Catch-at-age; age at first spawning; historical changes in growth; and natural mortality of SBT:

An integrated study of key uncertainties in the population biology and dynamics of SBT based on direct age estimates from otoliths

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1. NON TECHNICAL SUMMARY

1991/111	**Catch-at-age; age at first spawning; historical changes in growth; and natural mortality of SBT: An integrated study of key uncertainties in the population biology and dynamics of SBT based on direct age estimates from otoliths**

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Objectives:

1. Estimate and compare the age composition of catches in each of the major SBT fisheries; the three major Japanese fisheries in the Southern Ocean, the Indonesian fishery on the spawning ground, the Australian surface and longline fisheries in the AFZ, the New Zealand troll and longline fisheries and the Taiwanese fishery in the Indian Ocean.
2. Compare growth rates of fish collected from each fishery.
3. Develop an age-length-key for the population. Or, if there is an indication in the growth data of spatial heterogeneity in growth rates, develop age-length keys for discrete units within the population.
4. Estimate from otoliths collected on the spawning ground, the age at first spawning for SBT.
5. Using otoliths from fish spawned from each of the four decades in which the SBT fishery has operated, examine the hypothesis that growth rates have changed in response to population size or environmental conditions.
6. Use otolith-based age data to estimate the natural mortality rate for mature age SBT.

Outcomes achieved:

The outputs of this project have been used extensively by the CCSBT Scientific Committee in the development of fishery indicators and stock assessments:

- The new data on age composition of the Indonesian fishery catch is used as a significant indicator of the status and potential rebuilding of the spawning stock.
- The new data on age composition of the Taiwanese catch has provided for improvements in the catch-at-age matrices used in the stock assessments.
- The natural mortality estimates have been used in redefining the age-based natural mortality within stock assessments.

The finding that significant catches of 2-4 year old SBT are taken by the Taiwanese fleet in the western Indian Ocean during summer, at a time when the same cohorts also aggregate in coastal waters of southern Australia is the first significant evidence that the SBT stock may not be fully mixed at this age. This has very significant implications for the interpretation of conventional tagging data and estimates of fishing mortality rates derived from these data. Similarly, the interpretation of fishery independent estimates of recruitment in the Great Australian Bight also need to be reviewed in light of these data. Recognizing the significance of these findings, both Japan and Australia have recently developed conventional and archival tagging programs designed to examine the extent of mixing between these two areas.

The development of contacts and meaningful collaboration with Taiwanese fishery scientists and the description of Taiwanese longline fishery operations in the Indian Ocean were significant outcomes.

It is clear from the observations and the discovery of significant numbers of tag recaptures by the Taiwanese Indian Ocean fleet that there is rapid and extensive interaction between the Australian surface fishery and the Taiwanese fleet.

Non technical summary:

The CCSBT has recognized for a number of years that a better understanding of the population biology and demographics of southern bluefin tuna (SBT) is necessary for improved population modeling and stock assessments. In 1996, the CCSBT Scientific Committee identified three areas where our understanding of SBT biology was inadequate: catch-at-age, age-at-maturity and natural mortality. The Scientific Committee also highlighted the need to measure changes in the growth rates of juvenile SBT over the past 30-40 years. This project was developed in response to these concerns.

Determining the age structure of the SBT catch is a basic requirement for understanding the species population dynamics and undertaking age-based stock assessments. Validated ageing techniques have only recently been developed for SBT and a previous FRDC project (Gunn et al. 1996 - FRDC 92/42) estimated age for approximately 1,000 SBT, collected predominantly off Tasmania and in the Great Australian Bight (FRDC 92/42). During the current study, we selected a further 2000 SBT otoliths for ageing, and use these data in conjunction with those from FRDC 92/42 to complete our objectives.

To estimate and compare the age composition of catches in each of the major SBT fisheries (Objective 1), we developed several age-length-keys for SBT (Objective 3), and applied them to catch-at-length data to estimate the age composition of catches for each fishing ground/fleet. Two age-length-keys were developed based on samples collected from the Indonesian fishery on the spawning ground (separate key for each of two spawning seasons) and two for SBT caught south of the spawning ground (separate key for each sex).

Our results show that the distribution of ages within the catches varies significantly among areas and fleets. The Australian summer surface fishery in the GAB was dominated by 2 to

4 year-old SBT, while the Taiwanese winter longline fishery across the central Indian Ocean was dominated by 3 and 4 year-olds. This is consistent with archival tagging work that has shown that juveniles tagged in the GAB in summer undertake annual feeding migrations into the Indian Ocean during winter before returning to the GAB in early spring (Gunn and Block, 2001). Data collected from Taiwanese longliners transhipping in Mauritius show that 3 and 4 year-old SBT are also caught off south-east Africa from November to February, indicating that not all juveniles spend summer in the GAB. Although a few SBT as old as 7 years are caught in the Taiwanese fishery (30-35°S), it appears that adult SBT do not generally forage this far north.

