Biological parameters required for managing Western Blue Groper, Blue Morwong and Yellowtail Flathead

Coulson, P.G., Potter, I.C., Hesp, S.A. and Hall, N.G.

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Coulson, P.G.
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Hesp, S.A.
Hall, N.G.

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

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2004/057	Biological parameters required for managing Western Blue Groper, Blue Morwong and Yellowtail Flathead

PRINCIPAL INVESTIGATOR Professor Ian C. Potter
ADDRESS Centre for Fish and Fisheries Research
School of Biological Sciences and Biotechnology
Faculty of Sustainability, Environmental and Life Sciences
Murdoch University, South Street, Murdoch WA 6150
Ph: (08) 9239 8801 Fax: (08) 9360 6303

OBJECTIVES

1) Determine the size and age compositions, growth, reproduction and mortality of the Western Blue Groper *Achoerodus gouldii*, the Blue Morwong *Nemadactylus valenciennesi* and the Yellowtail Flathead *Platycephalus endrachtensis*.
2) Supply the above data to the Department of Fisheries, Western Australia, in a format that can readily be used for management purposes.
3) Use the results of the above studies to highlight the essential elements of age and growth studies that will produce data of the quality required for management.

NON-TECHNICAL SUMMARY

OUTCOMES ACHIEVED TO DATE

Fisheries managers will now have sound quantitative biological data for the Western Blue Groper, Blue Morwong and Yellowtail Flathead and detailed interpretations of their implications for management. They will thus be in a far stronger position to refine, in consultation with stakeholders, their ongoing plans for conserving the stocks of these important commercial and/or recreational fish species. Managers will also have been made aware that they will need to closely monitor the state of the stocks of Western Blue Groper as this species is close to or at full exploitation and possesses life cycle characteristics that make it particularly susceptible to overfishing. They will also be aware that the stocks of Blue Morwong and Yellowtail Flathead, which have been selected as indicator species for the fish faunas in the environments in which they are found, are apparently sustainable at their current levels of exploitation. The biological data now available for Western Blue Groper, Blue Morwong and Yellowtail Flathead are in a form and of a quality which, when incorporated in ecosystem-based models, will enhance the sophistication and reliability of the output of those models.

This study provides the sound quantitative data that are required by managers for developing plans for conserving the stocks of the Western Blue Groper *Achoerodus gouldii*, the Blue Morwong (previously Queen Snapper) *Nemadactylus valenciennesi* and the Yellowtail Flathead (previously Bar-tailed Flathead) *Platycephalus endrachtensis* in south-western Australian waters. The first two species are commercially and recreationally important in coastal waters and the third is one of the most important angling species in the Swan River Estuary. All three species have been identified by managers as requiring detailed studies of their biology, and Blue Morwong and Yellowtail Flathead are among a small suite of species selected as indicator species for the status of fish populations in marine and estuarine waters, respectively, in south-western Australia.

As juveniles, Western Blue Groper typically occupy reef areas in protected inshore waters along the coast and around neighbouring islands. As the individuals of this species increase in size, they move offshore to deeper and more exposed waters over reefs. Spawning occurs in the latter environment, between early winter and mid-spring.

The maximum length and age we recorded for Western Blue Groper were 1162 mm and 70 years, respectively, the latter age being the greatest by far yet recorded for any species of wrasse. However, most of the growth of this species occurs in the first 20 years of life. The Western Blue Groper is shown to be a monandric protogynous hermaphrodite, namely all of its individuals begin life as females and, after maturing, many subsequently change sex to males. Females typically first become mature at about 650 mm and 15-20 years and typically change to males at lengths of about 800-850 mm and ages of about 35-39 years. As sex change takes place over a narrower range in lengths (650 to 900 mm) than in ages (15 to 49 years), that change is apparently related more to size than age. The fact that sex change is typically accompanied by a change in body colour from green to blue can be used to determine the approximate size at which females change to males, without having to cut open the fish to determine whether it possesses ovaries or testes. Growth curves fitted to the lengths at age of individuals of each sex of this hermaphroditic species using a novel technique demonstrated that, with increasing age, the lengths of males became increasingly greater than those of females. Thus, at ages 15, 30 and 60 years, the "average" lengths of females were approximately 600, 670 and 680 mm, respectively, those of males were approximately 695, 895 and 975 mm, respectively.

As the Western Blue Groper is very long-lived and maturity and particularly sex change occur late, it is potentially very susceptible to overfishing. Thus, because the mortality estimates and per recruit analyses indicate that, at present, this species is close to or fully exploited, fisheries managers will need to take a precautionary and watchful approach to managing and thus conserving the stocks of this species.

As with Western Blue Groper, the Blue Morwong moves to deeper, offshore waters as it increases in size and then matures and spawns in those waters. Although Blue Morwong has a maximum length of close to 1 m and thus, like Western Blue Groper, is a moderately large fish species, it has a far shorter life span, namely 21 years compared with 70 years. While female Blue Morwong do not grow to as large a size as their males (max. lengths = 846 and 984 mm, respectively), the maximum age of both sexes was 21 years. From the growth curves, the average lengths attained by ages 3, 6 and 10 years were 435, 587 and 662 mm, respectively, for females, compared with 446, 633 and 752 mm, respectively, for males. Both sexes exhibited little growth after 10 years of age.

Juveniles of Blue Morwong less than 400 mm in total length were found exclusively in shallow, coastal waters on the south coast, whereas their adults were abundant in offshore waters of both the south and lower west coasts. The lengths and ages at which females and males typically mature in offshore waters of the south coast were about 600-800 mm and about 7-9 years. In contrast, the vast majority of females caught in offshore waters of the lower west coast (where they were of a similar length and age range to those in offshore waters on the south coast) became mature at lengths of 400-600 mm and 3-4 years of age. The attainment of maturity by Blue Morwong at far lesser lengths and ages on the lower west coast than south coast suggests that the former coast provides better environmental conditions for gonadal maturation and spawning. Furthermore, the contrast between the almost total absence of the juveniles of Blue Morwong in nearshore waters on the lower west coast and their substantial numbers in comparable waters on the south coast indicates that the larvae of this species produced on the lower west coast are transported southwards to the south coast, where they become juveniles. As spawning occurs between mid-summer and late autumn, the larvae, which spend a protracted period in the plankton, would be exposed, on the lower west coast, to the influence of the southwards-flowing Leeuwin Current at the time when that current is strongest.

Although Blue Morwong is caught by recreational line fishing and commercial gillnet fishing when they are as young as 3-4 years, they do not become fully vulnerable to these fisheries until they are about 9 years old. Consequently, the individuals of this species can potentially breed over a number of years before they become particularly prone to capture by fishers. Mortality estimates and per recruit analyses suggest that the Blue Morwong in south-western Australia is currently not overfished. A greater resilience to fishing by Blue Morwong than Western Blue Groper reflects, in part, its shorter lifespan, gonochorism (namely, it is not hermaphroditic) and early maturity.

The Yellowtail Flathead spawns in the Swan River Estuary between late spring and early autumn and completes the whole of its life cycle in this system. Although its females attain a far larger length (615 mm) than its males (374 mm), this species, unlike some of its relatives, is not a protandrous hermaphrodite, namely, it does not change from male to female with increasing body size. As the maximum age of both sexes is eight years, the far greater length attained by females is largely related to the far faster growth of that sex. Females outnumbered males in each age class in which the sample size exceeded 25, with the overall sex ratio being 2.7 females: 1 male. As the minimum legal length for retention of Yellowtail Flathead is 300 mm, and relatively few males exceed this length, the recreational fishery which targets this species is largely based on its females.

The estimates of mortality and results of the per recruit analyses provided no evidence that the Yellowtail Flathead is currently overfished. From a management point of view, it is advantageous that the current size limit for Yellowtail Flathead exceeds the average length at which its females (259 mm) attain maturity. Furthermore, this species appears to be resilient to capture and release.

The biological data provided in this study will be very useful for the ongoing development of management policies for three important commercial and/or recreational species in south-western Australian waters and will alert managers to the need to monitor closely the status of Western Blue Groper.

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1.0 INTRODUCTION

1.1 BACKGROUND

The Western Blue Groper *Achoerodus gouldii*, the Blue Morwong *Nemadactylus valenciennesi* (previously Queen Snapper) and the Yellowtail Flathead (previously Bar-tailed Flathead) *Platycephalus endrachtensis* are important recreational fish species in Western Australia, and the first two also contribute *c.* 74 tonnes annually to the overall commercial scalefish catch of this state (Fletcher and Head, 2006). The first two species are among the five scalefish species that are targeted most heavily by boat fishers on the south coast of Western Australia (Anon., 2000). More recently, Western Blue Groper and Blue Morwong have been recognised as key south coast recreational species for which biological data are required (Anon., 2003). In addition, the Blue Morwong and Yellowtail Flathead are both listed among a small suite of species that are considered indicator species for offshore and estuarine waters on the lower west coast of Australia, respectively, and the flathead is listed as a priority species for research (Harrison, 2001).

The Western Blue Groper is "reasonably common on coastal reefs of South Australia and southern Western Australia but are generally found in lower numbers in the more accessible areas due to higher fishing pressures" (Hutchins and Swainston, 1986). The susceptibility of the only other member of the genus, the Eastern Blue Groper *Achoerodus viridis*, to even moderate fishing pressure led, in 1969, to a moratorium being placed on the use of spear fishing to catch that species in New South Wales and, in 1980, also to a ban of their sale (Australian Museum, Eastern Blue Groper, *Achoerodus viridis*). Blue Gropers have been described as "highly vulnerable to overexploitation", presumably on the basis that they are likely to be long-lived and slow growing and may be site-associated (Shepherd *et al.*, 2002). The Blue Morwong, which is likely to possess similar life history characteristics in terms of growth and longevity and site-association, is also considered to be a threatened, territorial reef species (Department of the Environment and Heritage, Coast Care Week Fact Sheet). Since the Yellowtail Flathead can complete its life cycle in estuaries (Potter and Hyndes, 1999), it will be particularly prone to fishing pressure.

Despite the recognised importance of the above three species in Western Australia, there are no detailed biological data on any of these species. A preliminary study of the growth of Western Blue Groper was undertaken using ages based on the number of circuli in scales, without having validated that those circuli are formed annually (Shepherd *et al.*, 2002). As the use of scales often yields inaccurate estimates of age (Beamish and McFarlane, 1987; Casselman, 1987; Campana, 2001), the ageing data obtained for this large and potentially long-lived species may well be erroneous. Dr Keith Jones of the South Australian Research Development Institute (SARDI) has informed us that he would welcome reliable information on the biology of the Western Blue Groper and Blue Morwong, whose distributions extend throughout the coastal waters of South Australia. Although there is a considerable body of biological data for the Eastern Blue Groper (*e.g.* Gillanders 1995a, b, 1997a, b), it would be inappropriate to consider that these data are applicable to the Western Blue Groper. The very considerable differences in biology that can exist between congeneric species, even when they occur in the same environment, is very well illustrated by the marked differences in the biology of five other labrid species that belong to the genus *Choerodon* (Fairclough *et al.*, 2004). Furthermore, the absence of data on the reproductive biology of the Western Blue Groper is of particular concern because this species is likely be a protogynous hermaphrodite, *i.e.* individuals begin life as females and at least some later change sex to males. Our recent work on the yellowfin bream *Acanthopagrus latus* emphasised the importance of determining the sizes over which the individuals of this protandrous (male to female) hermaphroditic species change sex (Fairclough *et al.*, 2004). That study demonstrated that the minimum legal length for this species was equivalent to an age that was about three years less than that at which it would typically change sex, a finding which had important implications for developing plans for conserving that species. Essential information required for Western Blue Groper, Blue Morwong and Yellowtail Flathead include their age and size compositions, growth curves and a range of aspects of their reproductive biology, *e.g.* time, location and mode of spawning, size and age at maturity and fecundity. In the case of Western Blue Groper, such requirements would also include specific details of the characteristics of its presumed hermaphroditism and, in particular, the lengths and ages over which it changes sex.

The almost total lack of the types of biological data that are required for developing informed management plans for conserving Western Blue Groper, Blue Morwong and Yellowtail Flathead stocks clearly demonstrates that, by necessity, the bag and minimum size limits for these species were not able to have been based on sound biological criteria. There is thus no reason for assuming that the current regulations will be sufficient to sustain the stocks of these species. The results of the proposed study will provide definitive data that will allow future size regulations to be based on a knowledge of the biology of those species.

An examination of growth curve parameters derived for a wide range of fish species in the papers published in several high-quality international journals during the last four years revealed that these curves did not provide a good description of the growth throughout the full life of about half of those species. The growth parameters provided in the literature are often of limited value because the growth curves do not reflect the true pattern of growth of those species. For example, the estimated age at which a species has zero length is often highly negative, an anomaly that either represents errors in ageing or, more typically, unrepresentation within the sample of the lengths at age for small fish or the slow growing individuals of the younger age classes. In addition, a von Bertalanffy growth curve fitted to the observed lengths at age often yields an underestimate of the asymptotic length. Unreliable values for either the theoretical age at which a fish has zero length or the asymptotic length will inevitably lead to unreliable values for the growth coefficient *k*. Since von Bertalanffy growth parameters are often used for estimating mortality which, in turn are used for assessing the status of fish stocks, erroneous values for those parameters will lead to erroneous conclusions regarding the state of the stock and thus ultimately to inappropriate management decisions. The variable quality of age and growth studies demonstrates that research workers in this area need to be fully aware of the necessity of producing sound age and growth data for management purposes. Moreover, if the very widely-used von Bertalanffy growth curve provides inaccurate parameters, research workers should consider using an alternative growth curve, such as has been employed in Western Australia for describing the growth of shark and ray species (White *et al.*, 2002a, b).

This project was developed to meet the specific needs identified by Harrison (2001) and Anon. (2003) and for identifying the criteria that should be taken into account when fitting growth curves to length-at-age data. Details of the data required from this project have been discussed with Frank Prokop, the Executive Director of RecFishWest and with Dr Rod Lenanton, the then Supervising Scientist for finfish research at the Department of Fisheries, Western Australia. Subsequent to the initial submission, the FRDC requested that the application should be revised to address a number of specific points, which has been done. The project was endorsed in writing by Prof Peter Rogers, the then Executive Director, Department of Fisheries, Western Australia.

1.2 NEED

Successful management of a fishery for any species requires a thorough understanding of how that species will respond to different levels of exploitation. Such an understanding depends on managers possessing certain crucial biological data that have been acquired using an appropriate sampling regime, laboratory techniques and analysis of the results. The key biological data that are required for a species are as follows: a) age and size compositions, growth curves and age and length at maturity of both sexes, b) length and age at sex change in the case of hermaphroditic species, c) location and duration of spawning, d) fecundity and e) estimates of mortality. These data enable scientists to assess the status of the stock(s) and thereby enable them to provide advice to managers, who are then in a strong position to formulate appropriate management strategies.

The following three species have been identified as “indicator” species for management purposes: the Western Blue Groper *Achoerodus gouldii*, the Blue Morwong *Nemadactylus valenciennesi* and the Yellowtail Flathead *Platycephalus endrachtensis* (Fisheries Management Paper 153; Report of 2003 RFAC/RecFishWest research planning meeting). However, there are no reliable data on the crucial biological characteristics listed above for any of these species in Western Australian waters and which are required for management purposes.

Since the results of many of the age and growth studies of fish species in various regions are not of the requisite standard to produce reliable data for management purposes, these is a need to produce guidelines for the quality that are required by such studies for management purposes.

1.3 OBJECTIVES

1) Determine the size and age compositions, growth, reproduction and mortality of the Western Blue Groper *Achoerodus gouldii*, the Blue Morwong *Nemadactylus valenciennesi* and the Yellowtail Flathead *Platycephalus endrachtensis*.

2) Supply the above data to the Department of Fisheries, Western Australia, in a format that can readily be used for management purposes.

3) Use the results of the above studies to highlight the essential elements of age and growth studies that will produce data of the required quality for management.

2.0 GENERAL MATERIALS AND METHODS

2.1 SAMPLING

Achoerodus gouldii and *Nemadactylus valenciennesi* were collected from coastal waters off the lower west and south coasts of Western Australia, while *Platycephalus endrachtensis* was obtained from the Swan River Estuary on the lower west coast of Australia. Details of the sampling regime and aspects of the biology relevant only to one of the species are given in the subsequent chapters that deal individually with each species.

Offshore sea surface temperatures (SST) were derived from NOAA-AVHRR satellite imagery, complemented by surface temperatures recorded by shipping and drifting buoys since 1982 (Reynolds and Smith 1994). SSTs for each 1° latitude/ longitude grid square for offshore waters from Perth, Albany and Esperance were taken from the grid squares 31°S to 32°S and 115°E to 116°E, 34°S to 35°S and 118°E to 119°E and 34°S to 35°S and 122°E to 123°E, respectively. The corresponding monthly SSTs for 2004, 2005 and 2006 were averaged. Water temperatures for some months in inshore waters at Albany and Esperance during the current study were limited. Thus, the water temperatures recorded at irregular intervals over a longer period, *i.e.* 1994 to 2006, by the Department of Fisheries, Western Australia were pooled and the average for each calendar month calculated.

The water temperature and salinity at each site in the Swan River Estuary on each sampling occasion were recorded to the nearest 0.1ºC and 0.1, respectively, using a Yellow Springs Instruments YSI-30 salinity and conductivity metre.

2.2 LENGTH AND WEIGHT MEASUREMENTS

Each fish was sexed when its gonad could be identified macroscopically as an ovary or testis. The total length (*TL*) and wet weight (*W*), and also the wet weight of the gonad when the sex could be determined, were recorded to the nearest 1 mm, 0.1 and 0.01 g, respectively, for each individual of each species. The *TL vs W* relationships for the females and males of each species were compared using analysis of covariance (ANCOVA) and employing the natural logarithm of weight as the dependent variable, sex as the fixed factor and the natural logarithm of length as the covariate. The relationship between *W* and *TL* was used, in the case of each species, to estimate the weights of filleted fish that had been collected from fish processors and recreational fishers and had not been weighed.

2.3 AGE DETERMINATION AND GROWTH

One of the sagittal otoliths of each individual of each of the three species was embedded in clear epoxy resin and cut transversely through its primordium into *c.* 0.3 mm sections using an Isomet Buehler low-speed diamond saw. The sections were polished on wet and dry carborundum paper (grade 1200) and mounted on microscope slides using DePX mounting adhesive and a cover slip. Images of each sectioned otolith were photographed under transmitted light using a Olympus DP70 camera mounted on an Olympus BX51 compound microscope.

Validation that a single opaque zone is formed annually in the otoliths of each species was carried out using marginal increment analysis. The marginal increment, *i.e.* the distance between the outer edge of the single or outermost opaque zone and the outer edge of the otolith, was expressed as a proportion of the distance between the primordium and the outer edge of the single opaque zone, when only one such zone was present, or as the distance between the outer edges of the two outermost opaque zones when two or more opaque zones were present. All measurements, which were made perpendicular to the opaque zones on the anterior surface adjacent to the sulcus, were recorded to the nearest 0.01 mm employing the imaging package Leica Image Manager 1000 (Leica Microsystems Ltd. 2001). The marginal increments for the corresponding months of the different years were pooled for the various groups of otoliths, which were categorised on the basis of the numbers of their opaque zones, to calculate the mean monthly marginal increments and their standard errors for each of those groups.

Leica Image Manager 1000 was used by the first author to count the opaque zones in an image of each sectioned otolith on two occasions, and also on a third occasion if the first two counts were not the same. In the latter situation, two of the three counts were the same in 100% of *N. valenciennesi* and *P. endrachtensis* and in 91.0% of *A. gouldii* with otoliths containing ≤ 20 opaque zones and 70.4% for otoliths of that species with > 20 opaque zones. For each otolith for which two or three of the counts were the same, those were the counts that were used for ageing, whereas, in those cases where all three counts were different, the last of those was used for ageing. All counts of the opaque zones were made in the region adjacent to the sulcus of the otolith and on the anterior surface of otoliths with *A. gouldii* and *N. valenciennesi* and on the posterior surface of otoliths with *P. endrachtensis*.

The level of precision of the independent counts of opaque zones by two readers (P. G. Coulson and S. A. Hesp) for a subsample of otoliths from 150 *A. gouldii* and 100 of both *N. valenciennesi* and *P. endrachtensis* that, for each species, covered a wide size range, were assessed using the coefficient of variation (CV) (Chang, 1982; Campana, 2001). The equation is $CV_j = 100\% \left\{ \frac{\sqrt{\sum_{i=1}^{R} \frac{(X_{ij} - X_j)^2}{R-1}}}{X_j} \right\}$, where CV_j is the age precision estimate for the *j*th fish, X_{ij} is the *i*th age determination of the *j*th fish, X_j is the mean age estimate of the *j*th fish, and *R* is the number of time each fish is aged. The average values of CV_j across the 150 *A. gouldii* and 100 *N. valenciennesi* and *P. endrachtensis* were 2.2, 4.1 and 5.7, respectively.

Each fish was assigned an age based on the number of opaque zones in its otoliths, but taking into account the timing of delineation of those zones, the date of capture of the fish and the estimated average birth date for the members of the population. The dates of birth assigned to *A. gouldii*, *N. valenciennesi* and *P. endrachtensis*, which were taken as the approximate mid-point of the spawning period for each species, were 1 August, 1 March and 1 January, respectively (see Results in relevant chapters).

von Bertalanffy growth curves were fitted to the lengths at age of the females and males of *N. valenciennesi* and *P. endrachtensis* using SPSS Inc. (2001). The von Bertalanffy growth equation is $L_t = L_\infty\left(1-\exp\left(-k\left(t-t_0\right)\right)\right)$, where L_t is the length (mm *TL*) at age *t* (years), L_∞ is the asymptotic length (mm) predicted by the equation, *k* is the growth coefficient (year^{-1}) and t_0 is the hypothetical age (years) at which fish would have zero length.

Although the sex of *P. endrachtensis* > 100 mm (*TL*) during the spawning period could be determined macroscopically, this could not be achieved with fish caught outside the spawning period until they had reached a length of *c*. 150 mm. The lengths at age of these individuals whose sex could not be determined were allocated alternately to the female and male *P. endrachtensis* data sets used for calculating the von Bertalanffy growth curves.

In the case of *A. gouldii*, von Bertalanffy growth curves were fitted, using Microsoft Excel$^{\text{TM}}$, to the lengths at age of (a) all individuals irrespective of their sex, (b) females and males that had been sexed on the basis of gonadal type and (c) individuals that were green and blue among individuals used for (b). von Bertalanffy growth curves for each sex were next fitted to (d) the combination of the lengths at age of sexed and unsexed individuals, where the latter group comprised those fish for which the colour had been recorded from the logistic equation relating the sex of individuals to their lengths and colours (see later). See section 3.2 for further details for the treatment of ageing data for *A. gouldii*.

A likelihood-ratio test was used to compare the growth curves of the two sexes of *N. valenciennesi* and *P. endrachtensis* and of *A. gouldii* and *N. valenciennesi* in different regions. When comparing the growth curves of the two sexes or different assemblages, the difference between the log-likelihoods obtained by fitting a common growth curve to the data for the two groups and by fitting separate growth curves for each group was calculated, and the resultant value multiplied by two. The hypothesis that the growth of the two groups could appropriately be represented by a single growth curve was rejected at the $\alpha = 0.05$ level of significance if the above test statistic exceeded $\chi^2_\alpha(q)$, where q is the difference between the numbers of parameters in the two approaches, *i.e.* 3 (Cerrato, 1990). The log-likelihood, λ, for each curve, ignoring constants, was calculated as $\lambda = -(n/2)\ln(ss/n)$, where n refers to the sample size and ss refers to the sum of the squared residuals between the observed and expected lengths at age.

2.4 REPRODUCTIVE VARIABLES

On the basis of their macroscopic characteristics, the gonads of each fish that could be sexed were allocated to one of eight maturity stages, *i.e.* I/II = virgin and immature/resting; III = developing; IV = maturing; V = prespawning; VI = spawning; VII = spent and VIII = recovering, which were adapted from the criteria used by Laevastu (1965). Due to a lack of *A. gouldii* with gonads at stages III and IV, these stages were combined and termed developing. The characteristics of each macroscopic and corresponding histological stage in the development of the ovaries of *A. gouldii*, *N. valenciennesi* and *P. endrachtensis* are presented in Table 2.1. Mean monthly gonadosomatic indices (GSIs) for the females of *A. gouldii* and of both sexes of *N. valenciennesi* and *P. endrachtensis* were calculated using the equation GSI = W_1/W_2 x 100, where W_1 = wet gonad weight and W_2 = wet body weight and employing fish with lengths ≥ their respective L_{50}s at maturity (see Results in relevant chapters). In each month of sampling, gonads from a subsample of the females and males of each species and which encompassed all gonad stages recorded in that month were placed in Bouin's fixative for 24 to 48h. The gonads were dehydrated in a series of increasing concentrations of ethanol and their mid-regions embedded in paraffin wax and then cut into 6 µm transverse sections and stained with Mallory's trichrome. The sections were examined using a compound microscope to (1) ensure that the ovaries were assigned to their appropriate macroscopic stages of maturity, (2) determine whether each of these species had determinate or indeterminate fecundity and (3) elucidate whether *A. gouldii* and *P. endrachtensis* are hermaphroditic.

The lengths at which 50% of the females of *A. gouldii* and 50% of both the females and males of *N. valenciennesi* and *P. endrachtensis* attained maturity (L_{50}) were determined by fitting logistic curves to the probability that, during the spawning period, a female fish at a specific length would possess gonads at one of stages III to VIII. As such, fish were potentially destined to become mature or had reached maturity during that period, they are, for convenience, subsequently referred to as mature (see Results). The form of the logistic equation used for this analysis is $P = 1/\{1+\exp[-\log_e(19)(L-L_{50})/(L_{95}-L_{50})]\}$, where P = proportion mature, L = total length in mm, and L_{50} and L_{95} = the length in mm at which 50 and 95% of fish were mature, respectively. On the basis of its length, the likelihood of the jth fish possessing or not possessing gonads at stage ≥ III was calculated

Table 2.1. Description of the macroscopic stages in the development of the ovaries of female *Achoerodus gouldii*, *Nemadactylus valenciennesi* and *Platycephalus endrachtensis* and of the corresponding histological characteristics. Macroscopic stages are adapted from Laevastu (1965), while oocyte stages follow the terminology used by Wallace and Selman (1981).

Stage	Macroscopic characteristics	Histological characteristics
I/II – *Virgin* and *Immature/resting*	Gonad transparent and strand-like. Very difficult to differentiate between ovaries and testes (flathead). Ovary pink, very short and fat (groper). Ovaries pink with fine capillaries and often surrounded by fat (morwong).	Oogonia, chromatin nucleoloar and perinucleolar oocytes present. Oocytes neatly aligned along ovarian lamellae. Previtellogenic oocytes present in all subsequent stages of maturation.
III – *Developing*	Ovary occupies approximately ¼ of body cavity. Capillaries conspicuous on ovarian wall.	Cortical alveolar oocytes abundant. Yolk granule oocytes. absent.
IV – *Maturing*	Orange to yellow ovary, containing numerous yolked eggs visible to the naked eye, occupying about $^1/_3$ of body cavity.	Cortical alveolar and yolk granule oocytes abundant.
V – *Prespawning*	Orange. Large, tightly packed yellow eggs clearly visible through ovarian wall. Occupy about ½ of body cavity. Thick, red capillaries on ovarian walls.	Yolk granule oocytes dominate complement of larger oocytes. Migratory nucleus oocytes, hydrated oocytes and post-ovulatory follicles not present.
VI - *Spawning*	Similar size to stage V. Orange to red colour. Translucent hydrated oocytes and yellow yolk granule oocytes visible through ovarian wall. If caught close to spawning there may be a translucent region down the centre of both lobes where the hydrated oocytes have collected prior to release. Red, thick capillaries.	Cortical alveolar oocytes and yolk granule oocytes present along with either hydrated oocytes, migratory nucleus oocytes and post-ovulatory follicles.
VII - *Spent*	Dark red, flat and flaccid ovary with few remnant eggs visible through ovarian wall. Very similar to stage III in size. Capillaries reduced to thin lines. Very thick, tough, opaque ovarian wall (morwong)	Greater than 50% of yolked oocytes atreatic.
VIII - R*ecovering*	Ovary dark red/purple, occupying less than $^1/_4$ of body cavity. Round in cross-section.	Ovary disorganised, containing consisting of previtellogenic oocytes and connective tissue.

as *Pj* or 1-*Pj*, respectively. Setting *Xj* = 0, if the *jth* fish did not possess gonads at stage ≥ III, and *Xj* = 1, if it did possess such gonads, the overall log-likelihood was calculated as $\sum_j \left\{ X_j \log_e P_j + \left(1 - X_j\right) \ln\left(1 - P_j\right) \right\}$. The logistic equation was fitted using Markov Chain Monte Carlo simulation in WinBUGS (from 500,000 iterations, discarding the first 1,000 iterations as the initial burn in set and using a thinning interval of 100). After assessment in WinBUGS that convergence was likely to have been achieved, the point estimates and associated 95% confidence intervals of the parameters of the logistic equation, and of the probabilities of fish being mature at a range of specified lengths, were determined as the medians and the 2.5 and 97.5 percentiles of the estimates produced by WinBUGS.

2.5 FECUNDITY

To ascertain whether each of *A. gouldii*, *N. valenciennesi* and *P. endrachtensis* has determinate or indeterminate fecundity *sensu* Hunter and Macewicz (1985) and Hunter *et al.* (1985), the distribution of the diameters of 100 randomly-selected oocytes in histological sections of stage V ovaries of each of two females of each species were plotted. A fish species with determinate fecundity is one in which the total fecundity during an annual spawning period is determined prior to the onset of that period, whereas a fish species with indeterminate fecundity is one in which this is not the case. The diameter of each oocyte was derived from measurements of the circumference of that oocyte to the nearest 0.01 µm made using the computer imaging package Leica IM 1000 (Leica Microsystems Ltd. 2001). Note that measurements were restricted to oocytes in which the nucleus was clearly visible to ensure that the oocyte had been sectioned through its centre and that the stage in the development of each oocyte was recorded, *i.e.* early previtellogenic, cortical alveolar or yolk granule oocyte.

For determining the fecundity of *A. gouldii*, *N. valenciennesi* and *P. endrachtensis*, each of the two ovarian lobes of females with stage VI ovaries, which contained hydrated oocytes scattered throughout the ovary, was weighed to the nearest 0.1g. One of these ovarian lobes was preserved in 10% neutrally buffered formalin and used for calculating batch fecundity. The other lobe was preserved in Bouin's fixative and prepared, sectioned and stained in the same way as described earlier. The resultant histological sections were then used to confirm that 1) no newly-formed post-ovulatory follicles were present, 2) hydrated oocytes were not concentrated in the ovarian duct (*i.e.* ovulation had not occurred recently) and 3) yolked oocytes were not undergoing massive (> 50%) atresia. In other words, the number of hydrated oocytes in the ovaries of a female represented the true batch fecundity for that individual at the time of its capture. Note that most stage VI ovaries of the three species could not be used for fecundity estimates as the majority of fish with such ovaries had been frozen following capture by commercial fishers and were thus not suitable for processing for fecundity estimates.

The ovarian lobes that had been preserved in 10% neutrally buffered formalin were blotted dry with paper towel and weighed to the nearest 1 mg. Approximately 75-100 mg of tissue was then removed from the anterior, middle and posterior regions of each ovary and weighed to the nearest 0.001 mg. The ovarian tissue was placed in Petri dishes and covered in 100% glycerol. The tissue was teased apart under a dissecting microscope using probes and its number of hydrated oocytes recorded. The number of hydrated oocytes in each of the three regions of the ovarian lobe that was processed from a fish was then used, in conjunction with their weights and that of the other lobe of the ovary, to estimate the total number of hydrated oocytes (batch fecundity) in the ovaries of that fish.

2.6 ESTIMATES OF MORTALITY

The total mortality, Z, for *A. gouldii*, *N. valenciennesi* and *P. endrachtensis* were estimated by fitting catch curves simultaneously to the age composition data for the different years for each of those species, assuming that this mortality and annual recruitment were constant. In the case of *A. gouldii*, it also employed relative abundance analysis, which is an extension of catch curve analysis (Deriso *et al.*, 1985) and allows for the possibility that annual recruitment is variable. The analyses for the first two species used data obtained from the commercial gillnet fishery on the lower west and south coasts, while those for *P. endrachtensis* employed data obtained from recreational rod and line, commercial gillnet and research seine net fishing in the Swan River Estuary. The analyses for each species (except *N. valenciennesi*, see later) assumed knife edge recruitment into the fishery, and were therefore restricted to data for the descending limbs of the catch curves (Ricker, 1975). Total mortality was estimated for both sexes combined in the case of the protogynous *A. gouldii* and the gonochoristic *N. valenciennesi*, for which the lengths attained by the two sexes were not markedly different. However, as the females of *P. endrachtensis* grew to a far greater size than their males, and the fishery for this species is largely based on the former sex (see later), Z was estimated only for females.

For a fish stock that experiences a constant level of Z from the age of full recruitment, $a = t_c$ years, the estimated proportion $\hat{P}_{a,t}$ at age a in year t is

$$\hat{P}_{a,t} = \frac{R_{t-a}\exp\left[-(a-t_c)Z\right]}{\sum_{j=t_c}^{A} R_{t-j}\exp\left[-(j-t_c)Z\right]}$$

, where A is the maximum observed age. It is assumed that the age composition of fish with ages $t_c \le a \le A$ observed in year t represents a random sample from a multinomial distribution with uniform selectivity from the age of full recruitment and thereby overcomes the problem of applying a log transformation to the frequencies for older age classes with zero fish. Thus, ignoring constants, the log-likelihood λ of the age compositions observed in the various years may be calculated as, $\lambda = \sum_{t} \sum_{a=t_c}^{A} n_{a,t} \log\left[\hat{P}_{a,t}\right]$, where $n_{a,t}$ is the observed number of fish of age a in year t. Microsoft Excel™ was used to estimate Z for each of the three species by maximizing the log-likelihood, with the assumption that recruitment was constant.

For estimating Z for *A. gouldii*, when assuming variable recruitment, the average level of recruitment for each of the different year classes was initially set to a value of 1. The relative levels of recruitment of the different year classes were then, one by one, successively introduced as additional parameters to be estimated by the model, which involved estimating Z and a relative level of recruitment, R_y, for each candidate year class, y, in Microsoft Excel. The resulting log-likelihoods associated with these year classes were compared and the year class that produced the greatest increase in the log-likelihood was determined. A likelihood-ratio test was used to determine whether the difference between the log-likelihood after introducing the parameter R_y for this year class and that obtained prior to introducing the parameter was statistically significant (*e.g.* Cerrato,1990). If so, the parameter R_y for this year class was included as a parameter to be estimated in the model. This forward selection algorithm was then repeated, estimating Z and values of R_y for year classes already included in the model, to determine whether further year classes should be included (*e.g.* Sokal and Rohlf, 1995). The process was terminated when introduction of R_y as a parameter to be estimated for any further year class failed to produce a statistically significant improved fit of the model to the data, as determined using the likelihood-ratio test. At this stage, the relative levels of recruitment for year classes not included as parameters to be estimated in the model continued to be constrained to the average level.

