J. Appl. Ichthyol. 24 (2008), 7–17

ISSN 0175–8659

Received: August 11, 2006
Accepted: March 4, 2007
doi: 10.1111/j.1439-0426.2007.00913.x

Synopsis of biological, fisheries and aquaculture-related information on mulloway *Argyrosomus japonicus* (Pisces: Sciaenidae), with particular reference to Australia

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Summary

Argyrosomus japonicus is a member of the family Sciaenidae, which are commonly known as drums and croakers. *A. japonicus* occurs in estuarine and nearshore Pacific Ocean and Indian Ocean waters surrounding Australia, Africa, India, Pakistan, China, Korea and Japan. The biology of *A. japonicus* is relatively well studied in South Africa, and more recently studied in Australia, but no information is readily available from other areas of its distributional range. The early life history distribution of *A. japonicus* may differ among regions, with their distribution in estuaries linked to salinity, turbidity, freshwater flows and depth of water. Studies in South Africa and Australia found that juvenile fish grow rapidly, attaining 35 cm TL in 1 year and 87–90 cm TL in 5 years. Sexual maturity also differs among regions and is attained at 2–3 years of age and > 50 cm in eastern Australia, 5–6 years of age and > 80 cm TL in western Australia and southern Africa. The maximum reported length and age of *A. japonicus* is 175 cm and 42 years, respectively. Spawning most likely occurs in nearshore coastal waters although there is evidence to suggest that it may also occur in the lower reaches of estuaries. Time of spawning varies among geographic localities and is probably linked to water temperature and oceanography. Juvenile fish (< 2 years) appear to be relatively sedentary, but sub-adults and adults can move relatively long distances (> 200 km) and such movements may be linked to pre-spawning migrations. *A. japonicus* is important in many recreational and commercial fisheries, but like other sciaenids, is prone to overfishing. It is classified as recruitment overfished in South Africa and overfished in eastern Australia. Although much research has been done to minimize the capture of juveniles in Australian prawn-trawl fisheries, greater protection of spawners and improved fishing practices to enhance survival of discarded juveniles, particularly from prawn trawling, may be required. An aquaculture industry is developing for *A. japonicus* in Australia and preliminary research on the impacts and success of re-stocking wild populations has begun in an attempt to arrest the apparent decline in populations.

Introduction

Argyrosomus japonicus is a member of the family Sciaenidae, commonly referred to as croakers and drums. Sciaenids are mostly demersal fishes found in fresh, estuarine and coastal marine waters in subtropical to temperate regions of the Atlantic, Indian and Pacific oceans. The family contains approximately 70 genera and up to 270 species worldwide, with 28 species restricted to freshwater (Paxton and Eschmeyer, 1994; Froese and Pauly, 2003). Twenty species from nine genera have been recorded from Australia, with only two species occurring in temperate waters - *Argyrosomus japonicus* (Temminck and Schlegel, 1843) and *Attractoscion aequidens* (Cuvier, 1830) (Steffe and Neira, 1998). Sciaenids, including *A. japonicus*, are important in many commercial and recreational fisheries and form the basis of aquaculture industries in many regions of the world. Thus there has been significant biological, fisheries and aquaculture-related research done on many species. This review encompasses biological, fisheries and aquaculture related studies done on *A. japonicus*. While information on this species is available from Australia and South Africa, the lack of information from other areas where *A. japonicus* is distributed could be due to a lack of fisheries monitoring, no substantial fishery for the species, and/or the amalgamation of catch information for common species under a grouping class such as 'croakers'.

The taxonomic relationships among sciaenids have undergone much revision in recent years. Griffiths and Heemstra (1995) report that *A. japonicus* has been known by at least 13 other synonyms and, until 1995, was previously misidentified as *A. hololepidotus* in some areas, notably Australia and South Africa (Lin, 1940; Trewavas, 1977; Griffiths and Heemstra, 1995). A full description of the morphological characteristics of *A. japonicus* is given in Griffiths and Heemstra (1995). In this review, we therefore include relevant information on *A. hololepidotus* from Australia that was published prior to the most recent change in species name (i.e. to *A. japonicus*). In contrast, we do not include several earlier studies done on *A. hololepidotus* in South Africa because they most likely represent another previously misidentified species, *A. inodorus* (see Griffiths, 1996). The number of unreviewed literature documents cited and the inaccessibility of this literature internationally highlights the need for this review.

Distribution and stock structure

Argyrosomus japonicus is a nearshore coastal (< 100 m depth) species that also occurs in estuaries and is found in the Pacific and Indian Ocean waters surrounding Australia, Africa, India, Pakistan, China, Korea and Japan (Fig. 1). In Australia, it is distributed along the eastern, southern and western seaboards from the Burnett River in Queensland to North West Cape in Western Australia (Kailola et al., 1993). It is found along the African southeast coast from the Cape of Good Hope to southern Mozambique; in the northern Indian Ocean, it occurs off Pakistan and the northwest coast of India. In the Northern

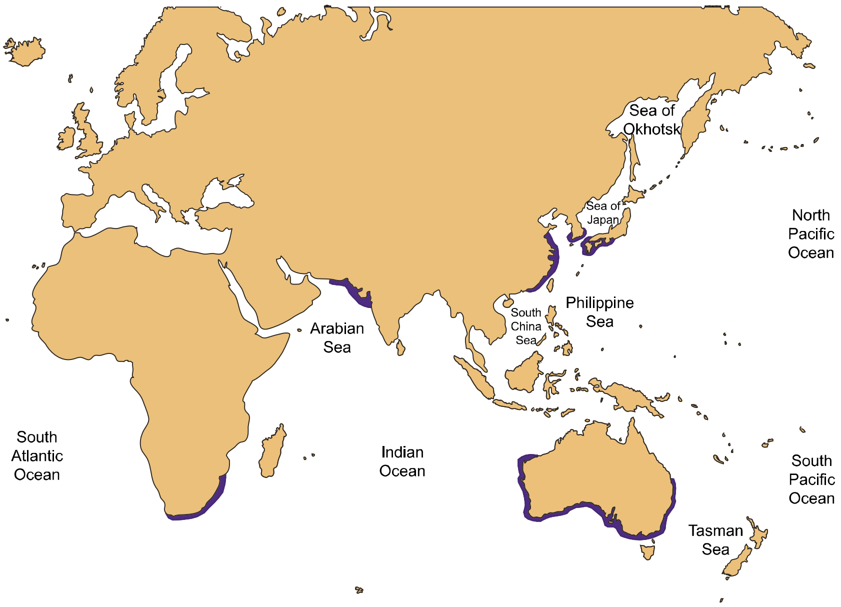

Fig. 1. World map showing distribution of *Argyrosomus japonicus*

Pacific it has been reported from Hong Kong, northwards along the Chinese coast, to southern Korea and Japan (Griffiths and Heemstra, 1995).

There is limited information available on the stock structure of *A. japonicus*. Genetic-based studies have been done only in Australia and the conclusions from these studies are limited as they were based on samples comprising very few individual fish from only a few locations. Black and Dixon (1992) provided some electrophoresis-based evidence that a separate sub-population of *A. japonicus* occurs in Western Australia compared to the southern (South Australia and Victoria) and eastern (NSW and Queensland) seaboards. They further hypothesised that there may be additional population sub-structuring between fish in South Australia and New South Wales, but preliminary data based on mitochondrial DNA (mtDNA) did not appear to support this. There are no other reported genetic studies done elsewhere on the species and therefore the degree of genetic division among populations along different seaboards and oceans is not known. Tag-recapture studies shed no further light on the general stock structure of the species. Whilst limited movements could be used to support stock separation along a coastline, no definitive conclusions can be made regarding the population structure of the species. Despite this, tagging studies were used by Griffiths and Hecht (1995) and Griffiths and Attwood (2005) to suggest that the population of *A. japonicus* in South Africa is a single genetic stock and that fish are well integrated in a short stretch of the South African coastline, respectively.

Early life history

Steffe and Neira (1998) give a full description of the larval development of *A. japonicus* based on reared and wild caught larvae. The previous description by Beckley (1990) of the larval development of *A. hololepidotus* is most likely that of *A. inodorus*. The eggs of *A. japonicus* are pelagic, approx. 938 ± 24 μm in diameter and, under laboratory conditions, hatch 28–30 h (at 23°C) after spawning, with the larvae being 2.2–2.3 mm TL upon hatching (Battaglene and Talbot, 1994).

