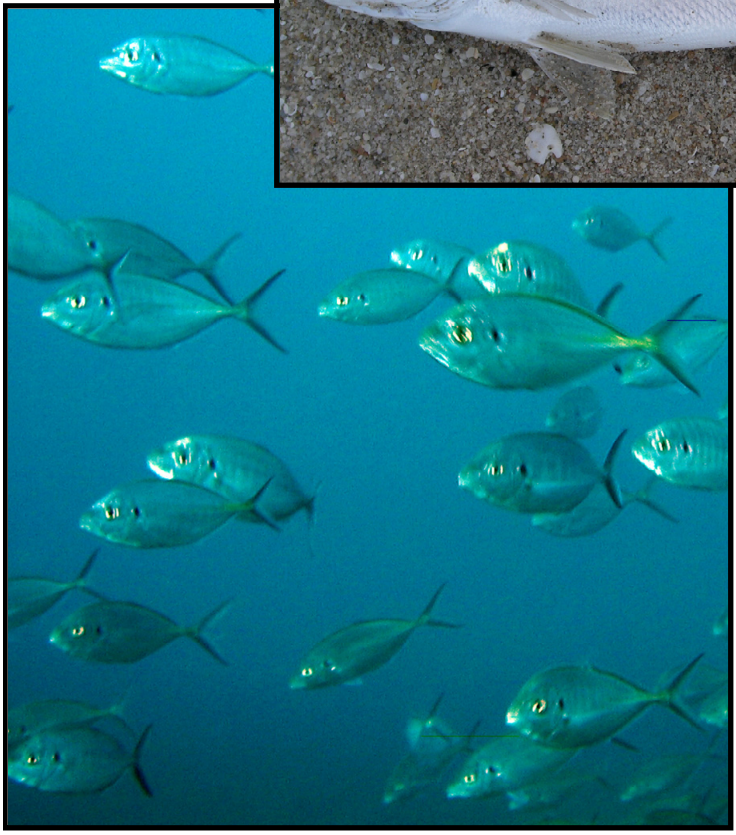
# Determination of biological parameters for managing the fisheries for Mulloway and Silver Trevally in Western Australia

*Farmer, B.M., French, D.J.W., Potter, I.C.,*
*Hesp, S.A. and Hall, N.G.*



Centre for Fish and Fisheries Research

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**Centre for Fish and Fisheries Research**
**Murdoch University, Murdoch**
**Western Australia 6150**

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| **PRINCIPAL INVESTIGATOR** | Professor I. C. Potter |
| **ADDRESS** | Centre for Fish and Fisheries Research<br>School of Biological Sciences and Biotechnology<br>Division of Science and Engineering<br>Murdoch University<br>South St, Murdoch WA 6150<br>Ph: (08) 9360 2524 Fax: (08) 9360 6303 |

## OBJECTIVES

1) To obtain the biological data that are required by managers to develop plans to conserve the stocks of Mulloway and Silver Trevally in Western Australia. This will require determining the following characteristics of both species.
2) Size and age compositions, growth rates and sizes and ages at which maturity is first reached.
3) Locations and periods of spawning, and whether they are multiple spawners.
4) Batch fecundity.
5) Estimates of mortality.
6) To elucidate patterns of distribution of the Silver and Sand Trevally, and thereby determine the ways in which they differ.

## NON-TECHNICAL SUMMARY

### OUTCOMES ACHIEVED TO DATE

The biological data required by fisheries managers to develop plans for conserving fish stocks have been obtained for Mulloway and Silver Trevally in Western Australian waters. The first species is commercially and recreationally important and the second is caught in large numbers by recreational fishers. We have produced, for managers in the Department of Fisheries Western Australia, data on crucial aspects of the biology of Mulloway and Silver Trevally. These include data on habitats, spawning periods, size and age compositions, growth and reproductive biology in the northern and southern parts of the distribution of these two species on the west coast of Australia. Although all of the results are relevant to developing management plans for conserving the stocks of these two important species, the following are of particular relevance. The females and males of Mulloway typically reach first maturity at lengths of about 930 and 880 mm, respectively. These lengths, which are usually attained at 5 - 6 years in age, are far greater than the minimum legal length (MLL) of 500 mm for the retention of this species. In the case of Silver Trevally, the average length of females at first maturity is 60 mm greater than the current MLL of 250 mm and thus the females are exposed to one year of fishing mortality before they are able to spawn. Thus, managers will need to assess whether the current MLLs for the above two species, and particularly for Mulloway, are appropriate for ensuring that the stocks of these heavily-fished species are conserved. Management policies will also need to take into account the schooling behaviour of Mulloway at spawning as this results in this species becoming an easy target for fishers at a crucial stage in its life cycle.

The progressive increase in fishing activities in Western Australia means that the stocks of a number of species, especially those which are iconic and commonly targeted, are potentially vulnerable. Fisheries managers thus require sound biological data on exploited species for developing management plans aimed at ensuring that the stocks of those species remain sustainable. The present study was undertaken to obtain data on crucial aspects of the biology of the Mulloway *Argyrosomus japonicus* and the Silver Trevally *Pseudocaranx dentex* on the west coast of Australia. In these waters, Mulloway is an important commercial and recreational species, while Silver Trevally ranks third among the species most frequently caught by recreational fishers.

The juveniles of Mulloway live in nearshore coastal waters, such as marine embayments, gutter formations in surf zones and in estuaries, whereas their adults are found both in these waters and around reefs in offshore waters in depths up to at least 110 m. The juveniles of the Silver Trevally are typically found in areas where there are structures, *e.g.* reefs, or patches of seagrass and/or detached macrophytes, whereas its adults typically occupy water associated with reefs and generally in deeper water. The largest Silver Trevally were found in deeper offshore waters. In contrast to the Silver Trevally, the Sand Trevally *Pseudocaranx wrighti* is found mainly over sandy substrates.

The females and males of Mulloway attain maturity at ~930 mm (7.12 kg) and ~880 mm (6.06 kg), respectively, which are typically reached at 5 - 6 years in age. The females of the Silver Trevally become mature at ~310 mm (~0.34 kg) and ~4 years of age, compared with ~280 mm (~0.25 kg) and ~ 3 years of age with males.

Mulloway spawn mainly during late spring and early summer and at night and predominantly around nearshore coastal reefs. However, this species also spawns around structure, *e.g.* boat wrecks, in the lower Swan River Estuary. Silver Trevally spawn for a longer period at lower than higher latitudes *i.e.* late winter to early summer *vs* spring, presumably reflecting the presence of elevated water temperatures for a more protracted period.

Mulloway and Silver Trevally are serial spawners with indeterminate fecundity, *i.e.* they spawn on more than one occasion during the spawning season and the number of eggs released by individual females is not determined prior to that season. Although Mulloway and Silver Trevally with ovaries containing hydrated oocytes were obtained, these fish were either frozen prior to examination or were already undergoing ovulation at the time of capture and were thus not suitable for estimating fecundity.

The maximum total lengths and ages recorded for Mulloway were 1437 mm and 31 years for their females and 1304 mm and 29 years for their males. At the completion of their second, fourth, sixth, tenth and twentieth years of life, females have attained lengths of ~533, 804, 971, 1137, and 1230 mm, respectively, compared with ~531, 791, 949, 1101, and 1182 mm, respectively, by their males.

The maximum recorded total lengths of females and males of Silver Trevally in inshore waters < 60 m depth were ~690 and 660 mm, respectively, and the maximum age of both sexes was 13 years. However, the maximum total length and age in offshore waters > 60 m depth were far greater, *i.e.* 885 mm and 18 years of age, reflecting greater growth rates after fish have reached ~350 mm and 5 years of age. Females and males of Silver Trevally in shallow inshore waters (< 60 m depth) grow at similar rates and have attained lengths of ~135, 270, 350 and 440 mm by the completion of their first, third, fifth and tenth year of life, respectively. In contrast, females in deeper water have already attained a length of 595 mm by the end of their tenth year of life. It is not clear at present whether the inshore and offshore assemblages are part of the same stock

The MLL for Mulloway in Western Australia is 500 mm, which is attained during their second year of life and at least three years before they typically reach maturity. The substantial recruitment of Mulloway into the fishery at an early stage in life will result in many individuals being caught before they have attained maturity. Mulloway is also potentially very vulnerable because, even though undergoing substantial migrations, it forms large schools in the same and known locations during each spawning season and can thus easily be targeted by commercial and recreational fishers during this period. For example, recreational fishers target the spawning aggregations of this species in a region of the Swan River Estuary where there are numerous hard structures, *e.g.* boat wrecks, which simulate the reef habitat in marine waters where this species typically spawns. The average length of females of Silver Trevally at first maturity is 60 mm greater than the MLL of 250 mm and this is not achieved until about one year after the MLL has been reached. From the above, it is clear that, when managers are developing plans for conserving the stocks of Mulloway and Silver Trevally, they need to recognise that the MLL of both species is well below the size at first maturity.

In the case of both Mulloway and Silver Trevally, the estimates derived for natural mortality, $M$, using the frequently-applied Pauly equation exceeded the estimates of total mortality, $Z$, calculated using life history characteristics and relative abundance (catch curve) analysis. This emphasises the crucial need to develop a new equation or approach for deriving a better estimate for natural mortality and thus to derive a reliable estimate of fishing mortality, $F$.

The rapid decline of spawning potential ratio for Mulloway with increasing fishing mortality to levels that fall below a reference point of 30% implies that more robust management strategies are required if the stock is to withstand further increases in fishing mortality.

**KEYWORDS:** Mulloway, Silver Trevally, age composition, growth, reproduction, habitat, mortality.

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We are indebted to Dick Lear and John Farell who provided numerous samples of Silver Trevally from their commercial catches and also provided free bait and astute advice on both the behaviour of, and locations in which to target, this species. Gratitude is extended to Allan Bevan of Shikari Charters for his tireless efforts in the collection of Mulloway and Silver Trevally from offshore metropolitan waters.

Thanks also to the many recreational fishers, and particularly Anthony Simper, Jamie Waite and members of the Marmion Angling Club (MAC), for sharing their wealth of knowledge on these species and helping to obtain samples.

Thanks are also due to Eric and Lem from Geraldton Fish market for providing numerous samples of both species and information on sampling locations. We are also grateful to Graham Maunder for always providing us with up-to-date advice on where to fish in the Geraldton region.

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# 1.0 INTRODUCTION

## 1.1 BACKGROUND

The Mulloway *Argyrosomus japonicus* and Silver Trevally *Pseudocaranx dentex* are very important recreational fish species in Western Australia and have been identified by the WA Recreational Fishing Advisory Committee (RFAC) as two of six major recreational fish species in Western Australia for which there are insufficient biological data to develop sound and appropriate management plans. The great importance of these species to recreational fishers and the need to conserve this important resource were recognised by Mr Frank Prokop (RecFishWest) and Mr Andrew Cribb (Recreational Fisheries Program Manager of the Department of Fisheries WA), who each strongly encouraged us to produce this proposal. Both species make a contribution to the commercial fisheries of Western Australia.

Mulloway is fished in estuaries and marine waters along the Western Australian coast southwards from Exmouth and eastwards along the south coast to the South Australian border (Hutchins and Swainston, 2002). It is an icon recreational fish species in the Swan River Estuary, which flows through Perth and Fremantle, and is the largest of the recreational fish species found in this and other south-western Australian estuaries. The abundance of Mulloway in these estuaries is considered by fishers to reflect the “health” of these systems.

Although there are no data on the size and age at which Mulloway attain maturity in Western Australia, these and other aspects of the reproductive biology of the species have been well studied in South Africa. In that region, Mulloway have been shown to attain maturity at a relatively large size and late stage in their life history, compared with those of sympatric species (Griffiths, 1996). Species with these types of characteristics are particularly susceptible to overfishing. It is thus relevant that historical commercial catches demonstrate that the abundance of this species in estuaries, such as the Peel-Harvey, has declined markedly during the last century (Bradby, 1997) and, although large post-spawning aggregations of Mulloway used to be observed, this is now no longer the case (R. Lenanton, Department of Fisheries WA, pers. comm.). The three-fold increase, from 20-60 tonnes, that has occurred in the commercial catch from 1996/97 to 2003/2004 suggests that commercial fishers are now targeting this species much more actively. Such an increase must clearly be exerting increasing pressure on a stock, which is already showing signs of heavy fishing pressure and raises the question among fishers of what is an appropriate sharing of this resource between the recreational and commercial fishing sectors.

In Australia, Silver Trevally has a similar distribution to Mulloway. This species is morphologically so similar to the smaller and congeneric Sand Trevally *Pseudocaranx wrighti* that the Department of Fisheries WA does not attempt to separate these two species from a management point of view. However, such an approach is a cause for concern since those biological characteristics of these two species, that would be of value in developing management plans, such as growth rates, size and age at maturity and fecundity, are likely to differ. The importance of the *Pseudocaranx* complex of species to anglers is demonstrated by the fact that it was ranked third in the total shore-based catch recorded during the 1994/95 recreational shore survey along the lower west and south coast of Western Australia (G. Nowara, Department of Fisheries WA, pers. comm.) and again during the subsequent 1996/97 recreational boat survey conducted between Kalbarri and Augusta (Sumner and Williamson, 1999).

A minimum size and bag limit have been applied to Mulloway and Silver Trevally. However, these regulations were not based on detailed information on such crucial features as growth, length and age at first maturity, fecundity and the location and time of spawning. Indeed, there are no such data for either of these important recreational species in Western Australia. Although aspects of the biology of these two species have been studied in eastern Australia, the coastal environment in that region differs markedly from that in Western Australia, and thus extrapolation of any results to Western Australia is fraught with risk. Furthermore, the most detailed of the previous studies on Mulloway in NSW was conducted on the juvenile stages, which appear to utilise estuaries in that region to a greater extent than in south-western Australia (*cf* Gray and McDonall, 1993). Moreover, it was recognised that the estimates of growth for Silver Trevally in the NSW study were biased (Rowling and Raines, 2000). Although various aspects of the biology of "Mulloway" have been studied in South Africa (*e.g.* Wallace, 1975; Wallace and Schleyer, 1979; Smale, 1985; Griffiths and Hecht, 1995a; Griffiths, 1996), it remains unclear as to the extent to which they are similar to those of Australian populations.

## 1.2 NEED

The progressive rise in the number of recreational fishers in Western Australia is increasing the fishing pressure on the most sought-after recreational fish species in this State. The potential thus exists for these species to become exploited at unsustainable levels. The absence of biological data for Mulloway, an icon recreational species, and Silver Trevally, the third most frequently-caught recreational fish species, has meant that regulations aimed at conserving and managing the stocks of these very important species, were not based on appropriate biological data. There is thus an urgent need to develop a sound database for these species, which encompasses such crucial features as size and age compositions, growth, length and age at first maturity, fecundity and the location and time of spawning.

Since the Sand Trevally, which is also fished recreationally, is morphologically so similar to Silver Trevally that it is very frequently confused with this species, and indeed is currently considered collectively with this species for management purposes, there is a need to understand the significance of those differences that are likely to exist between the habitats and biology of these two species.

The urgent need to acquire biological data on Mulloway and Silver Trevally to underpin management plans has been highlighted by both RFAC and RecFishWest.

## 1.3 OBJECTIVES

1) To obtain the biological data that are required by managers to develop plans to conserve the stocks of Mulloway and Silver Trevally in Western Australia. This will require determining the following characteristics of both of these species;
2) Size and age compositions, growth rates and sizes and ages at which maturity is first reached.
3) Locations and periods of spawning, and whether they are multiple spawners.
4) Batch fecundity.
5) Estimates of mortality.
6) Patterns of distribution of the Silver and Sand Trevally, and thus elucidation of the ways in which they differ.

# 2.0 GENERAL MATERIALS AND METHODS

## 2.1 STUDY AREAS

### 2.1.1 Mulloway, *Argyrosomus japonicus*

For the study on *Argyrosomus japonicus*, the coastline between Carnarvon (24°53´S, 113°39´E) and Augusta (34°19´S, 115°10´E) was divided at 28° S into northern and southern regions (Figure 2.1). For convenience, the waters in estuaries and those along the coast where depths are < 20 m are referred to as nearshore waters, whereas those along the coast where depths exceed 20 m are referred to as offshore waters.

### 2.1.2 Silver Trevally, *Pseudocaranx dentex*

For the study on *Pseuodcaranx dentex*, the coastline between Kalbarri (27°42´S, 114°10´E) and Augusta was divided at Lancelin (31°01´S, 115°20´E) into upper and lower west coast regions (Figure 2.2). The lower west coast region was further separated into inshore (*i.e.* < 60 m depth) and offshore coastal marine waters (*i.e.* 60-200 m deep).

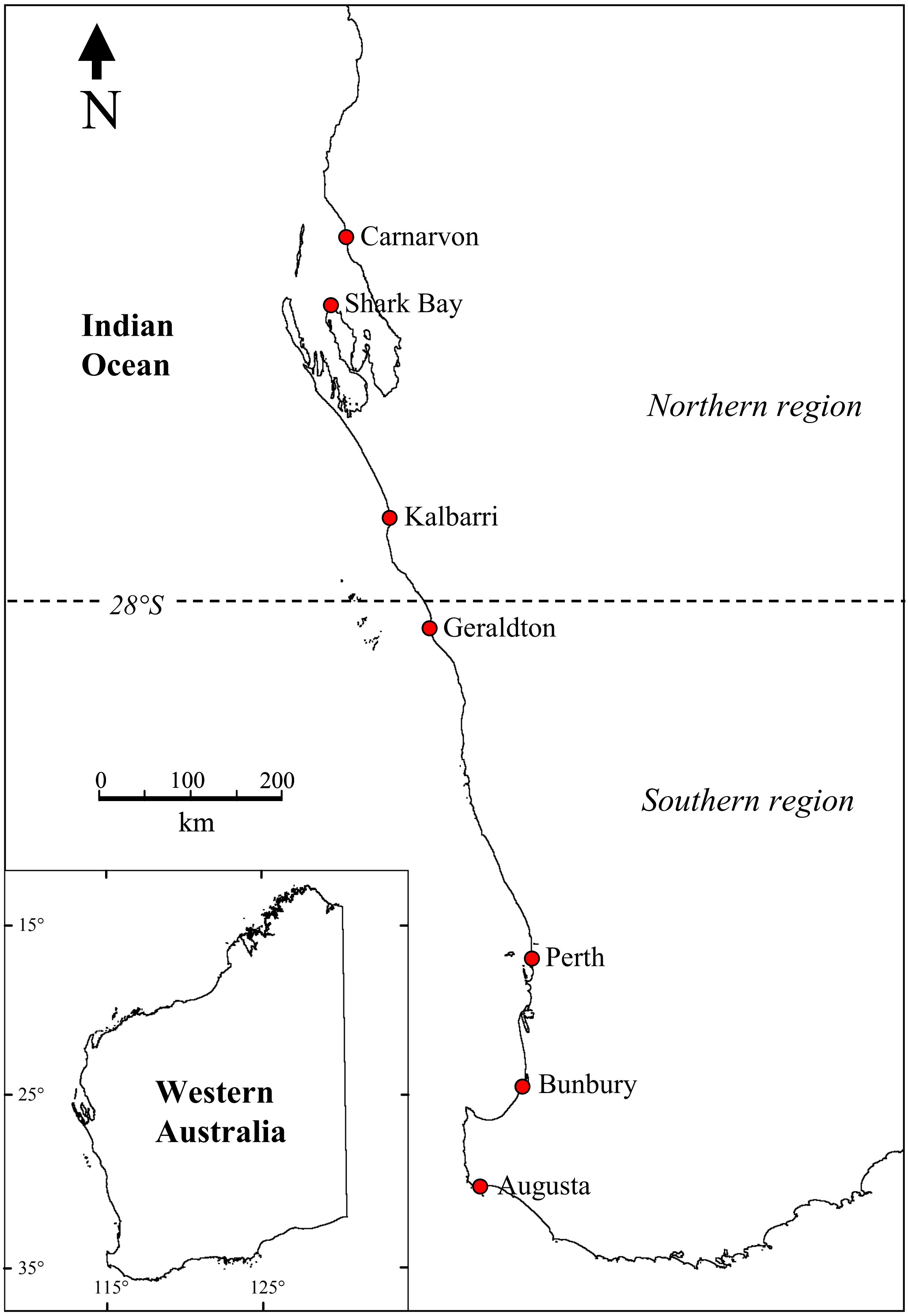

**Figure 2.1.** Map showing the main locations within the northern and southern regions on the west coast of Australia at which *Argyrosomus japonicus* was sampled

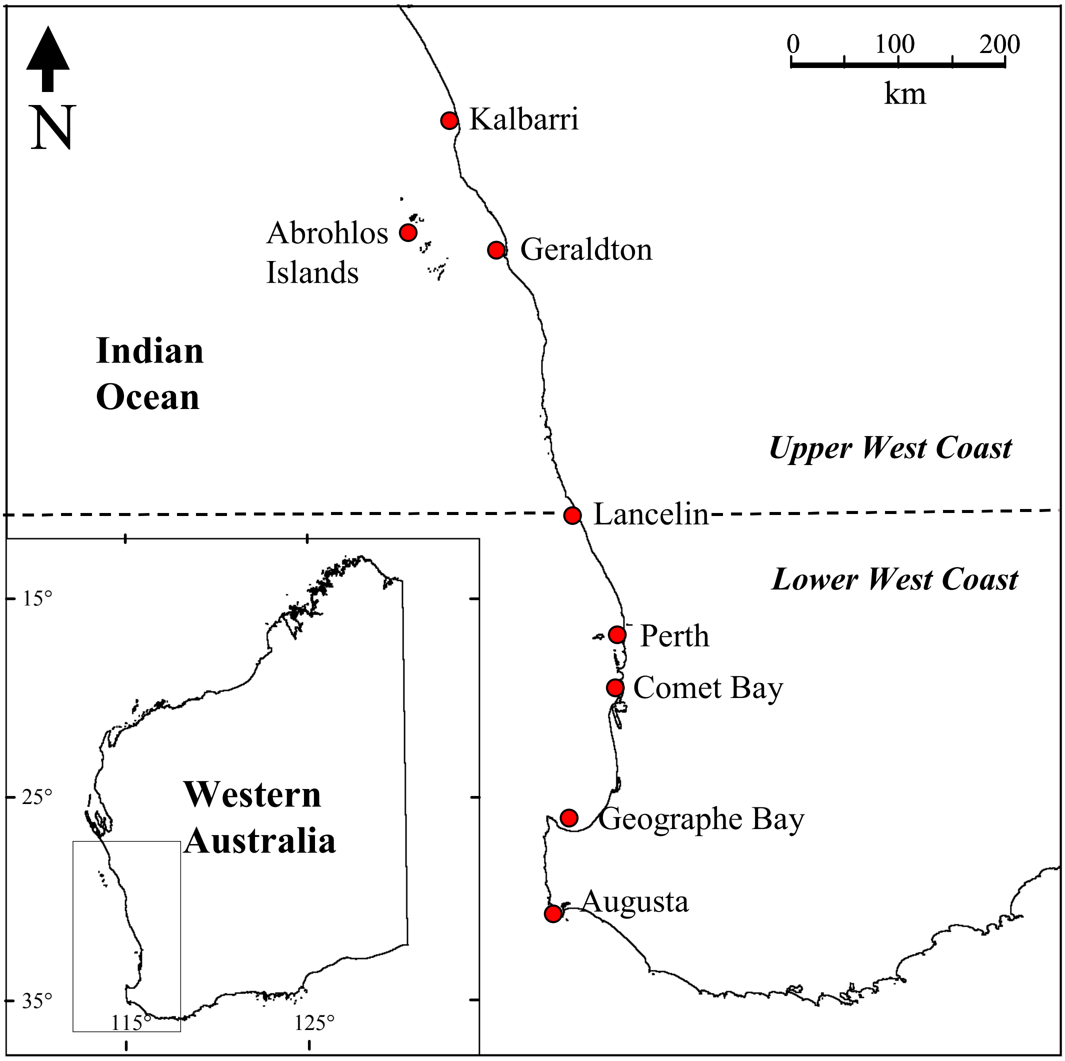

**Figure 2.2.** Map showing the main locations within the upper and lower regions on the west coast of Australia at which *Pseudocaranx dentex* was sampled.

## 2.2 SAMPLING REGIME

### 2.2.1 Mulloway

In the northern region, *Argyrosomus japonicus* was obtained at regular intervals between January 2002 and November 2005 from sites at Carnarvon and in Shark Bay (25°56´S, 113°34´E) and at Kalbarri (Table 2.1; Figure 2.1). Full details of sites, sampling gear, life cycle stages etc… are given in Table 2.1. Note that the size and age compositions of *A. japonicus*, retained by recreational fishers in Kalbarri and by commercial fishers in the northern and southern regions combined, are shown in Figure 3.4.

**Table 2.1.** Details of the sampling regime for *Argyrosomus japonicus* in the northern region, providing the source of fish, *i.e.* whether they were obtained during sampling trips or from commercial or recreational fishers, and the sampling gear(s) used (W, commercial wetline; L, rod and line; S, spear), and whether the fish were caught in nearshore or offshore waters.

| **Location** | **Site** | **Zone** | **Habitat** | **Life cycle stage** | **Gear** | **Source** |
|---|---|---|---|---|---|---|
| ***Carnarvon*** | Dirk Hartog Island | Nearshore | Intermittent sand/ reef substrate | Juvenile/ Adult | W | Commercial |
| | Prawning jetty | Nearshore | Shallow sand substrate | Juvenile | L | Sampling |
| ***Shark Bay*** | Useless Loop | Nearshore | Sand substrate interspersed with reef/seagrass | Adult | L | Recreational |
| | Skipjack Point | Nearshore | Intermittent sand/ reef substrate | Juvenile | L/S | Sampling |
| ***Kalbarri*** | Blueholes | Offshore | Intermittent sand/ reef substrate | Adult | W | Commercial |
| | Murchison coast | Nearshore | Surf zone with intermittent sand/ reef substrate | Juvenile/ adult | L | Recreational/ sampling |

In the southern region, Mulloway were obtained at regular intervals between January 2002 and November 2005 from sites near Geraldton (28°47´S, 114°37´E), Perth (31°57´S, 115°51´E) and Bunbury (33°20´S, 115°38´E) (Table 2.2; Figure 2.1). Full details of sites, sampling gear, life cycle stages etc… are given in Table 2.2.

*Agyrosomus japonicus* was also collected opportunistically from Dunsborough (33°37´S, 115°06´E), Augusta and Albany (35°01´S, 117°53´E). The size and age composition of *A. japonicus* retained by recreational fishers in the Swan River are provided in Figure 3.4.

**Table 2.2.** Locations in the southern region from which *Argyrosomus japonicus* was obtained. Category definitions are as outlined for Table 2.1.

| **Location** | **Site** | **Zone** | **Habitat** | **Life cycle stage** | **Gear** | **Source** |
|---|---|---|---|---|---|---|
| ***Geraldton*** | Offshore | Offshore | Intermittent reef substrate | Adult | W | Commercial |
| | Greenough | Nearshore | Surf zone with intermittent sand/ reef substrate | Adult | L | Recreational |
| | Wharf | Nearshore | Sand substrate near rock groynes | Juvenile | L | Sampling |
| ***Perth*** | Swan River | Nearshore | Sand substrate near artificial reef structures | Adult | L | Recreational/ Sampling |
| | South-west Rottnest | Offshore | Artificial reef | Adult | L | Recreational/ Sampling |
| | Madora | Nearshore | Surf zone with sand substrate | Adult | L | Recreational |
| ***Bunbury*** | Harbour | Nearshore | Shipping channel with sand substrate and some reef | Adult | L | Recreational |
| | Back Beach | Nearshore | Sand substrate near rock groynes | Juvenile | L/S | Sampling |

### 2.2.2 Silver Trevally

*Pseudocaranx dentex* was collected between Augusta and Lancelin on the west coast of Australia by using rod and line fishing in estuaries and in coastal marine waters up to 200 m in depth (Figure 2.2). Sampling was undertaken bimonthly between January 2002 and December 2004. Opportunistic samples of juvenile *P. dentex* were obtained from commercial prawn trawlers operating over predominantly sandy substrates in inshore waters of Cockburn Sound (32°12´S, 115°43´E) and Comet Bay (32°30´S, 115°43´E). Whole and filleted fish were also collected from commercial seine and wetline fishers and recreational anglers, who were operating between Augusta and Kalbarri. When available, frozen whole fish were also purchased from wholesale fish markets. In those months during 2004 when samples of *P. dentex* from the upper west coast region could not be obtained from wholesale fish markets, this species was caught by rod and line fishing in coastal waters off Geraldton. Details of the methods and regions in which *P. dentex* was collected are provided in Table 2.3.

*Pseudocaranx wrighti* were obtained from the catches of the commercial trawlers operating in the inshore waters of Cockburn Sound and Comet Bay (see above), and from trawlers operating in inshore waters around Rottnest Island (31°50´S, 115°30´E). Commercial trawlers were equipped with two nets, which were 1 m in height, with wings and a cod-end consisting of 51 and 45 mm mesh, respectively. The two nets had a combined effective fishing width of 8 m, and were towed at 4-5 km $h^{-1}$ for between 20 and 120 min. *Pseudocaranx wrighti* was also collected from inshore waters of Geographe Bay (33°34´S, 115°04´E) using the same commercial seine net as was used to catch *P. dentex*. Seine nets were deployed in waters < 8 m in depth over both bare sand and seagrass beds (consisting mainly of *Amphibolis* sp., *Posidonia* *australis* and *P. sinuosa*). Nets were between 180 - 380 m in length, with mesh sizes between 9 - 46 mm.

**Table 2.3.** Locations from which samples of *Pseudocaranx dentex* were obtained. Category definitions are as outlined for Table 2.1. (N.B. T, commercial trawler; SN, commercial seine). Inshore waters include estuaries and reefs in waters < 60 m deep, while offshore waters include all those marine waters deeper than *ca* 60 m.

| **Region** | **Site** | **Zone** | **Habitat** | **Life cycle stage** | **Gear** | **Source** |
|---|---|---|---|---|---|---|
| ***Upper west coast*** | Kalbarri to Dongara | Inshore | Intermittent reef substrate | Adult | W | Commercial |
| | Abrohlos Islands | Inshore | Intermittent reef substrate | Adult | W | Commercial |
| | Geraldton | Inshore | Sand substrate near rock groynes and reef | Adult/ juvenile | L | Sampling |
| ***Lower west coast*** | Perth | Inshore | Intermittent reef substrate/ sand interspersed with seagrass beds | Adult | L/W/ T | Commercial/ recreational/ sampling |
| | South-west Rottnest | Offshore | Artificial reef | Adult | L | Recreational/ sampling |
| | Geographe Bay | Inshore | Intermittent reef substrate/ sand interspersed with seagrass beds | Adult/ juvenile | L/SN | Commercial/ recreational |
| | Augusta | Inshore | Intermittent sand/ seagrass substrate | Juvenile | L | Sampling |

## 2.3 INITIAL MEASUREMENTS

The total length (TL) and wet weight of each *A. japonicus* and *P. dentex* obtained during sampling was measured to the nearest 1 mm and 1 g, respectively. Whenever possible, each fish collected from the fish market was weighed whole prior to filleting and its length and weight recorded to the nearest 1 mm and 10 g, respectively. The weights of all other *A. japonicus* or *P. dentex* that could not be obtained prior to filleting were estimated from the regression equation that, for each species, relates wet weight to total length (Chapters 3.3.4 and 4.3.4). The gonads of each fish were removed and weighed to the nearest 0.01 g, then examined macroscopically and recorded as either ovaries, testes or unsexed (*i.e.* gonads of small juveniles).

## 2.4 AGE AND GROWTH

The two sagittal otoliths of *A. japonicus* were removed ventrally by cutting away a portion of bone on the left side of the pro-otic/exoccipital region, which was exposed by removing the gill rakers. In contrast, the sagittal otoliths of *P. dentex* were more easily extracted by cutting dorsally into the same region and levering the head forward. Once excised, the otoliths of both species were washed, dried and stored in labelled paper envelopes.

As the whole sagittal otoliths of *A. japonicus* are thick and opaque and do not have discernible growth zones, all of these otoliths were sectioned (see Chapter 3.2.1). In contrast, the whole sagittal otoliths of *P. dentex* were much thinner and contained discernible growth zones. However, since these zones were sometimes hard to detect, the otoliths were sectioned to determine whether this enhanced their readability. Otoliths were taken from a subsample of 200 *P. dentex* that covered a wide size range and the numbers of growth zones visible in both the whole otolith and a section of the other sagittal otolith taken from the same fish were compared. As the growth zones became far more visible after sectioning (see Chapter 4.3.3), the otoliths of this species were sectioned prior to counting the growth zones.

The otoliths of each *P. dentex* and *A. japonicus* were mounted in clear epoxy resin and, using an Isomet Buehler low-speed diamond saw, cut through the primordium into *ca* 500 μm and 700 μm sections, respectively. The sections were then ground with fine wet-and-dry carborundum paper (grade 1200), washed, dried and mounted on microscope slides using DePX mounting medium. These sections were examined under reflected light against a black background using a Leica MZ 7.5 dissecting microscope (Leica Microsystems Ltd., 2001).

The opaque zones on each sectioned otolith of *A. japonicus* and *P. dentex* were counted on at least two occasions and without any prior knowledge of either the date of capture or the size of fish from which the otolith came. When the two counts of opaque zones on an otolith differed, the section was examined a third time. The third count, which invariably agreed with one or other of the previous two counts, it was used for subsequent analyses.

