Species compositions of elasmobranchs caught by three different commercial fishing methods off southwestern Australia, and biological data for four abundant bycatch species

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Abstract—Commercial catches taken in southwestern Australian waters by trawl fisheries targeting prawns and scallops and from gillnet and longline fisheries targeting sharks were sampled at different times of the year between 2002 and 2008. This sampling yielded 33 elasmobranch species representing 17 families. Multivariate statistics elucidated the ways in which the species compositions of elasmobranchs differed among fishing methods and provided benchmark data for detecting changes in the elasmobranch fauna in the future. Virtually all elasmobranchs caught by trawling, which consisted predominantly of rays, were discarded as bycatch, as were approximately a quarter of the elasmobranchs caught by both gillnetting and longlining. The maximum lengths and the lengths at maturity of four abundant bycatch species, *Heterodontus portusjacksoni*, *Aptychotrema vincentiana*, *Squatina australis*, and *Myliobatis australis*, were greater for females than males. The L_{50} determined for the males of these species at maturity by using full clasper calcification as the criterion of maturity did not differ significantly from the corresponding L_{50} derived by using gonadal data as the criterion for maturity. The proportions of the individuals of these species with lengths less than those at which 50% reach maturity were far greater in trawl samples than in gillnet and longline samples. This result was due to differences in gear selectivity and to trawling being undertaken in shallow inshore waters that act as nursery areas for these species. Sound quantitative data on the species compositions of elasmobranchs caught by commercial fisheries and the biological characteristics of the main elasmobranch bycatch species are crucial for developing strategies for conserving these important species and thus the marine ecosystems of which they are part.

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The impact of commercial fisheries on the populations of sharks and rays has, in recent years, become an issue of international concern (Stevens et al., 2000; Walker et al., 2005). It is important to recognize, however, that elasmobranchs are not only targeted by certain fisheries, but also comprise a substantial component of the bycatch of commercial fisheries, such as those employing trawl nets, gillnets, and longlines (Stevens et al., 2000; Stobutzki et al., 2001; Walker, 2005a). An assessment of the impacts of commercial fishing on the elasmobranchs taken as bycatch is hindered by the fact that most of that catch is typically reported as "unidentified shark" or "mixed fish," or not reported at all (Walker, 2005a). The numbers of sharks and rays taken as bycatch by commercial fisheries may, in some cases, exceed those of the targeted species, and many of those individuals die either during capture or after they are discarded (Bonfil, 1994; Stobutzki et al., 2002; Walker, 2005a). Although, in most studies of commercial fisheries, nontargeted species are referred to as bycatch, Walker et al. (2005) emphasized that some of those species are usually retained and thus constitute byproduct, whereas the others are usually discarded and therefore constitute bycatch in the strict sense.

In an assessment of various commercial fisheries throughout the world, it was shown that trawl fisheries targeting prawns generate the largest amount of bycatch (Cook, 2003) and that the mortality of individuals in that bycatch is substantial (Bonfil, 1994). Indeed, it has been estimated that approximately two thirds of the elasmobranchs caught as bycatch in Australia's northern prawn trawl fishery die while in the net (Stobutzki et al., 2002). Furthermore, that study demonstrated that most of these individuals are small, and more than half are immature and some are caught immediately after birth.

Many elasmobranchs are at or near the apex of marine food webs and thus their removal can have a significant impact on the trophic structure of an ecosystem (Camhi et al., 1998; Stevens et al., 2000; Shepard and Myers, 2005). Furthermore, certain biological characteristics of elasmobranchs, such as their long life spans, low fecundities, and late ages at maturity, limit their ability both to withstand fishing pressure, either when targeted or caught incidentally, and to recover from overexploitation (Stevens et al., 2000; Walker, 2005a; Gallucci et al., 2006). In general, the populations of endemic species or those that have localized distributions tend to be most prone to overfishing (Stevens et al., 2000). Moreover, there are little or no data on the reproductive biology of most bycatch species. Such data are required for determining the resilience of these species to fishing pressure, thereby enabling the development of management plans for conserving their populations (Frisk et al., 2001; Stobutzki et al., 2002; Walker, 2005b).

Most of the species in Australia's rich diversity of elasmobranchs are endemic and occupy demersal habitats on the continental shelf or slope (Last and Stevens, 2009) and are thus potentially prone to depletion by demersal fishing methods such as trawling, gillnetting, and longlining (Stobutzki et al., 2001, 2002; Coelho et al., 2003; Perez and Wahrlich, 2005, Walker et al., 2005). Analyses of fisheries data for 1994 to 1999 showed that the bycatch species *Heterodontus portusjacksoni* (Heterodontidae) and *Myliobatis australis* (Myliobatidae) are abundant in catches of the temperate demersal gillnet and longline fisheries of southwestern Australia (McAuley and Simpfendorfer, 2003). These two species and the rhinobatid *Aptychotrema vincentiana* and the squatinid *Squatina australis*, which are also caught as bycatch by commercial fisheries, collectively contributed as much as 17% to the total biomass of the 172 species of fish caught during extensive trawling along the lower west coast of Australia (Hyndes et al., 1999). It has been estimated that approximately half of the elasmobranchs taken as bycatch by commercial trawlers in this region are likely to die during or after capture (Laurenson et al.[1]). Despite the potentially detrimental effects of commercial fishing on the above four elasmobranch species and their ecological importance in the temperate waters of southern Australia, sound biological data have been collected only for *H. portusjacksoni* (McLaughlin and O'Gower, 1971; Tovar-Ávila et al., 2007; Jones et al., 2008; Powter and Gladstone, 2008).

The families to which the above four species belong are represented elsewhere in the world by species that are taken in substantial numbers as bycatch. For example, in the eastern Pacific, up to a thousand individuals of the heterodontid shark *Heterodontus mexicanus* may be caught in a single gillnet set, many of which die (Garayzar, 2006). In some parts of the world, the populations of several species of rhinobatid and squatinid have been so drastically depleted from overfishing that they have been listed as critically endangered (Morey et al., 2006; Lessa and Vooren, 2007). In eastern Australia, the commercial landings of *Myliobatis australis* have been steadily increasing to the point where their stocks now need to be monitored (White et al., 2006).

The first aim of the present study was to determine the numbers, and thereby the percent contributions, of the females and males of each shark and ray species in samples of commercial catches taken in southwestern Australian waters by demersal trawling for prawns and scallops and by demersal gillnetting and longlining for sharks. These data enabled the percent contributions made by the bycatch and byproduct to the total elasmobranch catch to be estimated for each fishing method. The percent contributions of each species to the catches obtained by trawling, gillnetting, and longlining were then used to compare statistically the species compositions of the elasmobranchs in the catches taken by each of these fishing methods.

Emphasis was next placed on determining the length compositions of the bycatch species *H. portusjacksoni, A. vincentiana*, *S. australis*, and *M. australis* in samples collected by trawling, gillnetting, and longlining and on estimating the lengths at maturity of the last three of these ecologically important species. The lengths of both the females and males at which 50% are mature (L_{50}) were first determined by using gonadal data as the criterion for determining maturity and then, in the case of males, by employing full clasper calcification as that criterion. The L_{50} calculated for the males of each species by using the two maturity criteria were then compared to ascertain whether the L_{50} derived by using clasper calcification as the index of maturity is a reasonable proxy for that derived using gonadal stage as that criterion. The L_{50} at maturity of *A. vincentiana*, *S. australis*, and *M. australis* and of *H. portusjacksoni* (Jones et al., 2008) were then employed to determine the proportions of both sexes of each of these four species that were caught by each fishing method before they had the opportunity to reproduce. Finally, the management and conservation implications of our data are considered.

Materials and methods

Sampling regime

The elasmobranchs were examined in commercial catches from 69 demersal trawls, 24 demersal gillnets, and 19 longline sets of fishing vessels operating in southwestern Australian waters southwards of 32° S lat. on the west coast and then eastwards to 118° E long. on the south coast (Fig. 1). Trawling targets the western king prawn (*Melicertus latisulcatus*) and the Ballot's saucer scallop (*Amusium balloti*), whereas demersal gillnetting and longlining target mainly the gummy shark (*Mustelus antarcticus*), the dusky shark (*Carcharhinus obscurus*), and the whiskery shark (*Furgaleus macki*) (McAuley and Simpfendorfer, 2003). Sampling, which was undertaken between November 2002 and November 2008, was designed to ensure that the catches of each fishing method were sampled at least once, and generally on at least three occasions, in each season of the calendar year. The trawl, gillnet, and longline fishermen, whose catches were selected for sampling, were those that fished regularly and readily allowed us onboard, and whose methods were representative of those used in the area that is fished. The numbers of each elasmobranch species caught by each fishing method on each sampling occasion were recorded, as also were the sexes of all individuals except for those of a few species in a small number of trawl samples when the catches of those species were particularly large, in which case the sexes of

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[1] Laurenson, L. J. B., P. Unsworth, J. W. Penn, and R. C. J. Lenanton. 1993. The impact of trawling for saucer scallops and western king prawns on the benthic communities in coastal waters off south-western Australia, 93 p. Fisheries Res. Report, Department of Fisheries, no.100 (part 1), Western Australia.

each individual in a large, randomly selected subsample were recorded. Each elasmobranch species caught by gillnetting and longlining was categorized as either targeted, byproduct, or bycatch, whereas those taken by trawling, where prawns and scallops are the target species, were categorized as either byproduct or bycatch.

