Wild Fisheries

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

J. Dent, S. Mayfield, P. Burch, D. Gorman and T.M. Ward

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SARDI Aquatic Sciences
2 Hamra Avenue West Beach SA 5024

January 2012

Report to PIRSA Fisheries and Aquaculture

Government of South Australia

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EXECUTIVE SUMMARY

1. This is the second report to document surveys and provide estimates of harvestable, mud-cockle (*Katelysia* spp.) biomass in a risk-analysis framework across South Australia's commercial fishery. This information is suitable for optimising harvest strategies and evaluating the current fishery management arrangements.

2. The fishery is based on three species: *K. scalarina* ('greys'), *K. peronii* ('whites') and *K. rhytiphora* ('yellows'); the current total allowable commercial catches (TACCs) in the West Coast and Coffin Bay fishing zones are 18 t and 48.1 t, respectively.

3. In Coffin Bay, median estimates of harvestable biomass at the legislated minimum legal size (MLS; 38 mm SL) were considerably lower than those at the current MLS (33 mm SL). The estimates were 753 t and 1,267 t, respectively.

4. Median estimates of legal-sized (i.e. mud cockles larger than the MLS of 30 mm SL), mud-cockle biomass from the West Coast were 94 t for *K. peronii*, 247 t for *K. rhytiphora* and 749 t for *K. scalarina*. Collectively, this provides a median harvestable biomass of 1,090 t, most of which was in Streaky Bay (55%) and Venus Bay (28%).

5. Setting TACCs and MLSs in spatially-complex, multi-species fisheries is complicated by differences in the distribution, relative biomass and size-at-first-maturity (L_{50}) of the harvested species.

6. If the 2010 harvest strategy was applied against the current biomass estimates to set the TACC for 2012/13, the TACCs would be ~47 t and ~27 t in the Coffin Bay and West Coast fishing zones, respectively. As the mud-cockle stocks in each of the three West Coast fishing grounds likely comprise separate stocks, catches should be harvested from these areas in approximate proportion to the biomass available for harvest.

7. Mud-cockle recruitment occurs periodically, which requires careful management of adult stocks to maintain adequate spawning biomass. Continuation of biennial surveys that monitor temporal changes in population length structures and the abundance of legal-sized and sub-legal-sized mud cockles will reduce the risks of population crashes, as has occurred in the Port River mud-cockle fishing zone, resulting in its closure from July 2011.

1. INTRODUCTION

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

In South Australia (SA), the harvest of mud cockles began in the early 1960's, initially for use as bait or berley. Most of the catch was obtained from the Port River and Kangaroo Island. Historical records suggest fishers first supplied the human consumption market in Melbourne in 1986. Despite increasing demand, 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 Port River 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 2011). 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. Thus, TACCs for the West Coast, Coffin Bay and Port River fishing zones in 2009/10 were 15.0 t, 56.0 t and 22.6 t, respectively, but the value of the fishery remained at approximately AU$1.2M (Knight and Tsolos 2011).

Following the first assessment of harvestable biomass across the fishery, TACCs for 2010/11 were set at 21.0 t for the West Coast, 48.1 t for Coffin Bay and 11.3 t for the Port River. In addition, the minimum legal size (MLS) in Coffin Bay was reduced from 38 to 33 mm shell length (SL), through ministerial exemption, on the basis of the first estimate of the size-at-first maturity from this fishing zone. MLSs in the other two fishing zones remained at 30 mm SL. In response to sustainability concerns, the mud-cockle fishery in the Port River was closed from July 1st 2011. The TACCs in 2011/12 for the remaining fisheries – West Coast and Coffin Bay – were 18.0 t and 48.1 t, respectively.

This is the second report on the distribution, biomass and biology of mud cockles in SA. It follows from Gorman et al. (2010), which described and provided estimates of biomass from the first surveys for these species in SA and the size-at-maturity of mud cockles in Coffin Bay. The objectives of this study were to (1) estimate the current harvestable biomass of mud cockles in the Coffin Bay and West Coast fishing zones and (2) determine the size-at-first-maturity (L_{50}) for *K. scalarina*, *K. rhytiphora* and *K. peronii* in the West Coast fishing zone. This information will inform discussions regarding the suitability of the current management arrangements for the fishery, particularly the TACCs and minimum legal size limits. The closure of the Port River fishery resulted in this area not being surveyed in 2011 and, hence, this component of the fishery has been excluded from this report.

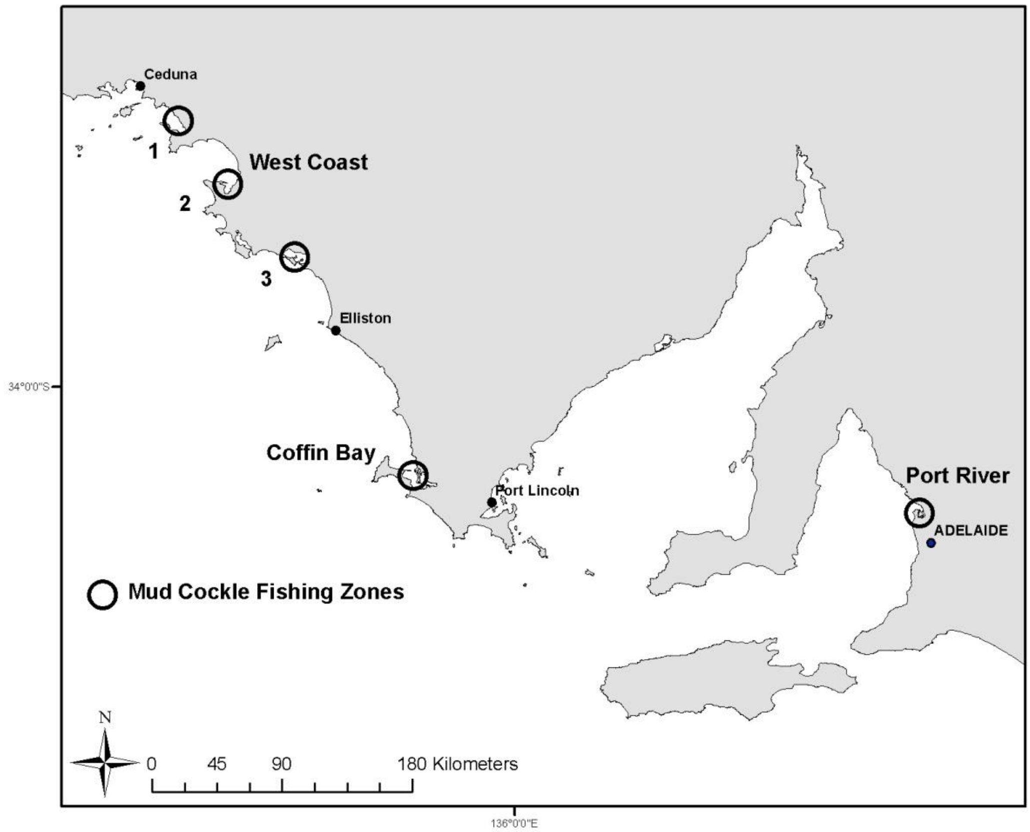

Figure 1. Map showing location of the three commercial mud-cockle fishing zones in South Australia: Port River, Coffin Bay and the West Coast. The West Coast zone comprises Smoky Bay (1), Streaky Bay (2) and Venus Bay (3).