Eggs have been collected near the surface in coastal waters off south-eastern Africa (Griffiths, 1996) and larvae (up to 10 mm TL) have been caught in estuarine and coastal waters (out to 200 m depth contour) off south-eastern Australia between January and April (Miskiewicz, 1987; Steffe, 1991; Gray and Miskiewicz, 2000; Smith, 2003). During daytime sampling in coastal waters of NSW, *A. japonicus* larvae (predominantly early pre-flexion stage) were caught in subsurface waters, with greatest concentrations below 30 m depth (Gray, 1995). Night plankton sampling found pre-flexion larvae in surface waters, however higher concentrations were found in waters of 20 to 60 m depth where water temperatures were 21–23°C (Smith, 2003). Similarly, most larvae captured in towed plankton nets in a coastal embayment (Botany Bay) in NSW, were close to the substratum (Steffe, 1991), suggesting that larval *A. japonicus* may prefer deeper parts of the water column.

Juvenile and adult distribution

Small (< 30 cm TL) juveniles are found in estuaries and nearshore coastal environments, including surf zones (Hall, 1986; Lenanton and Potter, 1987; Gray and McDonall, 1993; Griffiths, 1996; West and Walford, 2000). Some ambiguity exists, however, concerning the timing, age and length that individuals recruit to estuaries. Several authors suggest that early development of *A. japonicus* primarily takes place at sea and juveniles enter estuaries at a length between 10–20 cm TL and up to 1 year after birth (Hall, 1986; Potter et al., 1990; Anon, 1993). In contrast, Griffiths (1996) reported that *A. japonicus* recruit to estuaries in South Africa at 2–3 cm TL approx. 4 weeks after hatching and larvae and small juveniles (2–10 cm TL) have been caught in estuaries in NSW (Anon, 1981a; Steffe, 1991; Gray and McDonall, 1993; West and Walford, 2000).

In estuaries, juveniles (including early post-settlement stages) may favour deeper waters and not the shallow littoral fringes where most sampling for juvenile fishes has traditionally taken place. For example, in a study in two estuaries in northern NSW (West and Walford, 2000), most small *A. japonicus* (2–40 cm TL) were captured by trawling in the deeper waters of the main river channels, particularly where prawn abundances were high. None were caught in shallow waters or small tributaries (using small seine nets). Further, relatively few small juveniles have been caught along the shallow (< 2 m depth) vegetated (e.g. seagrass and mangrove) and non-vegetated fringes of estuaries, despite the extensive sampling of these habitats in south-eastern Australia and southern Africa (Anon, 1981a; Potter et al., 1990; Ferrell et al., 1993; Connolly, 1994; Paterson and Whitfield, 2000).

The horizontal distribution of *A. japonicus* in estuaries can vary substantially and is probably linked to environmental factors including salinity, freshwater flows, turbidity and life history stage. Griffiths (1996) reported that fish < 15 cm predominantly recruit to the upper regions of estuaries where salinities are < 5 ppt. Gray and McDonall (1993) found that most juvenile fish (10–20 cm TL) occurred at locations in an estuary where the salinity was 15 to 20 ppt. However, some juvenile fish were caught in upstream locations where salinity was < 5 ppt and also near the estuary mouth where salinity was > 25 ppt. Griffiths (1996) also found that juveniles were more prevalent in turbid versus non-turbid estuaries and hypothesised that juveniles may be more abundant in estuaries with significant freshwater flows. This may also be true in NSW where juveniles appear to be more prevalent in the deeper riverine type estuaries compared to the shallower barrier (coastal lagoon) estuaries. Both Hall (1984) and Griffiths (1996) further suggested that freshwater flow promoted recruitment of larval and juvenile *A. japonicus* to estuaries.

Sub-adult and adult *A. japonicus* occur in estuarine and ocean waters (Griffiths, 1996; Griffiths and Attwood, 2005). In estuaries, larger juveniles and sub-adult fish (> 40 cm TL) appear to be more abundant in the lower reaches where salinities are nearer to seawater (Anon, 1993; Griffiths, 1996). The distribution of these larger individuals may be related to particular hydrographic conditions. For example, Anon (1993) reported that larger fish moved from estuaries to the ocean in Western Australia in winter when estuarine salinity levels dropped. Large individuals are caught around the mouths of estuaries, in surf zones and around rocky reefs and ridges in offshore waters.

Movement

Several tag-recapture studies have been done on *A. japonicus*, although the objectives and scales of the studies, and the data published, have been variable and in some cases, unclear. In Australia, separate tag-recapture studies have been done on *A. japonicus* in NSW (Thomson, 1959; West, 1993; NSW Fisheries unpublished data), South Australia (Hall, 1984) and Western Australia (Anon, 1993), while in southern Africa there have been two published studies (Griffiths, 1996; Griffiths and Attwood, 2005).

The data concerning movements of tagged *A. japonicus* show that some fish appear to be relatively sedentary (predominantly juveniles), whereas others move significant distances along a coastline and from one estuary to another (Table 1). For example, in South Africa the majority of recaptures (primarily juvenile and sub adult fish < 120 cm) were found < 10 km from where they were tagged even though these fish recorded long periods of liberty (> 1400 days), whereas only a small proportion of fish were recaptured > 30 km from the initial tag location (Griffiths, 1996; Griffiths and Attwood, 2005). Similarly, in NSW 87% of tagged *A. japonicus* were recaptured in the original estuary but 70 fish moved between estuaries both north and south from the estuary where they were tagged (Fig. 2). The greatest distance migrated was approx. 400 km southward from the Clarence River to Wallis Lake (fish at liberty for 176 days) and the greatest northward migration was approx. 300 km from the Clarence River to the Brisbane River (fish at liberty for 851 days). Some tagged *A. japonicus* have moved relatively large distances in opposing directions elsewhere. In South Australia, Hall (1984, 1986) reported recaptured fish about 200 km from the tagging site and that recaptures occurred in both north and south directions. In South Africa, fish were recaptured up to approx. 260 km north and 190 km south from the place of tagging (see Fig. 12 in Griffiths, 1996). Griffiths and Attwood (2005) conclude that, due to the high percentage of recaptures occurring within 3 km of the tagging site, and that movement of large numbers of fish would have been detected due to the heavy targeting of this species, that there is a high degree of estuarine residency of fish < 115 cm TL.

Age, growth and mortality

Age and growth of *A. japonicus* has been well studied in South Africa where they grow to a large size and are relatively long lived, with a maximum reported length of 181 cm TL, weight of 75 kg (Griffiths and Heemstra, 1995) and age of 42 years

Table 1
Summaries of tag-recapture studies of *Argyrosomus japonicus*, showing numbers tagged and recaptured, proportion showing no movement (< 10 km from tag location), greatest distances travelled and maximum times at liberty

Study	No. of fish tagged	No. of fish recaptured	Fish with no movement	Days at liberty of fish with no movement	Greatest movement	Days at liberty of fish with greatest movement
Thomson (1959)	12	0	N/A	N/A	N/A	N/A
Hall (1984)	628	21 (3.3%)	Not reported	Not reported	1 fish ~200 km	~150 days
Hall (1986)	6000	180 (3%)	172 (95.4%) remained within the Coorong	Not reported	7 fish up to ~200 km. Other fish moved > 10 km within the Coorong	Not reported
Griffiths (1996)	Not reported	263	Approx. 218 (83%) recaptured < 10 km from tag site	> 1400	Approx 250 km. 5.7% moved > 30 km	Approx 900 days
Griffiths & Attwood (2005)	1032	73 (7%)	71% recaptured < 3 km from tag site	Not reported	102 km	Not reported
NSW Fisheries (unpublished)	2510	519 (20.7%)	452 (87%) recaptured within the tag estuary	1060	406 km	176 days. Greatest days at liberty = 1954 (fish moved 375 km)

