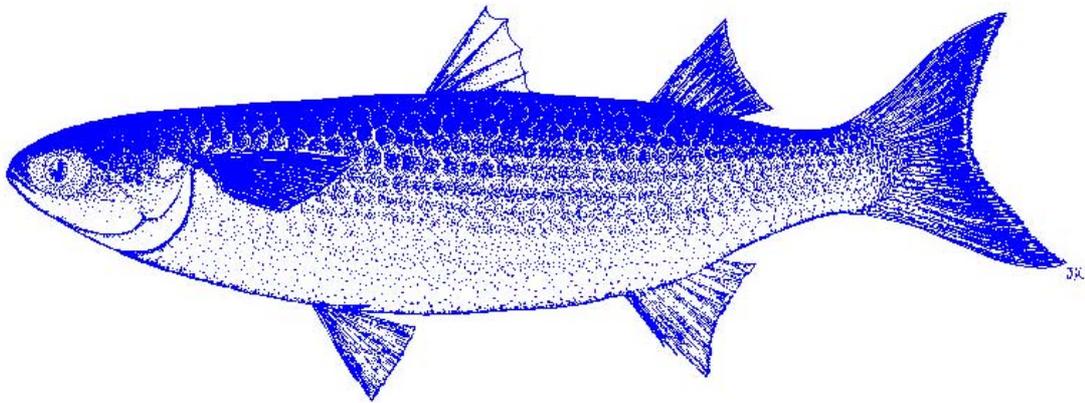


Review of biological information and stock assessment for the NSW sea mullet resource

K.A. Smith and K. Deguara



April 2002

NSW FISHERIES

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EXECUTIVE SUMMARY

Smith K.A. and Deguara K. 2002. Review of biological information and stock assessment for the NSW sea mullet resource. *NSW Fish. Res. Assess. Ser. 12.*

Sea mullet (*Mugil cephalus*) is an important species in many coastal fisheries of Australia. In 1999/00, sea mullet landings were the highest by quantity and total value of all finfish species caught by commercial fishers in New South Wales. Information regarding the biology of this commercially valuable species in Australia has not been comprehensively reviewed since Thomson (1963). There have been significant advances in understanding since this time, particularly the development and widespread use of otolith aging techniques (to replace scale readings). Age, growth and population structure of eastern Australian sea mullet have recently been characterised using these techniques (Virgona et al. 1998). Despite the development of larval and juvenile rearing techniques (e.g. Kuo et al. 1973), which have advanced our understanding of larval biology, the early life history of wild sea mullet is still poorly understood. Considerable effort in tag and release of Australian sea mullet has resulted in a partial understanding of movements, especially spawning migrations, but spawning locations and larval dispersal/recruitment processes remain unclear. The dearth of information regarding reproduction and early life history is somewhat remarkable, given the numerous sea mullet fisheries that target pre-spawning aggregations of fish.

In New South Wales, sea mullet are caught on ocean beaches and in estuaries. Most landings occur in central or northern NSW regions between March and June. In this period, fish aggregate and undertake a migration prior to winter spawning. Ocean and estuary landings are dominated by 4-6 and 2-3 y old fish, respectively. In both sectors, individuals are typically 30-40 cm in length. Maturity is reached at approximately 30-34 cm in length and 3-4 y in age. Maximum observed length/age in New South Wales is 60 cm/12 y. Females typically attain greater maximum size and age than males. Females are targeted by commercial fishers for roe, which is a valuable export product. Fecundity has not been examined within the New South Wales population, but estimates from other regions range between 1 and 4.8 million eggs, depending on female body size.

Monitoring of the length and age of NSW commercial sea mullet landings has occurred annually since 1995, and intermittently in earlier years. Future stock assessment of sea mullet will require spatially representative, annual monitoring of age and length composition of landings. The age/length composition of landings is variable among years, among regions and between sexes. Such variability must be considered when describing total stock structure or calculating average population parameters such as growth and mortality. From available data, estimates for the New South Wales stock are: 1) *von Bertalanffy growth parameters*, $K = 0.86$ (male) and 0.69 (female), $t_0 = 0.80$ (male) and 0.79 (female), $L_\infty = 359$ mm (male) and 413 mm (female); 2) *Total mortality*, $Z = 0.45$ (male) and 0.53 (female).

Prior to 1985, the NSW sea mullet fishery experienced a long period (30 years) of relatively stable catch level. Over this period, annual landings consisted of approximately 2000 t from estuaries and approximately 500 t from ocean waters. Such stability suggests that these 'historical' catch levels were sustainable. After 1985, quantities of ocean landings increased very significantly and exceeded estuarine landings for a six year period during the mid-1990's. Unprecedented quantities of spawning fish were removed from the stock by the ocean fishery during this period and it is possible that the spawning component of this stock was depleted. Significant declines in catch occurred after this period. In 1999/00, ocean catch levels were approaching (but still above) historical levels. The cause of the catch decline is unclear, and it is also unclear whether catch level has yet stabilised. Significantly, historically stable catch levels may no longer be sustainable under conditions of depleted spawning biomass.

Catch declines between 1998 and 2000 coincided with declines in the average age of landings. Trends in age structure may reflect recruitment variability and/or effects of fishing. Trends in catch and age structure in the NSW fishery are difficult to interpret in the absence of a reliable index of sea mullet abundance. The quality of catch and effort data reported by commercial fishers could be significantly improved and, with improvements, may provide an index of abundance. In combination, trends in catch and age structure suggest reduced availability of mature sea mullet in recent years.

Under current market conditions, ocean-caught fish are more highly valued than estuary-caught fish. Therefore, it is likely that ocean fish will continue to be highly targeted. The impact of this harvest strategy on the sea mullet stock is uncertain, given available data.

BIOLOGY

Distribution

Sea mullet is distributed throughout temperate and subtropical regions of the world, between approximately 42 °N and 42 °S (Thomson 1963). This distributional range coincides with minimum water temperatures of approximately 16-18°C. Sea mullet occur in coastal, estuarine and freshwater and tolerate salinities from 0 to 80 ppt (Thomson 1963, Wallace 1975a). Individuals display strong schooling tendencies at all developmental stages and adults undergo a seasonal pre-spawning migration. This migration usually involves movement from an estuary to coastal waters, where large schools then travel against the prevailing current.

Populations throughout the world, including those on the east and west coasts of Australia, are morphologically similar but genetically distinct (Thomson 1951, Rossi et al. 1998). Aspects of population dynamics, such as growth rate and sex ratio, may also vary among regional populations (e.g. Tamaru et al. 1996).