2. METHODS

This study integrated data from two sources. These were (1) fishery-independent surveys, and (2) estimates of L_{50} for *K. peronii, K. rhytiphora* and *K. scalarina* for the West Coast fishing zone.

2.1 Fishery-independent surveys

2.1.1 Study sites and survey design

The focus of the study was to provide estimates of the harvestable biomass of mud cockles in bounded, stratified survey regions within two of the commercial fishing zones: Coffin Bay and the West Coast. The latter comprises Smoky Bay, Streaky Bay and Venus 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) and previously for mud cockles in SA (Gorman et al. 2010, 2011). Fishers within each zone identified productive fishing grounds, with high and low mud cockle densities, on large-scale aerial photographs. Information on the location of these grounds from returned maps was uploaded into ArcGIS V9.3. Boundaries were drawn around the fishing grounds, showing the locations of high and low mud-cockle densities (termed strata). The resultant maps were returned to fishers to confirm the location of the fishing grounds. Once confirmed, point sampling locations were distributed systematically 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.

The Coffin Bay survey region comprised four survey areas (Figure 2). Three of these survey areas comprised both high and low density strata. The West Coast survey region comprised 22 survey areas: eight in Smoky Bay, three in Streaky Bay and eleven in Venus Bay (Figure 3).

2.1.2 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 (~40 cm in width by 20 cm in height), with a mesh insert (2 cm diagonal mesh size), was used to collect mud cockles along a 2-m belt transect. The contents of the mesh insert (sand, dead shell and cockles) was transferred to a plastic crate with square openings in the base (7 mm) and washed. Mesh selectivity was not examined. Surveys were undertaken in October 2011 at Coffin Bay and in November 2011 for the West Coast.

Collections obtained from each site were bagged, labelled and frozen. Each sample was sorted to remove any dead shells and separated by species (after Edwards 1999). The samples from the West Coast were then separated into the legal-sized (≥ 30 mm shell length (SL)) and sub-legal-sized components (< 30 mm SL). For Coffin Bay, the samples were separated into four size categories (< 30 mm; 30–32.9 mm; 33–37.9 mm; ≥ 38 mm). Each size category was counted and weighed. All mud cockles obtained from the West Coast were measured to the nearest 0.1 mm along the longest axis (SL) and the maximum shell width (SW), perpendicular to SL, using digital vernier callipers. For Coffin Bay all *K. rhytiphora* and *K. peronii* were measured as above, but the high number of *K. scalarina* obtained (> 6,500) necessitated sub-sampling, which was achieved by systematically selecting every third sample. Relationships between SL and SW were evaluated using Pearson's correlation.

2.1.3 Estimates of harvestable biomass

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.

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 mud-cockle biomass were ranked, and the 10%, 20%, . . . , 90% quantile confidence intervals (CI's) extracted. The median estimates of harvestable biomass presented in the results are the 50% quantile from this bootstrap. The bootstrap was implemented in the statistical package R 2.12.2.

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

Figure 3. Map showing the survey areas for the West Coast which includes Smoky Bay, Streaky Bay and Venus Bay

2.2 Size at first maturity

Approximately 200 mud cockles were collected from each of Smoky Bay, Streaky Bay and Venus Bay during November 2011. Specimens were fixed using formaldehyde (10% neutral buffered Formalin) and the preserved samples subsequently transferred into an ethanol solution (70% in seawater) prior to assessment of reproductive physiology.

In the laboratory, samples were separated by species. Each specimen was measured for SL and most were measured for SW to the nearest 0.1 mm using digital vernier callipers. For those samples from which SW was not measured, a species-specific relationship between SL and SW, from a linear regression (SW=a(SL)+b), was used to retrospectively assign a value for SW (*K. scalarina*: SW=0.49*SL-1.60; *K. peronii*: SW=0.38*SL-2.06). Thereafter, 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 4). Individual specimens were then examined under a dissecting microscope (up to 10 × magnification) and were assigned a gonad score, defined using a categorical scale from 1 to 5, modified from (Edwards 1999). This scale describes a qualitative series of developmental stages (Figure 4; Table 1) and relies on the assumption that the correlation between gonad score assignment and histological analysis from Coffin Bay in 2010 (Gorman et al. 2010, 2011) applies to the West Coast. Those individuals for which the gonad material indicated that they had spawned were considered mature, but allocated a gonad score of “post-spawned” (PS) to differentiate them from other specimens.

Mature gonads were observed in all individuals assigned a gonad score of ≥ 3 or PS. The proportion of mature individuals of each species was plotted for each 1-mm SL and SW class, and a logistic curve of the form $y = 1/(1+\exp(-(a+bx)))$ fitted to the data by maximum likelihood. The SL (L_{50}) and SW (W_{50}) at which 50% of individuals were mature (i.e. size-at-first maturity) were extracted from the logistic curve equation parameters.

Table 1. Criteria used to stage the gonad development of mud cockles from the West Coast. 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

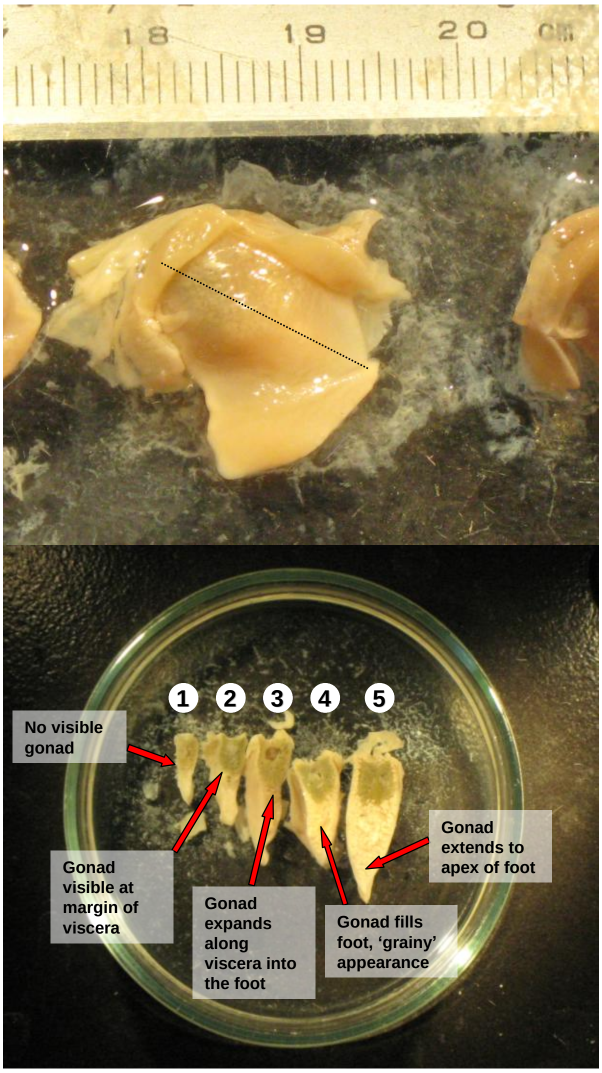

Figure 4. Photographs depicting the line of dissection (top) and gonad stage attributed to the variation in mud cockles (bottom).