The Japanese and Korean catches of SBT in the southern oceans comprised 2 to 30+ year-old fish, but the majority were less than 5 years old (25 kg). Our data showed that the relative proportion of these young fish varied between fishing grounds. We suspect that some of this variation is related to uneven discarding/targeting practices, rather than the true distribution and abundance of these age classes within the population. Therefore, the conclusions that can be made on juvenile distribution based on this information are limited.

When SBT less than 5 years old were removed from the analysis, the age distribution of SBT caught by the Japanese around southern Africa, the south-east Indian Ocean and Tasmania were very similar, and comparable to the age distribution of the Korean fishery. On these fishing grounds, approximately 75% of fish caught were 5-12 years old, 15% were 13-20 years old, and 10% were over 20 years old. Since fishing pressure has varied significantly between areas, we suspect that the similarity in age structures indicate that spatial partitioning or structure does not exist within the SBT stock.

Interestingly, we found that SBT catches around New Zealand (especially northern New Zealand) contained a much lower proportion of juvenile SBT suggesting that only a small proportion of juveniles cross the Tasman Sea after reaching Tasmania, and even fewer migrate north to the northern New Zealand ground. This decrease in juvenile abundance around New Zealand is not surprising since New Zealand lies at the eastern edge of the geographical range of SBT.

Based on the size structure of Japanese landings in the 1980s and 1990s, there has been a general decrease in the proportion of large SBT caught over time. The mean size of SBT caught decreased from 145.3 cm to 135.4 cm FL between decades. There are several possible explanations for this change such as: increased abundance of juveniles in the population; changed targeting and retention practices; or decreased abundance of adults.

Our objective to compare growth rates of fish collected from each fishery (Objective 2) could not be met due to uncertainty surrounding the timing of band formation and the bias this would introduce for fish sampled during the winter (when bands forms). This problem has been addressed as part of FRDC 99/104 "Integrated analysis of growth rates of SBT for use in estimating the catch at age matrix in the stock assessment". Using the direct age data, however, we determined that life expectancy was similar for both males and female SBT (41 and 38 years respectively), but that growth was significantly greater for males than females after an age of 6 years. We suspect that this sexual dimorphism in growth is related to gonad maturation and the onset of sexual maturity.

Another objective of the study was to determine the age distribution of SBT in the Indonesian longline catches on the spawning ground, and to estimate age at maturity (Objective 4). In the 1994-95 and 1996-97 spawning seasons, the Indonesian catch was dominated by 15-25 year-olds, but fish as young as 8 years and as old as 34 years were caught. We found some evidence of an increase in the relative abundance of 10-15 year old fish in the latter season, suggesting that cohorts spawned since the introduction of quotas in 1984 are now joining the spawning population. The data also indicates that the age at which SBT enters the spawning stock may be higher than previously thought. Using Davis' (1995) estimates of size at 50% maturity and our direct ageing data, we estimate the 50% maturity is reached at ages between 10-12 years.

Objective 5, examining the historic changes in juvenile SBT growth rates was investigated using back-calculated techniques on otoliths. The data showed that a change in the growth rates occurred around 1979-1980. It is possible that this increase in growth is the result of Lee's phenomenon, where increased growth is 'seen' in more recent years due to an effect associated with size-selective mortality. However, the abrupt nature of the growth change suggests that Lee's phenomenon is not influencing our data. The causes of the changes remain unresolved, but are likely to be a density-dependent response to changes in population size, a response to environment change or a combination of the two.

The final objective of the study was to estimate the natural mortality rate for mature age SBT. Based on catch data and direct age data, we obtained natural mortality estimates for SBT aged 11 to 31 years of about 0.1 yr-1, with standard errors of about 0.01. We found good agreement between the estimates obtained from the direct-age samples from the Japanese and Indonesian catches. From age 31 year to 40 years, the natural mortality rate dramatically increases to about 0.4 yr-1 from Japanese data, and to about 0.8 yr-1 from Indonesian spawning ground data. This is consistent with senescence in old animals, but it might be due, or partly due, to behavioral differences of old fish, particularly in the spawning ground. The analyses conducted by the project indicate that SBT natural mortality varies significantly with age.

Keywords: Southern bluefin tuna, age distribution, age-length keys, sexual dimorphism, age-at-first maturity, growth rates, natural mortality.