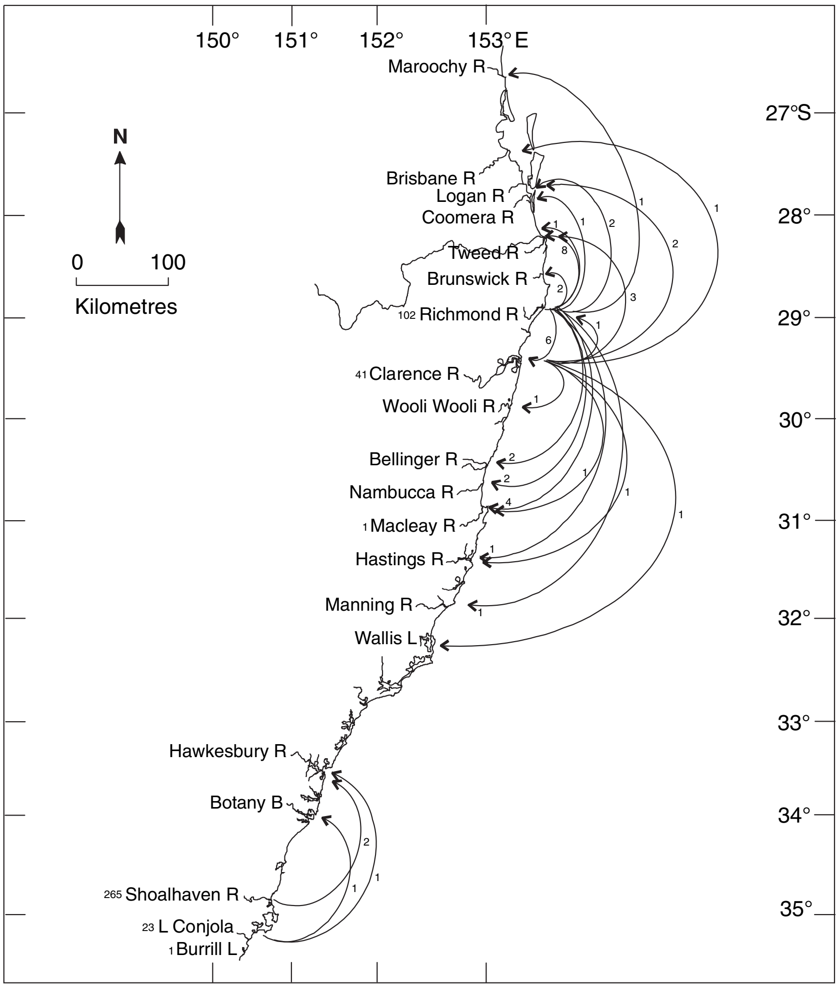

Fig. 2. Locations of release and recapture of tagged *Argyrosomus japonicus* in New South Wales, Australia. Each line and number = fish that travelled between locations; number at each estuary = how many recaptured in same estuary where released

(Griffiths and Hecht, 1995). Recently, Silberschneider and Gray (2005) found that in the waters of NSW, *A. japonicus* also grow to a large size (the largest fish sampled was approx. 169 cm) and are relatively long lived (maximum age of 24 years). In that study, the maximum weight of any one fish sampled was around 30 kg, but fish are known to be heavier than this. Farmer et al. (2005) also showed that, in Western Australian waters, that *A. japonicus* can grow to approx. 140 cm and can attain an age in excess of 30 years. A length of >200 cm has been reported for this species (Kailola et al., 1993), but no evidence is provided to support this. Rates of natural mortality have only been estimated for fish in South Africa and Australia, where it was estimated that M = 0.15 and 0.1, respectively (Griffiths, 1997c; Silberschneider and Gray, 2005).

The most detailed and reliable estimates of the growth of wild *A. japonicus* are provided by Griffiths and Hecht (1995) (validated otolith-based study; 3–175 cm TL), Silberschneider and Gray (2005) (5–169 cm), and Farmer et al. (2005) (15–140 cm). Growth of both sexes is initially rapid and similar for the first 5 years in Australia and South Africa, after which the rate of growth declines (see Table 2), with females growing faster to attain an overall greater length (165–170 cm in South Africa and 130^+ cm in Australia) and age (42 and 30^+ years in South Africa and Australia, respectively) than males (140–145 cm and age 30 years in South Africa, and 115^+ cm and age 25^+ in Australia). Griffiths and Hecht (1995) estimated growth curves for females as $L_t = 1473[1-e^{-0.228(t+2.620)}]^{2.468}$ and for males as $L_t = 1372[1-e^{-0.260(t+4.282)}]^{4.619}$. Although the rates of growth differed between sexes, the length/weight relationships for males and females did not differ significantly. In Western Australia, the rates of growth of females and males are described as $L_t = 123.9[1-e^{-0.24(t-(-0.33))}]$ and as $L_t = 118.9[1-e^{-0.25(t-(-0.35))}]$, respectively (Farmer et al., 2005). Growth curves were not estimated for each sex separately in Silberschneider and Gray (2005) due to small sample sizes, however the combined growth curve was calculated as $L_t = 131.7[1-e^{-0.197(t-(-0.552))}]$, while Griffiths and Attwood (2005) estimated a combined growth curve of $L_t = 1528.5[1-e^{-0.146(t+0.546)}]$ for South African fish.

Despite no further growth analysis information being available, comparative estimates of published mean length at age of *A. japonicus* are presented in Table 2, although we acknowledge there can be large variation in length at age (see Fig 3.1 in Silberschneider and Gray, 2005; and Fig. 6 in Griffith and Hecht, 1995). Gray and McDonall (1993), by following juvenile cohorts caught in prawn trawls, estimated that juveniles grew from a mean length of 7 to 15 cm TL and 16 to 25 cm TL in 6 months between April and October and that fish 15 cm in length were 6 months old. Based on tag-recapture data and scale readings, Hall (1984) estimated that *A. japonicus* grew to 46 cm (1.5 kg) in 2–3 years and a length of 80 cm (8 kg) in 5–6 years; however, ageing by scales tends to underage older fish. West (1993) analysed tag-recapture data and estimated that *A. japonicus* grew to 49 cm TL in 2 years and 56 cm TL in 3 years. The use of tag-recapture data to estimate growth of *A. japonicus* has been thrown into

Table 2
Comparisons of length (TL; cm) estimates at age for *Argyrosomus japonicus*

Age in years	Wallace and Schleyer (1979)[a,1,2]	Hall (1986)[b]	West (1993)[c]	Griffiths and Attwood (2005)[a,3]	Griffiths and Hecht (1995)[a,3]		Farmer et al. (2005)[a,3]		Silberschneider and Gray (2005)[a]	
					M	F	M	F	M	F
1	23.0	8.0	41.0	30.9	35.6	35.5				
2	44.0	24.0	49.0	47.5	50.3	51.1	53.1	53.3	48.0	47.7
3	62.0	41.0	56.0	61.8	64.6	66.0			58.2	58.0
4	77.0	53.0	65.0	74.1	77.6	79.5	79.1	80.4	68.3	69.2
5	90.0	65.0		84.8	89.0	91.3	88.0	89.7	87.4	87.5
6	102.0	81.0		94.1	98.6	101.5			89.7	73.1
7	112.0	96.0		102.1	106.6	110.0			92.3	121.4
8	120.0	107.0		109.0	113.1	117.1			103.1	107.7
9	128.0	114.0		114.9	118.3	122.9			102.7	120.8
10	134.0			120.1	122.4	127.7	110.1	113.7	99.6	107.8
11	139.0									
12	144.0									
14									93.3	130.8
15				137.1	133.1	140.8	116.4	120.9		
18										
20				145.2	136.1	145.2	118.2	123.0		
21										123.2
25				149.2	136.9	146.6				

Age estimated by: [a]otolith interpretation, [b]scale interpretation, [c]release-recapture data.
[1]Presumed to be *A. japonicus*.
[2]Lack of adults sampled and method used to fit growth curve overestimates growth of older fish.
[3]Lengths derived using growth equation and parameters given in manuscript.
M = Male, F = Female.

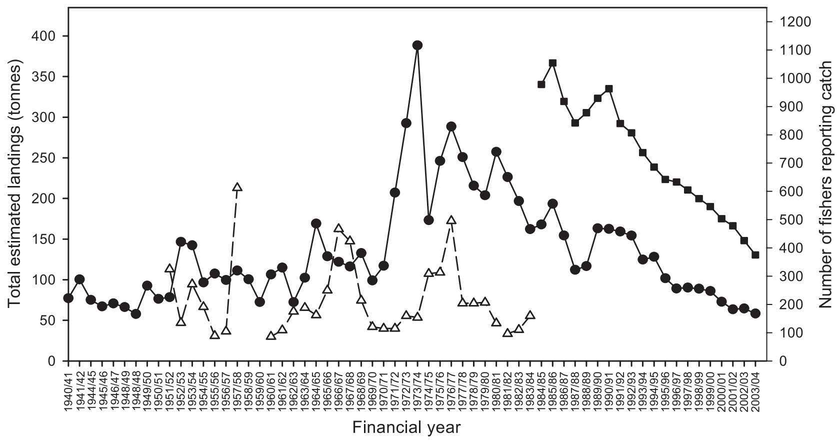

Fig. 3. Reported commercial catches of *Argyrosomus japonicus* in NSW and South Australia since 1940/41 and number of NSW fishers reporting catch of this species. Filled circles – NSW estimated landed weight; open triangles – SA landed catch (reproduced from Hall, 1986); filled squares – number of NSW fishers reporting *A. japonicus*

question by Griffiths and Attwood (2005); these authors demonstrated that growth rates of fish tagged with external dart tags were suppressed for fish < 75 cm but did not affect the growth of larger fish. The available data suggests that growth of *A. japonicus* is variable and that it can also vary greatly among different geographic regions.

