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Stock assessment of longtail tuna in Australian waters: data input, model selection and assessing population status

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Abstract

A stock assessment of longtail tuna (*Thunnus tonggol*) in Australian waters was undertaken using per-recruit analyses to assess the current stock status using best available information and a sensitivity analysis to demonstrate potential effects of using biased datasets on assessment outcomes. Exploited age compositions differed between the commercial (age classes 3-4 years) and sport fishery (4-6 years). The fishing mortality (F_{current}) from these fisheries for 2004-2006 was estimated as 0.167-0.320 yr^{-1}. Longtail tuna became vulnerable to both fisheries at age 2-3 years. Yield-per-recruit analyses revealed that the current fishing mortality rate did not exceed biological reference points. However, any significant increase in fishing mortality may result in recruitment overfishing due to longtail tuna being slow-growing and the stock currently in the vicinity of $F_{40\%}$ reference point. Various scenarios were modelled to demonstrate the effects of low quality length-at-age, ignoring gear selectivity, and underestimating age-at-maturity. Both low quality length-at-age data and ignoring selectivity had a profound effect on the estimated population status and inferred the population was at risk or being recruitment overfished, while assuming an age-at-maturity of 5 years instead of 2 years showed that the population may be growth overfished. These results highlight the importance of collecting high quality biological

data and unbiased fishery data before attempting to complete stock assessments intended to guide management policy.

1. Introduction

Longtail tuna (*Thunnus tonggol*) is a commercially-important pelagic species common in tropical to temperate neritic habitats throughout the Indo-Pacific. Its small size in comparison to other *Thunnus* species (maximum size 142 cm TL), restricted coastal distribution and tendency to form relatively small, fast-moving schools (Yesaki, 1993) has contributed to this species being difficult to catch in commercial quantities, and thus attracting little commercial interest. However, in recent years longtail tuna have become heavily exploited in rapidly expanding multispecies purse-seine, gillnet and troll fisheries in underdeveloped countries, such as Indonesia, Taiwan, Thailand and Iran.

Global catches of longtail tuna increased substantially to around 100,000 t yr^{-1} in 1985 and continued to increase to in excess of 200,000 t yr^{-1} after 2003 and reaching 248,000 t in 2007 (FAO, 2009). Over the past decade Thailand, Indonesia, Malaysia and Iran contributed most to the global landings. However, it is important to note that catch statistics are underestimates due to a high incidence of underreporting of longtail catches in underdeveloped countries, especially where the species is targeted in artisanal fisheries.

In contrast, longtail tuna has been only lightly exploited by commercial fisheries in Australia with annual reported landings averaging only 34 t since 1974 (FAO, 2009). However, catches of longtail tuna in the Taiwanese gillnet fishery that operated under bilateral agreement in northern Australian waters between 1979-1986 reached 2000 t yr^{-1}, which was primarily taken as a bycatch when fishers targeted sharks and Spanish mackerel (*Scomberomorus commerson*)

(Stevens and Davenport, 1991). Longtail tuna was recently recognised as being more important as a sportfish in Australia, and as a result, was declared a “recreational only” species by the Commonwealth government in 2006 (see www.daff.gov.au). However, an annual catch bycatch limit of 70 t is permitted for Australian Commonwealth commercial fisheries, which is double the average annual commercial catch since 1974 (FAO, 2009). The sport fishery for longtail tuna is primarily catch-and-release, although the retention rate in some recreational sub-fisheries, such as the land-based fishery where a preliminary harvest estimate of 70 t was made for south-eastern Australia (S.P. Griffiths unpublished data).

Despite the importance of longtail tuna to commercial and sport fisheries throughout their worldwide distribution, no stock assessments have been undertaken to determine whether current harvest rates are biologically sustainable. Stevens and Davenport (1991) raised concern over declining catch rates of some species targeted in northern Australia by the Taiwanese gillnet fishery in the early 1980s, although insufficient biological and catch data were available at the time to assess the status of longtail tuna. Although the Australian government has been pro-active in managing longtail tuna as a “recreational only” species in Australian waters, the efficacy of this management measure is unknown. However, recent completion of biological studies on longtail tuna in Australia (Griffiths et al., 2009) have provided the required information to undertake an assessment of the current and historic status of longtail tuna in Australian waters.

The specific aims of this paper were to: i) determine the length and age structure of the longtail tuna population exploited by commercial and sport fisheries in Australia, ii) estimate the current fishing mortality rate by fisheries in Australian waters, iii) undertake yield- and spawning stock biomass-per-recruit analyses to assess the current status of longtail tuna in Australian waters, and iv) assess the efficacy of size limits and reduced post-release mortality rates through improved handling practices on the sustainability of longtail tuna in Australian waters.

2. Materials and methods

2.1 Defining the stock

Limited data is available on the stock structure of longtail tuna throughout its worldwide distribution. Wilson (1981) suggested that longtail in Australia and Papua New Guinea are a single stock based on a small number of genetic samples analysed using electrophoresis. In contrast, Serventy (1956) analysed morphometric measurements and suggested that fish from western and eastern Australia form two separate stocks, and possibly that they may be separate subspecies. Recent tagging data from the New South Wales (NSW) Department of Primary Industries' Gamefish Tagging Program suggest that longtail tuna make extensive movements along the eastern Australian coast and it is likely these fish mix, at least to some degree, with fish from the Gulf of Carpentaria (GoC) in northern Australia (Fig. 1). Very little is know of the movements of fish in western Australia, or whether fish move from the Australian Economic Exclusion Zone into the waters of neighbouring countries such as Indonesia. In the absence of reliable evidence relating to stock structure, a precautionary approach was undertaken in this study and assumed that longtail tuna exist as a single stock from the central Arafura Sea and eastward along the eastern coast of Australia (Fig. 1). This was also the same region used by Griffiths et al. (2009) to define the population boundaries for an age and growth study of longtail tuna in Australian waters.

2.2 Fishery data used to estimate fishing mortality

Longtail tuna are not a target species of any state or Commonwealth commercial fishery in Australia. Consequently, there is currently no available time series data of catch and effort for undertaking detailed stock assessment analyses. However, there are limited sources of age or size composition data that can be used to estimate total mortality (*Z*) from linear catch curves (and thus *F*, assuming $F = Z\text{-}M$) to provide information for a preliminary assessment of the stock status of longtail tuna in Australia.

The largest data source available for longtail tuna in Australia was collected via logbooks and CSIRO scientific observers for the Taiwanese gillnet fishery between 1979-1986 across northern Australia (Stevens and Davenport, 1991). Vessels used gillnets with 145 mm to 190 mm monofilament mesh with an average length of 16,000 m. Logbook catch data from were available for 24,842 gillnet sets, but unfortunately longtail tuna were aggregated with several other species and reported as "Scombridae" or "Tuna" in logbooks and so detailed analysis of catch rates was not possible. Detailed information on catch and size composition of longtail tuna (and all other species caught) was recorded by scientific observers for 381 gillnet sets that were primarily made off northern Australia between 1981-1985. However, given the high size selectivity of this fishery, these data cannot be used to estimate a historic fishing mortality rate using catch curve analysis. Therefore these data were used in association with other data sources from the GoC and east Australian coast to describe possible ontogenetic migration and construct selectivity-at-age functions for gillnets.

In recent years, the Queensland (Qld) N9 gillnet fishery and the sport fishery were the only domestic fisheries that have had any significant interaction with longtail tuna. The N9 gillnet fishery chiefly operates in the GoC and uses similar gear as the Taiwanese gillnet fishery, using monofilament gillnets of around 1400 m in length with mesh size of 165 mm to target sharks and grey mackerel (*Scomberomorus semifasciatus*). Longtail tuna comprise a significant bycatch in this fishery, but a trip limit of only 5 fish has generally resulted in discarding and failure to record these catches logbooks. Catch and size-frequency data was used from 268 sets monitored by scientific observers throughout 2005 along the eastern coast of the Gulf of Carpentaria in northern Australia (Fig. 1).

Data for the sport fishery were collected from boat-based and land-based anglers from coastal regions throughout the study area (Fig. 1). Catch and size frequency data representing the boat-based sport fishery were collected from fishing tournaments and independent scientific sampling using typical sport fishing gear in the GoC and along the east coast described by Griffiths et al. (2007). Longtail tuna are a primary target species in the recreational land-based gamefish (LBG) fishery where anglers generally capture large specimens in the region extending from Gladstone, Qld to Jervis Bay, NSW. Catch and size composition from the LBG fishery was derived from unpublished data (S.P. Griffiths, CSIRO) collected data using on-site roving creel surveys and angler-reported electronic logbooks between 2005-2006. It is important to note that while the LBG fishery was sampled to Jervis Bay, NSW, catches of longtail tuna were only available as far south as Forster, NSW (Fig. 1).

2.3 Estimating mortality

Three empirical equations were used to estimate the instantaneous natural mortality rate (M) of longtail tuna. The first model is based on Pauly (1980):

$$log_e(M) = -0.0152 - 0.279\, log_e(L_\infty) + 0.6543\, log_e(K) + 0.463\, log_e(T), \text{ (Pauly 1980)} \quad (2)$$

where K and L_∞ are von Bertalanffy growth parameters of 0.223 yr^{-1} and 135.4 cm FL, respectively (Griffiths et al., 2009) and T is the annual mean water temperature throughout the study region estimated at 22.9°C (CSIRO unpublished sea surface temperature data).

The second model was that of Jensen (1996):

$$M = 1.60\,(K), \qquad (3)$$

where K is the von Bertalanffy growth parameter.

