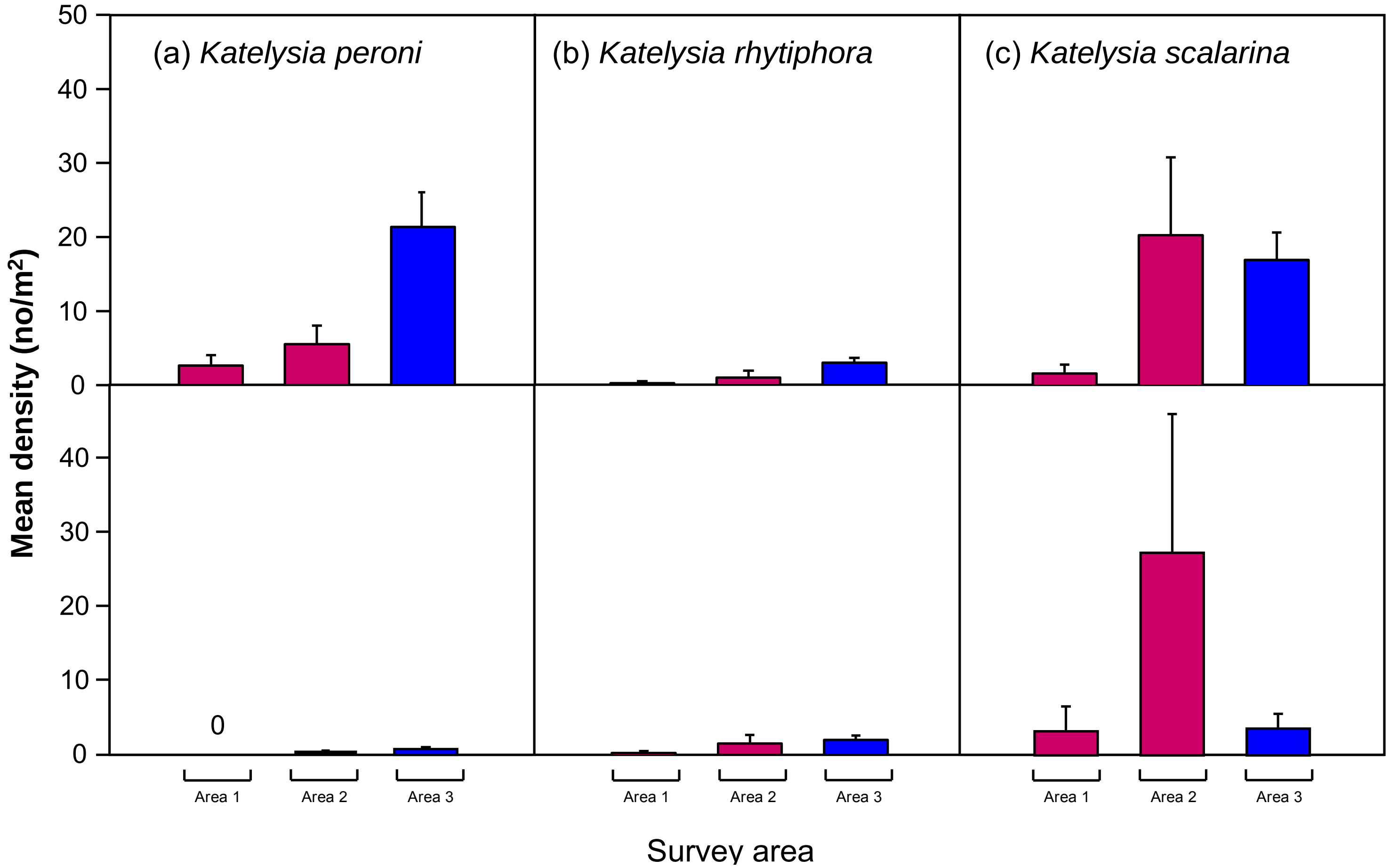


Figure 13. Density estimates (mean and SE) for three mud cockle species within the survey areas comprising the Port River fishing zone. Top panels show the legal-sized population (≥ 30 mm SL). Bottom panels show the sub-legal-sized population (< 30 mm SL). Red bars represent the low density strata and the blue bars the high density stratum.

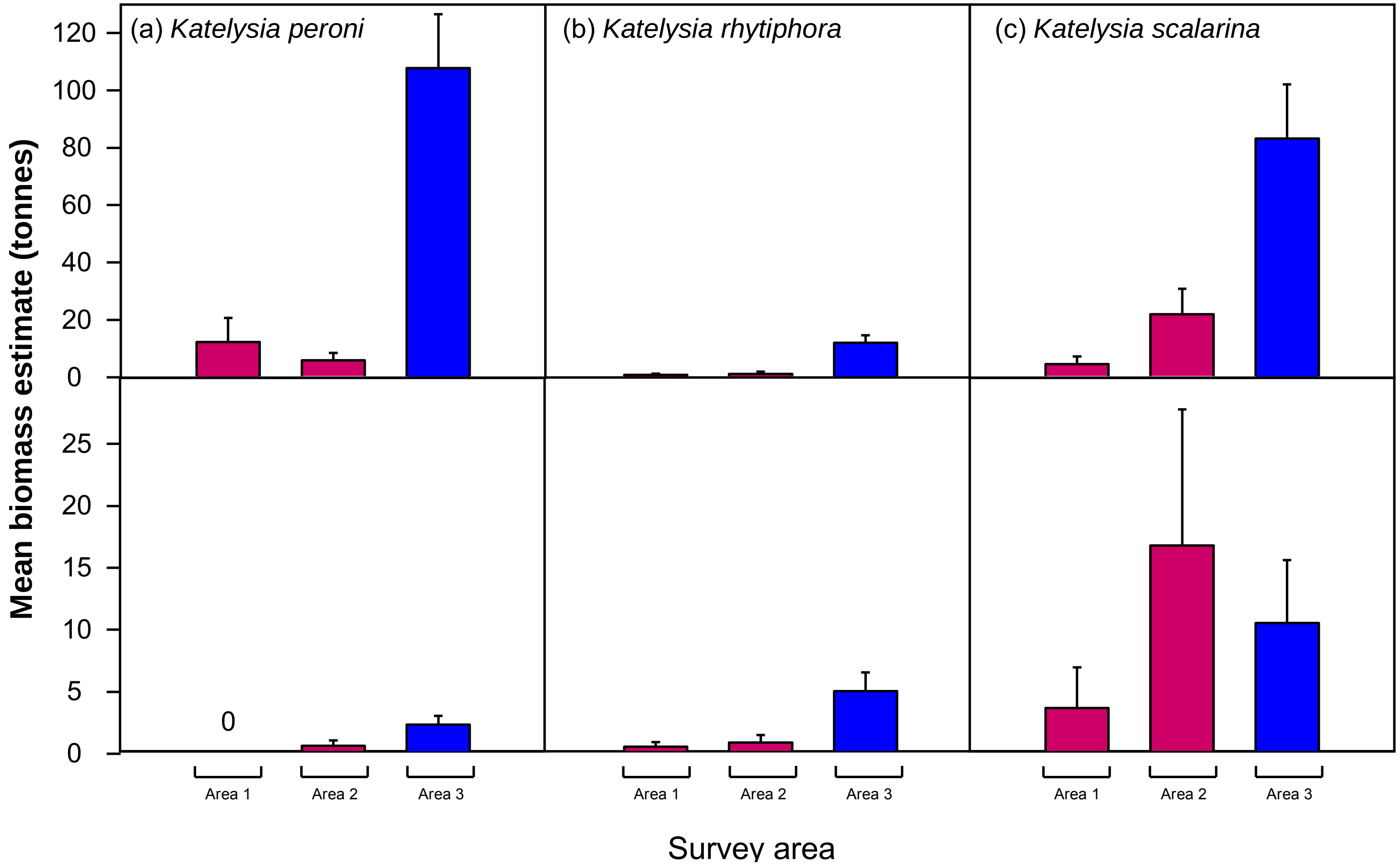


Figure 14. Biomass estimates (mean and SE) for three mud cockle species within the survey areas comprising the Port River fishing zone. Top panels show the legal-sized population (≥ 30 mm SL). Bottom panels show the sub-legal-sized population (< 30 mm SL). Red bars represent the low density strata and the blue bars the high density stratum.