In the case of *N. valenciennesi* and *P. endrachtensis*, the 95% confidence intervals for *Z* (determined assuming constant recruitment) were estimated through resampling, with replacement, *i.e.* bootstrapping. The age composition data for each species were randomly resampled to produce 1000 sets of bootstrap estimates for *Z*. The 95% confidence intervals were determined as the 2.5 and 97.5 percentiles of the corresponding estimated values. As it was not practical to use bootstrapping for estimating the 95% confidence intervals for *Z* for *A. gouldii*, when assuming variable recruitment, these intervals were obtained from the profile likelihood for *Z*, which was calculated using Microsoft Excel^{TM}. For consistency, the profile likelihood method (Hilborn and Mangel, 1997) was also used to estimate the 95% confidence intervals for *Z* for *A. gouldii* when assuming constant recruitment and fitting catch curves simultaneously to the age composition data for the different years.

The 95% confidence intervals for the natural mortality, *M*, of *A. gouldii*, *N. valenciennesi* and *P. endrachtensis*, as well as the point estimates, were obtained by including, for each species, the maximum recorded age for that species in the data set of Hoenig (1982) for the mortalities and maximum ages for 82 unexploited or lightly-exploited fish stocks. The data were then described using the form of the equation given by Hoenig (1983).

The approach of Hall *et al.* (2004) was used to determine, for *A. gouldii*, *N. valenciennesi* and *P. endrachtensis*, the likelihood for *M*, calculated using the likelihood for *Z*, as derived from the catch curve analysis. This estimation 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 using the method of Hoenig (1983).

A Monte Carlo resampling approach was used to derive estimates of *F* for fully-recruited age classes of each species. Estimates of *Z* and *M* were randomly resampled, with replacement, from their respective probability distributions. This involved combining, for each species, the estimate for Z from the catch curve or relative abundance analysis (derived assuming variable recruitment with *A. gouldii* and constant recruitment with *N. valenciennesi* and *P. endrachtensis*) and the value of M extracted using the Hall *et al.* (2004) approach. However, these estimates were rejected when the values for M were greater than those for Z. 10,000 sets of estimates of Z and M were produced, from which 10,000 estimates of F were 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 10,000 estimates derived from the resampling analysis.

The age compositions derived for *N. valenciennesi* from catches obtained by the recreational and commercial fishers in each year were pooled to produce a combined age composition that was assumed to represent the catches taken by each sector as a whole. The age compositions of the recreational and commercial fishing sectors were compared by expressing the observed frequency for each age class as a fraction of the total frequency of the fully-recruited fish in the pooled age-frequency data for that fishing sector and plotting the resulting values against age. Subsequently, an estimate of the relative number in the population at each age for fully-recruited fish, N_a, was calculated by multiplying the expected proportion at age by the total number of fully-recruited fish in the commercial sample, *i.e.* those fish with ages $t_c \leq a \leq A$. The fishing mortalities for age classes below the age at full recruitment to the fishery were then calculated by estimating the values F_a, such that $n_a = [F_a/(M + F_a)](1 - \exp[-(M + F_a)])N_{a+1}\exp[M + F_a]$, where n_a is the observed number of fish of age a in the pooled age composition of fish caught by the commercial fishers. After calculating each value of F_a, an estimate of N_a was calculated as $N_a = N_{a+1}\exp[M + F_a]$. An estimate of the relative vulnerability at age, V_a, was then obtained for *N. valenciennesi* by calculating the ratio of each F_a to the estimate of the fishing mortality of the fully-recruited age classes, F.

2.7 YIELD AND SPAWNING BIOMASS PER RECRUIT

The yield (YPR) and spawning stock biomass (SSB/R) per age 0 recruit were calculated for each species assuming constant recruitment at age 0, full recruitment to the exploited stock at age t_c, constant total mortality for fully-recruited fish and a maximum age of 100 years for *A. gouldii*, 50 years for *N. valenciennesi* and 25 years for *P. endrachtensis*. Recruitment was assumed to be knife-edged for *A. gouldii* and *P. endrachtensis*. Yield per recruit, YPR, for these two species was calculated as $YPR = \sum_{a=t_c}^{A} \frac{F}{Z}\left(1-\exp(-Z)\right)W_a \exp(-Za)$, where F and Z refer to the estimated current levels of fishing and total mortality, respectively, and W_a is the weight of the fish at age a. Because *N. valenciennesi* is recruited into the fishery gradually over several years, the age-dependent fishing mortalities for partially-recruited age classes of this species, F_a, were calculated by multiplying the fishing mortality for fully-recruited fish, F, by the age-dependent vulnerability, V_a. YPR for this species was calculated as $YPR = \sum_{a=1}^{A} \frac{F_a}{M+F_a}\left(1-\exp\left[-\left(M+F_a\right)\right]\right)W_a \exp\left[\sum_{j=0}^{a-1}\left(M+F_j\right)\right]$. W_a, the total body weight at age a, was determined from the predicted length at age determined using the von Bertalanffy growth curve for the species and employing the relationship between its total body weight (g) and length (mm). Note that combined values of Z, F and W_a for both sexes were used in the YPR (and subsequently SSB/R) analyses for *A. gouldii* and *N. valenciennesi*, whereas, because the fishery for *P. endrachtensis* is largely based on females (see Chapter 5), values for the above three variables for females were used in the YPR and SSB/R analyses for that species. The values for F 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 Microsoft Excel$^{\text{TM}}$. This value was used as the biological reference point for fishing mortality for each species against which the estimate of the current level of F was compared (Hilborn and Walters, 1992; Haddon, 2001).

The spawning stock biomasses per recruit, SSB/R, for the females and males of *A. gouldii* and *P. endrachtensis* were calculated as

$SSB/R = \sum_{a=t_c}^{A} W_a P_{sex,a} P_{mat,a} \exp(-Za)$ and those for *N. valenciennesi* as

$SSB/R = \sum_{a=1}^{A} W_a P_{sex,a} P_{mat,a} \exp\left[\sum_{j=0}^{a-1} \left(M + F_a\right)\right]$. 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) relationships for the females and males of both of those species. In the case of the hermaphroditic *A. gouldii*, the proportion of fish of age a that were of each sex, $P_{\text{sex},a}$, was determined from the logistic function relating the proportion at each length of that sex and the von Bertalanffy growth equation for that species. $P_{sex,a}$ for females was calculated as 1 minus the proportion of fish that had changed sex from female to male. For the gonochoristic *N. valenciennesi*, $P_{\text{sex},a}$ were always assumed to equal 0.5. The proportions of mature females of *A. gouldii* and of mature females and males of *N. valenciennesi* and *P. endrachtensis* at age a, $P_{mat,a}$, were determined using the logistic function relating the proportions of mature fish to length, and the lengths at age predicted using the von Bertalanffy growth function. All males of the protogynous *A. gouldii* were assumed to be mature.

Estimates for the current levels of YPR and SSB/R were determined for each of the 10,000 values generated for F by 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 as the ratio of SSB/R at a specified level of fishing mortality to that estimated for an unfished population (Goodyear, 1993).

3.0 BIOLOGY OF THE WESTERN BLUE GROPER *ACHOERODUS GOULDII*

3.1 INTRODUCTION

The Labridae, which is now considered to comprise three subfamilies, *i.e.* the Labrinae, Scarinae and Odacinae, is one of the largest and most speciose of all perciform families, comprising approximately 680 species and 82 genera (Allen *et al.*, 2006a). The Labrinae, which is by far the largest of the three labrid subfamilies, is found mainly in tropical and subtropical regions of the Atlantic, Indian and Pacific oceans and often in the vicinity of reefs (Allen *et al.*, 2006b; Nelson, 2006). While labrine species range from *c.* 5 to 250 cm in maximum length, the majority are small and generally do not exceed 40 cm in length (Choat and Bellwood, 1994; Allen *et al.*, 2006b). Although a few of the larger labrid species live for a substantially longer period, the oldest labrid yet recorded is still only about 35 years (Gillanders, 1995a; Choat and Robertson, 2002; Choat *et al.*, 2006). On the basis of demographic analyses of large labrid species, Choat *et al.* (2006) concluded that such species were characterised by relatively short life spans and indeterminate growth rates, *i.e.* growth does not tend to asymptote.

Most biological studies on labrids have been undertaken on subtropical and tropical species (Denny and Schiel, 2002). These have shown that most members of this family are protogynous hermaphrodites, *i.e.* change from female to male (e.g. Reinboth, 1970; Candi *et al.*, 2004; McBride and Johnson, 2007). Sex change in most protogynous labrids is broadly accompanied by a change in colour, *i.e.* they are sexually dichromatic (e.g. Warner and Robertson, 1978; Shapiro, 1981; Gillanders, 1995a). The protogynous species of labrids are either monandric, *i.e.* all males are derived from females (Gillanders, 1995a; Nardi *et al.*, 2006; McBride and Johnson, 2007), or diandric, *i.e.* males are derived directly from juveniles or from females (Reinboth, 1970; Shapiro and Rasotto, 1993). However, a few labrid species undergo reversed sex change (Ohta *et al.*, 2003; Kuwamura *et al.*, 2007) or are gonochoristic, *i.e.* do not undergo sex change (Dipper and Pullin, 1979; Bentivegna and Benedetto, 1989).

The Western Blue Groper *Achoerodus gouldii* is found throughout southern Australia, southwards from the Houtman Abrolhos Islands at 28° 30'S, 113° 40'E on the west coast and eastwards along the south coast to Portland in Victoria at 38° 21'S; 141° 36'E (Hutchins and Swainston, 1986; Gommon *et al.*, 1994), but is most abundant on the south coasts of Western Australia and South Australia. This species attains a maximum length of 175 cm (Gommon *et al.*, 1994), which, among labrids, is apparently exceeded only by *Cheilinus undulates* (Sadovy *et al.*, 2003). Although *A. gouldii* is the second most commercially-important species of scale fish on the south coast of Western Australia (McAuley and Simpendorfer, 2003), and is highly regarded by recreational fishers, detailed studies of its biology have been restricted to its foraging behaviour, diet and habitat and how these change with body size (Shepherd, 2005; Shepherd and Brook, 2007).

In contrast to the situation with *A. gouldii*, several aspects of the biology of the Eastern Blue Groper *Achoerodus viridis*, which is distributed along the eastern and south-eastern coasts of Australia (Hutchins and Swainston, 1986), have been studied (Gillanders, 1995a, b; 1997a, b; Gillanders and Kingsford, 1993, 1998; Leis and Hay, 2004). This congeneric species has thus been shown, for example, to be a monandric protogynous hermaphrodite that reaches lengths of 1 m, lives for up to 35 years and attains maturity at lengths of 200-280 mm (*FL*) and by 1-2 years of age. There is also a very marked tendency for the individuals of this species to change from red/brown as a female to blue as a male (Gillanders, 1995a). The detrimental effects of fishing on *A. viridis* in New South Wales led to this iconic species being protected from both recreational and commercial fishing in

1969, although these regulations were subsequently eased to some extent in 1974 (Gillanders, 1999).

The aim of the present study was to test the following hypotheses. 1) As with *A. viridis*, *A. gouldii* is a monandric protogynous hermaphrodite. 2) The far greater size of *A. gouldii* than *A. viridis* is accompanied by a far greater maximum age and a greater size and age at both the attainment of maturity by females and at sex change. If *A. gouldii* does live for a substantially longer period than *A. viridis*, it will have the greatest longevity of any labrid species. 3) Because protogynous labrids that exhibit dichromatism tend to change colour at about the same size and age as that at which sex change occurs, the L_{50} at colour change is similar to that at sex change, *i.e.* as determined from gonadal data. The extent to which the length at colour change can be used as a proxy for length at sex change is explored. 4) If, as hypothesized, *A. gouldii* is particularly long-lived, late-maturing and undergoes late sex change, this important commercial species would potentially be very vulnerable to fishing pressure and may thus already be experiencing an undesirable level of fishing mortality. Finally, the implications of the biological data for management plans aimed at conserving the stocks of *A. gouldii* are discussed in detail.

3.2 MATERIALS AND METHODS

3.2.1 ***Sampling regime***

Achoerodus gouldii was collected at monthly or bimonthly intervals between April 2004 and October 2007 from numerous sites in coastal waters between Albany at 35° 01'S, 117° 58'E and Esperance at 33° 45'S, 121° 55'E off the south coast of Western Australia (Fig. 3.1). These fish were either caught by spear fishing while free-diving or SCUBA diving in shallow (< 20 m) inshore coastal waters or were obtained from fish processors, who had been supplied by commercial gillnet fishers (mesh range = 165 - 178 mm)

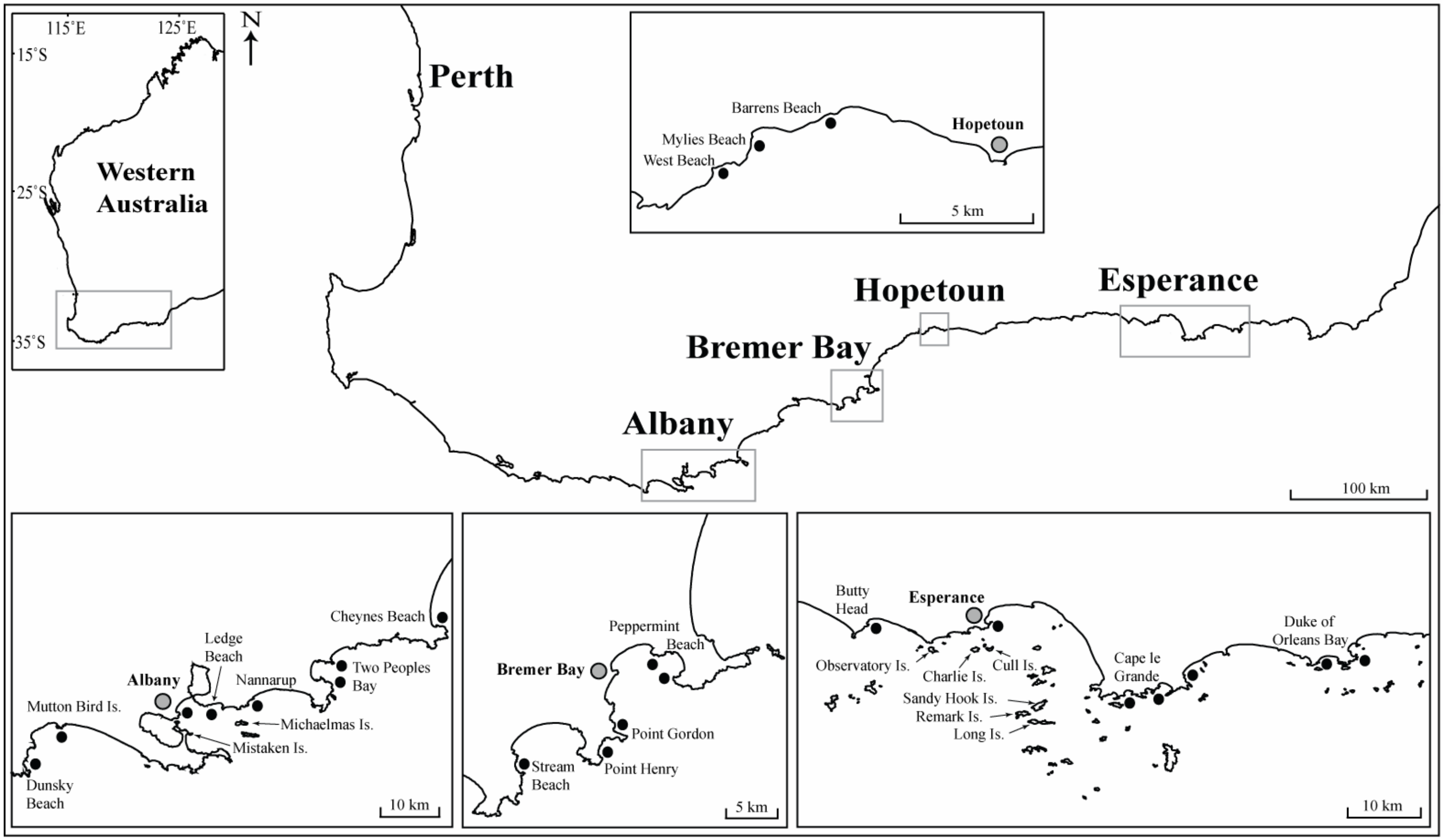

Figure 3.1. Map showing the five main sampling locations on the south and lower west coasts of Western Australia from which *Achoerodus gouldii* and *Nemadactylus valenciennesi* were collected. Insets show region of sampling in south-western Australia and the location of inshore sampling sites at each of the four main sampling locations on the south coast. Note that offshore samples were obtained mainly from waters off Esperance, Albany and Perth.

operating in deeper (*c.* 20 - 100 m) and more offshore waters. A small number of *A. gouldii* (*c.* 3% of all fish) was collected directly from commercial gillnet fishers operating in deeper, offshore waters at a latitude of about *c.* 32^{o} S on the lower west coast of Australia. Although most of the individuals obtained from commercial gillnet fishers on both coasts were supplied as gutted, filleted frames and could thus neither be sexed nor used to provide information on their gonadal status, some of those from the south coast were intact, *i.e.* still contained their gonads.

The method of capture (*i.e.* spear fishing or commercial gill netting) and length range of *A. gouldii* caught in each month during the study are provided in Table 3.1.

3.2.2 ***Laboratory procedures and analyses***

The following provides details of the methods used that were specific to *A. gouldii* (see General Materials and Methods details pertinent to all three species).

The colour of each *A. gouldii*, *i.e.* green or blue, was recorded. To facilitate comparisons between the total lengths of *A. gouldii* and those of the congener *A. viridis*, which were recorded as standard lengths (*SL*) by Gillanders (1995a), those latter standard lengths were converted to total lengths (*TL*) using the equation $TL = 1.19(SL) + 7.93$ ($n = 455$, $p < 0.001$, $r^2 = 0.99$), which was derived from data kindly provided by B. Gillanders. Note that as the tail of *A. gouldii* is not forked, the fork length of this species is the same as its total length. Thus, the total lengths for *A. gouldii* can be compared directly with the lengths of those other labrid species which were recorded as fork lengths by workers such as Choat *et al.* (2006).

Table 3.1. Sample sizes and length ranges of *Achoerodus gouldii* collected by spear fishing and from the commercial gillnet fishers on the south and lower west coasts of Western Australia.

		Spear fishing		Commercial gill netting	
Year	Month	*n*	Length range (mm)	*n*	Length range (mm)
2004	April	1	810	4	495-1039
	May			24	606-1091
	June			30	556-1058
	July			64	521-1033
	August	16	124-483	93	508-1121
	September			93	479-1104
	October	52	129-608	85	462-1024
	November			35	474-954
	December			48	475-844
2005	January			56	495-954
	February	11	184-301	20	529-998
	March	5	266-343	38	478-940
	April				
	May	100	108-921	21	567-939
	June	56	118-806		
	July			17	487-811
	August	88	152-705	39	482-1065
	September	83	83-657	23	511-950
	October			12	630-1014
	November				
	December	82	106-758		
2006	January	5	211-1050		
	February	74	60-954	55	471-950
	March	44	90-823	32	515-920
	April	48	104-849	45	478-937
	May	1	550	26	515-1080
	June	2	670-775	32	530-1151
	July	54	222-850	3	828-1162
	August			32	530-891
	September	6	541-1008	41	428-852
	October	1	764	29	500-1005
	November	45	40-1041	24	469-887
	December	9	291-647	3	921-1006
2007	January	21	154-659		
	April	1	704		
	July			4	526-690
	August	17	123-943	38	532-1059
	September			33	521-1063
	October			8	567-1134
Total		822	40-1041	1107	428-1162

3.2.3 *Sex change*

Logistic regression analysis was employed to relate the probability, p_M, that a fish was a male rather than a female to length and/or colour, where $p_M = \frac{1}{1+\exp[-\alpha - \beta_1 TL - \beta_2 x]}$ and α, β_1 and β_2 are constants and x is the value of the factor representing the colour of the fish (green = 0, blue = 1). The proportion of fish of length L that possess female gonads, p_F, was determined as $1 - p_M$. The Akaike Information Criterion (AIC) was used to determine which of the models based solely on length or colour or both length and colour provided the better prediction of the probability that a fish was male. The AIC is determined as AIC = $-2\lambda + 2K$, where λ is the log-likelihood and K = number of parameters. The model with the lowest AIC value was selected as the best of the alternative models. The likelihood ratio test was then used to determine whether the nested model that contained the combination of the two variables, *i.e.* length and colour, improved the prediction of the proportion of fish that were male.

3.2.4 *Growth*

A single von Bertalanffy growth curve was fitted to the lengths at age of all *A. gouldii* aged during the present study. The von Bertalanffy growth equation, which was fitted using SPSS Inc. (2001), is $L_t = L_\infty(1 - \exp(-k(t - t_0)))$, where L_t is the length (mm *TL*) at age t (years), L_∞ is the mean asymptotic length (mm) predicted by the equation, k is the growth coefficient (year^{-1}) and t_0 is the hypothetical age (years) at which fish would have zero length. Separate curves were then fitted to the lengths at age of females and males that had been sexed using gonad type and then again for the same fish but using colour, *i.e.* green or blue.

von Bertalanffy growth curves for each sex s (where $s = f$ for a female and m for a male) were next fitted to the combination of the lengths at age of sexed and unsexed individuals, where the latter group comprised those fish for which the colour had been recorded.

The expected length for each sex, s, was first calculated as

$$\hat{L}_j^s = \begin{cases} L_\infty^f \left(1 - \exp\left[-k^f \left(t_j - t_0^f\right)\right]\right) & \text{if } s = f \text{ or } t_j \le t_{\text{diverge}} \\ L_\infty^m \left(1 - \exp\left[-k^m \left(t_j - t_0^m\right)\right]\right) & \text{if } s = m \text{ and } t_j > t_{\text{diverge}} \end{cases}$$

where t_j is the age of fish j and t_{diverge} is the age at which the growth curve of the males was assumed to begin diverging from that of females. Note that, if L_{diverge} is the expected length of the females at age t_{diverge}, then t_0^m is determined as $t_0^m = t_0^f - \frac{1}{k^f}\log_e\left(1 - \frac{L_{\text{diverge}}}{L_\infty^f}\right) + \frac{1}{k^m}\log_e\left(1 - \frac{L_{\text{diverge}}}{L_\infty^m}\right)$. The observed lengths of fish of that age were assumed to be normally-distributed about the predicted length for each sex, with a common standard deviation, *i.e.* $L_j = \hat{L}_j^s + \varepsilon_j^s$, where L_j is the observed length for fish j and where $\varepsilon_j^s \sim N\left(0, sd^2\right)$. The value of the normal probability density function for the deviation ε_j^s was calculated for each sex s as $\phi_j^s = \frac{1}{\sqrt{2\pi\, sd^2}}\exp\left[-\frac{\left(L_j - \hat{L}_j^s\right)^2}{2\, sd^2}\right]$. The probability that fish j was of sex s was denoted by p_j^s, where $p_j^f = 1 - p_j^m$ and where

$$p_j^m = \begin{cases} 1 & \text{if the fish possessed male gonads} \\ 0 & \text{if the fish possessed female gonads} \\ \left(1 + \exp\left[-\alpha - \beta_1 L_j - \beta_2 C_j\right]\right)^{-1} & \text{if the fish had not been sexed} \end{cases}$$

The parameters α, β_1 and β_2 for estimating the probability that a fish of length L_j and colour C_j (0=green, 1=blue) is male were calculated using logistic regression analysis. The value of the log-likelihood, $\lambda = \sum_j \log_e\left(\sum_s p_j^s \phi_j^s\right)$ was maximised to estimate the parameters L_∞^f, k^f, t_0^f, L_∞^m, k^m, t_{diverge} and sd. Bootstrap confidence limits were calculated by resampling with replacement and fitting the model to the resampled data. The 2.5 and 97.5 percentiles of the resulting estimates from 1000 resampled data sets were taken as the approximate 95% confidence limits for the parameters.

Comparisons between the growth curves of *A. gouldii* were restricted to those derived for individuals in inshore waters of the only two areas (Albany and Esperance) where the samples contained a substantial number of fish that encompassed a wide length and age range of fish.

3.2.5 *Length, age and colour at sex change*

For determining the length and age at which *A. gouldii* change sex, the six fish with gonads containing both testicular and ovarian tissue, and which were thus considered to be changing from female to male (see Results), were combined with those fish with gonads comprising only testicular material. The lengths at which 50 and 95% of individuals of *A. gouldii* change sex and colour (L_{50}, L_{95}) were then estimated by fitting logistic curves to the probability that a fish, at a specified length, were male and blue, respectively. This was undertaken using Markov Chain Monte Carlo simulation in WinBUGS, as described above for length at maturity. Logistic curves were also fitted to the probability that individuals of *A. gouldii* at a specified length were blue, the colour found in the majority of fish that were males and which thus contrasted with the green colour that characterized most females.

The number of fish in each year class in each of three successive annual periods was determined. As 1 August coincides with the birth date designated for *A. gouldii* (see Results), these estimates of numbers encompassed each of the three successive 12 month periods between August and the following July in the years 2004 to 2007.

3.3 RESULTS

3.3.1 ***Validation of ageing method***

Sectioning of the otoliths of *A. gouldii* resulted in their opaque zones becoming clearly defined and demonstrated that those zones were numerous in otoliths of the largest fish (Fig. 3.2).

Although the monthly sample sizes of fish with otoliths with 1 opaque zone were often small, the mean monthly marginal increments on such otoliths could still be seen to undergo a clear seasonal pattern of change, with values declining markedly between late winter and mid-spring and rising between early autumn and winter (Fig. 3.3). The mean monthly marginal increments on sectioned otoliths of *A. gouldii* with 2-10 zones, for which the monthly sample sizes were far greater, remained relatively high (≥ 0.39) between July and October, before declining sequentially to 0.36 in November and to a minimum of 0.26 in January and February, and then rising progressively in the ensuing months (Fig. 3.3). Although the mean monthly marginal increments on otoliths with 11-20, 21-30 and > 30 zones followed very similar trends to those just described for otoliths with 2-10 zones, the minima of the last two groups were reached later. It thus follows that, as the number of zones in otoliths increases, the opaque zone in otoliths becomes visually detectable later, *i.e.* in autumn rather than mid-summer. The similar and single pronounced decline and subsequent progressive rise in the mean monthly marginal increments in sectioned otoliths, irrespective of the number of opaque zones they contained, provide strong evidence that a single opaque zone is formed annually in the otoliths of each *A. gouldii*. The number of opaque zones in these otoliths of *A. gouldii* can thus be used to facilitate the ageing of the individuals of this species.

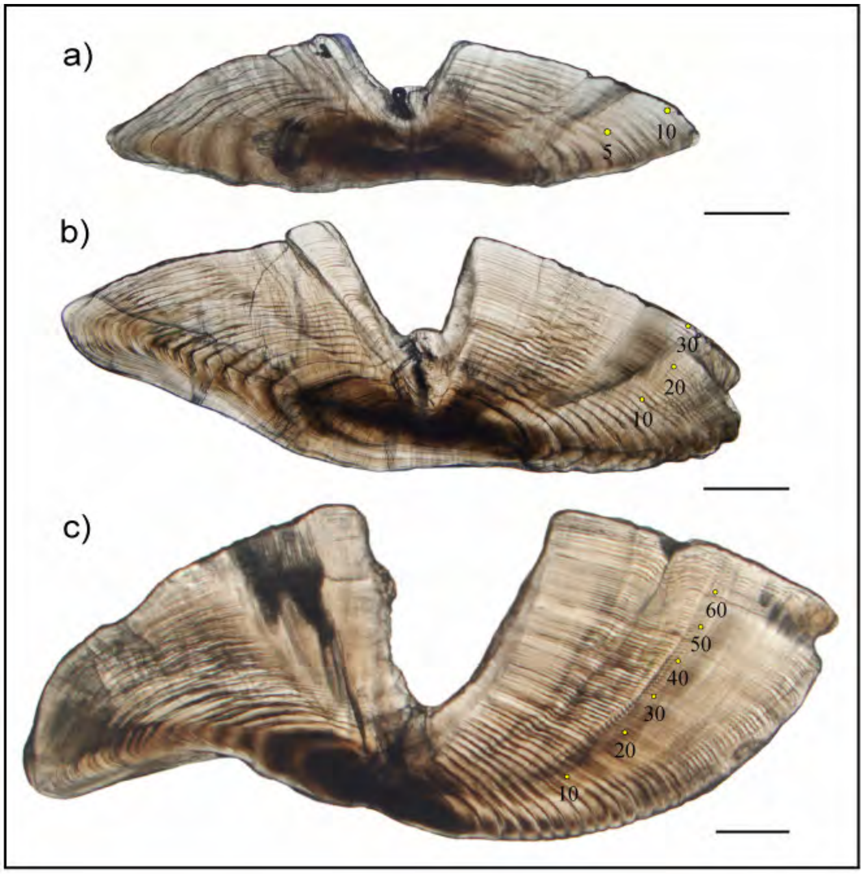

Figure 3.2. Sectioned otoliths of *Achoerodus gouldii* with a) 10, b) 30 and c) 69 growth (opaque) zones (●). Scale bars = 0.5 mm.

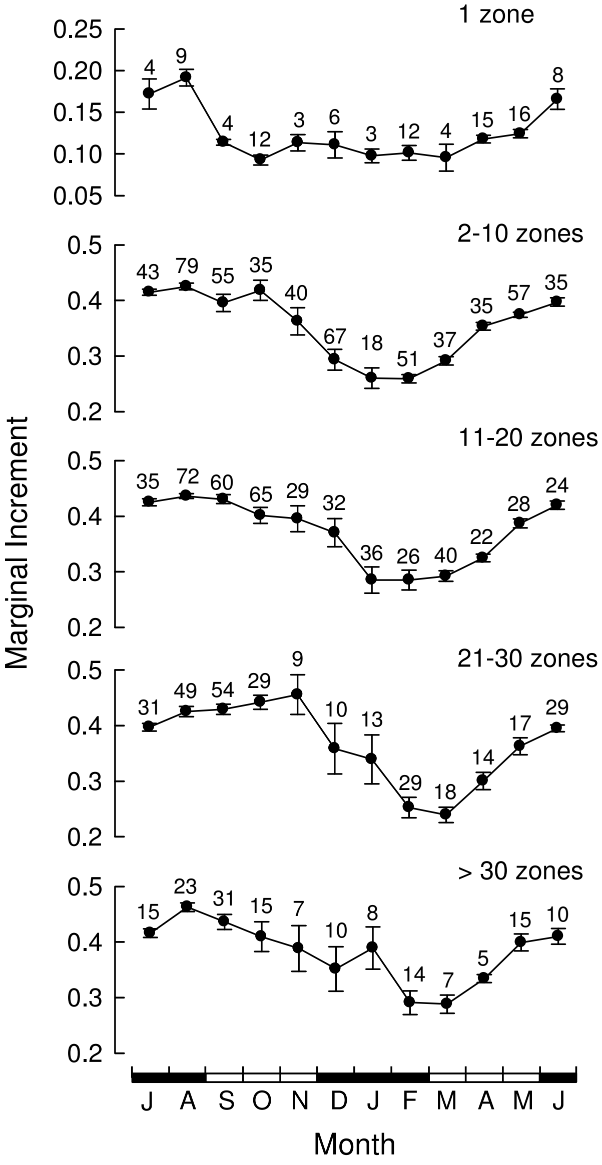

Figure 3.3. Mean monthly marginal increments ± 1 SE on sectioned sagittal otoliths of *Achoerodus gouldii* with different numbers of opaque zones. Sample sizes are shown above each mean. In this Fig. and Fig 3.6, closed rectangles on the x-axis refer to winter and summer months and the open rectangles to spring and autumn months.

3.3.2 *Length and age compositions and growth*

From the trends exhibited by the mean monthly GSIs and prevalence of females with stage V/VI ovaries in each month (see later), the approximate mid-point of the spawning period was estimated to be August, *i.e.* end of the Austral winter. The small fish caught in November were *c.* 40 mm in length, while those captured in February and March were *c.* 60 and 90 mm, respectively. The otoliths of these fish contained no opaque zones, which is consistent with these fish, on average, having been spawned in late winter and thus not having had the opportunity to lay down the opaque zone that is deposited annually during that season in older fish. The first of these zones becomes delineated in the spring of the second year of life, *i.e.* when fish are *c.* 140 mm in length and *c.* 18 months old.

The samples of *A. gouldii* contained individuals that ranged in length from 40 to 1162 mm and in age from a few months to 70 years (Fig. 3.4). The largest and oldest *A. gouldii*, from which the gonads had not been removed during gutting and filleting and could thus be sexed, were 880 mm and 49 years for females and 1134 mm and 57 years for males.

Although the 822 *A. gouldii* collected by spear fishing ranged from 40 to 1050 mm in total length, the majority of those individuals were between 100 and 600 mm, which correspond to ages of 1 to 11 years (Fig 3.4). The 1107 *A. gouldii* obtained from the commercial gillnet fishery ranged from 428 to 1162 mm in length and from 6 to 70 years in age, but most were between 500 and 800 mm 10 and 34 years (Fig. 3.4).