The third model was based on Hoenig (1983):

$$M = -\,log_e(0.01)/\omega \qquad (4)$$

where ω is maximum age (18.7 years; Griffiths et al., 2009), or more specifically, the age at which 1% of the population would survive in the absence of exploitation. Although a reasonably large sample of fish have been aged in the vicinity of the maximum recorded size for this species (Griffiths et al., 2009) the population has undergone various degrees of exploitation by commercial and sport fisheries since at least 1897 (Serventy, 1942). As a result, it is possible that the assumptions of this method were violated, so results were viewed with caution.

The three models were used to estimate M because this parameter is difficult to measure and the variability in this value needed to be accounted for. However, these three models assume that M remains constant across all age classes, which is often not the case for tunas. Hampton (2000) showed that in skipjack, bigeye and yellowfin tuna natural mortality-at-age tends to be "Ushaped" with rates being around 2-4 times higher during the first year than in subsequent years where *M* is generally more constant. Therefore, a modified natural mortality-at-age function for bigeye tuna in the Pacific Ocean was used (Langley et al., 2008), since this species has a similar intrinsic growth rate ($K = 0.238$ yr^{-1}) as longtail tuna ($K = 0.223$ yr^{-1}) and both species have a similar lifespan of about 18 years (Farley et al., 2006; Griffiths et al., 2009). The natural mortality-at-age function was adjusted proportionally so that the mean mortality across all age classes equalled the estimates from each of the three empirical equations.

Size-frequency data were converted to age using the length-at-age function of Griffiths et al. (2009) to undertake age-based catch curve analysis (Beverton and Holt, 1957) to estimate the total annual instantaneous mortality rate (*Z*). Estimates of *M* were subtracted from *Z* to derive the current annual instantaneous fishing mortality rate (*F*) for the period 2005-2007 using data combined for the N9 gillnet fishery, the boat-based sport fishery in northern and eastern Australia, and the land-based gamefish fishery along eastern Australia (F_{current}).

Because size selectivity patterns differed between commercial and sport fisheries, numbers-at-age in each fishery required adjustment prior to construction of catch curves. Total mortality of each length or age class, *t*, can be expressed in equilibrium state as:

$$Z_t = M_t + S_t^{commercial} F_t^{commercial} + S_t^{sport} F_t^{sport}$$

where M_t is the natural mortality rate of age class *t*, S_t and F_t is the selection probability and fishing mortality of age class *a*, for the commercial and sport fishery, respectively.

Selection probability-at-age in each fishery was estimated using one of two methods described by Sparre and Venema (1992). Selection probabilities in line fisheries (e.g. longline and hook and line) tend to follow a logistic function (Hovgård and Lassen, 2000) because the gear is usually capable of catching fish of any size after recruitment to the fishery. Although the length- and age-frequency distributions differed between sport fisheries in northern and eastern regions, they use similar techniques and gear so these differences were attributed to availability of fish of different size classes in specific regions, rather than differences in gear selectivity. Therefore, data were combined to estimate a selectivity function for the overall sport fishery. This was done by first regressing the natural logarithm of the number of fish in each age class against age, as per standard linear catch curve analysis. The probability of capture was then estimated by backwards extrapolation of the descending limb of the catch curve to include younger age classes that were likely to be underrepresented in the catch. A logistic function was then fitted to the selection probability-at-age data to estimate the age (*t*) at which 50% of fish were susceptible to capture (T_{50}) and was best described as:

$$S_t = \frac{1}{1 + e^{8.8842 - 2.2394t}}$$

A_{50} was considered to be the age of recruitment to the sport fishery, which was later used in per-recruit analyses.

In contrast to the sport line fishery, selection probability-at-age for gillnet fisheries generally follow a normal distribution and can be expressed as:

$$S_t = \exp\left[-\frac{(t - t_m)^2}{2 \times s^2}\right]$$

Where a_m is the age for fish most susceptible to capture and s is the standard deviation of the normal distribution. The Taiwanese and N9 fisheries used the same gear, although their catch-at-age distributions differed markedly, which probably reflects the presence of smaller fish in northwestern Australia where the Taiwanese fishery operated (see Results and Serventy, 1956), rather than differential gear selectivity. Therefore, these two curves were combined to describe the overall selectivity curve for a 6-inch gillnet as input into the per-recruit models. This was achieved using the methods detailed by Sparre and Venema (1992) where by the ascending limb of the curve catching the smaller-sized fish (Taiwanese gillnet fishery) was combined with the descending limb of the curve catching larger-sized fish (N9 fishery) and the selection probability for fish sizes in the region where the two curves overlap was 1.

Similar to the sport fishery, the numbers of fish in each size class in the commercial fishery were then adjusted given their probability of capture, and then combined with the sport fishery data for catch curve analysis. Total mortality was then estimated from the slope of a linear regression fitted to the declining limb of the age distribution. An estimate of F was then made by subtracting M from Z.

2.4 Per-recruit analyses

Yield-per-recruit (Y/R) and spawning stock biomass-per-recruit (SSB/R) of longtail tuna in northern and eastern Australia was assessed using the model of (Quinn and Deriso, 1999). This model was used in preference to the widely-used Beverton and Holt (1957) model since the knife-edge selectivity assumption for all age classes in was violated due to the sport and commercial fishery having different size selectivity patterns. The Quinn and Deriso (1999) model defines the age-specific annual exploitation rate (μ_t), which can be represented as:

$$\mu_t = \frac{F_t}{F_t + M}\left(1 - e^{-(F_t + M)}\right)$$

Here, the fishing mortality rate-at-age, F_t, is a separable product of age-specific selectivity, which was estimated from selectivity-at-age ogives in each fishery and expressed as:

$$F_t = S_t F$$

However, longtail tuna are caught by commercial and sport fisheries in Australia, each of which have different age selectivity patterns that can be expressed as:

$$F_t = \sum_j S_{t,j} F_j = \sum_j F_{t,j}$$

where $S_{t,j}$ and F_j is the age-specific selectivity probability and fishing mortality in the *j*th fishery, respectively (Quinn and Deriso, 1999).

There are no available maturity functions or estimates of the length or age at 50% maturity (L_{50} and A_{50}) for longtail tuna. However, histological data from 461 fish collected in Australian waters (Griffiths, S.P. unpublished data) indicates that most fish appear mature at 60 cm FL (2 years of age) and all fish are mature by 70 cm FL (~ 4 years of age). Therefore, a logistic maturity-at-age function was developed where A_{50} and A_{100} were 2 and 4 years, respectively. However, dues to uncertainty in A_{50}, a sensitivity analysis was undertaken to explore the effects of using an A_{50} of 3 or 4 years on SSB/R.

Due to uncertainty in natural mortality, Y/R and SSB/R analyses were undertaken using three values of M (0.2, 0.3 and 0.4), which captured the range of values estimated from three natural mortality equations. The change in Y/R and SSB/R was explored by hypothetically imposing different minimum legal lengths (MLL) (no MLL, 80 cm, 90 cm and 100 cm TL) as a method for managing the commercial and sport fishing harvest. This was undertaken by varying the age at first capture in the Y/R model. Although delaying the age (or increasing length) at first capture in a fishery will theoretically increase yield and the mean size of fish, this will only occur if the gear selectivity is modified to avoid capturing undersized fish or if released undersized fish do not incur significant post-capture mortality (Griffiths et al., 2006).

Tunas can incur significant physical trauma and physiological stress during capture, which has a significant affect on the probability of survival if a fish is released (Skomal, 2007). For species that interact with multiple gear types, such as longtail tuna, the post-capture survival rates from each fishery need to be incorporated into population models in order to understand the full extent of impact by each fishery (Skomal, 2007). Therefore, separate post-capture mortality estimates were applied to the commercial gillnet fishery and the sport fishery.

Post-release mortality is difficult and expensive to evaluate in large oceanic pelagic fishes, and there is currently no species-specific data available for longtail tuna. Longtail tuna are obligate ram ventilators that need to swim constantly in order for their gills to extract a sufficient oxygen from the water to maintain their body’s high metabolic rates (Korsmeyer and Dewar, 2001). Therefore, capture by gillnets in northern Australia, where soak times are often long (up to 12 hrs), normally results in all longtail tuna being dead upon capture. Consequently, post-capture mortality was assumed to be 100% for the N9 fishery.

In contrast, longtail tuna caught by the sport fishery are often released, but the probability of fish surviving release is likely to be dependent upon numerous factors including fight time, tackle used, hook type and hooking location (Skomal, 2007), as well as their vulnerability to predation once released (Kerstetter et al., 2004). There is no quantitative information on post-capture mortality of longtail tuna released by the sport fishery, although there is limited information on other high performance fishes such as tunas and billfishes that are caught by hook and line and suggest a wide range of survival rates of between 60% (Yuen et al., 1974) and 100% (Holland et al., 1990). Recently, Graves et al. (2002) and Kerstetter et al. (2003) used pop-up satellite tag technology to determine that the short-term post-release mortality rate of line-caught blue marlin was 11% and 22%, respectively. Skomal *et al*. (2002) found that around 28% of juvenile Atlantic bluefin tuna caught by sport fishing anglers off eastern United States incurred potentially lethal injuries due to deep hooking by standard “J” hooks. Therefore, longtail were also assumed to have a post-release mortality of 28% for all age classes less than the age of recruitment into the sportfish fishery. For these age classes, fishing mortality can therefore be expressed as:

$$F_t = \sum_j S_{t,j} P_{t,j} F_j = \sum_j F_{t,j}$$

where $P_{t,j}$ is proportion of fish incurring post-release mortality (assumed to be 0.28; Skomal et al., 2002) in each age class (t) less than the age at recruitment (i.e. a MLL) to the jth fishery.