2. ACKNOWLEDGMENTS

There are many people we would like to acknowledge for support during this project. We are grateful to the Australian and New Zealand scientific observers aboard Japanese longline vessels who obtained most of the otolith samples used in this study. Our thanks go to Tim Davis and Sofri Bahar who coordinated the sampling program for the otoliths in Indonesia as part of a joint CSIRO / Indonesian Research Institute of Marine Fisheries (RIMF) catch monitoring program. We also acknowledge Lynda Griggs at New Zealand National Institute of Water and Atmospheric Research (NIWA) for coordinating the collection of otoliths in New Zealand. We thank the Central Ageing Facility at Queenslcliff for preparing sections of all our otoliths. We are grateful to Dr. Shui Kai (Eric) Chang of the Overseas Fisheries Development Council in Taiwan, and Mr S.-F. Fuh and Mr. K. Lin of the Taiwan Deep Sea Tuna Boatowners and Exporters Association for their support in collecting SBT length frequency data from the Taiwanese longline fishery in the Indian Ocean. The project was funded by FRDC grant 97/111. AFFA's Fisheries Resources Research Fund jointly funded the Chinese Taipei catch-monitoring program.

3. BACKGROUND

In considering the major inputs required for decreasing uncertainties in the assessment of the SBT population, the 1996 CCSBT Scientific Committee Meeting (Anon, 1996) identified catch-at-age, natural mortality and age at maturity as areas in which our current understanding was inadequate and in need of urgent review. In addition, quantitative estimates of changes in the growth rates of juvenile SBT over the past 30+ years were also considered critical to interpretation of historical trends in population size.

While the background to these issues is considered in detail below, their resolution has a common prerequisite - accurate data on the age structure of the SBT population. Until very recently these data were not available as the methods for direct estimation of age from interpretation of banding patterns or chemical analysis of hard parts had either not been developed or adequately validated.

This situation changed with CSIRO's FRDC-funded project on the "Age and Growth of SBT" (FRDC 92/42). The project developed validated methods for the direct estimation of age throughout the size and age range of the SBT population. As a result, we were in a position to collect quality and validated data on the catch-at-age across the many components of the SBT fishery, and use these data to estimate a number of critical population biology parameters for the SBT population.

Catch-at-age

The 1996 CCSBT Scientific Committee meeting noted their "particular concerns about the accuracy of the catch-at-age matrix". As has been the case over the past 15 years, the VPA assessments in 1996 were conducted using estimates of the age structure derived from the conversion of lengths to age using growth curves based on tag return data. However, since it is now recognised that there is a very large overlap in the size range of SBT at different ages (ie size for larger fish is not a good predictor of age), the age estimated obtained are not considered accurate. Hearn et al. (1996) compared the estimates of age derived from tagging data-based growth curves with direct estimates from otolith readings and found that the former significantly underestimated age in fish as young as 6 years old. As a result, there remains significant uncertainty in the overall distribution of catch-at-age and in particular in the structure of what is termed the ‘plus group’, which includes all fish older than 12 years of age.

A preliminary length-age key was provided to the 1996 CCSBT Scientific meeting from data collected as part of FRDC 92/42. This was based on a small number of samples collected primarily from the Australian surface fishery in the Great Australian Bight and the Japanese winter fishery off Tasmania. The data demonstrated that the maximum age for the species is in excess of 40 years, twice that previously estimated on the basis of tag returns. A significant proportion of the samples collected from the Japanese longline catches were also in excess of 25 years old, a finding that dictates a very new interpretation of the dynamics of the "plus group". The current study aims to build on the data collected in FRDC 92/42 and develop age-length keys for SBT, which can be used to produce catch-at-age matrices.

Spatial structure within the catch-at-age distributions

It has been recognised for some time that the size distribution of fish within Japanese high seas SBT catches varies significantly across the geographic range of the fishery. These variations appear to be stable and in combination with apparent depletions or fish downs of historically productive fishing grounds, raise the question of whether there is spatial partitioning or structure within the SBT stock. At present, the SBT stock is considered for assessment purposes to be a single unit. If spatial structure is stable, then the current methods of assessment would need to take into account transfer rates, differential mortality vectors, etc.

An added dimension in the extent of spatial heterogeneity in the age distribution of SBT catches is that, with the exception of Indonesian catches, nothing is known of the size and age distribution of SBT caught by non-CCSBT countries. Taiwan and Korea are known to catch in excess of 2000 tonnes of SBT, primarily in subtropical and warm temperate waters of the Indian Ocean. Without data on the size and age distributions of these very significant catches, it is not possible to estimate the likely impact of their activities on the parental biomass and stock as a whole. One of the aims of the current study is to compare age compositions of catches in each of the major SBT fisheries to determine if there is spatial structure within the stock.