Reproduction

Griffiths (1996) reported that 50% of male and female *A. japonicus* in South Africa were mature at 92 and 107 cm TL, respectively, and that all males and females > 110 and 120 cm TL, respectively, displayed mature gonads. The 50 and 100% maturity levels correspond to 5 and 7 years of age for males, and 6 and 8 years for females, respectively. Surprisingly, the length and age at which male and female *A. japonicus* reach sexual maturity in NSW waters is much smaller and younger than in South Africa. Silberschneider and Gray (2005) found that 50% of males mature at around 51 cm TL (corresponding to 2^+ years of age), while 50% of females mature at approx. 68 cm TL (corresponding to 3^+ years). In this study, all males greater than 63 cm and all females greater than 79 cm were mature. A study in Botany Bay in eastern Australia collected *A. japonicus* up to 64 cm and all had immature gonads (Anon, 1981a). It is reported that *A. japonicus* in South and Western Australia do not become sexually mature until they attain about 70–80 cm (approx. 4 kg) and are 5–6 years old (Hall, 1986; Anon, 1993). More rigorous sampling in Western Australia has found that 50% of female *A. japonicus* mature at about 93 cm (approx. 6 years of age) and males mature at around 88 cm (equivalent to 5–6 years of age) (Farmer et al., 2005). No estimates of the fecundity of wild *A. japonicus* have been reported, but Battaglene and Talbot (1994) estimated that hatchery-kept fish around 10 kg could spawn approx. 1 million eggs and that the spawning mode is group synchronous.

The time of spawning appears to vary among geographic regions and with latitude and is probably related to water temperature and oceanography. For example, in southern Africa, Griffiths (1996) found that spawning varied along the coast from August to November (winter to spring) in the northern KwaZulu region (30–31°S), and from October to January (summer) in the southern and south-east Cape regions (33–35°S). Similarly, along the West Australian coast, Penn (1977) reported fish with mature gonads in September and October in Shark Bay (26°S) and Farmer et al. (2005) showed that fish in this region exhibit an extended spawning period from October to April / May. However, Anon (1993) reported that mature fish occurred between December and January in the Swan River (32°S) and, in general terms, it appears that the predominant spawning period for this species in Western Australia is November to January (Farmer et al., 2005). In South Australia, *A. japonicus* spawn throughout summer (November to February) (Hall, 1986). Based on the occurrence of larvae between February and April (Gray and Miskiewicz, 2000) and small juveniles 2–8 cm TL between April and June (Anon, 1981a), spawning in central NSW (around 35°S) appears to take place in late summer and autumn (January to April). This corresponds to the results from Silberschneider and Gray (2005), where fish were observed to have mature gonads from summer to autumn. However, West and Walford (2000) reported that juvenile *A. japonicus* (< 10 cm TL) were present year round in two estuaries in northern NSW (between 28°50′ and 29°30′S). Further, both Broadhurst (1993) and Gray and McDonall (1993) reported two distinct juvenile cohorts in an estuarine population within the same region, which suggests that not all spawning is synchronous within a region.

Several authors have hypothesised that *A. japonicus* spawn in nearshore coastal waters around the mouths of estuaries, reefs and in surf zones. This is based on observations in South Africa (Griffiths, 1996) and South and Western Australia (Hall, 1984, 1986; Anon, 1993) that fish with mature or spent gonads have been caught only in ocean waters, whilst fish in estuaries did not show development of mature gonads. Further, off the east coast of South Africa, eggs have only been collected in nearshore waters and not in the offshore Agulhas Current (see Griffiths, 1996) and larvae (but not eggs) have only been collected in low numbers in estuaries. Hall (1984) suggested that spawning may take place near the mouths of estuaries as large fish (80–150 cm TL) in spawning condition have been caught in the mouth of the Murray River in South Australia. However, in NSW about half of the mature males sampled and approx. one third of the mature females sampled came from estuarine catches (Silberschneider and Gray, 2005). This indicates that *A. japonicus* spawn predominantly at sea but may also spawn in the estuary or move frequently between these two areas since hydration of oocytes generally takes about 24 h, thus fish with ripe ovaries could move into ocean waters before they are ready to spawn. This latter scenario is more likely given the anecdotal evidence of spawning aggregations in NSW coastal waters, which are targeted by fishers, and strong evidence of a seasonal northern coastal spawning migration in South Africa (Griffiths and Heemstra, 1995). Similarly, recent findings from Western Australia show that female *A. japonicus* may spawn in the lower reaches of the Swan River as evidenced by the ovaries containing hydrated oocytes (Farmer et al., 2005). Hall (1984) further postulated that freshwater outflow during summer may promote aggregations of spawning fish near the mouths of estuaries as peak freshwater discharge generally coincided with, or just preceded, the spawning season. The spring / summer-spawning season in South Africa also coincides with the highest periods of rainfall and river discharge in that region. Griffiths (1996) hypothesised that *A. japonicus* may have adapted a river discharge-spawning relationship as an evolutionary tactic to enhance recruitment of juveniles to estuaries.

Diet

A. japonicus has a relatively large mouth with caniniform teeth, sharp gill rakers and a short intestine with a large distensible stomach (Anon, 1981a). It is regarded as a benthic carnivore but can apparently feed throughout the water column (Kailola et al., 1993). The importance of different dietary components has varied among studies and for different life history stages. Overall, crustaceans, notably penaeid, mysid and alpheid shrimp, and small teleost fish have been the primary dietary items observed in the stomachs of juvenile *A. japonicus* (Anon, 1981a; Marais, 1984; Hall, 1986; Fielder et al., 1999). Crustaceans accounted for between 14% (Fielder et al., 1999) and 81% (Anon, 1981a) of the reported diet of juveniles. The importance of crustaceans in the diet of *A. japonicus* appears to decrease with increasing fish size, resulting in fish and squid being the prey of greater relative importance in larger *A. japonicus* (Marais, 1984; Griffiths, 1997a,b).

Commercial and recreational fisheries

Estimates of total worldwide commercial and recreational harvests of *A. japonicus* are not possible to ascertain, as the quantities landed in many countries are either unknown or not reported. Moreover, regional estimates of catches are incomplete for many countries. Hence, available data concerning commercial and recreational catches for Australia only are presented (Table 3). The data show that harvests vary spatially and among fishing sectors and that estimated recreational catches in several states (NSW, Victoria and Western Australia) are of an equivalent or greater magnitude than reported commercial catches. Although there are no estimates of total

Table 3
Estimated commercial and recreational catches of *Argyrosomus japonicus* in Australia in 2001. Data on recreational catches from the National Recreational and Indigenous Fishing Survey (Henry and Lyle, 2003)

	Commercial catch	Recreational catch			
State	Total reported weight (kg)[a]	Total estimated no.	Standard error	Total estimated weight (kg)	Mean weight of fish (kg)[b]
NSW	73 800	136 852	21 678	273 703	2
Victoria	98	5421	2997	10 841	2
Queensland	na	73 243[c]	13 392	84 229[c]	1.2
SA	113 000[a]	27 004	5156	39 885	1.5
WA[c]	61 700	62 928[c]	14 921	359 699[c]	5.7
Total		323 460		925 057	

[a]Commercial catch data for 2001 / 2002 financial year.
[b]Mean weight of *A. japonicus* used to calculate estimated weight.
[c]Other sciaenid species most likely included in these data.

commercial or recreational catches available for South Africa or elsewhere, nearshore commercial line boat fishers in South Africa caught an average of 197 tonnes (t) per year of *A. japonicus* between 1988 and 1992 (Griffiths and Heemstra, 1995).

Most Australian fisheries for *A. japonicus* are managed by spatial and temporal fishing restrictions, gear regulations, minimum legal lengths (MLLs) and recreational bag limits. The MLL regulations and recreational bag limits for *A. japonicus* vary among state jurisdictions, with most MLLs set between 40 cm and 50 cm TL. This is comparable to South Africa where the current MLL ranges from 40 cm to 60 cm TL, depending on the region. These MLLs are not based on biological data, but for South Africa at least, it attempts to take account of species identification difficulties.