The growth curves of *A. gouldii* in inshore waters off Albany and Esperance, locations separated by 500 km and representing the extreme locations at which samples were obtained on the south coast, were not significantly different ($p < 0.05$). Thus, the lengths at age of fish from the different regions were pooled, and a common

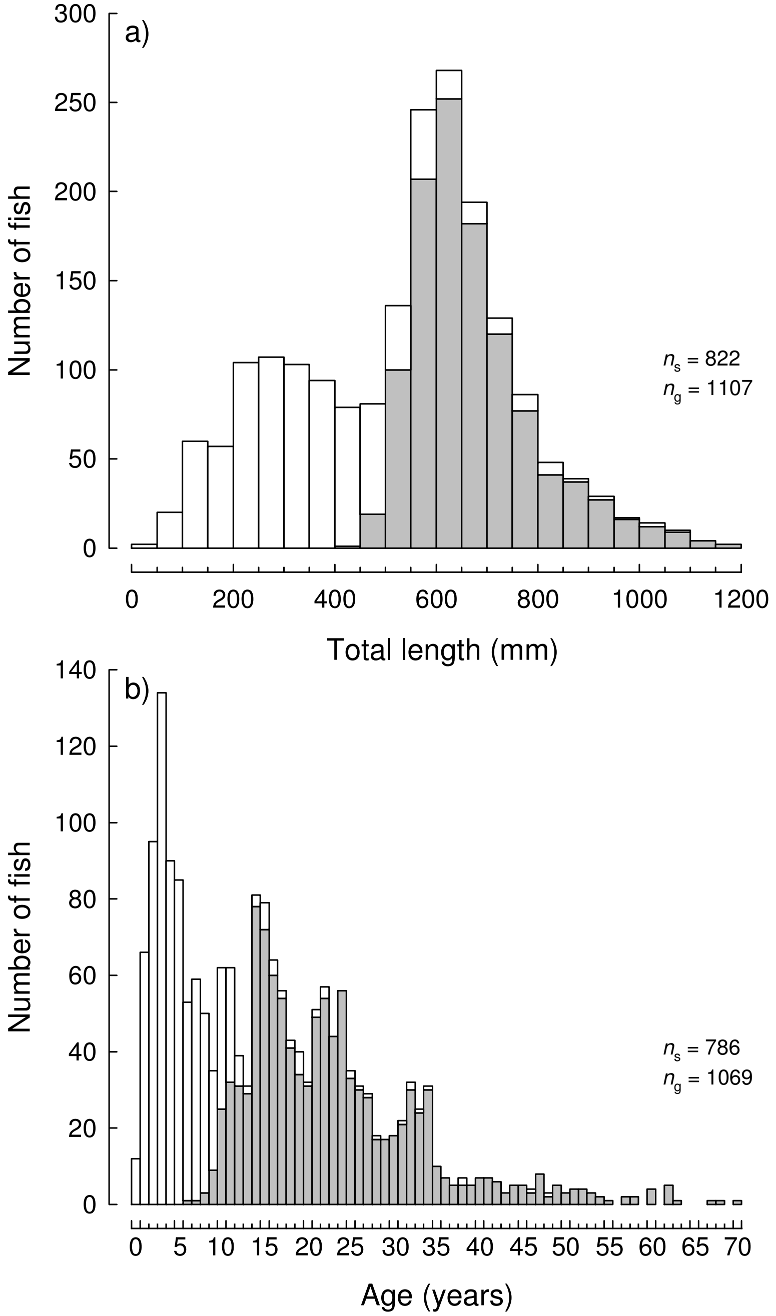

Figure 3.4. Length and age-frequency distributions for *Achoerodus gouldii* caught by spear fishing (open histograms) and commercial gillnetting (grey histograms). n_s and n_g, number of fish caught by spear fishing and gill netting, respectively.

growth curve constructed for all aged fish (Fig. 3.5a). A von Bertalanffy growth curve provided a good fit to the lengths at age of all fish, as is demonstrated by the relatively high value of 0.84 for the coefficient of determination (Table 3.2). On the basis of the von Bertalanffy growth equation, *A. gouldii* at ages 5, 10, 20, 30, 40 and 50 years attain, on average, lengths of 335, 509, 678, 741, 764 and 773 mm, respectively. The marked similarity in the estimated lengths at 30, 40 and 50 years of age reflects the markedly asymptotic pattern of growth of *A. gouldii*, with relatively little overall growth occurring after 30 years.

The von Bertalanffy growth curves fitted separately to the lengths at age of known females and males, *i.e.* those able to be sexed using gonadal criteria, demonstrated that, at corresponding ages, the males were always longer than females (Fig. 3.5b). Furthermore, with increasing age, the estimated lengths at age of males increasingly diverged from those of females. Thus, for example, at 20, 35 and 50 years, the estimated lengths at age for males were 805, 923 and 965 mm, respectively, and those for females were 679, 737 and 746 mm, respectively (Fig. 3.5b). The above differences in growth are reflected in the estimate for k for males (0.08 year^{-1}) being less than that for females (0.12 year^{-1}), whereas the reverse trend occurred with the L_∞, for which the respective values were 975 and 748 mm (Table 3.2). Unlike the situation with females, the 95% confidence limits for t_0 for males were very wide. This reflects the fact that, as none of the smaller fish was a male (as females do not change to male until a certain size and age has been reached), there were no length-at-age data for small males to “tie down” and refine the bottom end of the growth curve for that sex (Table 3.2).

When von Bertalanffy growth curves were fitted separately to the lengths at age of those individuals that were either green or blue, but constituted the same subset of fish as those just used to describe the growth of males and females, the values for L_∞ and k for

Table 3.2. The von Bertalanffy growth curve parameters L_∞, k and t_0 for *Achoerodus gouldii* caught in waters off the lower west and south coasts of Western Australia, together with their lower and upper 95% confidence limits. a) For all fish, b) for females and males sexed using gonad type, c) for the same fish as in b) but separated according to colour, *i.e.* green or blue, and d) for females and males using gonadal criteria, but including individuals with green and blue colour, respectively, taking into account the probability that such individuals were female and male, respectively. Parameters were derived from the lengths at age of individuals. L_∞ is the asymptotic length (mm), k is the growth coefficient (year^{-1}), t_0 is the hypothetical age (years) at which fish would have zero length, r^2 is the coefficient of determination and n is the number of fish.

		L_∞ (mm)	k (year^{-1})	t_0 (years)	r^2	n
a) All fish	Estimate	777	0.10	-0.65	0.84	1855
	Lower, upper	766, 789	0.09, 0.11	-0.90, -0.39		
b) Females	Estimate	748	0.12	-0.15	0.92	854
	Lower, upper	732, 764	0.11, 0.12	-0.30, 0.00		
Males	Estimate	975	0.08	-0.91	0.35	43
	Lower, upper	879, 1072	-0.02, 0.19	-22.84, 21.03		
c) Green	Estimate	748	0.12	-0.17	0.92	836
	Lower, upper	731, 765	0.11, 0.12	-0.32, -0.02		
Blue	Estimate	966	0.08	-0.10	0.53	61
	Lower, upper	867, 1055	0.03, 0.13	-8.38, 8.18		
d) Females	Estimate	682	0.14	0.06	0.93	1561
	Lower, upper	675, 692	0.14, 0.15	0.00, 0.10		
Males	Estimate	982	0.08	-0.48	0.93	132
	Lower, upper	952,1013	0.07, 0.09	-1.09, -0.14		

blue and for green fish were either identical or very similar to those for female and male fish, respectively (Fig. 3.5c; Table 3.2).

The von Bertalanffy growth curves were next fitted to the lengths at age of all sexed and unsexed individuals, but incorporating the probability that, in the latter group, the green fish will be females and the blue fish males (see Material and Methods). The resultant curves for the "females" and "males" fitted the length at age data very well (Fig. 3.5d), as is demonstrated by the high and identical r^2 values of 0.93 for both groups (Table 3.2). The inclusion of lengths at age for unsexed individuals, the majority of which were larger and older fish and taken by the commercial gillnet fishery, have resulted in slightly lower and higher values for the L_∞ for "females" and "males", respectively, than those for the subset of sexed fish (Table 3.2).

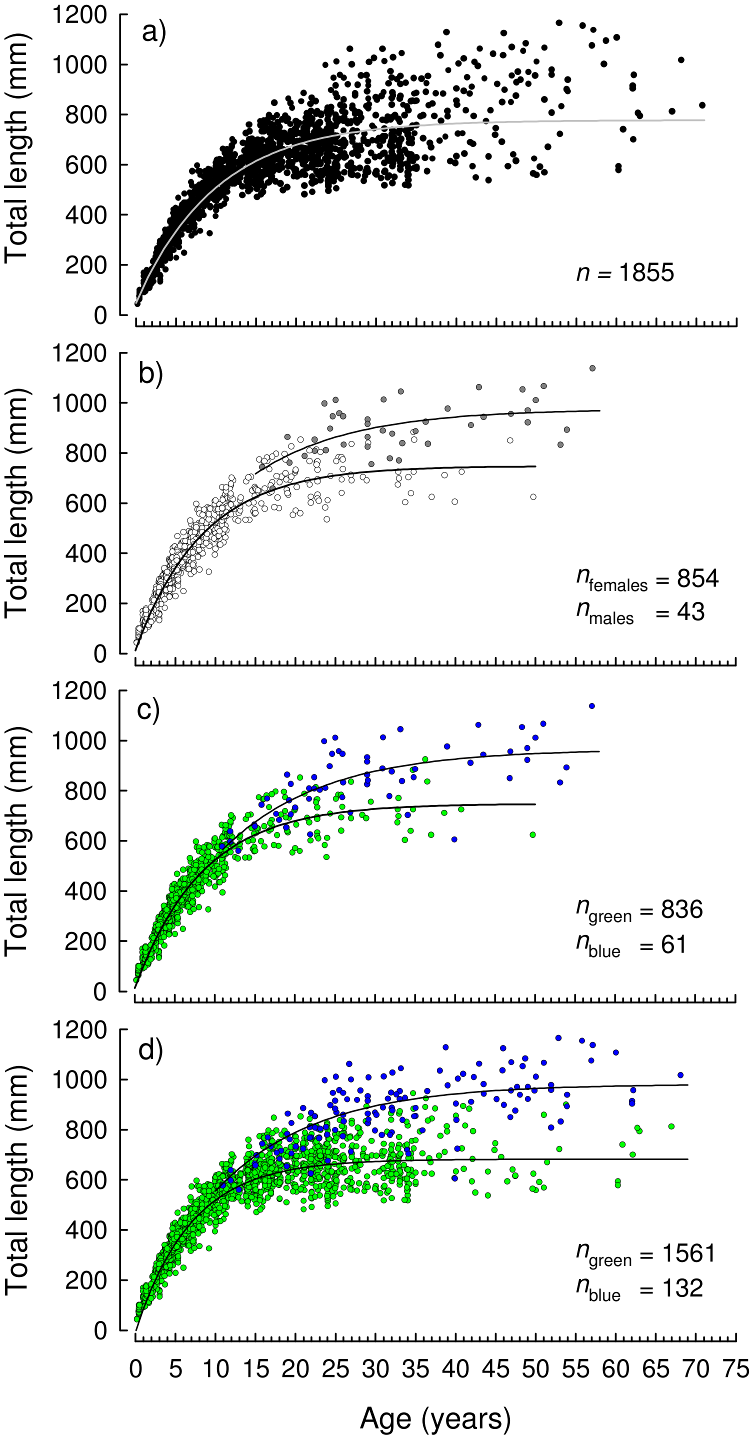

Figure 3.5. von Bertalanffy growth curves fitted to the lengths at age of a) all sexed and unsexed individuals, b) females (white circles) and males (grey circles) sexed on the basis of gonadal status, c) the same individuals as in b) but now sexed according to whether they are green or blue and d) for females and males using gonadal criteria but including individuals with green and blue colour, respectively, taking into account the probability that such individuals were female and male, respectively.

The relationship between the total length (*TL*) in mm and total weight (*W*) in g for *A. gouldii* is described by the following regression equation: $\ln W = 3.041(\ln TL) - 11.017$ ($r^2 = 0.997$, $p < 0.001$, $n = 756$). The relationship between standard length (*SL*) in mm and total length (*TL*) in mm for *A. gouldii* is described by the following regression equation: $TL = 1.20\ (SL) - 11.88$ ($r^2 = 0.995$, $p < 0.001$, $n = 101$).

3.3.3 *Water temperatures, gonadal development and time and duration of spawning*

Temperatures in inshore and offshore waters at both Albany and Esperance underwent seasonal changes (Fig. 3.6a, b). However, they were more pronounced, peaked earlier, *i.e.* mid-summer *vs* early autumn, and reached their minima earlier, *i.e.* late-winter *vs* mid spring, in inshore waters. Furthermore, the differences between water temperatures in inshore waters at the two locations in corresponding months were not as great as in offshore waters and, in many months, were greater at Esperance than at Albany. Although temperatures in deeper waters at Esperance on the south coast followed essentially the same seasonal trends as those at Albany, they were 1 to 1.5°C lower in each month.

The mean monthly GSIs for female *A. gouldii* $\geq$ the L_{50} at maturity, *i.e.* 653 mm (see later), remained low, *i.e.* < 0.50, between December and May, after which they rose sharply to reach a peak of 2.3 in July, before declining to 1.6 in October and 0.1 in November (Fig. 3.6c). The gonads of all females collected between November and May with lengths $\geq$ the L_{50} at maturity possessed immature/ resting ovaries (stage II). Female fish with ovaries at stages III and IV were caught in June and July and those with ovarian stages V/VI between June and October (Fig. 3.6c). The above monthly trends strongly indicate that females with ovaries that develop beyond stage II will become mature during the spawning period.

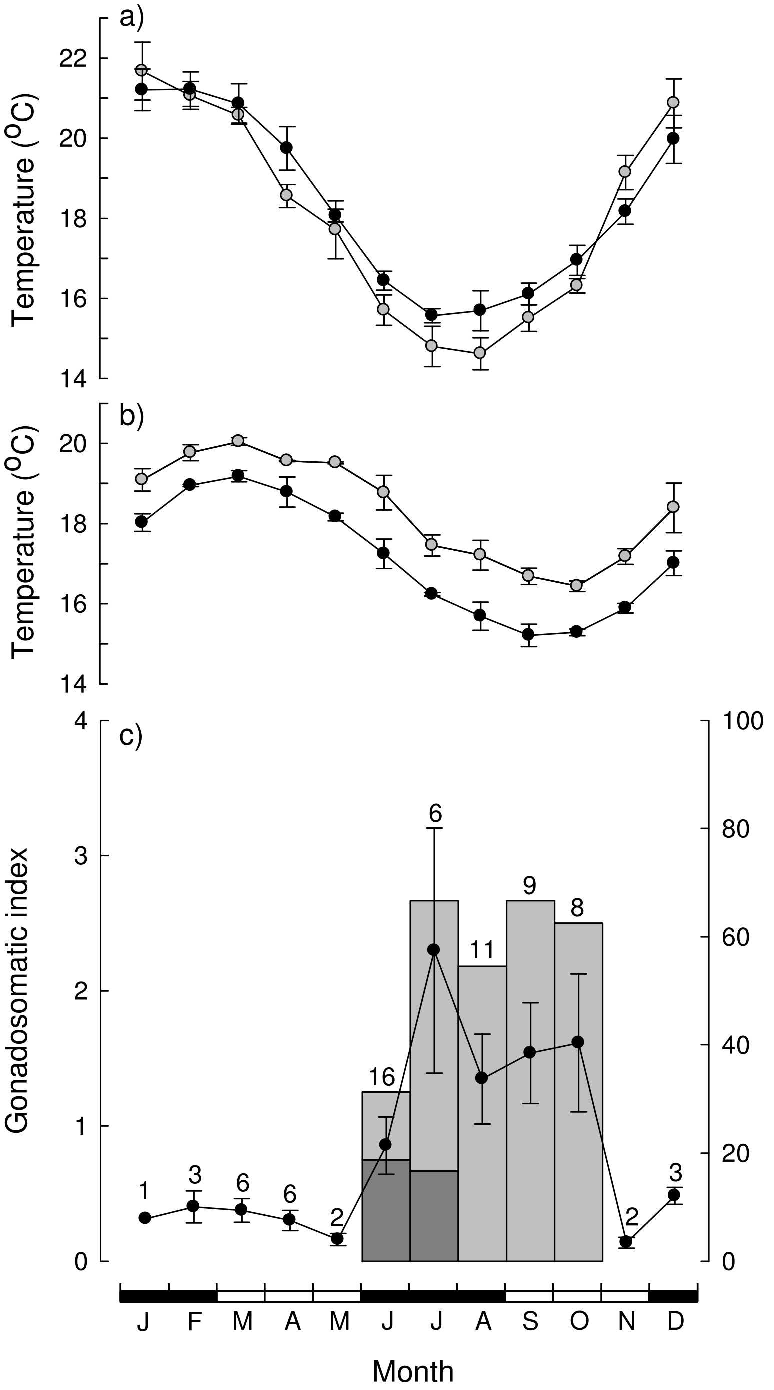

Figure 3.6. a) Mean monthly water temperatures ± 1 SE for a) inshore and b) offshore waters at Albany (grey circles) and Esperance (black circles) on the south coast of Western Australia and c) mean monthly gonadosomatic indices ± 1 SE for female *Achoerodus gouldii* and monthly percentage frequencies of occurrence of ovaries at stages III/IV (dark grey) and V/VI (light grey). Sample sizes for each month are shown on figure.

The above trends in the mean monthly values for the female GSIs and prevalence of females with stage V/VI ovaries demonstrate that spawning occurs predominantly between June and October.

3.3.4 *Length and age at maturity of females*

The smallest mature female (*i.e.* with ovaries at one of stages III-VII) caught during the spawning period measured 391 mm (Fig. 3.7a). The prevalence of mature females increased from 2% in the 350–399 length class to > 50% in the 700–749 mm and 750–799 mm length classes and to 100% in fish > 800 mm (Fig. 3.7a). The L_{50} for female *A. gouldii* at first maturity was 653 mm (Table 3.3).

The youngest mature female collected during the spawning period was 5 years old. The prevalence of mature females in sequential five year age categories increased from 7% in those fish aged 5-9 years to 63% in those fish aged 20-24 years (Fig. 3.7b). Despite the prevalence of mature females caught during the spawning period reaching 81% in those fish aged between 25 and 29 years, it did not reach 100% in either of the following age class categories (Fig. 3.7b).

Table 3.3. Estimates of the lengths, and their lower and upper confidence limits, at which 50% of female *Achoerodus gouldii* reach maturity (L_{50}) in waters of the lower west and south coasts of Western Australia.

	L_{50} (mm)	L_{95} (mm)
Estimate	653	926
Lower	623	853
Upper	693	1029

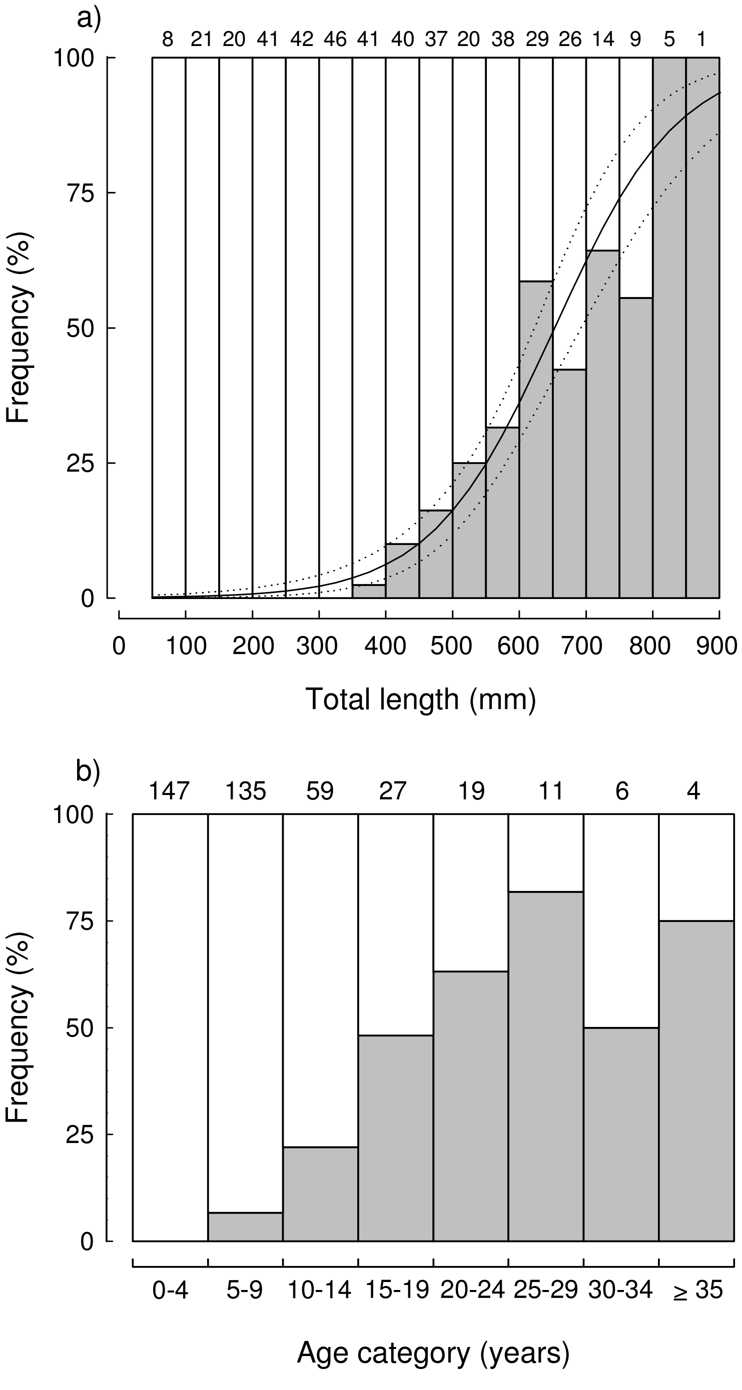

Figure 3.7. Percentage frequency of occurrence of female *Achoerodus gouldii* with mature gonads (grey histograms) in sequential a) 50 mm length classes and b) five year age categories in samples obtained during the spawning period, *i.e.* June to October. Logistic curve (solid line) and its 95% confidence limits (dotted lines) in (a) was derived from the probability that a fish at a given length would be mature. Sample sizes are shown above each histogram.

3.3.5 *Fecundity*

The frequencies of the various oocyte diameters in the ovaries of two typical mature (ovaries at stage V) female *A. gouldii*, and which contained early previtellogenic oocytes, *i.e.* chromatin nucleolar and perinucleolar oocytes, as well as cortical alveolar and yolk granule oocytes, formed essentially a continuous distribution (Fig. 3.8). This continuity provides very strong evidence that *A. gouldii* possesses indeterminate fecundity, *i.e.* annual fecundity is not fixed prior to the onset of the spawning season (*sensu* Hunter *et al.*, 1985).

Batch fecundity estimates for 12 females of *A. gouldii*, with lengths and weights ranging from 530 to 850 mm and from 3 to 14 kg, respectively, ranged from 150,420 to 402,912 and produced a mean ± 95% CL of 256,484 ± 54,983.

3.3.6 *Histological characteristics of gonads*

Among the 200 *A. gouldii* that ranged in length from 100 to 1041 mm and whose gonads were examined histologically, the gonads of all 150 individuals < 655 mm in length contained exclusively ovarian tissue (Fig. 3.9a) and were thus females. All but six of the 50 individuals with lengths ≥ 655 mm contained exclusively either ovarian tissue, as in Figure 3.10b, or testicular tissue (Fig. 3.9d). The gonadal tissue of those six exceptions, whose lengths ranged from 655 to 850 mm, comprised testicular tissue within which were scattered previtellogenic oocytes (Fig. 3.9c).

All immature ovaries, *i.e.* those containing only previtellogenic oocytes, possessed a prominent central lumen (Fig. 3.9a). This lumen was largely or fully occluded in mature and spawning ovaries (stage V/VI) (Fig. 3.9b). A conspicuous central lumen and peripherally-located sperm sinuses (Fig. 3.9d) were present in all testes examined histologically.

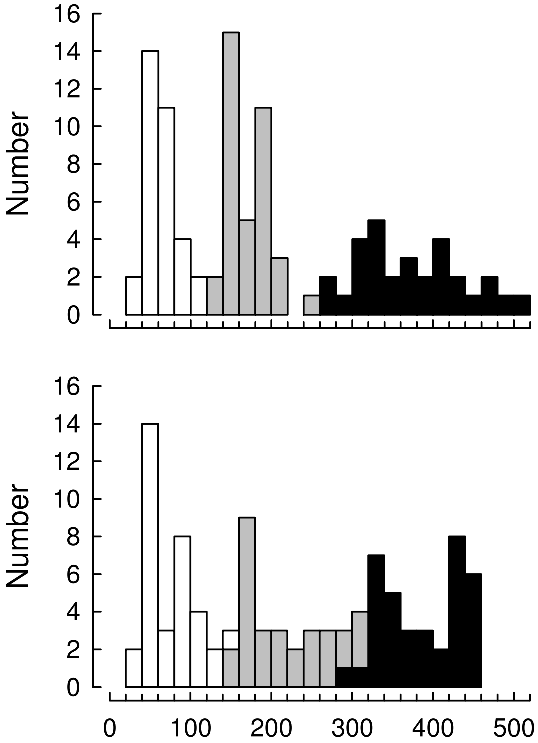

Figure 3.8. Oocyte diameter frequency distributions for two mature (stage V) female *Achoerodus gouldii*. Early previtellogenic oocytes (white), cortical alveolar oocytes (grey), yolk granule oocytes (black).

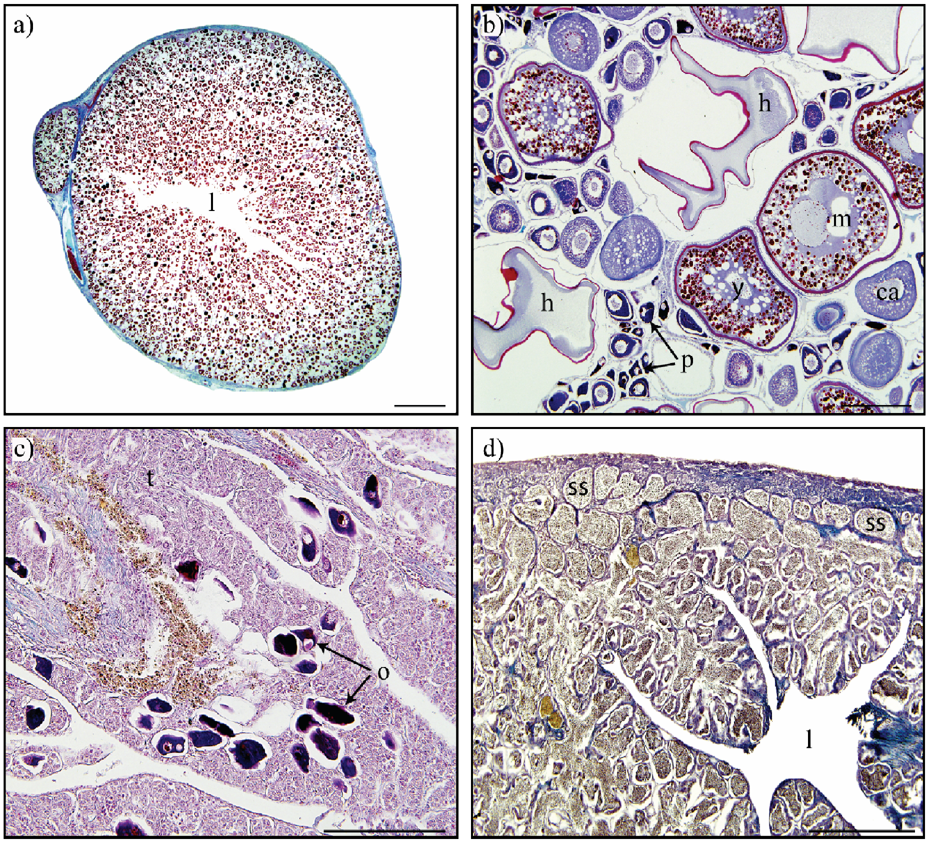

Figure 3.9. Histological sections of gonads of *Achoerodus gouldii*. a) Ovary of immature female containing numerous previtellogenic oocytes and a prominent lumen (l); b) ovary of mature female containing early previtellogenic oocytes (p), cortical alveolar (ca), yolk granule oocytes (y), migratory nucleolar oocyte (m) and hydrated oocytes (h); c) gonad comprising mainly testicular tissue (t) and numerous previtellogenic oocytes (o) and d) mature testes with prominent lumen (l) and sperm sinuses (ss). Scale bars = 1000 µm in (a) and 200 µm in (b), (c) and (d).

3.3.7 *Length and age at sex change*

On the basis of a macroscopic examination of all gonads dissected from fish and histological examination of a large subsample of those gonads, all *A. gouldii* < 655 mm in length were females (Fig. 3.10a). The prevalence of male fish increased progressively from 3% in the 650 – 699 mm length class to 80% in the 850-899 mm length class and 100% among fish ≥ 900 mm (Fig. 3.10a). The L_{50} at sex change was 821 mm (Table 3.4).

866 of the 891 females (97%) were blue and 39 of the 44 males (89%) were green. All fish < 550 mm were green (Fig. 3.10b). The prevalence of fish with blue coloration increased sharply from 8% in the 550 - 599 mm length class to 86% in the 800 - 849 mm length class and reached 100% prevalence in all fish ≥ 900 mm (Fig. 3.10b). The confidence intervals for the L_{50} of 779 mm at colour change overlapped those for the L_{50} of 821 mm at sex change (Table 3.4).

Table 3.4. Estimates of the lengths, and their lower and upper confidence limits, at which 50% of *Achoerodus gouldii* change sex to male (L_{50}) and the lengths at which 50% of *Achoerodus gouldii* change from green to blue (L_{50}) in south-western Australia.

		L_{50} (mm)	L_{95} (mm)
Sex change	Estimate	821	930
	Lower	800	930
	Upper	845	1102
Colour change	Estimate	779	961
	Lower	753	910
	Upper	809	1028

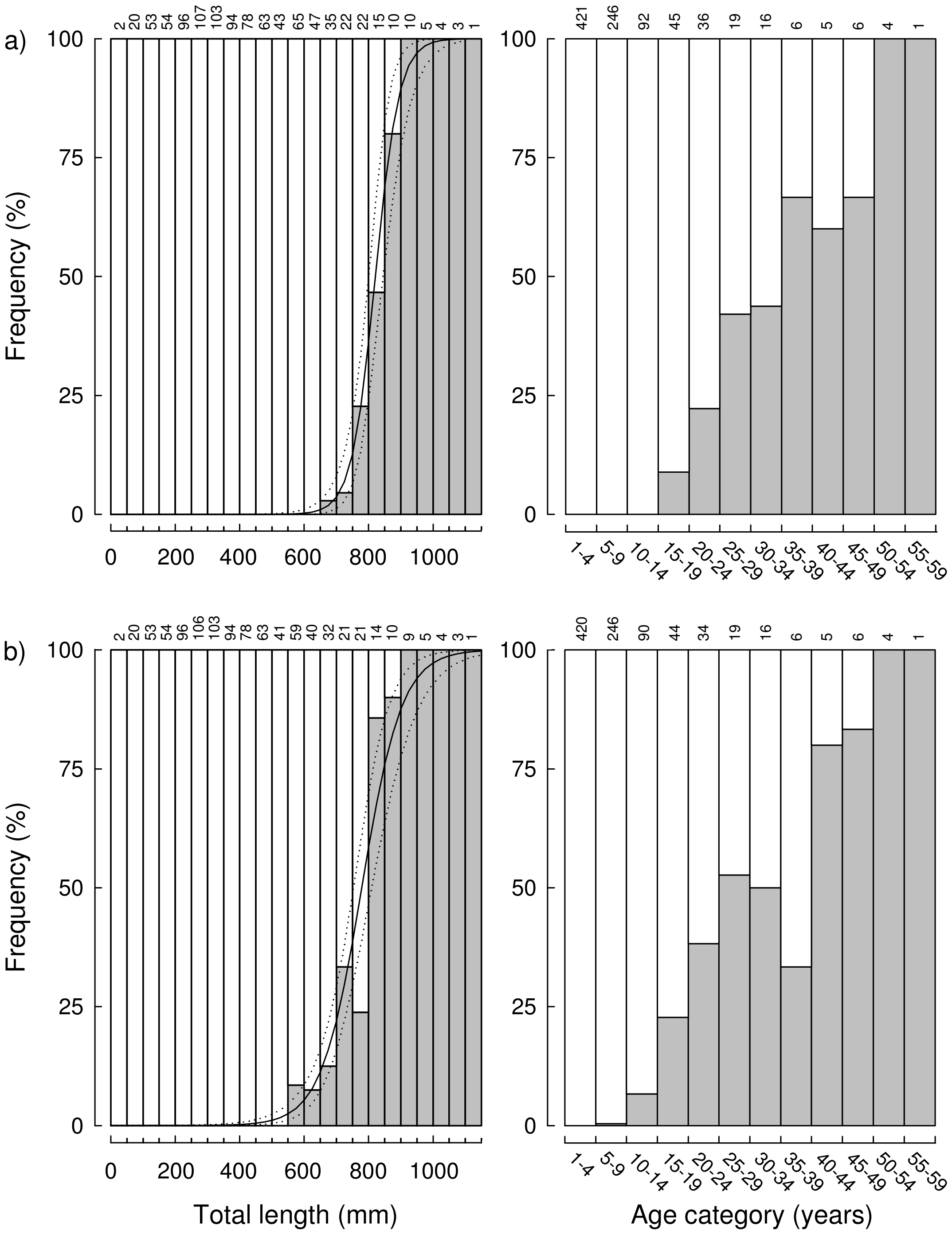

Figure 3.10. Percentage frequency of occurrence of *Achoerodus gouldii* with testes (grey histograms) in a) sequential 50 mm length classes and 5 year age categories and the percentage frequency of occurrence of *Achoerodus gouldii* with blue coloration (grey histograms) in b) sequential 50 mm length classes and 5 year age categories. Logistic curves (solid line) and their 95% confidence limits (dotted lines) in (a) and (b) were derived from the probability that a fish at a given length would have testes and were blue, respectively. Sample sizes shown above each histogram.

All fish < 15 years old were females (Fig. 3.10a). The prevalence of males subsequently increased with age to 67% in fish aged between 35 and 39 years and to 100% in those fish ≥ 50 years (Fig. 3.10a).

The values for the AIC showed that the dichotomous factor, colour, does not provide as good a predictor as the continuous variable, length, that an individual is male (Table 3.5). However, the likelihood ratio test demonstrated that the combination of colour and length provided a significantly better fit than length on its own ($p < 0.05$).

Table 3.5. Results of logistic regression analysis for determining whether colour or total length (*TL*), or colour and total length combined, were the best predictors as to whether an individual of *Achoerodus gouldii* was male. LL, log-likelihood; α, β_1, β_2, constants; AIC = Akaike Information Criterion.

Parameter	Colour	*TL*	Colour and *TL*
LL	-84.424	-48.644	-45.457
α	-4.631	-17.275	-15.505
β_1		0.021	0.018
β_2	4.979		1.477
AIC	172.847	101.289	96.913

3.3.8 *Variations in year class strength and estimates of mortality*

The frequencies of the different year classes of *A. gouldii* in the commercial gillnet catches taken between August and July in three successive 12 month periods, demonstrate that, in each of those periods, the 1990, 1983, 1980 and 1972 year classes were strong (Fig. 3.11). From the data shown in Figure 3.4, it is assumed that *A. gouldii* has become fully recruited to the commercial gillnet fishery by 15 years of age. The fact that a substantial number of fish in excess of 35 years in age were caught and the distribution of the lengths of the males does not appear to be truncated suggests that mesh selectivity was

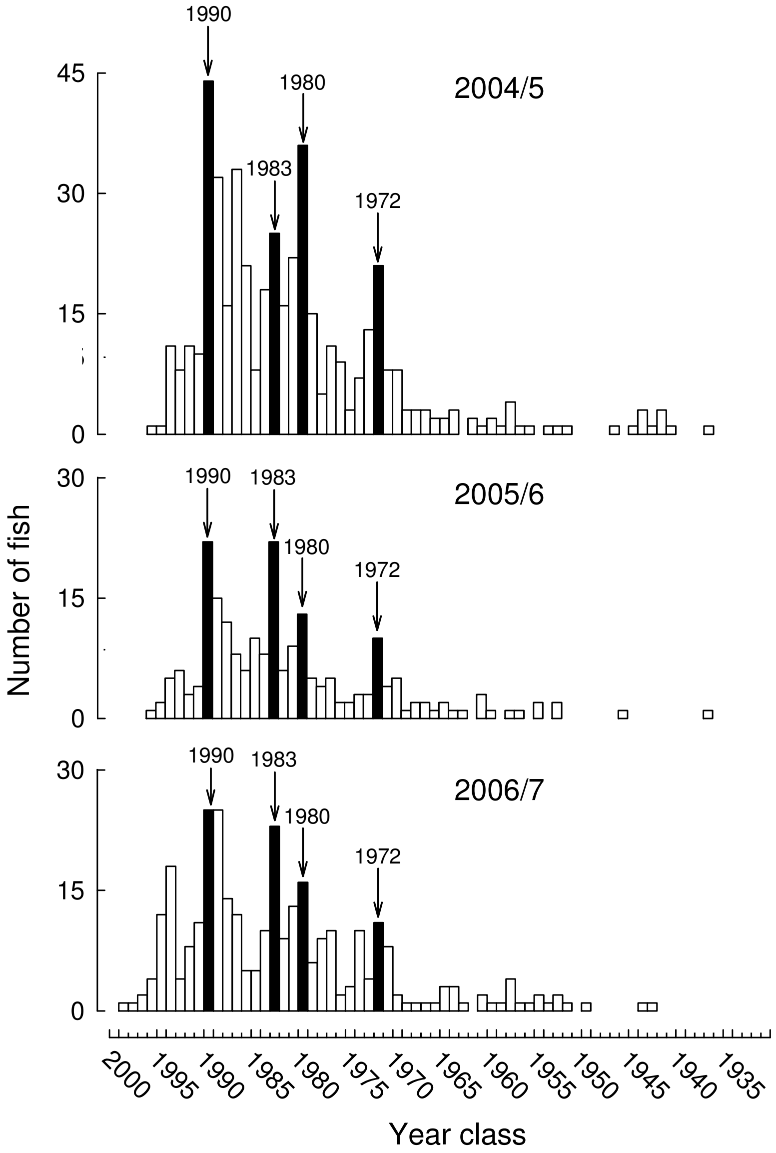

Figure 3.11. Numbers of individuals of each age class of *Achoerodus gouldii* in commercial gillnet samples obtained from the south coast of Western Australia between August and July in 2004/5, 2005/6 and 2006/7.

not having a major influence on the upper end of the length distribution.