Marginal increment analysis (MIA) was used to validate that opaque zones on the sectioned otoliths of *A. japonicus* and *P. dentex* are formed annually. The marginal increment of an otolith is the distance between the outer edge of its single or outermost opaque zone and the edge of that otolith. For MIA, measurements were made of the distance between the primordium and the outer edge of both the otolith and the single opaque zone, when only one such zone was present, and of the distances between the outer edge of the otolith and the outer edge of each of the two outermost opaque zones, when two or more opaque zones were present. The marginal increment on each otolith was measured three times, each from a different region of the sectioned otolith, and the mean of those three measurements was used for subsequent analyses. The above measurements, which were made perpendicular to the opaque zone/s and without knowledge of the date of capture of the fish from which that otolith had been removed, were recorded to the nearest 0.01 μm. The marginal increment was expressed as a proportion of the distance between the primordium and the outer edge of the opaque zone, when only one opaque zone was present, and as a proportion of the distance between the outer edges of the two outermost opaque zones, when two or more opaque zones were present. In this report, the term marginal increment subsequently refers to this ratio rather than to the actual distance between the outer edge of the single or outermost opaque zone and the edge of the sectioned otolith. The marginal increment data for month were grouped according to the number of opaque zones on the otoliths, *i.e.* 1, 2-4, 5-7, ≥8 for *A. japonicus* and 1, 2-3, 4-7, ≥8 for *P. dentex*.

The peak times of spawning of *A. japonicus* and *P. dentex* were estimated from the trends exhibited throughout the year by the gonadosomatic indices, gonadal maturity stages and pattern of oocyte development (Chapters 3.3.8 and 4.3.5) and was considered to correspond to the birth date. The birth date was then used in conjunction with the number of opaque zones on each sectioned otolith and the time of year when newly-formed opaque zones become delineated at the edge of the otoliths, to determine the age of individual fish on their date of capture. von Bertalanffy growth curves were fitted to the lengths at age of each female and male fish using non-linear regression in the Statistical Package for the Social Sciences (SPSS Inc., 2004). The lengths at age of juvenile fish that could not be sexed were randomly allocated to the female and male data sets. The von Bertalanffy growth equation is;

$$L_t = L_\infty\left(1 - \exp^{-k(t-t_0)}\right),$$

where $L_t$ is the predicted total length at age $t$ (years), $L_\infty$ is the mean asymptotic length predicted by the equation, $k$ is the growth coefficient (year$^{-1}$) and $t_o$ is the hypothetical age (years) at which fish would have zero length, if their growth had followed that predicted by the equation.

A likelihood-ratio test was used to compare the growth curves derived for females and males of *A. japonicus* and *P. dentex* from the northern and southern and the upper and lower west coast regions, respectively (Figures 2.1; 2.2), and for each sex between these regions. The null hypothesis, $\omega$, that the growth of females and males could be described by a common growth curve was compared with the alternative hypothesis, $\Omega$, that the data would be better described by a separate growth curve for each sex. The log-likelihood, *i.e.* $= -\left(\frac{n}{2}\right) \times \ln\left(\frac{ss}{n}\right)$ (ignoring constants), was determined for the null hypothesis and for the alternative hypothesis as $\lambda_\omega$ and $\lambda_\Omega$, respectively, where *n* is the total number of females and males, *ss* is the sum of the squared deviations between the observed and predicted lengths at age of the combined set of data for both female and male fish and 'ln' represents the natural logarithm of the associated argument. The test statistic for the likelihood-ratio test was calculated as $2(\lambda_\Omega - \lambda_\omega)$. The null hypothesis was rejected at the $\alpha = 0.05$ level of significance if the test statistic exceeded $\chi^2_\alpha(q)$, where *q* is the difference between the numbers of parameters in the two growth curves (*e.g.* Cerrato, 1990).

## 2.5 REPRODUCTIVE BIOLOGY

On the basis of macroscopic characteristics and the scheme outlined by Laevastu (1965), the gonads of each fish were allocated to one of the following eight numerical stages of gonadal development; I = virgin, II = maturing virgin/resting adult, III = developing, IV = maturing, V = mature, VI = spawning, VII = spent, and VIII = recovering spent (see Chapters 3.2.3 and 4.2.5). The fish which, during the spawning period, possessed gonads at stages III-VIII were classified as mature because they either had the potential to spawn (III-V), were spawning (VI) or had spawned (VII and VIII).

Each month, the gonads of up to 20 individuals covering a wide range of lengths and the full suite of gonadal stages observed in that month were retained and prepared for histological examination. For this purpose, a portion of the mid-region of each ovarian or testicular lobe was placed in Bouin's fixative for *ca* 48 hours (a longer period of fixation was used for the largest gonads) and dehydrated in a series of increasing concentrations of ethanol. The ovarian or testicular portions were then embedded in paraffin wax, cut transversely into 6 μm sections and stained with Mallory's trichrome. The stages in oocyte development in each section were then determined by examination using a Leica MZ 7.5 dissecting microscope (Leica Microsystems Ltd., 2001) to validate that the stage in gonadal development assigned to each ovary on the basis of macroscopic appearance was appropriate (see Chapters 3.2.3 and 4.2.5).

Histological sections of the mid-region of the ovaries of three mature individuals of both *A. japonicus* and *P. dentex*, *i.e.* fish with stage V gonads, were analysed further to assess the spawning mode of these species. Using the computer-imaging package Leica Image Manager 1000 (Leica Microsystems Ltd., 2001), the circumferences of 100 randomly-selected oocytes, which had been sectioned through their nuclei, were recorded to the nearest 0.1 μm. These data were then used to calculate the diameters of those oocytes.

The percentage contributions made, during the spawning period, by the immature and mature females and males of *A. japonicus* and *P. dentex* in each length class to the total number of females and males of those species, were plotted as histograms. Logistic regression analysis of the maturity data for individual fish was used to determine, for both sexes of each species, the relationship between the proportion of mature fish and their lengths.

This enabled the length at which 50 and 95% of the females and males of each species first reached sexual maturity to be determined. The data were randomly resampled and analysed to create 1000 sets of bootstrap estimates for the parameters of the logistic regression analysis and estimates of the probability of maturity within the range of recorded lengths. The 95% confidence limits of the $L_{50}$s and $L_{95}$s were taken as the 2.5 and 97.5 percentiles of the corresponding predicted values resulting from this resampling analysis. The point estimates of each parameter and of each probability of maturity at the specified length were taken as the medians of the bootstrap estimates. The form of the logistic equation is;

$$P = \frac{1}{1 + \exp[-\ln(19)(L - L_{50})/(L_{95} - L_{50})]},$$

where $P$ is the proportion mature, $L$ is the total length in mm, $L_{50}$ and $L_{95}$ are the lengths in mm at which 50% and 95% of fish reach sexual maturity, respectively, and ln is the natural logarithm.

The likelihood-ratio test outlined in Chapter 2.4 was used to compare the logistic equations fitted to the maturity data obtained for females and males of *A. japonicus* and *P. dentex*, and for the corresponding sexes of the latter species in the upper and lower west coast regions (Figures 2.2).

The gonadosomatic indices (GSI) was calculated separately for each female and male fish of both species using the equation;

$$\text{GSI} = \text{W1}/(\text{W2} - \text{W1}) \times 100,$$

where W1 = the wet weight of the gonad and W2 = the total wet weight of the fish, *i.e.* W2 – W1 = somatic weight. The indices were calculated using data for fish ≥ the estimated $L_{50}$ at first maturity for females and males of each species.

## 2.6 MORTALITY

The instantaneous coefficients for total mortality, *Z*, and natural mortality, *M*, for *A. japonicus* and *P. dentex* were estimated using the approach of Hall *et al.* (2004), which was developed during a previous FRDC project 2000/137. This method reconciles the inconsistencies among individual estimates of mortality and, through combining the different values, results in improved precision of the resulting estimates of natural and total mortality. The following is a summary of the methods for deriving each of the individual mortality estimates and of Hall *et al.*'s (2004) method for combining the various methods.

An estimate of the instantaneous coefficient of total mortality, *Z*, was determined for each species by subjecting the age composition data for those commercial catches of *A. japonicus* and the combined commercial and recreational catch of *P dentex*, that were considered to be unbiased, to relative abundance (catch-curve) analysis (Deriso *et al*., 1985). Some of the commercial samples of *A. japonicus* and *P. dentex* collected during the present study were known to be biased because the catches were often separated into different size categories at the wholesale fish processing plants, before being supplied to other smaller markets and restaurants. The samples used for relative abundance analysis were restricted to those considered unbiased, namely those obtained from large wholesale fish processing plants, which were known to come directly from commercial fishers, together with those from smaller markets for which it could be verified that fish had not been sorted into different sizes. Age-frequency histograms for the commercial catch of *A. japonicus* (Figure 3.4a) and for the combined commercial and recreational catch of *P. dentex* (Figure 4.6b) were used to determine the age at full recruitment of each species. Unless otherwise stated, the catch curves were derived from the age classes that were located on the descending limb of the age-frequency distribution (Ricker, 1975). The catch curves for each species were analysed using the assumptions that *Z* and the levels of annual recruitment are constant and that the age composition of fully-recruited fish represents a random sample from a multinominal distribution with uniform selectivity from the age of full recruitment (Hall *et al.*, 2004). The value of *Z* was estimated by maximising the log-likelihood using the SOLVER routine in Microsoft™ Excel. The data for each species were randomly re-sampled with replacement and the resulting samples were analysed to create 10,000 sets of bootstrap estimates. The point estimate of *Z* was taken as the median of the 10,000 bootstrap estimates. The 95% confidence limits were calculated as the 2.5 and 97.5 percentiles of the corresponding estimated values.

A second estimate of *Z* for each species was obtained using the relationship between total mortality and maximum age, as described by Hoenig's (1983) equation for fish. This relationship was refitted to the data given for the 82 fish stocks provided in Hoenig (1982). For each species, the maximum recorded age was then inserted into SPSS to obtain point estimates and associated 95% confidence limits, thereby taking into account the uncertainty of the parameter estimates and the variation of the data around the regression line.

A third estimate of *Z* for each species was determined using the simulation approach described by Hall *et al.* (2004). To provide more precise estimates for *Z* when using the simulation approach, the routine was modified slightly from that described by Hall *et al.* (2004) to use the number of fish within the sample that were older than a specified age, rather than the age associated with the oldest of those fish. The specified age for *A. japonicus* was 17 years, with 3 fish being above this age, while the specified ages for *P. dentex* occurring in the inshore waters off the lower and upper west coasts were both 11 years, with 4 and 6 fish being above this age, respectively.

The three estimates of *Z* derived for each species were then combined, using the Bayesian approach of Hall *et al.* (2004).

Estimates of natural mortality, $M$, for each species were calculated from the relationship between natural mortality, growth and water temperature as described by Pauly (1980). This relationship was refitted to Pauly's data for 175 fish stocks using SPSS. The values for $k$ (year$^{-1}$) and $L_\infty$ (cm TL) in the growth curves derived for each species, and mean annual surface water temperature, $T$, were then inserted into SPSS to obtain point estimates and associated 95% confidence limits for $M$. The mean annual surface water temperature used for each species was 22.5 $^{o}$C (= mean temperature between Karratha and Broome, derived from data recorded by the Australian Oceanographic Data Centre, http://www.AODC.gov.au).

The Bayesian approach of Hall *et al*. (2004) was used to determine, for each species, the likelihood for $M$, calculated using the combined likelihood for $Z$. The calculation assumed that, for each value of Z, there is a uniform probability that $M < Z$ (Hall *et al.*, 2004). The resulting likelihood for $M$ was then combined with the estimate for $M$ derived from the Pauly (1980) equation.

A Monte Carlo resampling approach was used to derive estimates of $F$ for each species. Estimates of $Z$ and $M$ were randomly resampled, with replacement, from their respective probability distributions (*i.e.* combined $Z$ estimate and Pauly (1980) estimate for $M$), but were rejected when corresponding values for $M$ were greater than for $Z$. These values were used to produce 5000 estimates for $F$, determined using the equation $F = Z – M$. The point estimate of $F$ and associated 95% confidence limits were taken as the median value and the 2.5 and 97.5 percentiles of the 5000 estimates derived from the resampling analysis.

## 2.7 YIELD AND SPAWNING BIOMASS PER RECRUIT

The yield per recruit (YPR) and spawning stock biomasses per recruit (SSB/R) to the stock for each species were calculated assuming knife-edge recruitment to the fishery at the age of full recruitment $t_c$, constant total mortality for fully-recruited fish and a maximum age of 50 years. Yield per recruit was calculated as;

$$YPR = \sum_{a=t_c}^{50} W_a \exp(-Za),$$

where $W_a$, the total body weight at age $a$, was derived from the predicted length at age determined using the von Bertalanffy growth curve for that species and employing the total body weight (g) to length (mm TL) relationship for each species. The values for the fishing mortality that maximises YPR, $F_{\max,}$ and that at which the derivative of YPR with respect to F is one tenth of that at the origin, $F_{0.1,}$ were estimated numerically in Excel™. These two values were used as the biological reference points for fishing mortality for each species against which the estimate of the current level of fishing mortality was compared.

The SSB/R for the females and males of each species was calculated as;

$$SSB/R = \sum_{a=t_c}^{50} W_a P_{sex,a} P_{mat,a} \exp(-Za).$$

$W_a$, the total body weight at age $a$, was determined from the length at age predicted using the von Bertalanffy growth curve and employing the total body weight (g) to length (mm TL) relationship. The proportion of recruits of the specified sex at age $a$ ($P_{sex,a}$) was always assumed to equal 0.5. For all species, the calculation for the proportion of mature fish at age a, *i.e.* $P_{mat,a}$, was determined using the logistic function relating the proportion of mature fish to length, and the length at age predicted using the von Bertalanffy growth function.

Estimates for the current levels of YPR and SSB/R were determined for each of the 5000 values generated for $F$ derived from the Monte Carlo resampling procedure. The point estimates and associated 95% confidence limits for the current level of YPR and SSB/R for each species were taken as the median and 0.025 and 0.975 percentiles of the resulting YPR and SSB/R values.

The spawning potential ratio (SPR) was calculated by dividing the value for spawning biomass per recruit for each fishing mortality by the corresponding value of the spawning biomass per recruit calculated for the unfished stock (Goodyear, 1993).

# 3.0 BIOLOGY OF *ARGYROSOMUS JAPONICUS* ON THE WEST COAST OF AUSTRALIA

## 3.1 INTRODUCTION

Morphological similarity amongst species of the Sciaenidae and particularly within the genus *Argyrosomus*, has led to considerable taxonomic confusion in this family (Griffiths and Heemstra, 1995). *Argyrosomus japonicus*, for example, has been accorded 13 scientific names throughout its worldwide distribution (Lin, 1940; Trewavas, 1977; Griffiths and Heemstra, 1995). The work of Griffiths and Heemstra (1995) led to this species being recognised, in both South Africa and Australia, as distinct from *Argyrosomus hololepidotus*, which is now considered to be confined to Madagascar. However, the geographical separation of the populations of *A. japonicus* in Australian and African waters, allied with pronounced differences in maximum size attained, raises the possibility that the populations on these two continents constitute at least separate subspecies.

*Argyrosomus japonicus* is an important recreational and commercial fish species throughout its extensive Indo-Pacific distribution. It is thus surprising that sound data on the age and size compositions, growth and reproductive biology of this sciaenid is largely confined to those obtained during studies of populations in southern Africa (*e.g.* Griffiths and Hecht, 1995a; Griffiths, 1996). Those studies demonstrated that, in southern Africa, *A. japonicus* reaches a maximum age and length of 42 years and 1750 mm and reaches maturity when it is about 6 years and 1070 mm with females and 5 years and 920 mm with males.

There have been detailed studies of the size compositions and movement patterns of juvenile *A. japonicus* in the Hawkesbury River in eastern Australia (Gray and McDonnal, 1995). Although Hall (1984; 1986) provided data on the age composition, growth and reproduction of *A. japonicus* in South Australia, the ageing was undertaken using the number of circuli on scales, which the present study showed did not provide reliable estimates of the age of the fish. The very limited data available for *A. japonicus* in Western Australia are given in the biological synopsis for this species by Norriss *et al.* (1998).

The first aim of this study was to validate that the opaque zones (annuli) in the otoliths of *A. japonicus* in Western Australian waters are formed annually and that the number of such zones can thus be used to age the individuals of this species. The second aim was to use the resultant data to determine the size and age compositions, growth and mortality rate of this species in the northern and southern regions of their distribution on the west coast of Australia. The third aim was to determine the duration of the spawning period and the length and age at first maturity. The results are considered in the context of their implications for management. Finally, the data for these characteristics of *A. japonicus* in Western Australia were compared with those determined for this species in South Africa.

## 3.2 MATERIALS AND METHODS

Details of the measurements and procedures that were common to both A*rgyrosomus japonicus* and *Pseudocaranx dentex* are given in Chapter 2. The following details refer specifically to *A. japonicus*.

### 3.2.1 Otoliths

The otoliths of *A. japonicus* are thick and opaque (Plate 3.1). After sectioning, distinct opaque and translucent zones could be seen in all otolith sections and were particularly clear beneath the cauda in and around an area referred to as “the window” (Griffiths and Hecht, 1995a) (Plates 3.2; 3.3).

### 3.2.2 Otolith-scale comparisons

Since scales were used for ageing *A. japonicus* in South Australian waters (Hall, 1986), these structures were examined for growth zones. Scales were removed from an area behind the left pectoral fin of 80 fish. Each scale was cleaned and dried and mounted between two glass slides, which were then bound together with cellulose tape. Each scale was examined under transmitted light using a Leica MZ 7.5 dissecting microscope and the circuli in these structures counted several times using the same protocols as for counting opaque zones on sectioned otoliths (see Chapter 2.4). The number of circuli on each scale was then compared with the number of opaque zones on sectioned otoliths, recognising that these opaque zones were validated as being formed annually (see Chapter 3.3.2)

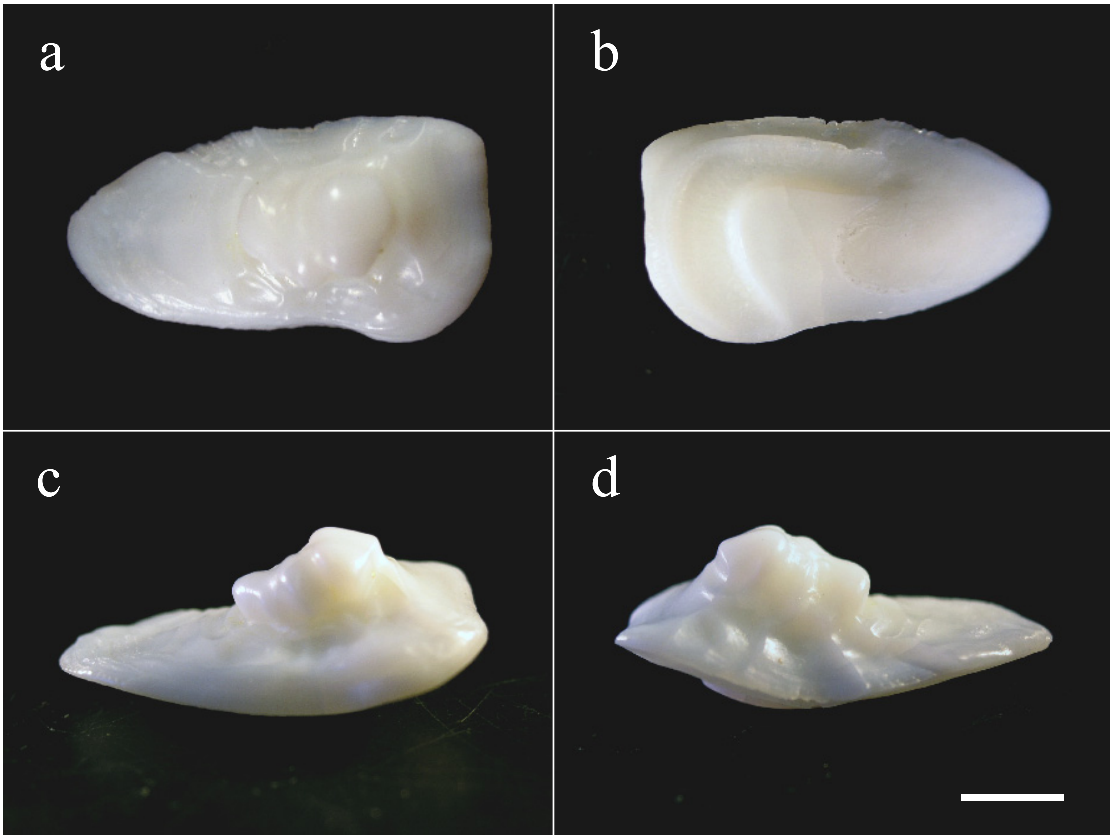

**Plate 3.1.** Sagittal otolith typical of *Argyrosomus japonicus* (1143 mm total length), showing the (a) lateral, (b) medial, (c) dorsal and (d) ventral surfaces. Scale bar = 5 mm.

**Plate 3.2.** Longitudinal section through the primordium of a sagittal otolith of *Argyrosomus japonicus* containing 1 opaque zone and viewed under reflected light. **o** = opaque zone. Scale bar = 2 mm.

**Plate 3.3.** Longitudinal section through the primordium of a sagittal otolith of *Argyrosomus japonicus* containing 17 opaque zones and viewed under reflected light. Scale bar = 2 mm.

### 3.2.3 Gonad stages

Although the same staging criteria were used to describe gonadal development in *A. japonicus* and *P. dentex* (Laevastu, 1963), the gonads of *A. japonicus* differed slightly in their macroscopic appearance (*cf* Tables 3.1; 4.1).

**Table 3.1.** Description of characteristics used to distinguish the various stages in ovarian and testicular development in *Argyrosomus japonicus* using macroscopic staging criteria and the ovaries of this species using histological staging criteria.

| Stage | Classification | Macroscopic characteristics | Histological characteristics |
|---|---|---|---|
| **I/II** | Immature/resting | Ovaries small and translucent, pink to orange in colour. Oocytes not visible through ovarian wall. Testes very thin and flat, pink to beige in colour. | Chromatin nucleolar oocytes predominant (these oocytes occur in all subsequent stages). Oogonia and perinucleolar oocytes sometimes detectable. Ovigerous lamellae highly organised. |
| **III** | Developing | Ovaries slightly larger. Oocytes visible through ovarian wall. Testes slightly larger, triangular in cross-section, beige in colour. Sperm present in main sperm duct. | Cortical alveolar oocytes abundant. |
| **IV** | Maturing | Ovaries larger, opaque, yellow to orange in colour. Yolk granule oocytes visible through ovarian wall. Testes larger, mottled beige and cream in colour. Softer texture, sperm present in tissue. Testes rupture when pinched. | Cortical alveolar and yolk granule oocytes abundant. |
| **V/VI** | Mature/spawning | Ovaries larger than stage IV, orange in colour. Testes larger, cream in colour and rupture under slight pressure. | Yolk granule oocytes predominate compliment of large oocytes. Stage VI ovaries contain migratory nucleus and/or hydrated oocytes and/or post-ovulatory follicles. |
| **VII** | Spent | Ovaries and testes far smaller than stage V/VI. Ovaries flaccid. Some yolk granule oocytes still visible through ovarian wall. Testes mottled-beige and cream in colour. Some sperm present in main duct and tissue. | Some remnant yolk granule oocytes, but generally atretic. Scar tissue present. |
| **VIII** | Recovering | Ovaries and testes were small. Similar to stage II, but ovaries red in colour. | No remnant yolk granule oocytes. Extensive scar tissue, ovarian lamellae highly disorganised. |

## 3.3 RESULTS

### 3.3.1 Habitats

The *A. japonicus* caught in nearshore waters ranged in length from 150 to 1400 mm and included a greater number of juveniles, *i.e.* < $L_{50}$ at first maturity, than adults (Figure 3.1a). In contrast, the *A. japonicus* caught in offshore waters contained no fish < 600 mm and comprised mainly adults (Figure 3.1b). The length ranges of the adults caught in nearshore and offshore waters were similar.

### 3.3.2 Validation of ageing procedure

The mean monthly marginal increments on sectioned otoliths of *A. japonicus* with 2 – 4 opaque zones remained at 0.5 – 0.6 from July to November and then declined precipitously to a minimum of *ca* 0.2 in December, after which it increased progressively to *ca* 0.45 in April and remained at about that level in the immediately ensuing months (Figure 3.2). Similar trends were exhibited by the mean monthly marginal increments on otoliths with 5 – 7 and ≥ 8 opaque zones (Figure 3.2). Although none of the fish caught in October, January and May contained otoliths with 1 opaque zone, the mean monthly marginal increments on otoliths with one such zone clearly followed a similar trend to that exhibited by otoliths with two or more opaque zones (Figure 3.2). The presence, during the year, of a single marked decline and subsequent rise in the mean monthly marginal increments demonstrate that, irrespective of the number of opaque zones, a single opaque zone is formed annually in the otoliths of *A. japonicus*. Furthermore, the trends exhibited by the mean monthly marginal increments demonstrate that each new opaque zone becomes delineated by the formation of a new translucent zone in November/December, *i.e.* late spring/early summer. Since the spawning for *A. japonicus* peaks in December, the first opaque zone is formed on the otoliths of 0+ *Argyrosomus japonicus* towards the end of their first year of life.

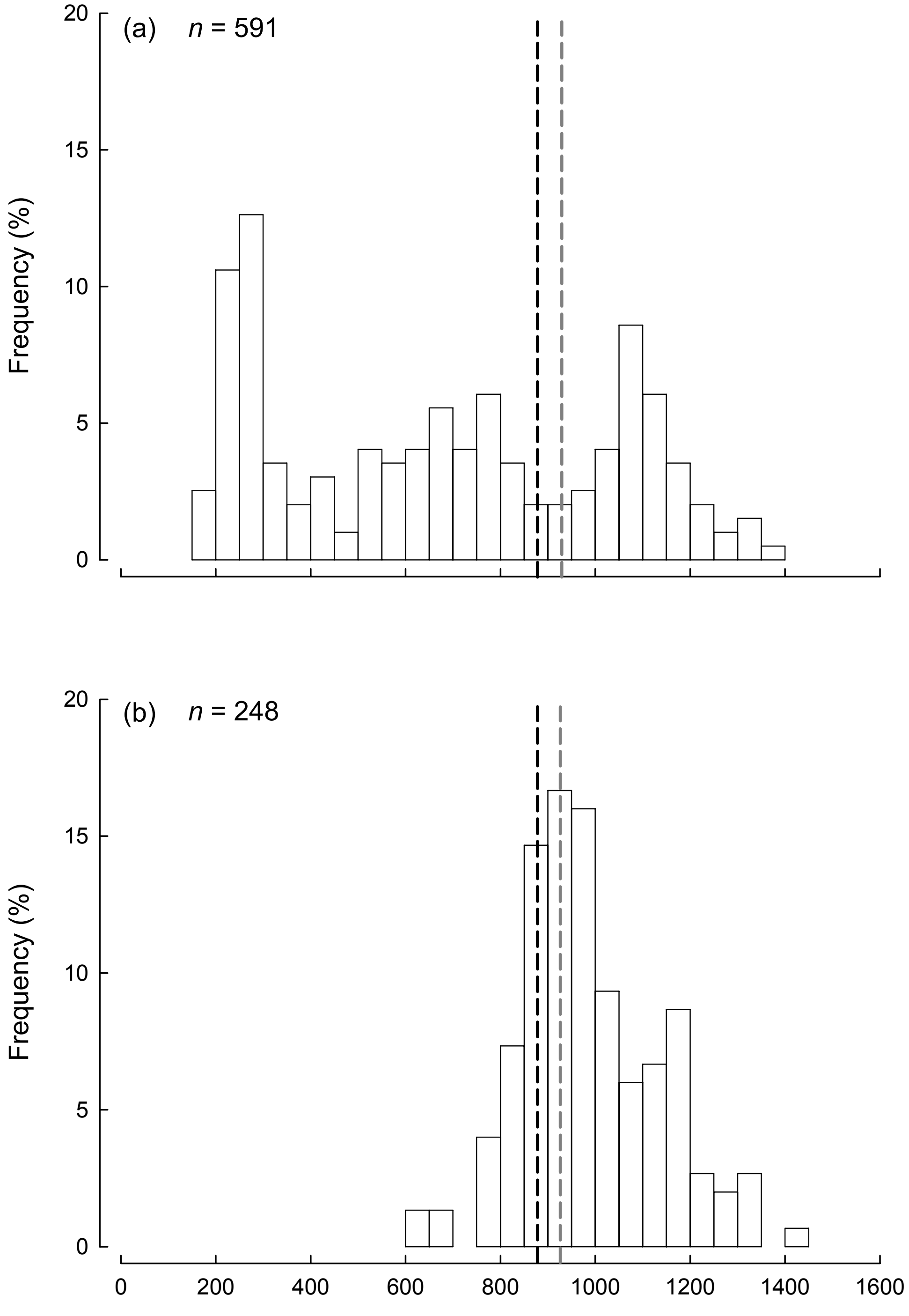

**Figure 3.1.** Length-frequency distributions for *Argyrosomus japonicus* caught in (a) nearshore waters, *i.e.* including rivers, estuaries and the surf zone, to a depth of *ca* 20 m and in (b) offshore waters, *i.e.* depths of 20-120 m. Black and grey dashed lines indicate the $L_{50}$s at first maturity for males and females, respectively.

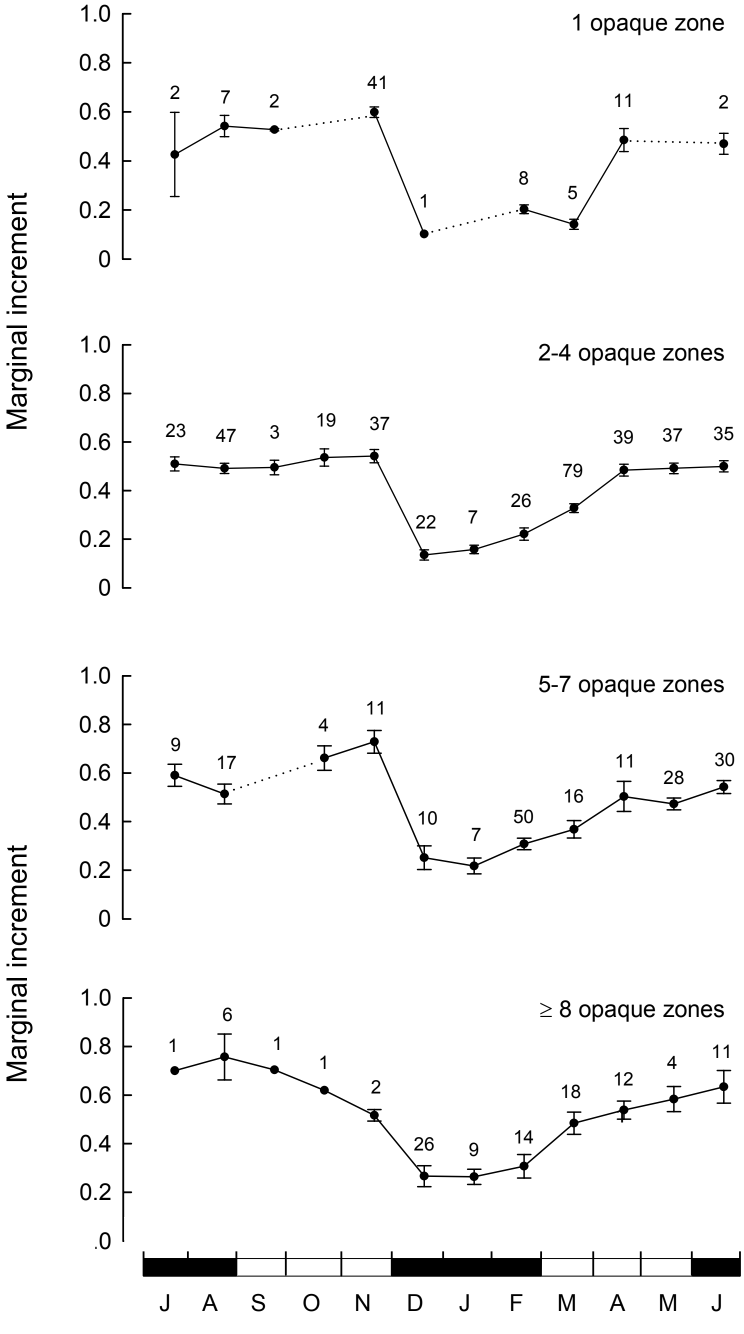

**Figure 3.2.** Mean monthly marginal increments ± 1 SE on sectioned sagittal otoliths of *Argyrosomus japonicus*. Sample size for each month is given. On the x-axis in this Figure and in Figures 3.6, 3.8 and 3.9, the closed rectangles refer to winter and summer months and the open rectangles to spring and autumn months.

### 3.3.3 Otolith-scale comparisons

The number of circuli on the scales of the 80 *A. japonicus* examined differed from the number opaque zones in the otoliths of the same individuals in *ca* 70% of these comparisons. The discrepancy between the counts for scale circuli and otolith opaque zones increased with the number of such zones, with the number of scale circuli being less than the number of otolith opaque zones in all but one of the 34 cases when the number of the latter zones was $\geq 5$.

### 3.3.4 Growth

The von Bertalanffy growth equation fitted to the lengths at age of females and males of *A. japonicus* in the northern region did not differ significantly from those derived for the corresponding sexes in the southern region ($p > 0.05$). Thus, the lengths at age for individuals of each sex in each region were pooled. The von Bertalanffy growth equation for females differed significantly from that of males ($p < 0.05$).