3. RESULTS

3.1 Estimates of density and harvestable biomass

3.1.1 Coffin Bay

A total of 8,755 mud cockles were obtained from the 254 sampling sites. *Katelysia scalarina* was the numerically dominant species (6,798; ~77%), followed by *K. rhytiphora* (1,932; ~22%) and *K. peronii* (25; < 1%). For *K. rhytiphora*, legal-sized individuals were observed in all areas/strata. Legal-sized *K. scalarina* were recorded in seven of eight strata, but sub-legal-sized individuals were collected from all of the areas surveyed. Legal-sized and sub-legal sized *K. peronii* were observed in half of the strata surveyed.

Estimates of the density of mud cockles <30 mm SL for *K. scalarina*, *K. rhytiphora* and *K. peronii* were 14.9 ± 3.9, 3.0 ± 0.6 and 0.1 ± 0.1 mud cockles.m^{-2}, respectively. In contrast, density estimates of large cockles (≥ 38 mm SL) were dominated by *K. rhytiphora* (5.0 ± 1.1 mud cockles.m^{-2}), with few *K. scalarina* (0.3 ± 0.1 mud cockles.m^{-2}) or *K. peronii* (0.01 ± 0.01 mud cockles.m^{-2}) exceeding this size.

The median estimate of total harvestable biomass, at a minimum legal size (MLS) of 33 mm SL, was substantially greater for *K. rhytiphora* (1,032 t) than for either *K. scalarina* (233 t) or *K. peronii* (1.6 t; Table 2). At an alternate MLS of 30 mm SL, median estimates of harvestable biomass were 1.7-times greater for *K. scalarina* (403 t) and 2.3-times higher for *K. peronii* (3.6 t), but similar for *K. rhytiphora* (1,117 t; Table 2).

The mean size of *K. rhytiphora* (34.3 mm SL) was larger than that of *K. scalarina* (27.4 mm SL). The small number of *K. peronii* (25) observed in Coffin Bay impedes calculation of a mean length. At the current MLS of 33 mm SL, the population structure of *K. rhytiphora* was dominated by legal-sized individuals (64%), while *K. scalarina* had a very high proportion of sub-legal-sized individuals (82%; Figure 5). Importantly, for both species, the proportions of the populations between 20 and 25 mm SL in 2011 (*K. rhytiphora*: 14%; *K. scalarina* 39%) were substantially greater than those in 2009 (*K. rhytiphora*: 6%; *K. scalarina* 14%). This suggests recent recruitment to both stocks.

Table 2. Potential catches (t, whole weight) of *K. peronii, K. rhytiphora* and *K. scalarina* at three alternate minimum legal sizes (top: 38 mm SL; middle 33mm 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 October 2011. 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.

(1) MLS 38mm SL

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(0.0)**	**(0.0)**	**(0.0)**	**(0.5)**	**(0.5)**	**(0.5)**	**(0.5)**	**(1.0)**	**(1.0)**
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
0.15	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
0.2	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
(b) *K. rhytiphora*	**(515.0)**	**(581.0)**	**(631.2)**	**(675.0)**	**(717.2)**	**(759.9)**	**(807.3)**	**(863.5)**	**(944.8)**
0.02	10.3	11.6	12.6	13.5	14.3	15.2	16.1	17.3	18.9
0.05	25.8	29.0	31.6	33.7	35.9	38.0	40.4	43.2	47.2
0.1	51.5	58.1	63.1	67.5	71.7	76.0	80.7	86.4	94.5
0.15	77.3	87.1	94.7	101.2	107.6	114.0	121.1	129.5	141.7
0.2	103.0	116.2	126.2	135.0	143.4	152.0	161.5	172.7	189.0
(c) *K. scalarina*	**(26.5)**	**(29.3)**	**(31.5)**	**(33.4)**	**(35.2)**	**(37.2)**	**(39.3)**	**(41.8)**	**(45.4)**
0.02	0.5	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9
0.05	1.3	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.3
0.1	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.2	4.5
0.15	4.0	4.4	4.7	5.0	5.3	5.6	5.9	6.3	6.8
0.2	5.3	5.9	6.3	6.7	7.0	7.4	7.9	8.4	9.1

Table 2. continued…

(2) MLS 33mm SL

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(0.4)**	**(0.8)**	**(1.1)**	**(1.3)**	**(1.6)**	**(1.9)**	**(2.2)**	**(2.6)**	**(3.2)**
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
0.05	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2
0.1	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3
0.15	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.5
0.2	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6
(b) *K. rhytiphora*	**(749.7)**	**(842.0)**	**(911.4)**	**(972.9)**	**(1032.3)**	**(1092.5)**	**(1158.0)**	**(1237.0)**	**(1350.9)**
0.02	15.0	16.8	18.2	19.5	20.6	21.8	23.2	24.7	27.0
0.05	37.5	42.1	45.6	48.6	51.6	54.6	57.9	61.9	67.5
0.1	75.0	84.2	91.1	97.3	103.2	109.2	115.8	123.7	135.1
0.15	112.5	126.3	136.7	145.9	154.8	163.9	173.7	185.6	202.6
0.2	149.9	168.4	182.3	194.6	206.5	218.5	231.6	247.4	270.2
(c) *K. scalarina*	**(189.0)**	**(203.6)**	**(214.5)**	**(224.1)**	**(233.3)**	**(242.6)**	**(252.8)**	**(265.2)**	**(282.8)**
0.02	3.8	4.1	4.3	4.5	4.7	4.9	5.1	5.3	5.7
0.05	9.4	10.2	10.7	11.2	11.7	12.1	12.6	13.3	14.1
0.1	18.9	20.4	21.5	22.4	23.3	24.3	25.3	26.5	28.3
0.15	28.3	30.5	32.2	33.6	35.0	36.4	37.9	39.8	42.4
0.2	37.8	40.7	42.9	44.8	46.7	48.5	50.6	53.0	56.6