From the catch curve analysis assuming constant recruitment (Fig. 3.12), Z was estimated to be 0.086 year^{-1} (Table 3.6). However, because the strengths of the different year classes varied markedly, a relative abundance analysis was undertaken to take into account this variable recruitment (see Section 2.6 in Materials and Methods). This analysis demonstrated that 11 of the year classes between 1936 and 1992 differed significantly from the average level of recruitment, set at 1. In terms of their influence on the resultant log-likelihood for the estimate for Z determined using the relative abundance analysis, the four most important of these year classes were those of 1972, 1980, 1983 and 1990, which were 3.6, 2.6, 2.1 and 1.5 times greater than the average level of recruitment, respectively, and which had been shown to be relatively strong in the initial plots of the age composition data (Fig. 3.12). Among the other year classes which differed significantly from the average level of annual recruitment, the 1981, 1958, 1971 and 1944 year classes were strong, whereas the reverse was true for the 1991, 1992 and 1985 year classes (Fig. 3.12).

Table 3.6. Estimates of mortality for *Achoerodus gouldii*. Total mortality (Z) was derived using catch curve analysis (CCA) assuming constant recruitment and relative abundance analysis (RAA) assuming variable recruitment, while natural mortality (M) was determined by refitting the empirical equation for fish of Hoenig (1983) and using the approach of Hall *et al.* (2004). Fishing mortality (F) was estimated employing a Monte Carlo resampling analysis and using the estimates of Z from the RAA assuming variable recruitment and of M from the method of Hall *et al.* (2004).

Method of analysis	Z, M or F (year^{-1})	Estimate	Lower 95%	Upper 95%
CCA (constant recruitment)	Z	0.086	0.080	0.092
RAA (variable recruitment)	Z	0.093	0.086	0.100
Refitted Hoenig (1983) fish equation	M	0.072	0.022	0.180
Combined M (Hall *et al.*, 2004)	M	0.054	0.021	0.090
Monte Carlo resampling	F	0.039	0.003	0.073

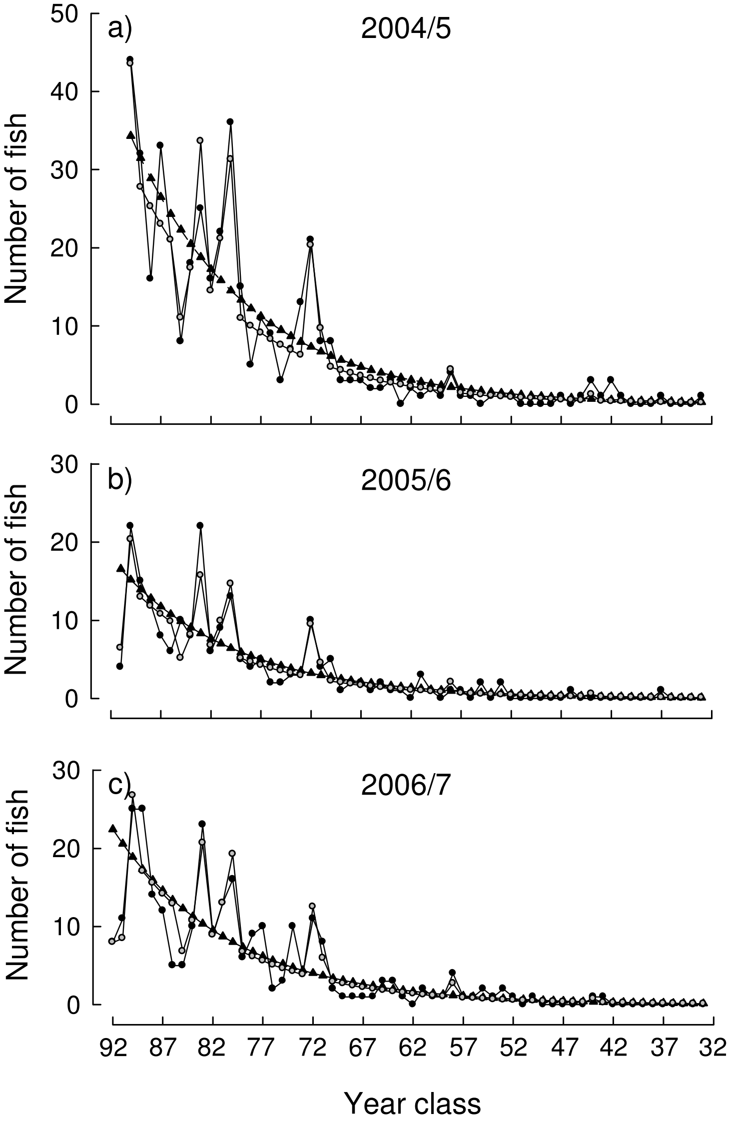

Figure 3.12. Numbers of individuals of the 1992 – 1933 year classes of *Achoerodus gouldii* in samples collected by commercial gillnetting on the south coast of Western Australia in a) 2004/5, b) 2005/6 and c) 2006/7. Relative abundance analyses were used to fit lines to the observed frequency of abundance of fish in each year class (black circles), assuming that recruitment is either constant (triangles) or variable (grey circles).

The point estimate for *Z* increased slightly from 0.086 year^{-1}, when constant recruitment was assumed, to 0.093 year^{-1}, when variable recruitment was taken into account (Table 3.6; Fig. 3.13). The point estimate for *M* derived from Hoenig's (1983) equation for fish (0.072 year^{-1}) was greater than the 0.054 year^{-1} derived when, by taking into account the probability distribution of *Z*, the approach of Hall *et al.* (2004) was used to modify that estimate of Hoenig (1983) (Table 3.6; Fig. 3.13). Furthermore, the use of the latter approach was accompanied by greatly reduced confidence intervals for the estimates of *M*.

The estimate of fishing mortality, *F*, estimated by Monte Carlo resampling and by employing the probability distribution derived for *Z* assuming variable recruitment and for *M* from the method of Hall *et al.* (2004), was 0.039 year^{-1} (Table 3.6).

3.3.9 *Current yield and spawning biomass per recruit and spawning potential ratio*

The von Bertalanffy growth parameters derived for the females and males of *A. gouldii* using the lengths at age for all individuals (Fig. 3.5d, Table 3.2) were used for the per recruit analyses. Yield per recruit (YPR) analyses for *A. gouldii*, which assumed that full recruitment into the fishery had occurred by 15 years of age, indicate that YPR increases with increasing fishing mortality until it reaches *c.* 0.07 year^{-1} and then begins to decline precipitously (Fig 3.14). At the current estimated level of *F* of 0.039 year^{-1}, the YPR is estimated to be 1.88 kg. The estimated level of *F* corresponding to the reference point $F_{0.1}$ is 0.051 year^{-1} (Table 3.7).

The current level of spawning stock biomass per recruit (SSB/R) was estimated to be 44.2 kg for both sexes, collectively, and 8.9 and 35.2 kg for females and males, respectively (Table 3.7). The current level of spawning potential ratio (SPR), in terms of SSB/R, is estimated to be 0.56 for both sexes combined, and 0.88 for females and 0.52 for males (Fig. 3.14, Table 3.7).

Table 3.7. Estimates for *Achoeodus gouldii* of the current level of yield per recruit (YPR), $F_{0.1}$ and the current levels of spawning stock biomass per recruit (SSB/R) and spawning potential ratio (SPR) for females, males and both sexes combined. Calculations assumed that full recruitment to the fishery had occurred by the age of 15 years.

Analysis	Estimate	Lower 95%	Upper 95%
YPR (kg)	1.88	0.08	5.69
$F_{0.1}$ (year^{-1})	0.051		
SSB/R (females & males)	44.2	25.3	72.7
SPR (females)	0.88	0.75	0.99
SPR (males)	0.52	0.27	0.96
SPR (females & males)	0.56	0.31	0.96

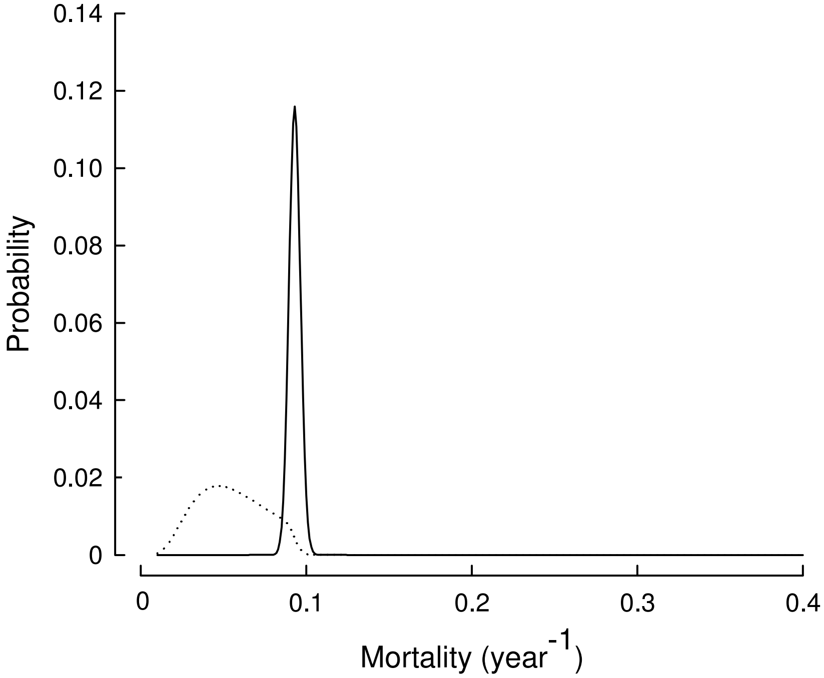

Figure 3.13. Probability distributions, for *Achoerodus gouldii*, of natural mortality, *M* (dotted line) (derived using the method of Hall *et al.* (2004) and an estimate of *M* obtained by refitting the Hoenig (1983) regression equation for fish) and total mortality, *Z* (solid line), determined using relative abundance analysis and assuming variable recruitment.

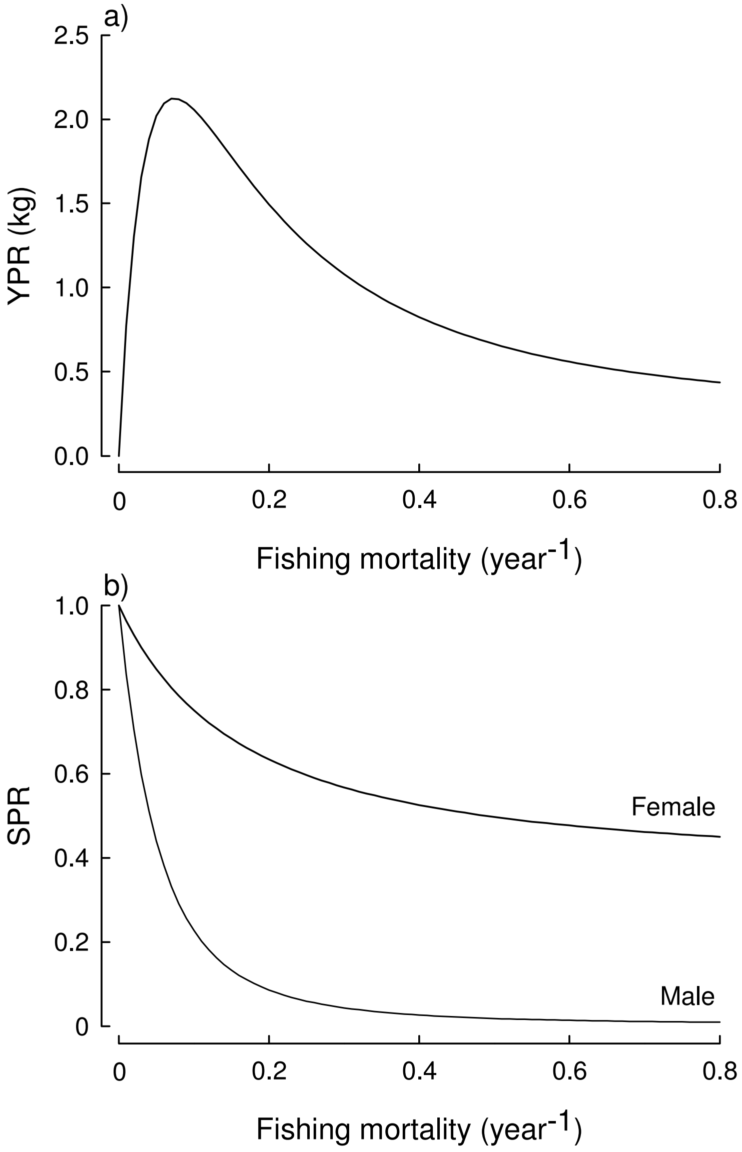

Figure 3.14. The effect of fishing mortality (*F*) at the current age at recruitment into the commercial gillnet fishery of *Achoerodus gouldii* on the a) yield per recruit (YPR) and b) spawning potential ratio (SPR).

3.4 DISCUSSION

3.4.1 ***Demonstration of protogynous hermaphroditism***

As all of the numerous *A. gouldii* caught with lengths < 655 mm were females and the males subsequently rose in prevalence with increasing body size to the point where this sex constituted 100% of the larger fish, this labrid is apparently a protogynous hermaphrodite. Such a conclusion is consistent with all but one of the 164 individuals < 15 years being females and the proportion of males thereafter increasing progressively to about 50% in individuals > 20 years old. It is also consistent with the results of our histological investigation of the gonads of a substantial number of individuals, covering the full size range of *A. gouldii* and all months of the year. These demonstrated that the mature testes of males contained conspicuous sperm sinuses in their outer walls and possessed a prominent and central lumen very similar to that found in the ovaries of females. Furthermore this prominent structure was present in the gonads of each of the six “intermediate-sized” individuals that contained both ovarian and testicular tissues and were thus assumed to be changing from female to male. Thus, as with other protogynous labrids, the prominent central lumen in the testis is considered to represent a retention of the ovarian lumen and, as in other protogynous hermaphroditic labrids, accounts for the peripheral location of the sperm ducts in those testes (*e.g.* Reinboth, 1970; Sadovy and Shapiro, 1987). From the above, it follows that *A. gouldii* possesses the characteristics that fulfill the criteria of Sadovy and Shapiro (1987) for demonstrating that it is a protogynous hermaphrodite, while the universal presence of a central “ovarian” lumen in testes and prominent peripherally-located sperm sinuses in mature testes show that this species is monandric, *i.e.* all males are derived from mature females.

3.4.2 *Growth*

Although the von Bertalanffy growth curve provided a good fit to the lengths at age of all aged individuals of *A. gouldii* irrespective of their sex, the variation in the lengths at age became very marked after *c.* 30 years of age (Fig. 3.5a). This variation clearly reflects a marked divergence in the growth of females and males among the larger and older fish (Fig 3.5b). The fact that the von Bertalanffy growth parameters for green and blue fish in the same subset of individuals were very similar to those derived for females and males demonstrate that growth curves based on colour provide a good proxy for those derived from known sex. Although a substantial number of the larger and older fish caught had been gutted prior to their receipt and could not thus be sexed and used for constructing growth curves for the two sexes, the colour of these unsexed fish was recorded. This led us to develop a novel technique for constructing growth curves for females and males which incorporated the lengths at age of all sexed and unsexed individuals, but took into account the probability that, on the basis of its length and colour, each unsexed fish would be either female or male. The von Bertalanffy growth curves thus derived for "females" and "males" are considered to provide very effective representations of the growth of the two sexes of *A. gouldii* and thus the associated growth parameters for those sexes were used for the per recruit models.

From the lengths at age of the two sexes shown in Fig. 5b, it is evident that the fastest growing *A. gouldii* have the greatest tendency to change from female to male. The greater length of the males than females at corresponding ages parallels the situation recorded for a number of other protogynous fishes, *e.g. Parapercis cylindrical*, *Chlorurus gibbus*, *Chlorurus sordidus*, *Scarus niger* and *Scarus frenatus* (Choat *et al.*, 2006, Munday *et. al.*, 2004; Walker and McCormick, 2004), as well as its congener *Achoerodus viridis* (Gillanders, 1995a). However, although all individuals had apparently become males by a length of *c.* 900 mm (Fig. 3.11a), approximately half of the oldest females had not become males (Fig. 5b). These data strongly indicate that some female *A. gouldii* are not destined to become males, as is also the case with *Cheilinus undulatus*, another large labrid (Choat *et al.*, 2006). Moreover, the conclusion that it is only the fastest growing *A. gouldii* that become males parallels that drawn by Munday *et al.* (2004) for the labrid *S. frenatus*. It is thus concluded that sex change is related more to size than age.

3.4.3 *Habitats and ontogenetic offshore movements*

The vast majority of the *A. gouldii* caught by spear fishing in nearshore waters were obtained from over the granite reefs that dominate the hard-structured substrate found in those waters along the south coast of Western Australia, including its islands (Kendrick, 1999; Sanderson *et al.*, 2000). The size composition of these catches is considered representative of those observed in the assemblages in the main productive sampling sites. The fact that these fish were predominantly < 600 mm and < 12 years old and few were mature during the spawning season strongly suggests that smaller, younger and immature fish occupy nearshore waters, which parallels the conclusions of Shepherd and Brook (2007). Although commercial gillnets would have selected for larger fish, the presence in deeper waters of large numbers of *A. gouldii* > 500 mm and many mature fish during the spawning season is consistent with the offshore movement recorded for this species by Shepherd and Brook (2007).

3.4.4 *Maximum length and age*

As hypothesized in the introduction, the greater total length attained by *A. gouldii* than *A. viridis*, as reflected in the 1162 mm *TL* recorded in the present study *vs* the 773 mm *TL* (after conversion from *SL*) recorded in the detailed study of Gillanders (1995a) was accompanied by a marked difference in the maximum age determined for these two species in those studies, *i.e.* 70 *vs* 35 years. The maximum age of *A. gouldii* is thus twice as great as that estimated by Gillanders (1995a) for *A. viridis*, which is apparently the greatest yet recorded for any other species of labrid, including the largest member of this family, *i.e. C. undulatus*, which reaches total lengths of 2300 mm and a maximum age of 32 years (Choat *et al.*, 2006; Nelson, 2006). From the above, it follows that *A. gouldii* does not have the relatively short life span that is typically a characteristic of large labrids (Choat *et al.*, 2006). It is thus relevant that the two *Achoerodus* species, which are the longest living labrids, are essentially temperate species, whereas *C. undulatus* and other large labrids are mainly tropical.

3.4.5 *Length and age at maturity and sex change*

The hypothesis that the far greater length and age attained by *A. gouldii* than *A. viridis* is accompanied by a far greater length and age at maturity of females has been confirmed. In the case of *A. gouldii*, no mature female was found at a length < 391 mm *TL* and the L_{50} of females at maturity was as high as 653 mm *TL*. Furthermore, only one of the 164 females < 5 years old was mature and maturity was only reached by *c.* 50% of females after they had reached 15-19 years in age. Although Gillanders (1995a) did not estimate the L_{50} at maturity for females, she recorded that females first matured at 200-220 mm *SL* (= 246-270 mm *TL*) and that the majority matured at 240-280 mm *SL* (= 294-341 mm *TL*). She also found that, while a few female *A. viridis* became mature at the end of their second year of life, the majority matured between their third and fifth years of life.

The trend for maturity to be attained at a greater length and age by *A. gouldii* than by the smaller *A. viridis* is paralleled by the situation with the length and even more particularly the age at sex change. Thus, whereas *A. gouldii* did not start changing sex until it was 655 mm *TL*, and its L_{50} at sex change was as high as 821 mm (*TL*), males of *A. viridis* were as small as 500 mm *SL* (= 603 mm *TL*) (Gillanders 1995a). Only four of

728 *A. gouldii* < 20 years old were males and their prevalence did not reach 50% until they had reached 35-39 years in age. In contrast, sex change was observed in *A. viridis* as young as 10 years old (Gillanders 1995a).

3.4.6 *Colour change*

Achoerdus gouldii undergoes the type of colour change that is found during the life cycle of most protogynous labrids and which is broadly associated with sex change (*e.g.* Gillanders 1995a; McBride and Johnson, 2007). This involved a change from green to blue in *A. gouldii*, compared with red/brown to blue in *A. viridis* (Gillanders, 1999). However, as with the latter congeneric species, some females (3%) were not of the initial colour and some males (11%) did not have the terminal colour. Furthermore, the continuous variable, length, was found to provide a better predictor of sex than the dichotomous variable, colour, but a combination of these variables further improved the predictive ability. This raised the question of whether the colour of *A. gouldii* could be used as a proxy for gonadal type, *i.e.* ovary or testis to derive a reasonable estimate of the length at sex change. The fitting of logistic curves to the length data for fish with testes and with blue coloration yielded L_{50}s of 821 and 779 mm, respectively. Although these two L_{50} differed by 42 mm, their 95% confidence limits overlapped. While caution must be exercised in using colour change to derive an L_{50} for sex change, it does enable a "ball park" value to be estimated when it is not possible to record the sex of individuals because, for example, they could not be dissected or were carcasses, *i.e.* their viscera had been removed.

3.4.7 *Management implications*

A combination of extreme longevity (maximum age = 70 years), late maturity (L_{50} = 653 mm and *c.* 20 years) and late sex change (L_{50} = 821 mm and *c.* 35 years), make *A. gouldii* potentially very susceptible to even moderate levels of fishing. Our data also demonstrated that the strength of recruitment of the different year classes varied greatly and thus certain year classes made large contributions to the overall catch. Consequently, truncation in the age composition through fishing mortality would be likely to increase the susceptibility of the stock to overfishing.

The yield per recruit analyses indicate that, at the current estimated level of exploitation (*i.e.* F/Z) of 45%, the yield per recruit (1.88 kg) is close to the maximum of 2.2 kg and that, if fishing mortality were to increase beyond 0.07 year^{-1}, growth overfishing would commence. The yield per recruit analyses also suggest that the current level of fishing mortality is close to the yield per recruit-based reference point of $F_{0.1}$ (year^{-1}), often considered more appropriate than the fishing mortality reference point associated with the maximum yield per recruit, $F_{\max}$.

In the context of the potential for recruitment overfishing of *A. gouldii*, it is relevant that its much smaller and earlier maturing congener, *A. viridis*, suffered such heavy mortality in eastern Australia that those waters were closed to commercial and recreational fishing for this species and still remain closed to spear fishing and commercial fishing (Gillanders 1999, NSW State of Fisheries Management Regulations 2002). Recently, the instantaneous rate of fishing mortality for heavily-fished local populations of *A. gouldii* in South Australia was estimated to be as high as 0.8 year^{-1} (Shepherd and Brook, 2007). As the current level of fishing mortality for *A. gouldii* in south-western Australian waters is estimated as corresponding to 74% of natural mortality, when using the recently-developed approach of Hall *et al.* (2004), this species is apparently close to or at full exploitation in these waters. Even if the unadjusted Hoenig (1983) point estimate of M is used, the corresponding value is still nearly 55%.

The conclusion that *A. gouldii* is close to or at full exploitation is consistent with the estimate of spawning potential ratio (SPR) for the males of this protogynous hermaphroditic labrid having declined to 0.52 and thus approaching the value of 0.30 often regarded as the one at which a stock is considered to be overfished (Mace & Sissenwine, 1993; Goodyear, 1993). Indeed, the lower 95% CL of 0.27 for SPR lies below this reference point. From a fisheries management point of view, it is also relevant that 52% of the *A. gouldii* taken by the commercial fishery are below the L_{50} of 653 mm at which females attain maturity, and 88% are below the L_{50} of 821 mm at which females change to males. The potential for overfishing of *A. gouldii* is compounded by the fact that its current minimum legal length (MLL) in Western Australia is 500 mm and thus well below the L_{50} at both maturity and sex change. This is particularly pertinent in the case of recreational line and spear fishing, which occurs most in accessible, shallow waters (< 20 m) and where the individuals of *A. gouldii* are smaller than in deeper waters.

From the above, it follows that, as with other hermaphroditic species, management plans for *A. gouldii* must take into account the ways in which the sizes and ages at which sex change occur are likely to influence that species susceptibility to fishing (see also Bannerot *et al.*, 1987; Buxton, 1992; Hesp *et al.*, 2004; Pember *et al.*, 2005). Furthermore, our data for *A. gouldii* emphasize that per recruit analyses for hermaphroditic species, in which the growth of the two sexes differs markedly, should ideally incorporate the separate estimates of growth of the females and males. This point is emphasized by the fact that the estimates of SPR for males decline more rapidly with increasing fishing mortality when the different growth of the sexes are taken into account, than when they are not included as separate components in the analysis.

The implications of the life cycle characteristics possessed by *A. gouldii* and the results of the per-recruit analyses demonstrate that managers will need to take a precautionary approach to managing *A. gouldii* to ensure its sustainability. They will also need to recognize that the individuals of *A. gouldii* often suffer barotrauma-related injuries when brought to the surface from deep waters (P. Couslon, pers. observ.), thereby paralleling the situation with many other demersal species (*e.g.* True *et al*., 1997; St John and Syers, 2005; Parker *et al*., 2006), including other species of labrid (Nardi *et al*., 2006). Plans for conserving *A. gouldii* will thus probably have to be directed towards controlling fishing effort, rather than, for example, regulating the size for legal retention.

4.0 BIOLOGY OF THE BLUE MORWONG *NEMADACTYLUS VALENCIENNESI*

4.1 INTRODUCTION

The 22 species of the Cheilodactylidae, which are found mainly in temperate regions of the southern hemisphere, with the exception of Japan, are characterised by their possession of thick fleshy lips and enlarged pectoral fins in which the lower fin rays are extended (Lowry and Cappo, 1999; Allen *et al.*, 2006c). Cheilodactylids make an important contribution to reef fish populations in New Zealand (Tong and Vooren, 1972; Leum and Choat, 1980; McCormick, 1989a, b), Australia (Branden *et al.*, 1986; Cappo, 1995; Lowry and Suthers, 1998a, b), South Africa, Japan and South America (Nielsen, 1963; Sano and Moyer, 1985; Lowry and Cappo, 1999). They attain maximum lengths of between 300 and 1200 mm and one species has a maximum age of 97 years (Hutchins and Swainston, 1986; Gommon *et al.*, 1994; Ewing *et al.*, 2007). All three genera in the Cheilodactylidae, *Nemadactylus*, *Cheilodactylus* and *Dactylophora*, are represented in waters along the southern coastline of Australia, where nine of the twelve species found in these waters occupy habitats ranging from inshore reefs to the continental slope (Allen *et al.*, 2006c).

The Blue Morwong *Nemadactylus valenciennesi*, which is readily distinguished by its bright blue colour and yellow lines radiating out from around the eyes, is common on inshore and offshore reefs in South Australia and south-western Western Australian waters where it reaches a length of *c.* 100 cm and a weight of *c.* 11 kg (Hutchins and Swainston, 1986; Lowry and Cappo, 1999). Although *N. valenciennesi* is the most abundant species of scalefish caught by the commercial gillnet fishery operating off the south coast Western Australia (McAuley and Simpfendorfer, 2003), there have been no studies of its biology.

The first aim of the present study was to determine the length and age compositions, growth and key aspects of the reproductive biology of *N. valenciennesi*. Comparisons have been made between the characteristics of the individuals caught in inshore and offshore waters and on the lower west and south coasts of Western Australia, in which, for example, water temperatures differ. The length and age compositions of *N. valenciennesi* caught by different methods (spear fishing, recreational line fishing and commercial gill netting) are compared. Finally estimates are made of mortality, yield per recruit and spawning stock biomass per recruit to ascertain whether there is evidence that this species is being heavily or over exploited.

4.2 MATERIALS AND METHODS

4.2.1 ***Sampling regime***

Nemadactylus valenciennesi was collected mainly by using the same methods and from the same localities (except Hopetoun) as described for *A. gouldii* (Chapter 3). Additional fish were obtained from weigh-ins held after annual recreational fishing competitions in Esperance, Bremer Bay and Albany and at monthly recreational fishing competitions in Perth (Fig. 3.1). The sources (*i.e.* spear fishing, recreational line fishing or commercial gill netting), locations and length ranges of *N. valenciennesi* in each of the total sample for each month of the calendar year are provided in Table 4.1.

4.2.2 ***Laboratory procedures and analyses***

Nemadactylus valenciennesi was subjected to the same procedures and analyses as described in the General Materials and Methods (Chapter 2). In addition, the fork length (*FL*) and total length (*TL*) in a subsample covering a wide size range of *N. valenciennesi* were recorded in order to derive the relationship between these two length variables and

Table 4.1. Sample sizes and length ranges of *Nemadactylus valenciennesi* collected by spear fishing, recreational line fishing and commercial gill netting on the south and lower west coasts of Western Australia.

		Spear fishing (south coast)		Line fishing (south coast)		Line fishing (lower west coast)		Gill netting (south coast)		Gill netting (lower west coast)	
Year	Month	*n*	Length range (mm)	*n*	Length range (mm)	*n*	Length range (mm)	*n*	Length range (mm)	*n*	Length range (mm)
2004	March					4	431-747				
	April			2	561-704	23	480-919				
	May					3	703-784	27	511-800		
	June					1	563	55	517-920		
	July					1	564				
	August					2	682-725			9	543-835
	September					5	556-808	3	618-844		
	October	9	270-720					19	445-877		
	December					6	550-879				
2005	January					8	549-870	4	651-723		
	February					3	540-660	32	535-850	33	540-850
	March					11	497-806	2	709-755		
	April					5	646-765				
	May	30	185-689			1	880	23	538-774		
	June	20	197-712			1	825	6	561-705		
	July					3	584-653	3	649-805		
	August	29	255-592	3	706-812	2	565-647	22	606-858		

	September	16	280-648			1	775	6	568-880		
	October					3	616-774	65	530-891	4	530-820
	November							79	568-897		
	December	65	261-660	1	712			12	552-790		
2006	January					4	619-784			14	576-802
	February	44	312-772	9	549-724	6	569-814-	73	452-940	31	517-800
	March	25	330-758	89	404-902	2	707-821	28	499-905		
	April	18	342-689	11	493-826	2	499-534				
	May			4	495	6	512-872	48	512-827	13	545-770
	June			30	495-984	3	614-716	108	442-870	7	555-800
	July	22	366-835					103	491-958		
	August							144	491-859		
	September	11	402-686	20	450-814	2	590-605	95	528-950		
	October	4	448-721			3	552-842				
	November	14	373-779	9	573-879	2	525-678				
	December							13	598-786		
2007	January	15	336-641	11	550-864			43	497-951		
	March			24	435-874						
	April			12	493-765						
	June			11	457-817						
	July			2	593-636						
	October			8	587-820						
Total		322	185-835	246	404-984	113	431-919	1013	442-958	102	517-850

thus facilitate comparisons between the lengths recorded in the present study and those in other studies of *Nemadactylus macropterus*, *Cheilodactylus spectabilis* and *heilodactylus fuscus* where *FL* rather than *TL* was recorded (Smith, 1982; Murphy and Lyle, 1999; Jordan 2001a; Lowry, 2003).

The growth curves of the females and males of *N. valenciennesi* caught in waters on the lower west coast were compared with those of the corresponding sexes on the south coast in the same manner as described in Chapter 2.

4.3 RESULTS

4.3.1 ***Environmental measurements***

Mean monthly water temperatures in inshore waters at Albany and Esperance, which, in most months, differed by < 1.5°C, rose from their minima of *c*. 14.5 to 15.5°C in July and August to *c*. 21.2 to 21.7°C in January and then declined to *c*. 15.5 to 16.5°C in June (Fig. 4.1). The mean monthly water temperatures were less at Albany than Esperance in July to October and from March to July, whereas the reverse was true for November to February.

Although the mean monthly water temperatures followed very similar trends throughout the year in the deeper waters at the three locations at which *N. valenciennesi* were caught, they were, in any one month, always greater at Rottnest than at Albany, which, in turn, were always greater than at Esperance (Fig. 4.1). The minimum mean monthly temperatures at those three localities, which were recorded in either September or October were 18, 16.5 and 15°C, respectively, whereas the maximum mean temperatures, which were recorded in March, were 22, 20 and 19°C, respectively.

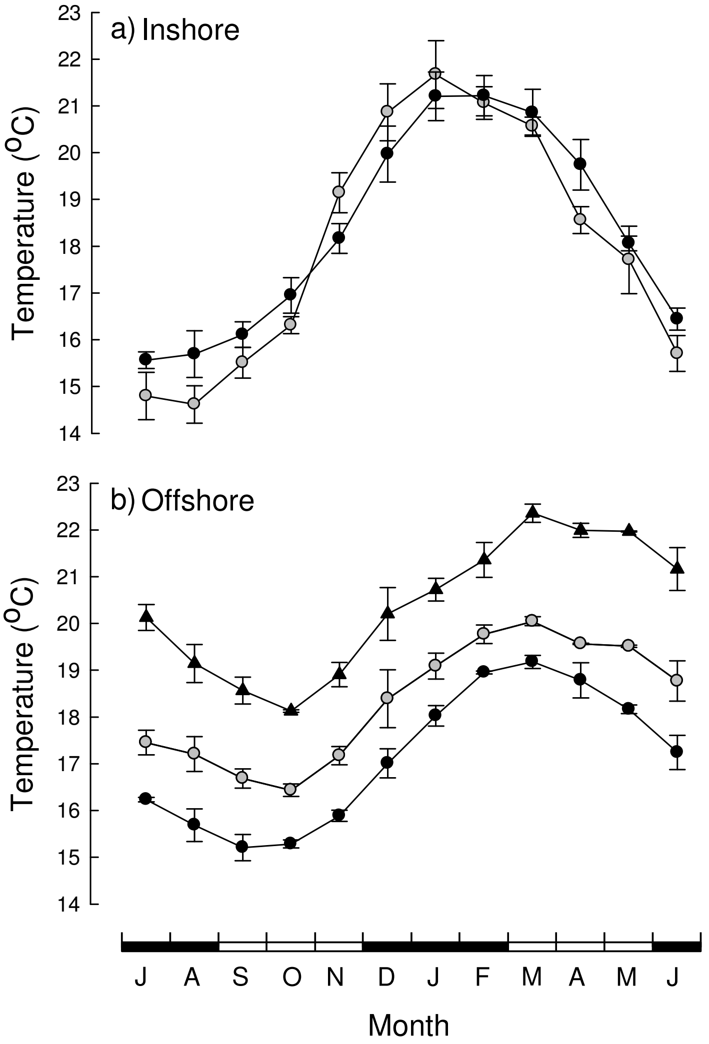

Figure 4.1. Mean monthly water temperatures ± 1 SE for a) inshore waters at Albany (grey circles) and Esperance (black circles) and b) offshore waters at Albany (grey circles), Esperance (black circles) and Rottnest (Black triangles) on the south and lower west coasts of Western Australia. In this Fig. and Figs. 4.3 and 4.6, closed rectangles on the x-axis refer to winter and summer months and the open rectangles to spring and autumn months.