Table 2. Potential, legal-sized (≥ 30 mm SL) catches (t, whole weight) of *K. peroni*, *K. scalarina* and *K. rhytiphora* under various assumed levels of harvest fraction and 10 – 90 % confidence for legal-size biomass estimates in the Port River survey region in May 2009. The probability percentages (10%, 20%, . . 90%) are quantiles used to separate ordered values of legal-size biomass estimates from a stratified bootstrap (n iterations = 200,000). They specify the confidence probability that the true value of harvestable mud cockle biomass is greater than or equal to the biomass values shown in round brackets beneath each corresponding confidence probability percentage. These estimates assume that the sampling gear was 100% efficient, which may not be correct.

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(b) *K. peroni*	**(98.7)**	**(107.0)**	**(113.2)**	**(118.6)**	**(123.8)**	**(129.0)**	**(134.7)**	**(141.6)**	**(151.3)**
0.02	2.0	2.1	2.3	2.4	2.5	2.6	2.7	2.8	3.0
0.05	4.9	5.4	5.7	5.9	6.2	6.4	6.7	7.1	7.6
0.1	9.9	10.7	11.3	11.9	12.4	12.9	13.5	14.2	15.1
0.15	14.8	16.1	17.0	17.8	18.6	19.3	20.2	21.2	22.7
0.2	19.7	21.4	22.6	23.7	24.8	25.8	26.9	28.3	30.3
(a) *K. rhytiphora*	**(9.7)**	**(10.7)**	**(11.5)**	**(12.3)**	**(12.9)**	**(13.6)**	**(14.4)**	**(15.3)**	**(16.6)**
0.02	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3
0.05	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.8	0.8
0.1	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.5	1.7
0.15	1.5	1.6	1.7	1.8	1.9	2.0	2.2	2.3	2.5
0.2	1.9	2.1	2.3	2.5	2.6	2.7	2.9	3.1	3.3
(c) *K. scalarina*	**(82.3)**	**(89.9)**	**(95.9)**	**(101.2)**	**(106.4)**	**(111.8)**	**(117.9)**	**(125.4)**	**(136.0)**
0.02	1.6	1.8	1.9	2.0	2.1	2.2	2.4	2.5	2.7
0.05	4.1	4.5	4.8	5.1	5.3	5.6	5.9	6.3	6.8
0.1	8.2	9.0	9.6	10.1	10.6	11.2	11.8	12.5	13.6
0.15	12.3	13.5	14.4	15.2	16.0	16.8	17.7	18.8	20.4
0.2	16.5	18.0	19.2	20.2	21.3	22.4	23.6	25.1	27.2

Density estimates for each of *K. rhytiphora* and *K. scalarina* varied among area, strata and size class (Figure 16). For both species, legal-sized individuals were observed in four of seven areas/strata, whereas, sub-legal-sized individuals were collected from all but one of the areas surveyed. For *K. rhytiphora*, the density of legal-sized individuals (i.e. ≥ 38 mm SL) varied among sites (ANOVA: $F_{6,244} = 6.26$, $P < 0.05$), a pattern driven strongly by the large number of individuals observed within Area 1, particularly in deeper water adjacent oyster leases. The density of sub-legal individuals displayed similar variability among sites and strata (Figure 16). In contrast, for *K. scalarina*, the density of legal-sized individuals was relatively low, resulting in no significant differences among areas or strata (ANOVA: $F_{6,244} = 1.70$, *P* > 0.05), while densities of sub-legal-sized individuals differed significantly among sampling locations ((ANOVA: $F_{6,244}$ = 2.64, *P* < 0.05; Figure 16). Biomass estimates were also different among areas and strata (Figure 17).

The median estimate of total harvestable biomass, at a MLS of 38 mm SL, was substantially greater for *K. rhytiphora* (657 t) than that for *K. scalarina* (45 t; Table 3). At an alternate MLS of 30 mm SL, median estimates of harvestable biomass were 10-times greater for *K. scalarina* (448 t) but just 25% greater for *H. rhytiphora* (816 t; Table 3).

The mean size of *K. rhytiphora* (37.5 mm SL) was larger than that of *K. scalarina* (30.6 mm SL). Thus, at the current MLS of 38 mm SL, the population structure of *K. rhytiphora* was dominated by legal-sized individuals (59%), while *K. scalarina* had a very high proportion of sub-legal-sized individuals (95%; Figure 18). There was no significant difference in the length frequency distributions between these two species (Kolmogorov-Smirnov test, *P* > 0.05).

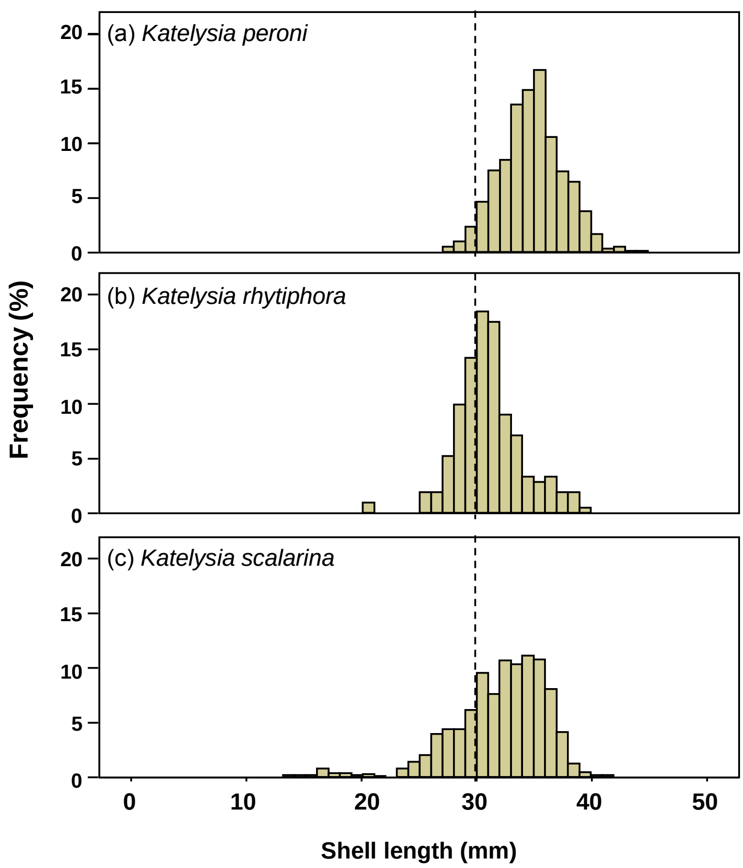


Figure 15. Length frequency distribution for three mud cockle species obtained from all survey points sampled in the Port River fishing zone. Dashed line indicates current minimum legal size limit (≥ 30 mm SL).