(3) MLS 30mm SL

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(1.7)**	**(2.2)**	**(2.7)**	**(3.2)**	**(3.6)**	**(4.0)**	**(4.6)**	**(5.2)**	**(6.1)**
0.02	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.05	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3
0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6
0.15	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9
0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2
(b) *K. rhytiphora*	**(813.8)**	**(912.3)**	**(986.7)**	**(1053.2)**	**(1117.3)**	**(1182.1)**	**(1252.8)**	**(1338.1)**	**(1461.3)**
0.02	16.3	18.2	19.7	21.1	22.3	23.6	25.1	26.8	29.2
0.05	40.7	45.6	49.3	52.7	55.9	59.1	62.6	66.9	73.1
0.1	81.4	91.2	98.7	105.3	111.7	118.2	125.3	133.8	146.1
0.15	122.1	136.8	148.0	158.0	167.6	177.3	187.9	200.7	219.2
0.2	162.8	182.5	197.3	210.6	223.5	236.4	250.6	267.6	292.3
(c) *K. scalarina*	**(327.6)**	**(352.2)**	**(370.9)**	**(387.2)**	**(402.9)**	**(419.1)**	**(436.9)**	**(458.2)**	**(488.5)**
0.02	6.6	7.0	7.4	7.7	8.1	8.4	8.7	9.2	9.8
0.05	16.4	17.6	18.5	19.4	20.1	21.0	21.8	22.9	24.4
0.1	32.8	35.2	37.1	38.7	40.3	41.9	43.7	45.8	48.9
0.15	49.1	52.8	55.6	58.1	60.4	62.9	65.5	68.7	73.3
0.2	65.5	70.4	74.2	77.4	80.6	83.8	87.4	91.6	97.7

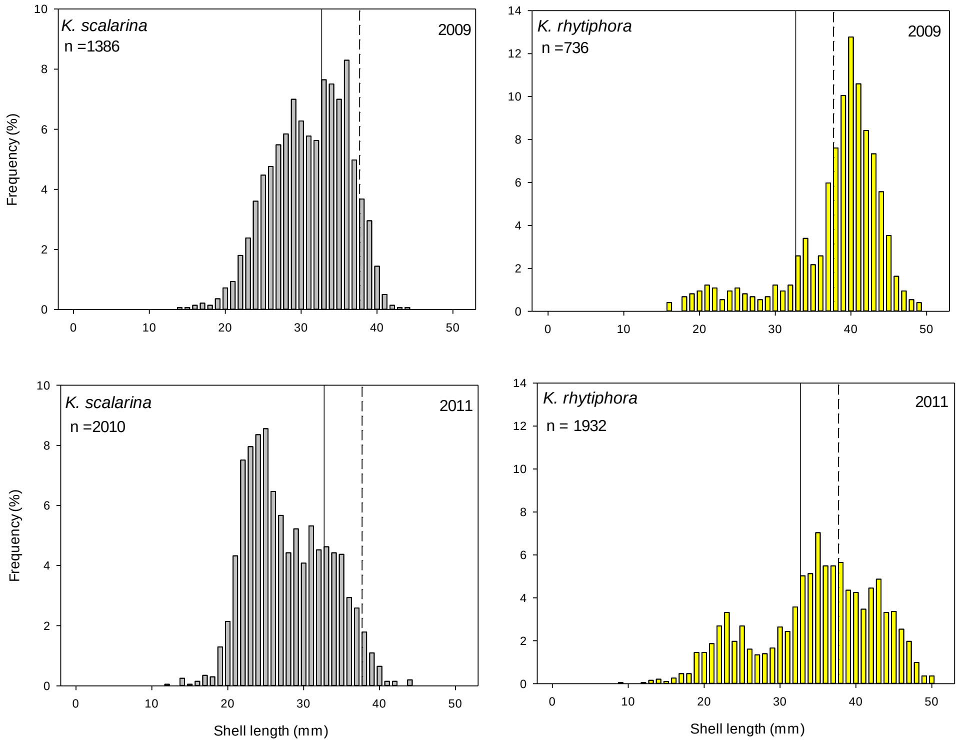

Figure 5. Length-frequency distributions for *K. scalarina* and *K. rhytiphora* obtained from Coffin Bay. The dashed line indicates the legislated MLS (38 mm SL) and the solid line indicates the current MLS of 33 mm SL, in place under a ministerial exemption. Note scales on y-axis vary.

3.1.2 West Coast

A total of 5,672 mud cockles were obtained from the 126 sampling sites. The numerically dominant species was *K. scalarina* (3,962; ~70%), followed by *K. peronii* (1,043; ~18%) and *K. rhytiphora* (667; ~12%).

The mean density estimates of legal-sized *K. scalarina* were 10.4 ± 2.4 mud cockles.m^{-2} at Smoky Bay, 26.0 ± 6.6 mud cockles.m^{-2} at Streaky Bay and 11.5 ± 4.0 mud cockles.m^{-2} at Venus Bay. For *K. rhytiphora*, the densities were 0.9 ± 0.2, 11.1 ± 3.9 and 2.1 ± 0.9 mud cockles.m^{-2} in these three areas, respectively. Mean densities of legal-sized *K. peronii* were typically low.

Median estimates of the total harvestable biomass of *K. scalarina* in Smoky Bay (158 t), Streaky Bay (400 t) and Venus Bay (191 t; Table 3) were generally substantially greater than those for either *K. rhytiphora* (range: 11–209 t) or *K. peronii* (range: 0.1–83 t). The median estimate of the total harvestable biomass for all species combined in the West Coast fishing zone was 1,090 t and was dominated by *K. scalarina* (749 t; ~69%). Most of the harvestable biomass was observed in Streaky Bay (619 t; 57%), rather than in either Smoky Bay (170 t; 15%) or Venus Bay (301 t; 28%).

Legal-sized individuals (≥ 30 mm SL) dominated the length-frequency distributions of mud cockles across the West Coast fishing zone (*K. scalarina*: 50%; *K. rhytiphora*: 82%; Figure 6). For *K. peronii*, 37.5% of cockles sampled were above the MLS and the proportion of the population between 20 and 25 mm SL has increased from 10% in 2009 to 27% in 2011, suggesting recent recruitment of this species. Mean sizes ranged from 29.5 mm (*K. scalarina*) to 35.0 mm (*K. rhytiphora and K. peronii*).

Table 3. Potential, legal-sized (≥ 30 mm SL) catches (t, whole weight) of *K. peronii*, *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 2011. 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.

(1) Smoky Bay

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(0.0)**	**(0.0)**	**(0.0)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.2)**	**(0.2)**
0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(b) *K. rhytiphora*	**(7.6)**	**(8.9)**	**(9.9)**	**(10.7)**	**(11.5)**	**(12.3)**	**(13.2)**	**(14.2)**	**(15.7)**
0.02	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
0.05	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8
0.1	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4	1.6
0.15	1.1	1.3	1.5	1.6	1.7	1.9	2.0	2.1	2.3
0.2	1.5	1.8	2.0	2.1	2.3	2.5	2.6	2.8	3.1
(c) *K. scalarina*	**(112.7)**	**(127.9)**	**(139.1)**	**(148.8)**	**(158.0)**	**(167.3)**	**(177.1)**	**(188.6)**	**(204.5)**
0.02	2.3	2.6	2.8	3.0	3.2	3.3	3.5	3.8	4.1
0.05	5.6	6.4	7.0	7.4	7.9	8.4	8.9	9.4	10.2
0.1	11.3	12.8	13.9	14.9	15.8	16.7	17.7	18.9	20.5
0.15	16.9	19.2	20.9	22.3	23.7	25.1	26.6	28.3	30.7
0.2	22.5	25.6	27.8	29.8	31.6	33.5	35.4	37.7	40.9