Age at maturity

The age at first maturity in SBT remains uncertain following recent analyses of the age of fish caught by Indonesian longliners operating on the SBT spawning grounds (Gunn et al. 1996). This study found that the minimum age of fish caught in these fisheries was 11-12 years with the bulk being older than 13-14 years. If these fish are representative of the spawning stock, then the age at first spawning is significantly higher than previous estimates of the age at first maturity derived from estimates of the size at maturity (Davis, 1995).

As CCSBT assessment scientists attempt to model the likelihood and probably timing of rebuilding of the parental biomass from their current historically low levels, the age at which fish first spawn, and thus enter the ‘parental biomass', is a critical issue.

Historical changes in growth rates

Data from large scale tagging experiments in the 1960s and 1980s suggest that at some time over the twenty-year interval between the two experiments, the growth rates of juvenile SBT changed significantly. This has had a major impact on the assessment process, which has used growth curves based on the data from the experiments to derive the catch-at-age matrices. In the absence of data with which to objectively estimate when the growth rates changed, and whether the change was a gradual or abrupt, the CCSBT has used linear interpolations over the 20-year interval. The potential for error in this method is of great concern to the CCSBT. Thus, one of their high priority research issues is to determine the nature and extent of changes in growth throughout the history of the fishery.

It was now possible to retrospectively examine changes in growth using otolith structure. Gunn et al. (In press) found that the size of SBT otoliths is closely related to fish length, particularly during the first 5 years. Thus, once an otolith/fish has been aged, it is possible to measure the radius of the first 1-5 bands to determine the size-at-ages 1-5 for each fish. That is, the thickness of the bands in the otoliths is proportional to fish length. As SBT are now known to live for at least 40 years, using otoliths from the CSIRO hardpart archives collected since the mid-1980s it should be possible to determine the growth rates of fish spawned since the 1950s. This would allow us to determine the nature and extent of changes since the very early days of the SBT fishery.

Natural mortality

Despite the fact that natural mortality is used in tuning the Virtual Popiulation Analyses (VPA) on which the SBT assessment process is based, little-to-nothing is known of the natural modality rates of the mature/spawning component of the stock. Tagging studies during the 1990s have provided much-needed estimates of natural mortality of 1-5 year olds, but are unlikely to provide any meaningful data for older fish. Thus, tuning of VPAs for natural morality vectors requires assumptions and subjective judgements on both the rates and age-dependence of mortality for older age classes.

As the findings of the FRDC92/42 have been integrated into the CCSBT assessment process, it has become clear that the natural mortality rates of the population as a whole, and the plus group / mature age classes in particular, are lower than previously accepted and factored in the VPA tuning. With more precise age estimates from representative samples of the population it should be possible to estimate directly the natural mortality rates of these older age classes.

4. NEED

The critical requirement for accurate assessments of SBT stocks is recognised internationally. In 1995-96, the SBT fishery was worth $100 million to Australia and $1 billion globally. However, in the same year the species received a CITES 2nd Appendix listing (a response to judgements that it is over-exploited and endangered) and Japan proposed a large-scale experimental fishing program (EFP) based on an increase in quota/catch.

The diametrically opposed position represented by CITES and the Japanese EFP result from fundamental problems in the stock assessment process. Uncertainties within the assessment – in the data on which they are based, in key biological parameters and in the interpretation of historical changes in catch, effort and population parameters – provide the scope for radically different interpretations of results from assessment models. It is likely that as long as these uncertainties remain, there will be the scope for interpreting the data "as it suits".

At the 1996 CCSBT Scientific Committee meeting, the significant uncertainties within the assessment process were identified. The proposed project addresses four of the high priority areas.

1. Accurate and validated age-length keys based on direct age estimation data are required for improving the catch-at-age matrices that are used as the basis for VPAs.
2. Accurate estimates of the age at first maturity are required for establishing the extent of the parental biomass.
3. Accurate estimates of the nature and extent of changes between the 1950s and 1990s in the growth of 1-4 year old SBT are required for understanding the effect of these on the current and past assessments.
4. Estimates of natural mortality of 8-40 year old SBT are required for tuning the VPAs and stock projections.

5. OBJECTIVES

1. Estimate and compare the age composition of catches in each of the major SBT fisheries; the three major Japanese fisheries in the Southern Ocean, the Indonesian fishery on the spawning ground, the Australian surface and longline fisheries in the AFZ, the New Zealand troll and longline fisheries and the Taiwanese fishery in the Indian Ocean.
2. Compare growth rates of fish collected from each fishery.
3. Develop an age-length-key for the population. Or, if there is an indication in the growth data of spatial heterogeneity in growth rates, develop age-length keys for discrete units within the population.
4. Estimate from otoliths collected on the spawning ground, the age at first spawning for SBT.
5. Using otoliths from fish spawned from each of the four decades in which the SBT fishery has operated, examine the hypothesis that growth rates have changed in response to population size or environmental conditions.
6. Use otolith-based age data to estimate the natural mortality rate for mature age SBT.