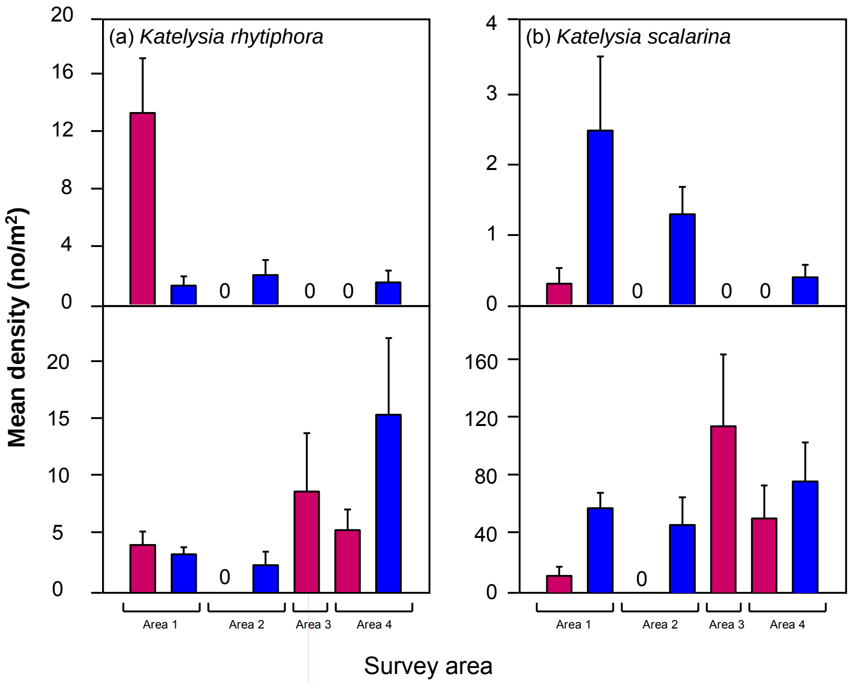


Figure 16. Density estimates (mean and SE) for two mud cockle species within the strata and survey areas comprising the Coffin Bay fishing zone. Top panels show the legal-sized population (≥ 38 mm SL). Bottom panels show the sub-legal-sized population (< 38 mm SL). Red bars represent the low density strata and the blue bars the high density strata.

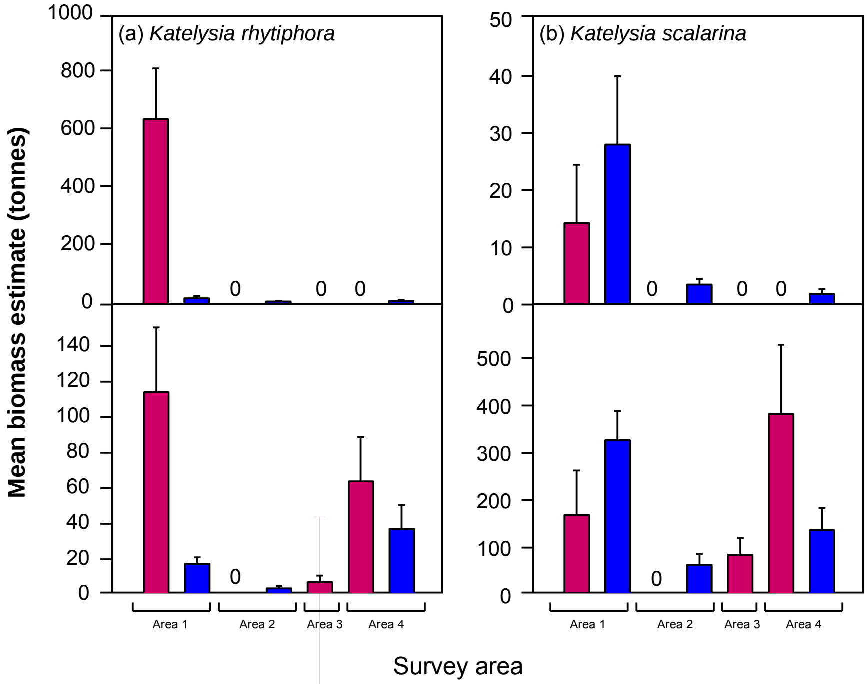


Figure 17. Biomass estimates (mean and SE) for two mud cockle species within the strata and survey areas comprising the Coffin Bay fishing zone. Top panels show the legal-sized population (≥ 38 mm SL). Bottom panels show the sub-legal-sized population (< 38 mm SL). Red bars represent the low density strata and the blue bars the high density strata.

Table 3. Potential catches (t, whole weight) of *K. scalarina* and *K. rhytiphora* at two alternate MLS (top: 38 mm SL; bottom: 30 mm SL) under various assumed levels of harvest fraction and 10 – 90 % confidence for legal-size biomass estimates in the Coffin Bay survey region in November 2009. The probability percentages (10%, 20%, . . 90%) are quantiles used to separate ordered values of legal-size biomass estimates from a stratified bootstrap (n iterations = 200,000). They specify the confidence probability that the true value of harvestable mud cockle biomass is greater than or equal to the biomass values shown in round brackets beneath each corresponding confidence probability percentage. These estimates assume that the sampling gear was 100% efficient, which may not be correct.

MLS: 38 mm SL

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. rhytiphora*	**(448.1)**	**(515.6)**	**(567.1)**	**(613.3)**	**(657.4)**	**(702.5)**	**(753.1)**	**(813.9)**	**(900.4)**
0.02	11.2	12.9	14.2	15.3	16.4	17.6	18.8	20.3	22.5
0.05	22.4	25.8	28.4	30.7	32.9	35.1	37.7	40.7	45.0
0.1	44.8	51.6	56.7	61.3	65.7	70.3	75.3	81.4	90.0
0.15	67.2	77.3	85.1	92.0	98.6	105.4	113.0	122.1	135.1
0.2	89.6	103.1	113.4	122.7	131.5	140.5	150.6	162.8	180.1
(b) *K. scalarina*	**(27.4)**	**(32.7)**	**(37.0)**	**(41.0)**	**(44.8)**	**(48.9)**	**(53.5)**	**(59.0)**	**(67.2)**
0.02	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.5	1.7
0.05	1.4	1.6	1.9	2.0	2.2	2.4	2.7	3.0	3.4
0.1	2.7	3.3	3.7	4.1	4.5	4.9	5.3	5.9	6.7
0.15	4.1	4.9	5.6	6.1	6.7	7.3	8.0	8.9	10.1
0.2	5.5	6.5	7.4	8.2	9.0	9.8	10.7	11.8	13.4

MLS: 30 mm SL

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. rhytiphora*	**(570.4)**	**(649.8)**	**(710.0)**	**(764.0)**	**(815.8)**	**(868.5)**	**(927.1)**	**(998.2)**	**(1100)**
0.02	14.3	16.2	17.7	19.1	20.4	21.7	23.2	25.0	27.5
0.05	28.5	32.5	35.5	38.2	40.8	43.4	46.4	49.9	55.0
0.1	57.0	65.0	71.0	76.4	81.6	86.8	92.7	99.8	110.0
0.15	85.6	97.5	106.5	114.6	122.4	130.3	139.1	149.7	165.0
0.2	114.1	130.0	142.0	152.8	163.2	173.7	185.4	199.6	220.0
(b) *K. scalarina*	**(360.3)**	**(389.4)**	**(410.8)**	**(429.8)**	**(448.1)**	**(466.8)**	**(487.4)**	**(511.6)**	**(546.4)**
0.02	9.0	9.7	10.3	10.7	11.2	11.7	12.2	12.8	13.7
0.05	18.0	19.5	20.5	21.5	22.4	23.3	24.4	25.6	27.3
0.1	36.0	38.9	41.1	43.0	44.8	46.7	48.7	51.2	54.6
0.15	54.1	58.4	61.6	64.5	67.2	70.0	73.1	76.7	82.0
0.2	72.1	77.9	82.2	86.0	89.6	93.4	97.5	102.3	109.3