Trawling was undertaken mainly at depths of 8 to 13 m in a marine embayment on the lower west coast of Western Australia and, to a lesser extent, at depths ≤32 m and at distances within 20 km from the mainland along that coast. The trawl net, in which the codend consisted of 45-mm mesh, was towed for 60–180 min at a speed of ~6.5 km/h. Commercial gillnet fishermen deployed up to 7000 m of either 165- or 178-mm stretched mesh net that was set for up to 24 hours at depths of 24–73 m, whereas longlines, consisting of 360 hooks attached to approximately 6400 m of mainline, were set for an average of 3 hours at depths of 65–73 m.

Multivariate analysis

The square root of the percent contribution of the number of each elasmobranch species to the total catch of all elasmobranchs recorded in each sample during regular onboard observations of the catches taken by each fishing method was used to construct a Bray-Curtis similarity matrix, which was then subjected to nonmetric multidimensional scaling (nMDS). One-way analysis of similarities (ANOSIM) was used to test whether the species compositions of the elasmobranch catches taken by the three fishing methods were significantly different and, if so, pair-wise ANOSIM tests were used to test for differences between the compositions of the elasmobranchs obtained by each pair of methods. The R-statistic value was then employed to ascertain the extent of any differences between the compositions of those catches (Clarke, 1993). R-statistic values approaching 1 demonstrate that the species composition of the *a priori* groups differed markedly, and a value of approximately 0 indicates that the species compositions of those groups are very similar. Similarity percentages (SIMPER; Clarke, 1993) were used to identify the species that typify the samples obtained by each fishing method and which species are responsible for discriminating between the samples caught by each pair of methods. The ordination and associated tests were undertaken with the PRIMER vers. 6 statistical package (Clarke and Gorley, 2006).

Length and weight measurements

A randomly selected subset of individuals collected during regular onboard observations, together with additional randomly selected individuals provided by commercial fishermen, yielded a total of 516 *H. portusjacksoni*, 340 *A. vincentiana*, 362 *S. australis*, and 218 *M. australis,* which were brought to the laboratory and processed. The data derived from the samples were used to construct length-frequency histograms and to derive sex ratios and reproductive data for the species. The sex of each individual was recorded and the total length (*TL*—tip of snout to tip of tail) and total weight (*W*) of each *H. portusjacksoni, A. vincentiana* and *S. australis* were measured and weighed to the nearest 1 mm and 1 g, respectively. The disc length (*DL*— tip of snout to the junction of the tail and pelvic fins) of each *M. australis* was measured to the nearest 1 mm and the disc width (*DW*) and weight of each fully intact individual were recorded to the nearest 1 mm and 1 g, respectively. The relationships between *DW* and *DL*, *DL* and *DW,* and between the natural logarithms of *W* and *DL* and of *W* and *DW* for intact *M. australis* were calculated by using least trimmed squares (LTS) regression. A resampling test was used to demonstrate that the above data for the two sexes could be pooled. The above relationships were used to estimate the *DW* and *W* of the small number of *M. australis* (~15%) whose pectoral fins had been removed by fishermen for commercial sale. Note that, in the results, the sample size (n) and coefficient of determination (r^2) refer to the trimmed data for the individuals used for the analyses.

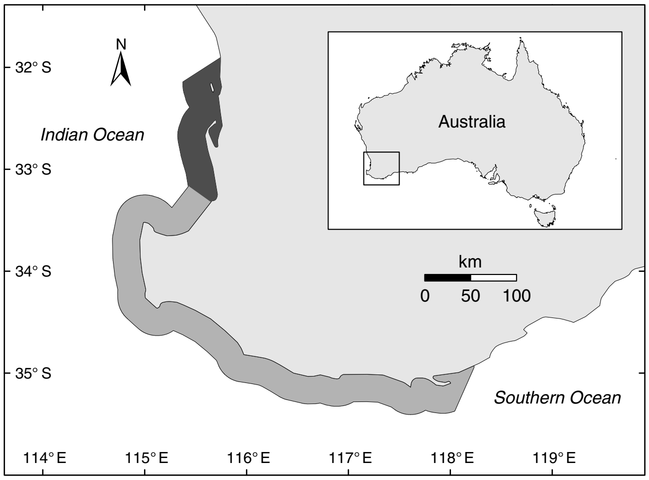

Figure 1

Map showing the region between the northernmost and easternmost limits of southwestern Australia from which elasmobranchs were recorded onboard commercial trawling (dark gray area) and gillnetting and longlining vessels (light and dark gray areas).

Length at maturity

The reproductive tracts of the females and males of *A. vincentiana*, *S. australis*, and *M. australis* were assigned to one of the following maturity stages by using the criteria outlined in White et al. (2001). For females, stage 1 = uteri small and thin and oocytes not macroscopically visible; stage 2 = uteri enlarging but still thin and oocytes becoming visible but not yet containing yolk; stage 3 = uteri enlarged and oocytes yolked; stage 4 = pregnant, and stage 5 = uteri or cloaca distended, indicating that parturition had recently occurred. For males, stage 1 = seminal vesicles small and thin and testes not well defined; stage 2 = seminal vesicles enlarging and starting to become coiled, but testes not yet lobed; stage 3 =

seminal vesicles tightly coiled and testes lobed; and stage 4 = similar to stage 3, but with semen present in the distal portion of the seminal vesicle. Individuals with reproductive tracts at stages 1 and 2 are regarded as sexually immature, whereas those at stages 3 and 4 and, in females, also at stage 5, can reproduce or have reproduced and are therefore considered mature. When we alternatively employed full clasper calcification as the indicator of maturity, we considered that males with noncalcified and partially calcified claspers were sexually immature, and those with fully calcified claspers were mature because they have the ability to copulate.

The probability (P) that an individual is mature was assumed to be a logistic function of its length (L):

$$P = \left\{1 + \exp\left[-(\alpha + \beta L)\right]\right\}^{-1}, \tag{1}$$

where α and β are parameters that determine the location and shape of the logistic curve.

The parameters α and β were transformed to the lengths L_{50} (TL_{50} or DL_{50}) and L_{95} (TL_{95} or DL_{95}) by which 50% and 95% of fish have attained maturity, respectively, using the equations

$$L_{50} = -\alpha / \beta, \tag{2}$$

$$L_{95} = \left[\log_e(19) - \alpha\right] / \beta. \tag{3}$$

The equation for the probability that a fish is mature thus becomes

$$P = \left\{1 + \exp\left[-\log_e(19)(L - L_{50})/(L_{95} - L_{50})\right]\right\}^{-1}. \tag{4}$$

Logistic relationships of the above form were derived for females and males of *A. vincentiana*, *S. australis*, and *M. australis* by using gonadal maturity status, i.e., ≥stage 3, as the criterion for maturity and, in addition, for males, employing full clasper calcification as the criterion for maturity. Logistic regression analysis was used to fit these logistic curves by using Solver in Excel (Microsoft, Redmond, WA) to maximize the log-likelihood. We used likelihood-ratio tests (Cerrato, 1990) to compare the L_{50} of the females and males of each species at maturity using gonadal status as the criterion for maturity and to compare the L_{50} derived for males using both gonadal and clasper calcification status as the criteria for maturity. For the likelihood-ratio tests, the hypothesis that the data for both the females and males of each species could be described by a common logistic curve was rejected at the α=0.05 level of significance if the test statistic, calculated as twice the difference between the log-likelihoods obtained by fitting maturity curves with a common value of L_{50} for both sexes and by fitting separate maturity curves for each sex, exceeded $\chi^2_{\alpha}(q)$, where q is the difference between the numbers of parameters in the two approaches. Note that the L_{50} of females and males of *H. portusjacksoni* at maturity had been determined previously with this approach (Jones et al., 2008). WinBUGS (Lunn et al., 2000) was also used to fit the logistic curves to the maturity-at-length data for the females and males of each species and to calculate the proportion that were mature at length, thereby enabling derivation of the upper and lower confidence intervals for the L_{50} and L_{95} values and for the proportion of mature males and females in each 50-mm length class (see Jones et al. [2008] for further details of this WinBUGS analysis).

Results

Species compositions by fishing method

A total of 4820 individual elasmobranchs, representing 10 families and 22 species of sharks and 7 families and 11 species of rays, were recorded during regular onboard examinations of the catches of commercial trawl, gillnet, and longline vessels operating off the southwestern coast of Australia (Tables 1–3).