Sea mullet has various common names around the world. These names include 'sea', 'grey' and 'striped' mullet.

Early Life History

The eggs of sea mullet are externally fertilized, and eggs and larvae are pelagic within marine waters. Initially, the yellow-pigmented eggs are positively buoyant but become negatively buoyant after fertilization (Kesteven 1942, Thomson 1963). Hatching takes approximately 48 h (Thomson 1963). Larvae sink during the first 10 days after hatching, and then exhibit strong positive phototaxis (Liao 1974). Hence, beyond 10 d of age (corresponding to a length of approximately 3.5 mm) larvae tend to occur at the surface (Kuo et al. 1973).

In the absence of detailed local observations, the distribution of larvae off the east Australian coast must be inferred from observations within similar oceanographic regimes elsewhere. The Gulf Stream is a northern hemisphere analogue to the East Australian Current, and occurs at similar latitudes. Sea mullet larvae within the vicinity of the Gulf Stream are generally found at the surface over the outer shelf and slope, and do not appear to vertically migrate but may undergo diel changes in rates of activity (Anderson 1958, Collins and Stender 1989, Ditty and Shaw 1996).

Post-larvae may enter estuaries between 11 and 40 mm, but typically enter at 20-30 mm length, at an estimated age of 2-3 months (Anderson 1958, Thomson 1963, Wallace and Van der Elst 1975, Major 1978, Chubb et al. 1981, Rajyalakshmi and Chandra 1987). Schooling commences whilst still in the plankton/pelagic phase and recruiting fry have been observed swimming into estuaries in "...an almost unbroken stream a few feet wide in shallow water along the shore" (Thomson 1955). Recruitment to estuaries typically occurs over a period of 4-6 months, and tends to occur earlier in higher latitudes (Kesteven 1942, Anderson 1958, Wallace and Van der Elst 1975, Chubb et al. 1981). Within Australian estuaries, new recruits have been observed in May-November (south-west coast, Chubb et al. 1981), June-October (south-east coast, State Pollution Control Commission 1981), and August-September (north-east coast, Kesteven 1942). Thomson (1963) suggested that the distribution of juveniles may sometimes extend into higher latitudes than that of adults, as a result of larval drift (with current) and opposing adult migration (against current).

Young juveniles first recruit to lower reaches of estuaries and spread to upper reaches over a period of months. Juveniles eventually become evenly distributed along waterways, from freshwater to the sea (Thomson 1963, Chubb et al. 1981). Freshwater is not obligatory to the life cycle, which is completed in saline waters in some regions (Thomson 1963). Additionally, the fact that juveniles often remain associated with sites within estuaries for months suggests that some individuals in lower reaches of estuaries may never migrate upstream to freshwater areas (Leber et al. 1995). Estuarine schools appear to have a degree of permanency, with some tagged individuals being recaptured again together after 6 months (Thomson 1955, 1959).

Very small (<50 mm) juveniles tend to inhabit the extreme shallows and intertidal areas (Whitfield and Blaber 1978, Chubb et al. 1981). This strategy may minimise intraspecific competition for resources between juveniles and adults and allow the smallest individuals to avoid predation by large fish. However, this strategy also exposes small fish to extreme temperature and salinity fluctuations that are, in some cases, near-lethal (Major 1978).

Diet

Sea mullet larvae feed primarily on micro-crustaceans within the plankton. After recruitment to estuaries, juveniles of 20-55 mm length undergo a gradual transition from planktonic carnivory to benthic grazing of phytoplankton and detritus (de Silva 1977). Juveniles feed during the day, with activity peaking between dawn and mid-day. Tides do not appear to influence feeding patterns. There are shifts in feeding activity, which are presumably in response to seasonal changes in food availability (de Silva 1977). A primarily benthic grazing habit is maintained throughout adult life (Cardona et al. 1996).

The adult diet comprises small particles, including detritus, zooplankton and large phytoplankton (Cardona et al. 1996).

As a result, mullet are efficient exploiters of primary protein. Mature and immature fish do not feed whilst migrating (Kesteven 1942, Thomson 1951).

Migration

After initially recruiting to estuaries on the east Australian coast, most juveniles appear to remain in estuarine waters until maturity. However, a number of immature fish have been recaptured in different estuaries to that in which they were tagged, suggesting that immature fish may sometimes migrate (Thomson 1955). A hardgut* migration is known to occur in summer in some years, and comprises mostly fish aged 3+ y (ie. mature) but also contains some younger individuals (Virgona et al. 1998). This movement of juveniles and adults appears to be the result of heavy rain causing flushing of fish from estuaries. (*these migrating fish do not feed and have undeveloped gonads, hence the term 'hardgut').

During the warmer months of the year, mature sea mullet begin to move downstream within estuaries (Chubb et al. 1981). These pre-spawning fish often aggregate at the estuary mouth before exiting to sea during late autumn or winter. Exit to sea by adults on the east coast frequently coincides with the occurrence of strong westerly winds (Thomson 1955). Tagging studies of sea mullet have mostly found northward migrations on both the east and west Australian coasts (Thomson 1951, Virgona et al. 1998). This is against the predominant current in each region. Northward migrations of up to 724 km per year have been observed on the east coast, although 100 km per year is more typical. Australian sea mullet appear to undertake spawning migrations over greater distances than some other populations. For example, 90% of migrations by tagged mullet in Florida were <33 km (Idyll and Sutton 1952).