The possible effects of reducing post-release mortality on the stock status was also explored through improved fish handling practices by sport fishing anglers via a national awareness campaign, if it was determined that imposing a size limit was ineffective or logistically difficult. Sawynok (2004) estimated that 35% of anglers adopted new release strategies following a recent campaign to promote best handling practices for sport fishing anglers in Australia. Therefore, a fourth management scenario simulating the effect of having no MLL but reducing post-release mortality-at-age by 35% was explored.

A number of reference points were used to assess the status of the longtail tuna population in Australia compared to the present fishing mortality rate (F_{current}), and for the period 1981-1985 during the operation of the Taiwanese gillnet fishery in northern Australia ($F_{\text{Taiwanese}}$). The reference points were: F_{MSY}, the fishing mortality rate that produces the maximum yield-per-recruit; $F_{0.1}$, the fishing mortality rate at which the slope of the yield-per-recruit curve is 10% of the slope at the origin; $F_{25\%}$ and $F_{40\%}$, the fishing mortality rate corresponding to the 25% and 40% of the spawning potential ratio (SPR), respectively. The SPR is the SSB/R at a given fishing mortality divided by the SSB/R where F=0.

3. Results

3.1 Age structure exploited by fisheries

Length- and age-frequency distributions differed markedly between fisheries that operated in distinctly different regions throughout the Australian distribution of longtail tuna. The Taiwanese gillnet fishery that operated intensively in the Arafura Sea off northern Australia during the early 1980’s captured a restricted size and age range of longtail tuna between 500-600 mm and 2+ years, respectively (Fig. 2). In the northeast of the region within the Gulf of Carpentaria, the domestic N9 gillnet fishery caught slightly larger and older fish between 700-800 mm and 3+ years (Fig. 2). The sportfishing fishery in the Gulf of Carpentaria also mainly caught fish between 700-800 mm and 3+ years, although the overall size range of fish caught was slightly narrower than the N9 gillnet fishery. In contrast, the sportfish fishery on the east Australian coast caught fish from a wide size range from 800-1100 mm and ages of 4+ to 8+ years (Fig. 2).

3.2 Age and size selectivity of fisheries

Selectivity analyses indicated that the age (and length) at which 50% of longtail tuna (A_{50}), became susceptible to the Taiwanese, N9 and sport fisheries was 2.3 yrs (569 mm), 3.2 yrs (705 mm) and 3.5 yrs (725 mm), respectively (Fig 3). Because the Taiwanese and the N9 fisheries used similar mesh sizes, the apparent difference in selectivity curves reflects the presence of smaller fish in the Arafura Sea, rather than differential gear selectivity. Therefore, these two curves were combined, as previously described, to provide an overall selectivity curve for the commercial fishery (that use 6-inch gillnets) in the per-recruit models.

3.3 Mortality estimates

Natural mortality (M) estimates differed depending on the empirical equations used; 0.246 yr^{-1} (Hoenig, 1983), 0.357 yr^{-1} (Jensen, 1996), 0.399 yr^{-1} (Pauly, 1980). Natural mortality-at-age curves were then constructed for input into per-recruit analyses (Fig. 4). Catch curve analysis incorporating sport and commercial catches for 2004-2006 yielded a total mortality (Z) estimate of 0.566 yr^{-1} (Fig. 5). By subtracting estimates of M from Z, this translates to an annual fishing mortality (F_{current}) of 0.167-0.320 yr^{-1} and an exploitation rate ($E = F/Z$) of 0.295-0.565 yr^{-1}.

3.4 Per-recruit analyses

Yield per recruit was strongly influenced by the value of natural mortality used, although the effect of increasing MLL was negligible with F_{MSY} varying across the four scenarios by only 41g, 12g and 0.1g per recruit for natural mortality rates of 0.2, 0.3 and 0.4, respectively (Fig. 6). The status of the longtail tuna population was independent upon the value of *M* used.

Under all four management scenarios the estimated present fishing mortality, F_{current}, did not exceed F_{MSY} for any value of *M* (Fig 6.). F_{current} also did not exceed was the precautionary $F_{0.1}$ reference point in each management scenario where *M*=0.3 or 0.4, but was in the vicinity of this reference point where only *M*=0.2. For all scenarios where *M*=0.3 or 0.4, fishing mortality could be increased to 0.5 and 0.7, respectively before the precautionary $F_{0.1}$ would be exceeded (Fig. 6).

Spawning stock biomass-per-recruit (SSB/R) was not significantly influenced by varying MLL, varying across the four scenarios and the three values of *M* by less than 105g (Fig. 7). The same pattern was apparent for all four management scenarios in that F_{current}, did not exceed either of the $F_{25\%}$ and $F_{40\%}$ references points for any value of *M*. An exception was where $M = 0.2$, which resulted in $F_{40\%}$ being exceeded in all four management scenarios (Fig. 7). If $F_{40\%}$ was used as a limit reference point, any increase in fishing mortality would not be recommened, except where $M = 0.4$ where fishing mortality could be approximately doubled (Fig. 7).

3.5 Sensitivity analyses

Yield per recruit and spawner biomass per recruit analyses were undertaken under a range of hypothetical ‘what if’ scenarios involving common data deficiencies in fisheries. These scenarios involved: i) ignoring or having incomplete gear selectivity-at-age data, ii) having low quality length-at-age data as a result of poorly designed biological studies that often fail to account for larger fish in the population and thus overestimate the von Bertalanffy growth parameter length at infinity and underestimate K, and iii) underestimating the age at first maturity.

YPR was strongly influenced by the removal of the selectivity function, assuming constant selectivity-at-age. This resulted in F_{current}, far exceeding the F_{MSY}, which was reduced to 0.18 and having a lower yield per recruit of 2257 g compared to the benchmark assessment (Fig. 8). The same result was produced for the scenario involving low quality growth parameters, with the difference being almost a four-fold increased in yield at F_{MSY}, (Fig. 8). A lack of selectivity had little effect on the SSB/R, while both low quality growth parameters and an age-at-maturity of 5 years both resulted in F_{current} exceeding the $F_{25\%}$ and $F_{40\%}$ reference points, indicating growth overfishing (Fig.9).

4. Discussion

The collation of data from contemporary studies and historic data from the Taiwanese gillnet fishery revealed interesting trends regarding the stock structure and possible movements of longtail tuna in Australian waters. It is clear that different ontogenetic stages exist in different regions where each respective fishery operates, which is primarily responsible for differences in size-frequency distributions rather than size selectivity of the gear used in each fishery. This was demonstrated by the Taiwanese gillnet fishery in the Arafura Sea and N9 gillnet fishery in the Gulf of Carpentaria (GoC) both using 15 cm monofilament mesh but having very different size-frequency distributions. However, the sportfish fishery in the GoC had the same size composition as the N9 fishery indicating their methods were largely unselective and catching fish from all available size classes. Lastly, the sportfish fisheries in the GoC and off eastern Australia both utilise the same methods (primarily high-speed spinning with metal lures or using live bait), yet their size compositions did not show any significant overlap with the presence of larger fish along the east coast. This provides strong support to the hypotheses of Serventy (1956) and

Wilson (1981) that longtail exist as a single stock in Australian waters and that northwestern Australia is a nursery habitat from which fish radiate eastward and southward. This information therefore provides a strong justification for treating longtail tuna as a single population in the current stock assessment.

The life history of longtail tuna appears to be very different to other similar-sized tropical tunas in that the species is relatively slow-growing and long-lived, similar to what has been observed for the large *Thunnus* species, such as bigeye tuna (*Thunnus obesus*), which can grow in excess of 200 kg and live for at least 16 years (Farley et al., 2006). Figure 10 illustrates the similarity of the growth dynamics of longtail tuna with larger, slower-growing *Thunnus* species, with growth dynamics standardised as the age at which each species attains 80% of L_∞.

Longtail tuna do, however, have an apparently high reproductive potential, having a protracted spawning period (Griffiths et al., 2007) and producing over one million eggs per spawning (S.P. Griffiths unpublished histological data), although it is unclear at what age fish become sexually mature in Australian waters. From the available evidence fish may mature relatively early in life at less than 60 cm FL and two years of age. However, no reproductive study to date has been able to assess maturity across the whole size range of the species during the spawning period using reliable histological analysis. Consequently, results from the spawner biomass per-recruit analyses need to be viewed with caution since an A_{50} of age 2 was used. Sensitivity analysis demonstrated that if A_{50} occurs at 3 or 4 years, the status of the stock would change significantly from currently being underfished in the vicinity of $F_{40\%}$ to most likely exceeding the $F_{25\%}$ limit reference point, thus deeming the stock recruitment overfished.

A lack of understanding of the biology of some tuna species has lead to inadequate management and overexploitation in many parts of the world (Fromentin and Powers, 2005; Dankel et al., 2008). For example, after southern bluefin tuna were confirmed to live for at least

32 years (Gunn et al., 2008) and reach sexual maturity at around 12 years of age (Gunn et al., 1996) fishery managers began to realise the severity of the existing stock depletion, and is now clearly evident with the species now listed on the IUCN Red List of Threatened Species as 'critically endangered'. In light of the similar slow growth of longtail tuna, coupled with its restricted coastal distribution throughout its worldwide distribution (Yesaki, 1993), this species may also be vulnerable to overexploitation if not managed in a precautionary manner until more quantitative biological data is collected, particularly length at sexual maturity. Furthermore, although first order estimates of longtail tuna catches by the sportfish fishery in Australia have recently become available (S.P. Griffiths, Unpublished data), a long-term monitoring program is required to provide quantitative catch data that can be used in more rigorous stock assessment models than the preliminary dynamic pool model used here.