The 2986 elasmobranchs caught by prawn and scallop trawling were dominated by rays, which comprised 10 of the 14 species and contributed 87% to the total elasmobranch catch (Table 1). The species of a single family of rays, the Urolophidae, comprising four species and two genera, contributed as much as 67% to the total trawl catch of elasmobranchs. The two species of shark (*H. portusjacksoni* and *S. australis*) and the two species of ray (*A. vincentiana* and *M. australis*), whose biological characteristics were determined (see later), each contributed between 4.5% and 8% to the total number of elasmobranchs caught by trawling and collectively as much as 25% (Table 1). Two species of shark, *M. antarcticus* and *C. brevipinna*, which were caught in very small numbers, were retained and thus constituted byproduct.

Gillnet catches yielded 1260 elasmobranchs, representing 19 species of shark and 6 species of ray, with sharks contributing 96% to the total catch of elasmobranchs (Table 2). The most abundant species in the gillnet catches was a targeted shark, *Carcharhinus obscurus*, which contributed more than a third to the total elasmobranch catch. The other two targeted species, *Mustelus antarcticus* and *Furgaleus macki*, which were dominated by females, ranked third and fifth in terms of abundance, respectively, and contributed an additional 14.2% and 6.5%, respectively (Table 2). The second most numerous species, however, was the shark *H. portusjacksoni*, a bycatch species, which constituted one-fifth of the total catch. None of the six species of ray caught by gillnetting was abundant in the catches obtained by this method. The byproduct and bycatch species contributed 18.7% and 25.7%, respectively, to the total gillnet catch. Thirteen of these species, which contributed more than one third to the total number of individuals of elasmobranchs caught, were always discarded as bycatch.

The 22 species of elasmobranch caught by longlining were dominated by one of the three targeted species, *M. antarcticus*, which made up 63% of the total catch of 574 individual elasmobranchs (Table 3). The next four most

Table 1

Number of females and males and percentage contribution of females of each elasmobranch species (sex determined during regular onboard observations) in the catches of trawl vessels fishing for prawns and scallops on the lower west coast of Australia. The total number of individuals of each species (including those whose sex could not be determined owing to logistic constraints) and the percent contribution of each species to the total elasmobranch catch are also given. Plain font* = byproduct species, i.e., those that are not targeted but usually retained; Bold font = bycatch species, i.e., those that are usually discarded.

Common name	Species name	Female *n*	Male *n*	Female %	Total *n*	Total %
Lobed stingaree	***Urolophus lobatus***	422	288	59.4	851	28.5
Sparsely-spotted stingaree	***Urolophus paucimaculatus***	235	349	40.2	726	24.3
Masked stingaree	***Trygonoptera personata***	84	66	56.0	277	9.3
Western shovelnose ray	***Aptychotrema vincentiana***	124	99	55.6	237	7.9
Port Jackson shark	***Heterodontus portusjacksoni***	112	110	50.5	223	7.5
Southern fiddler ray	***Trygonorrhina dumerilii***	94	118	44.3	220	7.4
Western shovelnose stingaree	***Trygonoptera mucosa***	23	27	46.0	153	5.1
Southern eagle ray	***Myliobatis australis***	67	81	45.3	148	5.0
Australian angelshark	***Squatina australis***	67	66	50.4	135	4.5
Smooth stingray	***Dasyatis brevicaudata***	2	6	25.0	8	0.3
Gummy shark*	*Mustelus antarcticus**	4	1	80.0	5	0.2
White-spotted guitarfish	***Rhynchobatus australiae***	1	0	100.0	1	< 0.1
Spinner shark*	*Carcharhinus brevipinna**	0	1	0	1	< 0.1
Coffin ray	***Hypnos monopterygius***	0	1	0	1	< 0.1
Total		1235	1213		2986	

abundant species, which were all bycatch, consisted of three species of rays and the shark *H. portusjacksoni* and collectively contributed nearly a quarter of the individual elasmobranchs obtained by longlining. The other two targeted species, *C. obscurus* and *F. macki*, contributed only 3.8% and 0.9%, respectively, to the total catch taken by longlining. The 19 nontargeted species caught by longlining comprised eight species that were always discarded as bycatch and represented one quarter of the total catch.

On the ordination plot, derived from the similarity matrix constructed by using percent contributions of the various species to the elasmobranch catches obtained by the three fishing methods, the samples for longlining lie above those for gillnetting, and both of these lie to the right of the discrete group comprising the trawl samples (Fig. 2). One-way ANOSIM confirmed that the compositions of the samples obtained by the three fishing methods were significantly different ($P=0.001$, global $R=0.753$). Pair-wise ANOSIM tests revealed that the compositions in the samples collected by each method differed significantly from those in the samples obtained by each other method (all $P<0.001$), and the R-statistic was similarly high for trawling vs. gillnetting (0.797) and trawling vs longlining (0.774) and greater than that for gillnetting vs longlining (0.515).

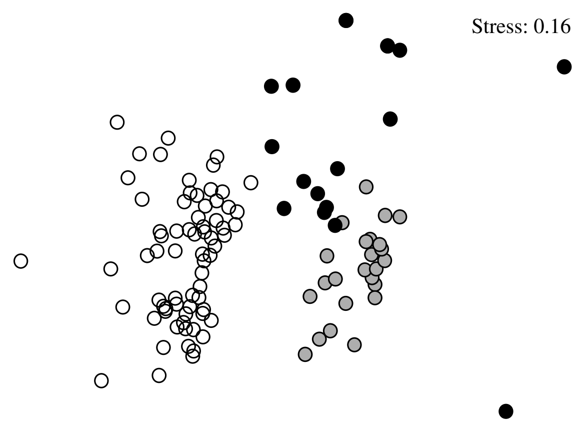

Figure 2

Nonmetric multidimensional scaling (nMDS) ordination plot, derived from the matrix constructed from the percentage contribution (square root transformed) of each elasmobranch species recorded during each of the regular onboard observations of the catches of commercial trawling (open circles), gillnetting (gray circles), and longlining vessels (black circles).

The most important of the typifying species for the trawl samples, i.e., those that were most abundant and were found most frequently, comprised two ray species, *A. vincentiana* and *Urolophus paucimaculatus*, and two shark species, *H. portusjacksoni* and *S. australis* (Table 4). *Heterodontus portusjacksoni* and *M. antarcticus* were also important typifying species for the elasmobranch catches taken by both gillnetting and longlining. *Carcharhinus obscurus* is a particularly important typifying species for the gillnet samples and the same is true for the bycatch ray species *Dasyatis brevicaudata* for the longline samples. Relatively greater

Table 2

Number of females and males, percent contribution of females, and the total number and percent contributions of each elasmobranch species that were recorded during regular onboard observations of catches from gillnet vessels on the southwest coast of Australia. Plain font = targeted species; Plain font* = byproduct species i.e., those species not targeted but usually retained; Bold font = bycatch species, i.e., those species that are usually discarded.

Common name	Species name	Female *n*	Male *n*	Female %	Total *n*	Total %
Dusky shark	*Carcharhinus obscurus*	229	208	52.4	437	34.7
Port Jackson shark	***Heterodontus portusjacksoni***	131	120	52.2	251	19.9
Gummy shark	*Mustelus antarcticus*	151	28	84.4	179	14.2
Sandbar shark*	*Carcharhinus plumbeus**	86	59	59.3	145	11.5
Whiskery shark	*Furgaleus macki*	69	13	82.9	82	6.5
Southern eagle ray	***Myliobatis australis***	18	14	56.3	32	2.5
Spinner shark*	*Carcharhinus brevipinna**	17	8	68.0	25	2.0
Western wobbegong*	*Orectolobus hutchinsi**	7	11	38.9	18	1.4
Gulf wobbegong*	*Orectolobus halei**	3	12	20.0	15	1.2
Smooth hammerhead*	*Sphyrna zygaena**	8	4	66.7	12	1.0
Cobbler wobbegong	***Sutorectus tentaculatus***	7	4	63.6	11	0.9
Bronze whaler*	*Carcharhinus brachyurus**	10	1	90.9	11	0.9
Spotted wobbegong*	*Orectolobus maculatus**	2	7	22.2	9	0.7
Western shovelnose ray	***Aptychotrema vincentiana***	2	4	33.3	6	0.5
Australian angelshark	***Squatina australis***	2	4	33.3	6	0.5
Common sawshark	***Pristiophorus cirratus***	4	1	80.0	5	0.4
Southern fiddler ray	***Trygonorrhina dumerilii***	3	2	60.0	5	0.4
Grey nurse shark	***Carcharias taurus***	2	0	100.0	2	0.2
Lobed stingaree	***Urolophus lobatus***	1	1	50.0	2	0.2
Floral banded wobbegong	***Orectolobus floridus***	2	0	100.0	2	0.2
Smooth stingray	***Dasyatis brevicaudata***	1	0	100.0	1	< 0.1
Pencil shark*	*Hypogaleus hyugaensis**	0	1	0.0	1	< 0.1
Ornate angelshark	***Squatina tergocellata***	1	0	100.0	1	< 0.1
Scalloped hammerhead*	*Sphyrna lewini**	0	1	0.0	1	< 0.1
Western shovelnose stingaree	***Trygonoptera mucosa***	0	1	0.0	1	< 0.1
Total		756	504		1260	

and more consistent numbers of *A. vincentiana* were particularly important for discriminating between the compositions of the samples caught by trawling and those obtained by both gillnetting and longlining, and greater and more consistent numbers of *C. obscurus* were especially important for discriminating between the samples taken by gillnetting from those obtained by both trawling and longlining (Table 4). The longline samples were discriminated from those obtained by both trawling and gillnetting by consistently greater numbers of *D. brevicaudata*.