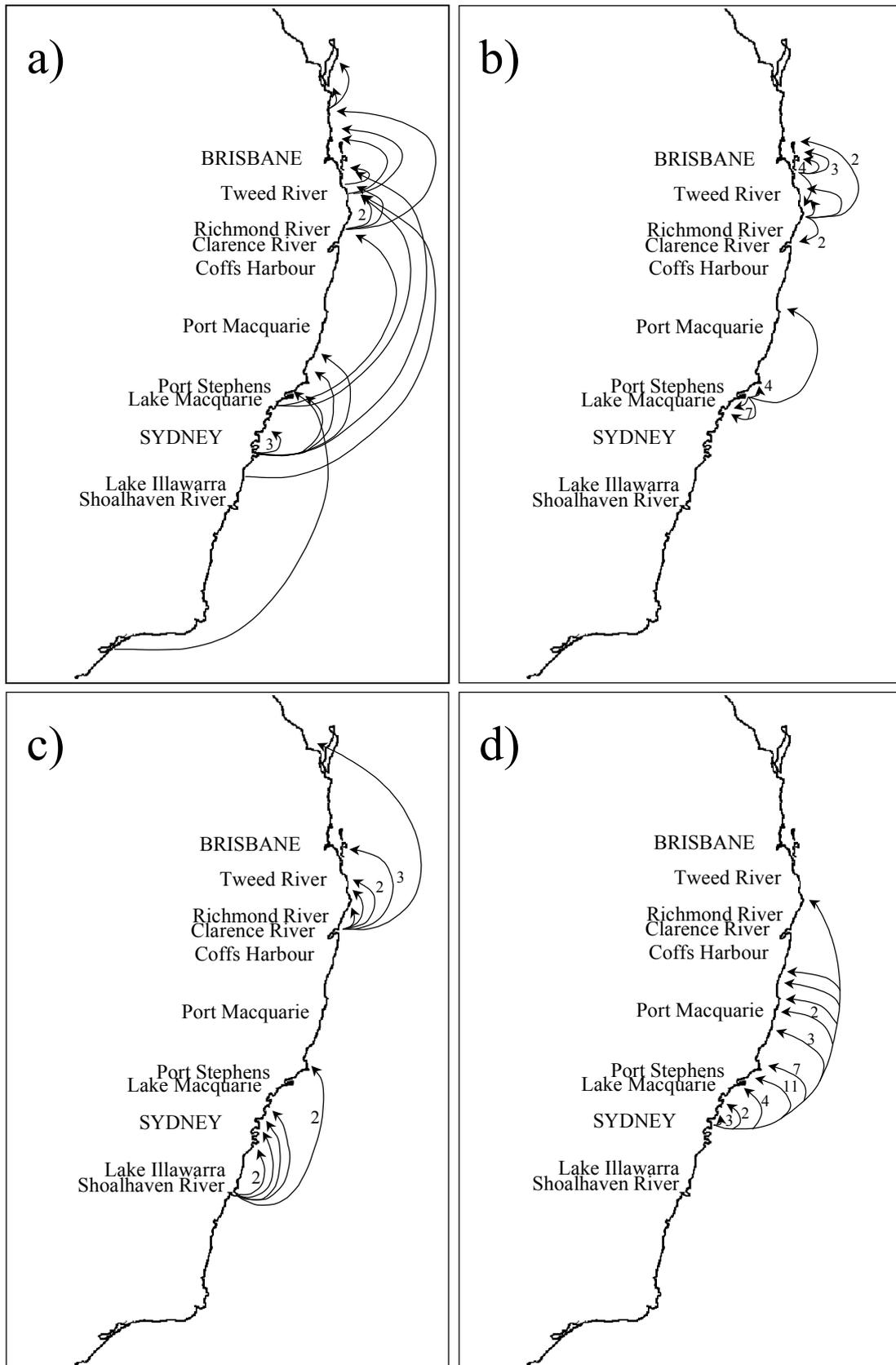


Figure 1. Movement of tagged sea mullet in New South Wales waters. Ocean releases by **a)** Kesteven 1953, and **b)** Virgona *et al.* 1997. Estuary releases **c)** in Clarence and Shoalhaven Rivers (Virgona *et al.* 1998), and **d)** in Hawkesbury River (D. Pollard unpubl. data). (number of fish with same movement shown where number >1)

A small number of fish tagged on the east Australian coast have moved south, which concurs with anecdotal reports by fishers of spent females travelling south. However, only relatively short southward migrations have been recorded (Fig. 1). The maximum recorded southward movement is 120 km, but the majority of recorded southward movement is less than 50 km (Virgona et al. 1998). Spent females have been observed at the end of the spawning season, apparently returning to estuaries (Render et al. 1995). Individuals tagged during ocean migrations have been recaptured after several years, suggesting that individuals do indeed return to estuaries after spawning and are likely to spawn more than once per lifetime (Virgona et al. 1998).

Some fish have been recaptured within the same estuary after 1 or more years at liberty, suggesting either a failure to undergo migration in some years, or a return to the same estuary after spawning (Thomson 1955). All adults may not migrate each year. If fish are prevented from leaving an estuary (e.g. obstruction by closure of a sandbar), spawning will not occur and oocytes are resorbed (Wallace 1975b).

Reproduction

Spawning

Documented observations of spawning are extremely rare, but include one report of night-time, surface spawning over the continental slope of the Gulf of Mexico (40-50 miles offshore, water depth of 850-1550 m, Arnold and Thomson 1958). Larval distributions in the Gulf of Mexico also suggest spawning over the mid- or outer shelf (Ditty and Shaw 1996). Anecdotal reports from fishers along the east Australian coast suggest spawning activity adjacent to coastal headlands and in the lower reaches of estuaries. Overall, the distribution of larvae and juveniles in continental shelf waters off Australia and elsewhere suggests spawning could occur in either coastal or offshore locations, including the shelf break region (Anderson 1958, Collins and Stender 1989, Virgona et al. 1998, Smith unpubl. data).

The fact that ripe gonads are resorbed by estuarine fish when denied access to the sea suggests that a marine environment may be a requirement for spawning and that spawning does not typically occur in estuaries (Wallace 1975b). The distribution of larvae in ocean waters suggests particular conditions of temperature and salinity may be required for spawning (Ditty and Shaw 1996). Avoidance of estuarine plume water may prompt adults to spawn further offshore in regions of high freshwater runoff (e.g. Florida) than in regions of low runoff (e.g. NSW).

There has been speculation over the exact nature of spawning in sea mullet. Females are thought to be isochronal spawners, producing a single clutch of eggs per year (Greeley et al. 1987). However, an individual may not release all eggs at once. Render et al. (1995) calculated that the female body cavity was not of sufficient volume to host a full clutch of hydrated eggs (~1 mm diameter each) and suggested that batches of oocytes may be hydrated on successive nights until the supply becomes exhausted. Individuals found with partially spent gonads lend some support to this suggestion (Stenger 1959).

All individuals may not spawn synchronously. Individual gonadosomatic index (GSI) values within a single school may vary, suggesting a difference in reproductive state among members at any one time (Apekin and Vilenskaya 1979).

Peaks in GSI values, as well as larval and juvenile occurrences, suggest a protracted spawning period of up to 7 months. Peaks in GSI slightly precede the appearance of larvae and juveniles. Throughout the species range, spawning typically occurs in autumn-winter or winter-spring, but may also occur in summer (e.g. Apekin and Vilenskaya 1979, Gomez et al. 1995). Mean GSI

values of 15-20 % (females) and >7 % (males) have been used to infer spawning times (Grant and Spain 1975, Su and Kawasaki 1995, Virgona et al. 1998). Values approach 0 % at other times.