In developing fisheries where little historical data on catch or effort is available, dynamic pool models such as yield per-recruit models can be a useful tool to obtain a preliminary assessment of the status of a fished population (Gabriel and Mace, 1999). However, fisheries managers need to exercise caution in establishing sensible reference points that will not drive the population below biologically sustainable limits, while at the same time allowing exploitation and equitable access to the resource among fishery stakeholders. Maximising yield by fishing a population at F_{MSY} has been deemed risky because it assumes constant recruitment that is independent of spawning stock size (see review by Gabriel and Mace, 1999). As a result, emphasis is placed on assessing the status of the longtail tuna stock relative to widely used $F_{0.1}$ reference point, which is more conservative and useful for data-limited fisheries and can reduce the risk of a stock collapse early in the development of a fishery (Gulland and Boerema, 1973). One criticism of yield-per-recruit models is that they do not take into account the stock-recruitment relationship and assume constant recruitment (Quinn and Deriso, 1999), and therefore are unable to detect recruitment overfishing. However, in an attempt to circumvent this problem F_{MSY} was assessed against the spawning potential ratio reference points $F_{25\%}$ and $F_{40\%}$, which can be used to assess recruitment overfishing (Clark, 1991; Goodyear, 1993; Rosenberg et al., 1994).

The recent declaration of longtail tuna as a "recreational only" species by the Commonwealth government may afford the species some protection from any increase in large-scale targeting by commercial fisheries. Although the yield per-recruit analyses revealed the stock is currently at an ideal status for a developing fishery where the precautionary $F_{0.1}$ reference point has not been exceeded, full utilisation of the current catch quota of 70t for Commonwealth commercial fisheries may begin to contribute to the stock being growth overfished, due to the dominance of small fish in commercial catches. Therefore, it is recommended that close monitoring of the stock continue to better understand the propensity of the population to withstand any increase in fishing mortality either by commercial or sportfish fisheries.

These results clearly highlight the need for precautionary management until more reliable estimates of biological parameters and fishing mortality are obtained to provide data for a more rigorous assessment of the stock, although it is unclear at this point what the most appropriate measure would entail. Introduction of a minimum legal length is usually one of the few practical management options for reducing the size at first capture, and thus reducing the fishing mortality, on species that have a large sport fishing catch. However, this is not likely to be effective for two reasons. Firstly, the yield-per-recruit analyses clearly showed that increasing the MLL has a negligible effect on the sustainability of the longtail tuna population. In most cases where a MLL has been successfully used as a management strategy to increase the sustainability of a stock, the MLL has been set to a length that corresponds to the length at which 50% of the population is sexually mature (L_{50}). However, all indications from the limited available data on the reproductive biology of longtail tuna are that they appear to reach sexual maturity early in life at around 60 cm FL (~2 years of age). Consequently, fish have an opportunity to spawn at least once before they become susceptible to capture by both commercial and sportfish fisheries at around 3 years of age. However, the sensitivity analysis of A_{50} values (Table 1) showed that if age-at-maturity occurs later than assumed in the assessment, then the spawner biomass-per-recruit would be significantly lower than reported here. As a result, the current fishing mortality is likely to exceed $F_{25\%}$ and $F_{40\%}$ and reference points, and suggest recruitment overfishing.

Secondly, longtail tuna are primarily an incidental catch in most Australian commercial fisheries, such as the N9 fishery, and an increase in size at first capture will only be achieved by increasing the mesh size of gillnets. This would increase the size of fish at recruitment, reduce fishing mortality and theoretically increase the yield and spawning stock biomass of longtail tuna. However, multispecies fisheries such as the Qld N9 fishery may experience reductions in the catch of their target species such as small sharks and grey mackerel, and ultimately become unprofitable.

The use of a MLL only becomes an effective management tool if undersized fish have high post-release survivorship. Although post-release mortality was accounted for in the model, species-specific data for longtail tuna was unavailable, and so mortality estimates for juvenile Atlantic bluefin tuna were used (Skomal et al., 2002). Nevertheless, the inclusion of this parameter did not have any significant effect on the model results because the selection probabilities for ages less than the hypothetical MLL were already very low as fish of this size had not yet become fully susceptible to the gear of either the commercial or sportfish fishery. Therefore, the 28% post-release mortality imposed on the already small proportion of the population that was captured by fisheries less than the MLL resulted in a negligible effect. If more rigorous stock assessments are to be undertaken in future it will be imperative to obtain species-specific data on post-release mortality, since estimates have been shown to vary significantly among large pelagic fishes (see review by Skomal, 2007). This has been successfully undertaken for tunas and billfishes using pop-up archival tags, which can be programmed to release from the fish a few days after release if the fish survives, or release once the fish ceases to display normal behaviour. Although expensive, the advantage of this approach is that fish are not required to be recaptured to determine their fate post-release, and there is no reliance upon fishers to report the recapture of a tagged fish.

5. Conclusions

This paper has demonstrated that longtail tuna are currently probably being fished at biologically sustainable levels, with some scope for a limited increase in fishing mortality. However, there is potential for recruitment overfishing if the true age-at-maturity is higher than the estimate of 2 years used here, despite the stock experiencing relatively low levels of exploitation by the sport fishery. Species of wide-ranging oceanic tunas may be able to withstand the fishing pressure by sport fisheries since fish may spend a large portion of their lives in areas inaccessible by most anglers. In contrast, longtail tuna may be particularly vulnerable to overexploitation by sport fishers owing to their restricted coastal distribution and their slow growth. The yield-per-recruit model was unable to provide any indication of appropriate precautionary management strategies for longtail tuna as ‘recreational only’ species, since the methods that can be easily and cost-effectively implemented to help decrease the fishing mortality rate (i.e. MLL and improved post-release survival rates) were ineffective. Further management options need to be explored, such as the implementation of daily catch limits for individual anglers and total catch quotas for the sport fishery (combined with the existing 70 t bycatch limit for commercial fisheries). These scenarios will require more accurate estimates of natural mortality, which may be obtained by a tagging program, post-release survival and age-at-50% maturity, as well as collection of long-term catch and effort data for the sport and commercial fishery. This will enable more sophisticated stock assessment models to be employed to assess the status of the stock.

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Figure captions

Figure 1. Map of the assumed stock region extending throughout the Arafura Sea, Coral Sea and Tasman Sea, Australia. Areas where samples were collected comprise the Queensland N9 offshore gillnet fishery (diagonal lines), the combined boat-based and land-based sport fishery (dotted area), and the Taiwanese gillnet fishery (cross hatched lines).

Figure 2. Length- and age-frequency distributions of longtail tuna caught in the Taiwanese gillnet fishery in the Arafura Sea (1981-1985), the Queensland N9 offshore gillnet fishery, and the sportfish fisheries (boat-based and land-based catches combined) in the Gulf of Carpentaria (GoC) and the eastern Australian coast.

Figure 3. Age selectivity curves for longtail tuna caught in the Taiwanese gillnet fishery in the Arafura Sea (1981-1985), the Queensland N9 offshore gillnet fishery, and the sportfish fishery (combined for boat-based and land-based catches in the Gulf of Carpentaria and eastern Australia). Dotted lines show the age at recruitment to each respective fishery, defined as the age at which 50% of fish become susceptible to capture by the gear used in each fishery.

Figure 4. Natural mortality-at-age functions used in the yield-per-recruit analyses where the overall natural mortality rates (M) were 0.2, 0.3 and 0.4, respectively.

Figure 5. Age-based catch curves used to estimate total mortality (Z) of longtail tuna caught in commercial and sportfish fisheries between 2004-2006 in northern and eastern Australia. Numbers of fish in each age class from each fishery were corrected using selectivity

probabilities-at-age before being combined to produce the overall catch curve for the longtail tuna stock.

Figure 6. Yield per-recruit curves using natural mortality (*M*) estimates of 0.2, 0.3 and 0.4 simulating five hypothetical management scenarios: a) no minimum legal length (MLL), b) 80 cm TL MLL, c) 100 cm TL MLL, and d) No MLL with a 35% reduction in post-release survival resulting from a national awareness campaign. Reference points F_{MSY} (solid circles) and $F_{0.1}$ (open squares) are shown in relation to the current fishing mortality rate, F_{current} (solid arrows).

Figure 7. Spawner biomass per-recruit curves using natural mortality (*M*) estimates of 0.2, 0.3 and 0.4 simulating five hypothetical management scenarios: a) no minimum legal length (MLL), b) 80 cm TL MLL, c) 100 cm TL MLL, and d) No MLL with a 35% reduction in post-release survival resulting from a national awareness campaign. Reference points $F_{40\%}$ (solid triangles) and $F_{25\%}$ (open squares) are shown in relation to the current fishing mortality rate, F_{current} (solid circles).

Figure 8. Yield per-recruit curves using natural mortality (*M*) estimates of 0.2 simulating three hypothetical scenarios involving: i) ignoring or having incomplete gear selectivity-at-age data (“No Selectivity”), ii) having low quality length-at-age data (“Large Inf – Small K”), and iii) an age at first maturity of 5 years (“A50 = 5 yrs”). The current fishing mortality rate, F_{current} is shown as solid arrows, while the biological reference point F_{MSY} is shown as circles.