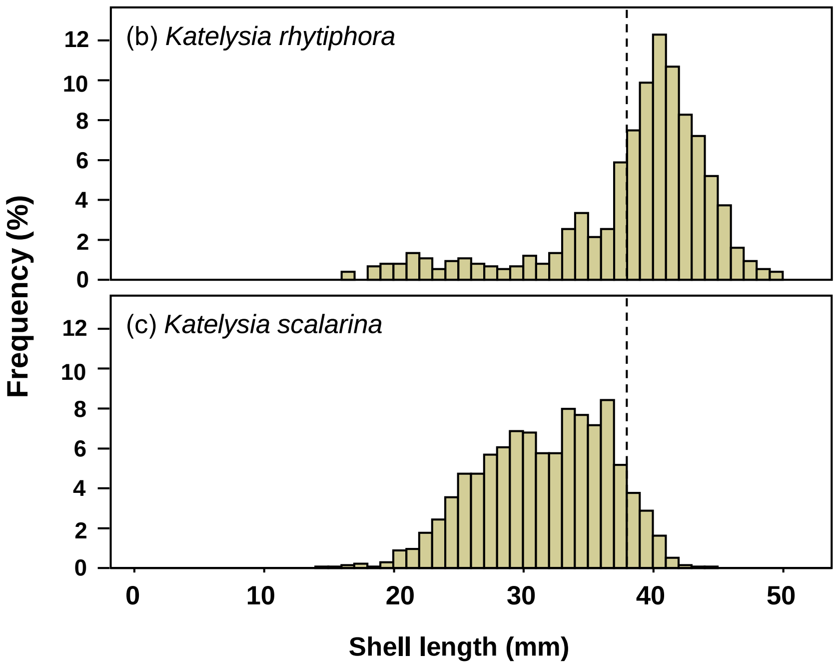


Figure 18. Length frequency distributions for two mud cockle species obtained from selected survey points within surveyed areas of Coffin Bay. Dashed line indicates current minimum legal size limit (≥ 38 mm SL).

3.2.3 West Coast

A total of 3,146 mud cockles were obtained from the 91 sampling sites. Across all locations, density estimates for *K. peroni* and *K. rhytiphora* were low (Figure 19). Notably, no *K. peroni* were sampled in Smoky Bay. Consequently, *K. scalarina* was the numerically dominant species (2,864; ~91%), followed by *K. peroni* (184; ~6%) and *K. rhytiphora* (98; ~3%).

The density of both legal-sized and sub-legal-sized *K. peroni* did not differ significantly among survey areas (ANOVA: $F_{2,81} = 1.19$, $P > 0.05$ and $F_{2,81} = 0.89$, $P > 0.05$, respectively). Densities of *K. rhytiphora* were similarly variable, with legal-sized and sub-legal-sized individuals observed from 5 and 4 out of 10 surveyed areas, respectively (Figure 19). The low relative densities of this species again resulted in the absence of any detectable difference among the three locations (ANOVA: legal-sized $F_{2,81} = 1.88$, $P > 0.05$; sub-legal-sized $F_{2,81} = 1.24$, $P > 0.05$). The spatial distributions of legal-sized and sub-legal-sized *K. scalarina* were broader than those observed for *K. peroni* and *K. rhytiphora*, being observed in all but 2 areas (Figure 19). Sub-legal-sized densities of *K. scalarina* differed significantly among Smoky Bay, Streaky Bay and Venus Bay (ANOVA: $F_{2,81} = 6.03$, $P < 0.05$), but that of legal-sized density did not (ANOVA: $F_{2,81} = 0.29$, $P > 0.05$). Estimates of biomass differed similarly among areas (Figure 20).

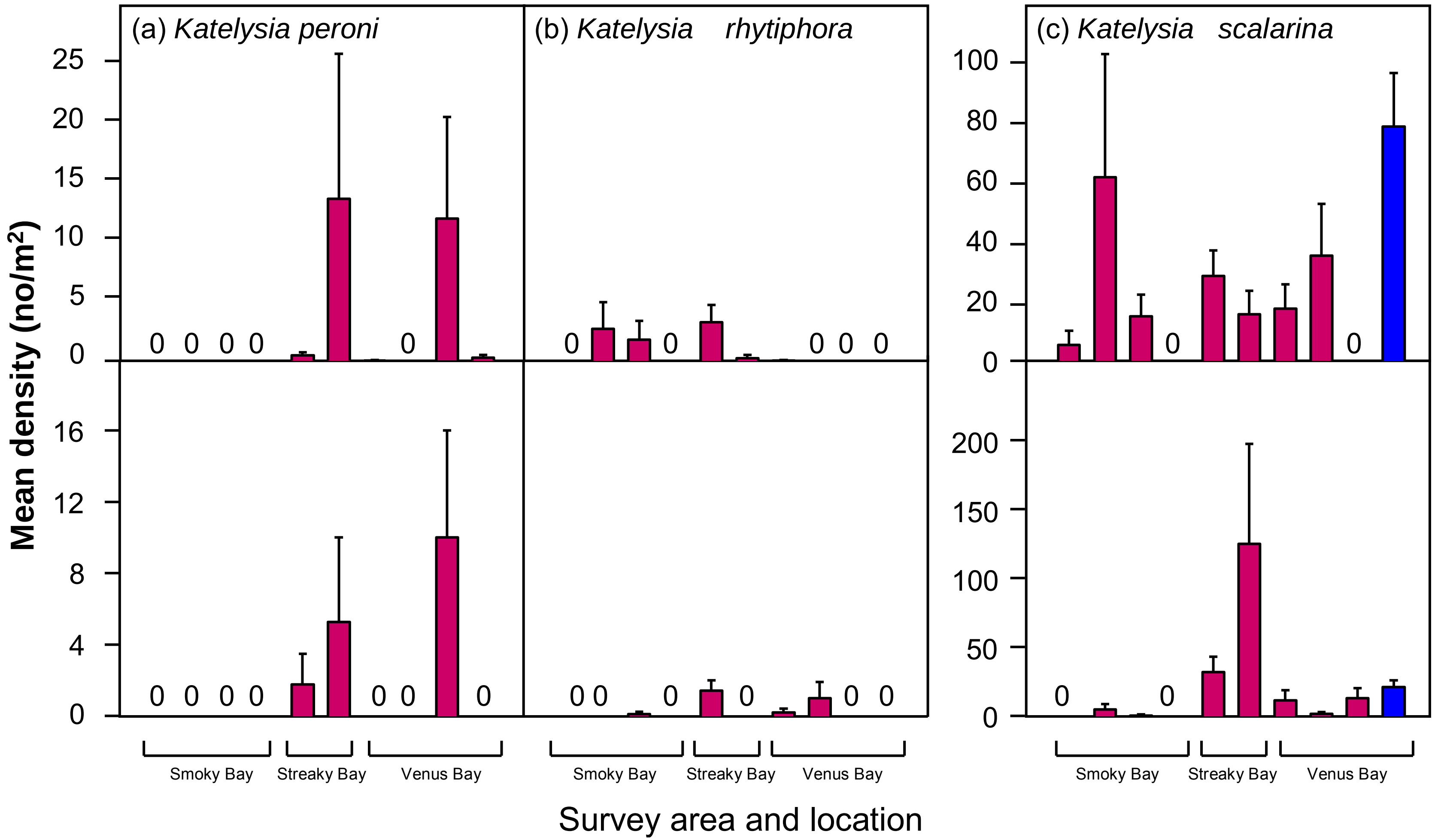


Figure 19. Density estimates (mean and SE) for three mud cockle species within the strata and survey areas comprising the West Coast fishing zone. Top panels show the legal-sized population (≥ 30 mm SL). Bottom panels show the sub-legal-sized population (< 30 mm SL). Red bars represent the low density strata and the blue bars the high density strata.