4.3.2 *Validation of ageing using otoliths*

The alternating opaque and translucent zones were clearly defined in sectioned otoliths of *N. valenciennesi* when these otoliths were viewed using transmitted light (Fig. 4.2). The primordial region of the otolith is wide and opaque and surrounded by a translucent zone. The first opaque zone is relatively wide and, like the previous translucent zone on its inner edge, becomes increasing less defined in older fish and particularly in those with > 9 opaque zones (Fig. 4.2). Each opaque zone, which was most clearly defined on the lower ventral region of the sectioned otolith, becomes successively narrower towards the otolith periphery.

The mean monthly marginal increments for otoliths with two to four zones remained > 0.37 between September and November and then declined precipitously to 0.30 in December and 0.25 in January, after which they increased progressively to 0.34 in July (Fig. 4.3). The mean monthly marginal increments for otoliths with 5 to 7, 8 to 10 and > 10 zones followed essentially the same trend as that described above for otoliths with 2 to 4 zones, with values declining markedly to their minima in mid-summer (Fig. 4.3). Although the number of fish with otoliths containing one opaque zone in many months was low, the trends exhibited by their mean monthly marginal increments followed the same seasonal pattern as those just described for otoliths with a greater number of opaque zones (Fig. 4.3). The single pronounced decline and then progressive increase undergone by the mean monthly marginal increments during the year demonstrate that a single opaque zone is formed annually in the otoliths of *N. valenciennesi* and that the number of opaque zones in those otoliths can thus be used to estimate the age of the individuals of this species.

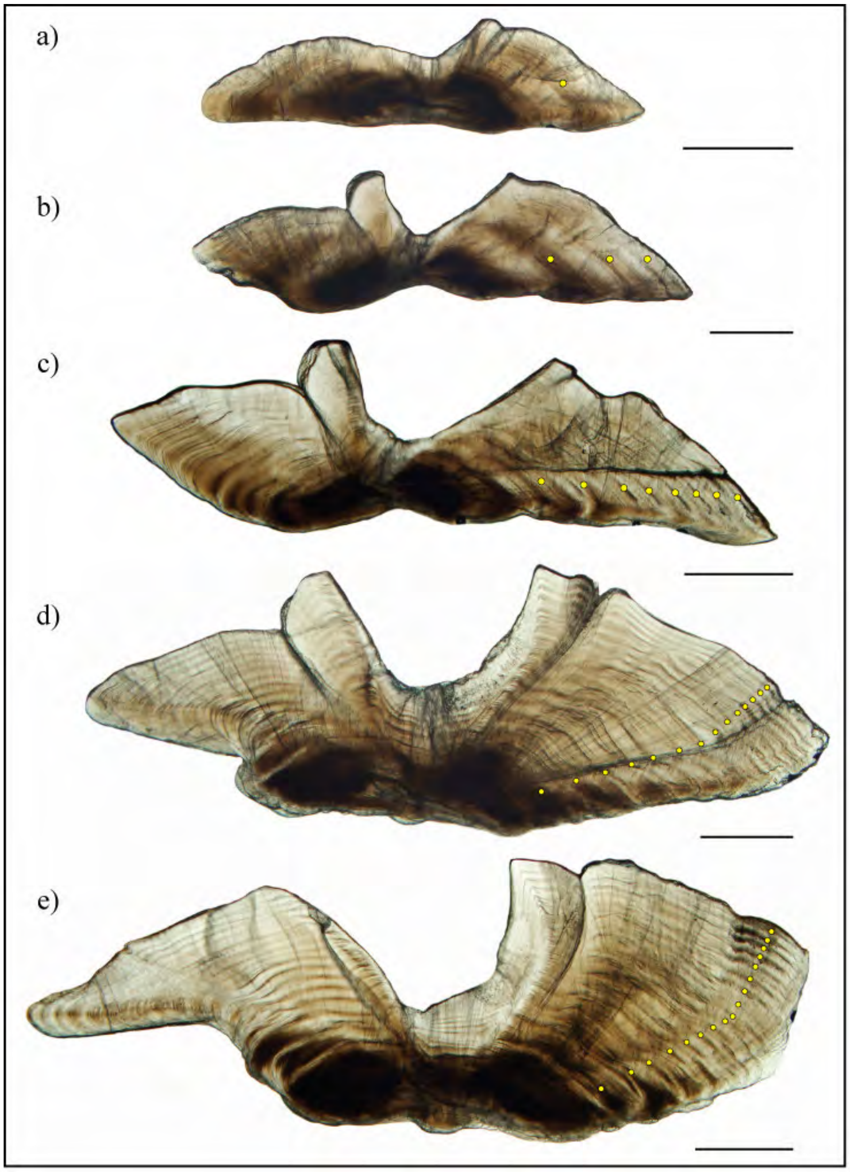

Figure 4.2. Sectioned otoliths of *Nemadactylus valenciennesi* with a) 1, b) 3, c) 8, d) 14 and e) 17 growth (opaque) zones (●). Scale bars = 0.5 mm.

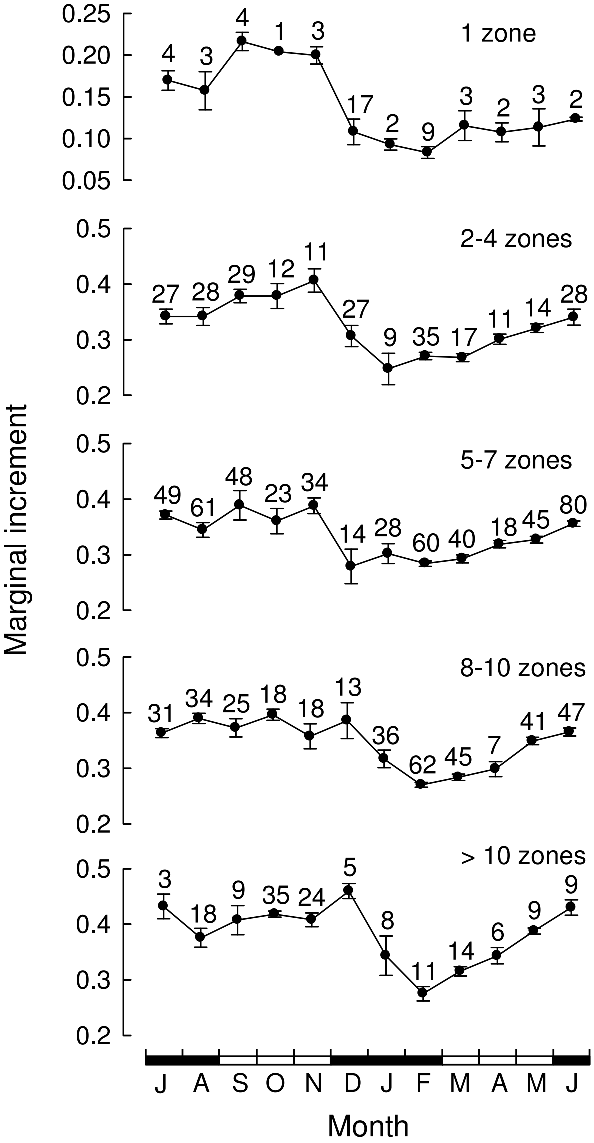

Figure 4.3. Mean monthly marginal increments ± 1 SE on sectioned sagittal otoliths of *Nemadactylus valenciennesi* with different numbers of opaque zones. Sample sizes shown above each mean.

For ageing purposes, 1 March was considered to represent the birth date of *N. valenciennesi* as the trends exhibited by reproductive variables demonstrated that the approximate mid-point of the spawning period of this species was March (see later).

The two smallest *N. valenciennesi*, whose otoliths were not damaged during capture, as occurred with the smallest fish of 157 mm, were caught in May and June and measured 185 and 197 mm, respectively, which, on the basis of studies of other cheilodactylids (*e.g. N. macropeterus*), is far greater than would be expected if they were derived from spawning in the immediately preceding summer/ autumn spawning period. Their otoliths contained a central opaque primordium and a surrounding translucent area and no clearly defined outer opaque zone. The smallest *N. valenciennesi* with otoliths containing a single, recently-delineated opaque zone measured 294, 297 and 299 mm in length and were caught in December. From the sizes and times of capture of the above fish and the characteristics of their otoliths, it is assumed that an opaque zone is laid down in the second winter of life when the fish are just over a year old. In other words, the fish caught in May and June were *c.* 15 and 16 months old, while those from December were *c.* 22 months old.

4.3.3 *Length and age compositions of catches*

The individuals of *N. valenciennesi* that could be sexed during this study ranged in length and age from 157 to 846 mm and 1 to 17 years for females and from 192 to 984 mm and 1 to 19 years for males. The largest and oldest *N. valenciennesi*, from which the gonads had been removed during filleting and could thus not be sexed, was 958 mm and 21 years.

The *N. valenciennesi* collected by spear fishing (inshore), recreational line fishing (offshore) and commercial gill netting (offshore) ranged in length from 157 to 868 mm ($\bar{x} = 494$ mm), 404 to 984 mm ($\bar{x} = 653$ mm) and 442 to 958 mm ($\bar{x} = 682$ mm), respectively (Fig. 4.4a). These lengths correspond to fish ranging in age from 1 to 16 years, 2 to 17 years and 3 to 21 years of age, respectively (Fig. 4.4b). The length and age compositions show that *N. valenciennesi* becomes fully recruited into the recreational and commercial fisheries at lengths of 600 to 649 mm and 650 to 699 mm, respectively, and at 6 and 9 years of age, respectively.

The likelihood ratio test demonstrated that, on both the south and lower west coasts, the growth curves of females and males of *N. valenciennesi* were significantly different ($p < 0.05$). Although the growth of the corresponding sexes on the two coasts were significantly different ($p < 0.05$), the differences in the lengths estimated from those curves for females and males at each age between five and 12 years, for which there were substantial samples, was always less than 4%. Thus, these differences between regions are considered to be of little biological significance and consequently the lengths at age of females and of males in the two regions have been pooled to produce a single growth curve for each sex in the two regions (Fig. 4.5).

von Bertalanffy growth curves provided good fits to the lengths at age of the individuals of both sexes (Fig. 4.5), as demonstrated by the relatively r^2 high values of 0.86 and 0.80 for the curves for females and males, respectively (Table 4.2). The growth curves of females and males were significantly different ($p > 0.001$). On average, at ages 5, 7 10, 13 and 15 years, females attain lengths of 550, 615, 662, 682 and 688 mm, compared with 583, 673, 752, 793 and 809 mm by males.

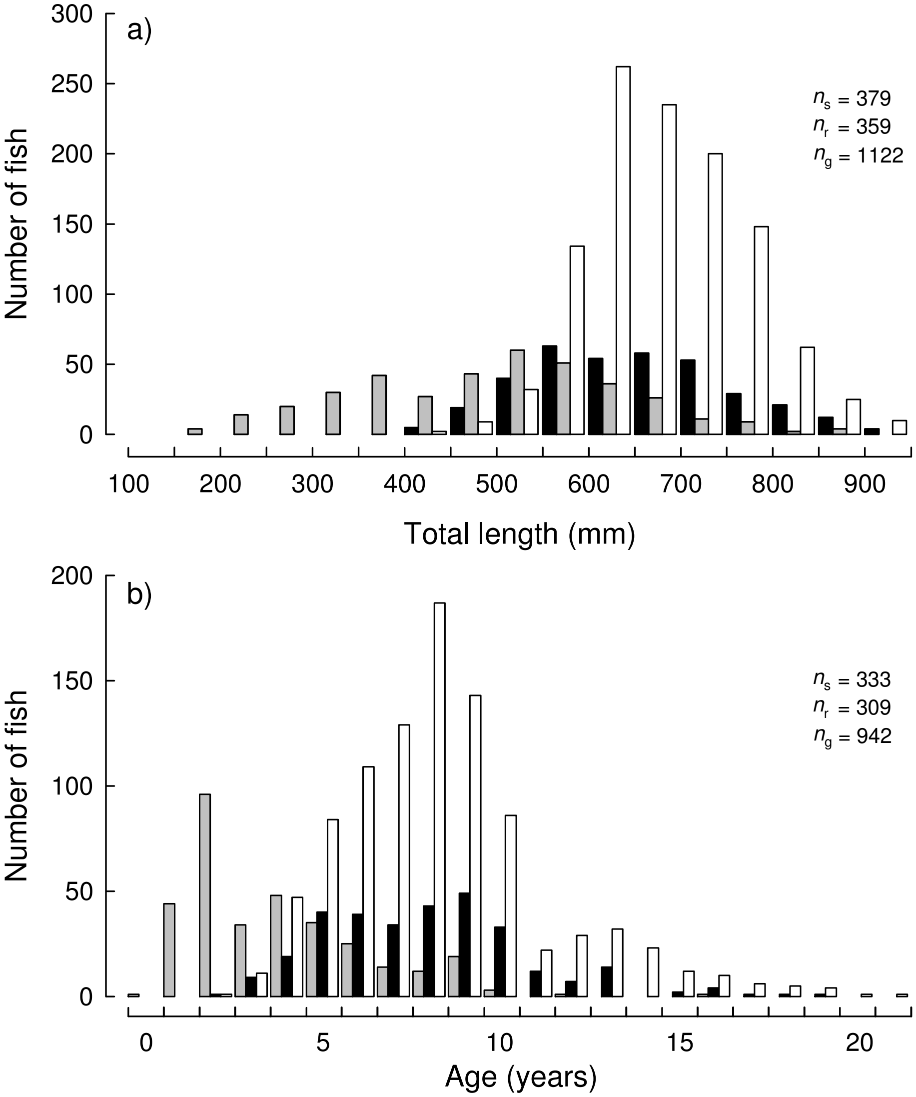

Figure 4.4. Length and age-frequency distributions for *Nemadactylus valenciennesi* caught in inshore waters by spear fishing (grey histograms), recreational line fishing (black histograms) and commercial gillnetting (white histograms) in offshore waters. n_s, n_r and n_g, number of fish caught by spear fishing, recreational line fishing and gill netting, respectively.

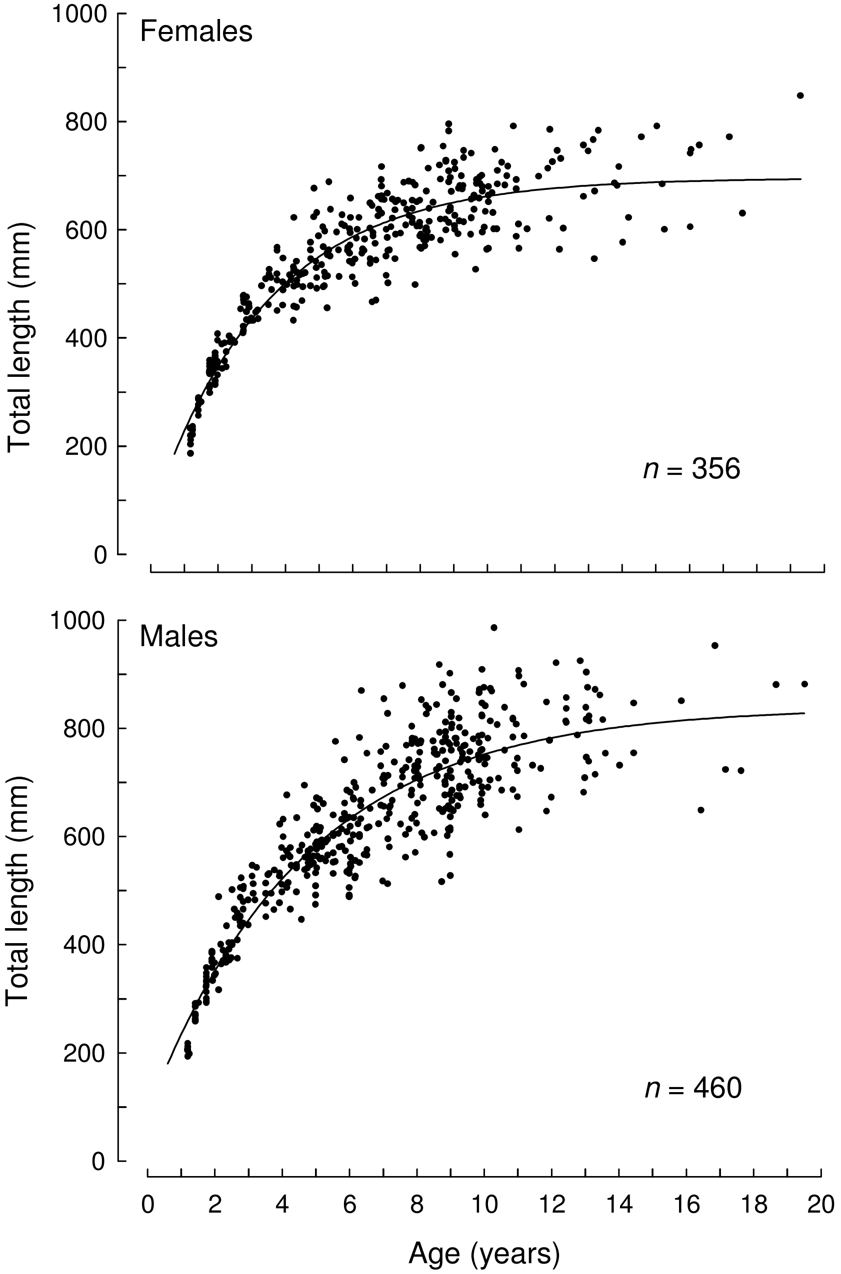

Figure 4.5. von Bertalanffy growth curves fitted to the lengths at age of females and males of *Nemadactylus valenciennesi*.

Table 4.2. von Bertalanffy growth curve parameters, L_∞, k and t_0, and their lower and upper 95% confidence limits, for the females and males of *Nemadactylus valenciennesi* in south-western Australia. L_∞ is the asymptotic length (mm), k is the growth coefficient (year^{-1}), t_0 is the hypothetical age (years) at which fish would have zero length, r^2 is the coefficient of determination and n is the number of fish.

		L_∞ (*TL* mm)	k (year^{-1})	t_0 (years)	r^2	n
Female	Estimate	696	0.29	-0.36	0.86	356
	Lower	678	0.25	-0.65		
	Upper	713	0.33	-0.07		
Male	Estimate	839	0.22	-0.52	0.80	460
	Lower	808	0.18	-0.87		
	Upper	870	0.25	-0.17		

The relationship between total length (*TL*) in mm and total weight (*W*) in g for *N. valenciennesi* is described by the following regression equation: $\ln W = 2.969(\ln TL) - 11.154$ ($r^2 = 0.991$, $n = 330$, $p = < 0.001$). The relationship between fork length (*FL*) and total length (*TL*) in mm for *N. valenciennesi* is described by the following regression equation: $TL = 1.118(FL) + 25.105$ ($r^2 = 0.993$, $n = 1374$, $p = < 0.001$).

4.3.4 *Reproductive biology*

As the vast majority of fish caught in inshore waters on the south coast were immature, the mean monthly GSIs were calculated for neither the females nor males in these waters. Although the prevalence of mature females and males in offshore waters of the south coast increased with total length, the pattern of change did not follow a logistic trend (see later) and thus the approximate length at which maturity was reached by 50% of females (650 mm) and males (725 mm) were derived from an examination of the data shown later in Figure 4.8b. The mean monthly GSIs for female *N. valenciennesi* in south coast offshore waters rose progressively from 0.8 in December to reach a maximum of 2.2 in March, before declining sharply to 0.5 in June (Fig. 4.6a).

As all or the vast majority of each length class of both the females and males of *N. valenciennesi* in offshore waters of the lower west coast were mature during the spawning period (see Fig. 4.8), the mean monthly GSIs for fish in these waters were constructed using the data for all fish caught in those waters. Although the mean monthly GSIs for female *N. valenciennesi* in lower west coast offshore waters thus displayed a similar seasonal trend the, mean monthly GSIs were much higher maximum than those in south coast offshore waters, *i.e.* 3.8 *vs* 2.2 (Fig. 4.6b).

The mean monthly GSIs for male *N. valenciennesi* in offshore waters of the south and lower west coasts displayed similar trends to those described for their females and likewise reached a higher maximum on the latter coast (Fig. 4.6a, b).

The ovaries of all females caught on the south coast from January to November were at stages I/II (Fig. 4.7). The prevalence of females with stages V/VI ovaries was low, *i.e.* ≤ 25%, in all months in which they were present except for March, *i.e.* 83%. Males with testes at stages V/VI were present only in February and March in these waters (Fig. 4.7). Females and males with ovaries and testes at stages V/VI, respectively, were more prevalent in the majority of those months in which they occurred and were present for a more protracted period in lower west coast offshore waters than in south coast offshore waters (Fig. 4.7).

The above trends in monthly values for female and male GSIs and prevalence of females and males with stages V/VI ovaries and testes, respectively, demonstrate that spawning occurs predominantly between January and May. For this reason, 1 March was chosen as the birth date for *N. valenciennesi*.

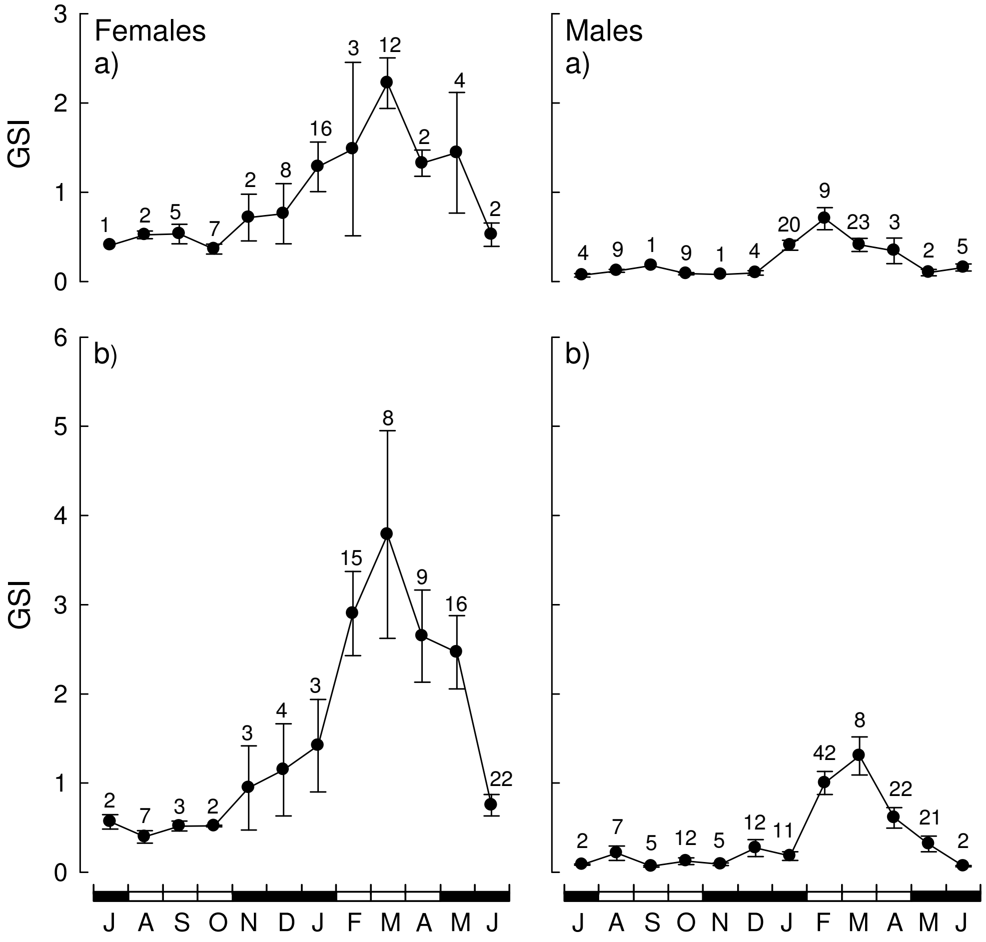

Figure 4.6. Mean monthly gonadosomatic indices ± 1 SE for a) female and male *Nemadactylus valenciennesi* ≥ L_{50} at maturity, *i.e.* 637 mm and 725 mm, respectively, from south coast waters and b) females and males ≥ 400 and 500 mm, respectively, from lower west coast offshore waters. Sample sizes shown above each mean.

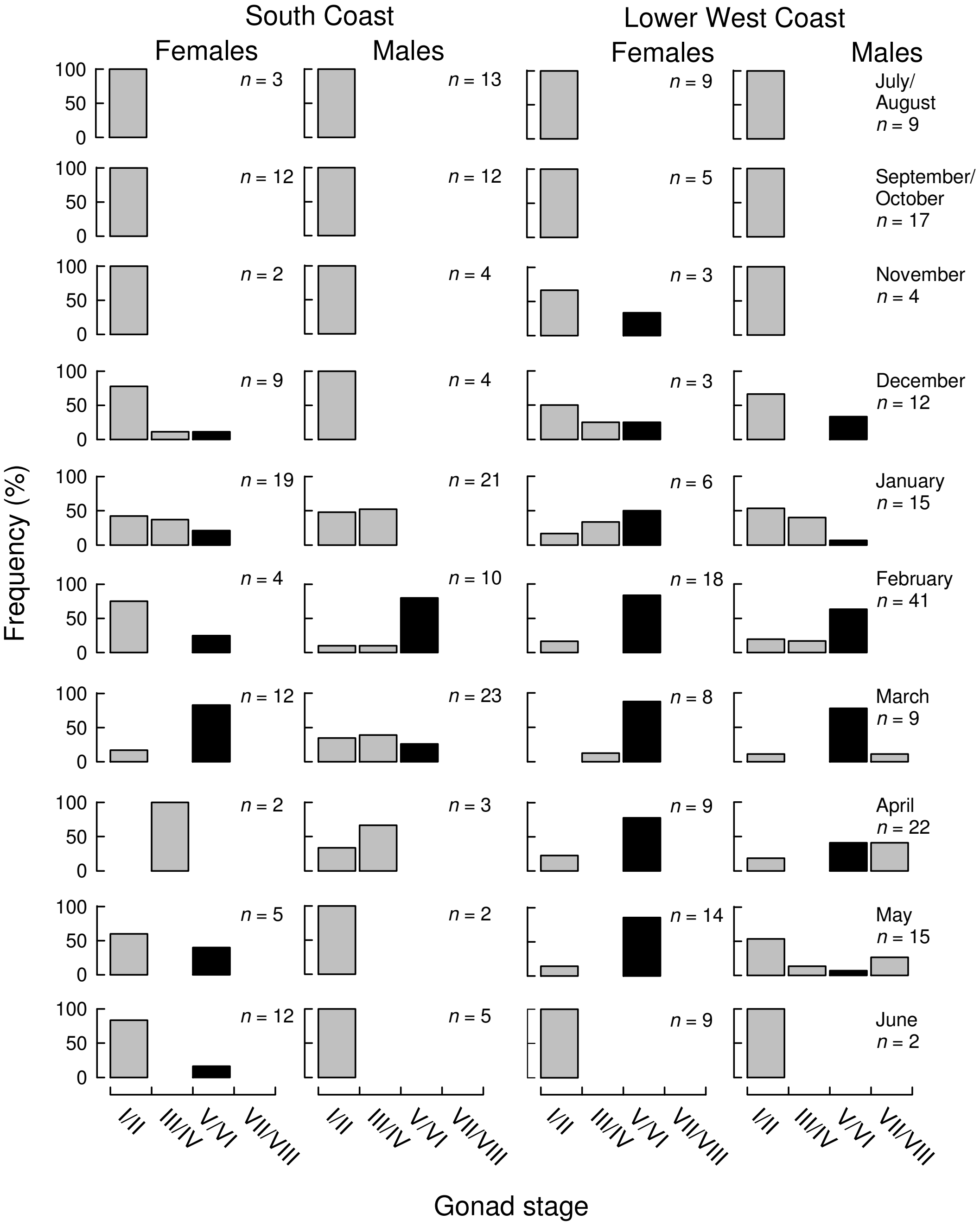

Figure 4.7. Monthly percentage frequencies of occurrence of sequential stages in gonadal development of females and males ≥ L_{50} at maturity, *i.e.* 637 mm and 725 mm, respectively, from south coast offshore waters and female and male *Nemadactylus valenciennesi* ≥ 400 and 500 mm, respectively, from west coast waters. Histograms for stages V and VI collectively are highlighted in black. *n* = sample size.

4.3.5 *Length and age at maturity*

Few mature females or males were caught in inshore waters of the south coast (Fig. 4.8a). The percentage of mature females in offshore waters increased progressively from 12% in fish of 500 to 549 mm to *c*. 50% in those of 600 to 699 mm and 100% in females > 750 mm (Fig. 4.8b). A similar trend occurred with males. The proportion of mature fish among females and males on the south coast were 48 and 43%, respectively. Although the length ranges of females and males in offshore waters of the lower west coast were similar to those on the south coast, the vast majority of females (89%) and males (82%) on the lower west coast were mature (Fig. 4.8c). The approximate lengths at which 50% of females in offshore waters of the south and lower west coasts of Western Australia were mature were 600 and 400 mm, respectively. The lengths at maturity for males in those same waters were 650 and 500 mm, respectively.

None of the females caught below the age of five years in nearshore waters of the south coast was mature and the same was true of males under the age of ten years (Fig. 4.9a). In south coast offshore waters, the percentage frequency of occurrence of mature females was as low as 16% in fish of six years, but subsequently increased in an essentially progressive manner to 100% in fish of ≥ 13 years (Fig. 4.9b). The prevalence of mature male fish in those waters also rose with increasing age (Fig. 4.9c). In contrast, all female *N. valenciennesi* caught in offshore waters of the lower west coast were ≥ three years old and, of those, all but four 5 year olds and two 9 year olds were mature (Fig. 4.9c). Similarly all males caught in these waters were ≥ three years old and the vast majority were mature (Fig. 4.9c).

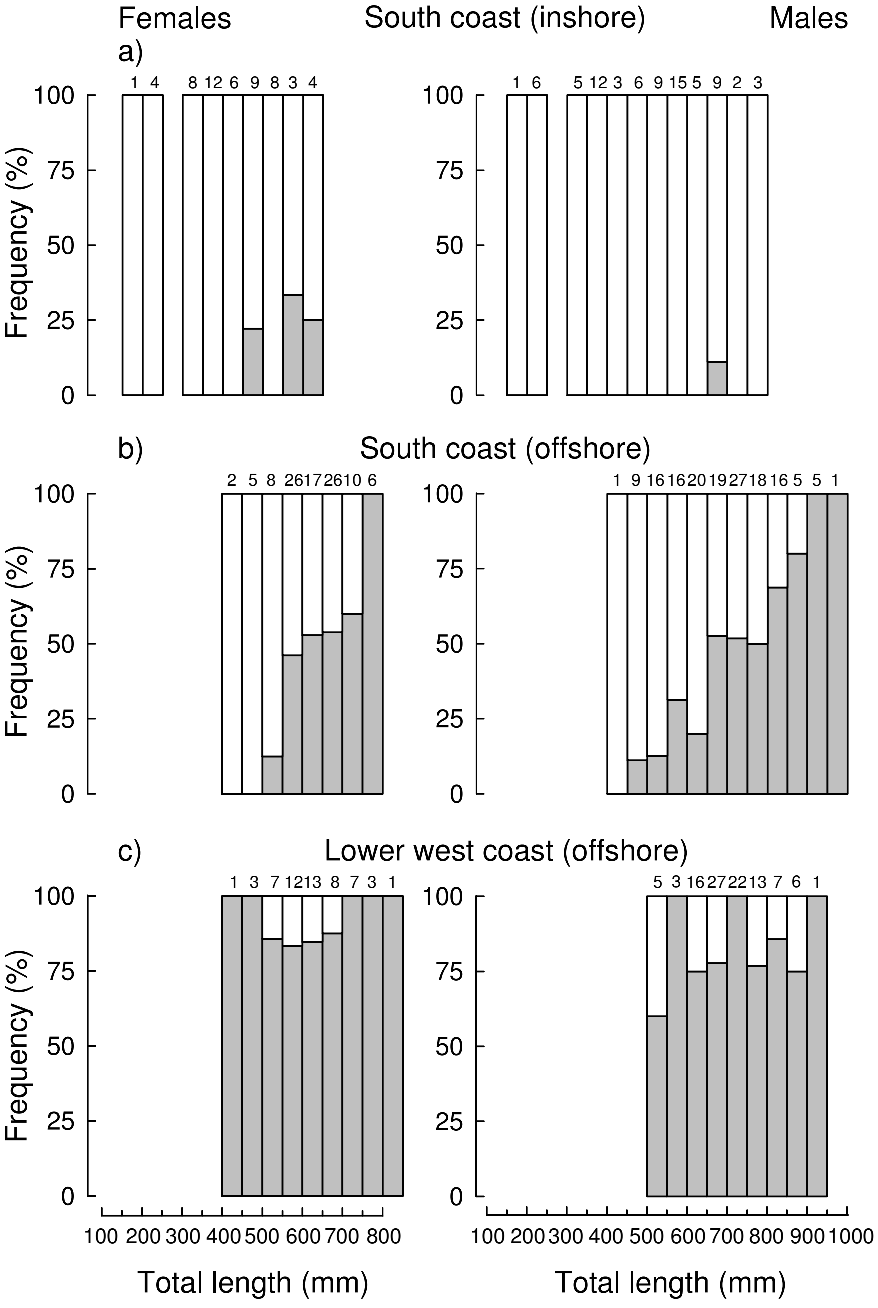

Figure 4.8. Percentage frequency of occurrence of female and male *Nemadactylus valenciennesi* with mature gonads (grey histograms) in sequential 50 mm length classes in samples obtained during spawning period, *i.e.* January to May. Sample sizes shown above each histogram.