Length-frequency compositions of the four selected bycatch species by fishing method

Wide size ranges of *H. portusjacksoni*, *A. vincentiana*, and *S. australis* and, to a certain extent, *M. australis*, were caught by trawling. However, the lengths of most *H. portusjacksoni* and *M. australis* were small and thus lay toward the lower end of their length ranges (Fig. 3). Although gillnetting also caught a broad size range of both *H. portusjacksoni* and *A. vincentiana,* it yielded predominantly larger *S. australis* and medium-size *M. australis* (Fig. 3). Although longline catches contained a wide size range of *H. portusjacksoni* and *M. australis*, they did not include the smallest individuals of these two species and only one of the *A. vincentiana* caught by this method was small (Fig. 3). No *S. australis* was caught by longlining.

The *H. portusjacksoni* obtained by all three fishing methods ranged from 180 to 1300 mm TL (Table 5), the latter length rarely being exceeded by this species throughout its range (Last and Stevens, 2009). The smallest individuals possessed conspicuous umbilical scars and were therefore neonates. The length-frequency distribution of female *H. portusjacksoni* is trimodal, whereas that of males is bimodal, and these modes correspond to the first two modes of females (Fig. 4). These differences account for the lengths of many females greatly exceeding the maximum length of 815 mm for males (Table 5). The weights of *H. portusjacksoni* ranged from 39 to 12,250 g (Table 5). The

Table 3

Number of females and males, percent contribution of females and the total number and percent contributions of all individuals of each elasmobranch species that were recorded during regular onboard observations of the catches from longline vessels on the southwest coast of Australia. Plain font = targeted species; Plain font* = byproduct species, i.e., those that are not targeted but usually retained; Bold font = bycatch species, i.e., those species that are usually discarded.

Common name	Species name	Female *n*	Male *n*	Female %	Total *n*	Total %
Gummy shark	*Mustelus antarcticus*	234	129	64.5	363	63.2
Smooth stingray	***Dasyatis brevicaudata***	21	20	51.2	41	7.1
Southern eagle ray	***Myliobatis australis***	15	19	44.1	34	5.9
Southern fiddler ray	***Trygonorrhina dumerilii***	24	8	75.0	32	5.6
Port Jackson shark	***Heterodontus portusjacksoni***	20	11	64.5	31	5.4
Dusky shark	*Carcharhinus obscurus*	16	6	72.7	22	3.8
Smooth hammerhead*	*Sphyrna zygaena**	8	1	88.9	9	1.6
Bronze whaler*	*Carcharhinus brachyurus**	4	1	80.0	5	0.9
Whiskery shark	*Furgaleus macki*	5	0	100.0	5	0.9
Western wobbegong*	*Orectolobus hutchinsi**	1	4	20.0	5	0.9
Common sawshark*	*Pristiophorus cirratus**	4	1	80.0	5	0.9
School shark*	*Galeorhinus galeus**	2	2	50.0	4	0.7
Western shovelnose ray	***Aptychotrema vincentiana***	3	0	100.0	3	0.5
Gulf wobbegong*	*Orectolobus halei**	1	2	33.3	3	0.5
Sandbar shark*	*Carcharhinus plumbeus**	2	0	100.0	2	0.4
Spotted wobbegong*	*Orectolobus maculatus**	0	2	0.0	2	0.4
Rusty carpetshark	***Parascyllium ferrugineum***	0	2	0.0	2	0.4
Melbourne skate	***Spinirija whitleyi***	2	0	100.0	2	0.4
Spinner shark*	*Carcharhinus brevipinna**	0	1	0.0	1	0.2
Australian sawtail catshark	***Figaro boardmani***	1	0	100.0	1	0.2
Pencil shark*	*Hypogaleus hyugaensis**	0	1	0.0	1	0.2
Scalloped hammerhead*	*Sphyrna lewini**	1	0	100.0	1	0.2
Total		364	210		574	

ratio of females to males of *H. portusjacksoni* differed significantly from parity among all individuals collectively (1 female:0.76 males; χ^2=9.46, $P<0.01$), but not for juveniles (1 female:1.20 males; χ^2=2.65, $P>0.05$). Note that, when calculating the sex ratios for juveniles, the term juvenile refers to females and males with lengths less than the smallest mature individual of their respective sex.

The *A. vincentiana* caught by all three fishing methods ranged from 201 to 1001 mm *TL* (Fig. 4; Table 5), and the smallest individuals lay within the length range recorded for the embryos of this species (A. Jones, unpubl. data) and the largest individuals exceeded the length of "at least 840 mm" reported for this species by Last and Stevens (2009). The length-frequency distributions of female and male *A. vincentiana* were both broadly bimodal and the numbers of both sexes were relatively low, between 500 and 699 mm (Fig. 4). However, the modal length class of 850–899 mm for the group of large females far exceeded that of 700–749 mm for the group of large males. Furthermore, the largest female *A. vincentiana* was both far longer (1001 mm) and heavier (3634 g) than the largest male, i.e., 872 mm and 1886 g, respectively (Table 5). The ratio of females to males differed significantly from parity among all individuals (1 female:0.67 males; χ^2=12.81, $P<0.001$), but not among juveniles (1 female:0.76 males; χ^2=3.52, $P>0.05$).

The smallest *S. australis* caught by all three fishing methods was 228 mm in *TL* (Fig. 4; Table 5) and thus only slightly longer than the length of 220 mm recorded for the largest embryo of this species in a concomitant study (A. Jones, unpubl. data). Although the maximum length of 1004 mm for *S. australis* in our samples is considerably less than the maximum length reported for this species by Last and Stevens (2009), it is still far greater than the TL_{50} for either females or males at maturity in southwestern Australian waters. Although individuals were represented in all 50-mm length classes between 200 and 1049 mm, the length-frequency distributions of females and males were both dominated by their 250–299 mm length classes (Fig. 4). The largest female *S. australis* was far longer (1004 mm) and heavier (10,970 g) than the largest male (859 mm and 5500 g) (Table 5). The ratio of females to males of *S. australis* did not differ significantly from parity among either all individuals collectively (1 female:1.05 males; χ^2=0.18, $P>0.05$) or among juveniles (1 female:1.11 males; χ^2=0.75, $P>0.05$).

Table 4

Main species that typified the catches of elasmobranchs recorded onboard trawl, gillnet, and longline vessels (shaded background), and those that discriminate between the catches of elasmobranchs obtained by each pair of fishing methods (unshaded background). Plain font = targeted species; Bold font = bycatch species; * Denotes that the species is relatively more abundant and consistently caught by the sampling method on the top (horizontal) row than on the side (vertical) column.

	Trawl	Gillnet	Longline
Trawl	***Aptychotrema vincentiana*** ***Heterodontus portusjacksoni*** ***Urolophus paucimaculatus*** ***Squatina australis***		
Gillnet	*Carcharhinus obscurus* ***Aptychotrema vincentiana**** ***Heterodontus portusjacksoni*** *Mustelus antarcticus* ***Myliobatis australis**** *Furgaleus macki*	*Carcharhinus obscurus* ***Heterodontus portusjacksoni*** *Mustelus antarcticus* *Furgaleus macki*	
Longline	***Dasyatis brevicaudata*** ***Aptychotrema vincentiana**** ***Trygonorrhina dumerilii**** ***Heterodontus portusjacksoni****	*Carcharhinus obscurus** ***Dasyatis brevicaudata*** *Mustelus antarcticus* ***Heterodontus portusjacksoni**** *Furgaleus macki**	***Dasyatis brevicaudata*** *Mustelus antarcticus* ***Trygonorrhina dumerilii*** ***Heterodontus portusjacksoni***

Table 5

Biological characteristics of four elasmobranch species caught as bycatch by commercial trawl, gillnet, and longline fisheries operating off southwestern Australia. Length measurements are given as total lengths (*TL*) for *Heterodontus portusjacksoni*, *Aptychotrema vincentiana*, and *Squatina australis*, and as disc lengths (*DL*) for *Myliobatis australis*. * denotes a value extrapolated from the regression equation of the relation between *DL* and *W*. The true weight could not be recorded because the pectoral fins had been removed by fishermen. Sample size for each sex of each species is shown on Figure 4.