GSI values of eastern Australian sea mullet indicate reproductive activity between March and July each year (Fig. 2). Differences in the timing of migration along the eastern coast suggest gonad maturation could commence earlier in fish at higher latitudes. However, insufficient data are currently available from individual regions to assess this possibility.

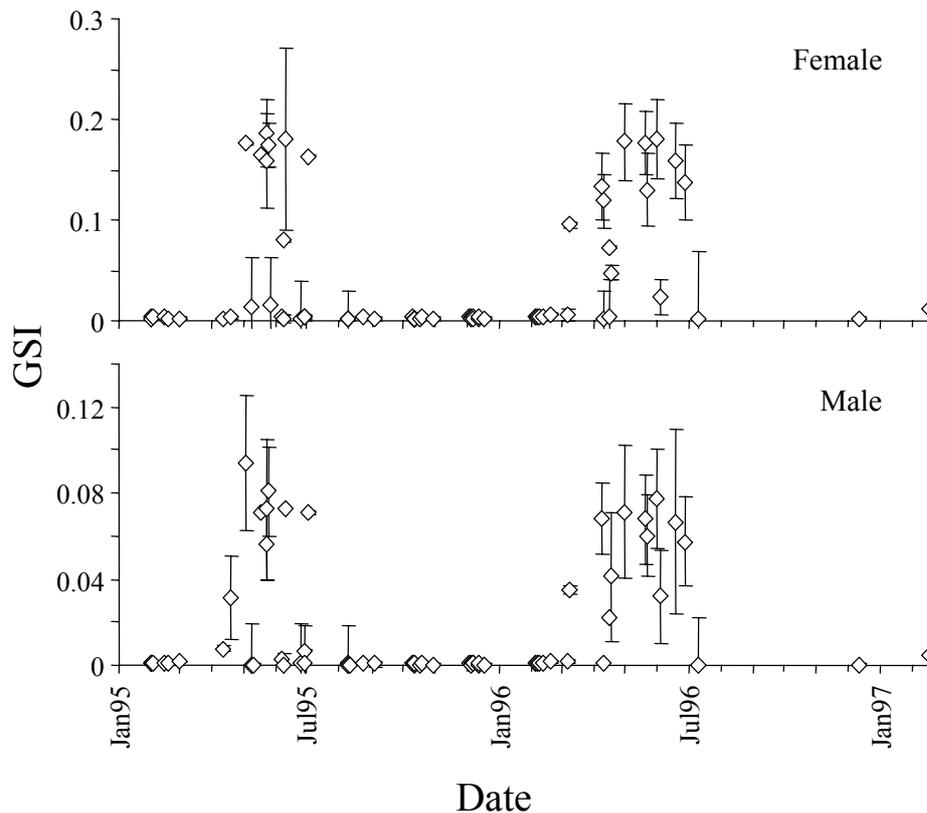


Figure 2. Mean (\pm s.d.) gonadosomatic index of female and male sea mullet versus date, sampled from NSW ocean and estuary landings, January 1995 to February 1997 (adapted from Virgona et al. 1998).

The usefulness of GSI values to infer reproductive stage and the timing of spawning has been questioned by some researchers. Gonad weight is proportionally less in younger individuals and diseased/malformed individuals. Hence, the use of mean GSI values may underestimate reproductive activity where there is a high proportion of very young females, or a high frequency of anomalous ovary development (Render et al. 1995).

Alternative indices of reproductive activity include histological staging of gonads and maximum oocyte diameter. Histology constitutes the most informative method but entails complex methodology. In comparison, measurement of oocyte diameter is rapid, low cost and may not require sacrifice of the individual (Thompson et al. 1989). Uniform oocyte development throughout the ovary further adds to the ease of use of this method (Greeley et al. 1987). Oocyte diameter at each reproductive stage may vary among months and years, suggesting environmental conditions could influence final oocyte size (Apekin and Vilenskaya 1979). Estimates from these alternative methods generally, but not always, correspond to the timing and magnitude of reproductive activity as estimated by GSI values (Thompson et al. 1989, Render et al. 1995). For

example, maximum GSI values may not always correspond to the occurrence of highest oocyte diameter (Apekin and Vilenskaya 1979).

Fecundity

Female sea mullet produce a large number of small eggs. Fecundity estimates range from 1 to 4.8 million eggs per female (Grant and Spain 1975, Su and Kawasaki 1995) and mature ovum diameter ranges from 0.6 to 1 mm (Thomson 1963). Various researchers have investigated the relationship between fecundity, ovary weight and body length (Table 1). Generally, fecundity increases with increasing fish length. Gonad weight increases in proportion to body size, and so GSI values tend to be similar among all mature fish (Fig. 4).

Within the south-eastern Australian population, relationships between egg production (fecundity, egg size) and body size are not documented. Similarly, the effects of environmental influences on egg production are unknown. Such factors could influence the quality and quantity of roe production within the NSW sea mullet stock.

Table 1. Relationship between sea mullet fecundity (F, number of eggs), ovary weight (W, in g) and body length.

Relationship	r ² value	Source
$F = (1.025*W + 62.309)*10^3$	0.81	Greeley et al. 1987
$F = 25.84*SL^{2.97}$	0.831	(where SL is standard length in cm)
$F = (6.34W + 44.51)*10^3$	0.998	Su and Kawasaki 1995
$F = 2.22*10^{-4}*L^{3.74}$	0.86	(where L is body length in mm)
$F = 0.009*FL^{3.16}$	not given	Grant and Spain 1975 (where FL is fork length in mm)
$F = 0.0056*FL^{3.18}$	0.85	Thompson et al. 1991 (where FL is fork length in mm)

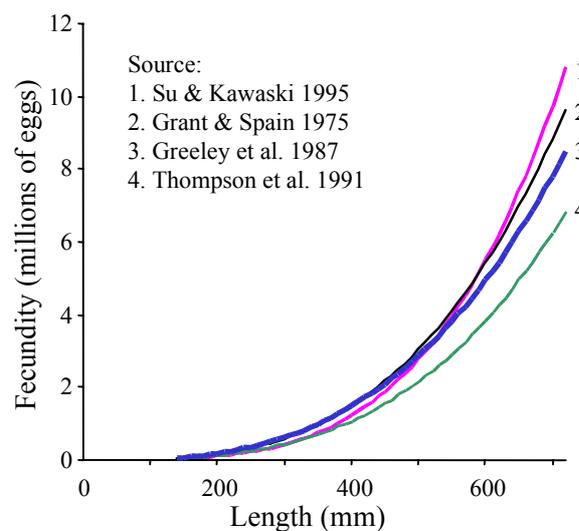


Figure 3. Fecundity versus length, as estimated by various sources (see Table 1 for definition of length used by each source)