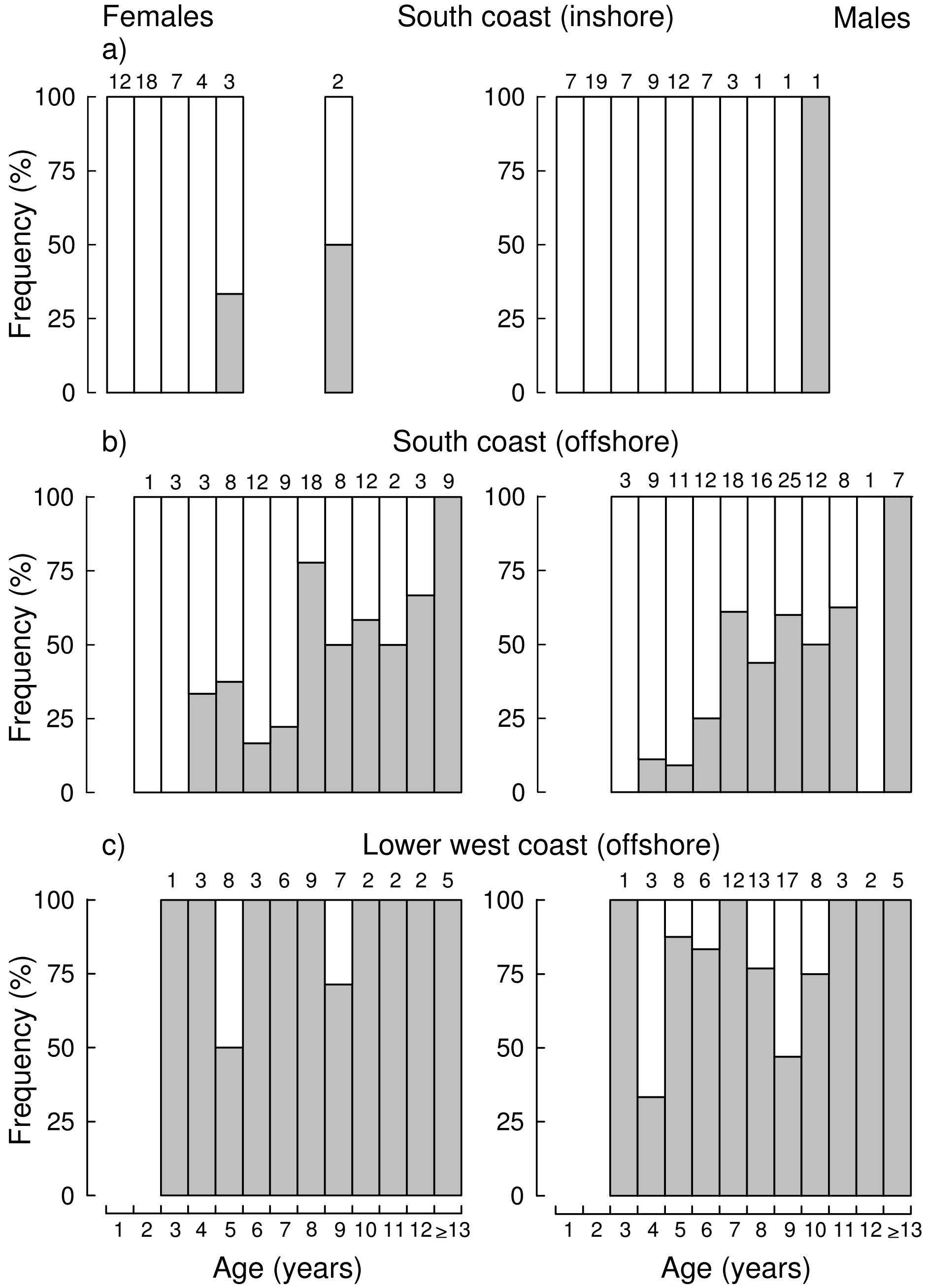

Figure 4.9. Percentage frequency of occurrence of female and male *Nemadactylus valenciennesi* with mature gonads (grey histograms) in age categories sampled during the spawning period, *i.e.* January to May. Sample sizes shown above each histogram.

4.3.6 *Fecundity*

The diameter frequencies of oocytes in the ovaries of two mature (stage V) female *N. valenciennesi*, and which contained early previtellogenic, cortical alveolar and yolk granule oocytes, formed essentially a continuous distributions (Fig. 4.10). This continuity in the distribution of the sizes of oocytes demonstrates that *N. valenciennesi* possesses indeterminate fecundity and strongly indicates that females release batches of eggs at intervals throughout its spawning period.

Batch fecundity estimates for 7 females of *N. valenciennesi*, with lengths and weights ranging from 534 and 710 mm and from 1.8 to 4.2 kg, respectively, ranged from 67,977 and 388,995 eggs and produced mean ± 95% CL of 231,006 ± 77,528.

4.3.7 *Estimates of mortality*

The data in Figure 4.4 demonstrate that *N. valenciennesi* has become fully recruited into the commercial gillnet fishery by an age of 9 years. Catch curve analysis of the commercial gillnet data (*i.e.* for which the data were most substantial) yielded an estimate of 0.40 year^{-1} for Z (Table 4.3). Note that, because there was marked interannual variability in recruitment strength, the data for the corresponding age classes in different years were pooled. The point estimate of 0.24 year^{-1} for M derived using the equation of Hoenig (1983) was greater than the 0.19 year^{-1} derived for this variable using the approach of Hall *et al.* (2004) (Fig. 4.11). As with *A. gouldii*, the use of this latter method produced far narrower confidence intervals for the estimate of M (Table 4.3). Fishing mortality, F, estimated using Monte Carlo resampling and employing the probability distributions derived for Z assuming constant recruitment and for M from the Hall *et al.* (2004) analysis, was 0.20 year^{-1} (Table 4.3).

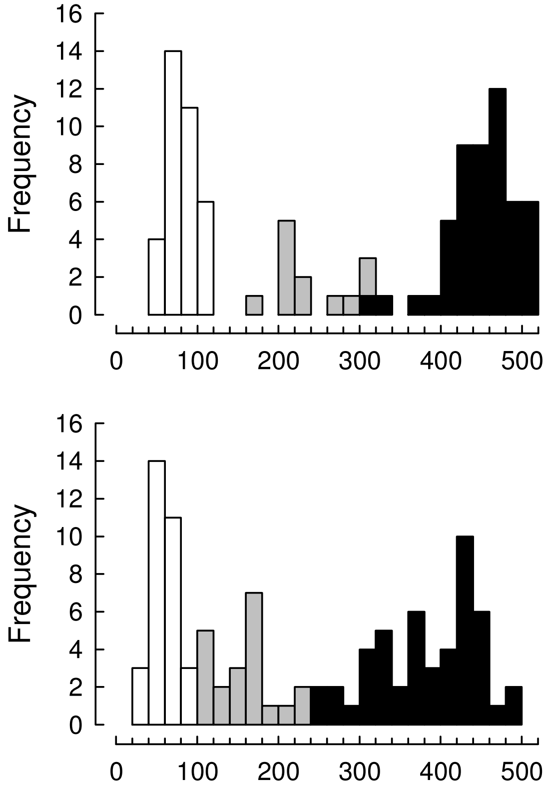

Figure 4.10. Oocyte diameter frequency distributions of two mature (stage V) female *Nemadactylus valenciennesi*. Early previtellogenic oocytes (white), cortical alveolar oocytes (grey), yolk granule oocytes (black).

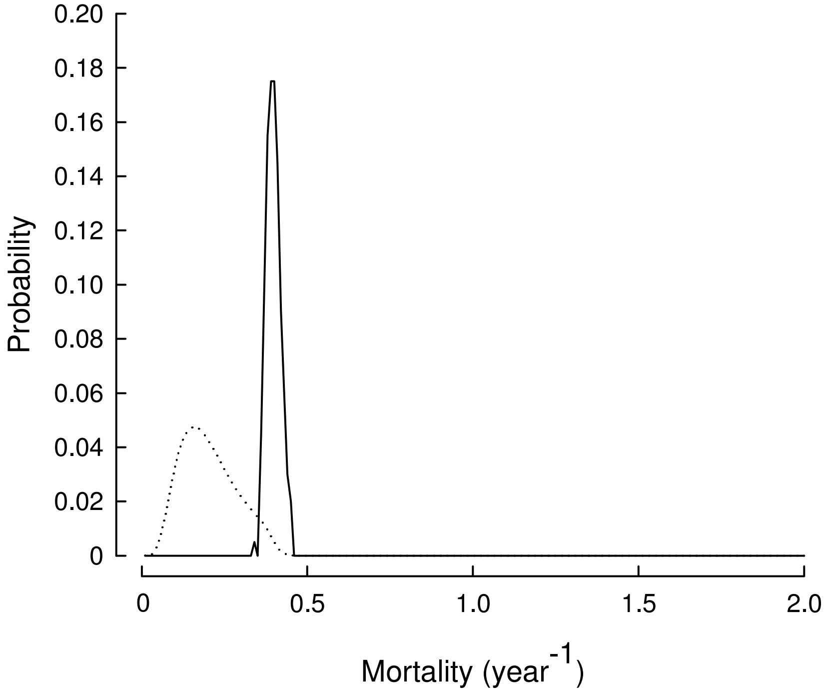

Figure 4.11. Probability distributions, for *Nemadactylus valenciennesi*, of natural mortality, *M* (dotted line) (derived using the method of Hall *et al.* (2004) and an estimate of *M* obtained by refitting the Hoenig (1983) regression equation for fish) and total mortality, *Z* (solid line), determined using catch curve analysis and assuming constant recruitment.

Table 4.3. Estimates of mortality for *Nemadactylus valenciennesi*. Total mortality (*Z*) was derived using catch curve analysis (CCA) assuming constant recruitment, while natural mortality (*M*) was determined by refitting the empirical equation for fish of Hoenig (1983) and using the approach of Hall *et al.* (2004). Fishing mortality (*F*) was estimated employing a Monte Carlo resampling analysis and using the estimates of *Z* from the CCA and of *M* from the method of Hall *et al.* (2004).

Method of analysis	*Z, M or F* (year^{-1})	Estimate	Lower 95%	Upper 95%
CCA (constant recruitment)	*Z*	0.40	0.36	0.44
Refitted Hoenig (1983) fish equation	*M*	0.24	0.08	0.58
Combined *M* (Hall *et al.*, 2004)	*M*	0.19	0.07	0.38
Monte Carlo re-sampling	*F*	0.20	0.02	0.33

After adjusting for sample size, the age compositions of fish collected from recreational and commercial catches of *N. valenciennesi* were very similar, suggesting that the selectivity curves of the fishing methods employed by the two fishing sectors, *i.e.* hand lining and gill netting, are also similar. This implies that estimates of age-dependent selectivity, derived using the age composition of fish collected from the commercial fishery, are likely to be representative of the selectivity curves for both sectors.

4.3.8 *Current yield and spawning biomass per recruit and spawning potential ratio*

Analysis of commercial gillnet data for *N. valenciennesi* indicates that yield per recruit (YPR) increases with increasing fishing mortality over the range from 0 to 0.80 year^{-1} (Fig 4.12). At the current estimated level of 0.20 year^{-1} for *F*, the YPR is estimated to be 0.54 kg. The estimated level of *F* corresponding to the reference point $F_{0.1}$ is 0.31 year^{-1} (Table 4.4).

The current level of spawning stock biomass per age 0 recruit (SSB/R) was estimated to be 2.40 kg for both sexes collectively and 1.48 and 0.91 kg for females and males, respectively (Table 4.4). The estimated current level of spawning potential ratio

(SPR), in terms of SSB/R, is 0.57 for both sexes combined, and 0.59 for females and 0.56 for males (Fig. 4.12, Table 4.4).

Table 4.4. Estimates of the current level of yield per recruit (YPR), $F_{0.1}$ and the current levels of spawning stock biomass per recruit (SSB/R) and spawning potential ratio (SPR) for females, males and both sexes combined of *Nemadactylus valenciennesi*. Calculations assumed that full recruitment to the fishery had occurred by the age of 9 years.

Analysis	Estimate	Lower 95%	Upper 95%
YPR (kg)	0.54	0.02	1.92
$F_{0.1}$ (year^{-1})	0.31		
SSB/R (females & males)	2.40	0.83	4.69
SPR (females)	0.59	0.24	0.93
SPR (males)	0.56	0.22	0.97
SPR (females & males)	0.57	0.23	0.97

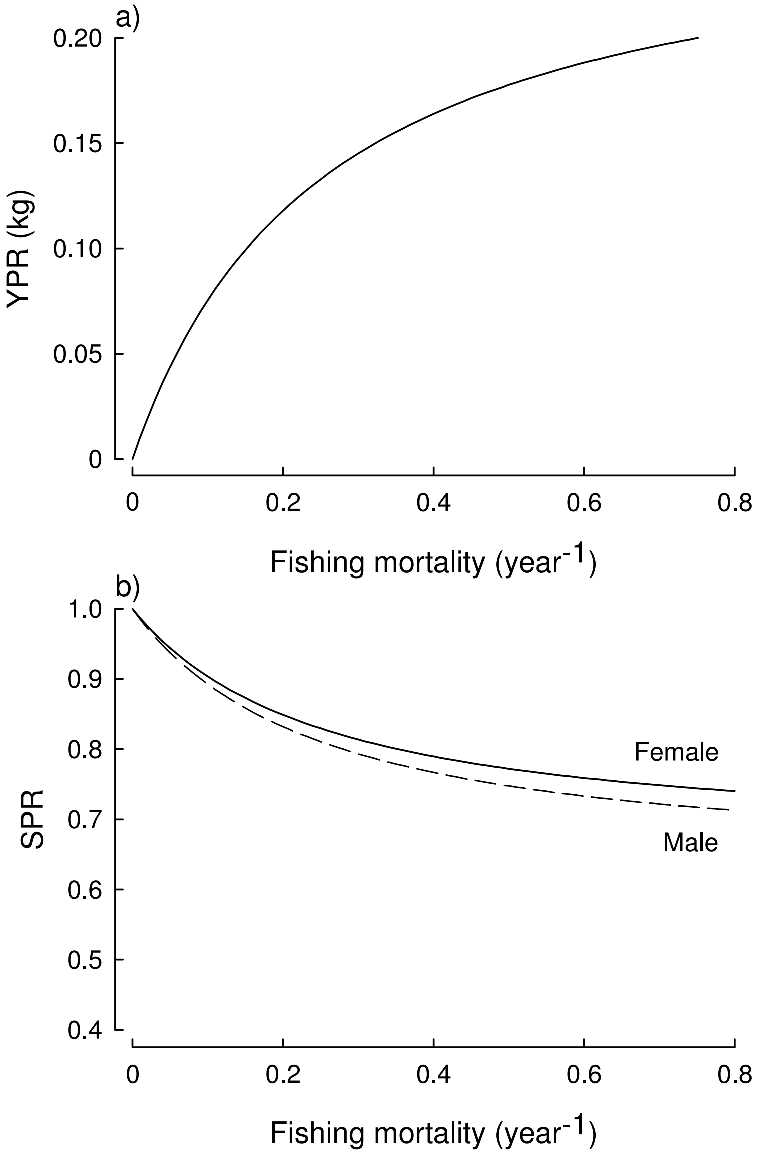

Figure 4.12. The effect of fishing mortality (*F*) at the relative vulnerability at age for the commercial gillnet fishery of *Nemadactylus valenciennesi* on the a) yield per recruit (YPR) and b) spawning potential ratio (SPR).

4.4 DISCUSSION

4.4.1 ***Ageing***

A preliminary comparison of the counts of opaque zones on the same otoliths of *Nemadactylus valenciennesi*, prior to and after sectioning, demonstrated that particularly the larger otoliths of this species required sectioning for all of their opaque zones to be revealed. This parallels the situation with the jackass morwong *Nemadactylus macropterus* in Tasmania, where the maximum ages derived using the number of opaque zones in sectioned otoliths was far greater than those estimated previously on the basis of the number of such zones in whole otoliths of this species in New South Wales (*c.f.* Smith, 1982; Jordan, 2001a; Table 4.5). Our use of marginal increment analysis for sectioned otoliths of *N. valenciennesi* demonstrated that, irrespective of the number of opaque zones on an otolith of this species, a new opaque zone is formed on that otolith annually. Thus, the number of opaque zones visible in sectioned otoliths of *N. valenciennesi* can be used for ageing this cheilodactylid. Since the individuals of *N. macropterus* in Tasmania were aged using the number of opaque zones in sectioned otoliths (Jordan, 2001a), and the same was true for *Cheilodactylus fuscus* in New South Wales (Lowry, 2003) and *Cheilodactylus spectabilis* in Tasmania (Murphy and Lyle, 1999), the ageing of those three species are likewise assumed to be reliable. In the case of the latter species, the validation process included the use of oxytetracycline and bomb radiocarbon methods (Ewing *et al*., 2007).

Because the individuals of *N. macropterus* in New South Wales were aged using counts of growth zones in whole otoliths (Smith, 1982), the age estimates derived for older fish in that study may have been artificially low. Yet, it could be argued that, in the case of *N. macropterus*, the seasonal trends exhibited by the mean monthly marginal increments on otoliths and the percentage of otoliths with a hyaline edge validate the use of

Table 4.5. Comparisons between growth and maturity characteristics of *Nemadactylus valenciennesi* and other species of the Cheilodactylidae for which there are substantial data.

				von Bertalanffy parameters					
		Max. Length (*FL* mm)	Max. Age (years)	L_∞ (*FL* mm)	k (year^{-1})	t_0 (years)	L_{50} (*FL* mm)	A_{50} (years)	
Nemadactylus valenciennesi	Female	731	19	599	0.29	-0.36	503	7	Western Australia
	Male	853	19	725	0.22	-0.52	600	7	(This study)
Nemadactylus macropterus	Female	455	30	384	0.33	0.40	250	3	Tasmania
	Male	423	41	362	0.42	0.15	270	3	(Jordan, 1998, 2001a)
Cheilodactylus fuscus	Female	460	34	376	0.22	-3.60			New South Wales (Lowry, 2003)
	Male	450	40	454	0.13	-5.39			
Cheilodactylus spectabilis	Female	428	94	432	0.45	0.15			Tasmania
	Male	513	97	550	0.30	-0.10			(G. Ewing *pers. comm.*
	Female						324	5	Murphy and Lyle, 1999)

the number of opaque zones for ageing this species. However, the above two otolith variables were recorded for a single presumed age cohort (V) and thus did not include otoliths with larger numbers of growth zones, which, as in the case of *P. speculator* (Hyndes *et al*., 1992a), might not show the same seasonal trends in their marginal increments as those recorded for the otoliths of fish with a small number of opaque zones. In other words, all of the opaque zones of *N. macropterus* and, in particular, those near the periphery of the otolith, may not have been clearly visible when viewing whole otoliths.

To facilitate comparisons between the biological variables for *N. valenciennesi* that involved length, the total length (*TL*) measurements for *N. valenciennesi* have been converted to fork lengths (*FL*), the form of length measurement used in other studies of the biology of cheilodactylids (Table 4.5). The females and males of *N. valenciennesi* have by far the greatest maximum lengths (731 mm for females and 853 mm for females) of any of the five species, but live for a maximum of only 21 years, whereas the females and males of the congeneric *N. macropterus*, which are much smaller (maximum lengths = 455 and 423 mm, respectively), live for up to 30 and 41 years, respectively (Table 4.5). Although the maximum length and age of *Cheilodactylus fuscus* are similar to those of *N. macropterus*, the maximum ages for the females and males of another similar-sized cheilodactylid species, *C. spectabilis*, were 97 and 94 years, respectively, and thus over twice that of any other member of this family (Table 4.5). There is thus no consistent pattern of relationship between maximum length and maximum age among the cheilodactylids listed in Table 4.5, even at the generic level.

The relationship between age at maturity and maximum age also varies markedly among cheilodactylids. Thus, although *C. spectabilis* can live for nearly 100 years, it reaches maturity as early as 5 years of age (Table 4.5). Likewise, *N. macropterus*, which can live for up to 30-40 years, attains maturity as early as 3 years of age (Table 4.5). In contrast, *N. valenciennesi* has a maximum age of 21 years and yet, on the south coast of Australia, does not attain maturity until 7 years of age.

4.4.2 *Growth*

The following comparisons of the patterns of growth in cheilodactylids will concentrate on those described in this report for *N. valenciennesi* and by Jordan (2001a) for *N. macropterus* and by Ewing *et al*. (2007) for *C. spectabilis*. Focus will not be placed neither on the growth curves of Smith (1982) for *N. macropterus* as the validity of the ageing of individuals in that study is questionable (see above). It will also not concentrate on those produced by Lowry (2003) for *C. fuscus* as the growth curves constructed in that study provided very poor fits to the length at age data, the number of older males was very restricted and the estimates for *k* appear erroneous in view of the shape of the von Bertalanffy growth curve.

The growth curves for females and males of *C. spectabilis* demonstrated that this very long-lived species exhibited an initial very fast growth phase, which terminated in an abrupt plateau near the asymptotic length, with little growth thus occurring after the fish had reached 14 years in age (Ewing *et al*., 2007). These features are reflected in the relatively high *k* values of 0.45 year^{-1} for females and 0.30 year^{-1} for males (G. Ewing, pers. comm). The growth curves for the two sexes of *N. macropterus* in Tasmania, where it has a shorter life cycle than *C. spectabilis*, were also markedly asymptotic, and this is likewise reflected in the substantial values for *k* of 0.33 year^{-1} for females and 0.42 year^{-1} for males. Although the growth curves of females and males of the shorter lived *N. valenciennesi* were also asymptotic, they did not show such a steep early rise and then pronounced levelling off as was the case with the above two species, which helps account for the lower values for *k*, *i.e.* 0.29 year^{-1} for females and 0.22 year^{-1} for males. While the growth of the two sexes of both *C. spectabilis* (Ewing *et al*., 2007) and *N. valenciennesi* exhibited sexual dimorphism, with males growing to larger sizes than females, this trend was not exhibited by *N. macropterus* in Tasmania (Jordon, 2001a). This thus provides another example of the plasticity in the life cycle traits exhibited by the various species of the Cheilodactylidae.

4.4.3 ***Movements, sexual maturation and spawning***

All individuals of *N. valenciennesi* caught at lengths < 400 mm *TL* were obtained by spear fishing over granite reefs and their immediately surrounding sandy areas. Furthermore, these small fish were all obtained from the south coast and nearshore shallow waters (< 20 m depth) along that coast or its islands. As few of even the larger fish in these waters, *i.e.* > 450 mm *TL*, were mature, these waters act as a nursery area and larger fish apparently move out when they approach maturity. The failure to catch or even observe the juveniles of *N. valenciennesi* in comparable waters depths along the lower west coast is consistent with the absence of this species in catches obtained during extensive sampling of those waters in other studies (*e.g.* Lenanton, 1982; Ayvazian and Hyndes, 1995; Hyndes *et al*., 1999). Although the length ranges of both the females and males of *N. valenciennesi* caught in offshore waters of the south coast were similar to those of the corresponding sexes in offshore waters of the lower west coast, the prevalence of mature fish in the two regions differ markedly. Thus, whereas the prevalence of mature fish increased progressively from low levels in the smaller fish to 100% in the larger fish in offshore waters of the south coast, the majority or all fish in each length class in those waters were mature.

From the above comparisons, it is proposed that the juveniles of *N. valenciennesi* are largely confined to the south coast and that substantial numbers of the fish on this coast subsequently move to the lower west coast where they become fully mature and presumably spawn. In contrast, it is hypothesised that the other larger individuals move out from their nearshore habitats into offshore waters on that coast, but do not typically become mature until they have become substantially longer and older. The suggestion that many *N. valenciennesi* move from the south to the lower west coast for spawning parallels, to a large extent, that proposed by Smith *et al.* (2004) for the champagne crab *Hypothalassia acerba* and, if valid, indicates that conditions on the lower west coast are more conducive for gonadal maturation, spawning and/or larval survival of certain species are better than those on the south coast.

Despite the presence of substantial numbers of fully mature *N. valenciennesi* on the lower west coast, trawling for fish larvae in waters near where those mature fish were caught, yielded only five cheilodactylid larvae (Muhling, 2006). In contrast, *Nemadactylus* larvae were abundant in trawl samples collected by Fletcher *et al.* (1996) from offshore waters of the south coast in the winter following the spawning period of *N. valenciennesi.* These results suggest that, after *N. valenciennesi* spawns on the lower west coast, their larvae are transported southwards and then become distributed eastwards along the south coast. Such a proposed movement by larvae would coincide with the time when the Leeuwin Current, which flows southwards and eastwards, is strongest (Smith *et al.*, 1991). Transport over such a substantial distance would be facilitated not only by that current, but also by the fact that the pelagic larval phase of cheilodactylids, such as that of its congener *N. macropterus*, is protracted (Vooren, 1972, 1973). The larvae of *N. macropterus* on the east coast of Australia are transported southwards by the Eastern Australian Current (Bruce *et al.*, 2001).

4.4.4 *Management implications*

The fact that the estimate for the current level of fishing mortality, F (0.20 year^{-1}) for *N. valenciennesi* of age 9 and older is very similar to that for natural mortality, M (0.19 year^{-1}), suggests that the stocks of fully-recruited age classes of this species in south-western Australia are experiencing substantial fishing pressure. In this context, *N. valenciennesi* is the most abundant scalefish species in the catches taken by the commercial gillnet fishery operating in marine waters off the south coast of Australia (McAuley and Simpendorfer, 2003). However, this fishing mortality for fully-recruited age classes lies well below the $F_{0.1}$ reference point (0.31 year^{-1}) and the point estimate of the current level of SPR (for SSB/R) for females and males combined (0.57) is well above the value of 0.3 at which a stock is often considered to be overfished (Mace & Sissenwine, 1993; Goodyear, 1993). Although fully-recruited age classes are subjected to a high level of fishing mortality, younger age classes, *i.e.* those less than 9 years old, are not fully-recruited and thus, with current fishing practices, are subjected to considerably less fishing mortality. Thus, in contrast to the situation with *A. gouldii* (Chapter 3), *N. valenciennesi* appears to be relatively resilient to fishing pressure. It is thus relevant that, in comparison with *A. gouldii* (Chapter 3), *N. valenciennesi* possesses life cycle characteristics that would make it less susceptible to fishing pressure, *i.e.* it is gonochoristic *vs* hermaphroditic, has a far shorter life span (max. age = 21 years *vs* 70 years) and typically matures at a younger age (3-7 years *vs* 20-24 years). Furthermore, full recruitment into the same commercial gillnet fishery occurs at 9 years for *N. valenciennesi*, and thus above the age at which maturity is typically attained, whereas the reverse is true for *A. gouldii*.

Although there is strong evidence that *N. valenciennesi* is more resilient to fishing than *A. gouldii*, the apparent implications of the results of the per recruit analyses should be treated with caution as there is considerable uncertainty in the estimates of both mortality and SPR, and the lower confidence intervals for current estimates of SPR for both females and males are lower (0.24 and 0.22, respectively) than the 0.3 reference point for a stock being overfished.

5.0 BIOLOGY OF YELLOWTAIL FLATHEAD *PLATYCEPHALUS ENDRACHTENSIS*

5.1 INTRODUCTION

The estuaries on the lower west coast of Australia are almost invariably open to the sea, whereas many of those along the south coast of this region of Australia are either seasonally or normally closed through the presence of sand bars across their mouths (Lenanton and Hodgkin, 1985). The estuaries of this region of Australia, which are microtidal when open, typically comprise a narrow and short entrance channel (lower estuary) that expands into a wide central basin area (middle estuary) fed by tributary river(s), the lower reaches of which (upper estuary) are saline (Chalmer *et al*., 1976; Potter and Hyndes, 1999). The permanently-open Swan River Estuary at *c*. 32°S is the second largest estuary on the lower west coast of Australia, occupying an area of 55 km^2, while the seasonally-open Wilson Inlet at *c*. 35°S is the largest estuary on the south coast, covering an area of 48 km^2 (Brearley, 2005). The latter estuary is opened artificially during winter or spring, when the water in the basin rises and threatens to flood roads, developments and farms in low-lying areas along the shoreline (Brearley, 2005).

The fish faunas of estuaries are typically dominated by marine species that use these systems as nursery areas (*e.g.* Blaber and Blaber, 1980; Kennish, 1990; Elliott and Dewially, 1995; Whitfield, 1999). However, in south-western Australia, a number of fish species complete their life cycles in estuaries (Potter and Hyndes, 1999). Some of these are confined to estuaries, *e.g.* the black bream *Acanthopagrus butcheri* and the western hardyhead *Leptatheria wallacei* (Prince *et al*., 1982; Potter *et al*., 1986; Laurenson *et al*., 1993; Sarre and Potter, 1999), whereas others, such as the estuary cobbler *Cnidoglanis macrocephalus* and the southern bluespot flathead *Platycephalus speculator*, are also represented by discrete marine populations (Hyndes *et al*., 1992a; b; Ayvazian *et al*., 1994).

The Platycephalidae, which comprises *c*. 65 species that represent 18 genera, is found in estuarine and coastal waters throughout mainly the Indo-Pacific region (Nelson, 2006). Several of its species are protandrous hermaphrodites (Aoyama *et al*., 1963; Okada, 1966, 1968; Fujii, 1970, 1971, 1974; Shinomiya *et al*., 2003). The 44 platycephalid species recorded in Australian waters contain 14 that belong to the genus *Platycephalus* (Paxton *et al*., 2006). Although the yellowtail flathead *Platycephalus endrachtensis*, which occurs across northern Australia and in New Guinea (Allen, 1997), is essentially a tropical species, it is found as far south as the Swan River Estuary, within which it is abundant and apparently completes its life cycle (Potter *et al*., 1990; Potter and Hyndes, 1999). In contrast, *Platycephalus speculator* is a temperate species, which is most abundant in estuaries and coastal embayments along the south coast of Western Australia, but is also found in protected coastal marine waters northwards along the west coast to *c*. 27°S (Hutchins and Swainston, 1986; Potter *et al*., 1990, 1993). *Platycephalus endrachtensis* and *P. speculator* are fished recreationally and commercially (Smallwood and Sumner, 2007; Smith, 2006), as also are several other *Platycephalus* species, such as *P. fuscus* in eastern Australian estuaries (Gray *et al*., 2002), *P. bassensis* in south-eastern Australian and Tasmanian waters (Jordan, 2001b) and *P. indicus* in Japanese waters (Masuda *et al*., 2000). Furthermore, *Platycephalus endrachtensis*, which is targeted by recreational anglers in the Swan River Estuary, has been identified as an "indicator" species for management purposes (Fisheries Management Paper 153; Report of 2003 RFAC/RecFishWest research planning meeting) and a priority for research (Harrison, 2001).

The present study provides quantitative data on the length and age compositions, growth, spawning period and length and age at maturity of *P. endrachtensis* in the Swan River Estuary. These data are used to confirm that this species completes its life cycle in this estuary, to determine whether it is gonochoristic or hermaphroditic and to ascertain, from mortality estimates and per recruit analyses, whether it is close to or being overfished. Our data will be provided to fisheries managers to facilitate the refinement of plans for conserving this species. Finally, our data are compared with those derived previously for the comparably-sized and morphologically and behaviourally similar congeneric *Platycephalus speculator* in Wilson Inlet (Hyndes *et al.*, 1992a, b).

5.2 MATERIALS AND METHODS

5.2.1 ***Sampling regime***

Platycephalus endrachtensis was collected monthly between August 2004 and December 2006 by using 21.5 and 40.5 m seine nets and rod and line angling at several sites located throughout the lower, middle and upper regions of the Swan River Estuary on the lower west coast of Western Australia (31° 57'S, 115° 52'E) (Fig. 5.1). The 21.5 m seine net comprised two 10 m long wings, each consisting of 6m of 9 mm mesh and 4 m of 3 mm mesh, and a 1.5 m long pocket made of 3 mm mesh. This net, which was laid parallel to the shore and then hauled on to the beach, fished a maximum depth of 1.5 m. The 40.5 m seine net contained two 20 m long wings, consisting of 25 mm mesh, and a 1.5 m wide central bunt made of 9 mm mesh. This net, which was laid outwards from the bank and then hauled back on to the beach, fished a maximum depth of 2 m.

In addition, whole or filleted *P. endrachtensis* were obtained monthly in 2005 from commercial fishers operating in the Swan River Estuary and whole fish were purchased from a local wholesale fish market during the winter and spring of 2005 and 2006. A number of fish were also kindly provided by recreational fishers. The sources, *i.e.* seine netting or recreational line fishing, and length ranges of *P. endrachtensis* collected by each method are provided in Table 5.1.

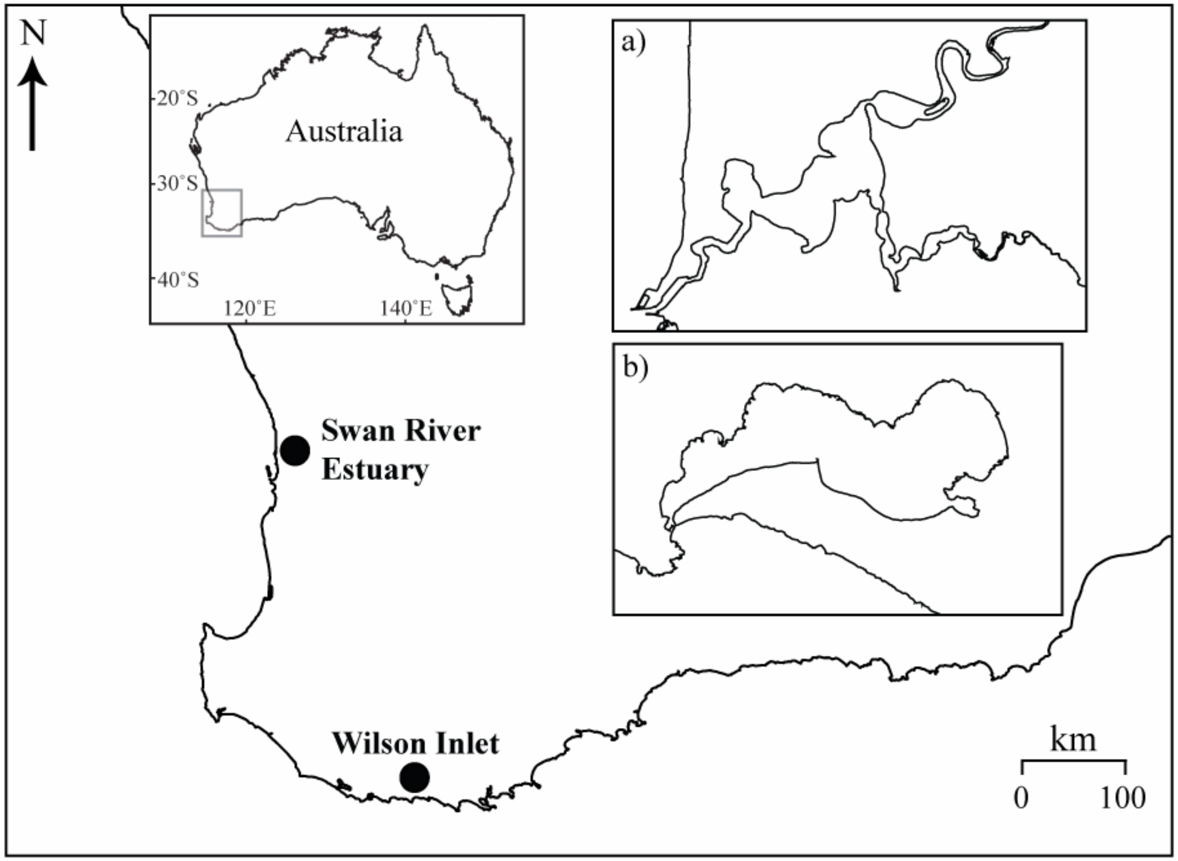

Figure. 5.1. Map of south-western Australia, with insets of a) the Swan River Estuary and b) Wilson Inlet. Box in inset of Australia shows region of south-western Australia illustrated in main map.