Temporal fluctuations in commercial landings of *A. japonicus* are prevalent in records available for South Australia and NSW (Fig. 3). Notably in NSW, commercial landings increased sharply to peak at 380 t in 1973/74 due to the rise of otter trawling in coastal waters and the removal of the MLL in 1971. Reported commercial estuarine and ocean catches have steadily declined since to a low of about 60 t in 2005/06 (valued at around $AUD 432 000). The corresponding catch per unit of effort (CPUE) for *A. japonicus* has generally remained stable throughout this decline (40–50 kg/fisher month from 1984/85 onwards and 3.5–5.2 kg day^{-1} from 1997/98 onwards), suggesting that the decrease in catch may be due to a reduction in the number of commercial fishers targeting *A. japonicus*. However, reported CPUE for *A. japonicus* in South Australia declined from approx. 15 kg day^{-1} in 1976/77 to about 5 kg day^{-1} in 1982/83 (Hall, 1986), with harvest rates increasing up to 49 kg day^{-1} in the late 1990s (Ferguson and Ward, 2003).

Reported commercial catches of *A. japonicus* throughout the past decade in NSW have generally been greatest in estuaries (52–65% of reported annual production) compared to ocean waters (26–40%). Fish are mostly caught using gillnets in estuaries and by hook and line in ocean waters. Reported estuarine commercial catches are generally greatest in the deep coastal rivers that experience high freshwater flows (Hawkesbury, Clarence and Shoalhaven rivers). In South Australia, approx. 80% of the *A. japonicus* commercial fishery centres on one large estuary (the Coorong) and 20% from waters immediately adjacent to the Coorong (Hall, 1986). Within the Coorong, the main fishing methods are gillnets and beach-seine nets (Hall, 1986). Commercial catches are generally greatest between December and June in NSW and between December and March in South Australia. The length composition of commercial landings in NSW has changed considerably over the past three decades (Fig. 4), corresponding to changes in MLL, with the modal length of fish harvested increasing as MLL increased. However, the majority of fish landed were < 10 cm TL above the MLL (when in existence).

Long-term estimates of recreational catches are not reported or known for any region. A recent study estimated that recreational anglers retained approx. 323 000 and released approx. 276 000 *A. japonicus* Australia-wide during 2001 (Henry and Lyle, 2003). Table 3 provides a breakdown of catches on a regional basis. Most other surveys of recreational harvests in Australia have been done on smaller spatial scales, which have generally covered one catchment or a restricted area of coastline. Nevertheless, these studies further document the importance of this species to recreational fishers (Anon, 1981b; West and Gordon, 1994; Steffe et al., 1996; Gartside et al., 1999). This is also true in South Africa, where recreational boat fishers are estimated to catch a quantity similar to commercial fishers (Griffiths and Heemstra, 1995) and, amongst shore anglers, *Argyrosomus* spp. are a highly ranked recreational target species (Brouwer et al., 1997).

Bycatch and discarding

Juvenile *A. japonicus* are a significant component of the discarded bycatch in several fisheries, particularly estuarine and oceanic prawn trawl fisheries (Gray et al., 1990; Broadhurst and Kennelly, 1994, 1995; Liggins and Kennelly, 1996; Liggins et al., 1996; Kennelly et al., 1998). In the NSW oceanic prawn trawl fishery up to 97% of *A. japonicus* caught were discarded (Kennelly et al., 1998) and very high discarding rates of small *A. japonicus* were also reported following floods,

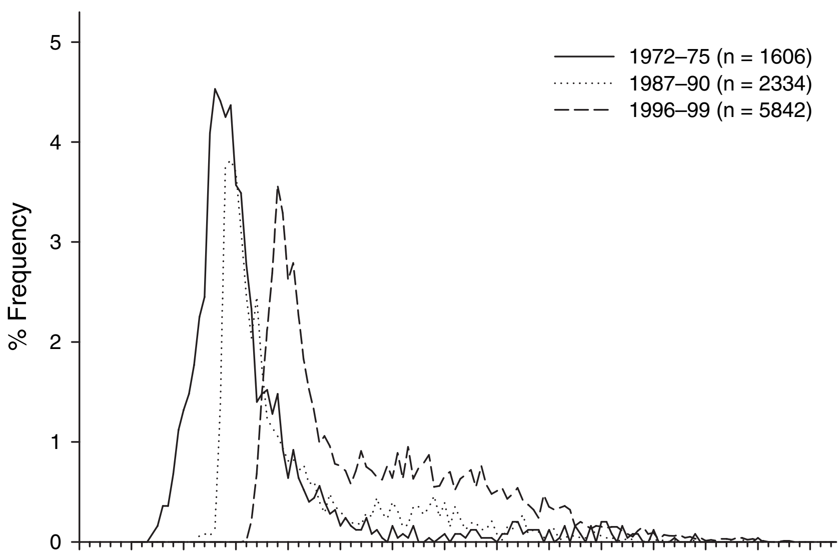

Fig. 4. Estimated length compositions of retained fish from commercial catches of *Argyrosomus japonicus* in NSW for three periods between 1972 and 1999

where small fish were flushed from estuaries (Miller, 2002). Fish discarded from the estuary prawn trawl fishery were predominantly < 20 cm TL (Gray et al., 1990; Liggins and Kennelly, 1996) and similar sized fish are also discarded in the estuarine prawn seine fishery in NSW, but in greatly reduced quantities than the trawl fisheries (Gray et al., 2003). *A. japonicus* also occurs as minor bycatch in the estuarine gillnet (comprising 0.7% of discards) (Gray, 2002) and beach-seine fisheries (Gray and Kennelly, 2003; Gray et al., 2003), and the coastal protective shark-meshing program (only 282 fish caught) (Krogh and Reid, 1996) in NSW.

Various Bycatch Reduction Devices to exclude small *A. japonicus* from capture in prawn fisheries have been developed (see Broadhurst, 2000 for a review). Alternative codend designs successfully reduced catches by up to 95% in the NSW estuarine prawn trawl fishery (Broadhurst and Kennelly, 1994). However, the potential benefits of these changes in fishing gear on stocks of *A. japonicus* have not been assessed.

The condition of released fish from recreational fisheries was not reported in Henry and Lyle (2003) and the impacts of recreational and commercial hook and release on survival remains largely unquantified for *A. japonicus*, particularly from deeper waters where fish may suffer barotraumata stress. Broadhurst and Barker (2000) showed that juvenile *A. japonicus* hooked in the mouth from a relatively shallow (< 2 m) depth and then released, had minimal effect on their overall condition and no mortalities were recorded over the 25-day holding time in experimental pond conditions. More recently, studies have shown that the survival of line-caught *A. japonicus* was dependent on hook location and the removal method (Butcher et al., in press). Significant mortalities (72%) were shown to occur when fish ingested the hook and the hook was removed, while the mortality rate was < 1% if the fish was mouth-hooked and the hook removed or line cut (Butcher et al., in press).

Aquaculture

Sciaenids are generally considered good aquaculture species because they are widely distributed, euryhaline, highly fecund, fast growing and with good food conversion ratios. Several species of scianeids are widely used in aquaculture and in the year 2000 an estimated 2220 t of scianeids were produced in aquaculture throughout the world (FAO, 2002). Sciaenids are not only reared for human consumption but also for enhancement of wild fish stocks. For example, in Texas, red drum (*Sciaenops ocellatus*) is mainly reared to enhance wild stocks and to improve catches in recreational fisheries (McEachron et al., 1995).

Unlike the vast amount of research into the aquaculture potential and actual aquaculture production of sciaenids throughout the world (Arnold et al., 1988; Chamberlain et al., 1990), only over the past decade has there been a developing aquaculture industry based on *A. japonicus* in Australia (Gooley et al., 2000). Reported commercial aquaculture production of *A. japonicus* in Australia in 1997 ⁄ 98 was 6.8 t and in NSW alone was 8.4 t in 2004 ⁄ 05 (O'Sullivan and Roberts, 2000; NSW DPI, 2005). Rearing juvenile *A. japonicus* in a trial using inland saline groundwater tanks has proved successful providing the potassium concentration of the groundwater is at least 40% of that found in seawater (Doroudi et al., 2006). There have been recent investigations into the aquaculture potential of this species in South Africa. *A. japonicus* shows a high degree of similarity in its ontogenetic development with other cultured sciaenids, including *S. ocellatus* and *A. nobilis*, and these similarities have assisted the development of hatchery techniques for *A. japonicus*.

Initial research done in NSW developed the methodology to induce captive adults to spawn, rear the larvae and grow out fish to a marketable size in controlled experimental ponds (Battaglene and Talbot, 1994; Fielder and Bardsley, 1999; O'Sullivan and Ryan, 2001). *A. japonicus* broodstock can be held in aquarium facilities and induced to spawn in tanks after injection with hormones and pellet implants (Thomas and Boyd, 1988; Battaglene and Talbot, 1994), although fish have spawned naturally in some facilities in both NSW and South Africa.