		Heterodontus portusjacksoni	*Aptychotrema vincentiana*	*Squatina australis*	*Myliobatis australis*
Females	Length range (mm)	198–1300	201–1001	228–1004	118–800
	Weight range (g)	39–12,250	32–3634	94–10,970	117–37,811*
	Smallest mature (mm)	715	754	825	444
	Largest immature (mm)	869	895	834	472
Males	Length range (mm)	180–815	214–872	246–859	129–545
	Weight range (g)	39–3920	33–1886	115–5500	152–12,373*
	Smallest mature (mm)	595	642	754	365
	Largest immature (mm)	654	792	707	433

The relationships between *DW* and *DL* for females and males of *M. australis* collectively are described by the following equations:

$$DW = 1.70\ DL + 8.16\ (r^2=0.997,\ n=96), \qquad (5)$$

$$DL = 0.58\ DW - 3.01\ (r^2=0.998,\ n=96). \qquad (6)$$

From the values obtained from the above equations, the following relationships between the natural logarithms of *W* and *DL*, and of *W* and *DW* for both sexes are described as

$$\log_e W = 2.91 \log_e DL - 8.92\ (r^2=0.999,\ n=91), \qquad (7)$$

$$\log_e W = 3.19 \log_e DW - 12.25\ (r^2=0.999,\ n=91). \qquad (8)$$

After correction for bias (Beauchamp and Olson, 1973), the respective back-transformed relationships became

$$W = 0.0001344\ DL^{2.91}, \quad (9)$$

$$W = 0.000004787\ DW^{3.19} \quad (10)$$

The *M. australis* caught by using the three sampling methods ranged from 118 to 800 mm *DL* (Fig. 4, Table 5), which corresponds to 198–1192 mm *DW*. The minimum *DW* is at the extreme lower end of the range reported for this species at birth, and the maximum *DW* is appreciably less than the maximum *DW* of 1600 mm recorded for *M. australis* (Last and Stevens, 2009). The largest female caught was 800 mm *DL* and 37,811 g *W*, which greatly exceeded the 545 mm *DL* and 12,373 g *W* of the largest male (Table 5). Both sexes were represented in each *DL* class between 100 and 549 mm, and females were also present in each subsequent size class up to 800–849 mm (Fig. 4). The length-frequency distributions for both sexes contained a single prominent modal length class at 150–199 mm. The ratio of 1 female:1.27 males of *M. australis* among the individuals caught by all methods collectively did not differ significantly from parity (χ^2=3.10, P>0.05), and the same was true for juveniles, i.e., 1 female:1.04 males (χ^2=0.06, P>0.05).

Lengths of females and males at maturity

The smallest female and male of *H. portusjacksoni* with mature gonads measured 715 and 595 mm *TL*, respectively (Table 5). Using gonadal stage as the index, we found that the TL_{50} for female *H. portusjacksoni* at maturity was 805 mm, and the TL_{50} for males was 593 mm, which represent 62% and 73% of their respective maximum *TL*. The TL_{50} for males was only 12 mm greater and not significantly different from the 581 mm derived by using full clasper calcification as the index of maturity (Table 6, see also Jones et al., 2008).

The smallest female and male of *A. vincentiana* with mature gonads were 754 and 642 mm, respectively, and all females ≥896 mm and males ≥793 mm were mature (Fig. 5, Table 5). The TL_{50} for females of 798 mm at maturity differed significantly (P<0.001) from the corresponding TL_{50} for males of 671 mm when using gonadal stage as the criterion for maturity (Table 6). The latter TL_{50} for males did not differ significantly from the TL_{50} of 654 mm derived by using full clasper calcification as the criterion for maturity (P>0.05) (Fig. 5, Table 6). The TL_{50} for female and male *A. vincentiana* at maturity, using gonadal status as the criterion for maturity, were 80% and 77% of their respective maximum *TL*.

On the basis of gonadal data, the *TL* of the smallest mature female and male *S. australis* were 825 and 754 mm, respectively, and all females ≥840 mm and all males ≥754 mm were mature (Fig. 5, Table 5). The TL_{50} for females (823 mm) and males of *S. australis* (734 mm), derived by employing gonadal stage as the criterion for maturity, were significantly different (P<0.001; Table 6). The latter TL_{50} was not significantly different (P>0.05) from the TL_{50} of 721 mm derived for male *S. australis* when using clasper calcification as the criterion for maturity (Fig. 5, Table 6). The TL_{50} calculated for females and males of *S. australis*, with gonadal stage as the criterion for maturity, were 82% and 85% of their respective maximum *TL*.

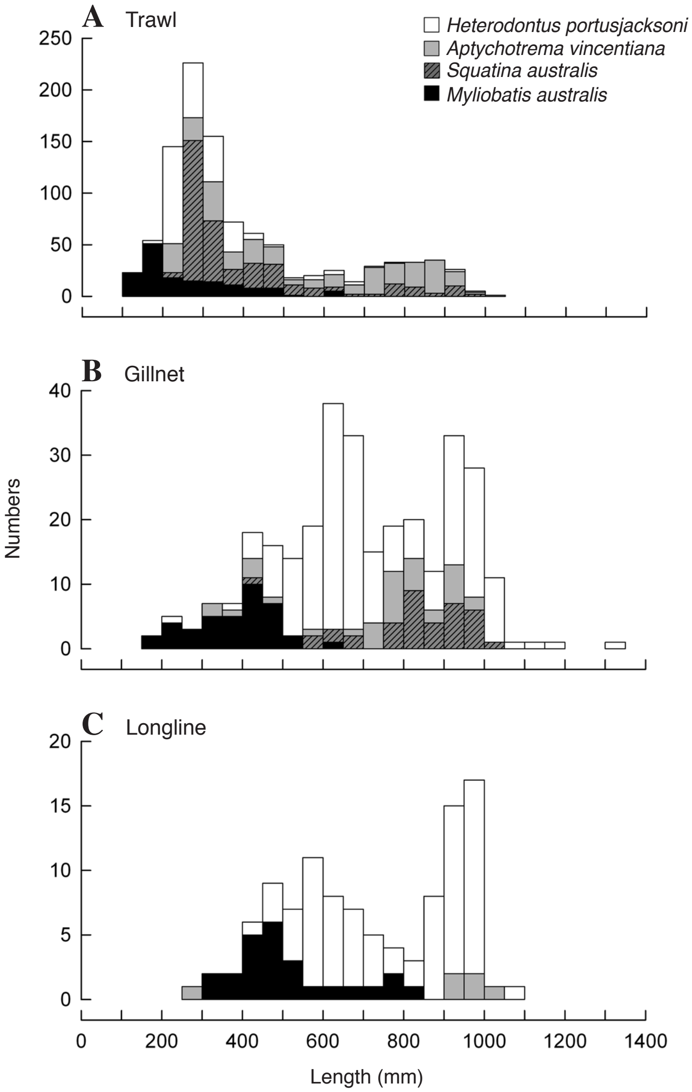

Figure 3

Length-frequency distributions for all males and females of *Heterodontus portusjacksoni, Aptychotrema vincentiana, Squatina australis*, and *Myliobatis australis* obtained from the commercial catches of (**A**) trawl, (**B**) gillnet, and (**C**) longline vessels. Length refers to total length (*TL*), except in the case of *M. australis* where it refers to disc length (*DL*).

The DL of the smallest females and males of *M. australis* with mature gonads were 444 and 365 mm, respectively, and all females and males with $DL \geq 513$ and 433 mm, respectively, were mature (Fig. 5, Table 5). The DL_{50} of 511mm (DW_{50}=879 mm) for females at maturity differed significantly ($P<0.001$) from the 399 mm (DW_{50}=689 mm) of males when gonadal status was used as the criterion for maturity (Table 6). The latter DL_{50} did not differ significantly ($P>0.05$) from the 388 mm (DW_{50}=670 mm) derived for males at maturity with clasper calcification as the criterion for maturity (Table 6). On the basis of gonadal criteria, the DL_{50} for females and males of *M. australis* at maturity were 64% and 73% of their $DL_{\max}$, respectively.

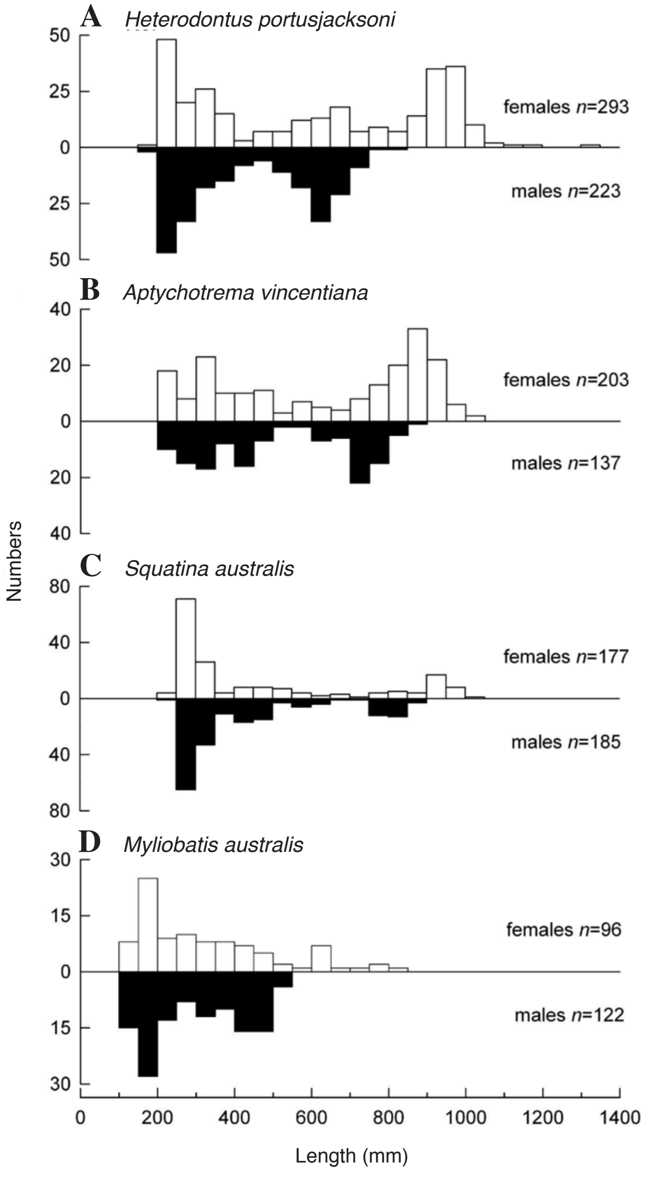

Figure 4

Length-frequency distributions for females (white histograms) and males (black histograms) of (**A**) *Heterodontus portusjacksoni,* (**B**) *Aptychotrema vincentiana,* (**C**) *Squatina australis*, and (**D**) *Myliobatis australis* obtained collectively by all three fishing methods. Length refers to total length (TL), except in the case of *M. australis* where it refers to disc length (DL).