The lengths at age of females and males of *A. japonicus* were described well by the traditional von Bertalanffy growth equation, as is demonstrated by the relatively high coefficients of determination, *i.e.* 0.913 and 0.907, respectively, and by ages at zero length that were close to zero, *i.e.* -0.33 and -0.35 years, respectively (Table 3.2; Figure 3.3). The estimates for the growth coefficient ($k$) and asymptotic length ($L_\infty$) were 0.24 year$^{-1}$ and 1239 mm, respectively, for females, and 0.25 year$^{-1}$ and 1189 mm, respectively, for males (Table 3.2).

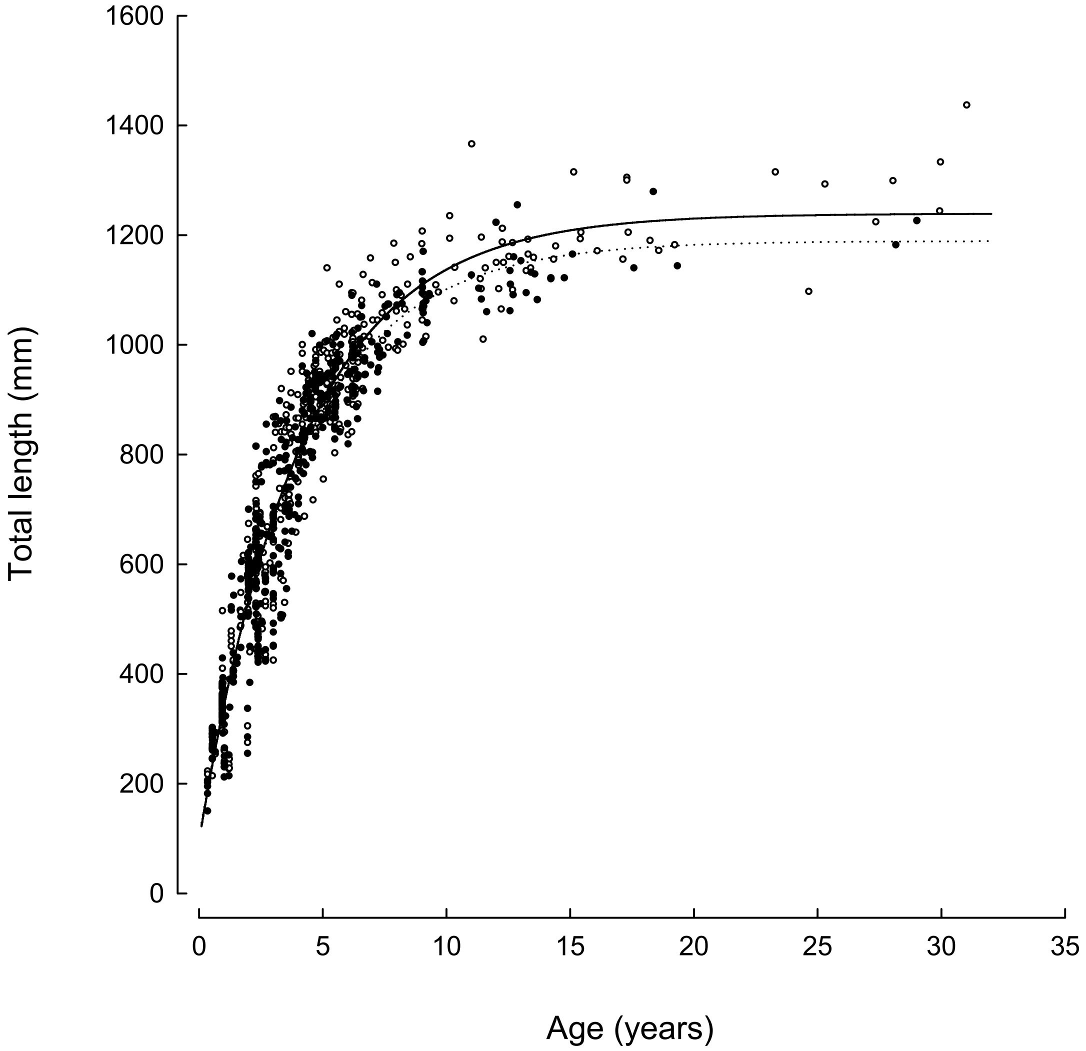

**Figure 3.3.** von Bertalanffy growth curves fitted to the lengths at age of females (solid line and open circles) and males (dotted line and closed circles) of *Argyrosomus japonicus*. $n_{\text{females}}$= 432, $n_{\text{males}}$ = 435.

The lengths derived for females and males of *A. japonicus* at each successive age, using the von Bertalanffy growth equations, demonstrate that the growth of both sexes was similar for the first 5 years, after which it slowed markedly and, to a slightly greater extent, in males than females (Figure 3.3). Thus, the lengths at ages 2, 4 and 5, predicted from the von Bertalanffy growth equation, were 533, 804 and 897 mm for females, compared with 531, 791 and 880 mm for males. By 10, 15 and 20 years of age, the predicted lengths of females were 1137, 1209 and 1230 mm, respectively, compared with 1101, 1164 and 1182 mm, respectively, for males (Figure 3.3). The maximum total length and age recorded for females of *A. japonicus* were 1437 mm (35.1 kg) and 31 years, respectively, while, for males, they were 1304 mm (18.2 kg) and 29 years, respectively. The females and males of *A. japonicus* both attained the minimum legal length for capture (MLL) of 500 mm at *ca* 2 years of age.

**Table 3.2.** von Bertalanffy growth parameters derived from lengths at age for female and male *Argyrosomus japonicus*, including lower and upper 95% confidence limits, the coefficient of determination ($R^2$) and number of fish aged ($n$).

| | | $L_\infty$ (mm) | $K$ (year$^{-1}$) | $t_0$ (years) | $R^2$ | $n$ |
|---|---|---|---|---|---|---|
| Female | **Estimate** | 1239 | 0.24 | -0.33 | 0.913 | 432 |
| | **Upper 95%** | 1269 | 0.26 | -0.19 | | |
| | **Lower 95%** | 1209 | 0.22 | -0.46 | | |
| Male | **Estimate** | 1189 | 0.25 | -0.35 | 0.907 | 435 |
| | **Upper 95%** | 1224 | 0.27 | -0.22 | | |
| | **Lower 95%** | 1155 | 0.23 | -0.49 | | |

### 3.3.5 Length/weight relationship

As the regression equations relating total length in mm ($L$) and weight in g ($W$) for female and male *A. japonicus* did not differ significantly ($p > 0.05$), the length-weight data for the two sexes were pooled. The resulting equation for both sexes collectively was $\log_e W = 2.933(\log_e TL) - 11.179$ ($n = 214$, $R^2 = 0.994$).

### 3.3.6 Length and age compositions in commercial and recreational fisheries

The data presented in this section is derived from the retained catches of commercial wetline fishers operating off the west coast of Australia and from the retained catches of recreational fishers in Kalbarri and the lower reaches of the Swan River Estuary, which are located in the northern and southern regions, respectively.

The distribution of the total lengths of the females and males of *A. japonicus* in the commercial wetline fishery were similar, ranging overall from 400 to 1250 mm (Figure 3.4a). Although these individuals ranged in age from 2 to 25 years, the majority of fish belonged to the 2 to 8+ age classes (Figure 3.4a). Note that, in 2003, the size limit for the retention of *A. japonicus* in Western Australian waters was increased from 450 to 500 mm, and that those *A. japonicus* within this size class (including 3 fish below the MLL) were obtained before such a change was implemented.

The total lengths of the females and males of *A. japonicus* caught and retained in the Kalbarri recreational fishery ranged from 550 to 1250 mm (Figure 3.4b). These fish ranged in age from 3 to 18 years, with the majority of individuals belonging to the 3 to 11+ age classes (Figure 3.4b). The total lengths of female and male *A. japonicus* caught and either retained or tagged and released in the Swan River recreational fishery ranged from 900 to 1300 mm (Figure 3.4c). These fish ranged in age from 4 to 29 years, with the majority of individuals belonging to the 7 to 10+ age classes (Figure 3.4c).

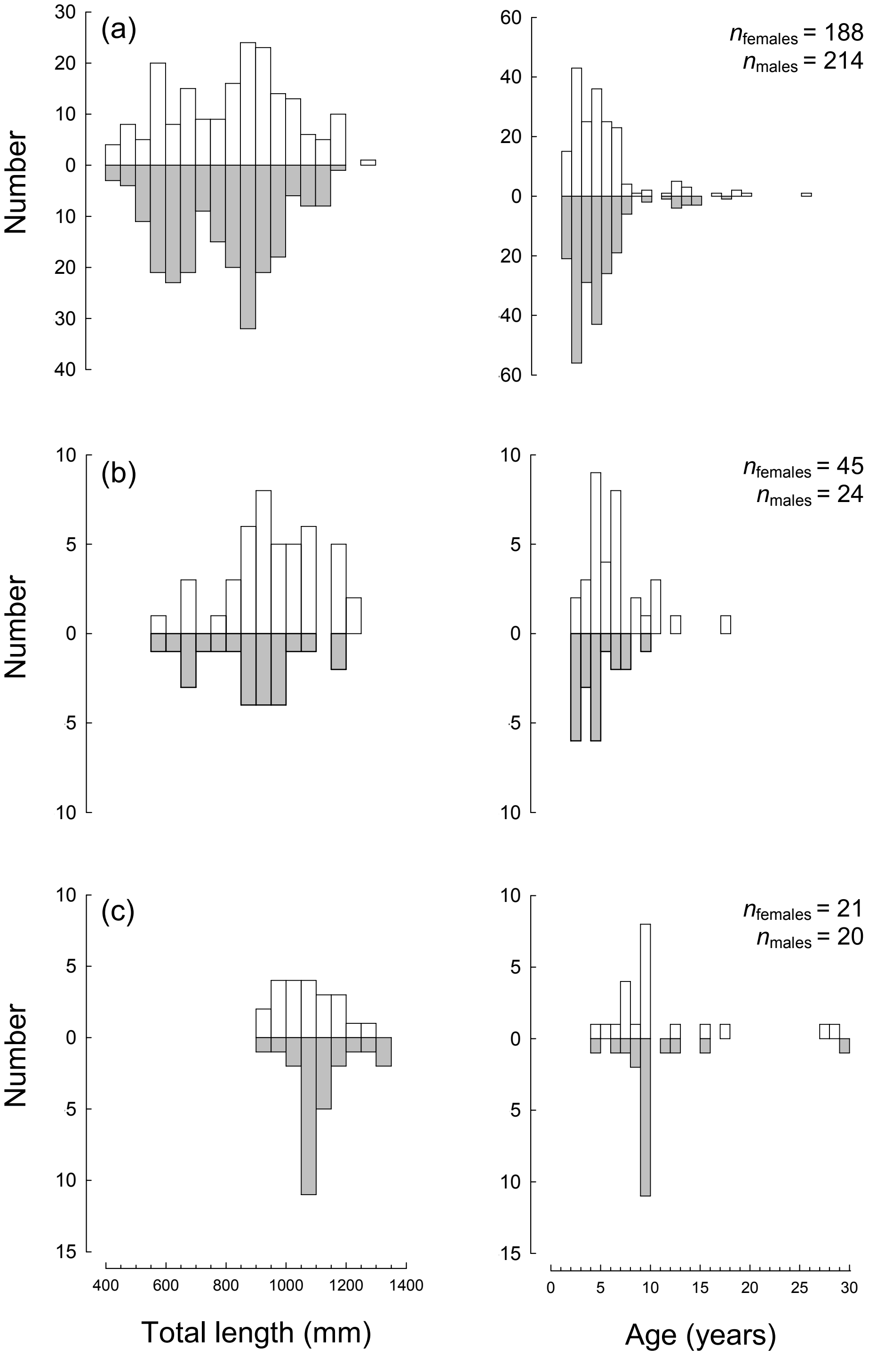

**Figure 3.4.** Length and age-frequency compositions for female (white) and male (grey) *Argyrosomus japonicus* retained in (a) the commercial wetline fishery, (b) the Kalbarri recreational fishery and (c) the Swan River recreational fishery.

### 3.3.7 Sex ratio

The numbers of females and males of *Argyrosomus japonicus* that were caught during the present study were virtually identical, *i.e.* 432 and 435, respectively.

### 3.3.8 Reproductive indices in coastal marine waters

Due to the low numbers of mature *A. japonicus* obtained from the northern region during the spawning period, the data for GSIs and prevalences of the different gonadal stages in the corresponding months in those two regions were pooled.

The females of *A. japonicus* that were ≥ $L_{50}$ and possessed resting ovaries, *i.e.* stage II, were most abundant between April and September (Figure 3.5). Females of *A. japonicus* with ovaries at stages III (developing) and IV (maturing) were first collected in May and those with ovaries at stages V-VI (mature or spawning) were first recorded in October. Although mature or spawning ovaries were present from October to May, they only became the most prevalent category in December. By February and March, the ovaries of the majority of females were at stages VIII or II (recovering or resting) (Figure 3.5). The trends exhibited in sequential months by the frequency of different stages in the gonadal development of males of *A. japonicus* ≥ $L_{50}$ at first maturity were similar to those just described for females (Figure 3.5). The above trends demonstrate that, during the spawning season, the vast majority of females and males with gonads at stages III-V will become fully mature, while, by definition, those with gonads at stage VI were in spawning condition and those with gonads at stages VII and VIII have recently spawned.

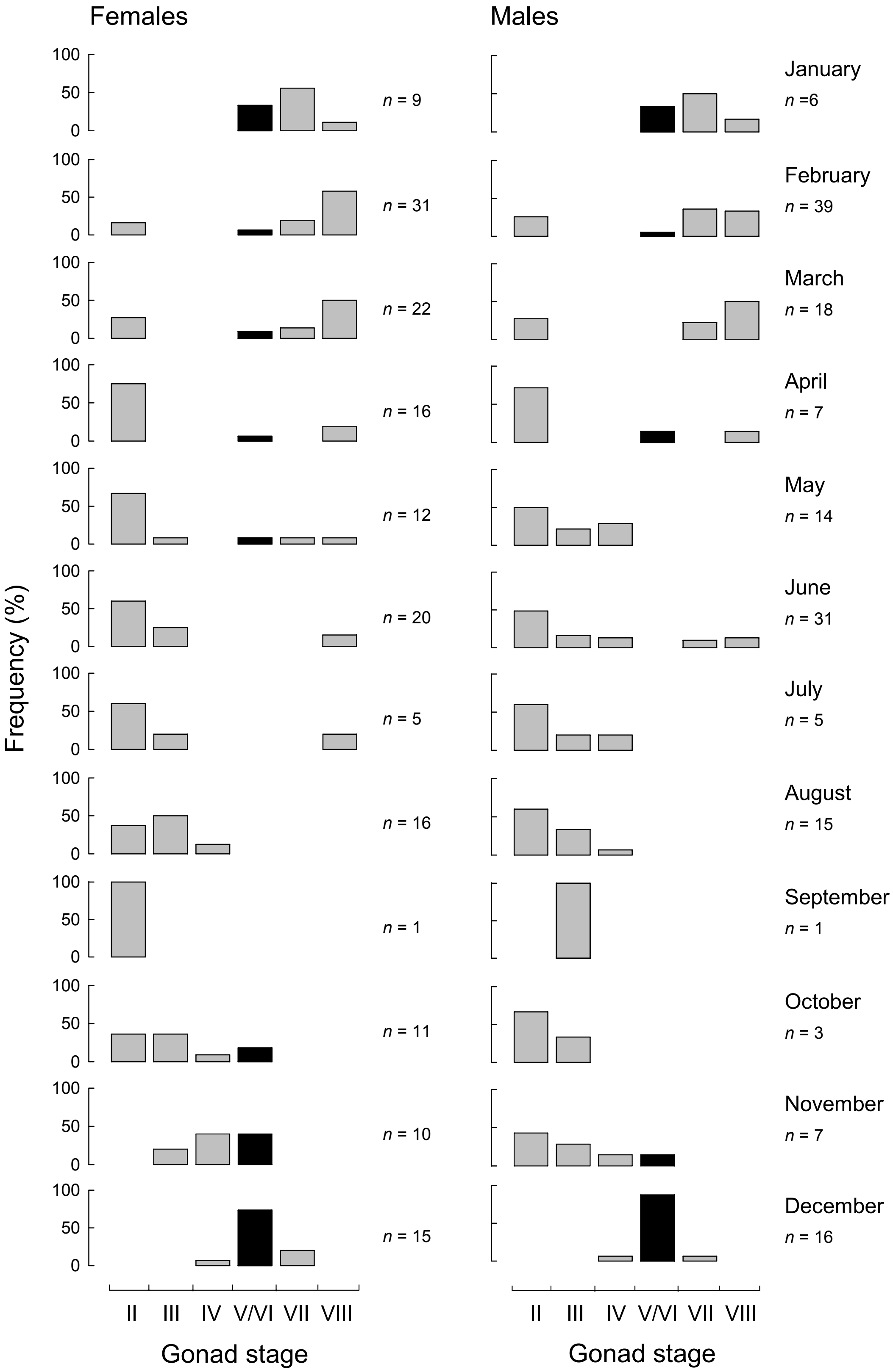

**Figure 3.5.** Monthly percentage frequencies of occurrence of sequential gonadal stages in female and male *Argyrosomus japonicus* ≥ $L_{50}$ at maturity in coastal marine waters. *n* = sample size in each month. In this figure and figures 3.6, 3.10 and 3.11, the data for northern and southern regions have been pooled.

The mean monthly gonadosomatic indices (GSIs) of female *A. japonicus* caught in coastal waters remained at < *ca* 1.5 from June to October and then rose to a peak of *ca* 4 in December and January, before declining to < *ca* 1.6 in February and the immediately ensuing months (Figure 3.6). The mean monthly GSIs of male *A. japonicus* caught in the same waters follows a very similar trend, with the peak of *ca* 3.5 being attained in December (Figure 3.6). The frequency of occurrence of females and males with stage V/VI, *i.e.* mature/spawning gonads, peaked sharply in December (Figure 3.6). As such gonads were found predominantly during November, December and January, it is concluded that spawning occurs mainly in these three months. The few female fish with stage V ovaries in October and in February to May and the male with stage V testes in February and May were caught in the northern region, which strongly indicates that spawning commences earlier and lasts longer in those waters.

The oocyte diameter frequency distributions in the ovaries of three female *A. japonicus* collected during the spawning period produced a prominent modal class at 40-79 μm (Figure 3.7), which represented oocytes at the chromatin nucleolar and perinucleolar stages. There was also a group of oocytes with diameters that lay mainly in the range of 360-419 μm and which, in two ovaries, produced a modal class of 380-399 μm, that represented predominantly yolk granule oocytes. As the oocytes with intermediate diameters were always cortical alveolar oocytes, the ovaries of each of the three fish contained each oocyte stage between the chromatin nucleolar and yolk granule stages. This accounts for the oocyte diameters of each of the three fish forming a largely continuous overall distribution (Figure 3.7). The ovaries of three of the female fish caught in the Swan River Estuary contained the same range in oocyte stages and also hydrated oocytes.

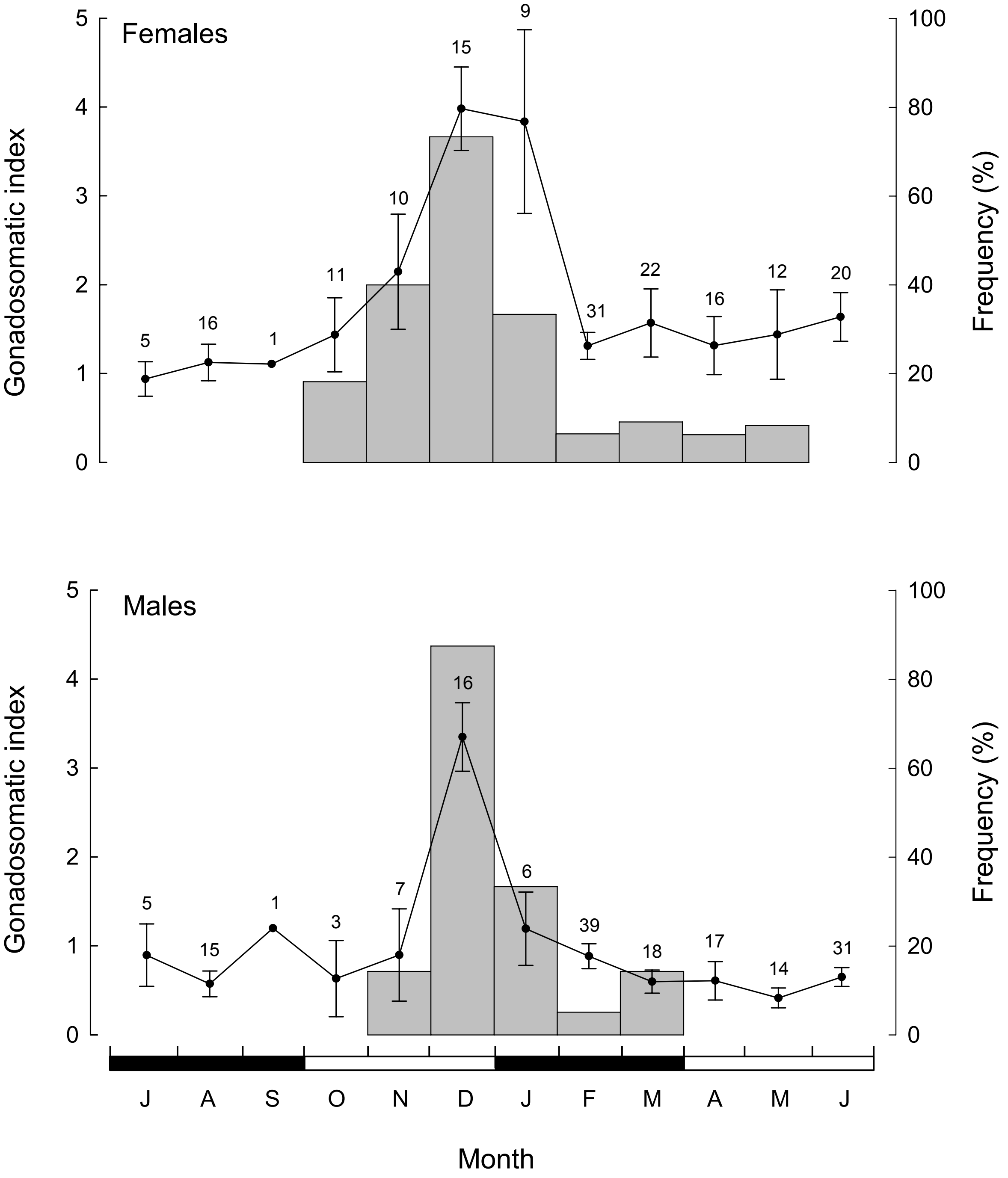

**Figure 3.6.** Mean monthly gonadosomatic indices ± 1 SE and monthly percentage frequencies of stage V/VI (mature/spawning) gonads of female and male *Argyrosomus japonicus* ≥ $L_{50}$ at first maturity. Sample sizes in each month are given.

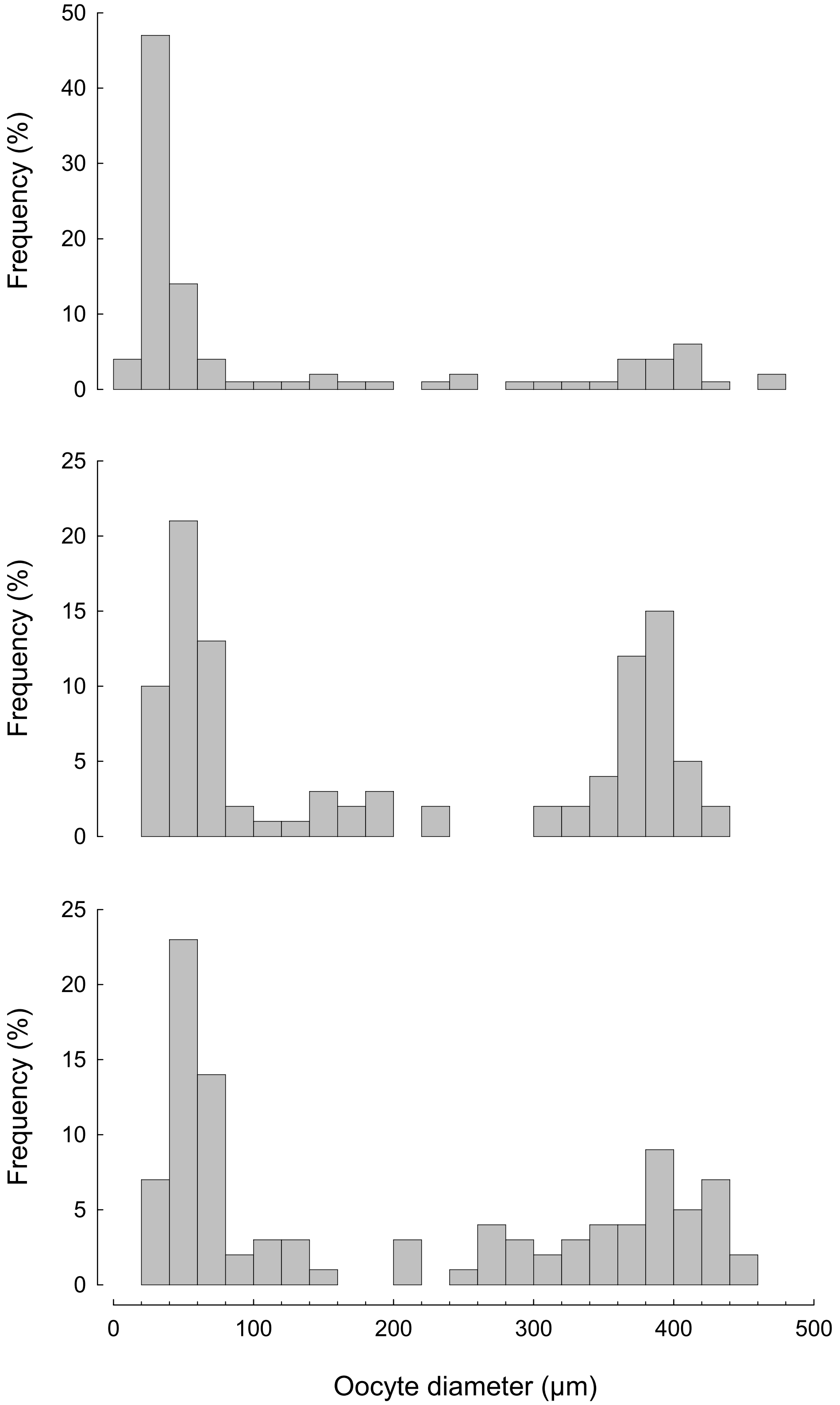

**Figure 3.7.** Oocyte diameter frequency distributions for stage V ovaries of three female *Argyrosomus japonicus*.

### 3.3.9 Seasonal occurrence and reproductive indices in the Swan River Estuary

The data presented in this section are derived from the recreational catches of *A. japonicus* obtained by identified and regular fishers in the lower reaches of the Swan River Estuary (Mosman Bay) and from sampling trips to this locality. Despite recreational fishing effort remaining relatively consistent throughout a typical year in the Swan River Estuary (Malseed and Sumner, 2001), no *A. japonicus* were caught by recreational fishers or ourselves between April and September (Figure 3.8). The majority of fish, *i.e.* 80%, were caught during the summer months (Figure 3.8).

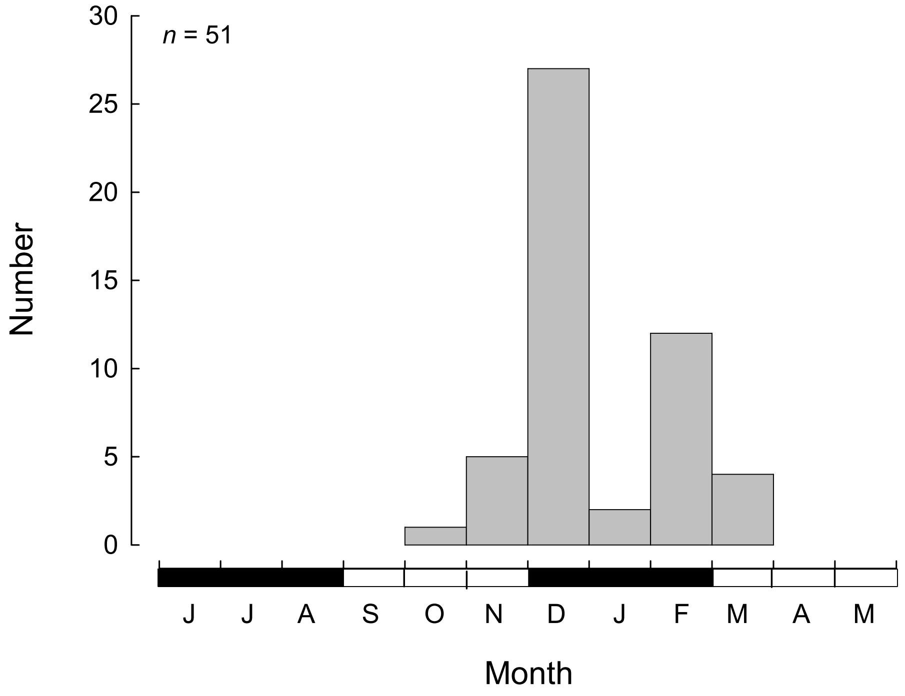

**Figure 3.8.** Monthly catches of *Argyrosomus japonicus* obtained by identified recreational fishers and during sampling trips in the lower Swan River Estuary. *n* = sample size.

The GSI of the single male *A. japonicus* caught in the Swan River Estuary in October was 1.25 (Figure 3.9). The mean monthly GSIs of males were *ca* 3.5 in November and December, and then declined to < *ca* 2 in January and February. The mean monthly GSIs of female *A. japonicus* were *ca* 4.5 in November and December, after which they declined to *ca* 1.5 in February (Figure 3.9). Since females and males of

*A. japonicus* with stage V/VI, *i.e.* mature/spawning gonads, were found predominantly during November and December (Figure 3.9), it is concluded that spawning in the Swan River Estuary occurs mainly during these months.

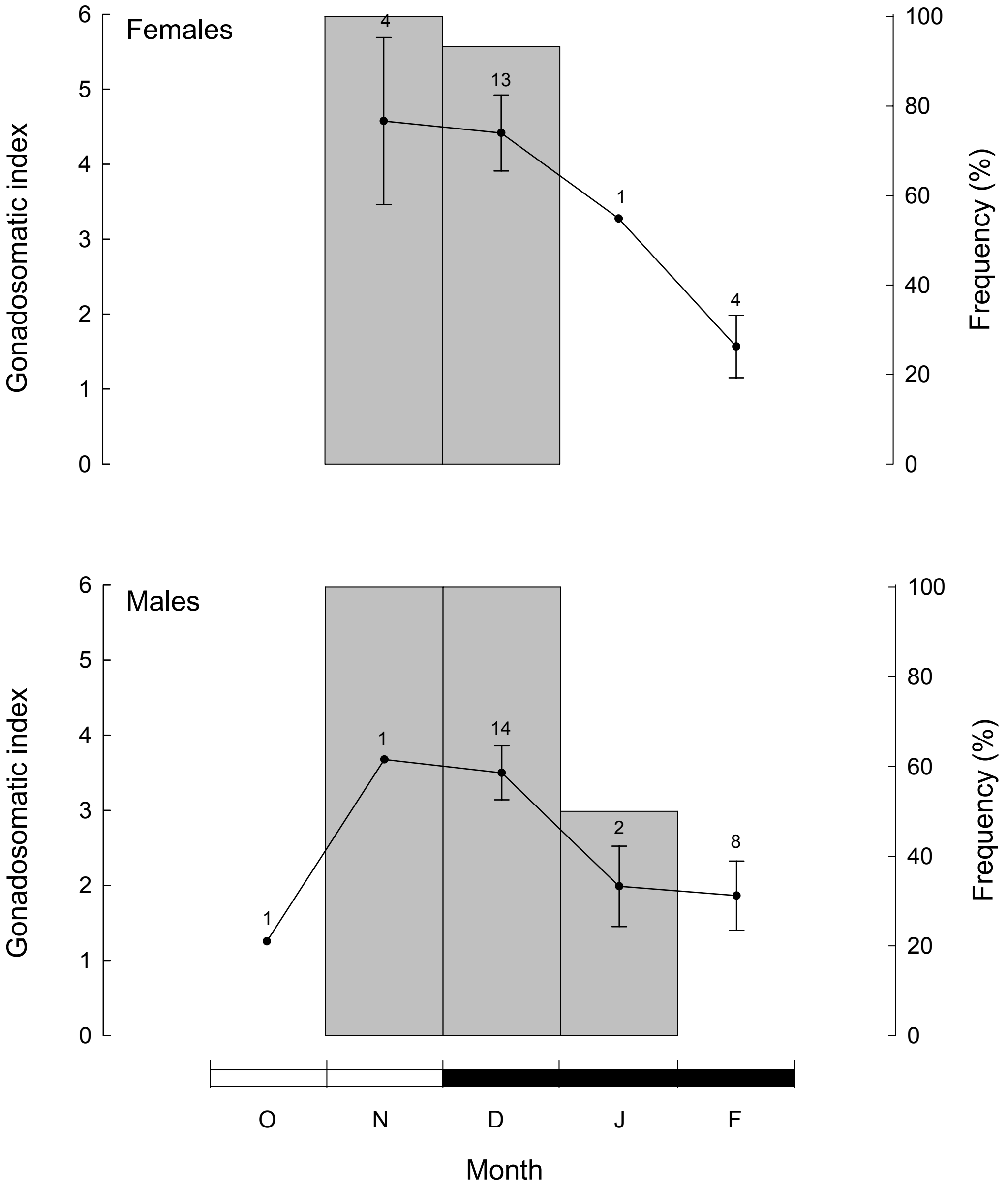

**Figure 3.9.** Mean monthly gonadosomatic indices ± 1 SE and monthly percentage frequencies of stage V/VI (mature/spawning) gonads of female and male *Argyrosomus japonicus* $\geq L_{50}$ at first maturity. Sample size for each month is given.