6. OUTLINE OF RESEARCH

The project had four major research components:

1. Catch-at-age / demographics,
2. Age-at-first spawning,
3. Change in the growth rate of juveniles, and
4. Natural mortality

These components are examined in chapters seven to ten of this FRDC final report. Each component was based on direct age estimates of SBT using otoliths. The following is a summary of the age estimate data used in the project.

Otolith based age estimates were obtained from a previous FRDC funded project; “The direct estimate of age and growth of southern bluefin tuna” (FRDC project 92/42), which developed techniques to directly age SBT. These age estimates were supplemented by an additional 2000 otoliths selected and read during the project. Where possible, the additional otoliths were selected to obtain sufficient numbers from the full size range of fish caught (stratified sampling rather than random sampling). The majority of otoliths selected were held in the CSIRO Hardpart Archives, which contain otoliths collected since the mid-1980s as part of a structured sampling program by Australian and international observers, CSIRO scientists and contractors. The archives included otoliths collected from each of the major Japanese fisheries, the Australian surface and longline fisheries, and the Indonesian longline fishery. Since the collection contained very few otoliths from New Zealand waters, we initiated otolith sampling by scientific observers aboard Japanese charter longline vessels within the New Zealand EEZ. The sampling was coordinated by the New Zealand National Institute of Water and Atmospheric Research (NIWA), and the otoliths were archived as part of the ‘Archival hard part collection’ project (Southern tuna and Billfish MAC and Eastern tuna and Billfish MAC).

Of the 2000 otoliths read during the project, a final age was assigned to 1904. Final age estimates were not given to the remaining otoliths, as they were too difficult to interpret. Of these otoliths, 183 were read by a secondary reader and the Average Percent Error (APE) between readings was 4.72% (Beamish and Fournier, 1981). This level of precision is better than the minimum recommended by Morison et al. (1998) of 5%. All age estimates were adjusted to account for birth and capture date. Since SBT spawn predominantly during the summer (Farley and Davis, 1998) and catches are spread throughout the year, using the number of bands as an estimate of age is misleading. To assign each fish to its correct cohort, we assumed a birth date of January 1 and a band formation date of July 1, and adjusted the number of bands counted accordingly. That is, if a fish was caught after July 1 but before January 1, we subtracted one year from the number of bands counted.

7. DEMOGRAPHICS OF SOUTHERN BLUEFIN TUNA, *THUNNUS MACCOYII*, IN THE SOUTHERN OCEANS WITH IMPLICATIONS FOR STOCK STRUCTURE.

Draft technical paper to be submitted to international fisheries journal.

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Abstract

Southern bluefin tuna (SBT), *Thunnus maccoyii*, is a heavily exploited species, and as a result the parental stock has declined substantially. It is acknowledged that the catch of SBT is patchy across its geographic range in the southern oceans and that the size composition of the catch varies significantly between fishing grounds. This has lead to suggestions that geographic structure may exist within the population. Very little is known about the age composition of the SBT catches, or the extent to which changes have occurred in the stock composition over time. The recent development of validated ageing techniques for SBT, however, has enabled us to examine the spatial structure within the catch-at-age of SBT. Separate age-length keys were developed for male and female SBT (as males were found to be larger-at-age than females after age seven) and were applied to length frequency data from collected from commercial catch during the 1990s. Despite weaknesses of using commercial catch data to estimate the age structure of a species such as SBT, our estimated age compositions show clear differences between fisheries and fishing grounds. SBT aged two to four years are caught on all grounds examined, while fish older than five years are predominantly caught in the cooler oceanic waters south of 35-40°S. Specific information that can be gained on the distribution and migration of juveniles from their relative abundance in catches is limited because of unknown discarding or targeting practices on some fishing grounds. When SBT aged less than five years were removed from the analysis and the data were grouped into age classes, the age distribution of SBT caught on Japanese fishing grounds around southern Africa, the south-east Indian Ocean and Tasmania were almost identical, and similar to the age distribution of SBT in the Korean fisheries off southern Africa and the south-east Indian Ocean: the majority being in the 5-12 years old age class. The similarity in age structures suggests that SBT in these areas probably form one well-mixed population rather than several independent groups, especially since fishing effort has been highest around southern Africa and we found no indication of a shortening in the size distribution of SBT caught on this ground between the 1980s and 1990s. Around New Zealand, the majority of fish caught were of spawning age suggesting that the Tasman Sea to the west may form the eastern boundary for juvenile migration. The size composition of the catch has changed between the 1980s and 1990s; there has been an increase in the relative abundance of SBT less than 150 cm FL on all fishing grounds examined.