Percentage of females and males caught by each fishing method

The percentage of females of *H. portusjacksoni*, *A. vincentiana*, *S. australis* and *M. australis* caught in trawls with lengths below the L_{50} (TL_{50} or DL_{50}) at maturity were very high and similar to those of males (Table 7). The percentage in trawl samples of both sexes with lengths less than their L_{50} at maturity ranged from 63% for *A. vincentiana*, to 90% for both *M. australis* and *S. australis*, respectively, to 97% for *H. portusjacksoni* (Table 7). In the case of gillnet samples for three of the four species, the percentage of females with lengths less than their L_{50} at maturity exceeded those of males and particularly so for *M. australis*, for which the values were 86% and 40%, respectively (Table 7). In longline samples, the percentage of males of *H. portusjacksoni* with lengths below their L_{50} at maturity slightly exceeded the corresponding value for females (37% and 32%, respectively).

Discussion

This study is the first to quantify the contribution of each elasmobranch species to the total elasmobranch catch obtained by co-occurring trawl, gillnet, and longline fisheries, and to calculate the contributions made by the bycatch and byproduct species to the catches taken by each fishing method. In addition, our results indicate that nMDS ordination and associated tests would be invaluable for detecting whether the species composition of elasmobranchs in the catch produced by each fishing method changes in the future in response to either variations in fishing activity or environmental factors and, if so, also for elucidating the magnitude of that effect. This study has also produced, for four abundant bycatch species, the sound quantitative biological data of the types required by managers for developing plans for conserving stocks and which are deficient for the vast majority of bycatch species (Stobutzki et al., 2002). The sizes at maturity that were determined for the four bycatch species in this study enabled the proportion of each species, which was caught by each fishing method before it had the potential to reproduce, to be estimated.

Table 6

Estimates of the L_{50} and L_{95} at maturity, and the upper and lower 95% confidence limits (CL), for females and males of *Heterodontus portusjacksoni*, *Aptychotrema vincentiana,* and *Squatina australis* recorded as total length (*TL*). For *Myliobatis australis*, these values were recorded as disc length (*DL*); extrapolated values for disc widths (*DW*) are also provided. Estimates were derived by using gonadal status as an index of maturity for females and males and also by using full clasper calcification as that index for males. Sample sizes for females and males of each species are provided in Figure 4.

		Female (gonads)		Male (gonads)		Male (claspers)	
		L_{50}	L_{95}	L_{50}	L_{95}	L_{50}	L_{95}
Heterodontus portusjacksoni	Estimate	805	896	593	647	581	652
	Upper 95% CL	826	931	605	674	594	689
	Lower 95% CL	781	866	579	628	563	629
Aptychotrema vincentiana	Estimate	798	877	671	766	654	707
	Upper 95% CL	815	920	695	833	676	756
	Lower 95% CL	774	855	631	736	618	679
Squatina australis	Estimate	823	852	734	735	721	723
	Upper 95% CL	842	927	753	806	753	806
	Lower 95% CL	771	826	673	714	674	714
Myliobatis australis	Estimate	511	585	399	472	388	453
	Upper 95% CL	558	696	416	518	404	491
	Lower 95% CL	480	538	376	440	366	420
		Female (gonads)		Male (gonads)		Male (claspers)	
		DW_{50}	DW_{95}	DW_{50}	DW_{95}	DW_{50}	DW_{95}
Myliobatis australis	Estimate	879	1006	689	813	670	781
	Upper 95% CL	960	1195	717	891	697	845
	Lower 95% CL	827	926	649	758	632	724

Table 7

Numbers of females and males and total number of *Heterodontus portusjacksoni*, *Aptychotrema vincentiana, Squatina australis,* and *Myliobatis australis* that were caught by each fishing method and examined in the laboratory, and the percentages of individuals with lengths less than their L_{50} at maturity when using gonadal status as the index of maturity. L_{50} refers to total length (TL_{50}), except in the case of *M. australis* where it refers to disc length (DL_{50}).

		Females		Males		Sexes combined	
Fishing method	Species name	*n*	$\% < L_{50}$	*n*	$\% < L_{50}$	*n*	$\% < L_{50}$
Trawl	*Heterodontus portusjacksoni*	121	98	128	96	249	97
	Aptychotrema vincentiana	182	62	116	66	298	63
	Squatina australis	155	89	169	91	324	90
	Myliobatis australis	71	92	83	87	154	90
Gillnet	*Heterodontus portusjacksoni*	115	44	76	30	191	38
	Aptychotrema vincentiana	16	38	20	30	36	33
	Squatina australis	22	18	16	19	38	18
	Myliobatis australis	14	86	25	40	39	56
Longline	*Heterodontus portusjacksoni*	57	32	19	37	76	33
	Aptychotrema vincentiana	5	0	1	100	6	17
	Squatina australis	—	—	—	—	—	—
	Myliobatis australis	11	36	14	7	25	20