Table 3. continued…

(2) Streaky Bay

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(4.9)**	**(6.8)**	**(8.1)**	**(9.3)**	**(10.8)**	**(12.0)**	**(13.4)**	**(15.1)**	**(17.7)**
0.02	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.4
0.05	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9
0.1	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.8
0.15	0.7	1.0	1.2	1.4	1.6	1.8	2.0	2.3	2.7
0.2	1.0	1.4	1.6	1.9	2.2	2.4	2.7	3.0	3.5
(b) *K. rhytiphora*	**(118.0)**	**(147.4)**	**(169.8)**	**(189.7)**	**(208.7)**	**(228.1)**	**(249.5)**	**(274.7)**	**(310.5)**
0.02	2.4	2.9	3.4	3.8	4.2	4.6	5.0	5.5	6.2
0.05	5.9	7.4	8.5	9.5	10.4	11.4	12.5	13.7	15.5
0.1	11.8	14.7	17.0	19.0	20.9	22.8	25.0	27.5	31.1
0.15	17.7	22.1	25.5	28.5	31.3	34.2	37.4	41.2	46.6
0.2	23.6	29.5	34.0	37.9	41.7	45.6	49.9	54.9	62.1
(c) *K. scalarina*	**(283.2)**	**(319.1)**	**(347.8)**	**(374.2)**	**(399.9)**	**(427.2)**	**(457.9)**	**(495.2)**	**(550.4)**
0.02	5.7	6.4	7.0	7.5	8.0	8.5	9.2	9.9	11.0
0.05	14.2	16.0	17.4	18.7	20.0	21.4	22.9	24.8	27.5
0.1	28.3	31.9	34.8	37.4	40.0	42.7	45.8	49.5	55.0
0.15	42.5	47.9	52.2	56.1	60.0	64.1	68.7	74.3	82.6
0.2	56.6	63.8	69.6	74.8	80.0	85.4	91.6	99.0	110.1

(3) Venus Bay

Harvest Fraction	Probability (%) (of legal biomass estimate, t)								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
(a) *K. peronii*	**(47.7)**	**(59.0)**	**(67.7)**	**(75.5)**	**(83.1)**	**(90.9)**	**(99.6)**	**(109.9)**	**(124.7)**
0.02	1.0	1.2	1.4	1.5	1.7	1.8	2.0	2.2	2.5
0.05	2.4	3.0	3.4	3.8	4.2	4.5	5.0	5.5	6.2
0.1	4.8	5.9	6.8	7.6	8.3	9.1	10.0	11.0	12.5
0.15	7.2	8.9	10.1	11.3	12.5	13.6	14.9	16.5	18.7
0.2	9.5	11.8	13.5	15.1	16.6	18.2	19.9	22.0	24.9
(b) *K. rhytiphora*	**(12.4)**	**(16.1)**	**(19.4)**	**(24.1)**	**(26.8)**	**(29.4)**	**(34.5)**	**(38.0)**	**(45.1)**
0.02	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9
0.05	0.6	0.8	1.0	1.2	1.3	1.5	1.7	1.9	2.3
0.1	1.2	1.6	1.9	2.4	2.7	2.9	3.5	3.8	4.5
0.15	1.9	2.4	2.9	3.6	4.0	4.4	5.2	5.7	6.8
0.2	2.5	3.2	3.9	4.8	5.4	5.9	6.9	7.6	9.0
(c) *K. scalarina*	**(125.6)**	**(144.2)**	**(161.1)**	**(176.6)**	**(191.3)**	**(206.8)**	**(225.2)**	**(247.5)**	**(280.1)**
0.02	2.5	2.9	3.2	3.5	3.8	4.1	4.5	5.0	5.6
0.05	6.3	7.2	8.1	8.8	9.6	10.3	11.3	12.4	14.0
0.1	12.6	14.4	16.1	17.7	19.1	20.7	22.5	24.8	28.0
0.15	18.8	21.6	24.2	26.5	28.7	31.0	33.8	37.1	42.0
0.2	25.1	28.8	32.2	35.3	38.3	41.4	45.0	49.5	56.0