### 3.3.10 Length and age at maturity

The ovaries of all female *A. japonicus*, with lengths of 200-849 mm in the period between November and January when spawning mainly occurs, were immature, *i.e.* stage I/II (Figure 3.10). Fish with ovaries at stages III-VIII were first recorded in the 850-899 mm length class, in which they accounted for 33% of all fish, and constituted 50% of all individuals in both the 900-949 and 950-999 mm length classes and all individuals in the 1000-1049 mm and subsequent length classes (Figure 3.10). From the logistic regression analysis, the $L_{50}$ for female *A. japonicus* at first maturity was 929 mm, which, on the basis of the von Bertalanffy growth equation, corresponds to an age of *ca* 6 years (Table 3.3; Figure 3.10).

**Table 3.3.** Estimates of lengths at maturity, $L_{50}$ and $L_{95}$, of *Argyrosomus japonicus* and their lower and upper 95% confidence limits.

| | | $L_{50}$ (mm) | $L_{95}$ (mm) |
|---|---|---|---|
| Females | **Estimate** | 929 | 1057 |
| | **Upper** | 977 | 1135 |
| | **Lower** | 881 | 992 |
| Males | **Estimate** | 878 | 998 |
| | **Upper** | 934 | 1054 |
| | **Lower** | 853 | 917 |

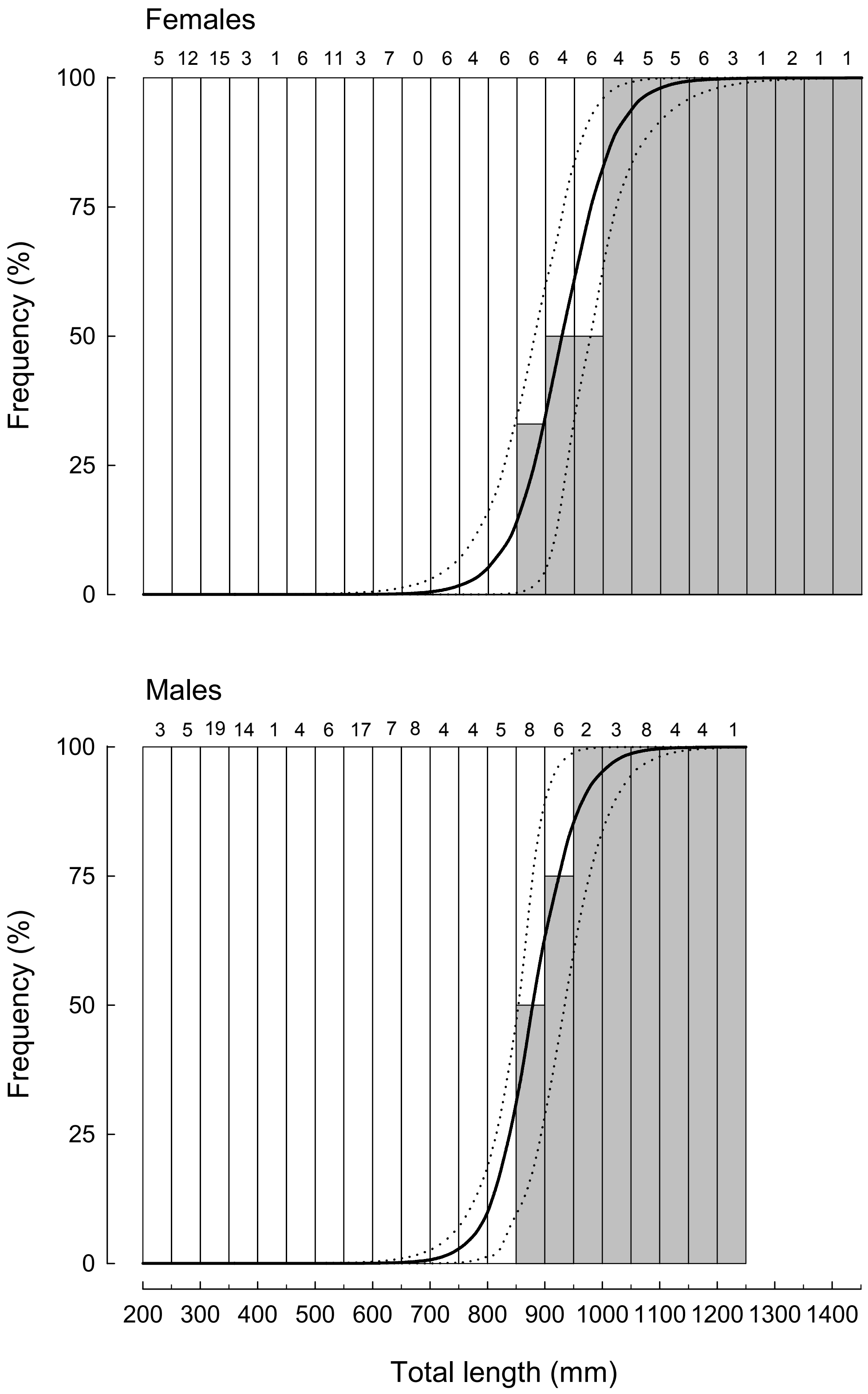

**Figure 3.10.** Percentage contributions made in each 50 mm length class during the spawning season by individual females and males of *Argyrosomus japonicus* with gonads at stages III-VIII. The predicted percentages (± 95% CIs) of mature fish at each length derived using logistic regression analysis are shown (solid and dotted lines). Grey bars denote percentage mature in each 50 mm length class and the sample size for each length class is shown.

During the spawning period, the percentage of male *A. japonicus* with testes at stages III-VIII increased progressively with body size from 0% in the 800-849 mm length class to 50% in the 850-899 mm length class and 100% in the 950-999 mm and all subsequent length classes (Figure 3.10). The $L_{50}$ of 878 mm (*ca* 5.5 years) for male *A. japonicus* at first maturity differed significantly ($p < 0.05$) from the 929 mm (*ca* 6 years) estimated for females (Table 3.3; Figure 3.10).

All females of *A. japonicus* that were caught during the spawning period and were < five years of age, were immature (Figure 3.11). Over half of the females caught at the end of their fifth, sixth and eighth years of life and all older females were mature (Figure 3.11). Among males, one individual became mature during its third year of life, while maturity was attained by over 50% of individuals at the end of their fifth and sixth years of life and by all older fish (Figure 3.11).

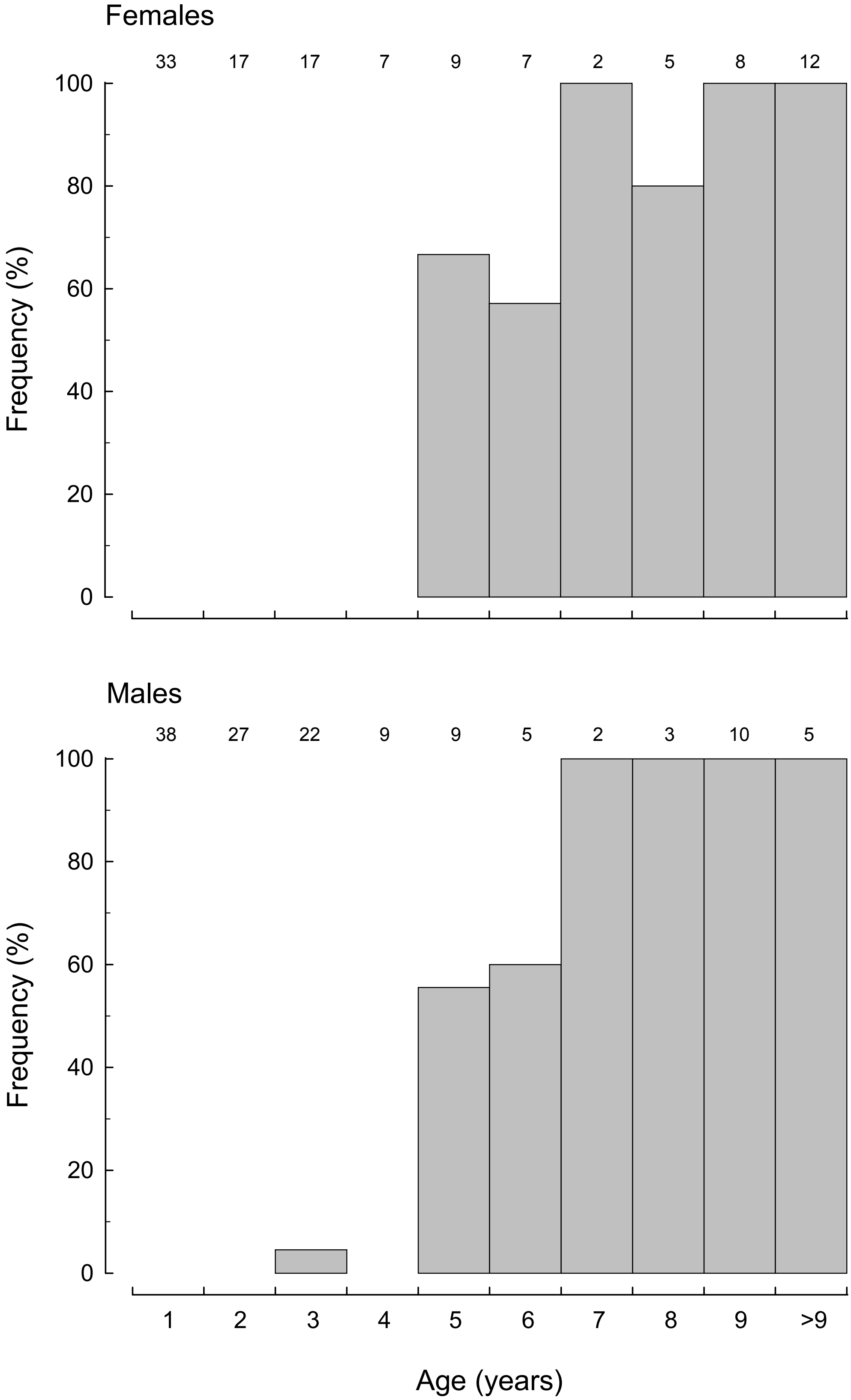

**Figure 3.11.** Percentage frequency of occurrence of gonads at stages III-VIII in sequential ages of female and male *Argyrosomus japonicus* during the spawning season, *i.e.* November-February. Sample sizes for each age category are given.

### 3.3.11 Mortality

The point estimates for the instantaneous coefficient of total mortality, *Z*, for *A. japonicus*, calculated using a refitted version of Hoenig's (1983) equation for fish, and, using an age of 3 years at full recruitment to the exploited stock, relative abundance (catch curve) analysis and simulation, based on the number of fish greater than a specified age, *i.e.* 17 years, were 0.17, 0.35 and 0.30 year$^{-1}$, respectively (Table 3.4). The point estimate for the instantaneous coefficient of natural mortality, *M*, for *A. japonicus*, derived by refitting Pauly's (1980) equation (0.43 year$^{-1}$) was greater than each of the above estimates for *Z* (Table 3.4). The posterior probability distribution determined for *Z* using the Bayesian method of Hall *et al.* (2004), which combines the separate likelihood distributions for the various estimates of *Z* (Figure 3.12), yielded a point estimate for that variable of 0.34 year$^{-1}$ (Table 3.4). The resultant posterior probability distribution for the point estimate for *M*, determined from the Pauly estimate, the combined likelihood distribution for *Z* and the requirement that $M \leq Z$, yielded a point estimate for *M* of 0.24 year$^{-1}$ (Table 3.4; Figure 3.13). The 95% confidence interval for this combined estimate of *M* for *A japonicus* was far narrower than for the point estimate of *M* derived by refitting Pauly's (1980) equation. The point estimates of the current level of fishing mortality, *F*, derived from the Monte Carlo analysis for *A. japonicus* (0.11 year$^{-1}$) is relatively low, *i.e.* < half the level of natural mortality, *M* (Table 3.4).

**Table 3.4.** Estimates (year$^{-1}$) of total, *Z*, natural, *M*, and fishing mortality, *F*, for *Argyrosomus japonicus* in Western Australia, calculated using life history models (Pauly, 1980; Hoenig, 1983), relative abundance analysis or simulation based on the three fish ≥ 17 years. Estimates for *Z* and *M* were also provided using a Bayesian method, which combines the data obtained using the other methods (Hall *et al.*, 2004).

| **Method of analysis** | ***Z*, *M* or *F*** | **Estimate** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|---|
| Refitted Hoenig (1983) fish equation | *Z* | 0.17 | 0.06 | 0.48 |
| Relative abundance analysis | *Z* | 0.35 | 0.31 | 0.40 |
| Simulation (3 fish ≥ 17 years ) | *Z* | 0.30 | 0.23 | 0.38 |
| **Combined *Z* (Bayesian method)** | ***Z*** | **0.34** | **0.31** | **0.39** |
| Refitted Pauly (1980) | *M* | 0.43 | 0.14 | 1.32 |
| **Combined *M* (Bayesian method)** | ***M*** | **0.24** | **0.12** | **0.36** |
| **Monte Carlo** | ***F*** | **0.11** | **0.00** | **0.36** |

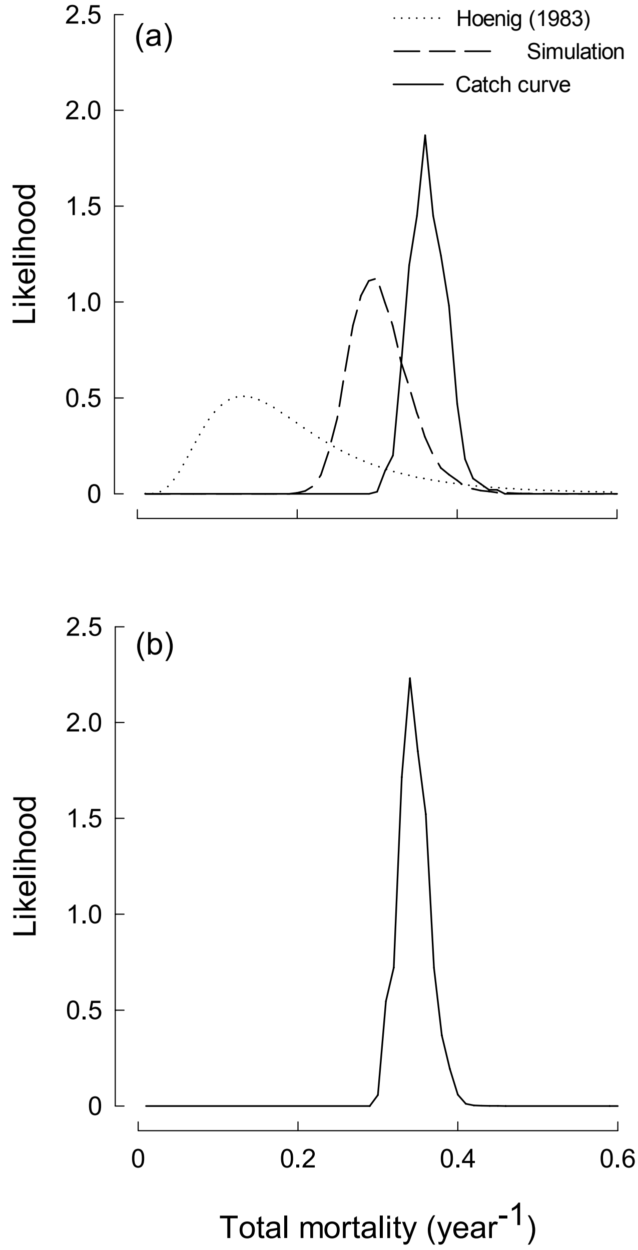

**Figure 3.12.** (a) Estimated likelihood functions for total mortality, *Z*, of *Argyrosomus japonicus* derived using Hoenig's (1983) regression equation for fish, relative abundance (catch curve) analysis, and a simulation method based on the number of individuals above a certain age and sample size. (b) Combined posterior probability distributions for *Z* for *A. japonicus* derived from the separate likelihood functions shown in (a).

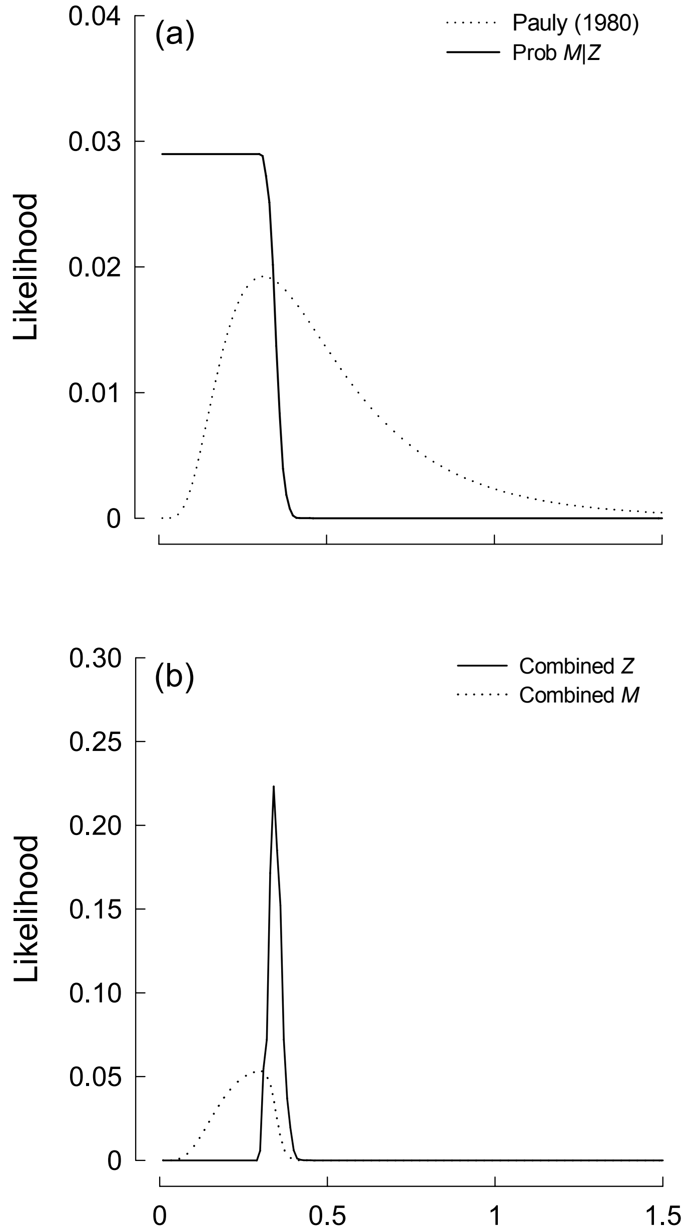

**Figure 3.13.** (a) Likelihood functions for natural mortality, *M*, for *Argyrosomus japonicus* from Pauly's (1980) equation and (b) the likelihood function for assuming that it is less than the combined estimate for *Z* and the combined posterior probability distributions for *Z* and *M*. Prob *M*|*Z* = probability of *M* given *Z*.

### 3.3.12 Yield per recruit and spawning potential ratio

Yield per recruit analysis (YPR) for *A. japonicus*, calculated using knife-edge selection, *i.e.* recruitment to the fishery at 3 years, as determined for this species in the commercial wetline fishery of Western Australia, indicated that, as fishing mortality, *F*, increases from 0 to 0.8 $\text{year}^{-1}$, the YPR will continue to increase (Figure 3.14a). The same situation would occur if the age at recruitment to the exploited stock was 4 years. However, if it was 2 years, the YPR begins to decline when *F* exceeds 0.38 $\text{year}^{-1}$ (Figure 3.14a). The YPR and associated 95% confidence intervals for *A. japonicus* at the estimated current level of *F* of 0.11 $\text{year}^{-1}$ and assuming knife-edge recruitment to the exploited stock at 3 years, is 0.95 kg $\text{year}^{-1}$ (0.00 – 6.38 kg $\text{year}^{-1}$). The estimated value of $F_{0.1}$ for *A. japonicus* is 0.32 $\text{year}^{-1}$.

Regardless of the age at recruitment, the spawning potential ratio (SPR) for both female and male *A. japonicus* decrease rapidly as fishing pressure increases (Figure 3.14b). In the case of both female and male *A. japonicus*, the rate at which SPR is predicted to decline decreases conspicuously as the age at recruitment increases. The current estimated SPRs for female and male *A. japonicus* are 0.49 (0.02 – 1.00) and 0.52 (0.02 – 1.00), respectively (Figure 3.14b).

**Table 3.5.** Estimates of the current level of yield per recruit (YPR), $F_{0.1}$, and the current levels of total spawning stock biomass per recruit (SSB/R) and spawning potential ratio SPR) for females and males, and for females and males combined, calculated using 3 years as the age of *Argyrosomus japonicus* at full recruitment to the exploited stock.

| | **Estimate** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|
| **YPR (kg $year^{-1}$)** | 0.95 | 0 | 6.4 |
| **$F_{0.1}$ ($year^{-1}$)** | 0.26 | - | - |
| **SSB/R (kg $year^{-1}$)** | 8.8 | 5.7 | 18.7 |
| **SPR (females)** | 0.49 | 0.02 | 1.00 |
| **SPR (males)** | 0.52 | 0.02 | 1.00 |
| **SPR (combined)** | 0.50 | 0.02 | 1.00 |

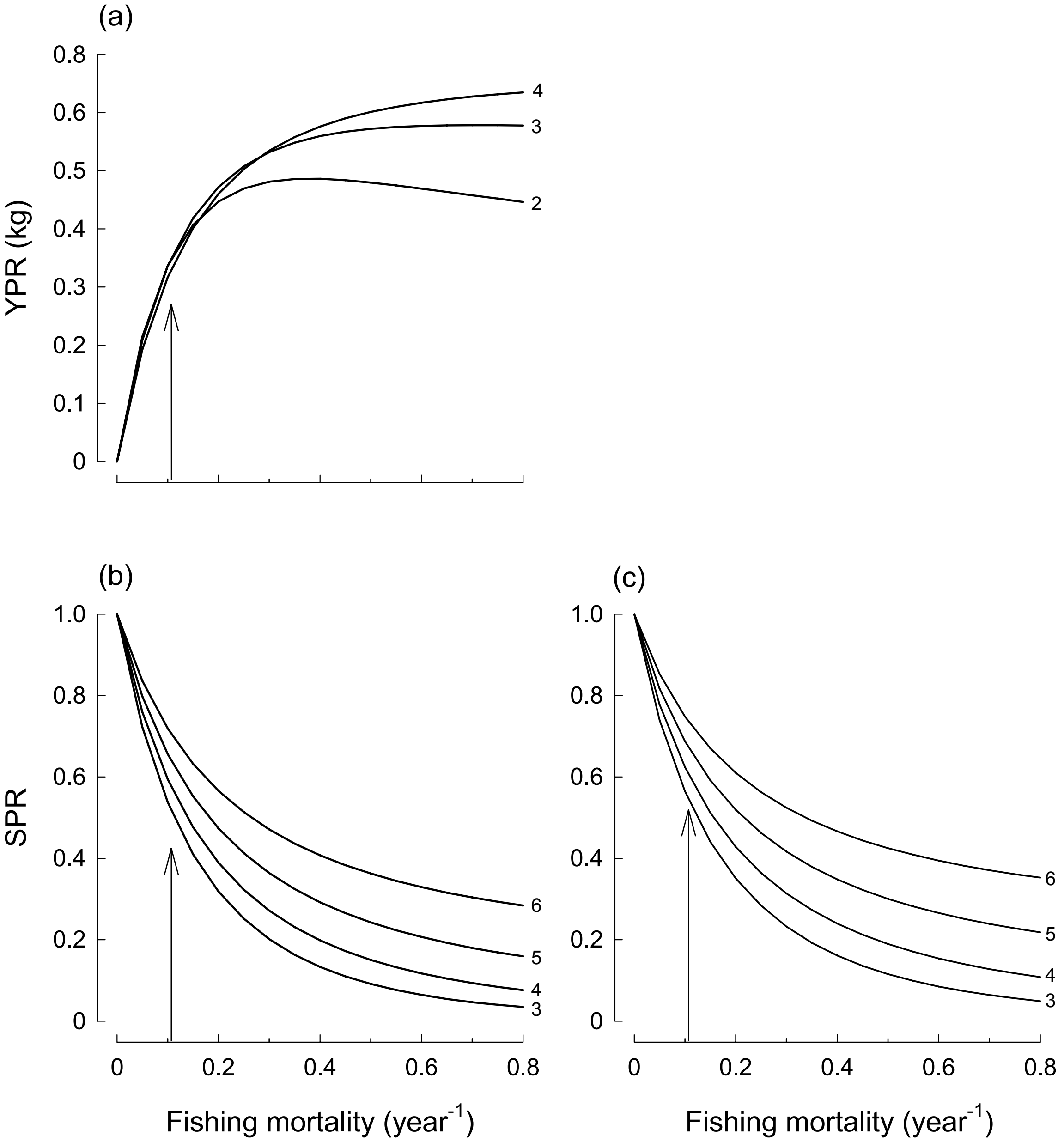

**Figure 3.14.** Effect on *Argyrosomus japonicus* of different levels of fishing mortality and at different ages at recruitment on the (a) yield per recruit and spawning potential ratio for (b) female and (c) male spawning stock biomass. Numbers indicate alternative ages of recruitment to the fishery. Arrows indicate the current level of fishing mortality.

## 3.4 DISCUSSION

### 3.4.1 Habitats

The juveniles of *A. japonicus*, *i.e.* individuals with lengths < $L_{50}$ at first maturity, were caught predominantly in water depths < 20 m. The paucity of juveniles and particularly of those < 600 mm in catches obtained from deeper waters is not a consequence of gear selectivity because the same sampling methods were used in deep water as in shallow water, where they yielded substantial numbers of juvenile fish. Although juveniles were occasionally caught in estuaries, they were more frequently caught in coastal marine waters and particularly in marine embayments and gutter formations (*i.e.* areas of deeper water) along surf beaches. In contrast, in New South Wales and south-eastern Africa, the juveniles of *A. japonicus* are most commonly found in estuaries, which are thus regarded as containing their main nursery habitats (Gray and McDonall, 1993; Griffiths, 1996).

The greater use of nearshore waters as nursery areas by *A. japonicus* in Western Australia than in either eastern Australia or South Africa is almost certainly related to differences in wave exposure along those coastlines. The presence, along much of the west coast of Australia, of a ridge of submerged barrier reefs and islands at distances of 3 to 10 km offshore, provides the nearshore waters of that coast with considerable shelter from offshore wave conditions (Masselink and Pattiaratchi, 2001; Valesini *et al.*, 2003). In contrast, the coastlines of New South Wales and south-eastern Africa are dominated by higher-energy waves regimes (Chapman *et al.*, 1982; Fennessey, 2000). It is thus proposed that, in Western Australia, the greater shelter offered to nearshore marine habitats, together with a paucity of permanently-open estuaries in a long stretch of coastline to the north of the Swan River Estuary, accounts for *A. japonicus* typically utilising habitats in nearshore marine waters as nursery areas.

In contrast to their juveniles, the adults of *A. japonicus*, *i.e.* individuals with lengths > $L_{50}$ at first maturity, were caught in the full range of water depths sampled, *i.e.* 2 – 110 m. Furthermore, aggregations of *A. japonicus*, consisting of mature-sized fish, were observed on several occasions in underwater video footage taken using a baited video camera in depths of 110 m and 50 m in offshore waters to the south-west of Rottnest (32°00′S, 115°30′E) and off Dongara (29°17′S, 114°56′E), respectively (A. Rowland, Murdoch University, pers. comm., 2005).

### 3.4.2 Validation of ageing procedure and growth

The trends exhibited by the mean monthly marginal increments on sectioned otoliths of *A. japonicus* demonstrate that a single opaque zone is laid down annually in the otoliths of this species and that each new opaque zone becomes delineated at the edge of otoliths in November/December, *i.e.* in late spring/early summer. This parallels the situation recorded for the otoliths of several other recreationally and commercially important teleost species in south-western Australia. These species include the Australian Herring *Arripis georgianus* (Fairclough *et al.*, 2000), Black Bream *Acanthopagrus butcheri* (Sarre and Potter, 2000), West Australian Dhufish *Glaucosoma herbraicum* (Hesp *et al.*, 2002) and Tarwhine *Rhabdosargus sarba* (Hesp *et al.*, 2004a). The trends exhibited by the mean monthly marginal increments of *A. japonicus* in Western Australia also parallel those recorded for this species in South Africa, where this sciaenid occupies a similar latitudinal range, *i.e. ca* 25 to 40˚S (Wallace and Schleyer, 1979; Griffiths and Hecht, 1995a). The correspondence between the time when the new translucent zone becomes formed and then undergoes rapid growth in the otoliths of *A. japonicus* along the coasts of two widely-separated continents reflects the similarity in the times when water temperatures start rising from their winter minima. The transition in the spring from an opaque zone to a translucent zone at the periphery of the otolith reflects a change in the chemical composition in that region of the otolith as temperature rises and the growth of the otolith increases (Campana and Thorrold, 2001).

The total lengths of individuals within each age class of *A. japonicus* in Western Australia varied considerably, as is also the case with this species in South Africa (Griffiths and Hecht, 1995a). This is a common trait of sciaenids, amongst which it has been recorded for *Micropogonias undulatus* (Barger, 1985; Barbieri *et al.*, 1994), *Sciaenops ocellatus* (Beckman *et* al., 1989; Ross *et al.*, 1995), *Pogonias cromis* (Beckman *et al.*, 1990; Jones and Wells, 1998), *Cynoscion nebulosus* (Murphy and Taylor, 1994), *Atractoscion aequidens* (Griffiths and Hecht, 1995b), *Argyrosomus inodorus* (Kirchner and Voges, 1999), *Leistomus xanthurus* (Piner and Jones, 2004), *Paralonchurus brasiliensis* (dos *et al.*, 2005) and *Micropogonias furnieri* (Norbis and Verocai, 2005). This variability probably reflects, in part, the fact that, as the juveniles grow very rapidly, those that are spawned first during the spawning period will be considerably larger than those produced last during that period (See Conover, 1992). This difference is illustrated by the wide range of 214 to 302 mm in the total lengths of *A. japonicus*, which, on average, would have been about six months old (Figure 3.3). It is also possible that variations in size reflect differences in the productivity of the habitats occupied during early life.

The growth of *A. japonicus* in Western Australian waters is particularly rapid during the first six years of life, but then slows down markedly as fish become sexually mature. The change in the pattern of growth at sexual maturity implies that energy resources become directed towards gonadal development rather than mainly towards somatic growth. This pattern of change in energy allocation, which maximises reproductive potential (Jennings *et al.*, 2001), has been recorded for many other fish species, including some in Western Australian waters (*e.g.* Coulson *et al.*, 2005) and for other sciaenids (Beckman *et al.*, 1989; Griffiths and Hecht, 1995b). However, after attaining the approximate size at maturity, the lengths of the females of *A. japonicus* at a given age are slightly greater than those of males, presumably reflecting a greater selection pressure for optimising egg than sperm production (see Roff, 1983). The females of *A. japonicus* also grow at a slightly faster rate and attain a larger size than their males in South Africa (Griffiths and Hecht, 1995a), a situation also recorded for the sciaenids *Otolithes ruber* and *Atrobucca nibe* (Fennessy, 2000).

### 3.4.3 Spawning mode and fecundity

As the ovaries of the mature females of *A. japonicus* caught during the spawning period contained previtellogenic, cortical alveolar and yolk granule oocytes, and occasionally hydrated oocytes and/or post-ovulatory follicles, this sciaenid is an indeterminate spawner *sensu* Hunter *et al*. (1985). The potential annual fecundity of *A. japonicus* is therefore not fixed prior to the commencement of the spawning period and thus any estimate of this variable must take into account both spawning frequency and batch fecundity.

Although fecundity has not been determined for any natural populations of *A. japonicus*, such data are available for cultured individuals (Battaglene and Talbot, 1994). The latter workers estimated that females with a total weight of *ca* 10 kg produce *ca* 1 000 000 eggs. However, it is not known to what extent estimates of fecundity derived from hormone-induced egg production by hatchery-reared fish would be similar to those derived from wild *A. japonicus*. Battaglene (1996) reported that, in captivity, *A. japonicus* is a group synchronous spawner.

Although sciaenids have a relatively high fecundity, which would be of value when their stocks are heavily exploited (Musick, 1999; Powles *et al*., 2000), there are examples of some members of this family being particularly vulnerable to fishing. For example, *Totoaba macdonaldi* has been fished to extinction in southern China (Sadovy and Cheung, 2003) and *Argyrosomus regius* is now no longer caught in the Wadden Sea (Wolff, 2000a; 2000b).

### 3.4.4 Seasonality and diel periodicity of spawning

The marked rise in the mean monthly GSIs for female *A. japonicus* from low levels in October to their maxima in December and January and their precipitous decline in February, together with the similarity in the monthly trends exhibited by the prevalences of stage V/VI ovaries, provide strong evidence that, in Western Australian waters, this species spawns mainly between November and January. Such a conclusion is also consistent with the trends in the mean monthly GSIs of males and the fact that the catches of fish with stage V testes were largely confined to these months. Although the mean monthly GSIs peaked in the same month in the northern and southern regions, fish with stage V ovaries were caught over a more protracted period in the northern region. The presence in northern waters of a few female fish with stage V ovaries in October and in February to May and of a male with stage V testes in February and April indicates that the spawning period extends from October to April/May in this region.