In controlled aquaculture conditions, initial growth of *A. japonicus* is dependent upon the type of technique used, with growth varying from 0.3–0.5 mm day^{-1} in intensive tank systems to 1.2–1.7 mm day^{-1} in extensive ponds (Fielder et al., 1999). Furthermore, captive fish with a mean length of 15 cm TL could maintain a growth rate of approx. 1 mm day^{-1} and reach 45 cm TL in 500 days (Fielder et al., 1999). The feeding schedules used for *A. japonicus* are comparable with those of other cultured sciaenids, including *S. ocellatus* (Robinson, 1988; Battaglene and Talbot, 1994). Enriched rotifers and brine shrimp can be fed to larvae while juveniles can be fed a variety of foods including adult brine shrimp, fishmeal and a 50% protein pellet.

The need for low culture densities to avoid cannibalism, coupled with the fast-growing attributes of juvenile *A. japonicus*, suggests that production of large quantities of the species may be best achieved by larval rearing in intensive tanks, followed by extensive larval culture methods in ponds, similar to that practiced with *S. ocellatus* (McCarty et al., 1986). The relative ease of larval rearing enhances the suitability of *A. japonicus* for aquaculture, however, the reliable supply of mature broodstock has been highlighted as a problem (Battaglene, 1996). *A. japonicus* matures at a larger size (and age) than most other cultured sciaenids and therefore the broodstock may have to be kept for longer periods than other cultured sciaenids before they spawn in captivity (Battaglene and Talbot, 1994).

The technology of rearing and raising *A. japonicus* in Australia has recently been transferred to industry and they are successfully being grown out in sea cages for a small domestic market (500 kg produced in 2001 ⁄ 02 in NSW). Currently, there are three commercial *A. japonicus* aquaculture operations using sea cages, however site availability for sea cages (due to conflicts with other waterway users) may limit the expansion of this industry.

Enhancement of wild fish stocks

Because of declining recreational and commercial catches, the potential to enhance wild stocks of *A. japonicus* is being assessed in eastern Australia. The first experimental release of small hatchery-reared *A. japonicus* was done in three intermittently opening-closing lagoons in NSW, with approx. 25 000 juveniles (chemically marked with oxytetracycline) stocked in each lagoon (Fielder et al., 1999). Commercial fishers recaptured many hundreds of released fish in one lagoon, but none were recaptured in the other two lagoons probably because the fish were flushed into ocean waters caused by flooding soon after being stocked (Fielder et al., 1999). As part of a larger environmental assessment of stock enhancement, a second experiment has recently begun with more than 100 000 small fish released into two estuaries in NSW. This study aims to assess the potential negative ecological impacts of stocking and determine the best strategy for enhancing wild populations and fisheries.

Conclusions and recommendations

The biology of *A. japonicus* has been well studied in South Africa and, more recently, also in Australia. These studies show some plasticity in its life history characteristics among different geographical regions. Studies that investigated the size at which juvenile *A. japonicus* recruit to estuaries propose different sizes at which fish first arrive into estuarine systems. We suggest that *A. japonicus* are present in estuaries from a very small size, but are probably not susceptible to capture with most common research sampling methods (i.e. larger meshed trawls, gillnets and seines) until they reach a larger length (see also Griffiths, 1996). We thus propose that the conclusions that young *A. japonicus* do not occur in estuaries until a larger size may be a result of inappropriate sampling regimes for catching small fish. Therefore, we conclude that *A. japonicus* is not dependent on shallow vegetated habitats as a juvenile nursery area, which is in direct contrast to several other sciaenids, including *Cynoscion nebulosus* (Rutherford et al., 1982).

In contrast to the above, where we propose that differences among studies are simply due to sampling differences, the discrepancy between size and age at maturity of *A. japonicus* in different regions may be due to the plasticity of fish to adjust life history strategies to maximise life-time fecundity. *A. japonicus* is a relatively fast growing and long-lived species (maximum age 42 years), and can mature between 2 and 8 years of age depending on the area studied. A lower age at maturity, as seen in fish sampled in NSW waters, will be selected for in situations where there is high fishing and/or natural mortality and chances of surviving to and after a greater age at maturity are lower. Indeed, size at which female fish in NSW reach sexual maturity occurs at about 50% of its maximum length whereas it is upwards of 70% in other areas (Table 4). This may also indicate that rates of mortality are higher in the NSW population of the species compared to elsewhere. The ages at which females reach sexual maturity compared to the maximum ages sampled are comparable among regions, largely due to long-lived individuals continuing to contribute to the populations. Water temperature, high levels of predation, and the productivity of estuarine and oceanic waters may also result in fish evolving life history strategies to maximise fecundity. Rates of growth, size and age at sexual maturity, length and age structure of populations and estimates of exploitation and mortality rates are required for other locations within the geographical distribution of *A. japonicus* to better understand the plasticity in life history strategies employed by this species.

To make informed decisions concerning the future management of the fisheries and wild populations of *A. japonicus* throughout Australia, more detailed information on the stock structure of the species is required. While tagging studies can assist in this regard, caution needs to be exercised in the interpretation of the release-recapture data provided. Much more information (e.g. distribution of sampling or fishing effort) is required to assess rates of movements in different directions among different estuaries and regions of a coastline. We suggest that future studies to assess the structuring of the species be approached using genetic markers such as mtDNA and/or microsatellite analyses of fish collected via a stratified sampling program, incorporating several replicate samples from predetermined regions along and between coastlines to assess within and between population variations in genetic structures. While microsatellites may detect structuring at a finer geographical scale, mtDNA analyses may be more useful to detect larger scales of divergence. Therefore the application of one or both of the above techniques may be determined by the geographical scale studied and by global developments in using genetic markers as indicators of stock structure. A good example of the utility and strength of such an experimental design in a genetic study is that of Gold et al. (2002) on *Cynoscion nebulosus*.

Sciaenids are prone to overfishing (Sadovy and Cheung, 2003; Piner and Jones, 2004) and *A. japonicus* has been declared recruitment overfished in South Africa (Griffiths, 1997c) with spawning stocks reduced to 2.3% of unexploited levels (Anon, 2005). This is based on sound knowledge of the species biology and estimates of growth, and natural, fishing and total mortality. In Australia, particularly NSW, commercial catches have declined over the past decade and *A. japonicus* has recently been assessed as overfished. Greater protection of juveniles from bycatch-associated mortality and spawning aggregations from fishing may be required to arrest the apparent decline in Australian populations and may provide some level of protection to heavily exploited populations elsewhere.

Acknowledgements

NSW Department of Primary Industries and the Australian Fisheries Research and Development Corporation as part of project 2002/005 provided funding for this desktop study. We thank D. Barker, B. Pease, L. Derwent, K. Rowling and T. Walford for providing unpublished data and K. Rowling, I. Potter and S. Kennelly for comments on the draft manuscript.

Table 4
Geographical comparison of life-history strategies of *Argyrosomus japonicus*

Region	Sex	T_{50}	T_{max}	L_{50} (cm)	L_{inf} (cm)	T_{50}/T_{max}	L_{50}/L_{inf}
NSW	females	3	20	68	131.7[a]	0.15	0.52
NSW	males	2	14	51	N/A	0.14	N/A
WA	females	6	31	93	123.9	0.19	0.75
WA	males	5	29	88	118.9	0.17	0.74
South Africa	females	6	42	107	147.3	0.14	0.73
South Africa	males	5	30	92	137.2	0.17	0.67

[a]Growth curves not calculated separately for each sex. The L_{inf} for combined growth curve presented here as it most likely reflects female growth (given that females grow to a larger size than males) and provides a guide to differences in parameters between regions.

References

Anon, 1981a: The ecology of fish in Botany Bay – Biology of commercially and recreationally valuable species. Report No. BBS 23B. State Pollution Control Comm., Sydney, Australia.

Anon, 1981b: Amateur angling in Botany Bay. Report No. BBS 24. State Pollution Control Comm., Sydney, Australia.

Anon, 1993: Mulloway. Fisheries Department of WA, Western Australia.

Anon, 2005: A brief rationale behind the new kob regulations. Tagging News No. 18. Oceanographic Research Institute, Durban, South Africa.

Arnold, C. R.; Holt, G. J.; Thomas, P., 1988: Red Drum Aquaculture, Proc. Symp. on the culture of red drum and other warm water fishes. Contributions in Marine Science. Supplement to Vol. **30**.

Battaglene, S. C., 1996: Hatchery production of juvenile snapper and mulloway. In: Marine finfish farming – Proceedings of a workshop. N. Quartararo (Ed.). NSW Fisheries Research Institute, Cronulla, NSW, pp. 9–36.

Battaglene, S. C.; Talbot, B. R., 1994: Hormone induction and larval rearing of mulloway, *Argyrosomus hololepidotus* (Pisces: Sciaenidae). Aquaculture **126,** 73–81.