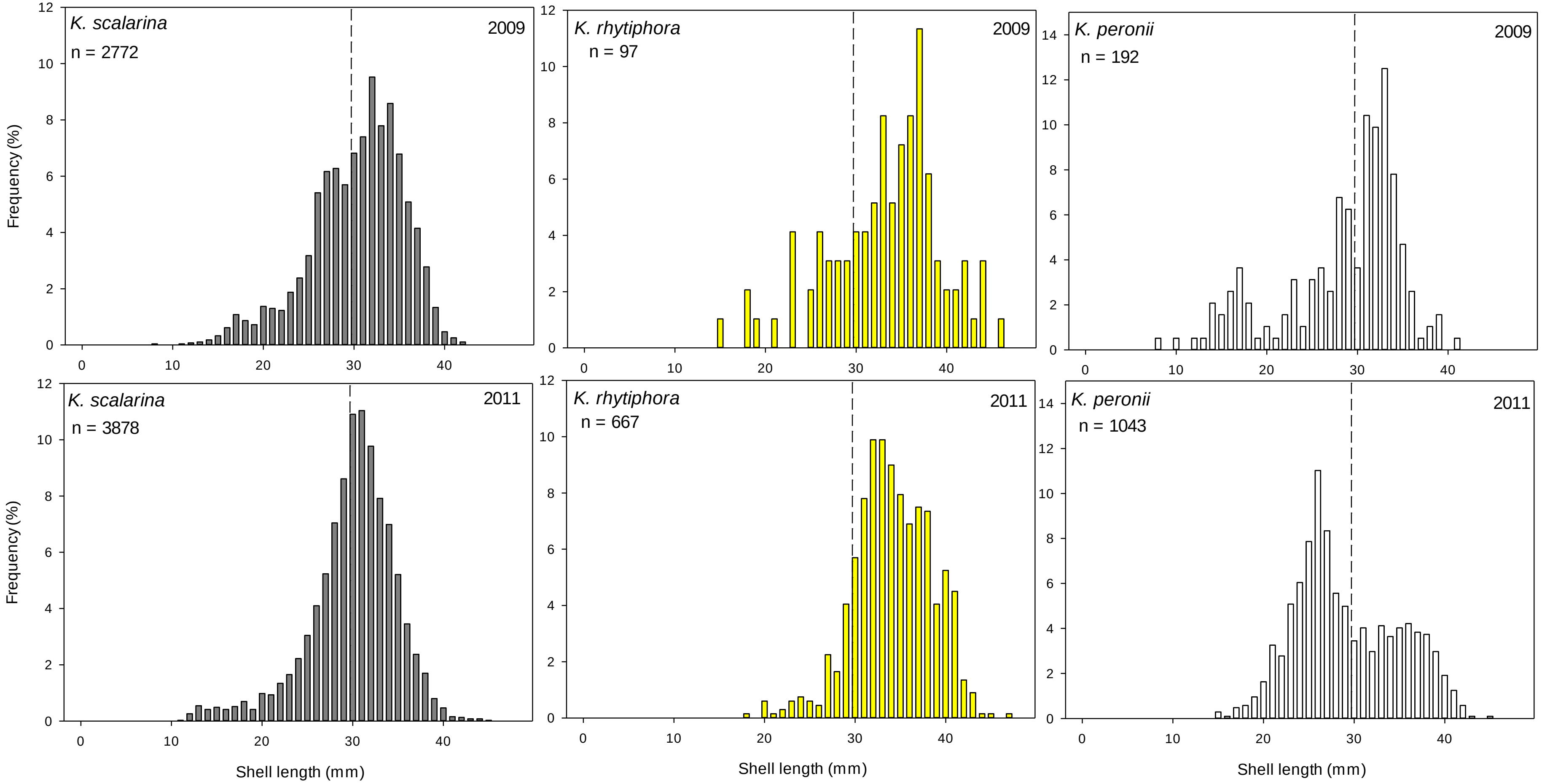

Figure 6. Length-frequency distributions for *K. scalarina*, *K. peronii* and *K. rhytiphora* obtained from the West Coast fishing zone. Dashed line indicates the MLS of 30 mm SL. Note scales on y-axis vary.

3.2 Relationship between shell length and shell width

There were strong, positive correlations between SL and SW for mud cockles obtained from the Coffin Bay (Pearson's correlation; *K. rhytiphora*: r = 0.96, P < 0.001, SW=0.47*SL-2.25; *K. scalarina*: r = 0.96, P < 0.001, SW=0.43*SL-0.53) and West Coast (*K. rhytiphora*: r = 0.88, P < 0.001, SW=0.47*SL-1.94; *K. scalarina*: r = 0.92, P < 0.001, SW=0.49*SL-1.18; *K. peronii*: r = 0.96, P < 0.001, SW=0.53*SL-2.38) fishing zones. However, despite the strength of these relationships, there was considerable variation in SW with SL. For example, for *K. scalarina* in Coffin Bay, SW ranged from 9.2 – 15.6 mm for those individuals that were within 1 mm SL of the current MLS (33 mm SL; i.e. 32 – 33.9 mm SL), although >70% had a SW between 13.1 and 14.6 mm (Figure 7). Similarly, for *K. rhytiphora* within the same SL range, most (>70%) individuals had a SW between 13.0 and 14.5 mm. In the West Coast fishing zone, variation in SW when SL was within 1 mm of the MLS (30 mm SL) was greatest for *K. scalarina* (range: 10.9–16.3 mm SW) and smallest for *K. peronii* (range: 11.5–15.3 mm SW; Figure 8).

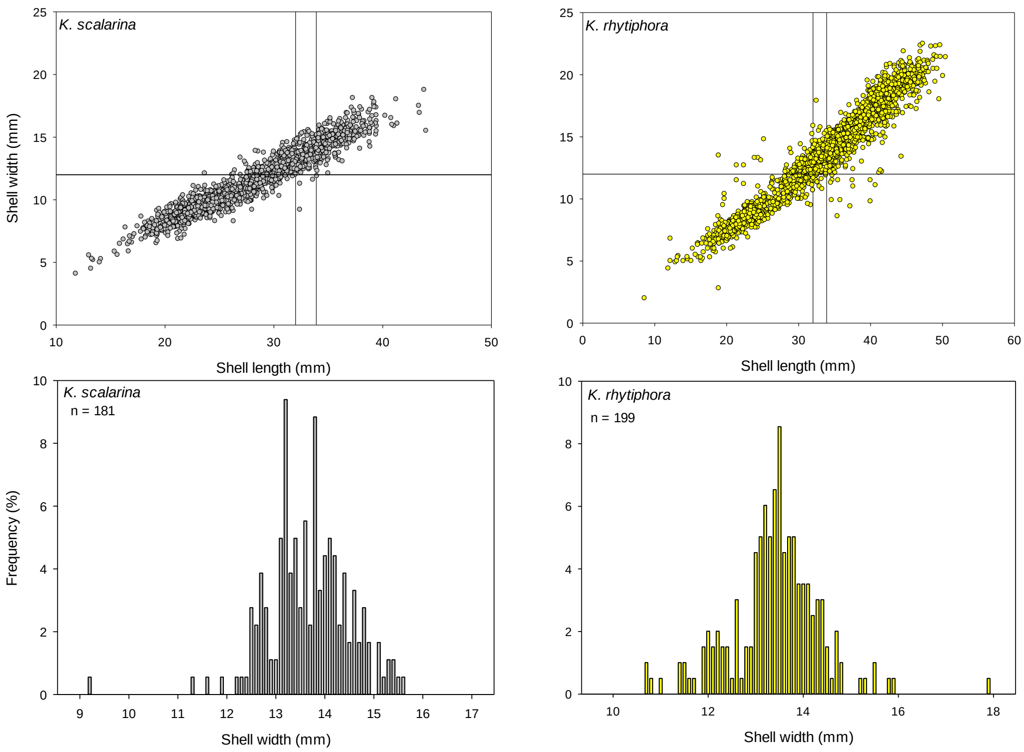

Figure 7. Relationship between SL and SW (top) and frequency distribution of SW (bottom) for *K. scalarina* and *K. rhytiphora* from Coffin Bay. In the top plots, vertical lines show the length range (32.0 – 33.9 mm SL) used for the width-frequency distributions and the horizontal line indicates a SW of 12 mm.