Introduction

Southern bluefin tuna (SBT), *Thunnus maccoyii*, is currently managed as a single stock. Mitochondrial DNA analysis failed to demonstrate heterogeneity within the species (Grewe et al., 1997) and there is only one known spawning ground, which is in the north-east Indian Ocean. Despite this single spawning ground, SBT are a highly migratory species, and are widely distributed throughout much of the southern oceans from the Atlantic across the Indian to the western Pacific Ocean (West Wind Drift). It has been recognised, however, that the distribution of catches across this region is patchy. The highest densities of fish generally occur close to the continents off Argentina, southern Africa, southern Australia and New Zealand, where Japanese longline vessels have targeted them since the mid-1960s (Shingu, 1978). This patchy distribution has led to suggestions that geographic structure (or even feeding ground fidelity) may exist within the stock, and that the areas of low abundance may be boundaries between populations. Recent studies have shown that low levels of mixing between isolated fish populations can be sufficient to remove any indication of genetic heterogeneity within a species (Bembo et al., 1996; Waples, 1998). It is, therefore, not known if harvesting from one fishing ground has a local or global effect on the population.

Much of what we understand about the distribution and migration of SBT is based on catch data from Australian and Japanese fisheries targeting the species. The Australian fishery has operated within the Australian southern coastal region since the 1950s, predominantly catching small SBT less than 150 cm in fork length (FL). The Japanese longline fishery began on the SBT spawning ground in the 1950s targeting large mature fish, before expanding into the southern oceans in the 1960s. By the 1970s, the fishery had reached it greatest extent with four areas receiving the greatest concentration of effort: west of New Zealand, south of Tasmania, south-west of Australia, and south of Africa (Shingu, 1978). Since that time, the spatial distribution of the fishery has contracted significantly (Campbell, 1998). Between 1987 and 1995, the effort (number of 1 degree squares with any fishing activity) decreased by between 32 and 72% depending on the quarter (Gunn et al., 1998b). In the 1990s, the Japanese fishery restricted most of its effort to the second and third quarters of the year (Tuck et al., 1996). The catch of SBT decreased from about 50,000 tonnes in the late 1960s to less than 12,000 tonnes after the introduction of quotas in the late 1980s. It is unclear if the spatial contraction in the fishery was due to a contraction in the distribution of SBT or increased targeting of high catch per unit effort (CPUE) areas after the introduction of quotas. The fact that SBT disappeared off New South Wales in the early 1980s (Caton et al., 1990) suggests to some extent that the distribution has contracted. Recently there has been an increase in the catch of SBT by non-quota holding nations, chiefly Indonesia, Taiwan and Korea. With the exception of Indonesia (Davis et al., 1995, 1998), little is known about the catch of SBT by these nations other than estimates of total catch.

Validated ageing techniques have recently been developed for SBT (Kalish et al., 1996; Clear et al., 2000), and age has been estimated for approximately 1,000 SBT caught predominantly off Tasmania and in the Great Australian Bight (Gunn et al., In press). The aims of the current study were to build on this initial work and examine the age structure of SBT throughout its geographical range to determine if there is spatial structure within the population. We also examine available data on the size composition of SBT caught in the 1980s and 1990s to determine if there have been any changes in the general size structure of fish caught over time or a reduction in the mean size, which is typical in exploited populations. Significant differences in age or size composition can provide indirect evidence of stock structure (Casselman et al., 1981; Ihssen et al., 1981; Beggs and Waldman, 1999; Begg et al., 1999), based on the assumption that environmental conditions and/or fishing pressure vary significantly between areas, and if separate populations exist they will have different population parameters. Fishing pressure for SBT has been high on all fishing grounds in the southern oceans, but especially intense around southern Africa. Between 1969 and 1995, the number of SBT caught in this area accounted for 40% of the total catch (Tuck et al., 1996). We hypothesise that if SBT show feeding ground fidelity, the size/age structure of SBT caught would differ between fishing grounds and shorten over time as a result of different fishing pressures.