Beckley, L. E., 1990: A description of the early life history stages of the kob, *Argyrosomus hololepidotus* (Pisces: Sciaenidae), from southern Africa. So. Afr. J. Zool. **25,** 224–228.

Black, M.; Dixon, P. I., 1992: Stock identification and discrimination of mulloway in Australian waters. FIRTA 86/16. Centre for Marine Sciences. The University of New South Wales, Australia.

Broadhurst, M. K., 1993: Aspects of the biology, distribution and selectivity of juvenile mulloway *Argyrosomus hololepidotus*: an important by-catch species from estuarine prawn-trawling in New South Wales, Australia. MSc thesis, Australian Maritime College, Launceston, Australia.

Broadhurst, M. K., 2000: Modifications to reduce bycatch in prawn trawls: a review and framework for development. Rev. Fish Biol. Fish. **1,** 27–60.

Broadhurst, M. K.; Barker, D. T., 2000: Effects of capture by hook and line on plasma cortisol, scale loss and survival in juvenile mulloway, *Argyrosomus hololepidotus*. Arch. Fish. Mar. Res. **48,** 1–10.

Broadhurst, M. K.; Kennelly, S. J., 1994: Reducing the by-catch of juvenile fish (mulloway *Argyrosomus hololepidotus*) using square-mesh panels in codends in the Hawkesbury River prawn-trawl fishery, Australia. Fish. Res. **19,** 321–331.

Broadhurst, M. K.; Kennelly, S. J., 1995: A trouser-trawl experiment to assess cod-ends that exclude juvenile mulloway (*Argyrosomus hololepidotus*) in the Hawkesbury River prawn-trawl fishery. Mar. Freshw. Res. **46,** 953–958.

Brouwer, S. L.; Mann, B. Q.; Lamberth, S. J.; Sauer, W. H. H.; Erasmus, C., 1997: A survey of the South African shore-angling fishery. So. Afr. J. Mar. Sci. **18,** 165–177.

Butcher, P. A.; Broadhurst, M. K.; Reynolds, D.; Reid, D. D.; Gray, C. A., (submitted): Effects of release method and anatomical hook location on the mortality of angler-caught yellowfin bream (*Acanthopagrus australis*) and mulloway (*Argyrosomus japonicus*). (in press).

Chamberlain, G. W.; Miget, R. J.; Haby, M. G., 1990: Red Drum Aquaculture. Accompanying publication to No. 132.

Connolly, R. M., 1994: A comparison of fish assemblages from seagrass and unvegetated areas of a southern Australian estuary. Aust. J. Mar. Freshw. Res. **45,** 1033–1044.

Doroudi, M.; Fielder, D. S.; Allan, G. L.; Webster, G. K., 2006: Combined effects of salinity and potassium concentration on juvenile mulloway (*Argyrosomus japonicus* Temminck & Schlegel) in inland saline groundwater. Aquacult. Res. **37,** 1034–1039.

FAO, 2002: FAO Fishery Information, Data and Statistics Unit. Aquaculture production statistics 1991–2000. Vol 90/2.

Farmer, B. M.; French, D. J. W.; Potter, I. C.; Hesp, S. A.; Hall, N. G., 2005: Determination of biological parameters for managing the fisheries for mulloway and silver trevally in Western Australia. Final Report on the Fisheries Research & Development Corporation Proj. No. 2002/004. 149P.

Ferguson, G.; Ward, T., 2003: Mulloway (*Argyrosomus japonicus*) fishery. Fishery Assessment report to PIRSA Fisheries for the Inland Waters and Marine Scalefish Fishery Management Committees. Publ. No. RD03/0040. South Australian Research and Development Institute, Adelaide. 55*p*.

Ferrell, D. J.; McNeill, S. E.; Worthington, D. G.; Bell, J. D., 1993: Temporal and spatial variation in the abundance of fish associated with the seagrass *Posidonia australis* in south-eastern Australia. Austral. J. Mar. Freshw. Res. **44,** 881–899.

Fielder, D. S.; Bardsley, W. J., 1999: A preliminary study on the effects of salinity on growth and survival of mulloway *Argyrosomus japonicus* larvae and juveniles. J. World Aquacult. Soc. **30,** 380–387.

Fielder, D. S.; Bardsley, W. J.; Allan, G. L., 1999: Enhancement of mulloway (*Argyrosomus japonicus*) in intermittently opening lagoons. FRDC Project No. 95/148. Final Report Series No. 14. NSW Fisheries, Australia.

Froese, R.; Pauly, D., 2003: FishBase. World Wide Web electronic publication. http://www.fishbase.org, version 16 June 2003.

Gartside, D. F.; Harrison, B.; Ryan, B. L., 1999: An evaluation of the use of fishing club records in the management of marine recreational fisheries. Fish. Res. **41,** 47–61.

Gold, J. R.; Stewart, L. B.; Ward, R., 2002: Population structure of spotted sea trout (*Cynoscion nebulosus*) along the Texas Gulf coast as revealed by genetic analysis. In: Biology of spotted sea trout. S. A. Bortone (Ed.). CRC Press, Boca Raton, FL, pp. 17–30.

Gooley, G. J.; De Silva, S. S.; Hone, P. W.; McKinnon, L. J.; Ingram, B. A., 2000: Cage aquaculture in Australia: a developed country perspective with reference to integrated aquaculture development within inland waters. In: Cage aquaculture in Asia: Proc. First Internat. Symp. on Cage Aquaculture in Asia. I. C. Liao and C. K. Lin (Eds). Asian Fisheries Society, Manila and World Aquaculture Society - Southeast Asian Chapter, Bangkok, pp. 21–37.

Gray, C. A., 1995: The influences of sewage plumes and oceanography on assemblages of larval fishes. PhD Thesis. Univ. Sydney, Sydney, pp. 439.

Gray, C. A., 2002: Management implications of discarding in an estuarine multi-species gill net fishery. Fish. Res. **56,** 177–192.

Gray, C. A.; Kennelly, S. J., 2003: Catch characteristics of the commercial beach-seine fisheries in two Australian barrier estuaries. Fish. Res. **63,** 405–422.

Gray, C. A.; McDonall, V. C., 1993: Distribution and growth of juvenile mulloway, *Argyrosomus hololepidotus* (Pisces: Sciaenidae), in the Hawkesbury River, South-eastern Australia. Austral. J. Mar. Freshw. Res. **44,** 401–409.

Gray, C. A.; Miskiewicz, A. G., 2000: Larval fish assemblages in south-east Australian coastal waters: Seasonal and Spatial Structure. Estuarine, Coastal Shelf Sci. **50,** 549–570.

Gray, C. A.; McDonall, V. C.; Reid, D. D., 1990: By-catch from prawn trawling in the Hawkesbury River, New South Wales: species composition, distribution and abundance. Austral. J. Mar. Freshw. Res. **41,** 13–26.

Gray, C. A.; Kennelly, S. J.; Hodgson, K. E., 2003: Low levels of bycatch from estuarine prawn seining in New South Wales, Australia. Fish. Res. **64,** 37–54.

Griffiths, M. H., 1996: Life history of the dusky kob *Argyrosomus japonicus* (Sciaenidae) off the east coast of South Africa. So. Afr. J. Mar. Sci. **17,** 135–154.

Griffiths, M. H., 1997a: Feeding ecology of the South African *Argyrosomus japonicus* (Pisces: Sciaenidae), with emphasis on the eastern cape surf zone. So. Afr. J. Mar. Sci. **18,** 249–264.

Griffiths, M. H., 1997b: Influence of prey availability on the disturbance of dusky kob *Argyrosomus japonicus* (Sciaenidae) in the Great Fish River Estuary, with notes on the diet of early juveniles from three other estuarine systems. So. Afr. J. Mar. Sci. **18,** 137–145.

Griffiths, M. H., 1997c: Management of South African dusky kob *Argyrosomus japonicus* (Sciaenidae) based on per-recruit models. So. Afr. J. Mar. Sci. **18,** 213–228.

Griffiths, M. H.; Hecht, T., 1995: Age and growth of South African dusky kob *Argyrosomus japonicus* (Sciaenidae) based on otoliths. So. Afr. J. Mar. Sci. **16,** 119–128.

Griffiths, M. H.; Heemstra, P. C., 1995: A contribution to the taxonomy of the marine fish genus Argyrosomus (Perciformes: Sciaenidae), with descriptions of two new species from southern Africa. Ichthyol. Bull. J. L. B. Smith Instit. Ichthyol. **65,** 1–40.