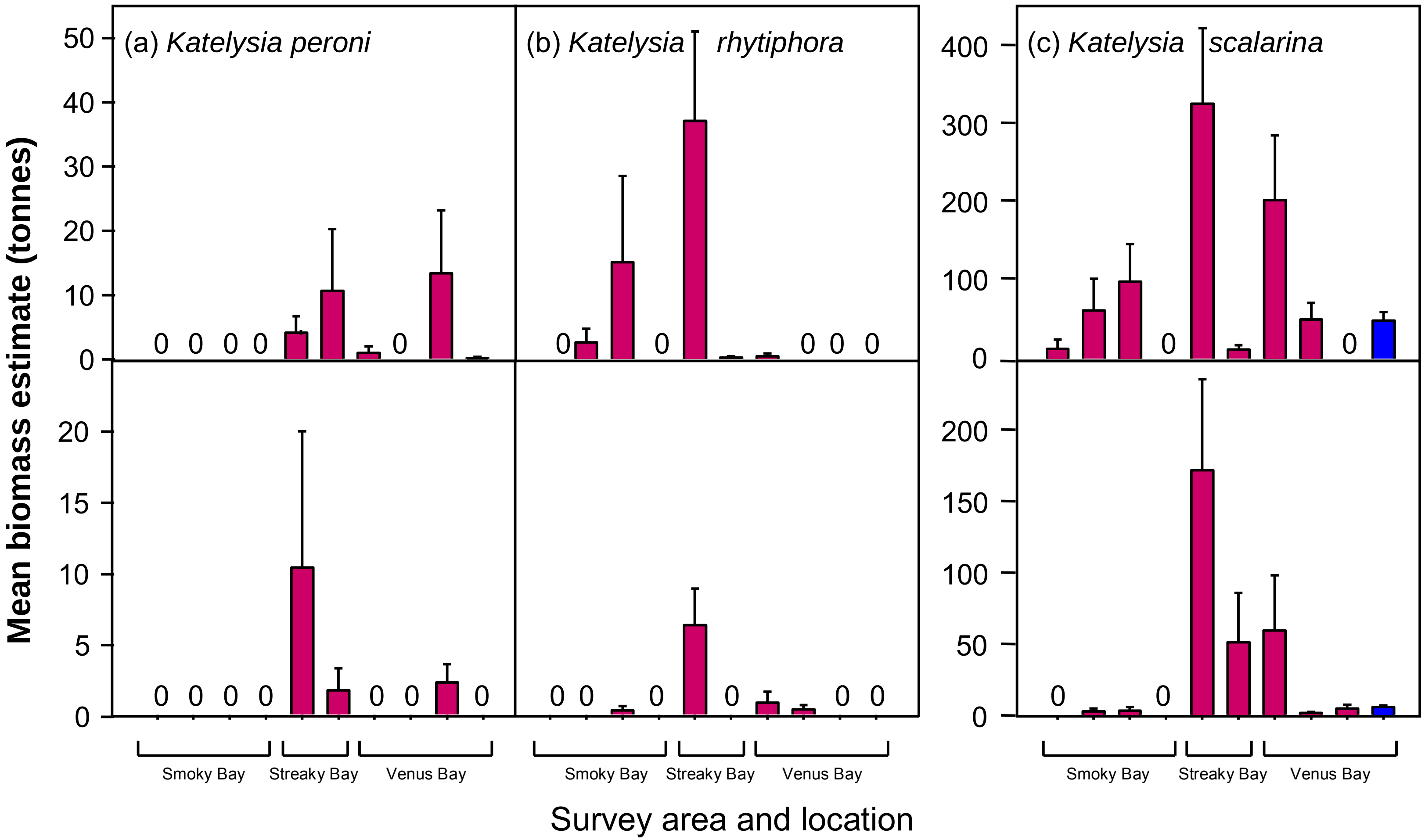


Figure 20. Biomass estimates (mean and SE) for three mud cockle species within the strata and survey areas comprising the West Coast fishing zone. Top panels show the legal-sized population (≥ 30 mm SL). Bottom panels show the sub-legal-sized population (< 30 mm SL). Red bars represent the low density strata and the blue bars the high density strata.

Median estimates of total harvestable biomass for *K. scalarina* in Smoky Bay (174 t), Streaky Bay (334 t) and Venus Bay (298 t; Table 4) were substantially greater than those for either *K. rhytiphora* (range: 0.5 – 36 t) or *K. peroni* (range: 0 – 16 t).

Legal-sized individuals (≥ 30 mm SL) comprised >50% of the sample for each species across the west coast (*K. scalarina*: 54%; *K. peroni*: 69%; *K. rhytiphora*: 56%). Mean sizes ranged from 29.0 (*K. peroni*) to 32.7 (*K. rhytiphora*). There was no significant difference in the length frequency distributions of the three mud cockle species (Kruskal Wallis test, $P > 0.05$).

Table 4. Potential, legal-sized (≥ 30 mm SL) catches (t, whole weight) of *K. peroni*, *K. scalarina* and *K. rhytiphora* under various assumed levels of harvest fraction and 10 – 90 % confidence for legal-size biomass estimates in Smoky Bay, Streaky Bay and Venus Bay, that comprise the West Coast survey region, in November 2009. The probability percentages (10%, 20%, . . 90%) are quantiles used to separate ordered values of legal-size biomass estimates from a stratified bootstrap (n iterations = 200,000). They specify the confidence probability that the true value of harvestable mud cockle biomass is greater than or equal to the biomass values shown in round brackets beneath each corresponding confidence probability percentage. These estimates assume that the sampling gear was 100% efficient, which may not be correct.

Smoky Bay

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. rhytiphora*	**(2.3)**	**(3.4)**	**(6.0)**	**(15.3)**	**(17.1)**	**(18.7)**	**(21.3)**	**(31.6)**	**(35.0)**
0.02	0.0	0.1	0.1	0.3	0.3	0.4	0.4	0.6	0.7
0.05	0.1	0.2	0.3	0.8	0.9	0.9	1.1	1.6	1.8
0.1	0.2	0.3	0.6	1.5	1.7	1.9	2.1	3.2	3.5
0.15	0.3	0.5	0.9	2.3	2.6	2.8	3.2	4.7	5.3
0.2	0.5	0.7	1.2	3.1	3.4	3.7	4.3	6.3	7.0
(b) *K. scalarina*	**(94.3)**	**(120.5)**	**(139.9)**	**(157.7)**	**(173.9)**	**(190.9)**	**(209.1)**	**(231.1)**	**(261.9)**
0.02	1.9	2.4	2.8	3.2	3.5	3.8	4.2	4.6	5.2
0.05	4.7	6.0	7.0	7.9	8.7	9.5	10.5	11.6	13.1
0.1	9.4	12.0	14.0	15.8	17.4	19.1	20.9	23.1	26.2
0.15	14.1	18.1	21.0	23.7	26.1	28.6	31.4	34.7	39.3
0.2	18.9	24.1	28.0	31.5	34.8	38.2	41.8	46.2	52.4