Material and methods

Southern bluefin tuna otoliths have been collected and archived by the CSIRO since 1985 as part of a structured sampling program collecting material from across the size and geographical range of the exploited population. Otoliths have been predominantly collected from three fisheries: the Australian surface fishery in the Great Australian Bight (GAB), the Japanese longline fishery in the southern oceans, and the New Zealand-Japan chartered longline fishery in the New Zealand EEZ. Otoliths from the Japanese fishery were collected from three main fishing grounds: southern Africa, the south-east Indian Ocean, and Tasmania (Fig. 1). To determine the age structure of the catch on each of these fishing grounds, it was necessary to obtain sufficient numbers of age estimates from a representative sample of the SBT catches across their geographic range. Ages estimated by Gunn at al. (In press) were supplemented by additional otoliths selected from the archives. Otoliths were selected by area of capture and size of fish, with the aim of increasing the number of age estimates to approximately 300 per fishing ground, and to include a representative sample of the size range of SBT caught. Fork length (FL) to the nearest cm was obtained for all fish sampled and sex data was obtained for most.

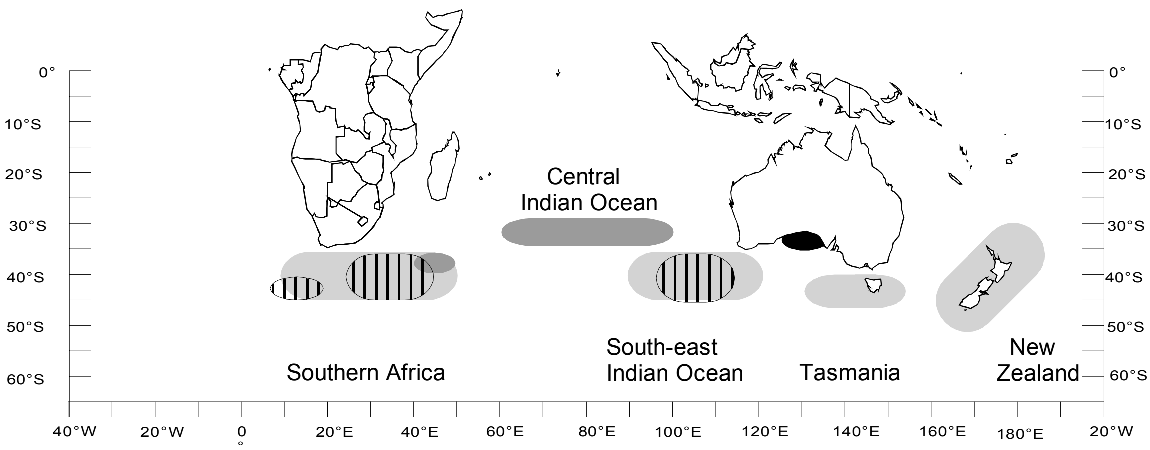

Figure 7.1. Map showing locations of Australian (black shading), Japanese (light grey), Taiwanese (dark grey) and Korean (hatched) southern bluefin tuna fishing grounds in the southern oceans where otoliths and/or length frequency data were collected.

All additional otoliths (n=1026) were prepared, sectioned and read using the techniques described by Clear et al. (2000) and Gunn et al. (In press). A primary otolith reader read each otolith twice and determined a final increment count. A second otolith reader read 10% of the otoliths between 1-3 times to ensure the consistency of age estimates. The second otolith reader was the primary reader of otoliths in Gunn et al. (In press). All readings were conducted without reference to the size of fish, date, area of capture or previous readings. To examine consistency in replicate readings (precision of readings) the index of average percentage error (IAPE) (Beamish and Fournier, 1981) and coefficient of variation (CV) (Campana et al. 1995) were calculated. Age-bias plots were examined to assess bias between readers.

The age estimates were combined with those of Gunn et al. (In press) giving a total number of aged fish of 460 from the GAB, 294 from southern Africa, 295 from the south-east Indian Ocean, 509 from around Tasmania and 297 from New Zealand. Since increments form annually between May and August (austral winter) in SBT otoliths (Clear et al., 2000; Gunn et al., In press) and SBT spawn predominantly during the austral summer (Farley and Davis, 1998), using the number of bands as an estimate of age can be misleading. To assign each fish to its correct cohort we assumed a birth date of January 1 and a band formation date of July 1, and adjusted the number of bands counted accordingly. That is, if a fish was caught after July 1 but before January 1, we subtracted one year from the number of bands counted.

To generate age frequency distributions, age-length keys were developed and applied to length frequency data collected during the 1990s from each of the main SBT fishing grounds. Age-length keys give the proportion of fish at age in each 5-cm length class, which enabled us to convert catch-at-length data to catch-at-age. To produce the keys, it was necessary to combine age data from different years in order to sample a wide cross section of age classes for each area. This may have biased the results if growth was variable among years. However, as our age data were drawn from fish sampled predominantly in the 1990s (90% of fish), and applied to length frequency distributions collected during the same decade, we believe the bias was minimal. To determine if separate keys were needed for each sex, the mean length-at-age was calculated for male and female SBT using the combined age data, and compared statistically with an unpaired t-test.