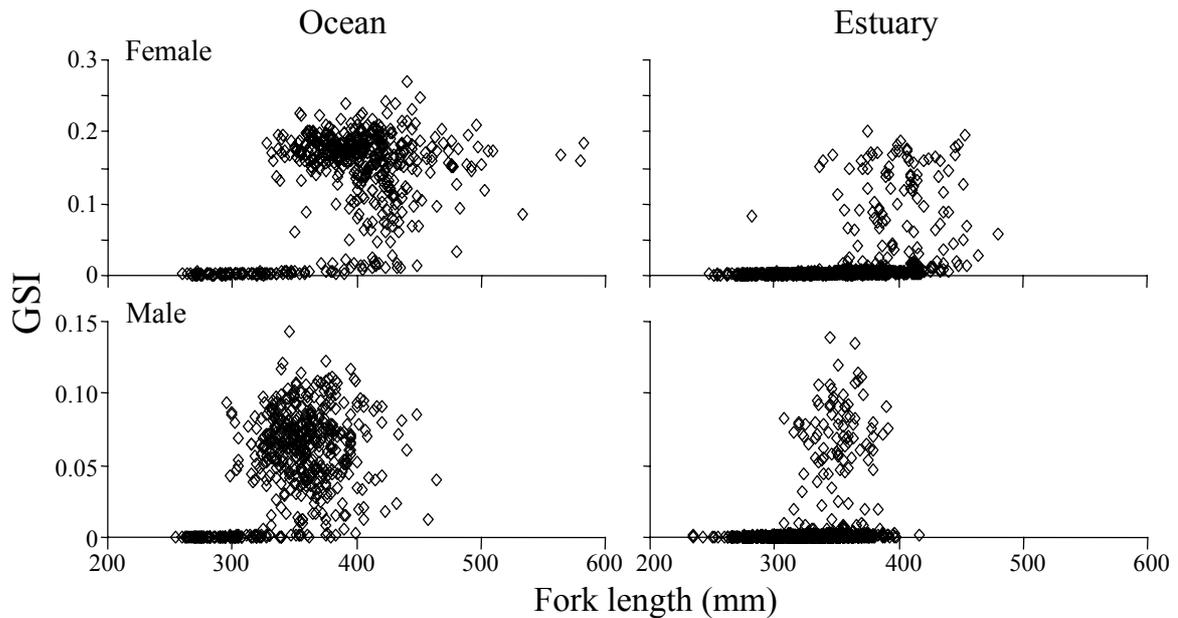


Figure 4. Gonadosomatic index (GSI) versus caudal fork length for male and female sea mullet, sampled from NSW ocean and estuary landings, 1995/96.

Sex ratio

Sea mullet are diandric, although there have been occasional observations of hermaphrodites and the ambiguous appearance of immature gonads led earlier researchers to question the sexuality of the species (Kesteven 1942, Johnson 1954, Stenger 1959).

The sex ratio (m:f) within and among populations exhibits considerable spatio-temporal variability. Often, but not always, males predominate and can be twice as numerous as females (Thomson 1963). This could be reflected in the act of reproduction, with several males apparently attending a single spawning female (Arnold and Thomson 1958). Among years, the sex ratio within a harvested population may remain very consistent (e.g. 68:32, Hwang et al. 1990). Within a single year, Virgona et al. (1998) reported a change in the sex ratio of spawning fish in Queensland ocean waters. The ratio shifted from 60:40 to 40:60 between the beginning and end of the spawning period (i.e. between May and August). NSW commercial fishers also report a dominance of males in landings during the early part of the fishing season.

At certain times, net selectivity is likely to strongly bias sex ratios towards females, which are larger than males. Thompson et al. (1989) found the girth of mature females to increase by 3 cm during the spawning season, contributing significantly to their selection by nets.

Age and Growth

Age/length at maturity

Individual sea mullet generally remain in estuaries for 3-6 years before undertaking their first spawning migration (Wallace 1975a, Thomson 1963, Virgona et al. 1998). These ages correspond to total lengths of 26-45 cm (females) and 25-44 cm (males) (Thomson 1963). The age and size at first maturity is variable, with smaller/younger sexually mature fish tending to occur in warmer regions (Thomson 1963). Total lengths at 50% maturity as low as 22/24 cm (male/female), which correspond to an age of 2 y, have been observed in some areas (Gulf of Mexico, Thompson et al.

1991). Off south-east Australia, two independent studies derived similar estimates of total length at first maturity, i.e. 30 to 34 cm (males and females, Kesteven 1942) versus 30/34 cm (males/females, Virgona et al. 1998). These lengths correspond to an approximate age of 3 to 4 years.

Age estimation

A number of early studies estimated age and growth of sea mullet from the number and width of scale annuli (e.g. Thomson 1963, Grant and Spain 1975). More recently, otolith annuli have been used to estimate age (e.g. Virgona et al. 1998). The use of scale and otolith annuli for aging purposes has resulted in contrasting estimates of growth rate. Early studies which used scales noted greater lengths-at-age than later studies which used otoliths (Table 2, Fig. 5). Scale readings may have underestimated age, particularly for older individuals.

Annual formation of increments has been validated for scales and otoliths, although there is uncertainty about the timing of formation of the first 'annulus' in both structures, with previous estimates ranging from 6 to 18 months (Thomson 1951, Grant and Spain 1975, Thompson et al. 1991). Within sagittal otoliths of sea mullet from south-eastern Australia, the first annulus (opaque mark) becomes fully visible at approximately 22 months of age (Smith and Deguara, in prep.). Subsequent opaque marks are deposited annually and fully formed annuli become visible during spring-summer (Smith and Deguara, in prep.).