Table 4 continued……

Streaky Bay

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peroni*	**(2.6)**	**(4.5)**	**(8.2)**	**(12.4)**	**(14.3)**	**(15.7)**	**(18.6)**	**(24.2)**	**(28.0)**
0.02	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6
0.05	0.1	0.2	0.4	0.6	0.7	0.8	0.9	1.2	1.4
0.1	0.3	0.5	0.8	1.2	1.4	1.6	1.9	2.4	2.8
0.15	0.4	0.7	1.2	1.9	2.1	2.4	2.8	3.6	4.2
0.2	0.5	0.9	1.6	2.5	2.9	3.1	3.7	4.8	5.6
(b) *K. rhytiphora*	**(20.6)**	**(25.4)**	**(29.3)**	**(32.8)**	**(36.3)**	**(40.0)**	**(44.1)**	**(49.2)**	**(56.6)**
0.02	0.4	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1
0.05	1.0	1.3	1.5	1.6	1.8	2.0	2.2	2.5	2.8
0.1	2.1	2.5	2.9	3.3	3.6	4.0	4.4	4.9	5.7
0.15	3.1	3.8	4.4	4.9	5.4	6.0	6.6	7.4	8.5
0.2	4.1	5.1	5.9	6.6	7.3	8.0	8.8	9.8	11.3
(c) *K. scalarina*	**(220.0)**	**(256.0)**	**(284.4)**	**(309.7)**	**(334.1)**	**(359.5)**	**(387.7)**	**(421.9)**	**(470.7)**
0.02	4.4	5.1	5.7	6.2	6.7	7.2	7.8	8.4	9.4
0.05	11.0	12.8	14.2	15.5	16.7	18.0	19.4	21.1	23.5
0.1	22.0	25.6	28.4	31.0	33.4	36.0	38.8	42.2	47.1
0.15	33.0	38.4	42.7	46.5	50.1	53.9	58.2	63.3	70.6
0.2	44.0	51.2	56.9	61.9	66.8	71.9	77.5	84.4	94.1

Venus Bay

Harvest fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peroni*	**(2.3)**	**(4.2)**	**(7.0)**	**(12.7)**	**(14.0)**	**(15.5)**	**(17.7)**	**(24.6)**	**(27.2)**
0.02	0.0	0.1	0.1	0.3	0.3	0.3	0.4	0.5	0.5
0.05	0.1	0.2	0.4	0.6	0.7	0.8	0.9	1.2	1.4
0.1	0.2	0.4	0.7	1.3	1.4	1.6	1.8	2.5	2.7
0.15	0.3	0.6	1.1	1.9	2.1	2.3	2.7	3.7	4.1
0.2	0.5	0.8	1.4	2.5	2.8	3.1	3.5	4.9	5.4
(b) *K. rhytiphora*	**(0.0)**	**(0.0)**	**(0.0)**	**(0.5)**	**(0.5)**	**(0.5)**	**(0.5)**	**(1.0)**	**(1.0)**
0.2	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
(c) *K. scalarina*	**(200.3)**	**(230.6)**	**(254.9)**	**(276.6)**	**(298.0)**	**(320.6)**	**(345.5)**	**(376.7)**	**(421.7)**
0.02	4.0	4.6	5.1	5.5	6.0	6.4	6.9	7.5	8.4
0.05	10.0	11.5	12.7	13.8	14.9	16.0	17.3	18.8	21.1
0.1	20.0	23.1	25.5	27.7	29.8	32.1	34.5	37.7	42.2
0.15	30.0	34.6	38.2	41.5	44.7	48.1	51.8	56.5	63.3
0.2	40.1	46.1	51.0	55.3	59.6	64.1	69.1	75.3	84.3

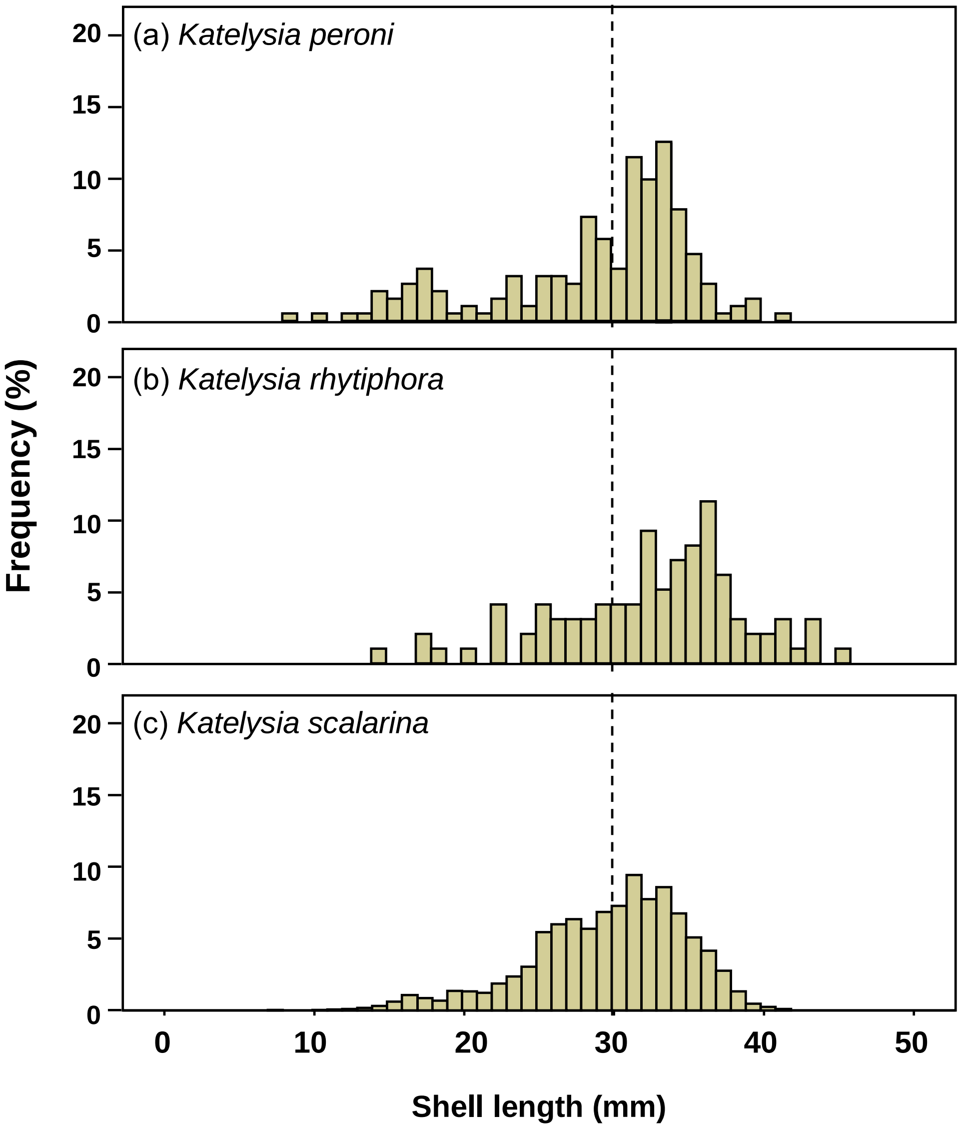


Figure 21. Length-frequency distribution for three mud cockle species obtained from all survey points within the West Coast fishing zone. Dashed line indicates current minimum legal size limit (≥ 30 mm SL).

3.3 Reproductive physiology

3.3.1 Size at first maturity

A total of 3,129 mud cockle specimens from Coffin Bay were examined and assigned a gonad score. Of samples examined 1,085 (35%) were *K. rhytiphora* and 2,044 (65%) were *K. scalarina*. Histological examination of a subsample (n = 10 for each species) of both species validated the gonad scores assigned to individuals (Figure 22). The strong, positive correlation between the gonad score given to specimens of both species and those based on histological assessment (Pearson's correlation: *K. rhytiphora* $r = 0.91$; $P < 0.001$; *K. scalarina* $r = 0.83$; $P < 0.05$) supported this validation. Size-at-first-maturity differed between species (Figure 23). For *K. rhytiphora*, L_{50} was 31.1 mm SL, where as for *K. scalarina* it was 26.1 mm SL.

3.3.2 Temporal variation in reproductive condition

Reproductive condition varied over the 12-month sampling period (Figure 24). Proportions of mature *K. rhytiphora* were highest in March (100% of individuals mature) and October (93% mature) and lowest during May and June (48% and 45%, respectively), but differences among months were not significant (ANOVA: $F_{11, 14} = 1.87$; $P > 0.05$). Similar temporal patterns were evident for *K. scalarina*, with the proportion of mature individuals greatest in January and October (96% and 98%, respectively). This species displayed significant variation among months (ANOVA: $F_{11, 32} = 3.75$; $P < 0.05$), with the mean gonad index significantly lower in June than in all other months.