Figure 9. Spawner biomass per-recruit curves using natural mortality (*M*) estimates of 0.2 simulating three hypothetical scenarios involving: i) ignoring or having incomplete gear

selectivity-at-age data ("No Selectivity"), ii) having low quality length-at-age data ("Large Inf – Small K"), and iii) an age at first maturity of 5 years ("A50 = 5yrs"). The current fishing mortality rate, F_{current} is show as solid arrows. Reference points $F_{40\%}$ (squares) and $F_{25\%}$ (circles) are shown.

Figure 10. Comparison of growth dynamics of seven *Thunnus* species: northern bluefin tuna (*Thunnus thynnus*) (Neilson and Campana, 2008), southern bluefin tuna (*T. maccoyii*) (Gunn et al., 2008), longtail tuna (*T. tonggol*) (Griffiths et al., 2009), albacore (*T. alalunga*) (Santiago and Arrizabalaga, 2005), bigeye tuna (*T. obesus*) (Farley et al., 2006), yellowfin tuna (*T. albacares*) (Lessa and Duarte-Neto, 2004) and blackfin tuna (*T. atlanticus*) (Doray et al., 2004). Age at which 80% of L_∞ was used as a standardised measure of growth dynamics to compare species that attain different maximum lengths.

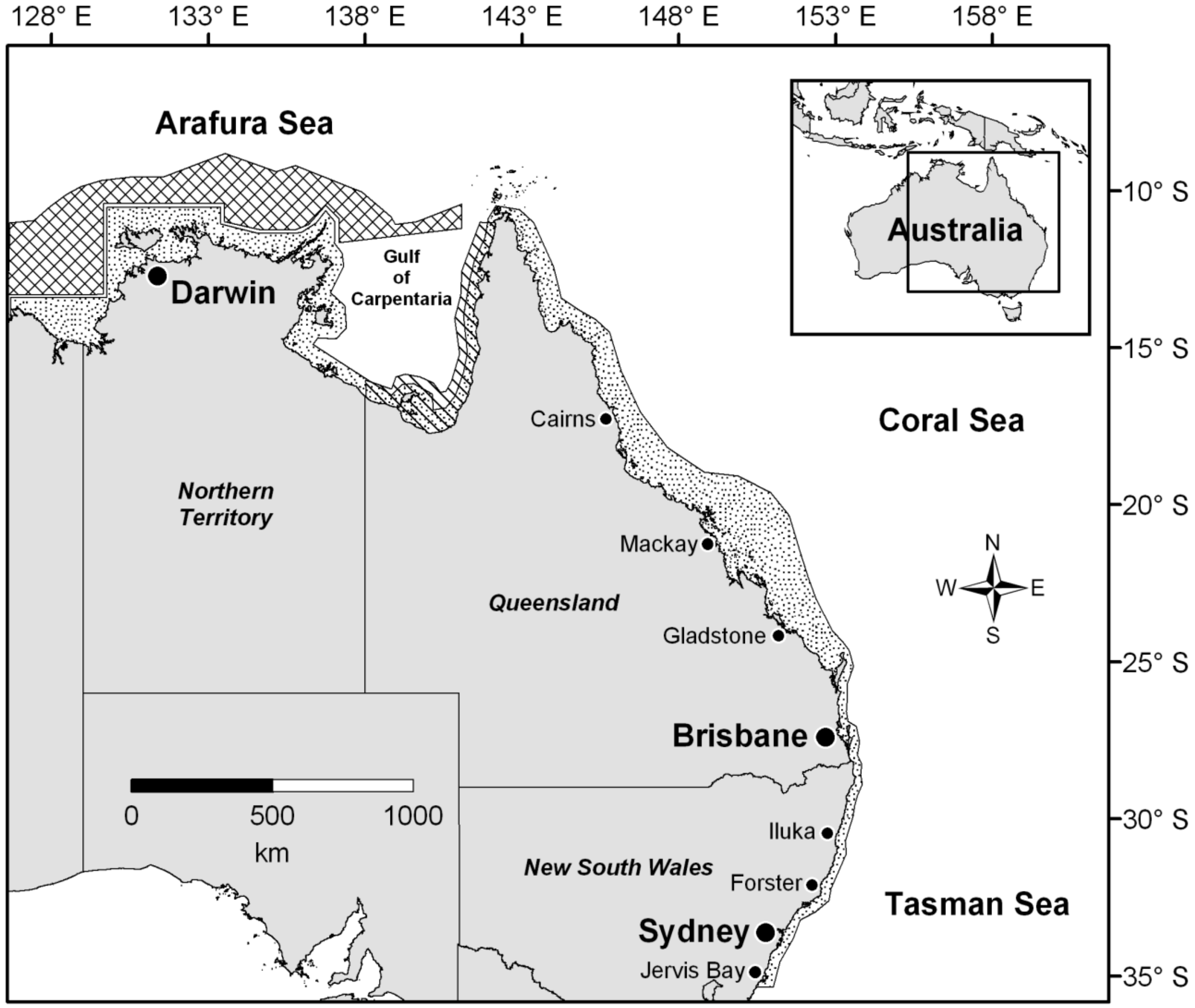
128° E
133° E
138° E
143° E
148° E
153° E
158° E
10° S
15° S
20° S
25° S
30° S
35° S
Arafura Sea
Darwin
Gulf of Carpentaria
Australia
Coral Sea
Cairns
Northern Territory
Mackay
Queensland
Gladstone
N
W
E
S
Brisbane
0
500
1000
km
Iluka
New South Wales
Forster
Tasman Sea
Sydney
Jervis Bay

Figure 1.

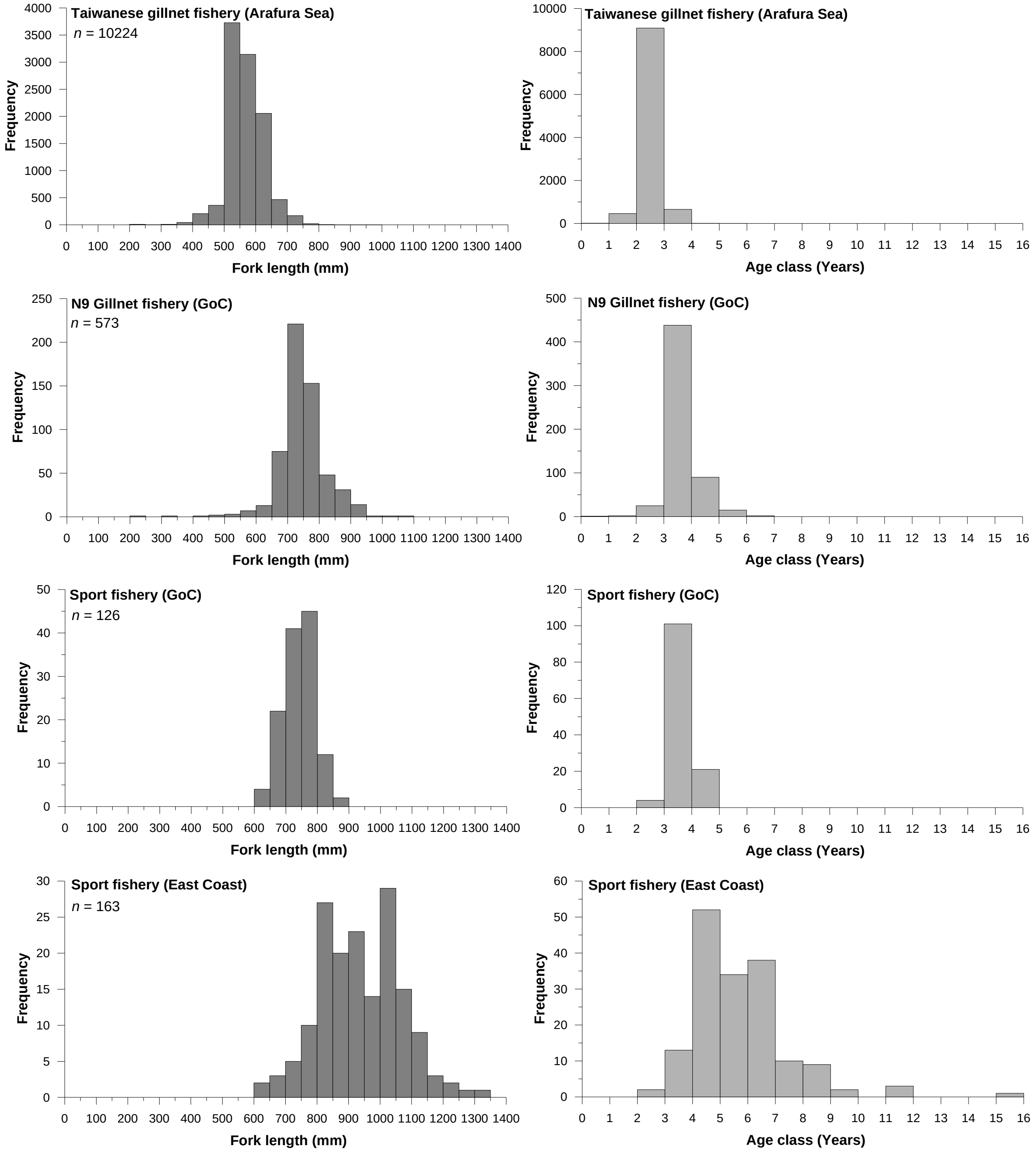
Taiwanese gillnet fishery (Arafura Sea)
n = 10224
Frequency
0
500
1000
1500
2000
2500
3000
3500
4000
Fork length (mm)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Taiwanese gillnet fishery (Arafura Sea)
Frequency
0
2000
4000
6000
8000
10000
Age class (Years)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
N9 Gillnet fishery (GoC)
n = 573
Frequency
0
50
100
150
200
250
Fork length (mm)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
N9 Gillnet fishery (GoC)
Frequency
0
100
200
300
400
500
Age class (Years)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sport fishery (GoC)
n = 126
Frequency
0
10
20
30
40
50
Fork length (mm)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Sport fishery (GoC)
Frequency
0
20
40
60
80
100
120
Age class (Years)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Sport fishery (East Coast)
n = 163
Frequency
0
5
10
15
20
25
30
Fork length (mm)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Sport fishery (East Coast)
Frequency
0
10
20
30
40
50
60
Age class (Years)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Figure 2.