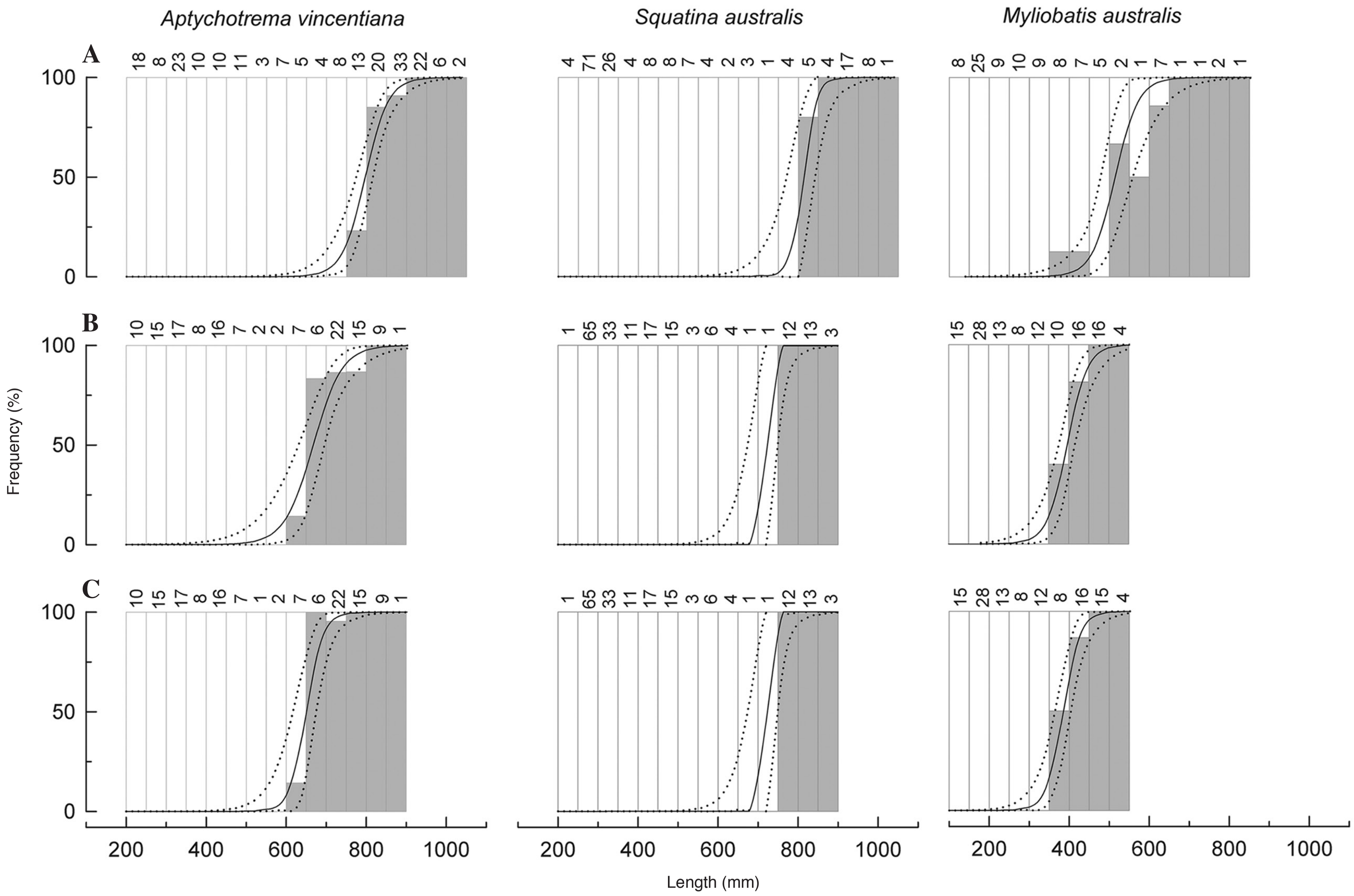

Figure 5

Percent frequencies of occurrence, including samples sizes, of mature *Aptychotrema vincentiana*, *Squatina australis,* and *Myliobatis australis* in sequential 50-mm length classes (gray bars) for (**A**) females and (**B**) males by using gonadal criteria as the indicator of maturity, and for (**C**) males by using full clasper calcification as the criterion. The logistic curve (solid line) and its 95% confidence limits (dotted lines) for each species show the probability that an individual is mature in relation to its total length. Sample sizes are shown above the histograms for each of the 50-mm length classes. Length refers to total length (*TL*), except in the case of *M. australis* where it refers to disc length (*DL*).

Compositions of the catches taken by the three fishing methods

Our results indicate that the elasmobranch component of the catches taken by demersal trawlers on the lower west coast of Australia is dominated by rays, which comprise 10 of the 14 elasmobranch species caught by this method. Furthermore, these batoids were either small species, e.g., stingarees, or represented by smaller individuals, e.g., *Aptychotrema vincentiana* and *M. australis*. Indeed, the four small species of stingaree (Urolophidae) caught by trawling contributed as much as two-thirds to the total trawl catch of elasmobranchs and were so abundant in samples collected during an extensive trawling study along the lower west coast of Australia that they collectively contributed 17.5% to the total biomass of the 172 fish species caught during that study (Hyndes et al., 1999). The large number of small batoids caught paralleled the situation recorded for other trawl fisheries, including the multispecies bottom trawl fishery off Argentina (Tamini et al., 2006). As with the large ray species, the only two shark species taken in appreciable numbers in our study, *H. portusjacksoni* and *S. australis*, were represented predominantly by small individuals.

The large number of elasmobranchs taken by prawn and scallop trawling emphasizes the lack of selectivity of this fishing method for its targeted species. Indeed, Bonfil[2] has stated that towed nets are the most indiscriminant of all fishing gears because they are designed to capture everything in their path and thus inevitably encounter a large number of nontarget species. The susceptibility of small demersal elasmobranchs to capture by trawling is due to their limited mobility and benthic lifestyle (see also Stobutzki et al., 2001, 2002; Walker, 2005a; Tamini et al., 2006) and to the trawlers often operating in nearshore waters, which typically act as nursery areas for several elasmobranch species, including *H. portusjacksoni* (White and Potter, 2004; Jones et al., 2008; Kinney and Simpfendorfer, 2009). The catches of elasmobranchs taken by trawls in our study comprised only six individuals that were retained as byproduct compared with the 2980 individuals discarded as bycatch.

Although the three species targeted by gillnetting, *C. obscurus, M. antarcticus*, and *Furgaleus macki*, collectively accounted for just over half of the total number of elasmobranchs caught by this method, the contribution of all retained species (i.e. including byproduct), accounted for three quarters of the total. This is very similar to the situation recorded for a gillnet fishery in southeastern Australia (Walker et al., 2005). The remainder of the catch (i.e., the bycatch) was still substantial, however, emphasizing that a considerable number of the sharks and rays caught by gillnet were discarded, as has been reported in gillnet fisheries elsewhere in the world (e.g., Perez and Warhlich, 2005).

The mesh sizes of the gillnets (165 and 178 mm) were selected to catch the three targeted species, *C. obscurus*, *M. antarcticus*, and *F. macki*, at a marketable size which, depending on the species, typically corresponded to modal fork lengths of between 800 and 1200 mm (McAuley and Simpfendorfer, 2003). This mesh selectivity accounts for the fact that the *TL* of the majority of *A. vincentiana* and *S. australis* in our gillnet catches fell within a relatively narrow range of 700–1000 mm, with the latter length closely approximating the maximum length recorded for these two species during the present study (Table 5). However, the *TL* for *H. portusjacksoni*, the second most abundant species in the gillnet catches, spanned the full range of this species in southwestern Australian waters (Jones et al., 2008). The capture by gillnet of a substantial number of *H. portusjacksoni* with lengths less than 700 mm is attributable to the tendency for all sizes of *H. portusjacksoni* to become entangled in gillnets as a result of their possessing prominent dorsal fin spines (Walker, 2005a). In the case of the ray *M. australis*, the larger individuals were proportionately less in gillnet than longline catches because this wide disc-shaped species becomes increasingly deflected from the net as it grows larger (Walker, 2005a).

Longlining was so successful at targeting *M. antarcticus* that this shark contributed nearly two thirds to the total elasmobranch catch taken by this method and, together with the other two targeted species, *C. obscurus* and *F. macki*, represented nearly 70% of that total catch. However, those last two species were not abundant in these catches. In fact, the second to fifth most abundant species were bycatch species. Although 11 of the 19 nontargeted elasmobranch species were typically retained as byproduct, none of those species was numerous and collectively accounted for only ~7% of the elasmobranch catch. From the above, it follows that the contribution of bycatch to the longline catches (~26%) was similar to that in the gillnet catches. However, unlike the situation with gillnetting, the bycatch species *S. australis* was never caught on longline hooks, presumably because this squatinid is an ambush predator that targets mobile prey such as teleosts and cephalopods (E. Sommerville, personal commun.[3]).

Although the use of nMDS ordination and associated tests emphasized that the species compositions of the elasmobranchs caught by trawling, gillnetting, and longlining differed markedly, SIMPER showed that *H. portusjacksoni* was a major typifying species for the elasmobranchs taken by trawling in relatively shallow waters and by gillnetting and longlining in deeper and more offshore waters. This bycatch species is thus clearly abundant and widely distributed throughout the inshore and more offshore coastal waters of southwest-

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[2] Bonfil, R. 2000. The problem of incidental catches of sharks and rays, its likely consequences, and some possible solutions. *Shark Conference 2000 online documents*, 8 p. (Pacific Fisheries Coalition, http://www.pacfish.org/sharkcon/documents/bonfil.html, accessed May 2010).

[3] Sommerville, Emma. 2007. Centre for Fish and Fisheries Research, Murdoch Univ., Murdoch, Western Australia, 6150.

ern Australia. The finding that the ray *D. brevicaudata* was the most important typifying species in the longline samples indicates that this bycatch species was consistently present in reasonable numbers in water depths of approximately 70 m. Although the total number of *M. antarcticus* obtained by longlining was far greater than that of *D. brevicaudata*, *M. antarcticus* was occasionally taken in large numbers and, at other times, not caught at all, reflecting the tendency for this shark species to school (Lenanton et al., 1990; Last and Stevens, 2009).

Length compositions, sex ratios, and habitats of the four selected bycatch species

Our data indicate that the maximum lengths of the females of *H. portusjacksoni*, *A. vincentiana, S. australis,* and *M. australis* exceed those of males by 37%, 13%, 14%, and 31%, respectively. Moreover, for each species, the sex ratio did not differ significantly from parity among their juveniles, and the females dominated the length classes of the larger individuals. The resultant trend for the overall sex ratios for *H. portusjacksoni* and *A. vincentiana* to significantly favor females indicates that the females of at least these two species live longer than their males. Such a conclusion for *H. portusjacksoni* in southwestern Australian waters is consistent with the results of Tovar-Ávila et al. (2009), who showed that, in southeastern Australia, the maximum age of the females (35 years) of this species is greater than that of males (28 years). Although the overall sex ratios of *S. australis* and *M. australis* did not differ from parity, those ratios were almost certainly attributable to the larger individuals of these two species being proportionately less well represented in the overall samples of those species. In the case of *S. australis*, the capture of fewer larger individuals was mainly due to this species not being taken by longlining fisheries in deeper, offshore waters, where they had been caught by gillnetting, and thus the overall samples were swamped by juveniles caught by trawls in their nursery areas. The conclusion that larger females were under-represented in the overall catch of *M. australis* is consistent with a tendency for the larger individuals, which would presumably have been predominantly females, to be deflected from the net.