Hall (1986) reported that *A. japonicus* spawns between November and January in South Australian waters, which is comparable to the spawning period determined for this species at a similar latitude in the southern region of Western Australia. A similar trend between spawning period duration and latitude has been reported for *A. japonicus* on the coast of New South Wales. In central New South Wales (*ca* 35˚S), the collection of larvae between February and April (Gray and Miskiewicz, 2000) and of small juveniles 2-8 cm in total length between April and June (Anon., 1981) suggests that spawning takes place in this region between January and April. However, West and Walford (2000) reported that juvenile *A. japonicus* < 10 cm total length were present throughout the year in two estuaries located between *ca* 28˚50'S and 29˚30'S in northern New South Wales. Further evidence that spawning is not always group synchronous within a region has been provided by the studies of Broadhurst (1993) and Gray and McDonall (1993), who found two distinct length cohorts in an estuarine assemblage within the same year.

Protracted spawning periods are common among sciaenids (*e.g.* Fennessy, 2000; da Costa and Araújo, 2003; Piner and Jones, 2004) and the extended spawning season of *A. japonicus* in the northern region appears to be typical of sciaenids in subtropical waters (Druzhinin, 1974). In South Africa, where *A. japonicus* occurs over a similar latitudinal range, *i.e. ca* 25-40˚S, spawning also commences earlier and lasts longer at lower latitudes (Griffiths, 1996). This trend is also paralleled by *Atractoscion aequidens*, which, in South African waters, occurs throughout a latitudinal range similar to *A. japonicus* (Griffiths and Hecht, 1995b). An earlier and more protracted spawning period at lower latitudes has also been recorded for several other sciaenids, including *Micropogonias furnieri* (Vazzoler, 1991; da Costa and Araújo, 2003), *Argyrosomus regius* (Chao, 1986), *Pogonias cromis* (Peters and McMichael, 1990), *Sciaenops ocellatus* (Ross *et al.*, 1995) and *Cynoscion regalis* (Shepherd and Grimes, 1984). The commencement of spawning has been linked to a rise in water temperature in many fish species (Conover, 1992), including sciaenids (Brown-Peterson and Thomas, 1988; Peters and McMichael, 1990; Saucier and Baltz, 1993; Wilson and Nieland, 1994; Connaughton and Taylor, 1995). It is thus relevant that, in comparison with the southern region, temperatures in the coastal waters of the northern region increase more rapidly after declining to their winter minima and remain elevated for a longer period (Pearce *et al.*, 1999).

As three female *A. japonicus* with ovaries containing hydrated oocytes were caught at night during the spawning period, this species presumably spawns at night in Western Australia. This species has also been reported to spawn at night in South Africa

(Griffiths, 1996) and is common amongst sciaenids in general (*e.g.* Holt *et al*., 1985; Saucier and Baltz, 1993; Connaughton and Taylor, 1995; Macchi *et al*., 2003; Bialetzki *et al*., 2004). Since many sciaenids use sound to locate mates during the spawning season (Holt *et al.*, 1985), they are not dependant on light for their courtship behaviour. Nocturnal spawning has a number of advantages. As zooplanktivores are mainly visual feeders, a nocturnal spawning regime may reduce the effects of predation and increase survivorship of eggs and larvae (Holt *et al*., 1985). Since sunlight can have a deleterious effect on particularly pelagic eggs, spawning during darkness may enhance the chances of eggs surviving (Saucier and Baltz, 1993).

### 3.4.5 Typical spawning locations

Between 2001 and 2005, large numbers of preflexion larval *A. japonicus* were consistently collected in plankton trawls conducted in late spring/early summer in nearshore marine waters of depths *ca* 5-22 m at a latitude of *ca* 32°S (C. Wakefield, Murdoch University, pers. comm.). Furthermore, *A. japonicus* eggs and larvae have not been recorded during extensive plankton trawling conducted farther offshore (B. Muhling, Murdoch University, unpubl. data). Early preflexion larvae have also been collected near the substratum in a water depth of *ca* 30 m in the coastal waters of New South Wales (Gray, 1995). Further plankton trawling conducted in the coastal embayment of Botany Bay in New South Wales, has also resulted in the capture of numerous early larvae of *A. japonicus* (Steffe, 1991). In Western Australia, substantial commercial catches of *A. japonicus* are taken from aggregations of the species occurring during the spawning period around reefs in *ca* 20-30 m of water offshore at 27˚42'S and at 34˚19'S, located in the northern and southern regions, respectively. Thus, from the distribution of early larvae and aggregations of mature adults, spawning probably occurs around reefs in the nearshore coastal waters of both the northern and southern regions of Western Australia, which would parallel the situation reported for *A. japonicus* in South Africa (Griffiths, 1996).

### 3.4.6 Spawning aggregations in the Swan River Estuary

The capture at night, of several female *A. japonicus* with ovaries containing hydrated oocytes in the same region of the lower reaches of the Swan River Estuary, implies that this species forms nocturnal spawning aggregations in this region of the estuary. It is thus proposed that the bathymetrical, hydrological and physiochemical characteristics of the lower reaches of this system in late spring/early summer provide conditions analogous to those in the coastal waters in which this species typically spawns. As the female fish with ovaries containing hydrated oocytes were also caught immediately prior to the peak of high tide, it is likely that any eggs fertilised in the lower reaches of the Swan River Estuary (Mosman Bay) would have been transported downstream and out of the system with the ebb tide. The conclusion that spawning in the estuary coincides with the ebb tide and that the resulting seaward current carries the eggs out of the estuary, is consistent with the absence of eggs and larvae of *A. japonicus* during extensive sampling of the ichthyoplankton of the lower Swan River Estuary (Gaughan *et al.*, 1990). *Rhabdosargus sarba* spawns at night during ebb tides and throughout the summer months in the lower reaches of the Swan River Estuary (Hesp *et al.*, 2004). As with *A. japonicus*, the eggs of *R. sarba* were also not present in samples obtained by Gaughan *et al.* (1990). Thus, the eggs of this species must also presumably pass rapidly out of the estuary and not be present in the water column at the time when plankton sampling was undertaken. Because planktivorous fishes are abundant in estuaries (Johnson *et al.*, 1990; Morgan, 1990), including the Swan River estuary where the planktivorous *Spratelloides robustus* was particularly numerous in seine net catches

(Hesp *et al.*, 2004), a rapid movement of the eggs of both of these species out of the estuary would enhance their chances of avoiding predation by that species.

Although few species typically spawn within estuaries in most other regions of the world (Haedrich, 1983; Dando, 1984), several species complete their life cycle in the estuaries of south-western Australia (Potter and Hyndes, 1999). Although this is the first reported case of estuarine spawning by *A. japonicus*, it has been reported for several other members of the Sciaenidae and is particularly common amongst sciaenids found in the vicinity of the Río de la Plata Estuary, which is located between Argentina and Uruguay. *Micropogonias furnieri* (Macchi *et al.*, 1996; Acha *et al.*, 1999), *Pogonias cromis* (Macchi *et al.*, 2002), *Macrodon ancylodon* (Millitelli and Macchi, 2000), *Paralonchurus brasiliensis* (Berasategui *et al.*, 2004) and *Cynoscion guatucupa* (Berasategui *et al.*, 2004) all spawn in this system at various times. However, several of the estuarine spawning species in the Río de la Plata Estuary, including *Micropogonias furnieri*, *Macrodon ancylodon* and *Paralonchurus brasiliensis*, spawn in marine waters in the Patos Lagoon region of Brazil (Sinque and Muelbert, 1997).

### 3.4.7 Length and age at maturity

The high $L_{50}$s at which female and male *A. japonicus* were estimated to attain maturity, *i.e.* 929 and 878 mm, respectively, are consistent with the similarly large size at maturity of the females and males of this species in South Africa, *i.e.* 1070 and 920 mm, respectively (Griffiths, 1996). The females of *A. japonicus* mature at a slightly greater length and age than their males, paralleling the situation with several other sciaenids (*e.g.* Cisneros-Mata *et al.*, 1995), including *A. japonicus* in South Africa (Griffiths, 1996). The $L_{50}$ for females of *A. japonicus* in Western Australia corresponds to 75% of the $L_{\max}$, which is similar to that reported for the females of this species in South Africa (Griffiths, 1996). However, Griffiths (1996) also reported that the $L_{50}$s of females of the congeneric species *A. thorpei* and *A. inodorus* were 30 and 23% of their respective maximum lengths. Thus, *A. japonicus* apparently attains maturity at a relatively larger size and age for members of its genus.

### 3.4.8 Mortality and management implications

The first three methods used to estimate the total mortality, *Z*, for each species in this study employ different data and are based on slightly different assumptions. The first approach, employing Hoenig's (1983) equation for fish, estimates *Z* for a species using the oldest age recorded for any individual in the samples obtained of that species. Implicitly, this estimate of *Z* reflects the average total mortality experienced throughout the life of individual fish from the age at which they were first recruited to the fishery for fish of this or older ages. The simulation approach employed the number of fish in a sample that were older than a specified age. Thus, such estimates of *Z* reflect the average total mortality experienced after recruitment to the fishery by those age classes that were older than the specified age. The estimates of *Z*, derived from relative abundance (catch curve) analysis, represents the average total mortality of the fish within all fully-recruited age classes, weighted towards those mortalities experienced in more recent years.

Each of the above three approaches for determining *Z* is based on the assumption that the total mortality experienced by the fish stock remained constant throughout the years in which each of the age classes considered in the analysis was subjected to full exploitation. The method of Hall *et al.* (2004) for determining total mortality uses a combination of the estimates derived by those three methods and is likewise based on the assumption that, after full exploitation, total mortality remains constant. However, such an assumption is unlikely to be valid for many fish stocks in Western Australia. This view is based on the fact that exploitation by both recreational and commercial fishers has increased through a combination of increased fishing activity and the introduction of improved fishing technology. Thus, the mortality values estimated using Hoenig's (1983) approach, employing maximum age, will be likely to reflect those occurring during a period of lower exploitation than present. In contrast, the estimate from relative abundance analysis reflects the mortality experienced in more recent years, which is likely to be greater than in earlier years and thus yield higher values for total mortality. As the simulation approach uses data for several older age classes, it is likely to yield values greater than those obtained using the Hoenig approach, but probably less than those derived using relative abundance analysis. This is precisely the trend exhibited by the estimates obtained for $Z$ for *A. japonicus*, using the three methods, and the same is also true for *P. dentex* (see Chapter 4.3.7).

The estimate of natural mortality, $M$, for a species, that is derived by employing Pauly's (1980) approach, which uses the parameters of the von Bertalanffy growth equation and the average annual temperature of the water occupied by the stock, is often greater than the estimates of $Z$ derived from Hoenig's (1983) approach and relative abundance analysis. This is clearly an erroneous situation. The use of the method described by Hall *et al.* (2004) ensures that $Z > M$. However, an erroneously high estimate of $M$ derived using Pauly's method will still influence the estimate of $M$ resulting from the use of this Bayesian method and thus produce a value for this variable that is large and lies close to the estimate of $Z$. The above scenario is the case found with Mulloway in the current study. Thus, the value of 0.43 year $^{-1}$ derived for $M$ using Pauly's (1980) equation, exceeded those derived from each of Hoenig's fish equation, relative abundance analysis and simulation, and the value for $Z$ only slightly exceeded that of $M$ when using the combined data and the Bayesian approach of Hall *et al.* (2004).

An erroneously high estimate of *M* will inevitably lead to an underestimate of fishing mortality, *F*. Thus, excessively large estimates of *M* derived using Pauly's (1980) method are likely to lead to the erroneous conclusion that the level of exploitation is low and that there is therefore no need to be concerned that the stock is being overexploited.

From the above discussion, there is clearly an urgent need to refine Pauly's (1980) method, which is the most widely-used empirical method for determining *M*, in order to obtain more reliable estimates of fishing mortality. In this context, it is important to recognise that Pauly's and other empirical methods are based on data sets produced several years ago and that, since that time, the methods, for example, for validating the ageing procedure and thus obtaining more reliable estimates of growth and for determining the length at maturity, have improved markedly. Thus, estimates of *M* based on life history-based traits will require, for example, growth parameters that are derived from reliable studies. Other methods for estimating *M*, *e.g.* tagging, need to be considered as they provide direct estimates of mortality and overcome a reliance on empirical relationships derived from growth and temperature data. However, the large individuals of Mulloway often die on capture, particularly when caught in deeper water, *i.e.* > 20 m, and thus this species is not a good candidate for using mark-recapture methods for providing reliable data on mortality.

To avoid any risk that, because of the unreliability of estimates of *M* derived using Pauly's (1980) method, the stocks of Mulloway may be experiencing undetected but excessive exploitation, it is important for managers to consider robust methods that will guard against the deleterious impact of excessive exploitation. Since, in contrast to their adults in deeper waters, the juveniles of Mulloway typically survive capture and release (Broadhurst and Barker, 2000), the use of a minimum legal length (MLL) based on the length at maturity would be an effective management tool. As Mulloway form spawning aggregations, of which the locations are becoming increasingly well known, as in the Swan River Estuary, the possibility of closing spawning areas during the spawning period needs to be seriously considered.

### 3.4.9 Yield per recruit and spawning potential ratio

The yield per recruit analysis for *A. japonicus*, assuming 'knife edge' selection at two years, indicates that the yield per recruit (YPR) will increase as $F$ increases from zero to 0.38 $\text{year}^{-1}$ (= $F_{\text{max}}$) and then decline. Although *A. japonicus* appears fully-recruited to the commercial fishery at 3 years, a large proportion of the stock recruits to the exploited stock at an age of 2 years. Thus, for such individuals of *A. japonicus* that are recruited into the fishery at this latter age, *i.e.* at a relatively small weight in terms of its maximum weight, the analyses demonstrate that, if fishing mortality was > 0.38 $\text{year}^{-1}$, this would lead to a reduction in yield due to growth overfishing. Because YPR analyses do not take into account the possibility of recruitment overfishing, the reference point $F_{0.1}$ (=0.26 $\text{year}^{-1}$ for *A. japonicus*) rather than $F_{\text{max}}$ is sometimes used as a more conservative measure of the level of $F$ associated with the optimum yield for a particular stock (Haddon, 2001). Unfortunately, the inability to obtain a reliable estimate for the current level of $F$ for *A. japonicus* means that it is also not possible to determine whether the true fishing mortality exceeds this reference point.

The spawning biomass per recruit (SSB/R) analysis is used to determine whether fishing mortality is likely to lead to recruitment overfishing. Thus, it has been considered that if the SSB/R of a species falls below 30% of its original level, *i.e.* its spawning potential ratio (SPR) is < 0.3, there may be insufficient reproductive capacity (egg production) for the population to remain sustainable (Mace and Sissenwine, 1993; Goodyear, 1993). The fact that the SPRs for female and male *A. japonicus* are predicted to decline dramatically at relatively low levels of fishing mortality, *e.g.* for females, to

$< 0.5$ at $F = 0.1$ year$^{-1}$, is largely because this species becomes fully recruited into the fishery at a size which is well below that at which they attain maturity. However, the analyses also demonstrate that, if the age at full recruitment of *A. japonicus* was increased, for example, by raising the MLL for this species, the SPR will decline far less dramatically with respect to increasing fishing mortality. Thus, as was proposed in the mortality section, it is strongly recommended that consideration should be given to increasing the MLL for this species to a length that is at least equivalent to that at maturity. The susceptibility of *A. japonicus* to fishing pressure in Western Australian waters parallels that found for this species on the south-eastern coast of Africa (Griffiths, 1997).

# 4.0 BIOLOGY OF *PSEUDOCARANX DENTEX* ON THE LOWER WEST COAST OF AUSTRALIA

## 4.1 INTRODUCTION

*Pseudocaranx dentex* is an important commercial species in eastern Australia (Tilzey, 2004), New Zealand (Sullivan *et al*., 2005) and Japan (Masuda and Tsukamoto, 2000). It is also an important recreational fish species in many regions, including Western Australia, where the *Pseudocaranx* complex, comprising mainly *P. dentex*, ranks third in terms of its abundance in the catches of recreational anglers (Sumner and Williamson, 1999).

The landings of Silver Trevally by the South Eastern Trawl fishery (SEF) have declined since the mid 1990s, which has led to the fishery for this species being classified as overfished (Tilzey, 2004). The fact that the modal length of *P. dentex* in these commercial catches has declined in recent years is consistent with the conclusion that this species is being growth-overfished in south-eastern Australia.

Previous studies of the biology of *P. dentex* in New South Wales were either biased towards faster-growing individuals of younger age classes (Rowling and Raines, 2000) or contained little data for individuals > 5 years of age (Kalish and Johnston, 1997). There is evidence that some of the biological characteristics of *P. dentex* vary markedly among populations. For example, the age of a number of individuals in the populations of *P. dentex* studied in New Zealand exceeded 30 years (James, 1984; Walsh *et al*., 1999), whereas most of the fish aged in New South Wales were less than 20 years old (Rowling and Raines, 2000). Studies on the reproductive biology of *P. dentex* demonstrate that, in southern and eastern Australia and New Zealand, this species typically spawns at some stage between early spring and early summer, with the precise period possibly varying with latitude (Shuntov, 1969; James, 1978; Kalish and

Johnston, 1997; Rowling and Raines, 2000). As with the maximum age, the length at maturity of *P. dentex* varies markedly among populations, being attained at a far smaller length in eastern Australia than in New Zealand (James, 1978; Kalish and Johnston, 1997; Rowling and Raines, 2000).

The aim of this study was to obtain comprehensive quantitative data on those aspects of the biology of *P. dentex* in Western Australia that are required for developing management plans for conserving the stocks of this important recreational species in this state. The first individual aim was to confirm that it was necessary to section the otoliths of *P. dentex* to reveal clearly all of their growth (opaque) zones, and to validate that the main growth zones in this hard structure are formed annually. The next aim was to determine the size and age compositions, growth, length and age at first maturity, spawning period and location and mortality of the females and males of *P. dentex* in the northern and southern parts of its distribution in Western Australia. The resultant data are compared with those recorded elsewhere in the distribution of *P. dentex* and their implications for management considered carefully. We also aimed to determine the distributions of *P. dentex* and the congeneric *P. wrighti*, which will provide important information as these two morphologically very similar species are currently grouped together for management purposes.

## 4.2 MATERIALS AND METHODS

Details of the measurements and procedures that were common to both *Pseudocaranx dentex* and A*rgyrosomus japonicus* are given in Chapter 2. The following details refer specifically to *P. dentex*.

### 4.2.1 Environmental measurements

The mean monthly ocean temperatures provided for Perth and Geraldton (the dominant sampling sites on the two west coast regions) were recorded by Pearce *et al.* (1999) and represent average water temperatures at these sites between 1990 and 1994. These data were recorded by WESDATA temperature data loggers which were deployed approximately 5 m below the surface in (1) waters *ca* 150 m offshore from Marmion Lagoon (31°51′S, 115°45′E) and (2) offshore at Seven Mile Beach (29°10'S, 114°54'E).

### 4.2.2 Length measurements

Comparisons between the maximum sizes, $L_\infty$ and length at maturity of *Pseudocaranx dentex* determined during this study with those of other studies (Williams and Lowe, 1997; Walsh *et al.*, 1999; Rowling and Raines, 2000) were facilitated by converting the length to caudal fork (LCF ) measurements used in those other studies to total length (TL). The likelihood-ratio test demonstrated that the regressions for LCF *vs* TL for female and male *P. dentex* caught on the west coast of Australia were not significantly different ($p > 0.05$) and thus the data for the two sexes were pooled and this yielded the following relationship.

$$\mathrm{TL} = 1.203(\mathrm{LCF}) - 0.6185 \ (R^2 = 0.998, n = 621),$$

where TL and LCF are recorded in mm, $R^2$ = the coefficient of determination and $n$ = sample size.

### 4.2.3 Density estimates

The area covered in each trawl was calculated from the width of the net's mouth (see Chapter 2.2.2) and the distance trawled, the latter being determined from the latitudes and longitudes at the start and finish of the trawl. The number of *P. dentex* and *P. wrighti* caught were then expressed as the number of fish $100^{-2}$.

### 4.2.4 Lengths at age

As a further means of testing whether the lengths at age of *P. dentex* in the upper west and lower west coast regions differed, the mean lengths of all *P. dentex* from the upper and lower west coast regions at 4+, 5+, 6+ and 7+ years, *i.e.* where there were sufficient samples, were compared employing multiple t-tests and using a Bonferroni correction.

### 4.2.5 Gonad stages

The macroscopic and histological characteristics used to assign the gonads of each fish to one of the eight numerical stages of gonadal development (see Chapter 2.5) are presented in Table 4.1.

**Table 4.1** Description of the characteristics used to distinguish the various macroscopic stages in ovarian and testicular development and the corresponding histological stages of ovarian development in *Pseudocaranx dentex*. N.B. Macroscopic stages have been adapted from Laevastu (1965), whilst the histological stages have been modified from Wallace and Selman (1981) and Mayer *et al*. (1988).

| **Stage** | **Classification** | **Macroscopic characteristics** | **Histological characteristics** |
|---|---|---|---|
| **I** | Virgin | Ovaries and testes very small and threadlike, positioned just under swim bladder. Transparent and colourless to pale pink. | Oogonia and chromatin nucleolar oocytes abundant. Oocytes organized neatly in rows along the ovarian lamellae. |
| **II** | Maturing virgin/ resting adult | Ovaries small, translucent, pink to dark pink, cone-shaped, and approximately one quarter the length of the ventral cavity. Oocytes not visible through ovarian wall. Testes small, pink to white, strand-like, flat and half the length of the ventral cavity. | Similar to stage I. All oocytes previtellogenic (previtellogenic oocytes present in all subsequent categories). |
| **III** | Developing | Ovaries slightly larger, pink and less transparent. Small oocytes visible through ovarian wall. Testes slightly larger and white to grey. Gonads half the length of the ventral cavity. | Cortical alveolar oocytes abundant. |
| **IV** | Maturing | Ovaries larger than stage III, pinkish to orange, red capillaries present on ovarian wall. Larger oocytes (than in stage III) visible through ovarian wall. Testes white and swollen with some capillaries present. Gonads occupy approximately half the volume of the ventral cavity | Cortical alveolar and yolk granule oocytes abundant. |
| **V/VI** | Mature/Spawning | Ovaries large, orange, and highly vascularized. Oocytes clearly visible through ovarian wall and tightly packed. Testes large, white, multi-lobed and vascularized. Gonads occupy the majority of the ventral cavity. | Yolk granule oocytes are tightly packed and dominate space within ovary. In stage VI ovaries migratory nucleus stage oocytes and/or hydrated oocytes and/or post-ovulatory follicles are present. |
| **VII** | Spent | Ovaries smaller than stage V and VI and more flaccid, but not completely empty. Ovaries red to brown, capillaries still present. Testes white to brown, a thick capillary runs the length of the entire lobe. Some large oocytes and sperm still present in ovaries and testes, respectively. | Yolk granule and cortical alveolus oocytes still present but often undergoing atresia. Spaces appear in ovary and some scar tissue visible. |
| **VIII** | Recovering | Ovaries deep red to brown. Testes similar in colour, also flaccid. Gonads still have some capillaries present and occupy one quarter to one third the length of ventral cavity. | Scar tissue abundant. Oocytes highly disorganized. All oocytes previtellogenic. |

## 4.3 RESULTS

### 4.3.1 Water temperatures

The mean monthly water temperatures at a depth of 5 m off Perth at ~ 31°S, near the mid-point of the lower west coast region, declined from their maxima of 22.2 - 22.6°C in January to March to their minimum of 15.9°C in August and then rose sharply during the spring and early summer months (Figure 4.1). The mean water temperature in any given month at Geraldton at ~ 29°S, near the mid-point of the upper west coast region, was always between 1 and 2°C greater than that at the same depth off Perth, with maximum and minimum values of 24.1 and17.5°C being recorded in January and July, respectively (Figure 4.1).

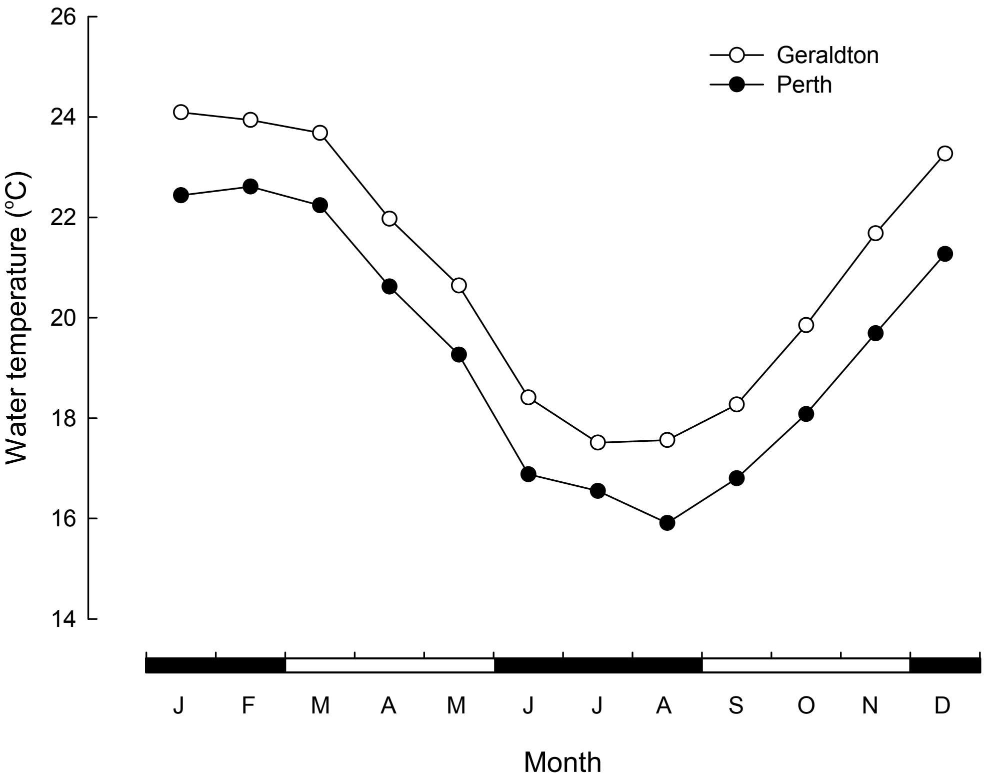

**Figure 4.1.** Mean monthly water temperatures recorded between 1990-1994 at water depths of 5 m off Seven-mile beach near Geraldton (29°10' S, 114°54' E) and off Perth (31°51'S, 115°45' E). In this Figure and Figures 4.3 and 4.7, the closed bars on the x-axis refer to summer and winter months, and the open bars to autumn and spring months.

### 4.3.2 Habitats of Silver and Sand Trevally

A total of 1935 *Pseudocaranx dentex* was caught collectively by trawling and seine netting, and angling over bare sand in areas where there were also patches of seagrass and by angling over reefs. The vast majority (94%) of the nearly 300 Silver Trevally caught over bare sand by the different sampling methods were < 250 mm in length, whereas over 90% of the more than 1600 individuals of this species caught over reefs were > 250 mm (Figure 4.2). At the completion of this study, seine netting around jetties and bridges in estuaries yielded 13 *P. dentex* ranging from 34 to 55 mm in length.

A total of 1291 *P. wrighti* was caught in the same trawl samples from over sand and in samples collected by angling over reefs where *P. dentex* was caught. No *P.wrighti* were caught by seining or angling over bare sand. In contrast to the situation with *P. dentex*, the percentage taken by trawling over sand was far higher (99 vs 6 %) while that obtained by angling over reefs was far lower (1 vs 85 %). The mean density of *P. wrighti* over sand was more than an order of magnitude greater in the more offshore and deeper waters (*ca* 30 m depth) around Rottnest (0.40 100 $m^{-2}$ ) than in the waters of Comet Bay (0.035 100 $m^{-2}$) where water depths were *ca* 10 m on average. The mean density of *P. dentex* in the same waters around Rottnest and in Comet Bay (both 0.003 100 $m^{-2}$) were very low and thus, even in the latter embayment, were an order of magnitude less than that of *P. wrighti*.

The lengths of *P. wrighti* caught by trawling ranged from 43 mm to 220 mm, but most were > 100 mm (Figure 4.2). The addition of a small mesh net (12 mm) inside the cod-end of the trawl did not result in a conspicuous change in the length composition of the catch of *P. wrighti* from that obtained without that small mesh net. The lengths of *P. dentex* in the trawl samples ranged from 74 to 190 mm.

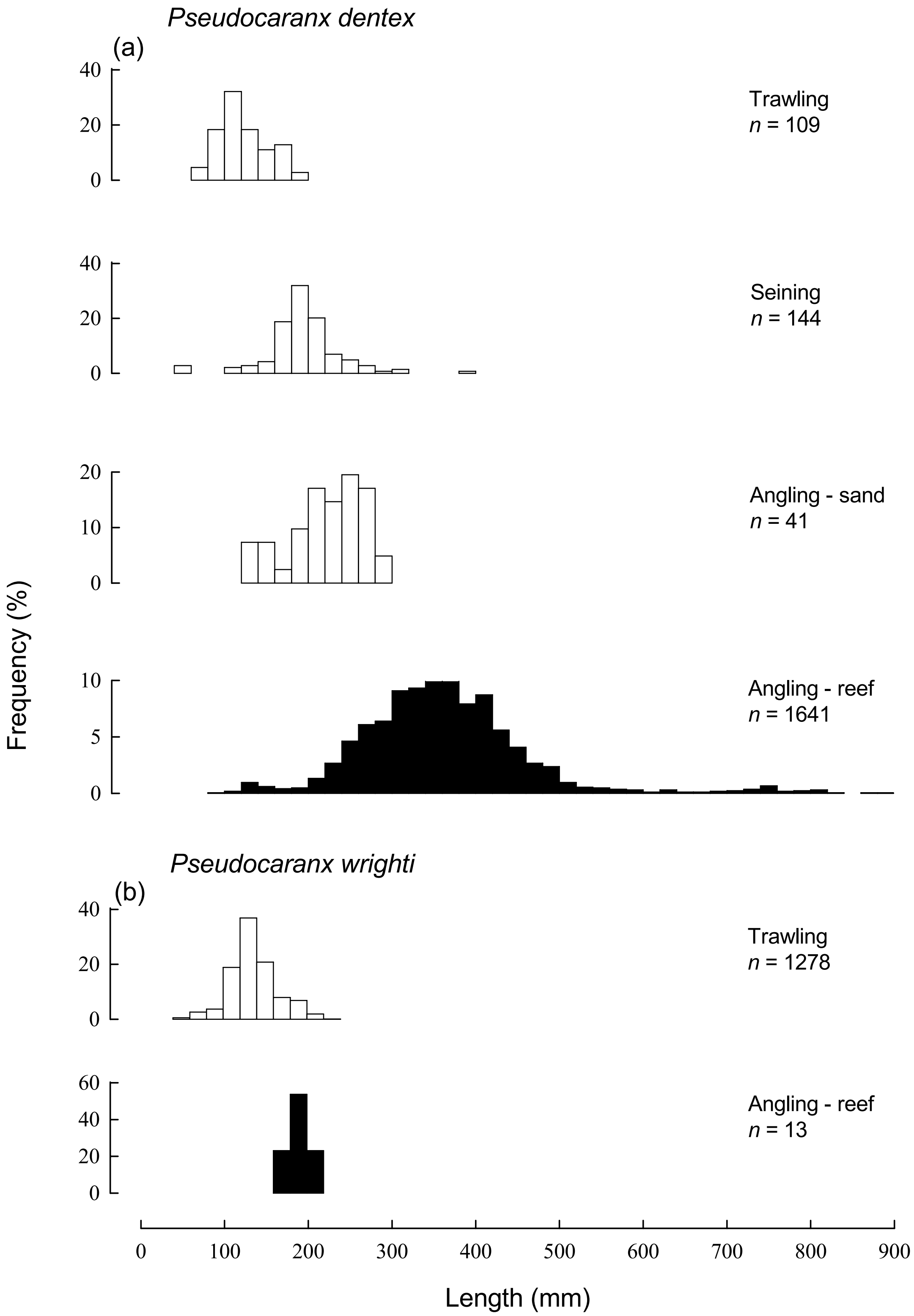

**Figure 4.2.** Length-frequency distributions for (a) *Pseudocaranx dentex* and (b) *P. wrighti* caught by commercial trawling, commercial seining and angling in marine and estuarine waters on the lower west coast of Australia. White and black bars represent sand and reef substrate, respectively. *n* = sample size.

### 4.3.3 Validation of ageing procedure

Opaque zones were hard to detect in whole otoliths as the individual zones often either appeared to merge or could not be distinguished readily from false zones. The clarity of these zones was markedly improved by sectioning the otoliths (*cf* Plates 4.1a,b). In 54% of otoliths examined, the number of opaque zones visible on whole otoliths differed from that detectable on the same otoliths after they had been sectioned. Furthermore, the frequency and extent of such discrepancies increased as the number of detectable opaque zones in sectioned otoliths increased. For example, the number of opaque zones visible in whole and sectioned otoliths differed by one for sectioned otoliths with one opaque zone in 33 % of those otoliths and was > one, and frequently ≥ four, for sectioned otoliths with ≥ five opaque zones on 51% of those otoliths. Thus, it was considered necessary to section all of the otoliths to age this species.