Table 5.1. Sample sizes and length ranges of *Platycepahlus endrachtensis* collected from the Swan River Estuary by each sampling method.

Method	*n*	Length range (mm)
21.5 m seine	121	24-541
40.5 m seine	72	69-506
Rod and line	144	231-531
Gill net (commercial)	197	253-615
Total	534	24-615

5.2.2 ***Laboratory procedures and analyses***

The procedures and analyses used for *P. endrachtensis* are the same as those described in the General Materials and Methods (Chapter 2) and which were applicable to all three species. *Platycephalus endrachtensis* could be sexed on the basis of the macroscopic appearance of its gonads when individuals had reached lengths of *c.* 100 mm during the spawning period and < 150 mm at other times.

5.3 RESULTS

5.3.1 ***Validation of ageing method***

The opaque zones in the otoliths of *Platycephalus endrachtensis* became clearly visible once the otoliths of this species had been sectioned (Fig. 5.2).

The mean monthly marginal increments on sectioned otoliths of *P. endrachtensis* with two or three opaque zones remained just below 0.40 between July and September and then decreased to a minimum of 0.15 in December, after which they rose progressively to 0.37 in June (Fig. 5.3). The mean monthly marginal increments for sectioned otoliths with ≥ 4 opaque zones followed essentially the same trend as that just described for otoliths with two or three opaque zones, with values declining precipitously to a minimum in

December. Although none of the fish caught in January and June contained otoliths with one opaque zone, the mean monthly marginal increments for otoliths of such fish in other months of the year followed a similar trend to that just described for fish with greater numbers of opaque zones (Fig. 5.3). The single pronounced decline and then progressive increase undergone by the mean monthly marginal increments during the year demonstrate that a single opaque zone is formed annually in the otoliths of *P. endrachtensis* and that the number of opaque zones in those otoliths can thus be used for estimating the age of the individuals of this species.

As the trends in the monthly gonadosomatic indices and percentage frequencies of gonads at different maturity stages indicated that *P. endrachtensis* spawns predominantly from late spring to early autumn (see later), the individuals of this species were assigned, for the purpose of ageing, a birth date in the middle of this period, *i.e.* January 1.

5.3.2 *Length and age composition and growth*

The structure of the length-frequency distributions for the females and males of *P. endrachtensis* differed markedly (Fig. 5.4a). Thus, all but four of the males were < 350 mm, whereas 57% of the females exceeded this length. The strongest length classes were the 300-349 and 350-399 mm for females and the 250-299 and 300-349 mm for males. The largest male was only 374 mm and thus far smaller than the largest female, which measured 615 mm.

In contrast to the situation with length classes, females and males were both represented in each of the nine age classes recorded in the samples (Fig. 5.4b). However, the number of females was greater than that of males in each of the 1+ to 6+ age classes,

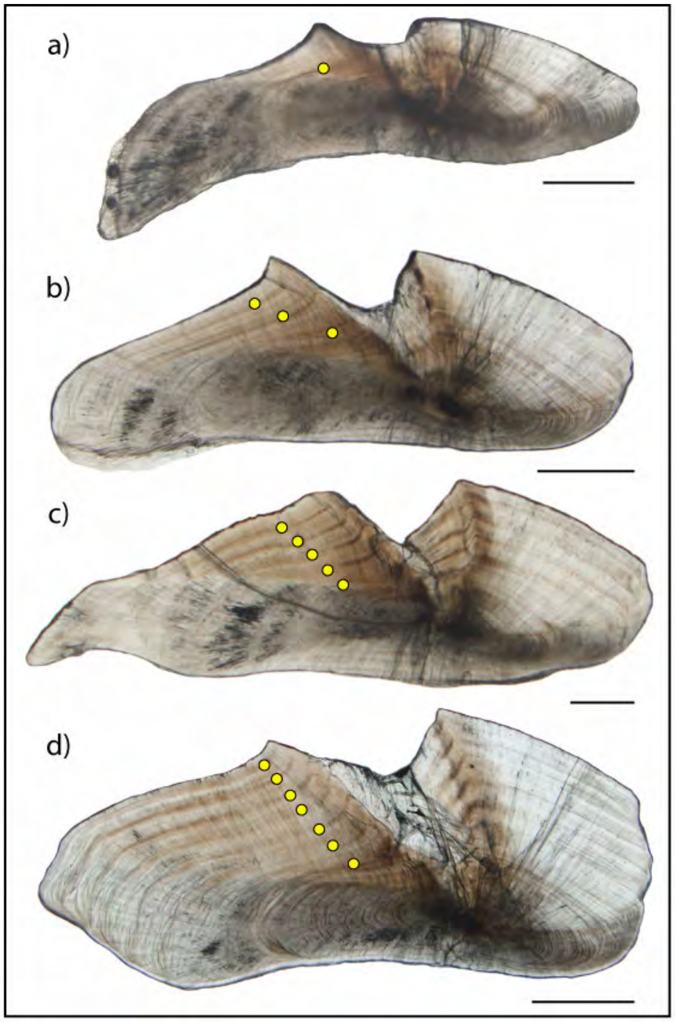

Figure 5.2. Sectioned otoliths of *Platycephalus endrachtensis* with a) 1, b) 3, c) 5 and d) 7 opaque zones (●). Scale bars = 0.5 mm.

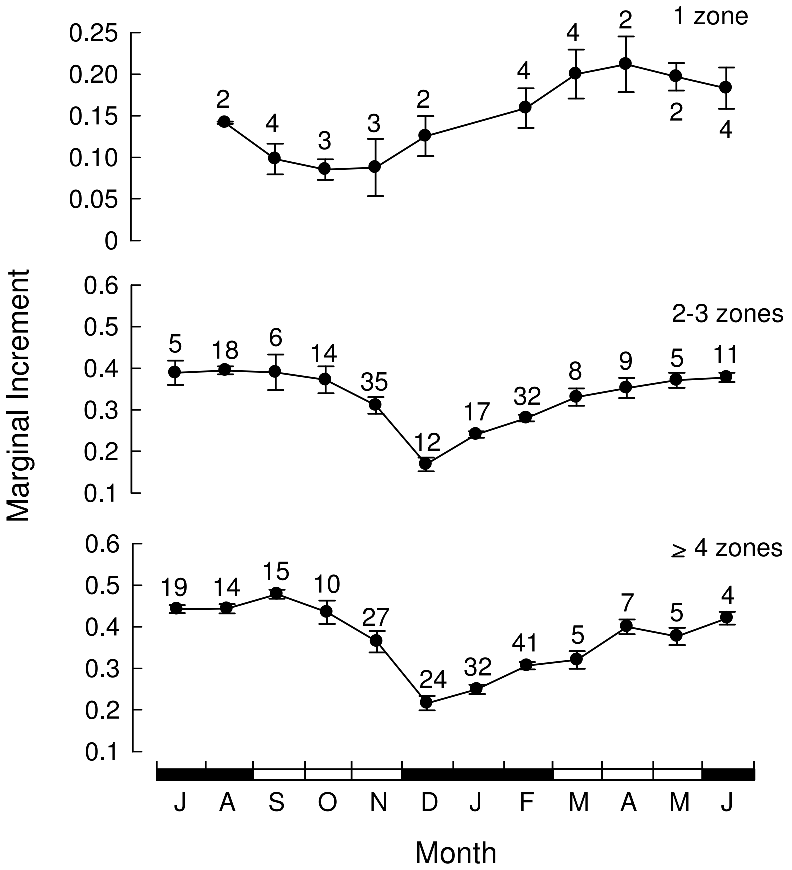

Figure 5.3. Mean monthly marginal increments ± 1 SE on sectioned sagittal otoliths of *Platycephalus endrachtensis* with different numbers of opaque zones. Sample sizes are shown above each mean. In this Fig. and Fig. 5.6, closed rectangles on the x-axis refer to winter and summer months and the open rectangles to spring and autumn months.

and thus for all of those for which the sample size was substantial, *i.e.* at least 25. The ratio of females to males in those age classes ranged from 2.2:1 to 4.9:1 and was significantly different from parity in all cases except the 6+ age class, with all p values < 0.001 and χ^2 values ranging from 12.8 to 56.9. The overall sex ratio of 2.7 females to 1 male was significantly different ($p < 0.001$) from zero ($\chi^2 = 109.1$).

The length-weight relationships for the females and males of *P. endrachtensis* were not significantly different ($p > 0.05$) and thus the length-weight data for the two sexes were pooled and then described by the equation $\ln W = 3.144(\ln TL) - 12.776$ ($r^2 = 0.994$, $n = 388$).

The von Bertalanffy growth curves provided a good fit to the lengths at age of both the females and males of *P. endrachtensis* (Fig. 5.5), as is demonstrated by the relatively high r^2 for both sexes (Table 5.2). The growth curves for the two sexes were significantly different ($p < 0.001$). These growth curves and the associated von Bertalanffy growth parameters demonstrate that the patterns of growth of females and males differed markedly (Fig. 5.5; Table 5.2). Thus, the L_∞ was far greater for females (530 mm) than males (319 mm), whereas k was far less for females (0.41 year^{-1}) than males (0.82 year^{-1}) (Table 5.2). The above differences between the values for L_∞ and k are reflected in an increasing divergence in the lengths of the two sexes as age increased. Thus, for example, from the von Bertalanffy growth equation, the lengths at ages 1, 2, 3, 5 and 7 years were 184, 300, 377, 462 and 500 mm, respectively, for females, compared with 173, 255, 291, 313 and 317 mm, respectively, for males.

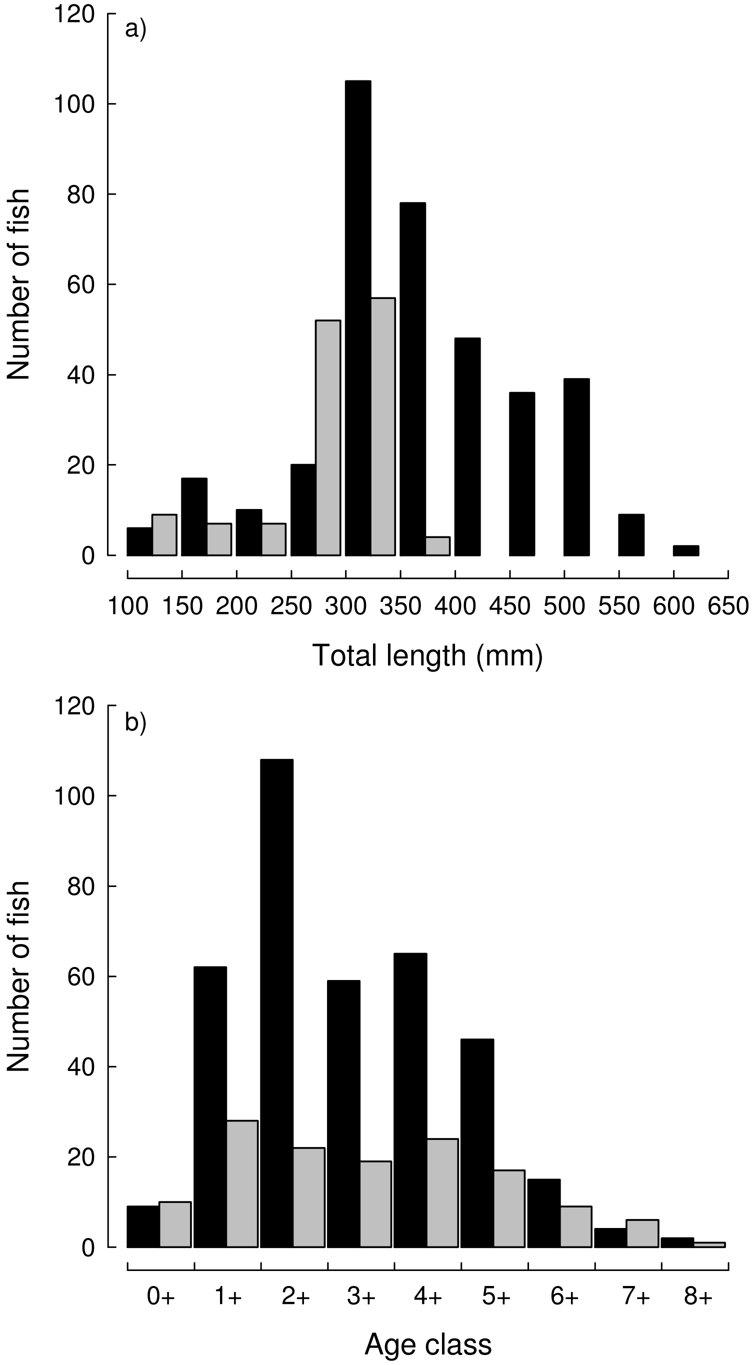

Figure 5.4. a) Length-frequency and b) age-frequency distributions for females (black bars) and males (grey bars) of *Platycephalus endrachtensis*.

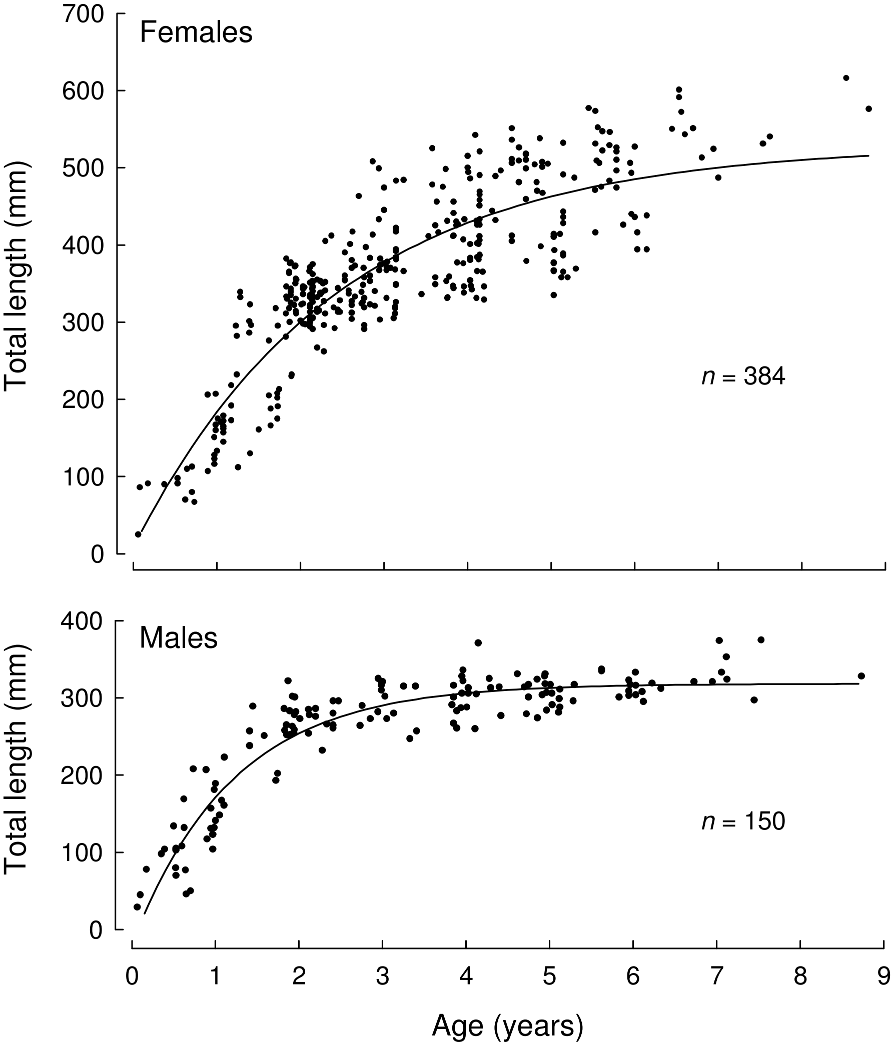

Figure 5.5. von Bertalanffy growth curves fitted to the lengths at age of females and males of *Platycephalus endrachtensis*. The lengths of the small individuals that could not be sexed were assigned alternately to the female and male data sets.

Table 5.2. von Bertalanffy growth curve parameters, L_∞, k and t_0, and their lower and upper 95% confidence limits, for the females and males of *Platycephalus endrachtensis* in the Swan River Estuary and of *Platycephalus speculator* in Wilson Inlet. Parameters were derived from the lengths at age of individuals. Data for Wilson Inlet were taken from Hyndes *et al.* (1992a). L_∞ is the asymptotic length (mm), k is the growth coefficient (year^{-1}), t_0 is the hypothetical age (years) at which fish would have zero length, r^2 is the coefficient of determination and n is the number of fish.

		L_∞ (mm)	k (year^{-1})	t_0 (years)	r^2	n
Platycephalus endrachtensis (Swan River Estuary)						
Female	Estimate	530	0.41	-0.04	0.76	384
	Lower	502	0.34	-0.22		
	Upper	557	0.48	0.14		
Male	Estimate	319	0.82	0.05	0.88	150
	Lower	310	0.71	-0.05		
	Upper	327	0.95	0.15		
Platycephalus speculator (Wilson Inlet)						
Female	Estimate	482	0.59	-0.06	0.89	711
	Lower	469	0.55	-0.11		
	Upper	494	0.64	-0.00		
Male	Estimate	429	0.57	-0.13	0.93	630
	Lower	420	0.53	-0.20		
	Upper	438	0.62	-0.07		

5.3.3 *Water temperatures and reproductive biology*

The mean monthly water temperatures at the main sites at which *P. endrachtensis* was caught in the Swan River Estuary rose progressively from a minimum of *c*. 16ºC in mid-winter to *c*. 21ºC in mid-spring and then to a maximum of *c*. 25ºC in late summer and early autumn, after which they fell precipitously to *c*. 17ºC in early winter (Fig. 5.6a). Although the mean monthly temperatures followed the same overall trend in Wilson Inlet, the corresponding monthly values in that estuary were generally at least 3°C less than those in the Swan River Estuary (Fig. 5.6a).

An examination of histological sections of 150 fish covering essentially the full length range of individuals in the samples failed to find either any testes with ovarian tissue or any ovaries with testicular tissue.

The mean monthly GSIs for female *P. endrachtensis* ≥ the L_{50} of females at maturity, *i.e.* 259 mm (see later), rose sharply from 1.9 in October to 3.3 in November and then to a well defined maximum of 5.4 in December, after which it declined precipitously to 3.6 in February and 1.6 in April and finally to a minimum of 0.8 in June (Fig. 5.6b). Although the mean monthly GSIs for male *P. endrachtensis* ≥ the L_{50} of males at maturity, *i.e.* 187 mm (see later), followed the same trend as that for females, and thus likewise reached a maximum in December, the maximum mean monthly GSI for males was substantially less than that for females (Fig. 5.6c).

All female *P. endrachtensis* that were sampled in July and August and were ≥ the L_{50} at maturity possessed either immature/resting (II) or recovering spent (VIII) ovaries (Fig. 5.7). The percentage of females possessing stage II ovaries declined progressively after September and remained low or absent until April. Female *P. endrachtensis* with ovaries at stage III (developing) and stage IV (maturing) first appeared in September and were both present in October and November, but not in the ensuing months. Females with stage V/VI (prespawning/spawning) ovaries were first caught in October and dominated the samples from November through to March. Fish with stage V/VI ovaries were still present in April and May, when females with stage VII (spent) ovaries were also found (Fig. 5.7). The presence of several females with stage III and stage IV ovaries in September to November, together with the contrast between their virtual absence and an abundance of females with stage V/VI ovaries during the following four months, implies that any female with gonads that develop to stage III would potentially progress through to later stages and thus become mature. Indeed, the ovaries of some female fish had already

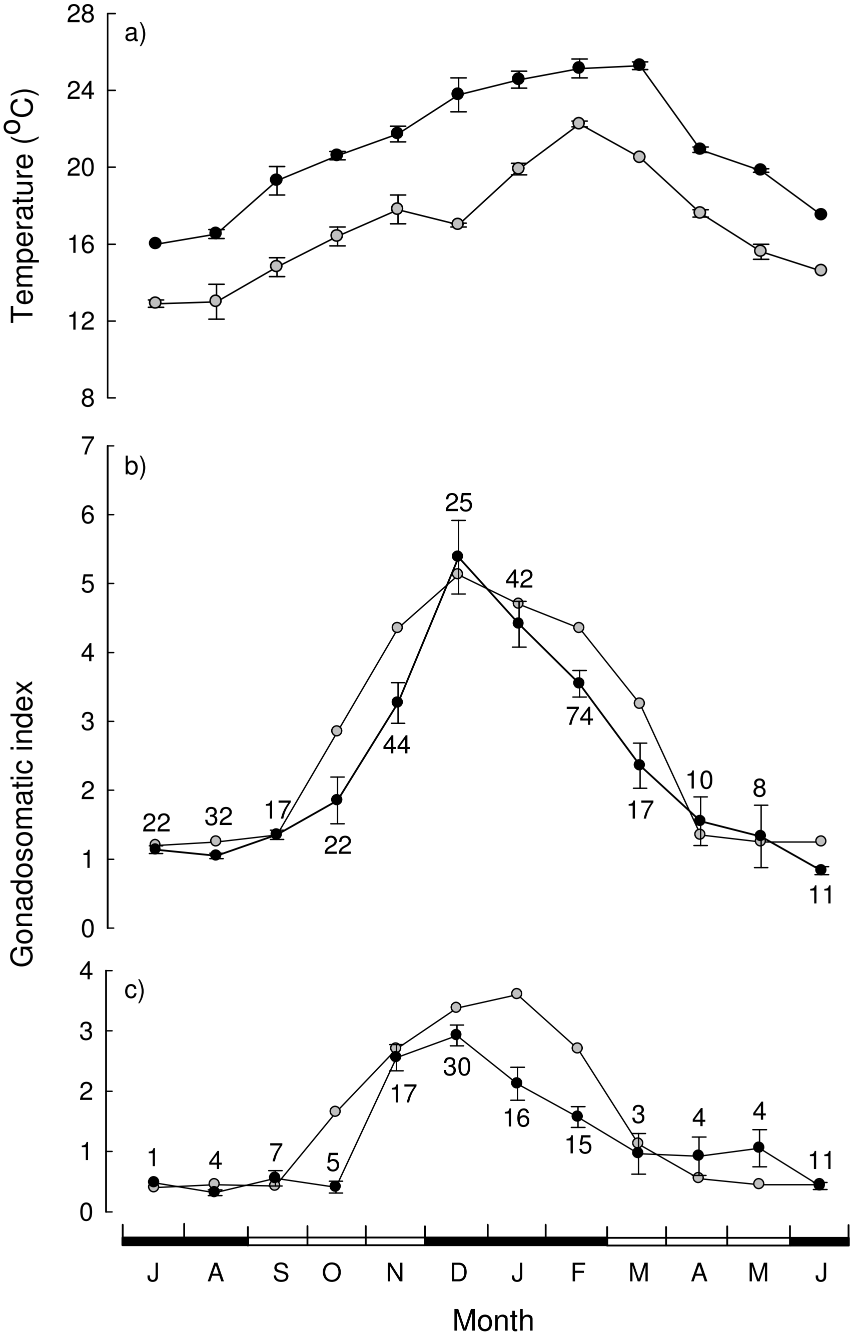

Figure 5.6. a) Mean monthly water temperatures ± 1 SE at sites sampled in the Swan River Estuary (black circles) and Wilson Inlet (grey circles) and mean monthly gonadosomatic indices ± 1 SE for b) females and c) males of *Platycephalus endrachtensis* ≥ L_{50} at maturity (black circles) from the Swan River Estuary and of *Platycephalus speculator* ≥ 2+ (grey circles) from Wilson Inlet. Sample sizes for gonadosomatic indices for females and males of *Platycephalus endrachtensis* are shown above or below each mean. Water temperatures and gonadosomatic indices for *Platycephalus speculator* in Wilson Inlet represent pooled data for the years shown in Hyndes *et al.* (1992a, b).

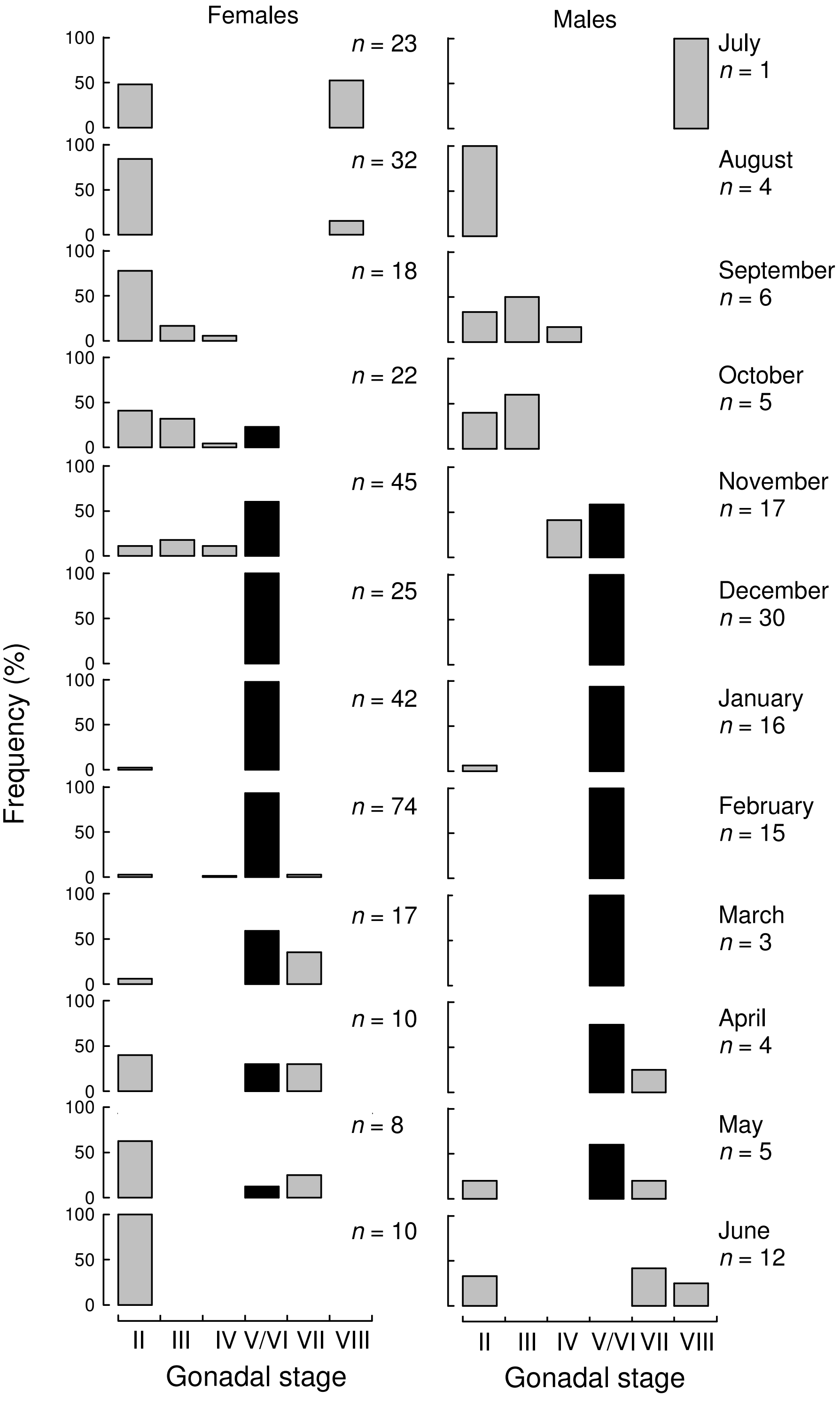

Figure 5.7. Monthly percentage frequencies of occurrence of sequential stages in gonadal development of female and male *Platycephalus endrachtensis* ≥ L_{50} at maturity. Histograms for stages V and VI collectively are highlighted in black. *n* = sample size.

reached the prespawning stage by October and more particularly November. The trends exhibited by the monthly percentage frequencies for the sequential stages in the gonadal maturation of male *P. endrachtensis* followed closely those of females (Fig. 5.7). Thus, for the purpose of estimating the L_{50} at maturity, fish with either ovaries or testes at stages III to VIII are considered mature.

5.3.4 *Length and age at maturity*

The lengths of the smallest mature female and male caught during the spawning period of *P. endrachtensis* were 231 and 156 mm, respectively. In this period, few females with lengths of 200 - 249 mm were mature. However, the vast majority of those between 250 and 399 mm and all of those > 400 mm possessed ovaries at stages III to VIII and were thus mature (Fig. 5.8). All males caught during the spawning period with lengths > 200 mm contained testes at stages between III and VIII and were thus mature (Fig. 5.8). The L_{50} at maturity was far greater for females than males, *i.e.* 259 *vs*. 187 mm, respectively (Table 5.3). Although few females and relatively few males of *P. endrachtensis* had attained maturity by the end of their first year of life, the majority of females and all males had reached maturity by the end of their second year of life (Fig. 5.8).

Table 5.3. Estimates of the lengths at which 50% of the females and males of *Platycephalus endrachtensis* reach maturity (L_{50}) in the Swan River Estuary and their lower and upper confidence limits.

		L_{50} (mm)	L_{95} (mm)
Female	Estimate	259	344
	Lower	233	323
	Upper	280	369
Male	Estimate	187	233
	Lower	163	199
	Upper	211	272

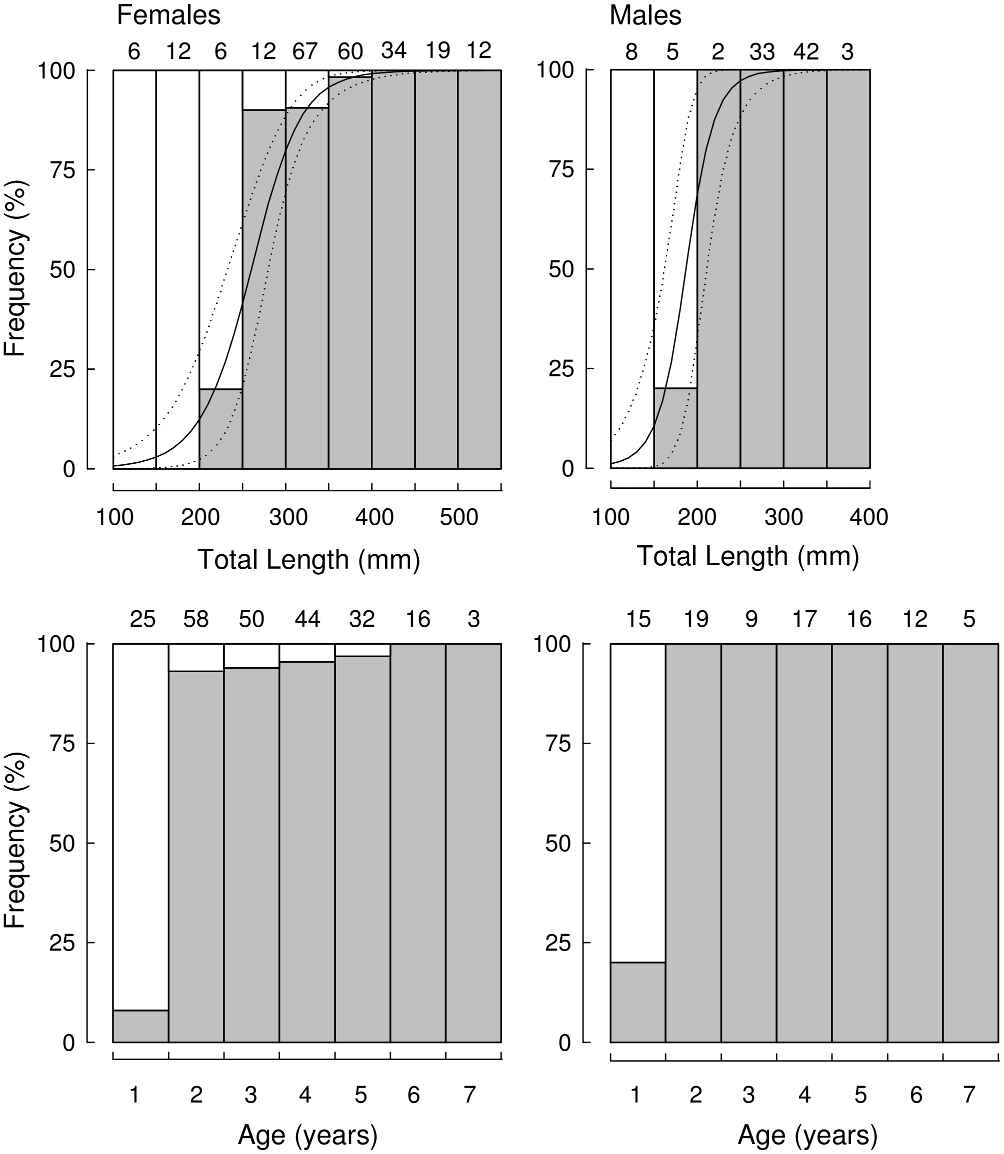

Figure 5.8. Percentage frequency of occurrence of fish with gonads at stages III-VIII (grey histograms) in sequential 50 mm length classes and ages of female and male *Platycephalus endrachtensis* caught between November and March. Logistic curves (solid lines) and their 95% confidence limits (dotted lines) describing the probability of fish at each length being mature are plotted. Sample sizes are shown above each histogram.

5.3.5 *Fecundity*

The abundance and continuous distribution of previtellogenic, cortical alveolar and yolk granule oocytes in the oocyte diameter frequencies in the ovaries of two mature (stage V) female *P. endrachtensis* collected during the spawning period demonstrate that this species has indeterminate fecundity (Fig. 5.9).

Batch fecundity estimates for seven females of *P. endrachtensis*, with lengths and weights ranging from 354 to 541 mm and from 300 to 1115 g, respectively, ranged from *c*. 14,200 and 197,650 eggs and produced a mean ± 95% CL of 56,825 ± 48,317.

5.3.6 *Mortality and per recruit analyses*

The estimate of fishing mortality (0.39 year^{-1}) for female *P. endrachtensis*, the sex on which the fishery for this species in the Swan River Estuary is largely based, is 80% of the estimate for natural mortality (0.49 year^{-1}) (Table 5.4). The yield per recruit (YPR) analysis for female *P. endrachtensis*, which assumed full recruitment into the fishery occurred at 4 years, indicated that YPR for female *P. endrachtensis* continues to increase towards an asymptote with increasing fishing mortality (Fig 5.10). At the current estimated level of F, the estimated YPR for females is 0.09 kg. The level of F associated with the $F_{0.1}$ reference point is as high 0.84 year^{-1} (Table 5.5). The estimate for current female spawning stock biomass per recruit (0.57 kg), which represents 82% of the level estimated for females for an unfished stock (Fig. 5.11, Table 5.5).