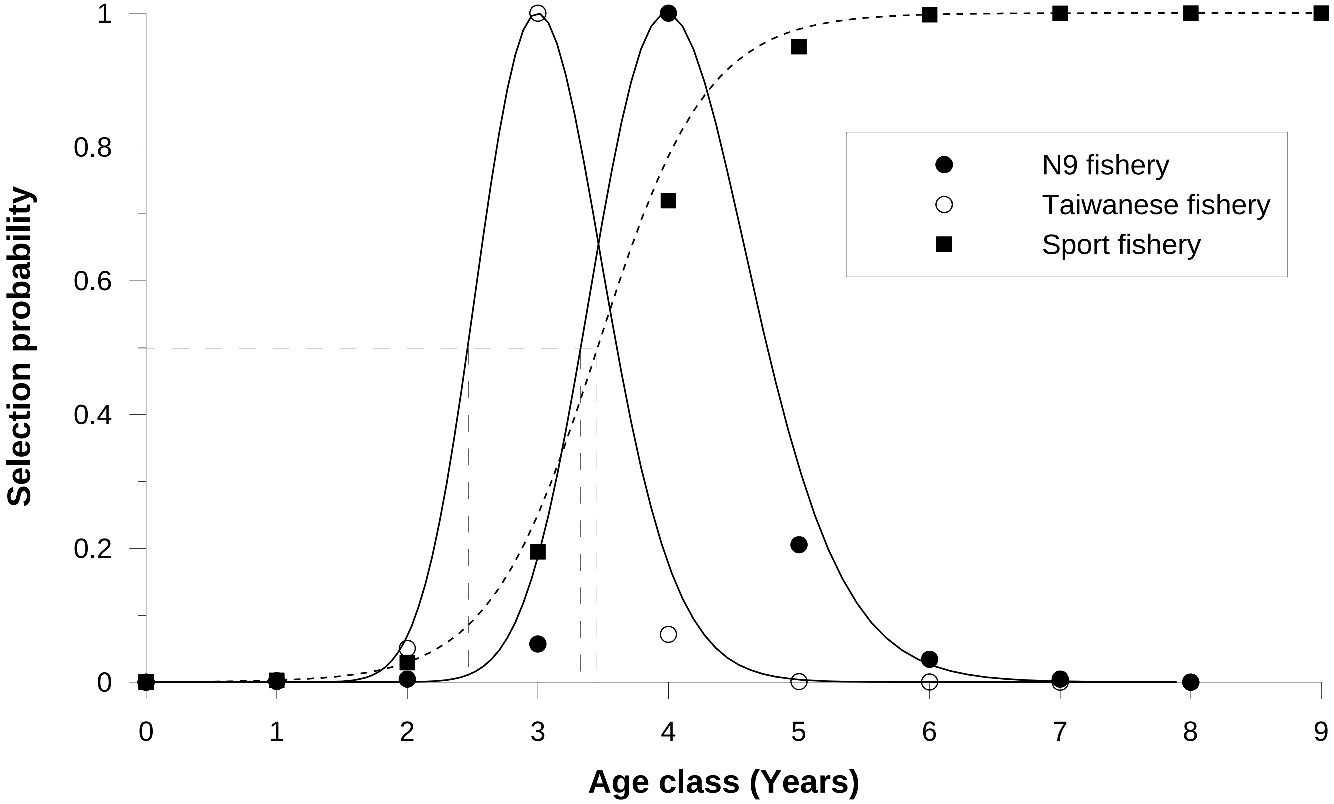
Selection probability
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
6
7
8
9
Age class (Years)
● N9 fishery
○ Taiwanese fishery
■ Sport fishery

Figure 3.

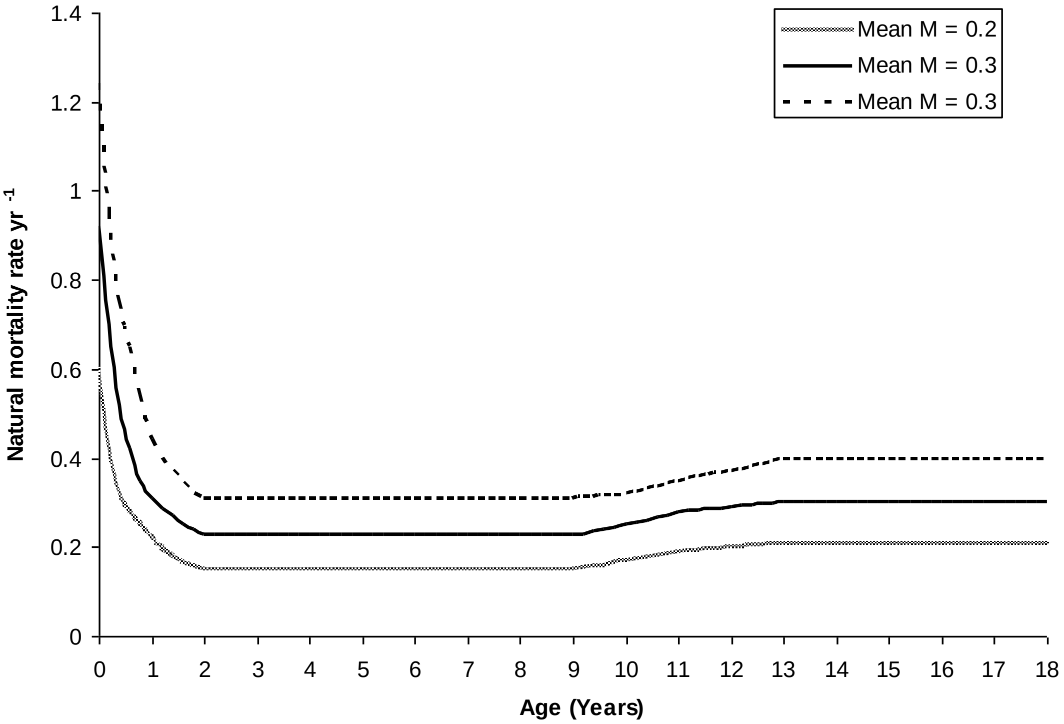
Mean M = 0.2
Mean M = 0.3
Mean M = 0.3
Natural mortality rate yr -1
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Age (Years)

Figure 4.

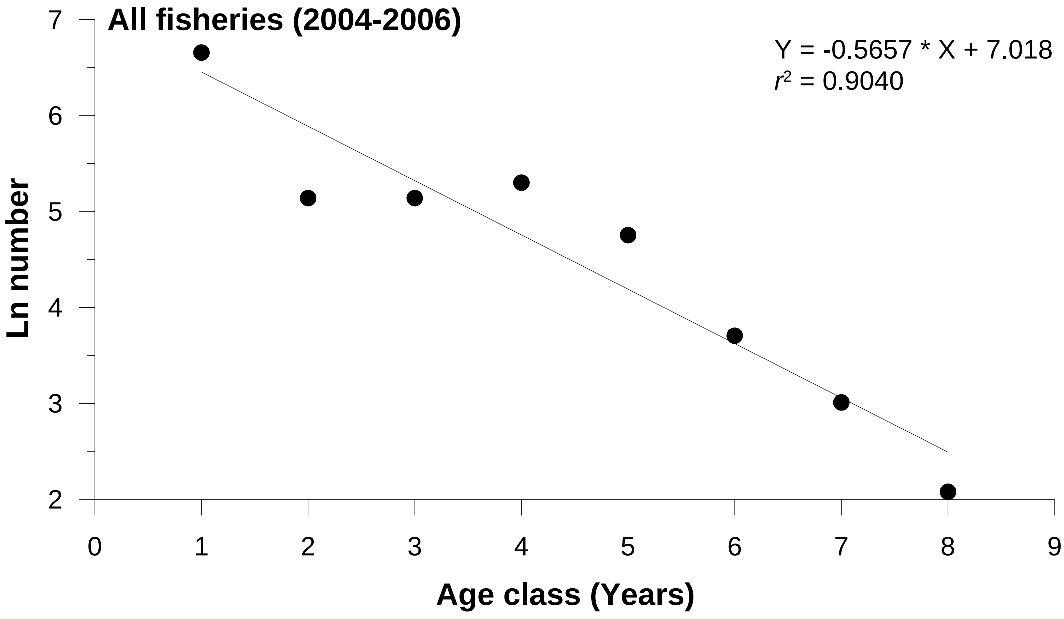
All fisheries (2004-2006)
Y = -0.5657 * X + 7.018
r^2 = 0.9040
Ln number
7
6
5
4
3
2
0
1
2
3
4
5
6
7
8
9
Age class (Years)

Figure 5.