Table 2. Mean lengths-at-age observed by various independent studies. (see also Fig. 5)

Source	Location	Aging method	FL (mm) at age										
			0+	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+
Grant & Spain 1975	Queensland	scale	106	268	342	374	452	505	532	566	-	-	-
Thomson 1951	W. Australia	" "	140	245	336	405	467	505	537	-	-	-	
Kesteven 1942	E. Australia	" "	136	207	282	351	420	472	-	-	-	-	
Thompson et al. 1989	Gulf of Mexico (1986)	otolith	-	-	-	370	381	404	411	-	-	-	
" "	Gulf of Mexico (1987)	" "	-	-	-	342	359	389	393	400	-	-	
this report	NSW estuary (males)	" "	-	229	320	342	343	346	351	361	385	380	
" "	NSW estuary (females)	" "	-	341	323	330	322	313	311	319	-	-	
this report	NSW ocean (males)	" "	-	300	332	340	346	355	359	361	373	390	
" "	NSW ocean (females)	" "	-	336	359	381	394	418	417	408	405	407	

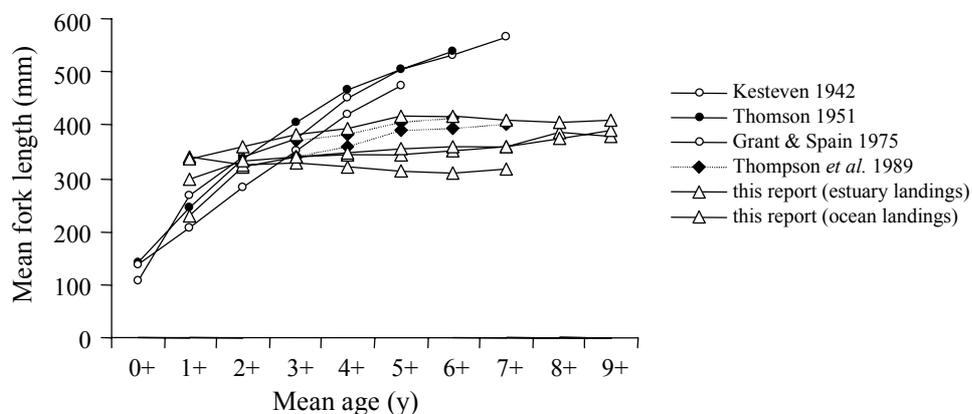


Figure 5. Mean age-at-length observed by various independent studies (from Table 2). Males and females plotted separately from Thompson *et al.* 1989 and this report.

Daily periodicity of increments in larval otoliths has also been validated (Radtke 1984). Daily increment formation commences on day 1 after hatching in sagitta and lapilli, and the width of increments appears to reflect daily growth rate.

In adult fish, the opaqueness of whole otoliths inhibits observations of growth increments, and so sectioned otoliths are typically used to estimate age (Thompson et al. 1991, Virgona et al. 1998). Annuli do not form uniformly along all axes of the otolith. Thompson et al. (1991) observed that the most uniform growth tends to occur along “either side of the sulcus acousticus” within the sagittal otolith, although annuli do not form simultaneously on each side. These aspects of otolith growth introduce some subjectivity to age estimation.

The factors which contribute to the formation of annuli are not clear. The two growth phases represented by opaque and translucent material in otoliths may reflect seasonal variations in growth due to water temperature variation, or the annual diversion of energy to gonad maturation. However, immature fish in warm climates also show annuli, suggesting that other factors also contribute to annulus formation (Grant and Spain 1975). Environmental factors which influence annulus formation may vary among regions and, therefore, the timing of annulus formation may also vary among regions. This may account for some differences in the timing of formation of the first annulus, as reported by previous studies.

Growth rate

Length-frequency distributions of estuarine populations of sea mullet tend to be bimodal, reflecting the smaller sizes of 0+ aged fish and the larger sizes of the rest of the population (Anderson 1958, Chubb et al. 1981). Juvenile growth rate in the year following settlement can be estimated by following the increase in mean length of the smaller size class. However, an extended winter recruitment season and very slow initial growth tend to produce a widely spread juvenile cohort comprising individuals with an age difference of several months. Estimates of juvenile length/weight-at-age by this method can therefore be variable (e.g. Anderson 1958, Chubb et al. 1981).

Differences in estuarine temperature experienced by early and late recruiting fish may contribute to variations in growth among individuals, especially during the first year of life. Faster growing individuals tend to have a competitive advantage over slower growing fish – the “bigger is better” concept (e.g. Leber et al. 1995, Tupper and Boutilier 1995). Priority use of resources could also enhance survival of earlier recruits compared with later recruits.

Differences in growth rates among years, seasons and estuaries suggest that growth may be variously influenced by temperature, reproductive activity and availability of resources (Thomson 1951, Chubb et al. 1981). Thompson et al. (1991) observed that otolith growth of sea mullet in Louisiana, USA, was largely restricted to the 4 months preceding the reproductive season (i.e. summer-autumn). A similar otolith growth pattern has been observed in south-eastern Australia (Smith and Deguara in prep.). It is not clear whether somatic growth follows similar seasonal trends.

Gender also influences growth patterns. Adult females tend to grow faster than males and attain larger sizes-at-age (Gomez et al. 1995, Su and Kawasaki 1995, Virgona et al. 1998). Maximum size and age of females is generally greater than males. Adult growth is isometric in both sexes (Thomson 1951, Grant and Spain 1975, Gomez et al. 1995). Body weight is closely related to body length, although the relationship becomes more variable for larger fish (Table 3, Fig. 6).

Table 3. Relationships between sea mullet body weight, W (g), caudal fork length, FL (mm), total length, TL (mm), and standard length, SL (cm).

Relationship	Sex	r ² value	Source
$FL = 0.866 * TL + 0.735$	M & F	0.98	Thomson 1963
$FL = 0.881 * TL + 2.889$	M & F	0.99	this report
$W = 0.013 * SL^{3.126}$	F	0.97	Greeley et al. 1987
$W = 9.6 * 10^{-6} * FL^{3.06}$	M	0.94	Thompson et al. 1989
$W = 2.6 * 10^{-5} * FL^{2.85}$	F	0.89	" "
$W = 2.1 * 10^{-5} * FL^{2.93}$	M & F	0.99	Thompson et al. 1991
$W = 10^{-5} * FL^{3.0371}$	F	0.99	this report (see Fig. 5a)
$W = 10^{-5} * FL^{3.0144}$	M	0.99	this report (see Fig. 5b)