The difference between the maximum lengths of the females and males of *H. portusjacksoni* in southwestern Australian waters (37%) was far greater than the 19% and 10% differences recorded for two populations of this species in southeastern Australian (Tovar-Ávila et al., 2007) and the 15% difference found farther north in eastern Australia (Powter and Gladstone, 2008). The trend for females to attain a larger size than that of males parallels that reported by Cortés (2000) for populations representing 164 species and 19 families of sharks. However, the average difference between the sizes of females and males reported by Cortés (2000) was 10% and thus smaller than the differences observed for particularly *H. portusjacksoni* and *M. australis*.

Comparisons of the length-frequency distributions for each of *H. portusjacksoni*, *A. vincentiana, S. australis,* and *M. australis* in samples obtained from trawling in inshore waters, and by gillnetting and longlining farther offshore, indicated that all four species use shallow, inshore waters as nursery areas and that substantial numbers of the adults of *S. australis* and *M. australis* are also present in these inshore habitats. The tendency for *M. australis* to use inshore areas as nursery areas in southwestern Australia is emphasized by the considerable numbers of juveniles of this species that were caught during a study of a permanently open estuary on the south coast of Western Australia (Potter and Hyndes, 1994). Furthermore, the juveniles of *H. portusjacksoni* are also abundant in inshore waters off eastern Australia (McLaughlin and O'Gower, 1971). Because several of the mature females of *A. vincentiana* caught in inshore waters contained full-term embryos, they would have been poised to give birth in those waters. However, because adults of *H. portusjacksoni*, *A. vincentiana,* and *M. australis* were caught by gillnetting and longlining, and *S. australis* was caught by longlining, some individuals of each of these species move offshore as they increase in size and some may even live permanently in offshore waters.

Lengths at maturity and their implications

The greater maximum length attained by females than by males of each of the four elasmobranch species was accompanied, on the basis of gonadal criteria, by a greater L_{50} at maturity, and the differences in L_{50} ranged from 12% for *S. australis* and 19% for *A. vincentiana* to as high as 28% for *M. australis* and 36% for *H. portusjacksoni*. The trend for the females of these species to mature at a larger size than that of males follows the overall trend exhibited by shark species (Cortés, 2000).

The values derived for the L_{50} at maturity for the males of *A. vincentiana, S. australis*, and *M. australis* by using full clasper calcification as the criterion for maturity did not differ significantly from the corresponding values derived by using gonadal maturity as that criterion. This result parallels that recorded for *H. portusjacksoni* by Jones et al. (2008), for *Squalus magalops* by Braccini et al. (2006), and for *Trygonorrhina dumerilii* by Marshall et al. (2007). Thus, to obtain data that can subsequently be used to derive a reasonable proxy for the L_{50} for males at maturity, scientists can rapidly record the lengths of males, determine whether or not their claspers are calcified, and then immediately return them live to the sea. Furthermore, for each of the four species, all of the males with uncalcified claspers and most of those with partially calcified claspers possessed immature (stage 1 or 2) gonads, whereas those with fully calcified claspers almost invariably contained mature (stage 3 or 4) gonads and this finding thus accounts for the L_{50} at maturity not being significantly different when gonadal and clasper calcification criteria are used.

On the basis of our calculations of the L_{50} at maturity for females and males of each of the four selected bycatch species, the overall percentages, in trawl samples, of *H. portusjacksoni*, *S. australis*, and *M. australis*, whose individuals would not typically have had the potential to reproduce, were particularly high, with values ranging from 90% to 97%. These high values are attributable to trawling taking place mainly in shallow inshore waters that typically act as nursery areas. The importance of protecting the newborn and young juveniles of species that have well-defined nursery areas has been emphasized by Walker (2005a). The far lower percentage of *A. vincentiana* with lengths less than the L_{50} at maturity in trawl samples than was the case with the other three species is attributable to the tendency for this species to occupy inshore waters throughout its life.

The smaller proportion of individuals of *H. portusjacksoni*, *A. vincentiana, S. australis*, and *M. australis* with lengths less than their L_{50} at maturity in gillnet than in trawl catches reflects a combination of the following: 1) differences in gear selectivity; the mesh sizes of gillnets are chosen with the purpose of catching targeted species at a sufficient size to be commercially marketed (Simpfendorfer and Unsworth, 1998; McAuley and Simpfendorfer, 2003) and thereby obtaining proportionately more of the larger, mature individuals of these four bycatch species than their juveniles; and 2) the location of gillnetting in deeper, offshore waters and thus beyond typical nursery areas.

Mortality

Onboard sampling of the catches obtained by the three fishing methods during commercial operations was made difficult by the small size of the fishing boats and the rapidity with which the fishermen worked to retrieve the retained species and discard the bycatch. It was thus not possible to determine precisely the fishing-induced mortality of the individuals of each bycatch species taken by each fishing method and, in particular, the mortality of *H. portusjacksoni*, *A. vincentiana*, *S. australis*, and *M. australis.* From our observations, however, it is apparent that, in the case of trawling, many individuals died while in the net and those that survived were often so badly injured during sorting that they would have been unlikely to survive after release. From our observations, we believe that the level of mortality associated with trawling is greater than that suggested by Laurenson et al.[1], who proposed that approximately half of the elasmobranchs taken by trawling during a research project on the lower west coast of Australia was likely to die during capture or after being discarded. Indeed, in a detailed study of the bycatch of Australia's northern prawn trawl fishery, Stobutzki et al. (2002) showed that as much as two-thirds of the sharks and rays caught by this method died while still in the net, and thus the overall mortality, i.e., including individuals that subsequently died from the trauma of capture, would have been higher. It should also be recognized that the pregnant females of the smaller species of rays (White and Potter, 2004) and *S. australis* and *M. australis* tended to abort after capture, thus adding a further detrimental effect to the populations of those species.

It was evident that the individuals of most species, including those of the three targeted species, *M. antarcticus*, *C. obscurus*, and *F. macki*, and several bycatch species, such as *M. australis* and *S. australis*, had died by the time the gillnet was retrieved. It is proposed that this high mortality was related to the very long soak times of the gillnets (up to 24 h), which is consistent with the observation that mortality was far lower in a gillnet study conducted in southeastern Australia in which soak times were only ~8 h (Walker et al., 2005). Furthermore, the long soak times led to the elasmobranchs in the nets becoming infested by sea lice (*Cirolana* sp.) and to attack by leatherjackets (*Monacanthid* spp.), thus hastening the death of species such as *M. australis*. Moreover, although *H. portusjacksoni* frequently survived capture by gillnets, the individuals of this species were often severely injured while being forcibly removed from the gillnets.

In contrast to the situation with gillnetting, the majority of elasmobranchs survived capture by longlining and thus, in general, the individuals of bycatch species caught by hooks were able to be returned to the sea alive. The high survival of elasmobranchs caught by longlining in southwestern Australia is presumably attributable, at least in part, to the short set times (~3 h) for this fishing method.

Implications for ecosystem-based fisheries management

Traditional fisheries management has focused on ensuring that the populations of targeted species are maintained at levels that are considered sustainable. However, fisheries regulations aimed at constraining the exploitation of targeted species may provide little protection for bycatch species, and thus commercial fisheries can have an equal or even greater impact on the populations of bycatch species. In contrast, ecosystem-based fisheries management, i.e., an ecosystem approach to fisheries, requires that the populations of bycatch species in an ecosystem, as well as those of the targeted and byproduct species, are sustained. It is thus relevant that our study revealed that many individuals of the elasmobranch bycatch species caught by commercial fisheries, and particularly by trawling, were immature and, together with our observations and the results of other studies, strongly indicated that mortality is high among these individuals. The problems posed by such fisheries-induced mortalities on these bycatch species are exacerbated because elasmobranchs have low biological productivity and are therefore susceptible to overexploitation (Stevens et al., 2000; Walker, 2005a). Thus, while it is recognized that the trawl, gillnet, and longline fisheries of southwestern Australia are not large, the removal of even moderate numbers from the population of any elasmobranch species has the potential to affect that population at a local level (Walker, 2005a).

In the context of the ecosystem-based fisheries management framework, every attempt should be made to reduce, where practical, the amount of bycatch. In view of the high mortality of the bycatch species taken by trawlers and gillnetters, commercial fishermen should be encouraged to explore ways of reducing the amount of bycatch and of increasing survival among discarded individuals. Thus, with trawling for example, fishermen could explore the effectiveness of bycatch reduction devices, reduce the duration of trawls and onboard handling time, and unload the catch into water tanks before sorting. In the case of gillnetting, fishermen could explore whether a reduction in the soak time of their nets leads to a decrease in the mortality of the bycatch and an increase in the market quality and thus the value of the flesh of the retained species.

The biological and catch data produced during this and other studies on locally abundant bycatch species of elasmobranchs (White et al., 2001; 2002; White and Potter, 2005; Marshall et al., 2007) indicate that trawl, gillnet, and longline fisheries may be having a direct impact on the populations of these species in southwestern Australia. The acquisition of these data now enables managers to determine whether the impacts of commercial fisheries on the populations of bycatch species justify modifying fishing regulations to ensure that the risks to the sustainability of these species are reduced and that the integrity of the ecosystem is thus maintained. Such risks could readily be achieved through the use of rapid assessment techniques, such as those described by Stobutzki (2001; 2002) and Walker et al. (2005).

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