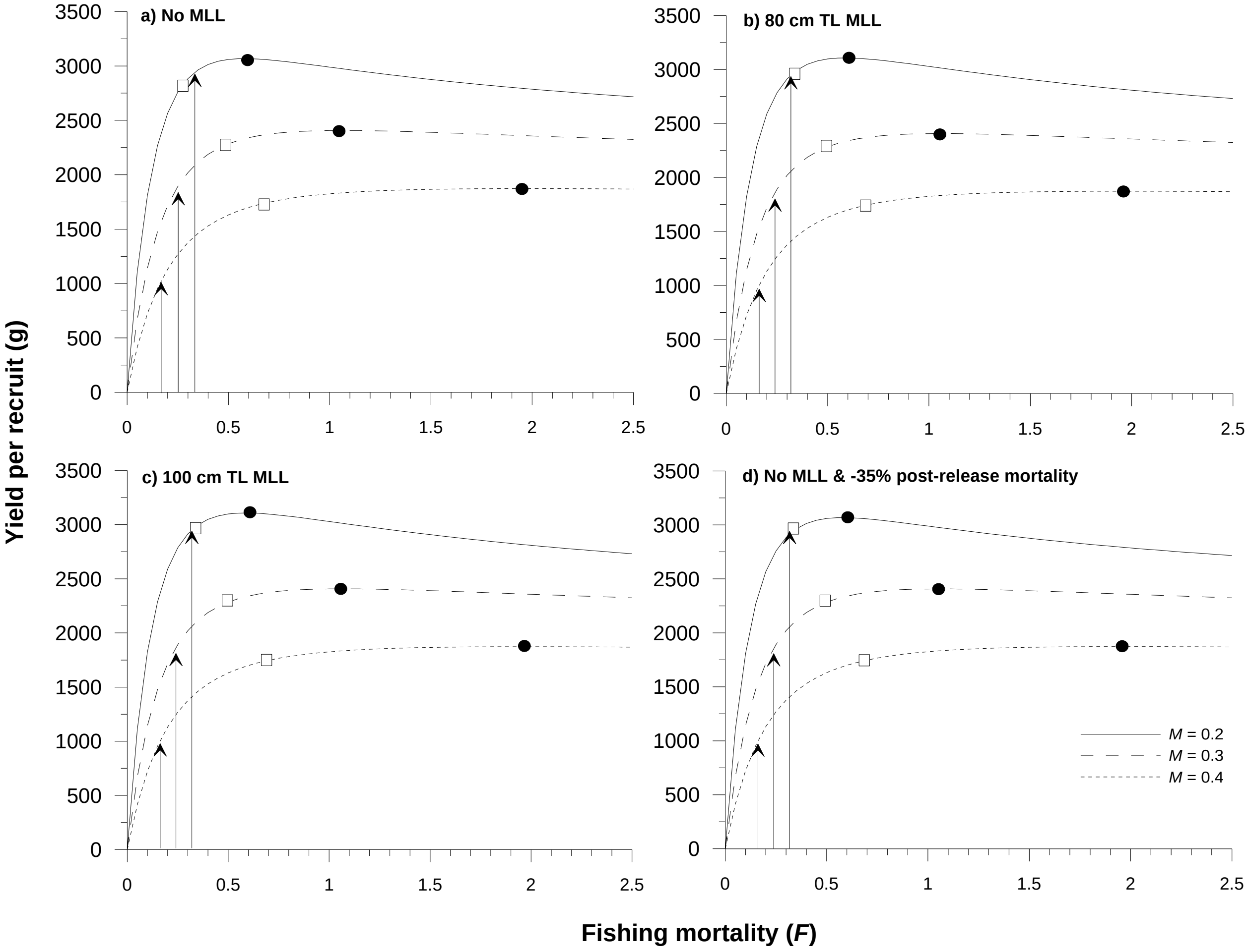
a) No MLL
b) 80 cm TL MLL
c) 100 cm TL MLL
d) No MLL & -35% post-release mortality
Yield per recruit (g)
Fishing mortality (F)
0
500
1000
1500
2000
2500
3000
3500
0
0.5
1
1.5
2
2.5
M = 0.2
M = 0.3
M = 0.4

Figure 6.

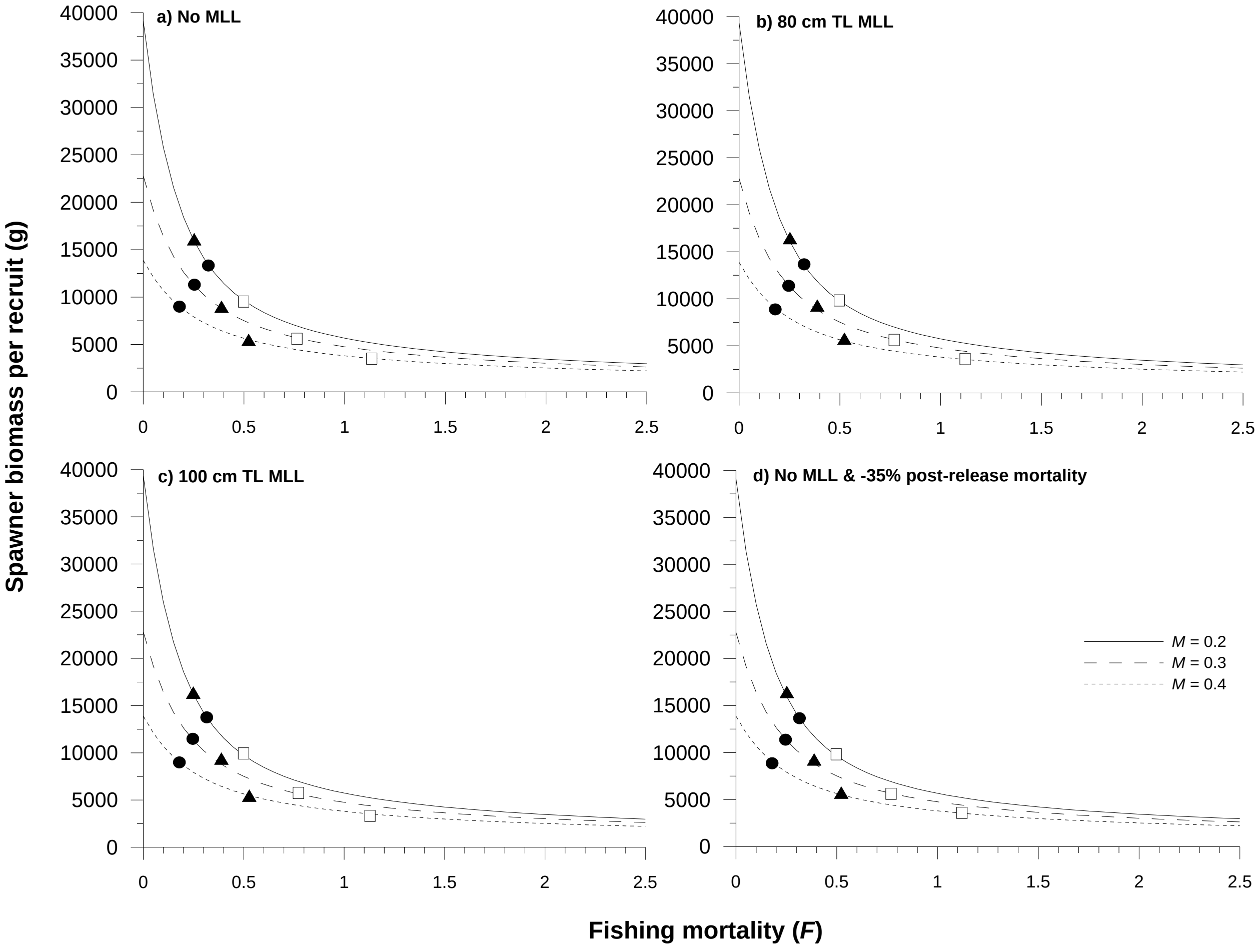
a) No MLL
b) 80 cm TL MLL
c) 100 cm TL MLL
d) No MLL & -35% post-release mortality
Spawner biomass per recruit (g)
Fishing mortality (F)
0
5000
10000
15000
20000
25000
30000
35000
40000
0
0.5
1
1.5
2
2.5
M = 0.2
M = 0.3
M = 0.4

Figure 7.