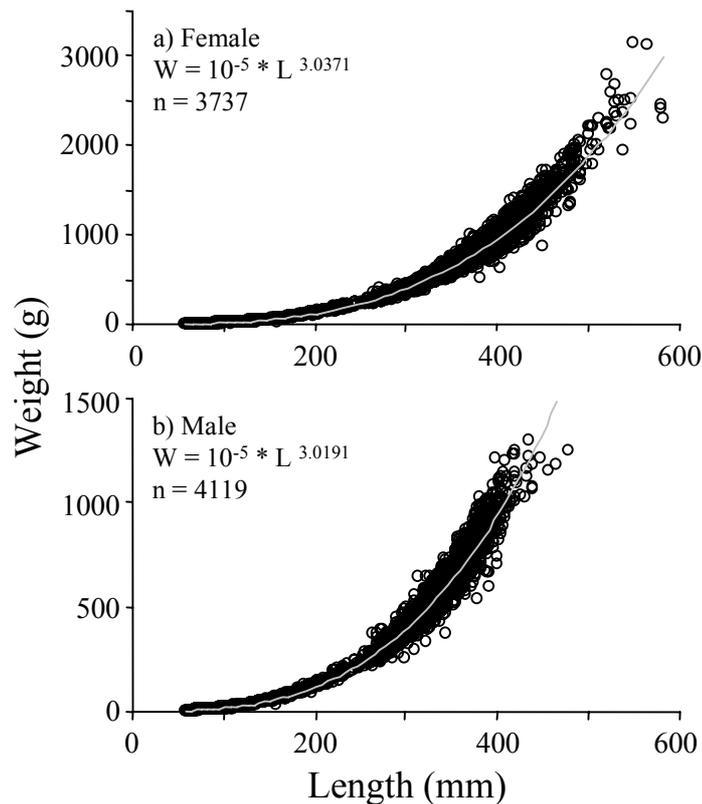


Figure 6. Body weight (W) versus caudal fork length (L) of **a)** female and **b)** male sea mullet, sampled from NSW ocean and estuary landings. (Equations describe fitted lines; n - number of fish sampled)

A change in the relationship between age and length is apparent at the transition from larval to juvenile, and juvenile to adult (Grant and Spain 1975, Su and Kawasaki 1995). Possession of three distinct growth phases is typical among fishes. However, the larval and juvenile phases represent a relatively small proportion of the life span, and are often disregarded in models of length-age relationships. The von Bertalanffy growth equation, $L_t = L_{\text{inf}}[1 - e^{-K(t-t_0)}]$ (Bertalanffy 1957), provides a reasonable approximation of this relationship, notwithstanding a poorer fit with the youngest ages (Table 4, Fig. 7).

The choice of fishery dependent data used in analyses affects estimates of growth rate. In NSW, ocean samples contain fish of greater lengths-at-age than estuary samples, especially at younger ages (Fig. 7). This may result from the selection of faster growing/earlier maturing individuals by the ocean fishery. To reduce this bias, estuary individuals < 2 y old and ocean < 4 y old were excluded from analyses to estimate growth parameters in this report (Table 4, Fig. 7). These are approximate ages at recruitment to each fishery.

Fishery-dependent sampling can result in significantly different estimates of growth rate, compared with results obtained from fishery-independent sampling of the same population. When using fisheries-dependent data, the selection of larger individuals by commercial fishers may lead to higher estimates of size-at-age, especially at younger ages (Thompson et al. 1989, Thompson et al. 1991). This appears to be the case in the NSW fishery, in which 2-4 year old fish display greater lengths-at-age than expected, based on comparisons with 0-2 year old fish caught during fishery-independent sampling (Fig. 7). This observation can be explained by early maturation, and early fishery selection, of faster growing individuals. Also, older fish in exploited populations may display a smaller than expected size-at-age.

Fish surviving to an old age in exploited populations may be relatively slow growing individuals that recruited to the fishery, or became vulnerable to fishing gear, late in life (Smith, unpubl. data).

A linear relationship exists between scale radius and body length, and between otolith radius and body length (Thomson 1951, Grant and Spain 1975, Su and Kawasaki 1995). Hence, it may be possible to construct individual growth histories of sea mullet from the widths of scale or otolith increments. Otolith increments have been widely employed to infer growth patterns in many fish species, but this is yet to be investigated in sea mullet.

Otolith weight is positively related to age, length and body weight, although considerable variability is associated with each relationship (possibly due to poor precision of measurements or sampling practices which damage otoliths) (Fig. 8). These relationships sometimes differ between sexes (e.g. Thompson et al. 1989, Thompson et al. 1991). Due to high variability, otolith weight is a relatively poor predictor of age or body size.

Unusual growth patterns can occur in some populations. For instance, populations that are denied access to the ocean, and therefore do not spawn, may exhibit greater lengths/weights at age (Thompson et al. 1991). In such cases, energy which would normally be spent on gonad maturation may remain available for somatic growth.

In addition to regional and annual differences in growth, which are attributable to environmental factors, the length-at-age relationship within a stock may also show apparent variation among months (Thompson et al. 1989, 1991). This could reflect fishery selection of faster growers earlier within a year (i.e. at same size but younger age) than slower growers. Alternatively, it could reflect changes in regional contributions to monthly catch. For example, in NSW, fish from higher latitudes migrate earliest in the year and will therefore comprise a high proportion of ocean landings at the start of the fishing season. The effect of regional variability of growth rates on catch composition has not been assessed for the NSW fishery.

Table 4. Parameters for Von Bertalanffy growth relationship as estimated by various independent studies of sea mullet.

Parameter				Reference
L_{inf}	K	t_0	Sex	
604.6	0.344	0.14	M & F	Grant and Spain 1975
366.98	0.36	-0.15	M	Thompson et al. 1991
471.7	0.28	0.03	F	" "
535	0.227	-2.303	M, where age > 2.1 y	Su and Kawasaki 1995
560	0.206	-2.687	F, where age > 2 y	" "
359	0.86	0.80	M	this report
413	0.69	0.79	F	" "
385	0.49	0*	M	this report (*assumed)
445	0.40	0*	F	" "