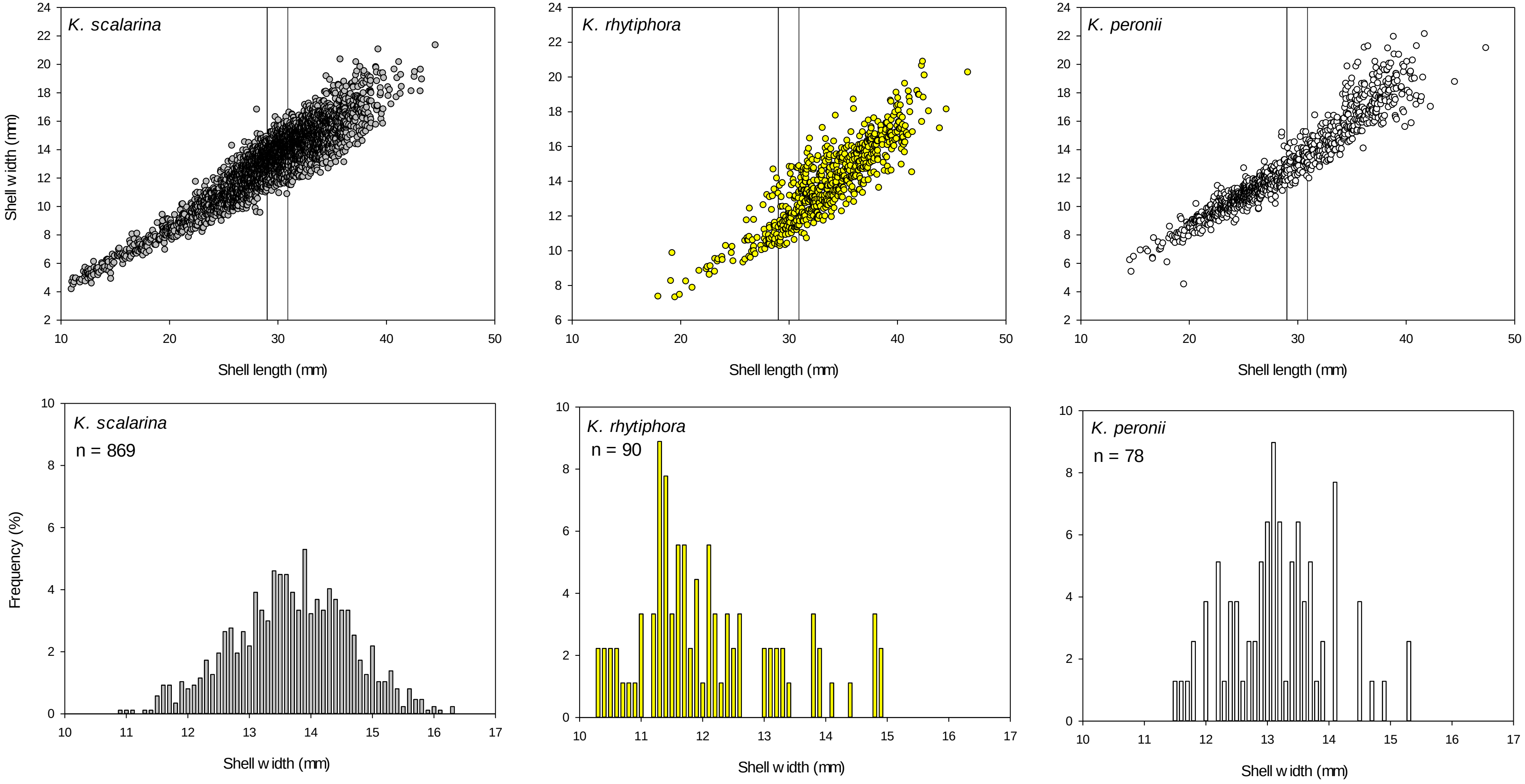

Figure 8. Relationship between SL and SW (top) and frequency distribution of SW (bottom) for *K. scalarina*, *K. rhytiphora* and *K. peronii* from the West Coast. In the top plots, vertical lines show the length range (29.0 – 30.9 mm SL) used for the width-frequency distributions.

3.3 Size at first maturity

Of the 738 mud-cockle specimens collected, 84 were *K. peronii* (11.4%), nine were *K. rhytiphora* (1.2%) and 645 (87.4%) were *K. scalarina*. The low number of *K. rhytiphora* meant that an estimate of size at maturity could not be obtained for this species. For *K. scalarina*, the estimates of L_{50} and W_{50} were 23.2 mm SL and 9.3 mm SW, respectively (Figure 9). No definitive assessment of the size at which *K. peronii* mature was possible. However, all individuals < 25 mm SL were immature and > 80% of individuals larger than 27 mm SL were mature, suggesting that L_{50} for *K. peronii* is likely to be larger than that estimated for *K. scalarina*.

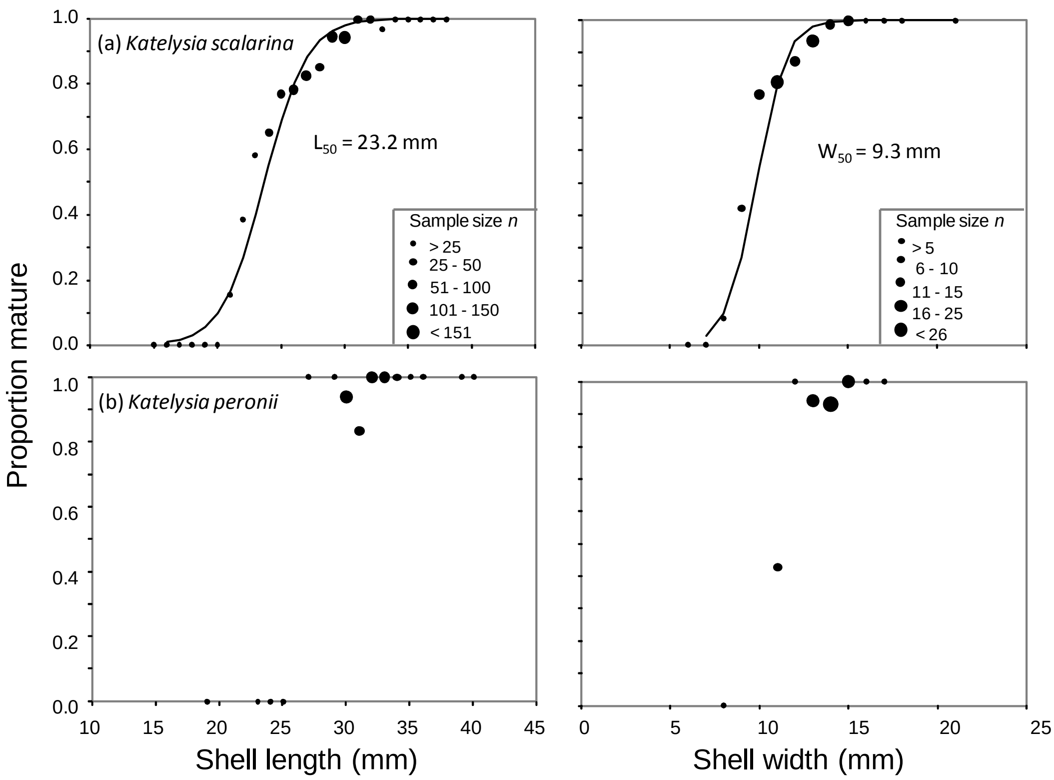

Figure 9. Proportion of mature *K. scalarina* (top) and *K. peronii* (bottom) within each 1-mm shell length (left hand side) and shell width (right hand side) class. Estimates of L_{50} and W_{50} were derived from the parameters of the logistic equation fitted to the data. Note data are pooled across the three bays comprising the West Coast fishing zone.