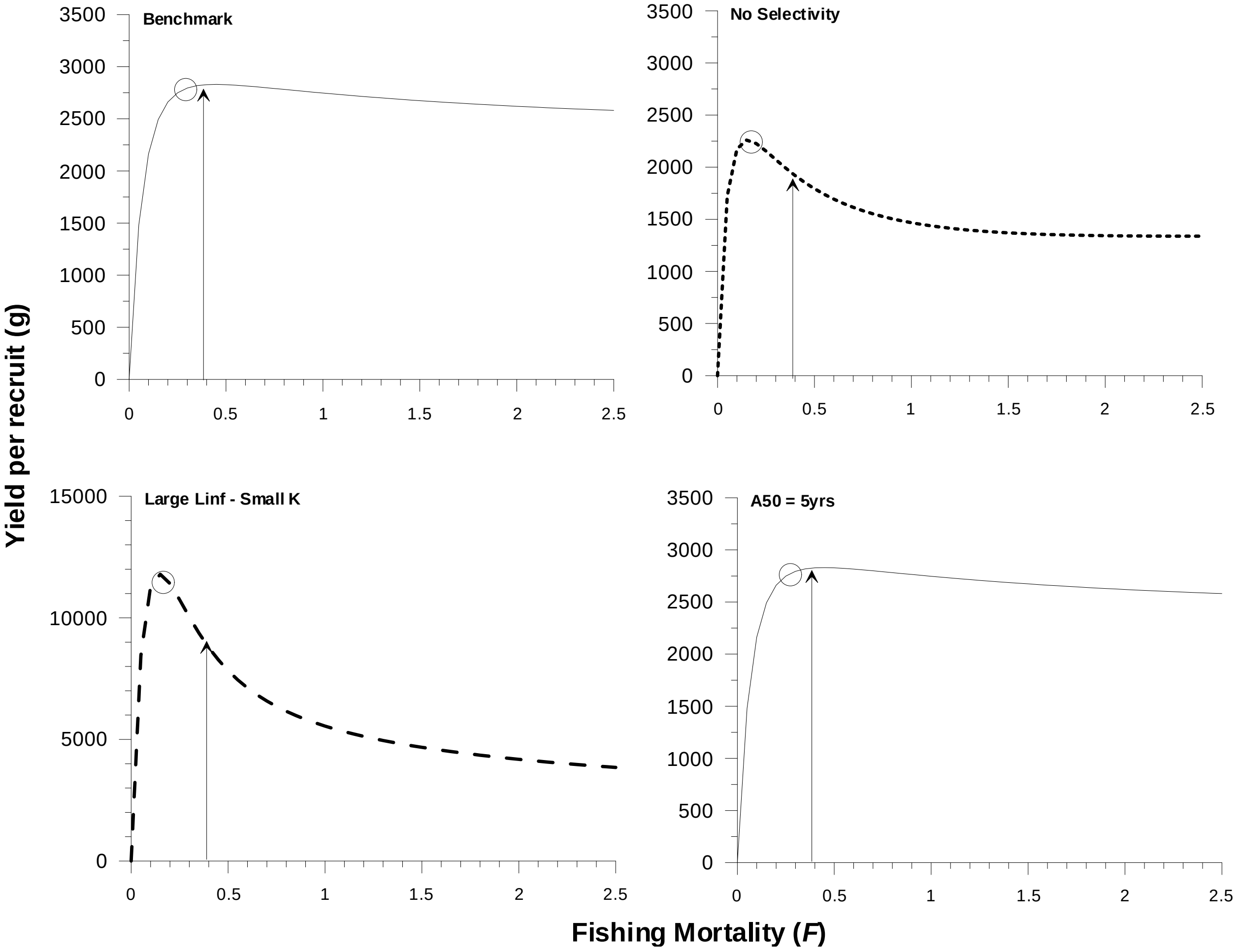
Benchmark
No Selectivity
Large Linf - Small K
A50 = 5yrs
Yield per recruit (g)
Fishing Mortality (F)
0
500
1000
1500
2000
2500
3000
3500
5000
10000
15000
0.5
1
1.5
2
2.5

Figure 8.

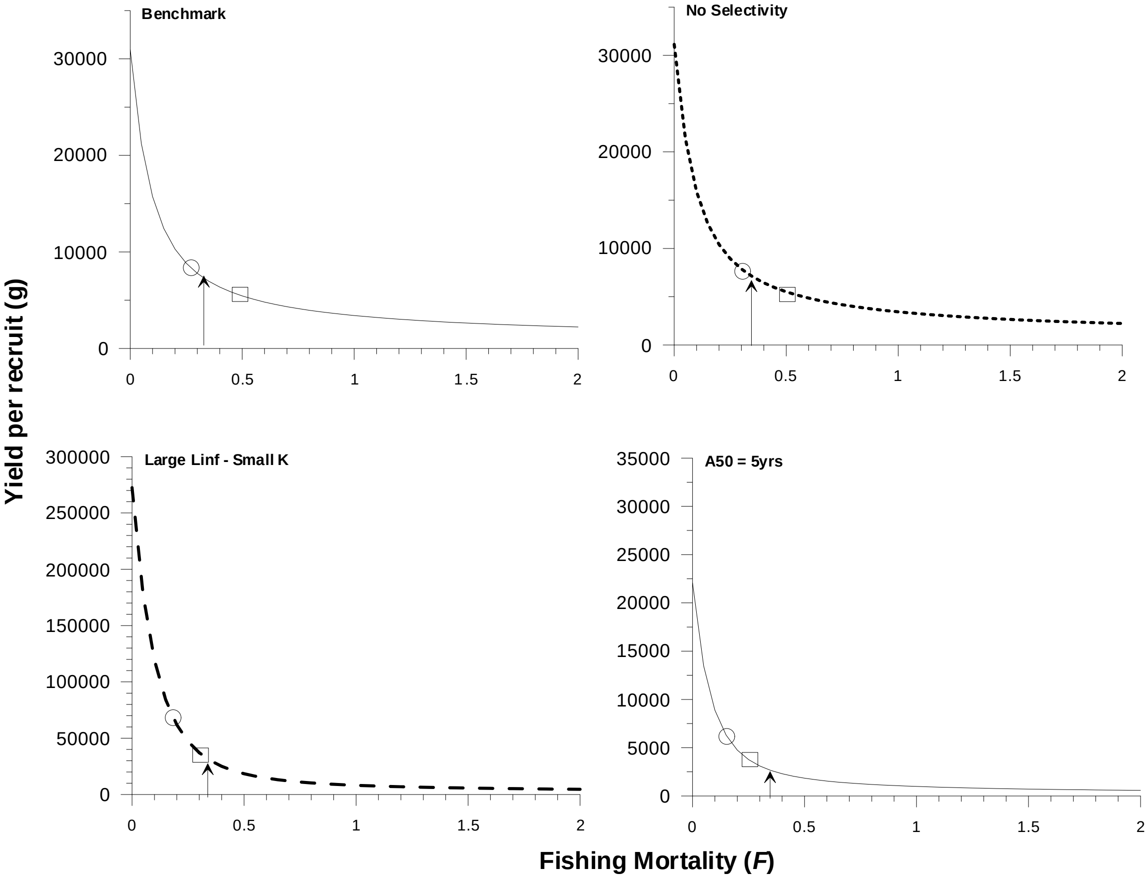
Benchmark
No Selectivity
Large Linf - Small K
A50 = 5yrs
Yield per recruit (g)
Fishing Mortality (F)
0
10000
20000
30000
5000
15000
25000
35000
50000
100000
150000
200000
250000
300000
0.5
1
1.5
2

Figure 9.

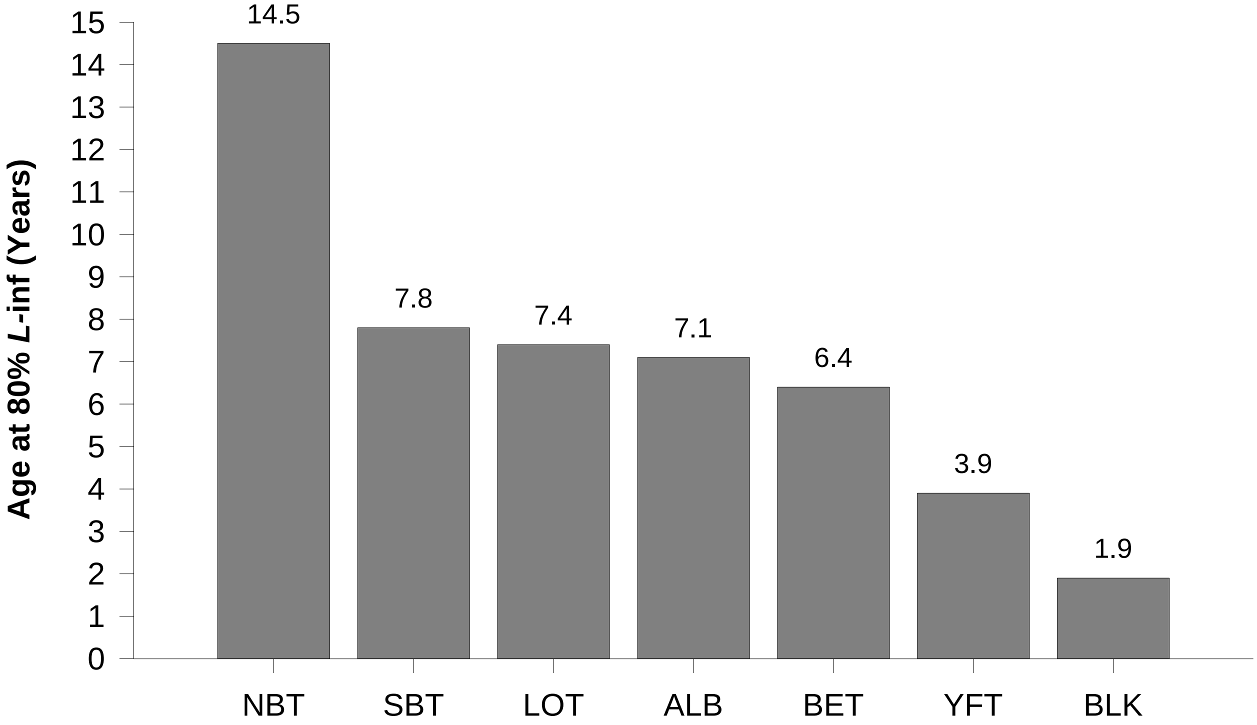
Age at 80% L-inf (Years)
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
14.5
7.8
7.4
7.1
6.4
3.9
1.9
NBT
SBT
LOT
ALB
BET
YFT
BLK

Figure 10.