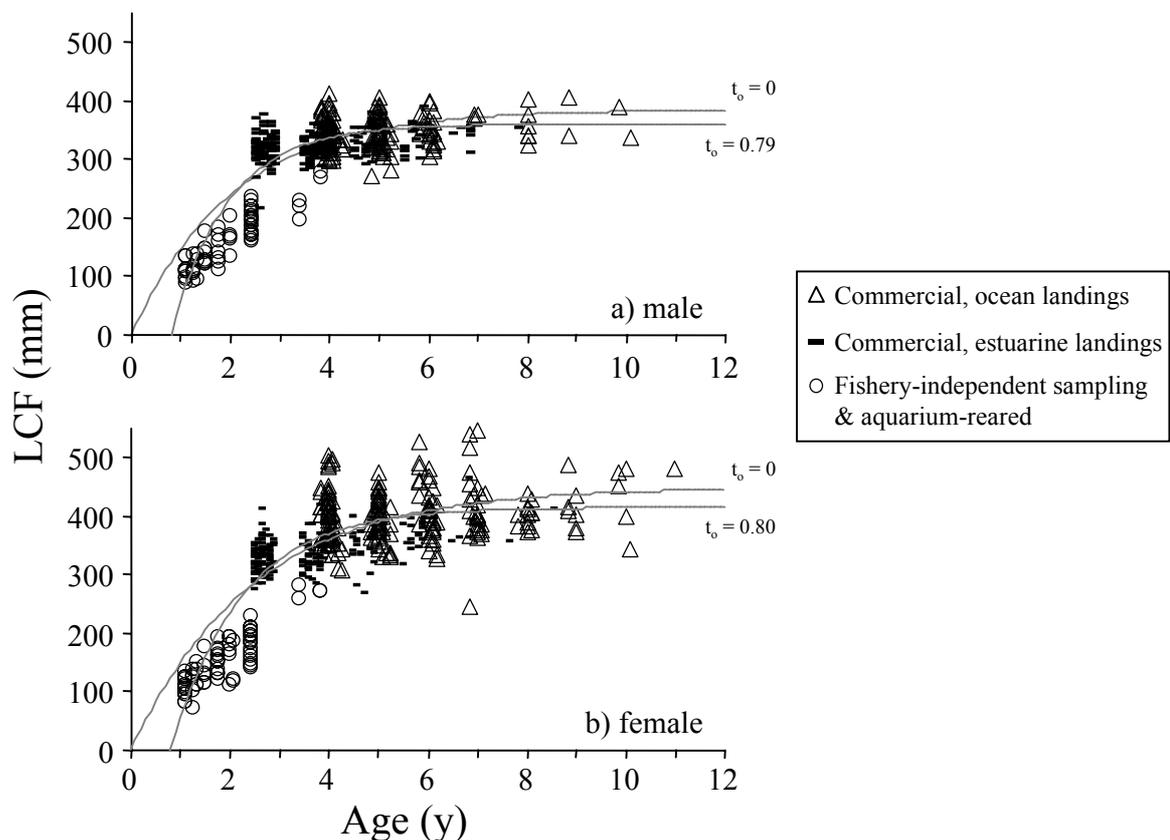


Figure 7. Age versus caudal fork length of **a)** male and **b)** female *M. cephalus* sampled from NSW estuary fishery, (Aug-Feb, where age > 2 y), ocean fishery (Apr-Jun, where age > 4 y), and aquarium-reared fish caught by fishery-independent method. Von Bertalanffy growth curves fitted (see Table 4 for parameter values). Random subset of data point shown. Curves estimated from full data set, where $N_{\text{female}} = 1016$ (estuary) + 1020 (ocean) + 367 (reared), and $N_{\text{male}} = 1234$ (estuary) + 1240 (ocean) + 367 (reared).

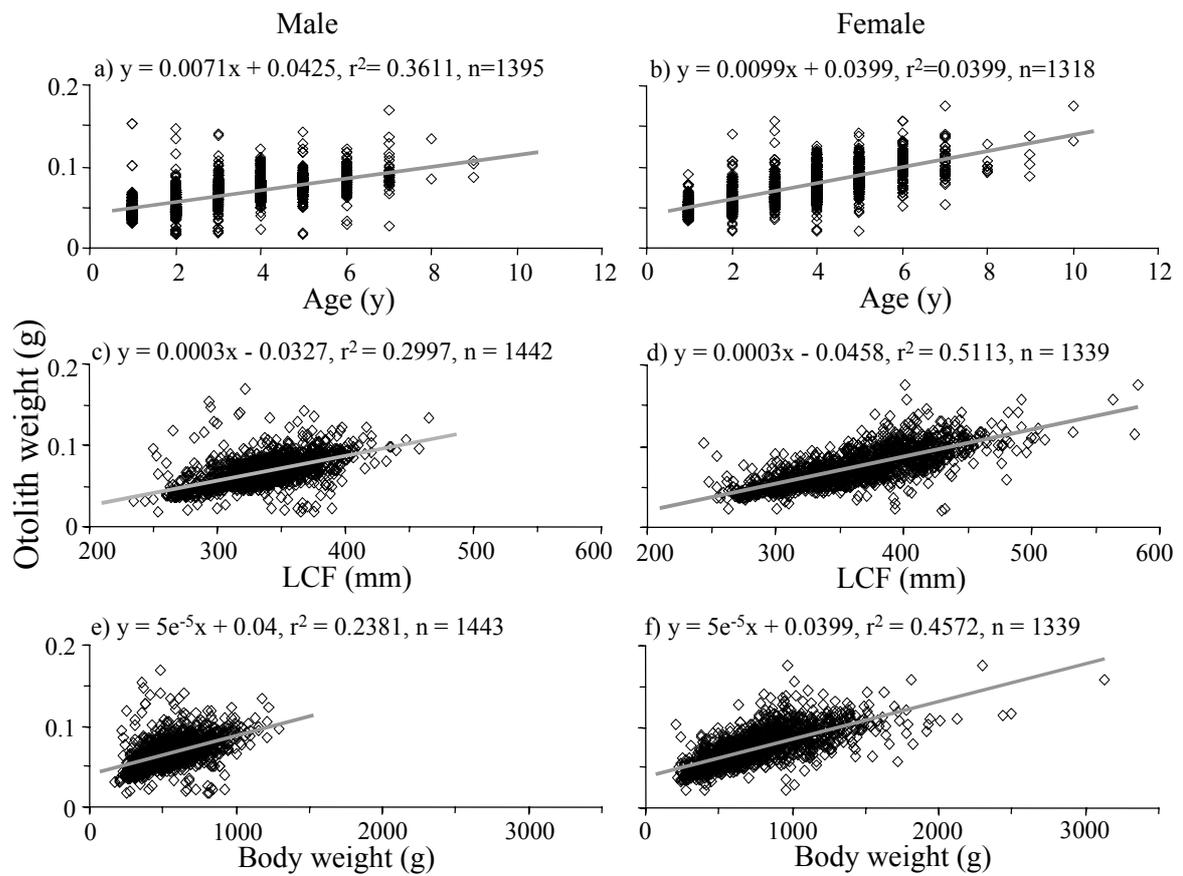


Figure 8. Weight of sagittal otolith of male and female sea mullet against **a, b)** age; **c, d)** length to caudal fork; and **e, f)** body weight. Linear regressions fitted.