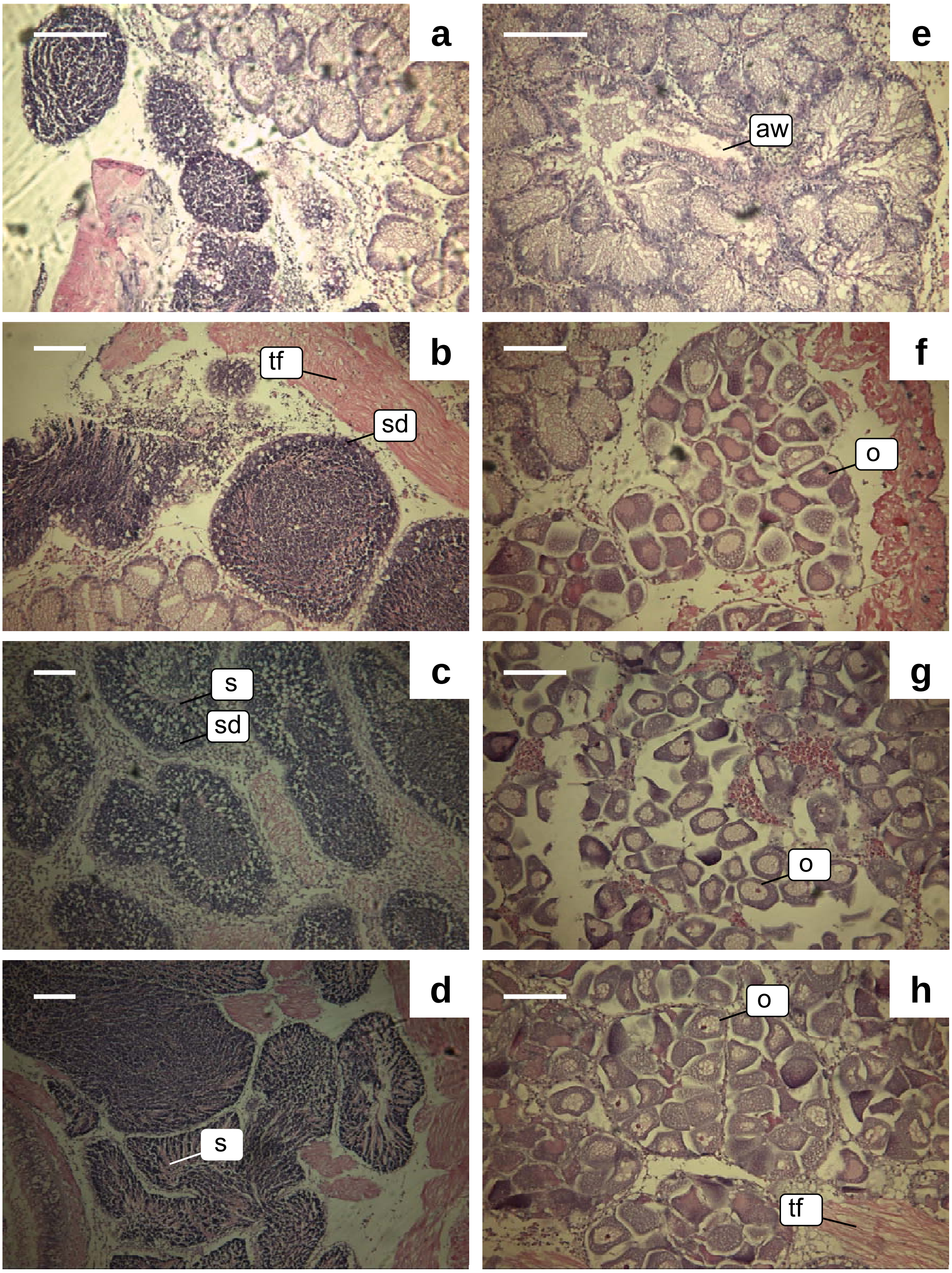


Figure 22. Photographs of histological sections from male (a – d) and female (e – h) mud cockle gonads that represented stages 2 – 5 (top to bottom). Labels *s*, *sd*, *aw*, *o* and *tf* refer to sperm, spermatids, alveolar wall, oocyte, and transverse fibre. Scale bars show 100 μm.

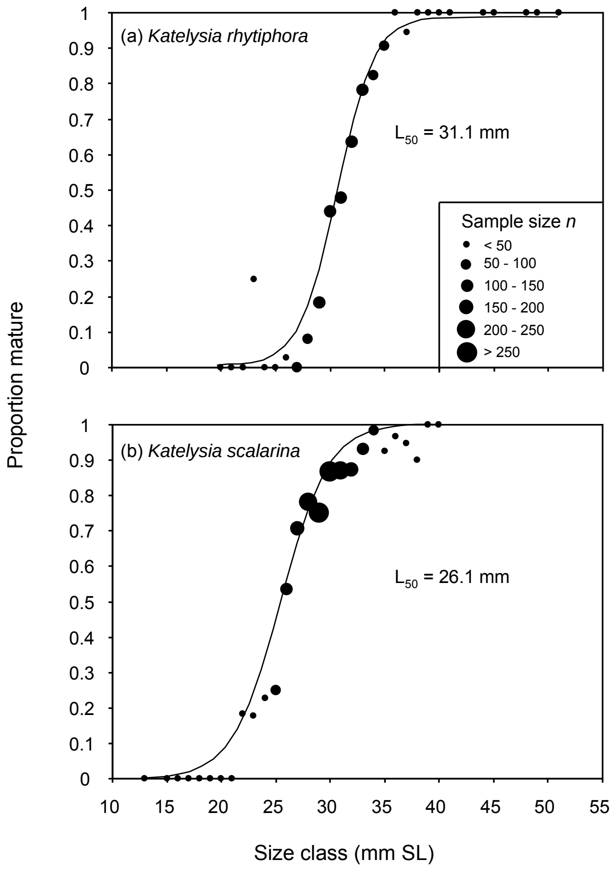


Figure 23. Proportion of mature mud cockles within each 1-mm length class for *K. rhytiphora* and *K. scalarina* collected from Coffin Bay. Data are pooled across sites and months.

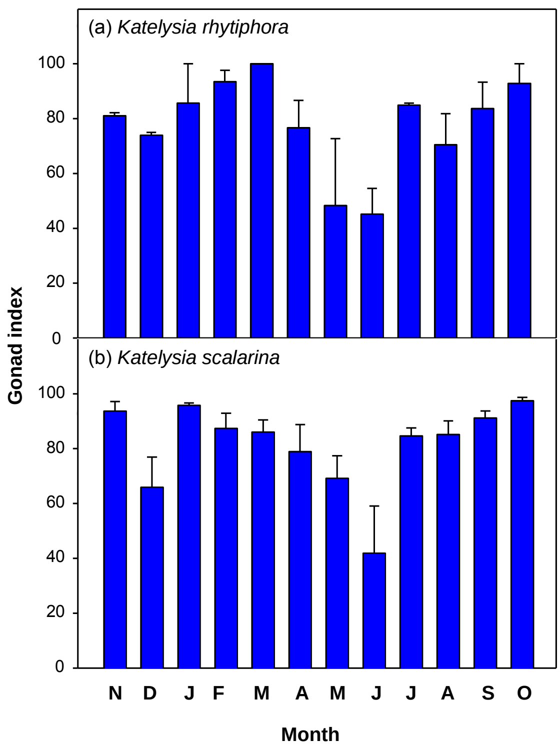


Figure 24. Temporal variation in the reproductive condition of *K. rhytiphora* and *K. scalarina*, measured as mean gonad index. Data includes all collected individuals greater than the size of first maturity (i.e. ≥ 32 mm SL and ≥ 27 mm SL, respectively).