The mean monthly marginal increments on sectioned otoliths of *P. dentex* with two to three opaque zones rose gradually from 0.45 in January to 0.79 in August and then declined precipitously to 0.24 in November (Figure 4.3). The trends exhibited during the year by the mean monthly marginal increments on the otoliths with four to seven and ≥ eight opaque zones were essentially the same, with the values rising from their minima in late spring to their maxima in winter and then undergoing a pronounced decline during spring (Figure 4.3). Although no fish possessing otoliths with one opaque zone were caught in June and August, the trends exhibited by the mean marginal increments during the other months is consistent with those just described for fish with otoliths containing more than one opaque zone.

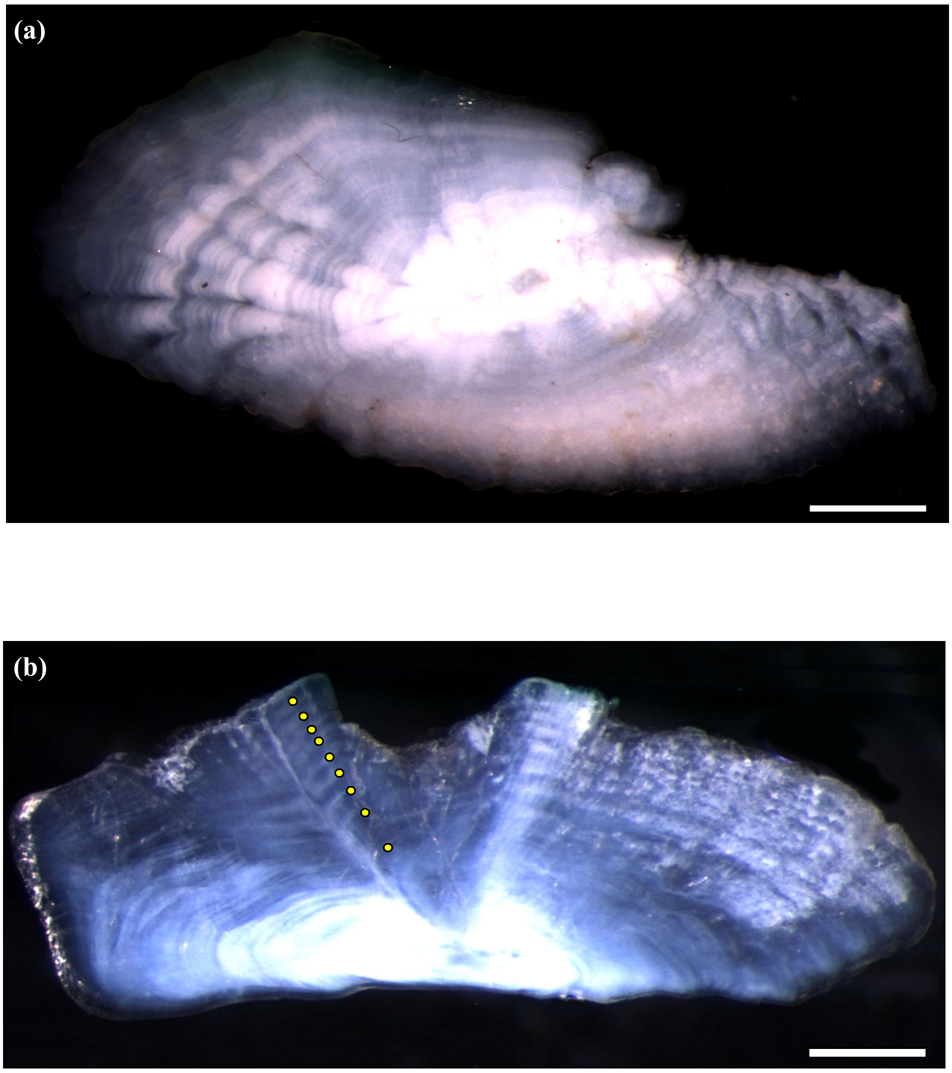

**Plate 4.1.** (a) Whole otolith of *Pseudocaranx dentex* with several opaque zones (scale bar = 100 µm) and (b) a 500 µm thick section of the same otolith showing nine zones, the location of which is denoted by yellow dots (Scale bar = 50 µm).

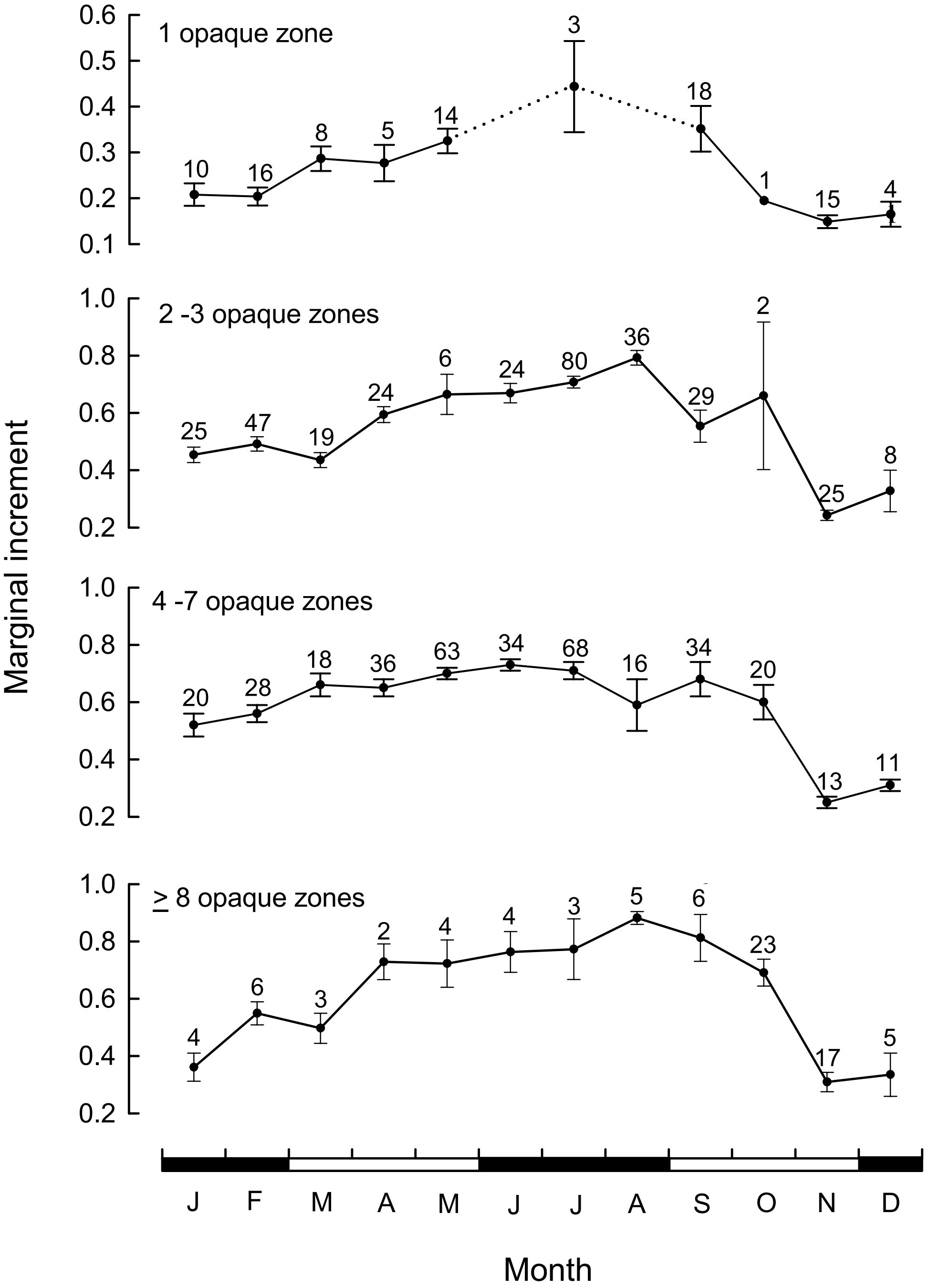

**Figure 4.3.** Mean monthly marginal increments ± 1 SE on sectioned sagittal otoliths of *Pseudocaranx dentex* with different numbers of opaque zones. Numbers refer to sample sizes.

### 4.3.4 Growth

The trends exhibited by the reproductive variables demonstrated that *P. dentex* spawned mainly between September and November on the lower west coast and mainly between August and December on the upper west coast (see Chapter 4.3.5). Thus, the approximate mid-point of these periods, which was the same in each region, *i.e.* October 1, was assigned as the birth date of this species in both of those regions.

von Bertalanffy growth curves provided a good fit to the lengths at ages of female and male *P. dentex* from inshore waters on the lower west coast (Figure 4.4), as is reflected in the high values of 0.819 and 0.843 for the coefficient of determinations for females and males, respectively (Table 4.2). The lengths at age of fish caught in inshore waters varied more on the upper west coast than lower west coast region, which accounts, in part, for the lower $R^2$ values of 0.662 and 0.664, respectively, for the von Bertalanffy growth curves for female and male *P. dentex* (Figure 4.4). The von Bertalanffy growth curves for female and male *P. dentex* in inshore waters did not differ significantly on the lower west coast ($p > 0.05$), but were significantly different on the upper west coast ($p < 0.05$). The maximum ages recorded for female and male *P. dentex* in inshore waters were 13 and 11 years, respectively, and 13 years on the upper west coast (Figure 4.4). However, the maximum lengths of females and males in these waters were both greater in the upper than lower west coast, *i.e.* 690 and 658 mm *vs* 650 and 568 mm, respectively (Table 4.2). The growth curves of both female and male *P. dentex* from the two regions were significantly different ($p < 0.05$). The mean lengths of 4+, 5+, 6+ and 7+ *P. dentex* from the lower and upper west coast regions were also significantly different ($p < 0.05$), *i.e.* 336, 358, 397 and 387 mm *vs* 385, 411, 439 and 477 mm for females and 334, 377, 382 and 387 mm *vs* 377, 410, 424 and 435 mm for males, respectively.

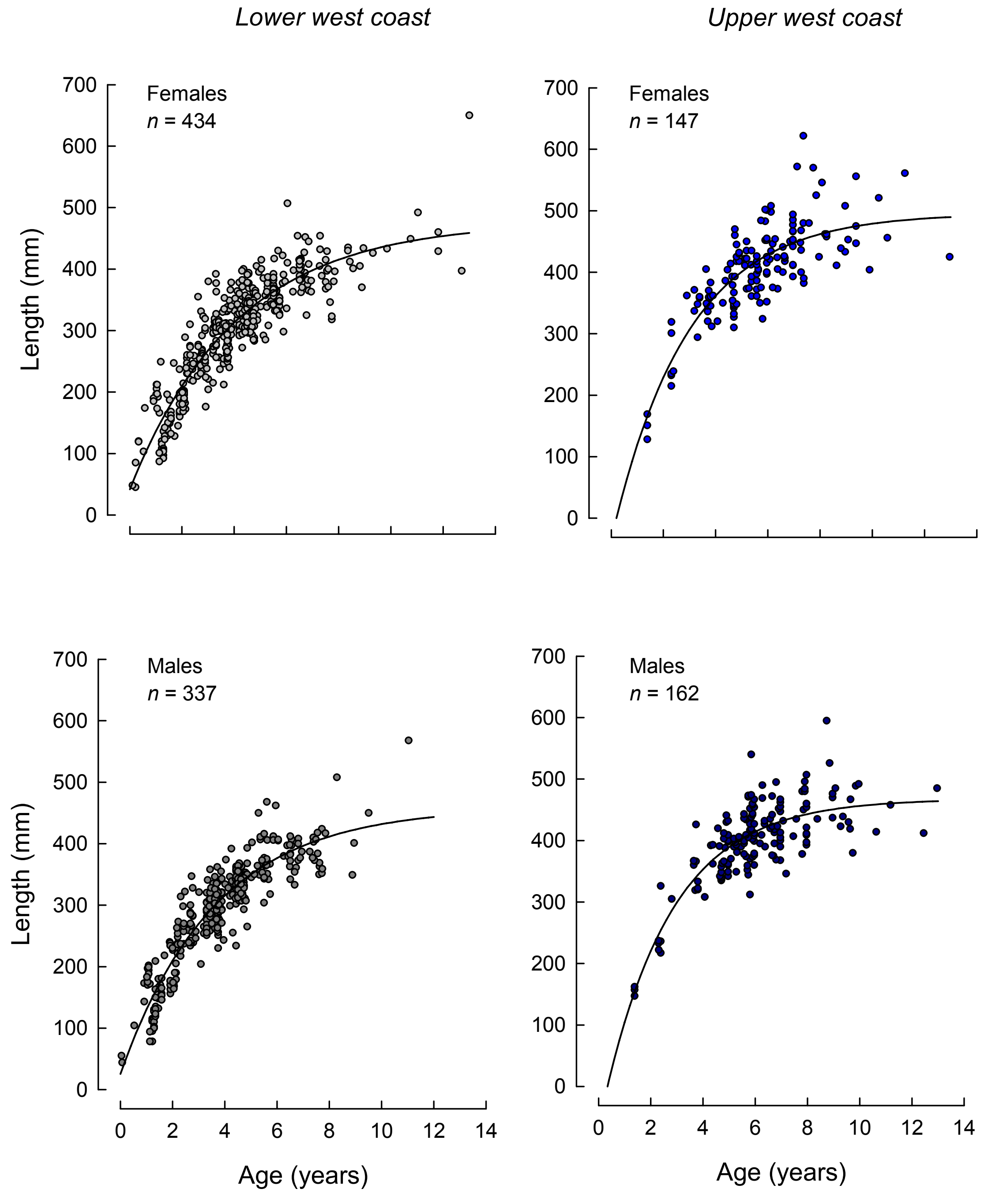

**Figure 4.4.** von Bertalanffy growth curves fitted to the lengths at age of female and male *Pseudocaranx dentex* from inshore waters (*i.e.* < 60 m depth) in the lower and upper west coast regions. *n* = sample size.

**Table 4.2** von Bertalanffy growth parameters, including upper and lower 95% confidence limits, derived from lengths at ages of female and male *Pseudocaranx dentex*, and maximum lengths and ages of individuals from inshore waters (< 60 m depth) in the lower and upper west coast regions and from offshore waters (> 60 m depth) in the lower west coast region.

| | **$L_\infty$ (mm)** | **$k$ (year$^{-1}$)** | **$t_0$ (years)** | **$R^2$** | **$n$** | **Max length (mm)** | **Max age (years)** |
|---|---|---|---|---|---|---|---|
| ***Lower west coast (inshore)*** | | | | | | | |
| *Female* | | | | | | | |
| Estimate | 477.1 | 0.24 | -0.37 | 0.819 | 434 | 650 | 13 |
| Upper | 505.0 | 0.28 | -0.15 | | | | |
| Lower | 449.2 | 0.20 | -0.60 | | | | |
| *Male* | | | | | | | |
| Estimate | 459.2 | 0.27 | -0.22 | 0.843 | 337 | 568 | 11 |
| Upper | 488.1 | 0.32 | 0.01 | | | | |
| Lower | 430.2 | 0.23 | -0.42 | | | | |
| ***Upper west coast (inshore)*** | | | | | | | |
| *Female* | | | | | | | |
| Estimate | 495.9 | 0.34 | 0.20 | 0.662 | 147 | 690 | 13 |
| Upper | 528.1 | 0.44 | 0.78 | | | | |
| Lower | 463.8 | 0.24 | -0.38 | | | | |
| *Male* | | | | | | | |
| Estimate | 467.7 | 0.38 | 0.34 | 0.664 | 162 | 658 | 13 |
| Upper | 489.9 | 0.48 | 0.80 | | | | |
| Lower | 445.5 | 0.29 | -0.12 | | | | |
| ***Lower west coast (offshore)*** | | | | | | | |
| *Female* | | | | | | | |
| Estimate | 3467.9 | 0.01 | -3.17 | 0.755 | 53 | 825 | 18 |
| Upper | 20139.1 | 0.09 | 3.48 | | | | |
| Lower | -13227.1 | -0.07 | -9.81 | | | | |
| *Male* | | | | | | | |
| Estimate | 1383.8 | 0.05 | -1.16 | 0.739 | 55 | 885 | 18 |
| Upper | 2818.8 | 0.14 | 3.34 | | | | |
| Lower | -51.8 | -0.04 | -5.65 | | | | |

As the von Bertalanffy growth curves for female and male *P. dentex* from offshore waters on the lower west coast were not significantly different ($p > 0.05$), the lengths at age for the individuals of both sexes in these waters were combined (Figure 4.5). The lack of data for the smaller *P. dentex* from these offshore waters helps account for the negative estimate of $t_0$ of -2.29 years. However, the likelihood-ratio test showed that a traditional three parameter von Bertalanffy growth model provided a statistically better fit ($p < 0.001$) than a less complex two parameter growth model in which $t_0$ was constrained to zero. Thus, the former model was used for all subsequent analyses. The growth curves for *P. dentex* in inshore and offshore waters of the lower west coast were significantly different ($p < 0.001$). The length derived for *P. dentex* at any given age was far greater for fish in offshore waters than for those in inshore waters at the same age. For example, at 5, 8, 10 and 15 years of age, *P. dentex* were estimated to reach lengths of 369, 512, 595 and 771 mm, respectively, in offshore waters compared with 349, 414, 436 and 461 mm, respectively, in inshore waters. Furthermore, the *P. dentex* caught in offshore waters were generally larger and older than those in shallower, inshore waters (Figure 4.6). This difference is reflected in the greater maximum lengths and ages recorded for *P. dentex* in deep than shallow waters, *i.e.* 885 *vs* 650 mm and 18 *vs* 13 years, respectively.

The likelihood-ratio test demonstrated that the regressions for the logarithms of total length *vs* total weight for the two sexes were not significantly different ($p > 0.05$). The relationship for the combined data for females and males is;
$\log_e W = 2.992(\log_e TL) - 11.331$ ($R^2 = 0.996$, $n = 1424$), where ln represents the natural logarithm, $W$ = total body weight in g, $TL$ = total length in mm, $R^2$ = the coefficient of determination and $n$ = sample size.

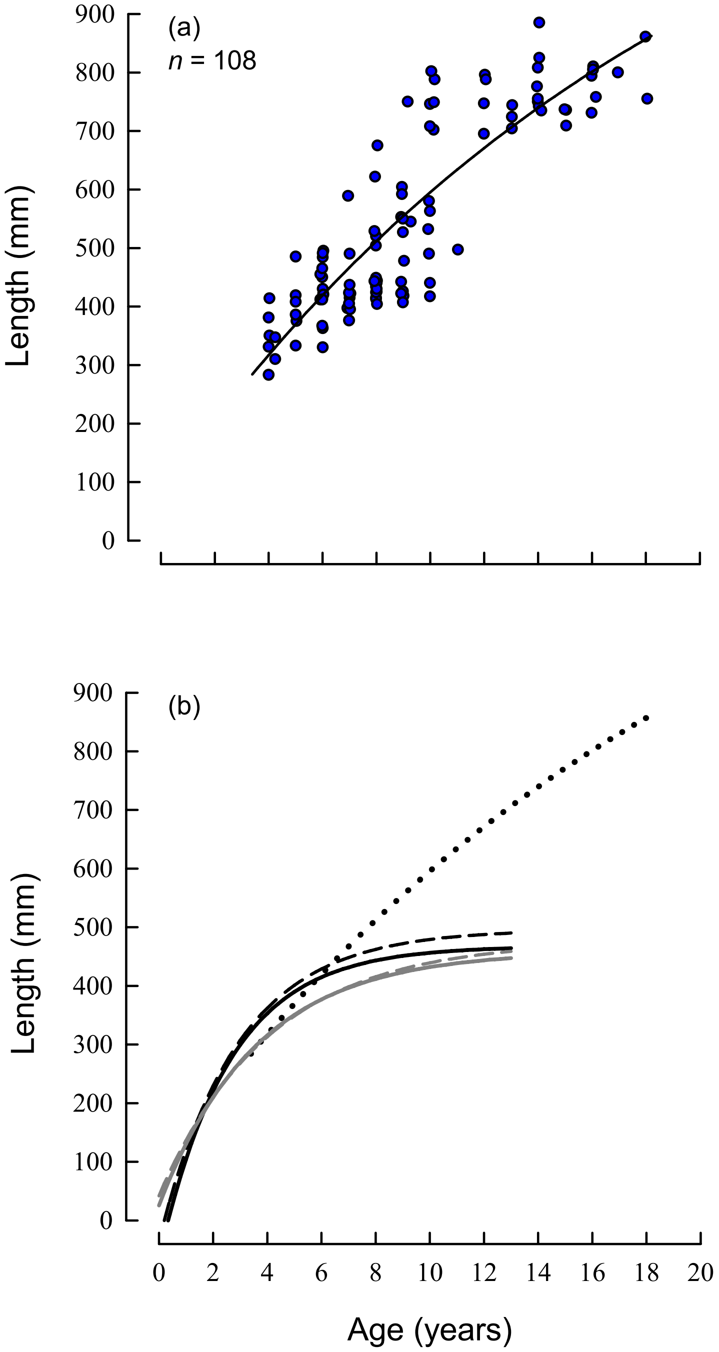

**Figure 4.5.** von Bertalanffy growth curves fitted to lengths at age for *Pseudocaranx dentex* caught from (a) offshore waters (> 60 m depth) on the lower west coast (both sexes pooled) and (b) for females (grey dashed line) and males (grey solid line) of *P. dentex* on the lower west coast (< 60 m depth), females (black dashed line) and males (black solid line) on the upper west coast (< 60 m depth), and both females and males (black dotted line) on the lower west coast (> 60 m depth). *n* = sample size.

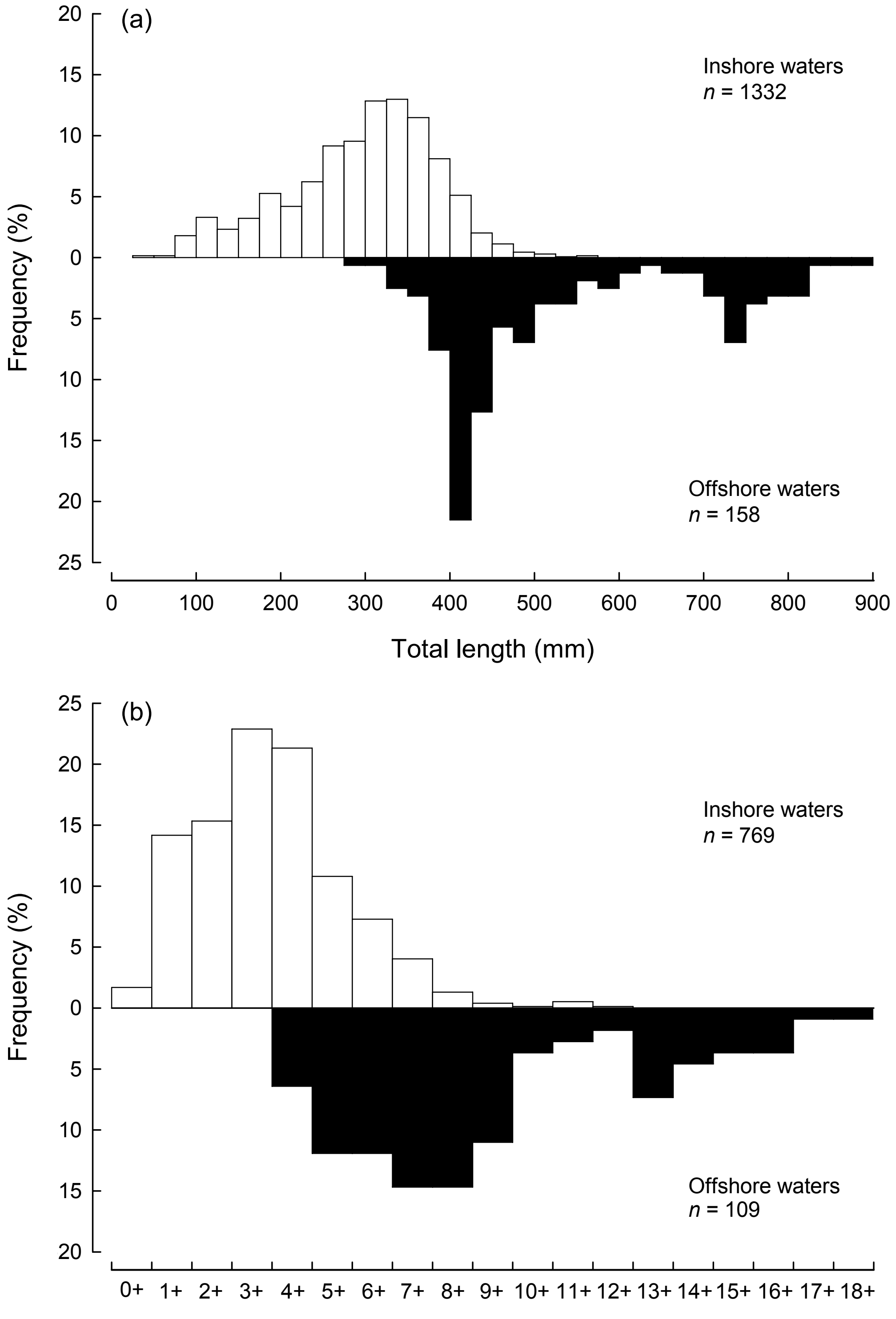

**Figure 4.6.** (a) Length-frequency and (b) age-frequency distributions for *Pseudocaranx dentex* caught in inshore (< 60 m depth) and offshore (> 60 m depth) waters in the lower west coast region. *n* = sample size.

### 4.3.5 Reproductive indices

The mean monthly GSIs of female *P. dentex* ≥ the $L_{50}$ at which individuals first attain maturity on the lower west coast region, *i.e.* 310 mm (see Chapter 4.3.6), rose sharply from 0.7 in July to a maximum of 3.8 in October, before declining precipitously to < 1.0 between December and June (Figure 4.7). The trends exhibited by the mean monthly GSIs for male *P. dentex* ≥ the $L_{50}$ at first maturity from the same region, *i.e.* 279 mm (see Chapter 4.3.6) were similar, with values rising to a maximum of 5.3 in October and then declining markedly (Figure 4.7). The mean monthly GSIs of female and male *P. dentex* (≥ the $L_{50}$ at first maturity) on the upper west coast region, *i.e.* 328 and 256 mm, respectively, remained elevated for a more protracted period, *i.e.* between July and January (Figure 4.7). However, the maximum mean monthly GSIs attained by female and male *P. dentex* in this region, *i.e.* 2.6 and 4.5, respectively, were less than those attained by females and males on the lower west coast region (Figure 4.7).

The ovaries of all female *P. dentex* ≥ the $L_{50}$ at first maturity on the lower west coast region between March and June were at stage I/II (Figure 4.8). The percentage frequency of fish with this ovarian stage gradually decreased in the following months to zero in October and November. Fish possessing stage III and stage IV ovaries were first caught in July and August, respectively. Fish possessing stage V/VI ovaries were first caught in August and the percentage frequency of such individuals was highest between September and November. Fish possessing stage VII and VIII ovaries were initially caught in November and were not found in March and the ensuing months (Figure 4.8). The trends displayed by the monthly frequencies of the stages of gonadal development for male *P. dentex* on the lower west coast were very similar to those of females (Figure 4.8).

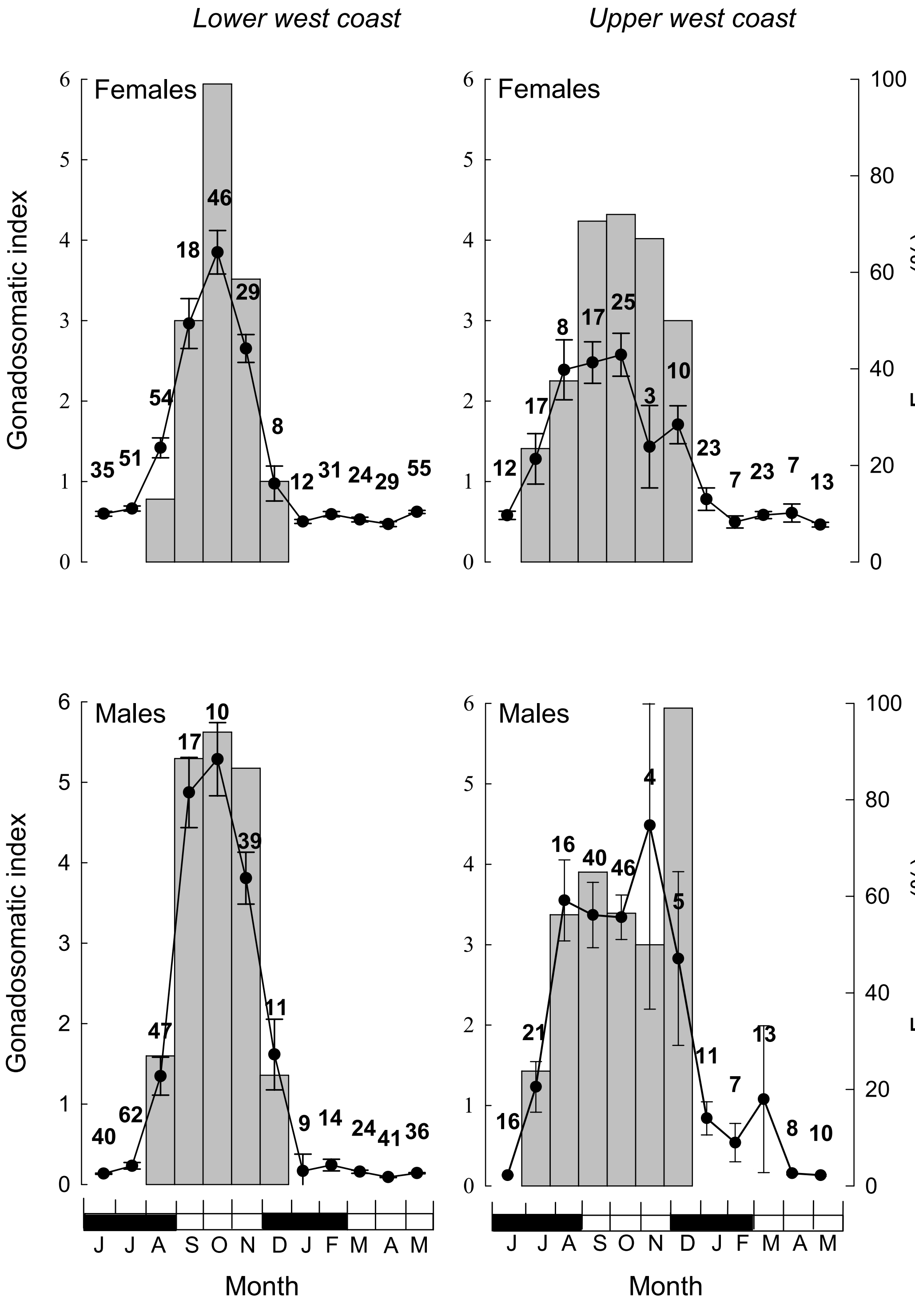

**Figure 4.7.** Mean monthly gonadosomatic indices ± 1 SE and mean percentage frequencies of stage V/VI gonads of female and male *Pseudocaranx dentex* ≥ $L_{50}$ caught in inshore waters on the lower and upper west coast regions. Numbers refer to sample sizes in each month.

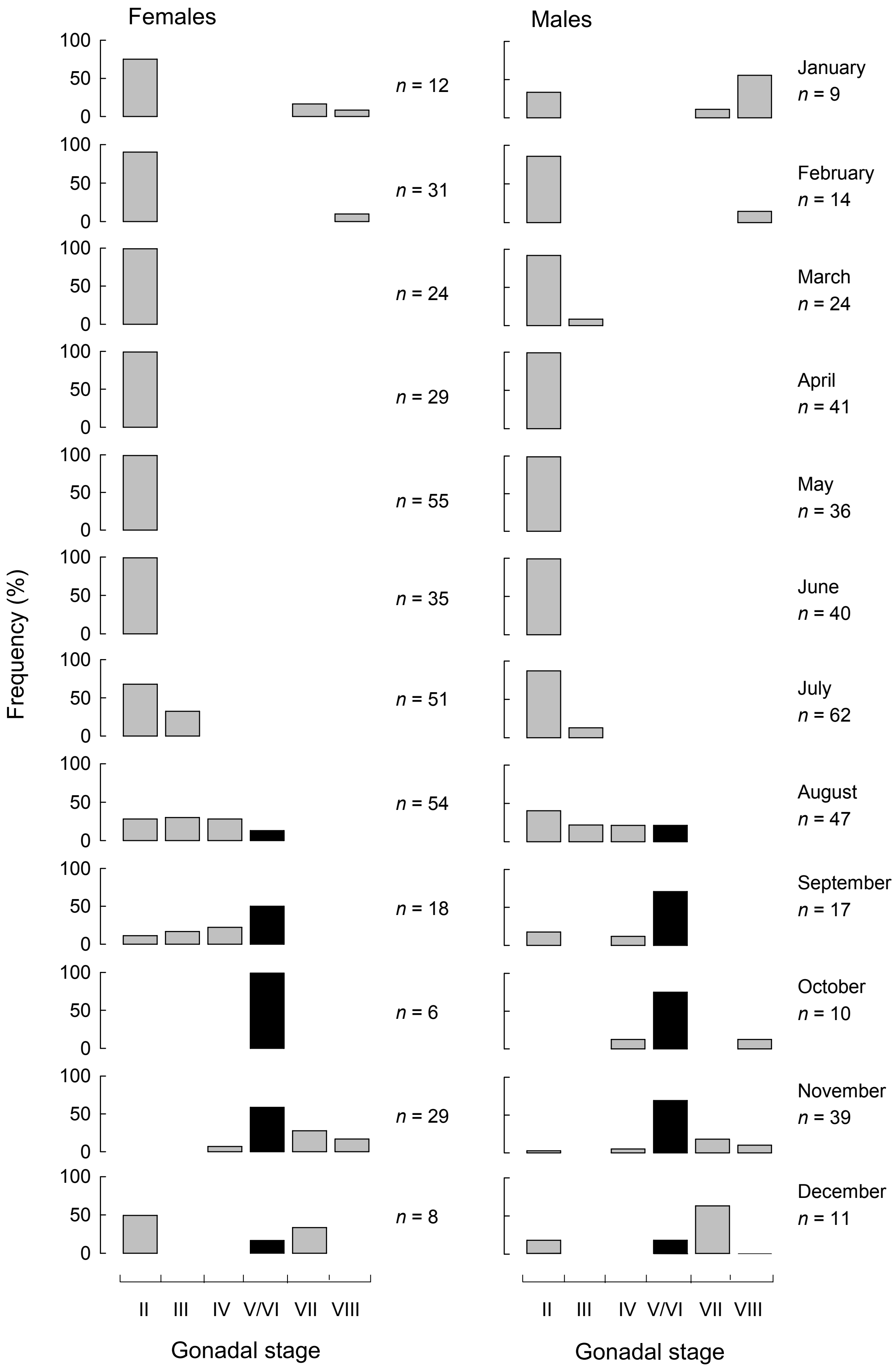

**Figure 4.8.** Monthly percentage frequencies of occurrence of sequential gonadal stages in female and male *Pseudocaranx dentex* ≥ $L_{50}$ caught in inshore waters (< 60 m depth) on the lower west coast of Australia. *n* = sample size in each month.