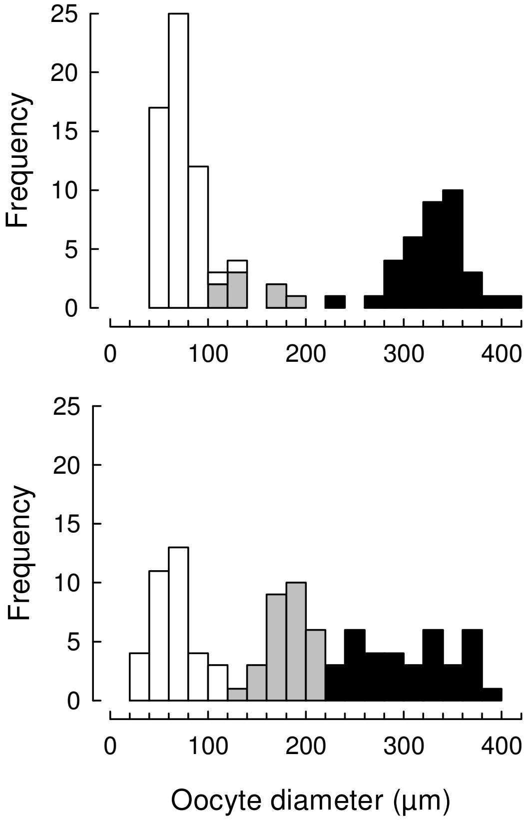

Figure 5.9. a, b) Oocyte diameter frequency distributions of two mature (stage V) female *Platycephalus endrachtensis*. Early previtellogenic oocytes (white), cortical alveolar oocytes (grey), yolk granule oocytes (black).

Table 5.4. Mortality estimates for females of *Platycephalus endrachtensis*. Total mortality (*Z*) was calculated using catch curve analysis (CCA) assuming constant recruitment, while natural mortality (*M*) was determined using the empirical equation of Hoenig (1983) and the method of Hall *et al.* (2004). Fishing mortality (*F*) was calculated using a Monte Carlo re-sampling analysis.

Method of analysis	Z, M or F (year^{-1})	Estimate	Lower 95%	Upper 95%
CCA (constant	Z	0.89	0.77	1.02
Refitted Hoenig (1983) fish	M	0.63	0.20	1.53
Combined M (Hall *et al.*,	M	0.49	0.19	0.87
Monte Carlo re-sampling	F	0.39	0.03	0.83

Table 5.5. Estimates for female *Platycephalus endrachtensis* of the current level of yield per recruit (YPR), $F_{0.1}$ and the current levels of spawning stock biomass per recruit (SSB/R) and spawning potential ratio (SPR). Calculations assumed that full recruitment of female *P. endrachtensis* to the fishery had occurred by the age of 4 years.

Analysis	Estimate	Lower 95%	Upper 95%
YPR (kg)	0.09	0.02	5.36
$F_{0.1}$ (year^{-1})	0.84	-	-
SPR (females)	0.82	0.42	1

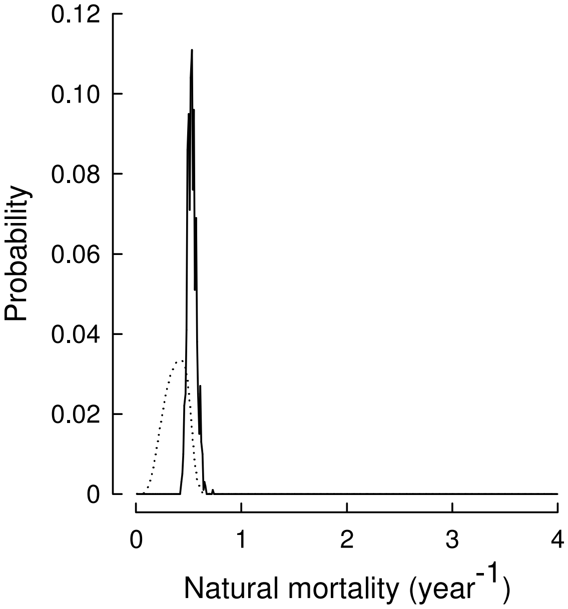

Figure 5.10. Probability distributions, for females of *Platycephalus endrachtensis*, of natural mortality, *M* (dotted line) (derived using the method of Hall *et al.* (2004) and an estimate of *M* obtained by refitting the Hoenig (1983) regression equation for fish) and total mortality, *Z* (solid line), determined using catch curve analysis and assuming constant recruitment.

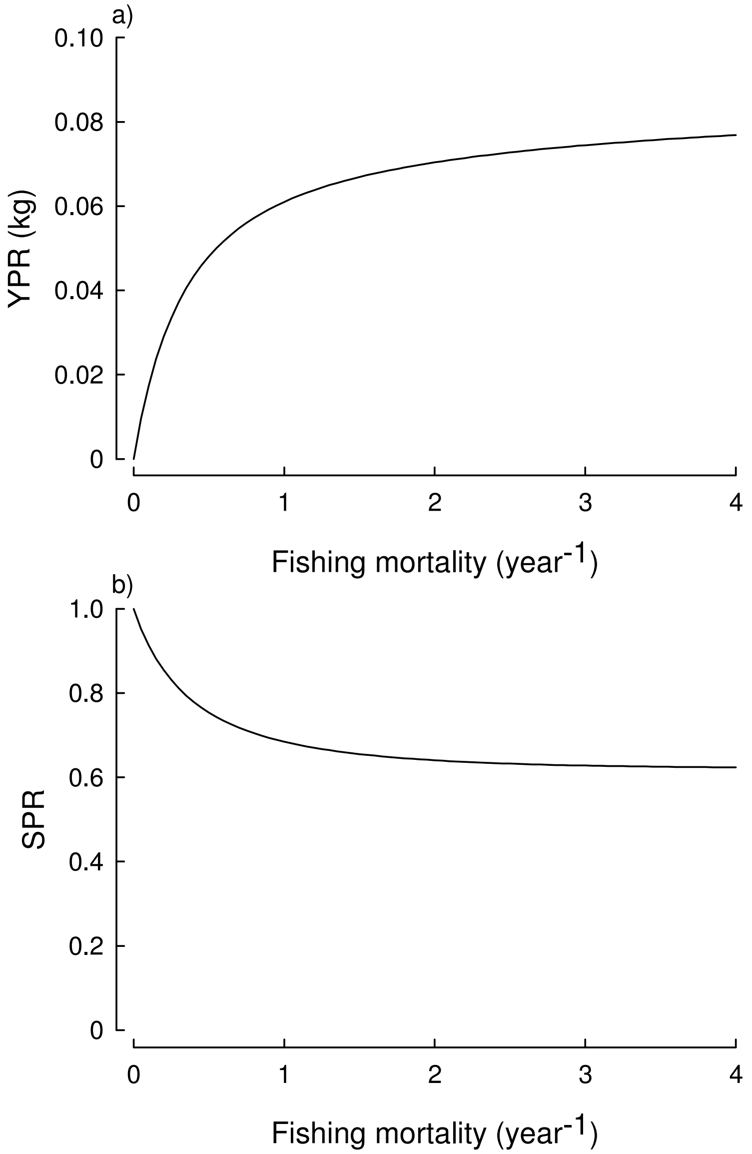

Figure 5.11. The effect of fishing mortality (*F*) at the current age at recruitment into the commercial gillnet fishery of female *Platycephalus endrachtensis* on the a) yield per recruit (YPR) and b) spawning potential ratio (SPR).

5.4 DISCUSSION

The samples of *Platycephalus endrachtensis* from the Swan River Estuary contained individuals that ranged widely in length from 24 to 615 mm and, during the spawning period, comprised substantial numbers of females and males with prespawning, spawning and spent gonads. Several larvae of this platycephalid were also caught at sites throughout this estuary during a previous study (Neira *et al*., 1992). However, no individuals at any stage in the life cycle of yellowtail flathead were caught during extensive sampling of estuaries either further south (*e.g.* Potter *et al*., 1990, 1993, 2000; Potter and Hyndes, 1994, Valesini *et al*., 1997) or in the only estuary immediately to the north (Young *et al*., 1997). Furthermore, this species was either not caught (Ayvazian and Hyndes, 1995) or rarely caught (Valesini *et al*., 2004) during thorough and frequent sampling of the coastal waters and marine embayments of this region. Thus, in south-western Australia, *P. endrachtensis* is essentially restricted to the Swan River Estuary, well to the south of its typical subtropical and tropical distribution. It is therefore hypothesised that the colonisation of the Swan River Estuary by *P. endrachtensis* occurred following the southwards transport of its larvae and/or juveniles by the warm Leeuwin Current, which is known to transport such life cycle stages of other fish species in this manner (Hutchins, 1991). They would then have entered the Swan River Estuary, where the environment proved to be conducive to their recruitment and subsequent development through to maturation and successful spawning.

Platycephalus speculator is found in coastal waters and estuaries of south-western Australia (Ayvazian and Hyndes, 1995; Potter and Hyndes, 1999; Valesini *et al*., 2004) and has been shown to complete its life cycle in some estuaries on the south coast of Western Australia, such as Wilson Inlet, in which it is abundant (Hyndes *et al*., 1992a, b). *Platycephalus endrachtensis* and *P. speculator* are thus among a suite of species, which contains populations whose individuals are permanent residents of estuaries in south-western Australia (Potter and Hyndes, 1999). The unusually high prevalence of estuarine species in south-western Australian estuaries has been attributed to the selection for adaptations that would facilitate this life style among marine species that enter estuaries in a region in which those systems are often cut off from the sea for variable periods by the formation of sand bars at their mouths (Potter and Hyndes, 1999). While the Swan River Estuary now has a relatively deep entrance, access from the sea in the past, prior to the removal of the rock bar at the entrance, was far more restricted (Brearley, 2005). Although several estuaries in southern Africa also become closed for periods, the prevalence of such species is, for some reason, not as high in this region (Whitfield, 1999). While *P. endrachtensis* is, at least largely restricted to estuaries in the southern part of its distribution on the lower west coast of Australia it lives in marine embayments, such as Shark Bay, in those areas further to the north where there are no estuaries (Travers and Potter, 2002), thus paralleling the situation with the terapontid *Amniataba caudavittata* (Lenanton, 1977; Potter *et al*., 1994; Wise *et al*., 1994).

The presence of substantial numbers of *P. endrachtensis* in the Swan River Estuary contrasts with the absence of *P. speculator* from this system, particularly as the latter species is found in estuaries immediately to the south (Loneragan *et al*., 1986; Valesini *et al*., 1997; Potter *et al*., 2000) and occurs in coastal waters much further north (Hutchins and Swainston, 1986; Ayvazian and Hyndes, 1995). This suggests that, in the Swan River Estuary, *P. speculator* may have been displaced by the morphologically and behaviourally very similar *P. endrachtensis*.

5.4.1 *Growth and length and age distributions of females and males*

The representation of females and males throughout the full age range of *P. endrachtensis* in the Swan River Estuary and the fact that the number of females exceeded the males in all but the 0+, 7+ and 8+ age classes, for which there were limited numbers, strongly indicate that this species is gonochoristic. This conclusion is substantiated by the fact that, in histological sections of the gonads of individuals covering a wide size and age range and time of year, testicular and ovarian tissues were never found together in the same gonad.

Although both sexes of *P. endrachtensis* were represented in all age classes and thus each had the same maximum age (8+ years), the females grew to a far larger size than their males. This accounts for the fact that, in our samples, 57% of the 368 females were > 350 mm, whereas only four of the 134 males were greater than this length and none exceeded 375 mm. Females also greatly outnumbered males (3.7 females: 1 male) in the total catch of *P. endrachtensis* collected by Jones (1971) from an embayment on the tropical east coast of Australia and within which all fish were greater than 300 mm in length. An extreme dominance of females among the larger length classes has also been recorded for other platycephalid species and led, in some cases, to the erroneous conclusion that those species were protandrous hermaphrodites, such as occurred, for example, with *Platycephalus indicus* in Japanese waters (see Masuda *et al.*, 2000).

During the early years of life, the females and males of *P. endrachtensis* in the Swan River Estuary did not grow as fast as *P. speculator* in Wilson Inlet (Fig. 5.12). This parallels the differences in growth that would typically be expected if these species represented conspecific populations, *i.e.* growth was slower at the lower latitude. However, although the growth curves for the females and males of both

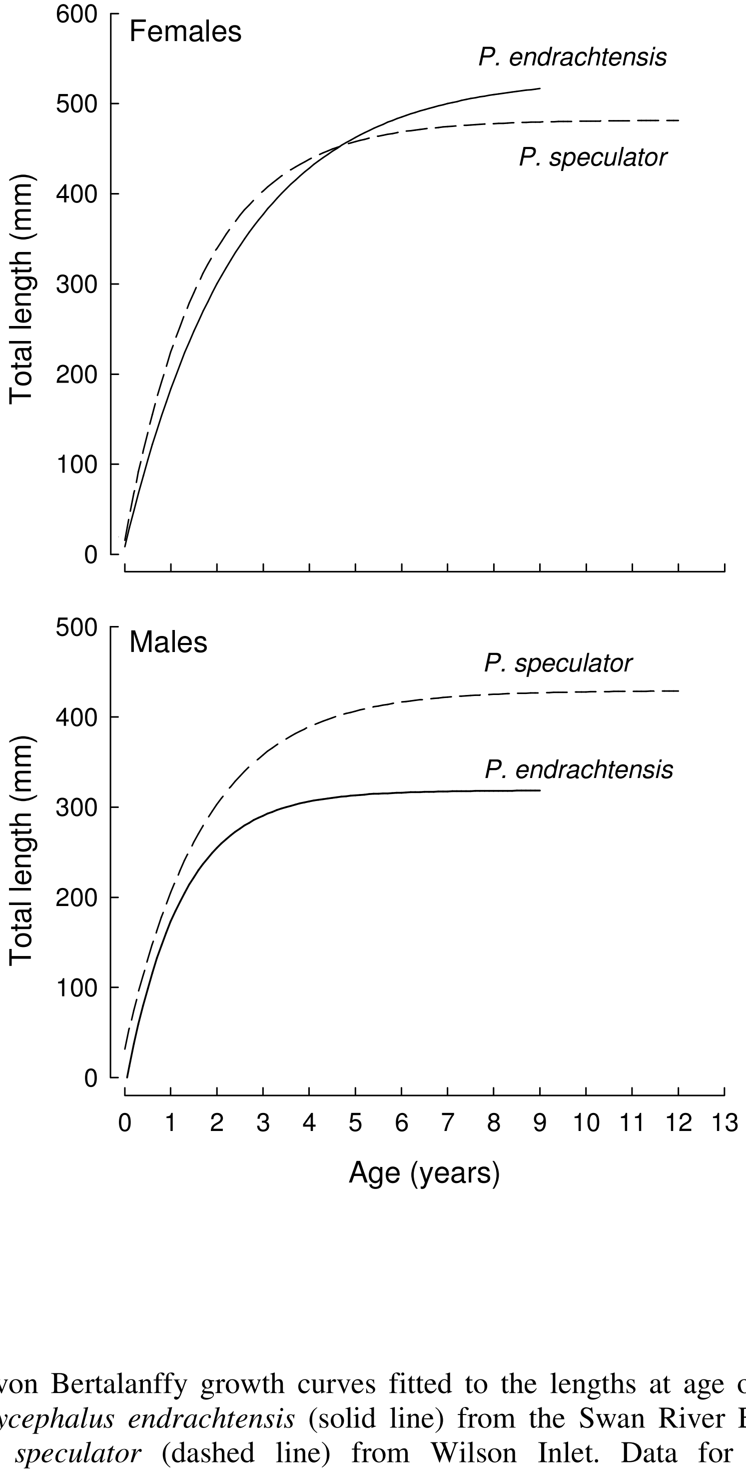

Figure 5.12. von Bertalanffy growth curves fitted to the lengths at age of females and males of *Platycephalus endrachtensis* (solid line) from the Swan River Estuary and of *Platycephalus speculator* (dashed line) from Wilson Inlet. Data for *Platycephalus speculator* were taken from Hyndes *et al*. (1992a).

P. endrachtensis and *P. speculator* were significantly different, the differences in the pattern of growth of the two sexes were far more pronounced in the former species (Fig. 8). Thus, in the von Bertalanffy growth equations, the L_∞ was 66% greater for females than males with yellowtail flathead, compared with only 12% for the southern bluespot flathead, and the value for k was 50% less for females than males with the former species, whilst differing little between the sexes of the latter species (Table 1). Although the maximum ages of 8+ years recorded for both the females and males of *P. endrachtensis* were less than those recorded for the corresponding sexes of *P. speculator*, *i.e.* 10+ and 12+, respectively, the vast majority of the individuals of both species were < 7+ years.

The attainment of far greater lengths by females than males with *P. endrachtensis* than with *P. speculator* was accompanied by a far greater domination of the samples by females with the former species (2.7 females: 1 male) than latter species (1.1 females: 1 male). In addition, although *P. endrachtensis* does not grow as fast as *P. speculator* early in life, its growth also does not asymptote so rapidly and thus its length at its maximum age (8+ years) is greater than that of *P. speculator* at the same age. The above trends indicate that there has been particularly strong selection for a large size of females and thus for egg production in *P. endrachtensis* and suggest that the above characteristics could represent the type of intermediate step that was taken by gonochoristic platycephalids in their development of the protrandrous hermaphroditic condition found in some species of this family (Aoyama *et al*., 1963; Okada, 1966, 1968; Fujii, 1970, 1971, 1974; Shinomiya *et al*., 2003). As the sex ratio remained biased towards females throughout the length and age range over which the gonads had become sufficiently well developed for the sex of the fish to be determined macroscopically, that bias developed early in life, *i.e.* through those genetic and/or environmental factors that influence sex determination or through differential mortality of the sexes during the larval or early juvenile stage.

5.4.2 *Gonadal maturation and spawning period*

In the case of *P. endrachtensis*, the presence of elevated mean monthly female GSIs (> 3) and a predominance of females with ovaries at stages V/VI between November and March, together with the occurrence of low mean monthly female GSIs (< 2) in all other months, demonstrate that this species spawns predominantly between late spring and early autumn in the Swan River Estuary. This period is similar to that estimated for *P. speculator* in Wilson Inlet (Hyndes *et al.*, 1992b). However, as females of *P. endrachtensis* with ovaries at stages V/VI were caught in October, April and May, and males with testes at those stages were found in the last two of those months, its spawning season in the Swan River Estuary apparently extends from mid-spring to late autumn.

Water temperature plays an important role in initiating gonadal recrudescence and the timing of spawning in teleosts (Lam, 1983). In the case of *P. endrachtensis*, the prevalence of fish with gonads at stages ≥ III increases between September and November and thus just after water temperatures have started rising from their winter minima (Fig. 5.5). Although the mean water temperature in each month was almost invariably 3-6 ºC less in Wilson Inlet than in the Swan River Estuary, the overall trends exhibited by the mean monthly GSIs of particularly the females of *P. endrachtensis* in that system and those recorded for *P. speculator* in Wilson Inlet are very similar (Fig. 5.5). Thus, although the gonads of both species are apparently responding in the same way to the very similar patterns of change in water temperature, gonadal recrudescence and spawning activity are triggered by higher temperatures in the case of *P. endrachtensis* in the Swan River Estuary than with *P. speculator* in Wilson Inlet. However, the mean monthly GSIs of *P. endrachtensis* rose less rapidly early and declined more rapidly later, which implies that spawning peaks more sharply in the former species. Yet, the spawning period of *P. endrachtensis* in the Swan River Estuary is still relatively protracted, a point emphasised by the fact that the sparid *Acanthopagrus butcheri*, another important recreational fish species in the Swan River Estuary, spawns over only four months in that estuary (Sarre and Potter, 1999). Thus, the population of *P. endrachtensis* in this temperate estuary has apparently become adapted to breeding at lower temperatures than it normally does in its typical subtropical/ tropical environment. Such a view is consistent with the fact that the mean water temperatures in the Swan River Estuary at the beginning and end of the spawning period are less than even the lowest mean monthly water temperatures at, for example, a latitude of 20-22°S on the north-west tropical coast of Australia (Lough, 1998).

Our data demonstrate that, while maturity is attained by relatively few *P. endrachtensis* at the end of their first year of life, it is achieved by the vast majority of the individuals of this species by the end of their second year of life. In the case of females, this parallels the situation with *P. speculator* (Hyndes *et al.*, 1992b). Thus, as female *P. endrachtensis* does not grow as rapidly as female *P. speculator* in the first two years of life, its L_{50} at maturity is less. In contrast to the situation with female *P. speculator*, the males of this species typically reach maturity at the end of their first of life and therefore one year earlier than those of *P. endrachtensis* and thus at a smaller size. Thus, although the females of *P. endrachtensis* matured at a smaller size than of those of *P. speculator*, this was not case with their males.

5.4.3 *Management implications*

The following points strongly indicate that female *P. endrachtensis*, the sex on which the fishery for this species is based and the one which, for gonochoristic species, is typically assumed to be the key for ensuring sustainability, is not currently overfished. 1. The estimate of fishing mortality (0.39 year^{-1}) is less than that for natural mortality (0.49 year^{-1}). 2. The current fishing mortality lies well below the yield per recruit-based reference point $F_{0.1}$. 3. The estimate of current SPR (0.82) lies well above the 0.3 reference point for SPR at which stocks are often considered overfished (Mace & Sissenwine, 1993; Goodyear, 1993).

As the spawning potential ratio (SPR) does not decline markedly, even at high levels of fishing mortality, *P. endrachtensis* is apparently resilient to fishing pressure under the existing management regulations for this species. In this context, it is relevant that the current MLL for *P. endrachtensis* exceeds the L_{50} at maturity for both its females (259 mm) and even more particularly its males (187 mm). Thus, as there is no indication that the individuals of this species suffer high mortality after release, it is likely that the individuals caught prior to reaching the MLL will potentially have the opportunity subsequently to mature and spawn. Furthermore, the short life-span (8 years) and early maturity (essentially all fish by 2 years) are likely to make this species resilient to overfishing. This resilience is particularly important as the individuals in the population of *P. endrachtensis* in the Swan River Estuary complete their life cycle within this system. From the above, it follows that the current management policies for *P. endrachtensis* are working effectively for ensuring the sustainability of the stocks of this species in the Swan River Estuary.

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7.0 BENEFITS

This study of the Western Blue Groper, Blue Morwong and Yellowtail Flathead has produced the following benefits:

1. Provision, for the first time, of the high quality biological data and information on stock status that are required by fisheries managers, in consultation with stakeholders, for the ongoing development of plans for conserving the above three commercially and/or recreationally important species. The data for Blue Morwong and Yellowtail Flathead are also of particular value as these species are considered important indicators for the fish species in the environments in which they are found.
2. Alert fisheries managers of the need to take into account the fact that the life cycle characteristics of Western Blue Groper make this species potentially very prone to the effects of fishing and that, at the present time, this species is close to or at full exploitation.
3. Managers will now be aware that there is no evidence that either the Blue Morwong or Yellowtail Flathead are currently overfished. The management policies for these two species are thus considered appropriate and effective.
4. Provision of estimates of the current levels of mortality that can act as the basis for fisheries scientists and managers to detect any changes which might occur in the fisheries for the three species in the future.
5. Facilitate, through robust management, the sustainability of the stocks of the three species and thus ensure that recreational and commercial fishers will be able to take appropriate catches of each of these species.

8.0 FURTHER DEVELOPMENT

Once the final report is accepted by the FRDC, it will be provided to fisheries managers and scientists at the Department of Fisheries, Western Australia so that they can fully assess the results and their implications. The full realisation of the benefits that flow from the biological data produced during this study for Western Blue Groper, Blue Morwong and Yellowtail Flathead will depend on the acceptance of our results and their implications by fisheries managers, stakeholders and ultimately the State Minister for Fisheries. Assessment of the results and implications will have to take into account a number of other issues, such as the need for ecologically sustainable development (EST), 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 the opportunity to read the report, they, and the recreational and commercial fishers who have shown an interest in the project, will be invited to discuss with us any points they wish to raise regarding the project results and their implications.

The results of the studies on the biology of Western Blue Groper, Blue Morwong and Yellowtail Flathead will be submitted for publication in high quality journals so that they will be subjected to international peer review. The feedback from the referees will enable us to continue to refine the way we approach our biological studies of recreational and commercial fish species.

9.0 PLANNED OUTCOMES

Key biological data for the Western Blue Groper, Blue Morwong and Yellowtail Flathead will be made available to fishery managers and fishery scientists for use in their assessments of the status of the fisheries for these species. Managers will also be able to include the data in ecosystem models and employ them for determining appropriate management strategies for the commercial and recreational fisheries that exploit these species. Managers will be informed that, while the stocks of Blue Morwong and Yellowtail Flathead appear to be sustainable at current levels of fishing, there is the strong possibility that those of the Western Blue Groper are currently fully exploited and, because of the life cycle characteristics of this species, its stocks need to be monitored closely. Managers will also be made aware that, because Blue Morwong and particularly Western Blue Groper in deeper waters are potentially susceptible to barotrauma-induced mortality, the imposition of size and bag limits are likely to be of limited use as tools for managing the stocks of these two species. In contrast, Yellowtail Flathead survive well following capture and release by anglers in the Swan River Estuary, and thus size and/or bag limits are likely to be an effective tool for managing this species in this estuary.

The essential elements of the age and growth studies that were required to produce data of the necessary quality for management of Western Blue Groper, Blue Morwong and Yellowtail Flathead have been identified. The report will also assist in identifying earlier studies that are likely to be inadequate and thereby alert managers to the potential that management advice based on such studies may be biased. If the data and their implications that are provided in our report are taken into account, they will result in improved stock assessments and more informed evaluations of the effectiveness of alternative management strategies. The benefits of such improvements in the quality of age and growth studies will flow through to both commercial and recreational fishers.

10.0 CONCLUSION

We have met all of the objectives listed in the original application for FRDC 2004/057. During this study, we studied the biology of the Western Blue Groper *Achoerodus gouldii* and the Blue Morwong *Nemadactylus valenciennesi* in waters off the south and lower west coasts of Western Australia and of the Yellowtail Flathead *Platycephalus endrachtensis* in the Swan River Estuary. Focus was placed on aspects that would be required by fisheries managers for developing plans for conserving the stocks of these species. The major findings are as follows:

- The juveniles of *A. gouldii* live in reef areas in protected inshore waters along the coast and around neighbouring islands. With increasing size, they move offshore to deeper, more exposed waters over reefs where spawning occurs between early winter and mid-spring.
- *Achoerodus gouldii* is a monandric protogynous hermaphrodite, *i.e.* all of its males are derived from mature females.
- *Achoerodus gouldii* has a maximum total length of over 1.1 m and lives for the relatively very long period of 70 years.
- The females of *A. gouldii* typically attain maturity at a total length of *c*. 650 mm and ages of 15-20 years.
- The change from female to male by *A. gouldii* typically occurs at total lengths of *c*. 800-850 mm and the relatively old age of 35-39 years. However, sex change is related more to length than age and some smaller females do not change to males.
- Data on the prevalence of different-sized *A. gouldii* with the blue body colouration typical of males can be used to derive a good approximation of the length at which 50% of this species change sex.

- The combination of longevity, late maturity and late sex change make *A. gouldii* particularly susceptible to overfishing.
- Estimates of mortality and yield and spawning biomass per recruit indicate that *A. gouldii* is now close to or at full exploitation.
- *Nemadactylus valenciennesi* has a maximum length of nearly 1 m and lives for up to 21 years, with most of its growth occurring during the first 10 years of life.
- As with *A. gouldii*, *N. valenciennesi* moves to deeper, offshore waters as it increases in size and then matures and spawns in those waters.
- Females and males typically mature in offshore waters of the south coast at lengths of about 600-800 mm and ages of about 7-9 years.
- Juveniles of *N. valenciennesi* are found in shallow, coastal waters on the south coast, whereas their adults are abundant in offshore waters of both the south and lower west coasts.
- *Nemadactylus valenciennesi* attains maturity at far lesser lengths and ages on the lower west coast than south coast, suggesting that the former coast provides better environmental conditions for gonadal maturation, spawning and/or larval success.
- The contrast between the almost total absence of the juveniles of *N. valenciennesi* in shallow, inshore waters on the lower west coast and their substantial numbers in comparable waters on the south coast indicate that the larvae of this species produced on the lower west coast are transported southwards, where they become juveniles. It is thus proposed that such transport is facilitated by the southwards-flowing Leeuwin Current. As spawning occurs between mid-summer and late autumn, the larvae of *N. valenciennesi* would be exposed to the influence of the Leeuwin Current at the time when that current is strongest.

- Our data provided no evidence that *N. valenciennesi* is currently over-exploited. Although Blue Morwong is caught by recreational line fishing and commercial gillnet fishing when they are as young as 3-4 years old, they do not become fully vulnerable to these fisheries until they have reached an age of about 9 years (maximum age = 21 years). Consequently, the individuals of this species can potentially breed over a number of years before they become particularly prone to capture by fishers. Furthermore, this species possesses life cycle characters that make it less prone to overfishing than *A. gouldii*. Thus, in comparison with *A. gouldii*, it is gonochoristic rather than hermaphroditic, lives for a far shorter duration and attains maturity far earlier.
- Although *P. endrachtensis* is found mainly in tropical and subtropical waters, it is abundant and completes its life cycle in the temperate Swan River Estuary.
- Although the maximum age of both sexes of *P. endrachtensis* was the same (8+ years), females grow to a far larger size, which is reflected in their greater maximum lengths (615 *vs* 374 mm) and asymptotic lengths (547 *vs* 317 mm).
- Females outnumbered males in each age class for which the sample size exceeded 25, with the overall sex ratio being 2.7 females : 1 male.
- A far faster growth by the females of *P. endrachtensis* and domination of the largest size classes by that sex may represent the type of intermediate condition through which those other species of *Platycephalus*, which are protandrous hermaphrodites, passed during their evolution of that form of hermaphroditism.
- The females matured (L_{50}) at a far greater length than males, namely 259 *vs* 187 mm.
- As the minimum legal length for retention of *P. endrachtensis* is 300 mm, the fishery for this species is based largely on females and allows both sexes the

potential to breed before they reach the minimum legal size for capture and retention. The latter point, allied with the fact that this species appears to be very resilient to capture and release, helps account for the fact that mortality and per recruit analyses provided no evidence that this recreationally-targeted species is currently overfished.

- The biological data provided in this study will be very useful for the ongoing development of management policies for three important commercial and/or recreational species in south-western Australian waters and alert managers to the need to follow closely the status of Western Blue Groper.

11.0 ELEMENTS REQUIRED FOR PRODUCING HIGH QUALITY AGE COMPOSITION AND GROWTH DATA FOR MANAGERS (OJECTIVE 3)

1. A carefully and appropriately designed sampling regime is required to obtain comprehensive and high quality quantitative data on the biology of a species. It is important that the samples used for ageing the individuals in the stock are collected regularly throughout the year and represent as comprehensively as possible the actual size and age compositions of that stock. This will almost inevitably require the use of multiple gear types for sampling.
2. The sample size required to provide the appropriate precision or necessary statistical power when using age composition and/or length-at-age data will depend on the objectives of the analyses. For example, the minimal sample sizes required for providing age composition data for producing reliable estimates of mortality and undertaking sound stock assessments will differ from those needed for deriving length-at-age data for constructing quality growth curves. In the case of producing age composition data, Quinn and Deriso (1998) describe several methods for

determining the sample sizes required to achieve certain levels of precision or statistical power. The sample sizes required for constructing growth curves of appropriate precision will typically be less than for age composition data, but will depend on the purpose for which the growth analyses are to be used. It is reiterated that any sampling regime must yield samples that are, as far as possible, representative of the size and age range of the population being investigated.

3. In any ageing study that uses counts of annually-formed growth zones in hard structures, it is important to assess the reliability of those counts. Thus, it is initially essential that the counts recorded by the main reader for individual otoliths on different occasions are shown to have a high level of consistency and, in the case of those with large numbers of growth zones, not to differ markedly. It is next important to verify that the counts recorded by the first reader, who will have become very familiar with the characteristics of the otoliths of the species being aged, can be repeated by a second reader, who is experienced in interpreting what constitutes annually-formed growth zones in otoliths. This is crucial when growth zones are numerous and/or difficult to interpret. When the level of reproducibility of counts is not very high, it is particularly important to assess the level of precision by calculating the values for either average percent error (APE) or coefficient of variation (CV), as described in Campana (2001).
4. The samples should also include gonadal material collected from adults throughout the year so that the reproductive period can be determined and a reliable birth date be assigned for the stock being studied.
5. As it has become conventional to use otoliths for ageing teleost fish and we have used otoliths in our study, the following points regarding ageing will be based on this hard structure. Counts of opaque zones in otoliths from a wide size range of

fish should be recorded prior to and after sectioning to determine whether the otoliths require sectioning to reveal all of their opaque zones and, if so, whether this applies to the otoliths of small fish, whose otoliths have few opaque zones, as well as to those of larger fish, whose otoliths have a greater number of opaque zones.

6. Attention should be paid initially to establishing which method is best for viewing and detecting opaque zones, *i.e.* reflected or transmitted light and dissecting or compound microscope, and whether it is beneficial to use computer software to enhance the resolution of the image. Enhanced resolution can prove crucial when counting opaque zones on otoliths with large numbers of zones, such as was the case with our study of *A. gouldii*.
7. Marginal increment analysis for validating that (opaque) zones are formed annually and can thus be used to help age fish, should be performed on groups of otoliths with different numbers of opaque zones and which cover the full range of numbers of opaque zones in the otoliths of the samples of the species under investigation. The use of a compound microscope and imaging software to produce highly magnified images of the peripheral region of those otoliths of *A. gouldii* which possessed large numbers of opaque zones was particularly valuable for obtaining reliable measurements of the marginal increment on these otoliths.
8. The trends exhibited by the mean monthly values for the marginal increments demonstrate the time of year when the outermost (opaque) zone typically becomes delineated as the result of the formation of a new translucent zone at its outer edge. This timing must be taken into account when examining the otoliths of individual fish around that period and counting the number of opaque zones.

9. The number of otolith opaque zones, in combination with the date of capture, birth date and time of year when the opaque zones become delineated from the periphery of otolith, can then be used to produce a reliable estimate of the age of each fish.
10. Note that a correspondence between the strengths of the same year classes in samples collected in sequential years provides further evidence of the validity and precision of the ageing procedure and that this is particularly useful with long-lived species such as *Achoerodus gouldii*.
11. A growth curve should be fitted to the lengths at age of the individuals of each sex. The von Bertalanffy growth curve often produces a good fit to such data and, because of its wide use, provides data for parameters that can be compared with those derived in other studies. However, when this type of growth curve does not provide a good fit, alternative forms, such as that of Schnute (1981), should be explored.
12. Marked deviation of the estimate of the theoretical age at which the expected length is zero from a value of zero may indicate biased selection of the larger of the younger fish, inadequate samples of younger fish or consistently inaccurate ageing.
13. Significance tests should be used to explore whether the growth of females and males, and of fish from different regions, are significantly different. In cases where there are no significant differences, the data for the two groups can be pooled.
14. In the case of growth curves, the values for the various parameters and their upper and lower 95% confidence limits, and the sample sizes and coefficients of determination, should be provided.

12.0 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

Mr Peter Coulson

Professor Ian Potter

Dr Alex Hesp

Professor Norm Hall