4. DISCUSSION

The estimates of harvestable biomass and measures of size at first maturity (L_{50}) obtained in this study provide robust information for evaluating the suitability of the current management arrangements in the fishery, especially TACCs and size limits. This is because (1) the study provided a direct estimate of absolute harvestable biomass which is useful for setting TACCs (McGarvey et al. 2008; Mayfield et al. 2008); (2) the precision of the biomass estimates was maximised by targeting survey effort into productive fishing grounds identified by commercial fishers, with less sampling effort in unproductive areas; and (3) the measures of L_{50} were obtained from >3,000 mud cockles collected monthly from multiple locations in Coffin Bay. As estimates of L_{50} are likely to vary spatially, the primary limitation of this study is the lack of similarly robust estimates of L_{50} from the West Coast and Port River.

Data from the fishery-independent surveys show that densities of the three species comprising the fishery vary among and within fishing zones. All species were observed in each fishing zone. However, *K. peroni* was rare in Coffin Bay and absent from one area in the West Coast (Smoky Bay), and *K. rhytiphora* was uncommon in the West Coast and Port River fishing zones. In contrast, *K. scalarina* was relatively evenly distributed among fishing zones.

There were frequently large differences between the legal-sized and sub-legal-sized density for each species in each area. For example, no sub-legal-sized *K. peroni* were obtained from Area 1 on Section Bank, despite legal-sized *K. peroni* being present at low densities. Similarly, no legal-sized *K. rhytiphora* or *K. scalarina* were obtained from Area 3 in Coffin Bay even though the sub-legal-sized densities of both species in this area were substantial. This probably reflects periodic recruitment rather than use of different habitats by legal- and sub-legal-sized individuals.

Estimates of harvestable biomass are derived from the relationship between mud cockle density and the area of the survey regions. Thus, large areas with low densities (e.g. Area 3 on Section Bank) and small areas with high densities (e.g. Area 4 in Venus Bay) can both provide high levels of biomass.

In the Port River, the median estimates of harvestable biomass were 124 t for *K. peroni*, 13 t for *K. rhytiphora* and 106 t for *K. scalarina*. Collectively, these represent a median harvestable biomass of 243 t. The “80/10” rule (i.e. 10% harvest fraction from the 80% confidence limit of biomass) was used to set the 2009/10 TACC in this fishery at 22.6 t. This TACC was 77% below that in 2008/09 (100 t), which highlights the difficulty of setting sustainable TACCs using catch history alone.

In Coffin Bay, median estimates of harvestable biomass were 657 t and 44.8 t for *K. rhytiphora* and *K. scalarina*, respectively. The low density of *K. peroni* prevented biomass estimates of this species in this fishing zone. Application of the "80/10" rule in Coffin Bay would result in a TACC of 55 t. This is similar to the 2009/10 TACC of 56 t and about 20% lower than the TACC in 2008/09.

Estimates of the harvestable biomass of mud cockles from the West Coast were 28 t for *K. peroni*, 54 t for *K. rhytiphora* and 806 t for *K. scalarina*, which collectively provide a median harvestable biomass of 888 t. Most of this harvestable biomass was in Streaky Bay (384 t) and Venus Bay (312 t), with a smaller amount in Smoky Bay (191 t). Application of the "80/10" rule to the West Coast would result in a TACC of ~64 t, suggesting the current TACC of 15 t is conservative (i.e. "80/2.5") in comparison to those in the Coffin Bay and Port River commercial fishing zones.

Use of a simple harvest strategy rule (e.g. "80/10") to set TACCs is complicated in multi-species fisheries by differences in the biomasses of each species which are available for harvest due to variability in L_{50}. This can result in uneven exploitation rates across species. For example, the MLS in Coffin Bay is 38 mm SL, whereas estimates of L_{50} for *K. scalarina* and *K. rhytiphora* were 26.1 and 31.1 mm SL, respectively. Thus, the MLS in Coffin Bay exceeds L_{50} by 12 mm SL for *K. scalarina* and by 7 mm SL for *K. rhytiphora*. Whilst ~60% of *K. rhytiphora* exceed the MLS of 38 mm SL and are available for capture, only 5% *K. scalarina* exceeded this MLS. Thus, the biomass available for harvest in Coffin Bay is comprised almost entirely of *K. rhytiphora* (51.6 t; 94%), with *K. scalarina* (3.3 t; 6%) lightly exploited. The most biologically appropriate approach to enabling a greater proportion of *K. scalarina* to be harvested would be to develop species- and zone-specific management arrangements, including TACCs and size limits. However, the difficulty of distinguishing among the species and potential need for enhanced compliance arrangements need to be considered. An alternative approach would be a MLS that reflects a compromise between the L_{50} values for *K. rhytiphora* and *K. scalarina*. The primary difficulty with this option is that exploitation rates could still vary considerably among species.

In the Port River, the MLS (30 mm SL) appears relatively conservative for *K. scalarina*, as it exceeds L_{50} by 4 mm SL. However, the L_{50} for *K. peroni*, which comprises >50% of the harvestable biomass, is poorly understood. Edwards (1999) estimated L_{50} for *K. peroni* in the Port River at <25 mm SL. However, this estimate was obtained from limited data, and a more reliable measure of L_{50} is necessary to evaluate the suitability of a 30 mm SL MLS for this species. Nevertheless, *K. peroni* and *K. scalarina* have similar spatial distributions, population length structures and harvestable biomasses across Section Bank, and *K. rhytiphora* are uncommon (~5% of harvestable biomass). Hence, both species are equally available to the fishery, and are likely to be captured in proportion to their relative abundance. Thus, application of a consistent harvest rule (e.g. “80/10” rule) in the Port River fishing zone is less problematic than in Coffin Bay.

Estimates of harvestable biomass in the West Coast were dominated by *K. scalarina* (>90%), and the MLS of 30 mm SL seems relatively conservative for this species. Further, as all three species have similar population length structures and spatial distributions, each species is equally available to the fishery suggesting application of a consistent harvest rule (e.g. “80/10” rule) is appropriate. However, the MLS may provide inadequate protection for the spawning biomass of *K. rhytiphora* because the L_{50} for this species (31.1 mm SL) is larger than the MLS. More robust estimates of L_{50} for *K. peroni* are required to assess the suitability of a 30 mm SL MLS for this species in this fishing zone.

Determining harvest strategies from survey estimates of harvestable biomass in this multi-species fishery is complicated by the low and sporadic recruitment events exhibited by these species. Densities of sub-legal-sized mud cockles were typically much lower than those of legal-sized individuals in each fishing zone. Consequently, the survey length-frequency data were typically dominated by legal-sized individuals, and demonstrated the low abundance of small mud cockles (<25 mm SL) for all species in all fishing zones. The low abundance of small mud cockles confirms that recruitment occurs periodically (Eglinton 2001, Cantin et al. 2008) and provides no evidence of recent recruitment events.

In the absence of annual biomass surveys, application of the “80/10” rule relies on relatively stable recruitment to ensure consistent exploitation rates. If the TACC remains static across years, in the absence of surveys, and no recruitment to the fishable stock occurs, then the exploitation rate will increase over time. Consequently, under circumstances where recruitment is periodic and/or biomass surveys are not undertaken annually, the “80/10” rule may not ensure retention of adequate reproductive capacity to support future catches. The irregular recruitment displayed by mud cockles, in combination with recent, spatially-consistent reductions in CPUE, suggests existing adult stocks need to be managed using conservative harvest strategies. Surveys should also be undertaken regularly (e.g. biennially) to measure harvestable biomass and identify recruitment events.

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