In comparison with the trends just described for females on the lower west coast region, stage III and V/VII ovaries were first detected one month earlier in the upper west coast region, *i.e.* during June and July, and the prevalence of female and male fish with stage V/VI gonads was greater during December (Figure 4.9).

The trends exhibited by the reproductive variables indicate that *P. dentex* spawns mainly between September and November on the lower west coast and for a more protracted period on the upper west coast region, *i.e.* August to December. The progressive changes in the frequencies of the different gonadal stages of females and males in sequential months throughout the year demonstrate that those individuals of both sexes that possess stage III and IV gonads at the onset of the spawning season progress through to maturity by the end of spawning season. The above trends demonstrate that the vast majority of females and males with gonads at stages III-VIII during the spawning season will become fully mature and spawn or have spawned already during that spawning season

The distributions of the oocyte diameters in the spawning ovaries (*i.e.* stage VI) of two female *P. dentex* each produced a prominent modal class at 40-59 μm, which predominantly represented chromatin nucleolar or perinucleolar oocytes (Figure 4.10). Oocytes at several different stages of development, *i.e.* cortical alveolar and yolk granule oocytes, as well as either migratory nucleus oocytes or post-ovulatory follicles, were also present in these ovaries. In the case of both ovaries, there was no distinct gap in oocyte distribution between the small previtellogenic oocytes and the large vitellogenic (*i.e.* yolk granule) oocytes (Figure 4.10).

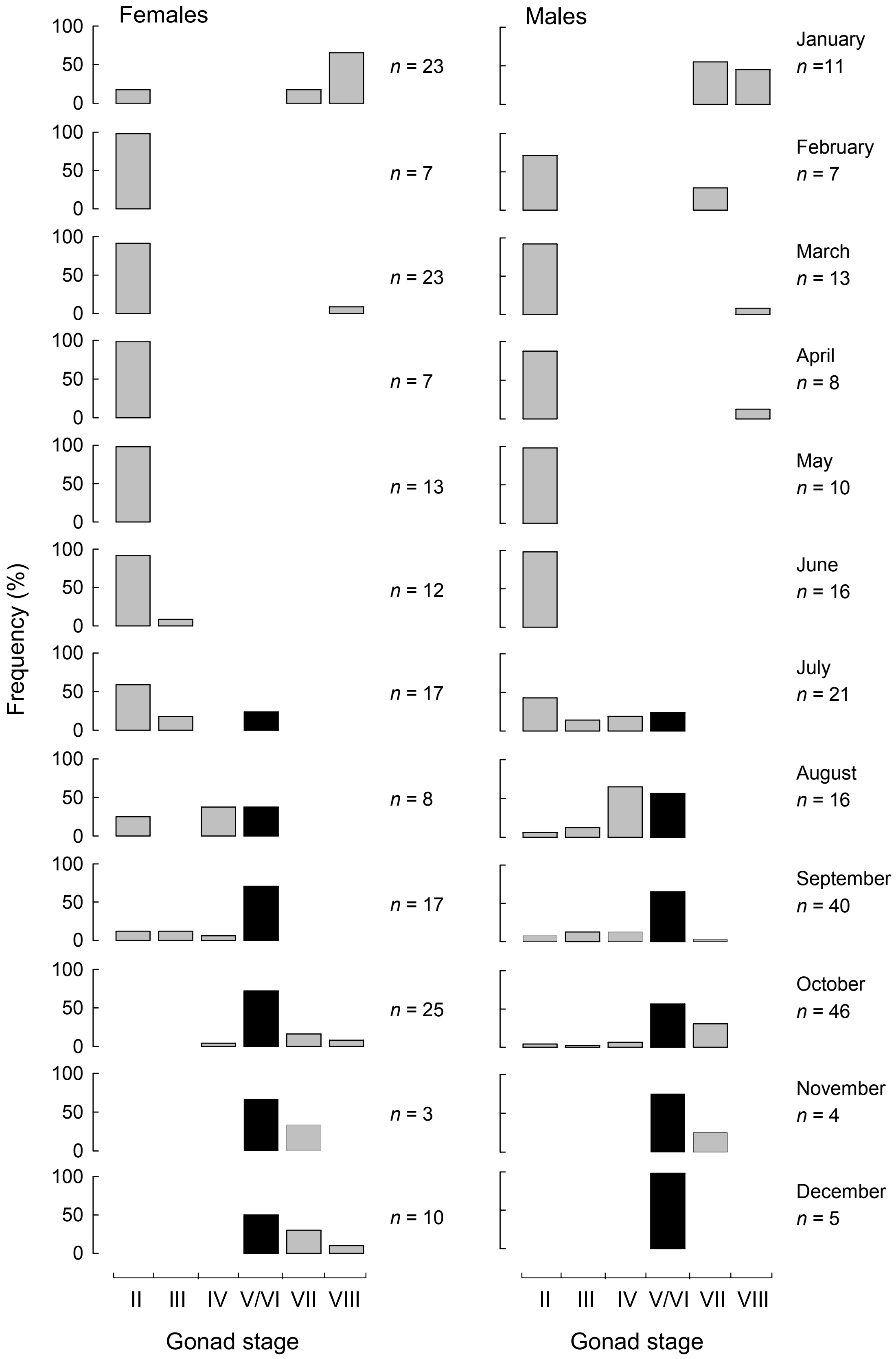

**Figure 4.9.** Monthly percentage frequencies of occurrence of sequential gonadal stages in female and male *Pseudocaranx dentex* $\geq L_{50}$ in inshore waters (< 60 m depth) in the upper west coast region. *n* = sample size in each month.

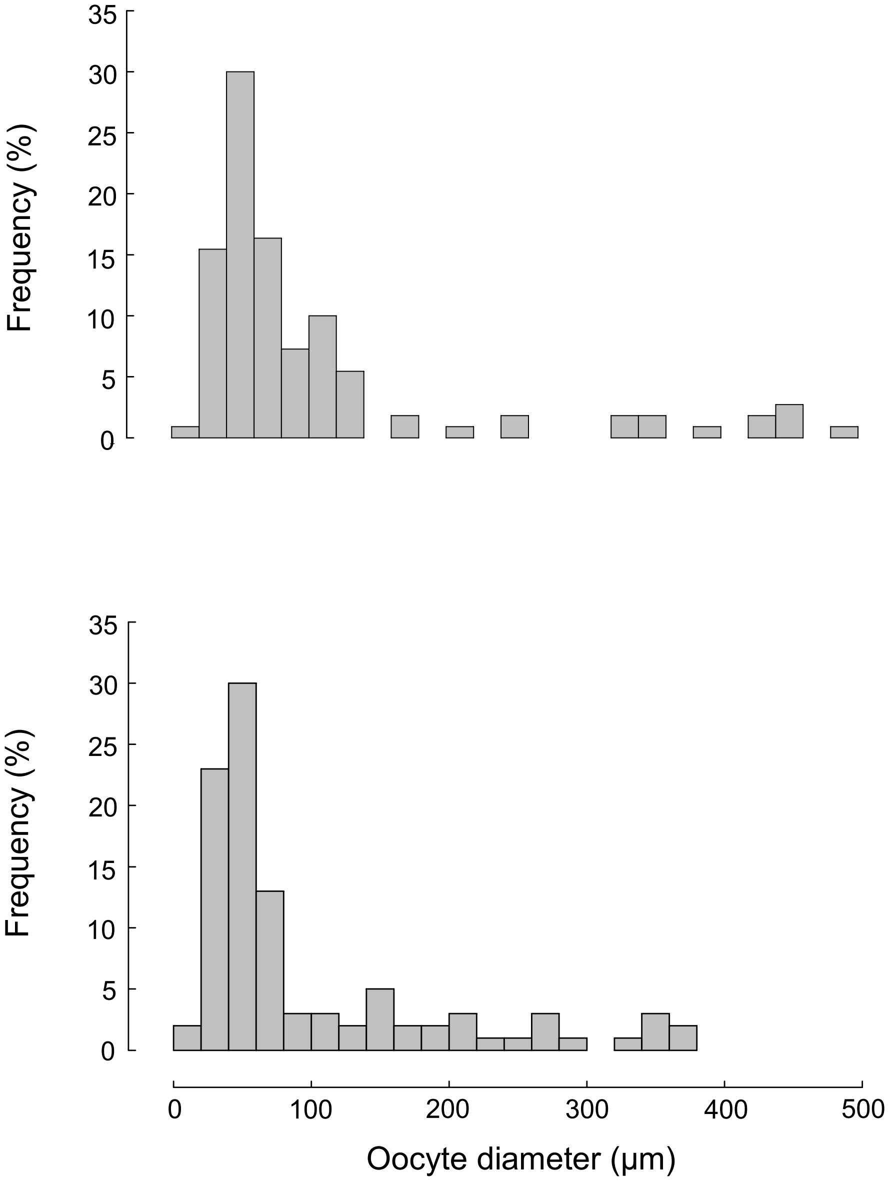

**Figure 4.10.** Oocyte diameter frequency distributions for stage VI ovaries of two female *Pseudocaranx dentex*.

### 4.3.6 Length and age at maturity

During the spawning season of *P. dentex* in inshore waters on the lower west coast, females and males with gonads at one of stages III to VIII were found in fish of 200-249 mm (Figure 4.11). The prevalence of such fish increased with size, reaching *ca* 50% in females of 300-349 mm and 50 % in males of 250-299 mm and virtually all fish in the succeeding length classes (Figure 4.11). The $L_{50}$s at which female and male *P. dentex* on the lower west coast first attained maturity, *i.e.* 310 and 279 mm, respectively, differed significantly ($p < 0.05$). The trends exhibited by the prevalence of fish with gonads at stages III to VIII on the upper west coast were similar to those just described for the lower west coast except that no females < 300 mm possessed gonads at one of these stages (Figure 4.11). The $L_{50}$s at which female and male *P. dentex* from this region first attained maturity, *i.e.* 328 and 256 mm, respectively (Table 4.3), were not significantly different ($p > 0.05$). The $L_{50}$s at first maturity of the females and males from the upper west coast region did not differ significantly from those of the corresponding sex on the lower west coast region ($p > 0.05$).

**Table 4.3** Length at maturity ($L_{50}$/$L_{95}$) and 95% confidence limits derived for *Pseudocaranx dentex* caught in inshore waters (< 60 m depth) in the lower and upper west coast regions.

| | | ***Lower west coast*** | | ***Upper west coast*** | |
|---|---|---|---|---|---|
| | | **$L_{50}$ (mm)** | **$L_{95}$ (mm)** | **$L_{50}$ (mm)** | **$L_{95}$ (mm)** |
| Female | **Estimate** | 310 | 378 | 328 | 398 |
| | **Lower** | 299 | 348 | 307 | 342 |
| | **Upper** | 322 | 402 | 356 | 438 |
| Male | **Estimate** | 279 | 323 | 256 | 367 |
| | **Lower** | 266 | 301 | 202 | 306 |
| | **Upper** | 293 | 337 | 282 | 413 |

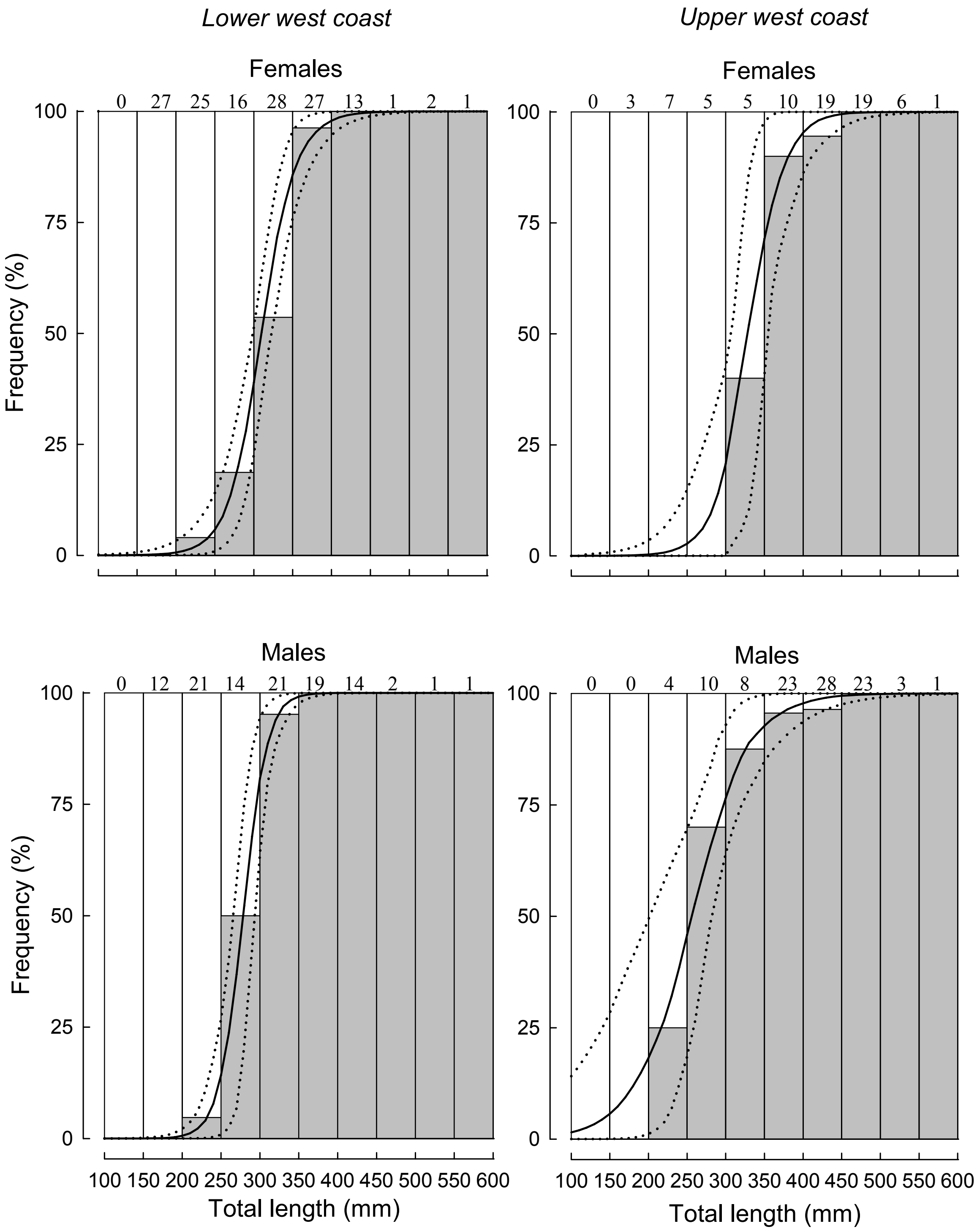

**Figure 4.11.** Percentage contributions made to each length class during the spawning season by female and male *Pseudocaranx dentex* with stage III-VIII gonads. Data are provided for both the lower and upper west coast regions. The predicted percentage (± 95% CIs) of mature fish at each length derived using logistic regression analysis is shown (solid and dotted lines). Sample size for each 50 mm length class is shown. Grey bars denote percentage mature in each 50 mm length class.

No female or male *P. dentex* on the lower west coast region had reached maturity by the end of their second year of life. In this region, maturity had been attained by 4 % of the females and 5 % of the males by the end of their third year of life and by *ca* 54% of females and 50% of males by the end of their fourth year of life (Figure 4.12). All individuals of both sexes had attained maturity by the end of their seventh year of life. Similar trends were observed for the corresponding year classes of female and male *P. dentex* on the upper west coast region.

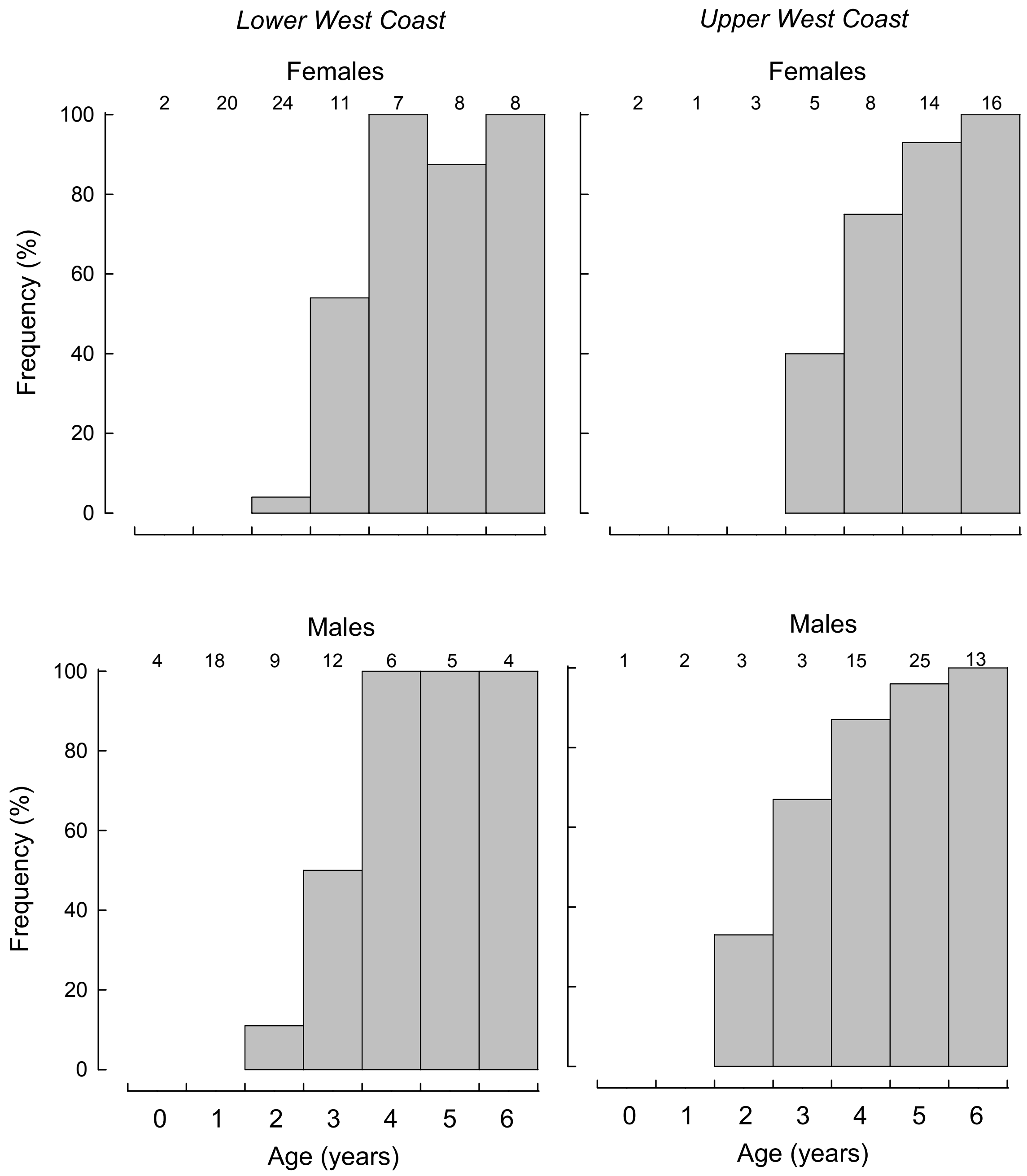

**Figure 4.12.** Percentage frequency of occurrence of female and male *Pseudocaranx dentex* with gonads at stages III-VIII in sequential age groups caught during the spawning season in inshore waters (< 60 m depth) on the lower and upper west coast. Grey bars refer to gonads at stages III-VIII. Sample sizes in each age category are given.

### 4.3.7 Mortality

Estimates for the instantaneous coefficient of total mortality, $Z$, for *P. dentex* in inshore waters (< 60 m depth) of the lower west coast, derived by refitting Hoenig's (1983) equation for fish, relative abundance (catch curve) analysis and simulation based on the number of fish ≥ 11 years, were 0.33, 0.57 and 0.49 year$^{-1}$, respectively (Table 4.4). However, the confidence intervals for the Hoenig equation were very broad (Table 4.4). The instantaneous coefficient of natural mortality, $M$, which resulted from refitting Pauly's (1980) equation (see Chapter 2.6), provided a point estimate (0.59 year$^{-1}$) that was greater than each of the above three point estimates for $Z$ (Table 4.4).

A posterior probability distribution for $Z$, derived using the Bayesian method of Hall *et al.* (2004), which combines the separate likelihood distributions for the various estimates of $Z$, yielded a point estimate for this coefficient of 0.54 year$^{-1}$ (Table 4.4, Figure 4.13a). The resultant posterior probability distribution for the point estimate for $M$, determined from the combined likelihood distribution for $Z$ and the requirement that $M \leq Z$, yielded a point estimate for $M$ of 0.38 year$^{-1}$ (Table 4.4, Figure 4.14a,b).

The point estimates derived for $Z$ for *P. dentex* in inshore waters of the upper west coast using Hoenig's equation, relative abundance analysis and simulation using the number of fish ≥ 11 years, were similar to the above values obtained using the corresponding methods for fish in inshore waters on the lower west coast (Table 4.4, Figure 4.14a, c). Furthermore, as in inshore waters on the lower west coast, the point estimate of 0.75 year$^{-1}$ derived for $M$ using Pauly's equation for fish in inshore waters on the upper west coast exceeded each of the above three estimates for $Z$. The estimate derived for $M$ on the upper west coast, 0.54 year$^{-1}$, using Bayesian analysis and a combination of different variables, was the same as that estimated using this approach for fish in inshore waters on the lower west coast (Table 4.4). Moreover, following the use of the Bayesian method, the value for $M$ was slightly less than that for $Z$.

The estimates of the current level of fishing mortality, *F*, derived from Monte Carlo analysis of data for fish in inshore waters of the lower (0.15 year$^{-1}$) and upper west coasts (0.10 year$^{-1}$) are relatively low, *i.e.* < half the level of *M* (Table 4.4).

**Table 4.4** Estimates (year$^{-1}$) of total, *Z*, natural, *M*, and fishing mortality, *F*, for *Pseudocaranx dentex* in inshore waters on the lower and upper west coasts of Western Australia. The values were calculated using life history models (Pauly, 1980; Hoenig, 1983), relative abundance analysis and simulation based on the number of fish above the specified ages. Estimates for *Z* and *M* were also provided using a Bayesian method, which combines the data obtained using the other methods. Data are not provided for *P. dentex* in offshore waters on the lower west coast because it was not possible to obtain reliable estimates of the parameters in the von Bertalanffy growth equation, which are required for estimating *M*.

| **Method of analysis** | ***Z, M or F*** | **Estimate** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|---|
| *Lower west coast (inshore)* | | | | |
| Refitted Hoenig (1983) fish equation | *Z* | 0.33 | 0.12 | 0.93 |
| Relative abundance analysis | *Z* | 0.57 | 0.42 | 0.69 |
| Simulation (4 fish > 11 years) | *Z* | 0.49 | 0.39 | 0.61 |
| **Combined *Z* (Bayesian method)** | ***Z*** | **0.54** | **0.47** | **0.68** |
| Refitted Pauly (1980) | *M* | 0.59 | 0.19 | 1.80 |
| **Combined *M* (Bayesian method)** | ***M*** | **0.38** | **0.18** | **0.62** |
| **Monte Carlo** | ***F*** | **0.15** | **0.00** | **0.40** |
| *Upper west coast (inshore)* | | | | |
| Refitted Hoenig (1983) fish equation | *Z* | 0.33 | 0.12 | 0.93 |
| Relative abundance analysis | *Z* | 0.57 | 0.42 | 0.70 |
| Simulation (6 fish > 11 years) | *Z* | 0.58 | 0.41 | 0.78 |
| **Combined *Z* (Bayesian method)** | ***Z*** | **0.54** | **0.47** | **0.68** |
| Refitted Pauly (1980) | *M* | 0.75 | 0.24 | 2.28 |
| **Combined *M* (Bayesian method)** | ***M*** | **0.41** | **0.21** | **0.63** |
| **Monte Carlo** | ***F*** | **0.10** | **0.00** | **0.35** |

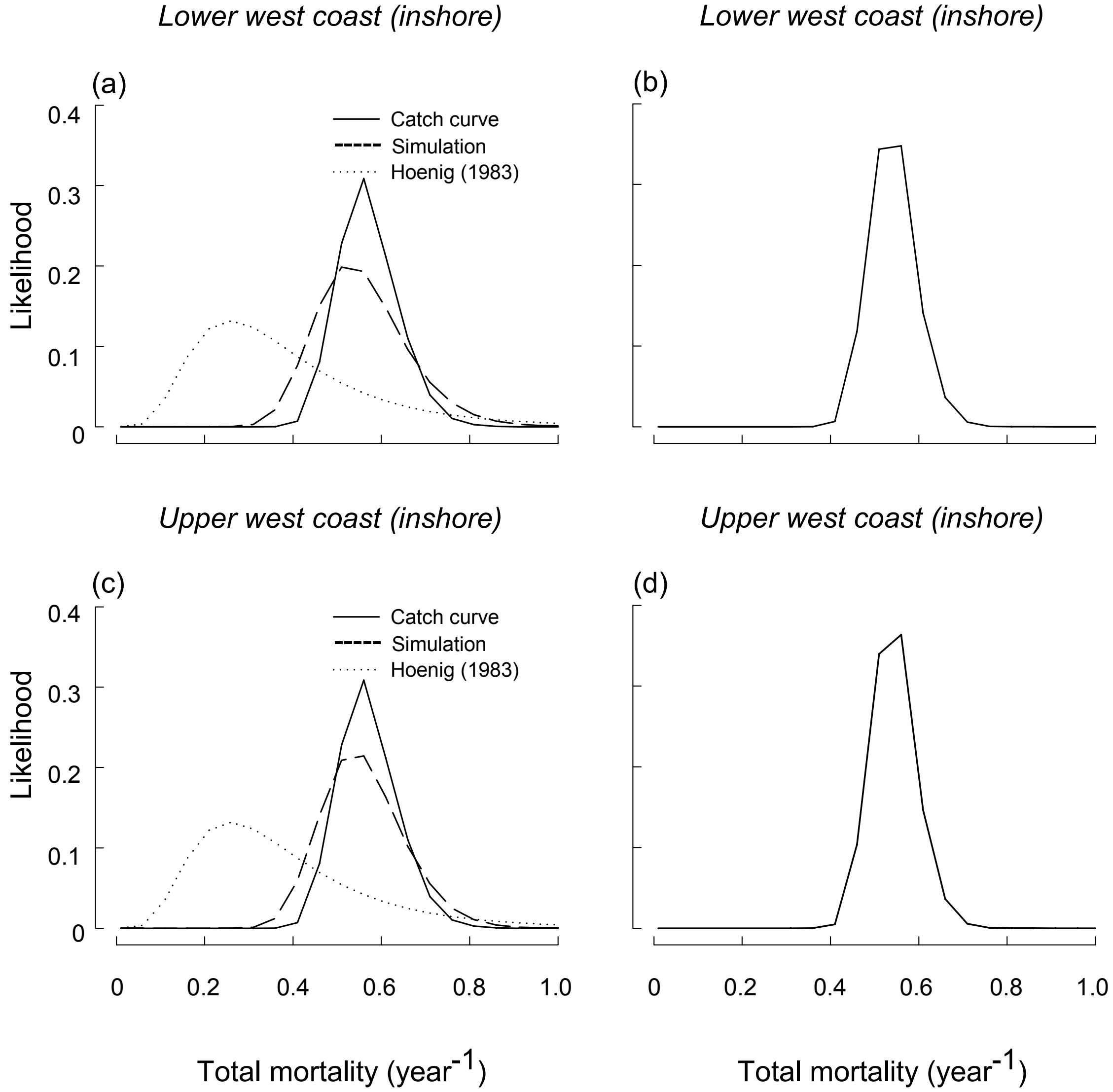

**Figure 4.13.** Estimated likelihood functions for total mortality, *Z*, of *Pseudocaranx dentex* caught in inshore waters (< 60 m depth) in the (a) lower and (c) upper west coast regions derived using Hoenig's (1983) regression equation for fish, relative abundance (catch curve) analysis and a simulation method based on the numbers of individuals above a certain age and sample size. Combined posterior probability distributions for the afore mentioned regions (b, d), respectively, derived from the separate likelihood functions shown in a and c.

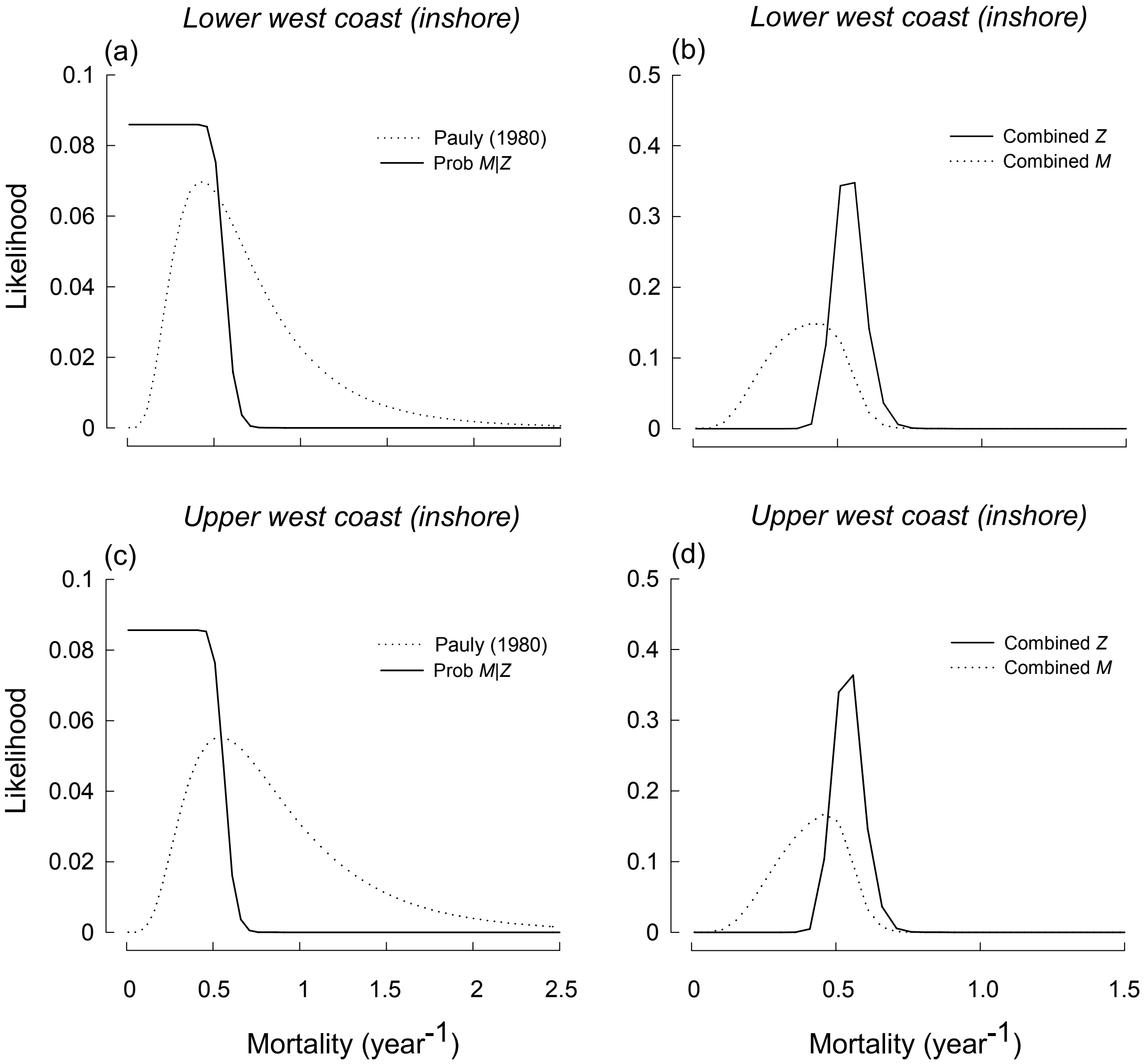

**Figure 4.14.** Likelihood functions for natural mortality, *M*, for *Pseudocaranx dentex* caught in inshore waters (< 60 m depth) in the (a, b) lower and (c, d) upper west coast regions using Pauly's (1980) equation and the likelihood function for *M* assuming that it is less than the combined estimate for *Z* and the combined posterior probability distributions for *Z* and *M* for the afore mentioned regions (b, d), respectively. Prob *M*|*Z* = Probability of *M* given *Z*.