Griffiths, M. H.; Attwood, C. G., 2005: Do dart tags suppress growth of dusky kob *Argyrosomus japonicus*? Afr. J. Mar. Sci. **27,** 505–508.

Hall, D. A., 1984: The Coorong: Biology of the major fish species and fluctuations in catch rates 1976–1983. SAFIC **8,** 3–17.

Hall, D. A., 1986: An assessment of the mulloway (*Argyrosomus hololepidotus*) fishery in South Australia with particular reference to the Coorong Lagoon. Dept. Fisheries, South Australia.

Henry, G. W.; Lyle, J. M., 2003: The National Recreational and Indigenous Fishing Survey. Final Report to the Fisheries Research & Development Corporation and the Fisheries Action Program. Project No. 1999 ⁄ 158. NSW Fisheries Final Report Series No. 48. ISSN 1440-3544. 188 pp.

Kailola, P. J.; Williams, M. J.; Stewart, R. C.; Reichelt, R. E.; McNee, A.; Grieve, C., 1993: Australian Fisheries Resources. Bureau of Resource Sciences, Department of Primary Industries and Energy, and the Fisheries Research and Development Corporation. Canberra, Australia.

Kennelly, S. J.; Liggins, G. W.; Broadhurst, M. K., 1998: Retained and discarded by-catch from oceanic prawn trawling in New South Wales, Australia. Fish. Res. **36,** 217–236.

Krogh, M.; Reid, R., 1996: Bycatch in the protective shark meshing programme off south-eastern New South Wales, Australia. Biol. Conserv. **77,** 219–226.

Lenanton, R. C. J.; Potter, J. C., 1987: Contribution of estuaries to commercial fisheries in temperate Western Australia and the concept of estuarine dependence. Estuaries **10,** 28–35.

Liggins, G. W.; Kennelly, S. J., 1996: By-catch from prawn trawling in the Clarence River estuary, New South Wales, Australia. Fish. Res. **25,** 347–367.

Liggins, G. W.; Kennelly, S. J.; Broadhurst, M. K., 1996: Observer-based survey of by-catch from prawn trawling in Botany Bay and Port Jackson, New South Wales. Mar. Freshw. Res. **47,** 877–888.

Lin, S. Y., 1940: Croakers of the South China Sea. J. Hong Kong Fish. Res. Station **1,** 243–254.

Marais, J. F. K., 1984: Feeding ecology of major carnivorous fish from four eastern Cape estuaries. So. Afr. J. Zool. **19,** 210–223.

McCarty, C. E.; Geiger, J. G.; Sturner, L. N.; Gregg, B. A.; Rutledge, W. P., 1986: Marine fish culture in Texas: A model for the future. In: The role of fish culture in fishery management. R. Stroud (Ed.). Internat symp on the use of cultured fish in fishery management American Fisheries Society, Bethesda, MD, pp. 249–262.

McEachron, L. W.; McCarty, C. E.; Vega, R. R., 1995: Successful enhancement of the Texas red drum (*Sciaenops ocellatus*) population. In: Proc. 22nd U. S.-Japan Aquaculture Panel Symp.: Interactions between cultured species and naturally occurring species in the environment. August 21–22, 1993. M. R. Collie, J. P. and McVey (Eds). Homer, Alaska. UJNR Technical Report No. 22 ⁄ Alaska Sea Grant Report AK-SG-95-03. Accessed 29 ⁄ 10 ⁄ 02 from http://www.lib.noaa.gov/japan/aquaculture/report22/mceachro.html

Miller, M., 2002: Survey of prawn trawl bycatch in the Richmond River oceanic fishing closure (April – July 2001). In: Scientific reports on the recovery of the Richmond and Macleay rivers following fish kills in February and March 2001. S. Kennelly and T. McVea (Eds). NSW Fisheries, Cronulla. NSW Fisheries Final Report Series, Report No. 39.

Miskiewicz, A., 1987: Taxonomy and ecology of fish larvae in Lake Macquarie and New South Wales coastal waters. PhD Thesis, Univ. New South Wales.

NSW Department of Primary Industries, 2005: Aquaculture production report – 2004 ⁄ 05. NSW DPI, NSW.

O'Sullivan, D.; Roberts, N., 2000: Status of Australian Aquaculture in 1997 ⁄ 98. Austasia Aquacult. Trade Directory 2000.

O'Sullivan, D.; Ryan, M., 2001: Mulloway trials suggest opportunities for brackish water ponds. Austasia Aquacult. April ⁄ May, 22–26.

Paterson, A. W.; Whitfield, A. K., 2000: Do shallow-water habitats function as refugia for juvenile fishes? Estuarine, Coastal Shelf Sci. **51,** 359–364.

Paxton, J. R.; Eschmeyer, W. N., 1994: Encyclopedia of Fishes. University of New South Wales Press, Sydney, Australia.

Penn, J. W., 1977: Trawl caught fish and crustaceans from Cockburn Sound. Report No. 20. Department of Fisheries and Wildlife Western Australia. Perth, WA.

Piner, K. R.; Jones, C. M., 2004: Age, growth and the potential for growth overfishing of spot (*Leiostomus xanthurus*) from the Chesapeake Bay, eastern USA. Mar. Freshw. Res. **55,** 553–560.

Potter, I. C.; Beckley, L. E.; Whitfield, A. K.; Lenanton, R. C. J., 1990: Comparisons between the roles played by estuaries an the life cycles of fishes in temperate Western Australia and South Africa. Env. Biol. Fishes **28,** 143–178.

Robinson, E. H., 1988: Nutritional requirements of red drum: a review. Contrib. Mar. Sci. **30**(Suppl.)**,** 11–20.

Rutherford, E. S.; Thue, E. B.; Buker, D. G., 1982: Population characteristics, food habits and spawning activity of spotted seatrout, *Cynoscion nebulosus*, in Everglades National Park. Report T-688. South Florida Research Centre, Homestead, Florida: Everglades NP, 48 pp.

Sadovy, Y.; Cheung, W. L., 2003: Near extinction of a highly fecund fish: the one that nearly got away. Fish Fisher. **4,** 86–99.

Silberschneider, V.; Gray, C. A., 2005: Arresting the decline of the commercial and recreational fisheries for mulloway (*Argyrosomus japonicus*). Final Report on the Fisheries Research & Development Corporation Project No. 2001 ⁄ 027. 72 pp.

Smith, K. A., 2003: Larval distribution of some commercially valuable fish species over the Sydney continental shelf. Proc. Linnean Soc. NSW **124,** 1–11.

Steffe, A. S., 1991: Larval fish distributions within Botany Bay: Implications for estuarine recruitment and management. PhD thesis, Macquarie University, Sydney.

Steffe, A. S.; Neira, F. J., 1998: Sciaenidae: Croakers and drums. In: Larvae of Temperate Australian Fishes. F. J. Neira, A. G. Miskiewicz and T. Trnski (Eds). Univ. Western Australia Press. Nedlands, Western Australia, pp. 278–283.

Steffe, A. S.; Murphy, J. J.; Chapman, D. J.; Tarlinton, B. E.; Gordon, G. N. G.; Grinberg, A., 1996: An assessment of the impact of offshore recreational fishing in New South Wales waters on the management of commercial fisheries. Project No: 94 ⁄ 053. NSW Fisheries. Cronulla, Australia.

Thomas, P.; Boyd, N., 1988: Induced spawning of spotted seatrout, red drum and orangemouth corvina (Family: Sciaenidae) with luteinizing hormone-releasing hormone analog injection. Contrib. Mar. Sci. **30**(Suppl.)**,** 43–48.

Thomson, J. M., 1959: Some aspects of the ecology of Lake Macquarie, NSW, with regard to an alleged depletion of fish. Austral. J. Mar. Freshw. Res. **10,** 375–387.

Trewavas, E., 1977: The sciaenid fishes (croakers or drums) of the Indo-West Pacific. Trans. Zool. Soc. London **33,** 253–541.

Wallace, J. H.; Schleyer, M. H., 1979: Age determination in two important species of South African angling fishes the kob (*Argyrosomus hololepidotus* Lacep.) and the spotted grunter (*Pomadasys commersonni* Lacep.). Trans. Royal Soc. So. Afr. **44,** 15–25.

West, R. J., 1993: Estuarine fisheries resources of two southeastern Australian rivers. PhD thesis. University of New South Wales, Sydney.

West, R. J.; Gordon, G. N. G., 1994: Commercial and recreational harvest of fish from two Australian coastal rivers. Australian J. Mar. Freshw. Res. **45,** 1259–1279.

West, R. J.; Walford, T. R., 2000: Estuarine fishes in two large eastern Australian coastal rivers - does prawn trawling influence fish community structure? Fish. Managem. Ecol. **7,** 523–536.

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