4. DISCUSSION

Optimising harvests in multi-species, spatially-complex fisheries is challenging and typically requires information on the composition, distribution, abundance, biomass and basic biology of the component species (Mangel *et al*. 1996; Haddon *et al*. 2006). This is clearly exhibited by the large reductions in TACCs across the SA mud-cockle fishery, initially set on the basis of catch history, following surveys in 2009 to estimate harvestable, mud-cockle biomass (Gorman et al. 2010, 2011). Consequently, the information presented in this report, which is the second to document the surveys and analysis of size-at-maturity across SAs commercial mud-cockle fishery, remains the most suitable for optimising harvest strategies and evaluating the suitability of current management arrangements in this fishery, including TACCs and MLSs (Mayfield et al. 2008; McGarvey et al. 2008; Gorman et al. 2010, 2011). The estimates of harvestable biomass and size-at-first maturity (L_{50}) obtained in these studies provide robust information because (1) they provide an estimate of absolute harvestable biomass from which TACCs can be set directly (Mayfield et al. 2008; McGarvey 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 (Ault et al. 1999); and (3) measures of L_{50} have been obtained from > 3,000 and > 700 mud cockles across the Coffin Bay and West Coast fishing zones, respectively.

The assessment of mud-cockle distribution, harvestable biomass and biology undertaken in Coffin Bay in 2009 (Gorman et al. 2010) identified that (1) the median estimates of the harvestable biomass (i.e. > 38 mm SL) of *K. rhytiphora* and *K. scalarina* were 657 t and 45 t, respectively; (2) ~60% of *K. rhytiphora* but only 5% of *K. scalarina* exceeded this SL and were available for capture; and (3) that there were large differences in the estimates of L_{50} between *K. rhytiphora* (31.1 mm SL) and *K. scalarina* (26.1 mm SL) that warranted consideration of species-specific MLSs and TACCs. Subsequent to discussions among all stakeholders, the MLS was reduced to 33 mm SL and the TACC set using a simple harvest strategy rule (i.e. the “80/6” rule (6% harvest fraction from the 80% confidence limit of biomass)). However, in consideration of the length-frequency distributions of the two species and their different estimates of L_{50}, this TACC was determined by applying the 80/6 rule to the biomass of *K. rhytiphora* and *K. scalarina* above 38 and 33 mm SL, respectively. If this approach was applied to the current estimates of harvestable biomass, the TACC would be set at ~47 t, which is similar to the 48.1 t TACC allocated to the Coffin Bay fishing zone in 2010/11 and 2011/12. The minor adjustments to TACCs that would arise from the re-application of the harvest strategy used in 2010 suggests there has been little change in the harvestable biomass of mud cockles across this fishing zone since the 2009 survey.

Despite the downward adjustment of the MLS in Coffin Bay (38 – 33 mm SL) from 2010/11, that increased fishers access to *K. scalarina*, the use of a single, smaller MLS in this fishery does not adequately overcome the problems created by differences in the biology (especially variability in L_{50}) among species and the relative proportions of those species that exceed the MLS (Haddon et al. 1996; Cranfield and Michael 2001; Prince et al. 2008; Gorman et al. 2011). For example, the current MLS (33 mm SL) exceeds the estimates of L_{50} for *K. scalarina* and *K. rhytiphora* by ~7 and ~2 mm SL, respectively. Similarly, whilst ~68% of *K. rhytiphora* exceed the current MLS and are available for capture, only 23% *K. scalarina* achieved this size. Thus, the biomass available for harvest in Coffin Bay (i.e. > 33 mm SL) is dominated by *K. rhytiphora* (80%), with *K. scalarina* (20%) remaining lightly exploited.

As identified previously (Gorman et al. 2011), the most biologically appropriate means of resolving this discrepancy, and thereby enabling a greater proportion of *K. scalarina* to be harvested, would be the development of species-specific size limits and TACCs. An alternative to the use of a MLS based on SL would be to develop a comparable measure based on shell width (SW). Whilst this approach may be more suited to the grading process undertaken by the commercial fishers in the fishery, selection of a single minimum legal width (MLW) is problematic because SW varies considerably both among individual mud cockles with the same SL and between the two species. Thus, if the MLS was set at, for example, 12 mm SW, then a large number of immature *K. rhytiphora* (based on SL) could potentially be harvested. Conversely, if a SW of 15 mm formed the basis of the MLS, few *K. scalarina* would be available for harvest. Although these difficulties confirm that species-specific MLSs remain the most tenable approach to resolving the problems generated by use of a single MLS, the perceived difficulty of distinguishing among species and the potential need for enhanced compliance arrangements also need to be re-considered.

With the exception of Streaky Bay, where the median estimate of harvestable biomass was ~50% greater in 2011 (618 t), when compared with that in 2009 (384 t), estimates of harvestable biomass obtained from the West Coast fishing zone were similar across surveys. The difference at Streaky Bay primarily reflected the inclusion of additional commercial fishing grounds to the area surveyed, rather than an increase in the density of mud cockles in this area between surveys. In 2010/11, the

TACC for this fishing zone was set at 21 t using an 80/3.3 rule, predominantly because commercial fishers identified that there was inadequate capacity to effectively or efficiently harvest a larger TACC (Gorman et al. 2011) that would have been available had the rule applied in Coffin Bay been used (i.e. 80/6; 39 t). Application of the 80/3.3 rule to the 2011 survey data results in a TACC of ~27 t, which is considerably greater than that set for 2010/11 or 2011/12 (18 t). Importantly, the spatial distribution of the harvestable biomass – 55% in Streaky Bay, 28% in Venus Bay and 17% in Smoky Bay – suggests that current strategies, which target commercial harvests into the three bays in approximate proportion to the distribution of the harvestable biomass, should remain. This is because the mud-cockle stocks in each fishing ground likely comprise separate metapopulations (Morgan and Shepherd 2006), requiring this spatial structure to be formally incorporated into management of the fishery (Taylor and Dizon 1999; Lorenzen et al. 2010).

Consistent with documented spatial variation in the biology of mud cockles (Cranfield and Michael 2001) and other benthic marine invertebrates – at both local and regional scales (Saunders and Mayfield 2008) – the lower estimate of L_{50} obtained for *K. scalarina* in the West Coast (23.2 mm SL), whilst similar to previous estimates (Fowler and Eglinton 2002), was smaller than that obtained from Coffin Bay (26.1 mm SL; Gorman et al. 2010, 2011). Estimates of L_{50} are also required for the other two species, especially for *K. rhytiphora* as the proportion of this species contribution to the harvestable biomass has increased substantially between surveys. However, there is a less urgent need for species-specific size limits in the West Coast fishery than in Coffin Bay. This is because the estimates of harvestable biomass in the West Coast remain dominated by *K. scalarina* (> 70%) and the MLS exceeds L_{50} for this species by > 6 mm SL.

Continued use of the harvest strategies now established for use in the SA mud cockle fishery needs to consider the infrequent and sporadic recruitment typically exhibited by cockles (Warner and Chesson 1985; Sakurai et al. 1998; Ripley and Caswell 2006). This is perhaps best achieved by the (1) continuation of biennial surveys that monitor temporal changes in population length structures and the abundance of legal-sized and sub-legal-sized mud cockles, and (2) the ongoing use of conservative harvest strategies so that the risks of population crashes are reduced (Ripley and Caswell 2006). The need for conservatism is well demonstrated by the history of the Port River mud-cockle fishery where unconstrained catches, the use of catch history to set excessive TACCs and mass mortality from two extended heatwaves have culminated in the closure of this fishery from July 2011.

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