### 4.3.8 Yield per recruit and spawning potential ratio

Yield per recruit (YPR) analyses for *P. dentex* in inshore waters, which assumed that this species is fully recruited to the fishery at 5 and 6 years on the lower and upper west coasts, respectively, indicate that, as fishing mortality increases from 0 to 1.5 $\text{year}^{-1}$, the YPR will continue to increase (Figure 4.15a, c). The same situation occurs if the age at recruitment to the exploited stock is reduced to 3 years or increased to 7 years on the lower west coast or reduced to 4 years or increased to 8 years on the upper west coast (Table 4.5; Figure 4.15a, c). However, when the age at recruitment to the fishery is reduced to 2 years, the YPR declines when the fishing mortality reaches ~ 0.7 $\text{year}^{-1}$ on the lower west coast and 0.50 $\text{year}^{-1}$ on the upper west coast (Figure 4.15a, c). At the estimated current level of $F$ of 0.15 $\text{year}^{-1}$ (0.00 – 0.40 $\text{year}^{-1}$) for the lower west coast and 0.10 $\text{year}^{-1}$ (0.00 – 0.35 $\text{year}^{-1}$) for the upper west coast and with estimated ages at recruitment to the exploited stock of 5 and 6 years, respectively, the YPRs are *ca* 0.02 kg $\text{year}^{-1}$ (0 – 0.20 kg $\text{year}^{-1}$) and 0.02 kg $\text{year}^{-1}$ (0 – 0.18 kg $\text{year}^{-1}$), respectively (Figure 4.14a,c). The corresponding spawning stock biomass per recruit (SSB/R) for female and male *P. dentex* from the lower and upper west coast regions are 0.35 kg $\text{year}^{-1}$ (0.16 – 0.99 kg $\text{year-}^{1}$) and 0.46 kg $\text{year}^{-1}$ (0.18 – 1.34 kg $\text{year}^{-1}$), respectively (Table 4.5).

The spawning potential ratio (SPR) for female and male *P. dentex* caught in inshore waters on the lower and upper west coast regions is predicted to decrease with increasing fishing mortality (Figure 4.15b,d). The rate at which the SPR of female and male *P. dentex* declines is greater if the age at recruitment to the fishery is reduced by 2 years from that currently assumed to be the case for their respective regions, while the reverse occurs if the age at recruitment to the exploited stock is increased by 2 years (Figure 4.15b,d). The estimated SPRs for female and male *P. dentex* from the lower and upper west coast regions, at the current estimated levels of *F* for these two regions, are 0.81 (0.32 – 1.00) and 0.91 (0.54 – 1.00), respectively (Table 4.5; Figures 4.15b,d).

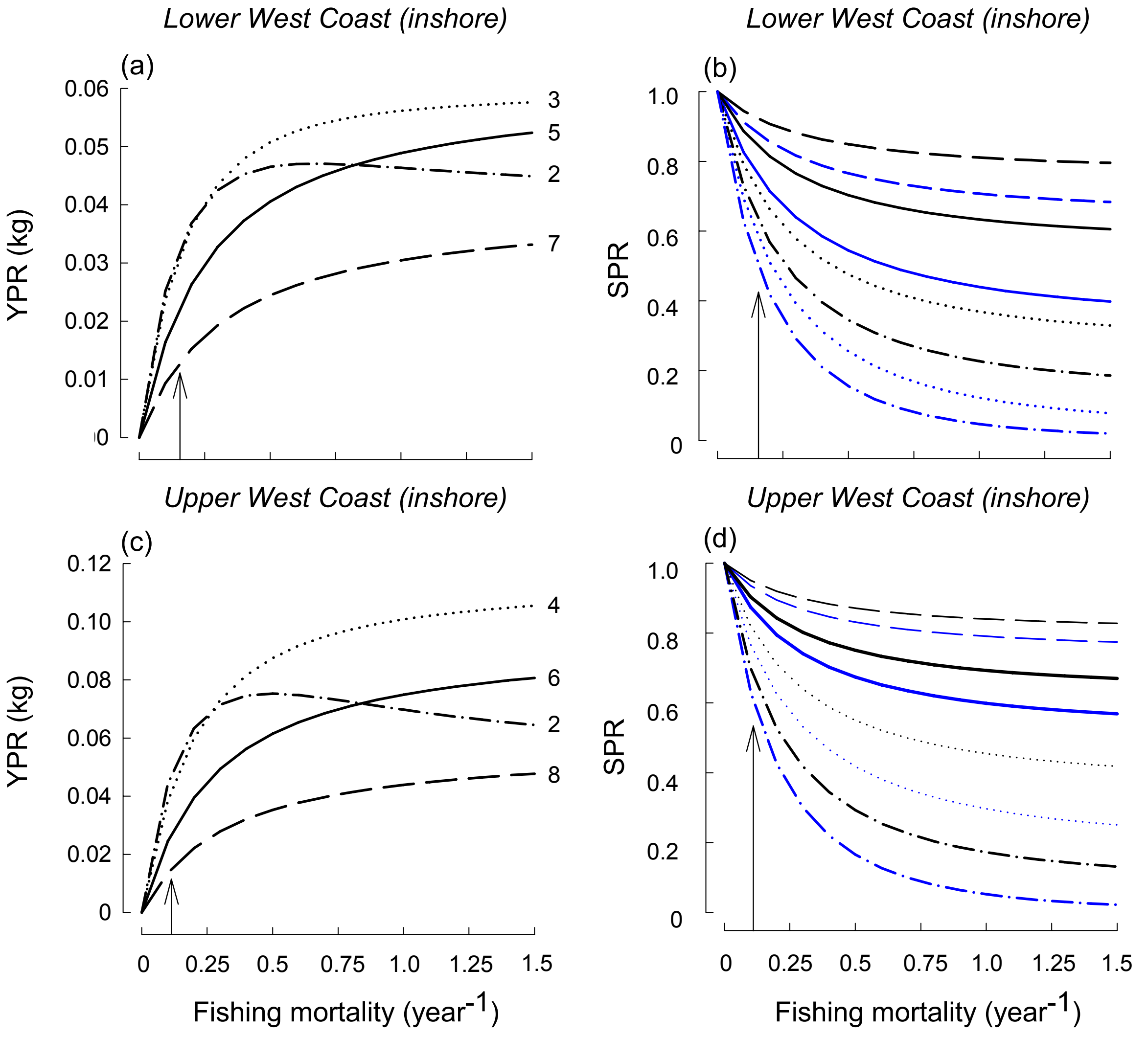

**Figure 4.15.** Effect, for *Pseudocaranx dentex* caught in inshore waters (< 60 m depth) on the lower (LWC) and upper (UWC) west coasts, of different levels of fishing mortality and at different ages at recruitment on the yield per recruit (a, c) and spawning potential ratio (b, d). Blue and black (b, d) represent females and males, respectively, and the curves corresponding to ages 2, 3, 5 and 7 years (b), and 2, 4, 6 and 8 years (d) at full recruitment are represented by dashed/dotted, dotted, solid and dashed lines, respectively. The arrows indicate the current level of fishing mortality.

**Table 4.5.** Estimates of the current level of yield per recruit (YPR), $F_{0.1}$, and the current levels of total spawning stock biomass per recruit (SSB/R) and spawning potential ratio (SPR) for females and males, and for females and males combined, for *Pseudocaranx dentex* on the lower and upper west coasts, calculated using 5 and 6 years, respectively, as the age at full recruitment to the exploited stock for the samples from each region.

| **Analysis** | **Estimate** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|
| *Lower west coast* | | | |
| **YPR (kg year$^{-1}$)** | 0.02 | 0 | 0.20 |
| **$F_{0.1}$ (year$^{-1}$)** | 0.69 | -- | -- |
| **SSB/R (kg year$^{-1}$)** | 0.35 | 0.16 | 0.99 |
| **SPR (females)** | 0.75 | 0.28 | 1.00 |
| **SPR (males)** | 0.84 | 0.36 | 1.00 |
| **SPR (combined)** | 0.81 | 0.32 | 1.00 |
| *Upper west coast* | | | |
| **YPR (kg year$^{-1}$)** | 0.02 | 0 | 0.18 |
| **$F_{0.1}$ (year$^{-1}$)** | 0.63 | -- | -- |
| **SSB/R (kg year$^{-1}$)** | 0.46 | 0.18 | 1.34 |
| **SPR (females)** | 0.89 | 0.51 | 1.00 |
| **SPR (males)** | 0.92 | 0.57 | 1.00 |
| **SPR (combined)** | 0.91 | 0.54 | 1.00 |

## 4.4 DISCUSSION

### 4.4.1 Habitats

Samples collected by seine netting, trawling and angling, demonstrated that, in waters on the lower west coast of Australia, the juveniles of *P. dentex* live mainly in areas where the water depth is < 20 m and there is some structural complexity brought about by the presence of either seagrass, detatched macrophytes or structures, such as reefs, rocks, pillars or jetties. A comparison of the catches obtained by the different methods also provided strong evidence that this species moves to deeper waters over reefs as it increases in size, and that the largest and oldest fish typically live in water depths > 60 m. The above pattern of size-related movements is essentially the same as recorded for Silver Trevally in Japanese waters (Masuda and Tsukamoto, 1999).

The data obtained from the above samples demonstrate that, unlike the situation with *P. dentex*, the adults of *P. wrighti* live predominantly over sand rather than over reefs. Seine netting, trawling and angling in marine waters yielded only a few juveniles of *P. wrighti* < 12 months old. Since small juveniles were also not caught when a small mesh (12 mm) was added to the cod end of the trawl net, they do not apparently occupy the same habitat as their adults. However, small juveniles of *P. wrighti*, *i.e.* 12-40 mm, have recently been caught under the umbrellas of jellyfish in inshore waters.

### 4.4.2 Ageing procedure and validation

Whole otoliths of *P. dentex* have been regarded as unsuitable for ageing this species as their annual growth zones are often unclear or can easily be confused with false checks or zones (Kalish and Johnston, 1997; Walsh *et al.*, 1999; Rowling and Raines, 2000). The ability to detect these annual growth zones in *P. dentex* can be enhanced by breaking and burning the otoliths (James, 1984) or by baking and producing thick sections of the otoliths (Walsh *et al.*, 1999). However, most authors agree that, for this species, the production of thin sections of otoliths is the most effective method for improving the clarity of annual growth zones (Kalish and Johnston, 1997; Walsh *et al.*, 1999; Rowling and Raines, 2000).

In Western Australia, the number of growth zones observed after sectioning the otoliths of *P. dentex* often differed markedly from those detectable in those otoliths prior to sectioning and this was even the case in otoliths with few growth zones. By sectioning, the growth zones towards the periphery and in the innermost region of otoliths became more easily detectable. Furthermore, the false checks and zones, which are characteristic of many whole otoliths of *P. dentex*, and of some other species, such as *Promethichthys prometheus* (Lorenzo and Pajuelo, 1998) and *Sebastes alutus* (MacLellan, 1997), could be more easily recognized in sectioned otoliths. Walsh *et al.* (1999) used baked, thicker sections of otoliths for ageing studies as it resulted in a reduced preparation time and only a slight decline in the clarity of zones.

Despite a marked improvement in the clarity of the growth zones in the otoliths of *P. dentex* after they had been sectioned, these zones were seldom continuous throughout the otolith and were still sometimes difficult to detect using conventional light microscopy. However, the use of the Leica IM 1000 computer imaging package (Leica Microsystems Ltd., 2001) enabled the lighting and level of magnification to be modified and thus optimize the clarity of the growth zones in sections of these otoliths.

The mean monthly marginal increments in the otoliths of *P. dentex*, irrespective of their number of annuli, underwent a single marked decline and subsequent progressive rise, demonstrating that a single opaque zone is deposited annually in the otoliths of this species. Thus, as with Silver Trevally in New South Wales (Kalish and Johnston, 1997; Rowling and Raines, 2000) and New Zealand (James, 1984; Walsh *et al.*, 1999), it is appropriate to use the number of annuli in sectioned otoliths of *P. dentex* to age this species in Western Australia. The seasonal pattern of formation of opaque zones on the otoliths of *P. dentex* parallels that of most other species which have been studied in the temperate waters of Western Australia, such as the Australian herring *Arripis georgianus* (Fairclough *et al*., 2000) and the West Australian dhufish *Glaucosoma hebraicum* (Hesp *et al*., 2002).

### 4.4.3 Size and age compositions

Our data shows the size and age compositions of the females and males of *Pseudocaranx dentex* were relatively similar on both the lower and upper west coast regions of the study area in Western Australia. Furthermore, in both regions, the vast majority of the individuals of this species obtained from inshore waters (< 60 m depth) were less than 500 mm in length and less than 12 years old (Figure 3.3). However, the numbers of fish with lengths and ages greater than 400 mm and 8 years, respectively, were slightly greater in the upper west coast. This difference almost certainly reflects, in part, the fact that a large proportion of the fish from the upper west coast were obtained from fish markets and thus commercial fishers. These fishers tended to target larger species and to fish in slightly deeper waters, which would have increased their likelihood of catching larger *P. dentex*. In comparison, the samples from inshore waters on the lower west coast were obtained, very largely, from our own sampling and those of recreational fishers in waters that, on average, would have been slightly shallower than those from which fish were obtained on the upper west coast.

In contrast to the situation in inshore waters of both the lower and upper west coasts, a substantial number of the *P. dentex* caught in offshore waters (> 60 m depth) off the lower west coast were greater than 500 mm in length and more than 9 years old. Furthermore, the maximum length of 885 mm and maximum age of 18 years in offshore waters far exceeds the corresponding values of 690 mm and 13 years for inshore waters of the lower west coast. Genetic studies were unable to elucidate whether the inshore and offshore assemblages of this species on the lower west coast were part of the same stock (Bearham, 2004), and thus whether the presence of larger and older fish in deeper waters reflected a size-related offshore movement.

The maximum total lengths of 650 and 690 mm recorded for *P. dentex* in inshore waters on the lower and upper west coasts, respectively, were similar to the 685 mm recorded by Rowling and Raines (2000) for populations in New South Wales, but greater than the *ca* 600 mm recorded by Kalish and Johnston (1997) for populations in that state. However, the maximum ages of 24 and 21 years recorded for *P. dentex* in those two NSW studies were far greater than the maximum of 13 years we recorded for fish from inshore waters on both the lower and upper west coast regions in Western Australia. Furthermore, they were even greater than the maximum age we recorded in offshore waters in Western Australia, *i.e.* 18 years, despite the fact that *P. dentex* grows to a far larger size in those latter waters.

In New Zealand, *P. dentex* is recorded by Walsh *et al*. (1999) as attaining a maximum total length of *ca* 810 mm. The maximum age recorded for Silver Trevally by the same authors was 43 years, and a number of individuals in their study were greater than 30 years old. Williams and Lowe (1997) demonstrated that *Pseudocaranx dentex* can attain a length of 1580 mm TL in Hawaiian waters, which is far greater than the maximum length recorded for any waters in Australia or New Zealand. However, there are no precise data on the age composition of *P. dentex* in those Hawaiian waters.

As was recognised by Rowling and Raines (2000), the trawling which provided their samples of *P. dentex* selected the fast-growing fish, which in turn accounts for the very high negative values for $t_0$ in their von Bertalanffy growth equation. As this will have markedly influenced the values for $k$ and $L_\infty$ in their growth equations, it is difficult to make valid quantitative comparisons between the growth of this species on the west and east coasts of Australia.

The values for $t_0$ in the von Betalanffy equations for *P. dentex* from two locations in New Zealand were both close to zero (Walsh *et al.*, 1999), as they also were in our study of this species in inshore waters on the west coast of Australia. Furthermore, although the values for $L_\infty$ (525 – 572 mm) in New Zealand waters were greater than those we recorded for inshore waters in Western Australia, the values for $k$ (0.28 – 0.36) were comparable to those of the present study. However, as the points for the lengths at age for virtually all of the numerous fish > 15 years old lay above the von Bertalanffy growth curve for the New Zealand samples (Walsh *et al.*, 1999), that growth curve does not provide a good description of the growth of *P. dentex* in New Zealand waters.

The fact that, in offshore waters on the lower west coast of Australia, the $t_0$ for males (-1.16 years) and more particularly females (-3.17 years) diverged conspicuously from zero is attributable to the absence of fish < 4 years of age and thus of fish that would influence the early part of the growth curve.

### 4.4.4 Aspects of spawning

As pointed out earlier, the adults of *P. dentex* were caught predominantly over reefs. However, our data also strongly suggest that the spawning of *Pseudocaranx dentex* is not restricted to any specific region along the coast or water depth. This view is based on the fact that females with large yolk granule oocytes and others with post-ovulatory follicles were collected from waters located at distances of 0.5 to 35 km from the shore and in depths ranging from 5-120 m.

The fact that the mean monthly GSIs of female and male *P. dentex* in the lower west coast rose sharply between July and October and then declined precipitously through to January suggests that, in this region, the Silver Trevally spawns predominantly between August and December. This conclusion is substantiated by the fact that individuals of both sexes with stage V gonads were caught only between late winter and early summer. Furthermore, as the GSIs and prevalence of fish with stage V gonads were the greatest by far in September to November, spawning presumably peaked during these spring months.

In comparison to the situation on the lower west coast, the mean monthly GSIs started to rise one month earlier, *i.e.* in July, and did not subsequently show such a strongly defined peak. Furthermore, fish with stage V gonads were also found in July, and thus one month earlier than on the lower west coast. This strongly indicates that, on the upper west coast, spawning commences one month earlier and that the spawning period is more protracted. This earlier commencement and longer duration of the spawning period in the lower latitude parallels the situation recorded for *Sillago schomburgkii* in Western Australia (Coulson *et al*. 2005). It also parallels that found with other species of teleosts that are distributed over a wide latitudinal range, *e.g.* the Atlantic Silverside *Menidia menidia* (Conover, 1992) and the Killifish *Fundulus heterclitus* (Kneib, 1986). *Pseudocaranx dentex* is reported as spawning in spring and summer elsewhere in Australia and this can extend into autumn in South Australia, *i.e.* at higher latitudes than in Western Australia and New South Wales (Shuntov, 1969; James, 1984; Kalish and Johnston, 1997; Rowling and Raines, 2000).

The shorter duration of the spawning period on the lower west than upper west coast is accompanied by lower mean monthly GSIs in the middle months of that spawning period. This parallels the situation recorded for the Atlantic Silverside *Menidia menidia* in North America, in which the maximum GSIs of the populations in the north are approximately twice those in more southern and warmer locations (Conover, 1992). It has been proposed that in, conspecific populations, the greater GSIs in the higher than lower latitudes reflects a greater investment of energy into reproductive output at the time of peak spawning, which thus compensates for the possession of a shorter spawning period (Conover, 1992).

It is also relevant that, during the main part of the spawning season in both regions, the GSIs of males exceeded those of females. From the results of studies on other species, this suggests that *P. dentex* is a broadcast spawner, in which it would be advantageous for the males to produce particularly large numbers of sperm to optimize the chances of fertilization occurring when the males and females do not form a close pairing at the time of sperm and egg release (Wootton, 1990; Taborsky, 1998). Such a situation is often found in species that form schools at spawning time, as probably occurs with *P. dentex* (D. Lear, commercial fisher, pers. comm.).

It is relevant that previtellogenic, cortical alveolar and yolk-granule oocytes stages were all found in the ovaries of mature (stage V) ovaries of *P. dentex* and that each of these oocyte stages were often present, together with migratory nuclear stage oocytes or post-ovulatory follicles (late stage V and stage VI), in the ovaries of some fish that were either in spawning condition or had just released eggs, but were not fully spent. This implies that this species has indeterminate fecundity, *i.e.* the annual fecundity is not fixed prior to the commencement of the spawning season, and that it is a multiple spawner, *i.e.* releases more than one batch of eggs during a spawning season (de Vlaming, 1983; Hunter *et al*., 1985). As no female fish contained ovaries with hydrated oocytes, it was not possible to determine the batch fecundity for *P. dentex*.

### 4.4.5 Length at maturity

The $L_{50}$s at which female and male *P. dentex* were estimated as reaching sexual maturity in inshore waters on the lower west coast, *i.e.* 310 and 279 mm, respectively, were greater than the $L_{50}$s of 203 and 209 mm SL recorded for females and males, respectively (Kalish and Johnston, 1997) and of 228 mm TL for both sexes combined in

New South Wales (Rowling and Raines, 2000). However, the earlier attainment of maturity by *P. dentex* in eastern Australia may reflect a response to the severe growth over-fishing to which, on the basis of a recent marked decline in its mean lengths in commercial catches, it has been concluded that this species is being subjected (Tilzey, 2004). The length at first maturity has been found to have declined in heavily-exploited fish populations of several species (Beacham, 1983a,b; Bowering *et al*., 1996) and is assumed to reflect an increase in selection pressures for earlier maturation (Beacham, 1983a,b).

### 4.4.6 Mortality and management implications

The reader is referred to Chapter 3.4.8 for a detailed discussion of the problems that frequently arise in estimating mortality through using traditional empirical approaches based on life history traits. Particularly relevant in this regard is the fact that the estimate for natural mortality, $M$, often exceeds that of total mortality, $Z$, which is, of course, an erroneous result. Furthermore, even with the Bayesian approach of Hall *et al*. (2004), which ensures that $M$ is less than $Z$, an excessively high value for $M$ derived from Pauly's (1980) equation, which is used in this Bayesian approach, will result in a value for $M$ that is unrealistically close to $Z$. This, in turn, will tend to underestimate the extent of fishing mortality, $F$.

The above problems, which were found with Mulloway, are likewise found with Silver Trevally. Thus, the values of 0.59 and 0.75 year$^{-1}$, derived for $M$ from the refitted Pauly equation for the assemblages of *P. dentex* on the lower and upper west coasts, respectively, were both greater than the values for $Z$ derived using the refitted Hoenig equation, relative abundance analysis and simulation (Table 4.4). Moreover, when using the Bayesian approach of Hall *et al*. (2004), the value for $M$ was not markedly less than that for $Z$. Although fishing mortality on *P. dentex* was consequently estimated to be low, which may be the case, it has to be recognised that this latter value for $M$ would have been influenced by incorporating in its analysis the particularly high value for $M$ derived from Pauly's (1980) equation.

The considerable uncertainty regarding the precision of the estimates for $F$ for *P. dentex* means that managers need to adopt a cautionary approach when developing management plans for this species. This is justified on the grounds that, at least in south-eastern Australia, there is evidence that the stocks of this carangid have suffered from overfishing by commercial fishers (Tilzey, 2004). Although *P. dentex* is not fished heavily by commercial fishers in Western Australia, the *Pseudocaranx* complex, comprising mainly *P. dentex*, is the third most important recreational fish species in south-western Australia in terms of numbers of individuals caught (Sumner and Williamson, 1999) and the amount of recreational fishing is constantly increasing. Thus, as the minimum legal length (MLL) is about 60 mm less than the length of females at maturity, it would be highly appropriate for managers to consider increasing the MLL for Silver Trevally. In this context, it is relevant that *P. dentex* is a relatively hardy species and that, if handled carefully, the smaller individuals apparently survive both capture and release (D. French, pers. obs). The recent reductions of the maximum daily bag limit for *P. dentex* from 20 to 8 per individual (or 16 per boat) will help counteract the increasing pressure on this species from the rapidly expanding recreational fishing sector.

### 4.4.7 Yield per recruit and spawning potential ratio

Our analyses indicate that, when assuming the age at full vulnerability to the fishery for *P. dentex* is 5 – 6 years, the yield per recruit (YPR) for *P. dentex* in inshore waters on both the lower and upper west coasts will continue to increase as fishing mortality, $F$, increases from zero to a relatively high level, *i.e.* 1.5 year$^{-1}$. In other words, the YPR analyses indicate that growth overfishing of *P. dentex* in these two regions is unlikely to occur, even at a relatively high level of *F*. The apparent likelihood that growth overfishing will not occur reflects a combination of the rapid growth of *P. dentex* in the first few years of life and the assumption of this model of knife-edge recruitment to the exploited stock at 5 – 6 years of age. Consequently, in terms of weight, *P. dentex* is predicted to attain well over half its maximum weight before they become fully recruited into the fishery. Because the growth of *P. dentex* early in life is so rapid, this analysis predicts that the YPR would only decline if the age at full recruitment for this species is as low as 2 years or less. However, as the commercial catches and catch per unit effort of *P. dentex* in eastern Australia have declined (Tilzey, 2004), this species can presumably suffer from the effects of heavy fishing, *i.e.* may experience recruitment overfishing. Thus, caution must be exercised in drawing conclusions from the YPR analysis for *P. dentex* in this study.

In contrast to the YPR analysis, the spawning biomass per recruit (SSB/R) analysis determines whether fishing mortality is likely to lead to recruitment overfishing. Thus, it has been considered that if the SSB/R of a species falls below 30% of its original level, *i.e.* its spawning potential ratio (SPR) is < 0.3, the reproductive capacity (egg production) may be insufficient to sustain the population (Mace and Sissenwine, 1993; Goodyear, 1993). The SPR demonstrates that, as the assumed age at full recruitment to the fishery declines, the level of SPR declines more dramatically with respect to increasing fishing mortality. Thus, for example, if the ages at recruitment to the exploited stock are assumed to be 5 and 6 years, respectively, for the lower and upper west coasts, the SPR is not predicted to decline at even relatively high levels of *F* (1.5 year$^{-1}$). However, if the ages at recruitment in the two regions are assumed to be 2 and 3 years, respectively, the SPR is predicted to decline below the reference point of 0.3 if *F* is > 0.50 year$^{-1}$ in the region. Yet, it must be recognised that, because of the large uncertainty in the estimates of *F* for *P. dentex* (see Chapter 4.4.6), it was not possible to obtain precise estimates for the current levels of YPR and SSB/R. Consequently, it also was not possible to compare with confidence the levels of YPR and SSB/R against the appropriate reference points for these variables. Thus, in view of the progressive increase in recreational fishing pressure, it would be prudent for managers to consider increasing the MLL so that it at least approximates the length at first maturity, as was proposed in the previous section.

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## 6.0 BENEFITS

This study has the following major benefits.

1. Provision for the first time of sound quantitative data on crucial aspects of the biology of the Mulloway *Argyrosomus japonicus* and the Silver Trevally *Pseudocaranx dentex* in Western Australian waters.
2. This will enable fisheries managers, in consultation with stakeholders, to develop effective and appropriate strategies for managing and thus conserving the stocks of these two important recreational and commercial fish species in Western Australia.
3. The provision of baseline data on the current biological characteristics and levels of total mortality will enable fisheries managers to detect any changes that occur in these crucial fisheries parameters in the future.
4. The provision of sustainable stocks through robust management will ensure that recreational and commercial fishers will be able to continue to enjoy fishing for Mulloway and Silver Trevally.

## 7.0 FURTHER DEVELOPMENT

The full realization of the benefits that flow from the biological data produced on Mulloway and Silver Trevally during this study will depend on the acceptance of the results and their implications by fisheries managers, stakeholders and ultimately the Minister for Fisheries. Thus, once accepted by the FRDC, the final report will be provided to fisheries managers and scientists in the Department of Fisheries Western Australia so that they can fully assess those results and their implications. Such assessment will need to take into account a number of other issues, such as the need for ecologically sustainable development (ESD), integrated fisheries management (IFM) and recognition of the multi-species nature of the fisheries.

The report and a number of copies of the non-technical summary will be provided to authorities within the Western Australian Fishing Industry Council, Recfishwest and the Recreational Fishing Advisory Committee. Once those authorities have had a chance to read the report, they, and the recreational and commercial fishers who have shown an interest in the project will be invited to Murdoch University to clarify any points they wish to raise and to discuss the implications of the results.

The results of the various studies on Mulloway and Silver Trevally will be submitted for publication in high quality journals so that they will be subjected to international and peer group review. The feedback from the referees will facilitate the refinement of the approaches we are using to studying crucial aspects of the biology of important recreational and commercial fish species.

This study has highlighted the need to develop more reliable methods for determining natural mortality and thus be able to derive better estimates of fishing mortality and stock status from life history characteristics.

## 8.0 PLANNED OUTCOMES

The following planned outcomes outlined in B6 of the original project application have been achieved.

1. Produced data on the size and age compositions, growth rates, reproductive biology and mortality of the Mulloway and Silver Trevally for use by fisheries managers for conserving these species and underpinning future management decisions.
2. The ability for recreational and commercial fishers to understand the biological basis for the plans developed by managers to conserve the above species.
3. Clearly delineate between the habitats occupied by the Silver Trevally (*sensu stricto*) and the far smaller and less recreationally important Sand Trevally.
4. Human resource development in the form of students who have relieved training and experience in certain important aspects of fisheries science.

## 9.0 GENERAL CONCLUSIONS

We have met all of the numerous objectives listed in the original application for FRDC 2002/004, except for determining the batch fecundity for Mulloway and Silver Trevally. The inability to derive estimates for this variable were due to a paucity of freshly caught mature females with ovaries containing hydrated oocytes. However, it was possible to calculate indices of spawning biomass for both females and males from catch rates, age composition data and the maturity ogives developed for these species. Such an index may be used as a proxy of egg production when evaluating the effectiveness of alternative management strategies.

During this study, we investigated aspects of the biology of *Argyrosomus japonicus* and *Pseudocaranx dentex* in Western Australia. The major findings are as follows;

- The juveniles of *A. japonicus* typically occur in nearshore coastal waters (< 20 m deep), whereas its adults are found both in these waters and around reefs in offshore waters in depths up to at least 110 m.
- The juveniles of *P. dentex* are typically found in areas where there are structures, *e.g.* reefs, pillars etc., or patches of seagrass and/or detached macrophytes, whereas its adults typically occupy waters associated with reefs and generally in deeper water. The largest *P. dentex* were found in deep offshore waters.
- In contrast to *P. dentex*, *P. wrighti* is found mainly over sandy substrates.
- The females and males of *A. japonicus* attain maturity at a total length of *ca* 930 mm and 880 mm, respectively, which are typically reached at 5-6 years of age.
- The females of *P. dentex* become mature at *ca* 310 mm and 4 years of age, compared with *ca* 280 mm and 3 years of age with males.
- *Argyrosomus japonicus* spawns at night during late spring and summer and predominantly around nearshore coastal reefs. Some individuals of this species also spawn around structures in the lower Swan River Estuary.
- *Pseudocaranx dentex* spawns from late spring to early summer in coastal waters of the upper west coast and during spring in waters of the lower west coast.
- *Argyrosomus japonicus* and *P. dentex* are both serial spawners with indeterminate fecundity.
- The maximum total lengths and ages recorded for *A. japonicus* were 1437 mm and 31 years for their females and 1304 mm and 29 years for their males. At the completion of their second, fourth, sixth, tenth and twentieth years of life, females have attained, on average, lengths of *ca* 530, 805, 970, 1140 and 1230 mm, respectively, compared with *ca* 530, 790, 950, 1100 and 1180 mm, respectively, by their males.
- The maximum recorded total lengths of females and males of *P. dentex* in inshore waters < 60 m depth were *ca* 690 and 660 mm, respectively, and the maximum age of both sexes was 13 years. However, the maximum total length

and age in offshore waters > 60 m depth were far greater, *i.e.* 885 mm and 18 years of age.

- Females and males of *P. dentex* grow at similar rates and have attained lengths of *ca* 135, 270, 350 and 440 mm by the completion of their first, third, fifth and tenth years of life, respectively. In contrast, females in deeper water have already attained a length of 595 mm by the end of their tenth year of life. It is not clear at present whether the inshore and offshore assemblages are part of the same genetic stock.
- The current minimum legal length (MLL) for *A. japonicus* in Western Australia is 500 mm, which is attained during their second year of life and at least three years before typically reaching maturity. The substantial recruitment of this species into the fishery at an early stage in life will result in many individuals being caught before they have attained maturity.
- *Argyrosomus japonicus* is also very vulnerable because, even though undergoing substantial migrations, it forms large schools in the same and known locations during each spawning period and can thus be easily targeted by recreational and commercial fishers at this time. For example, recreational fishers target the spawning aggregations of this species in a region of the Swan River Estuary where there are numerous hard structures, *e.g.* boat wrecks, which simulate the reef habitat in marine waters where this species typically spawns.
- The $L_{50}$ at first maturity of female *P. dentex* is attained at a length of 60 mm greater than the current MLL of 250 mm and thus the females are exposed to one year of fishing mortality before they are able to spawn.
- In the case of both Mulloway and Silver Trevally, the estimates derived for natural mortality using the frequently-applied Pauly equation exceeded the estimates of total mortality calculated using life history characteristics and relative abundance (catch curve) analysis. This emphasises the crucial need to develop a new equation or approach for deriving a better estimate for natural mortality and thus to derive a reliable estimate of fishing mortality.
- The rapid decline of spawning potential ratio for Mulloway with increasing fishing mortality to levels that fall below a reference point of 30% implies that more robust management strategies to constrain further increases in fishing mortality for this species.

# 10.0 APPENDICES

## APPENDIX 1

### INTELLECTUAL PROPERTY

The value of the intellectual property will be 50.04% based on PART C of the FRDC project proposal.

### STAFF OF THE RESEARCH CENTRE

Prof. Ian Potter
Prof. Norm Hall
Dr Alex Hesp

### RESEARCH STUDENTS

Mr Bryn Farmer
Mr Daniel French
Mr Tim Carter