Length frequency data were obtained from several sources, but mainly from measurements taken at sea by the fleets or in port sampling programs. The Australian and Japanese fisheries have been well sampled during the 1990s with length measurements taken for between 40% and 60% of the catch on each fishing ground. We have used the Japanese length frequency data for the measured portion of their catch for the fishing grounds around southern Africa, the south-east Indian Ocean, Tasmania and New Zealand (north and south) as well as the Australian catch-at-length data from the GAB for the years 1990-1997. Catch-at-length data for the Korean longline fishery was obtained from data presented at the 1997 CCSBT scientific committee meeting in Canberra (Moon et al., 1997) for the years 1992-96. Although the Korean fleet operated in three areas of the southern oceans (Fig. 1), the data obtained were for all the areas combined. Catch-at-length data for the Taiwanese longline fleet operating in the Indian Ocean was obtained by converting weight frequency data to length frequencies with standard growth curve conversions. The weight frequency distributions were obtained from the logbooks of 29 vessels operating in central Indian Ocean during the winters of 1998 and 1999 (June to September), and three vessels operating south-east of Africa during the summers (November to March) of the same years (Appendix 1 and 2).

The length frequency data obtained for each fishery and fishing ground were not separated by sex. Therefore, it was necessary to estimate the proportion of males to females in each 5-cm length class before age-length keys could be applied. To do this, we used sex ratio data collected by scientific observers aboard Japanese longliners operating in the southern oceans and within the Australian Fishing Zone. Observers collected data on the sex of southern bluefin tuna caught between 1981 and 1996 (n≥50,000). It was assumed that the ratio of males to females in each length class was stable over time, and can be applied to the length frequency distributions obtained for each fishery.

To determine the changes that have occurred in the size composition of SBT caught in the Japanese fishery between the 1980s and 1990s, we compared length frequency data for the years 1980-89 and 1990-97 for each fishing ground in the southern oceans. Although the Japanese fishery was not well sampled during the 1980s with length measurements taken for only 1.3% of the catch (nearly 40,000 fish), we have assumed the data to be representative of the total catch. The length frequency distributions were scaled up to the total number of SBT caught on the respective fishing grounds.

Results

Precision of age estimates

In 44% of cases, blind counts of increment in otoliths were identical, and in 96% of cases the first reading was within two years of the second reading. The IAPE was 4.55% and the CV was 6.43% indicating that the otoliths were interpreted consistently. The IAPE between the primary and secondary readers was 5.51% and the CV was 7.79%. There was no systematic bias between readers (Fig. 2).

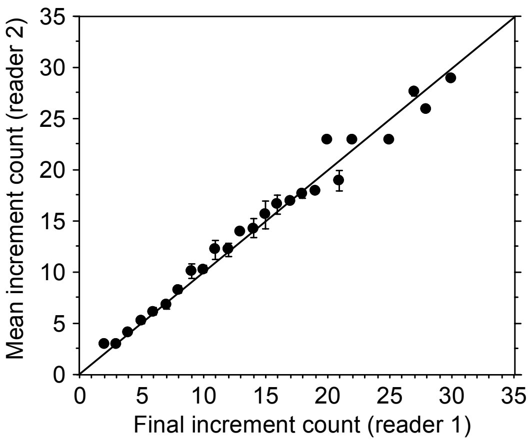

Figure 7.2. Age-bias plot comparing the final increment count by the primary otolith reader with the mean (+/- SE) of increment counts by the secondary otolith reader. The 1:1 line is shown.

Growth between sexes and sex ratio

Large variations in age were detected within length classes, especially above 155 cm FL. For example, fish in the 165 cm length class ranged in age from 9 to 32 years. Mean length-at-age was not significantly different for males and females up to age six years (Table 1). After this age sexual dimorphism in growth is apparent; males are 4.3 cm larger than females at age 10, 7.2 cm larger at age 20, and 9.1 cm larger at age 25. Maximum ages, however, were similar for both sexes with the oldest male aged at 41 years, and female, 38 years.

No significant difference was found in the distribution of ages between male and female SBT (Kolmogorov-Smirnov test $p = 0.202$). In other words, the sex ratio did not change substantially with age. However, data collected by high-seas observers on Japanese longliners suggests that sex ratio does change substantially with length. That is, males outnumbered females in both small (≤105 cm FL) and large (≥175 cm FL) length classes (Table 2). The cause of the bias towards males for small SBT is unclear, but may be related to identification of sex by gross examination of gonads. Schaefer (2001) reported that sex ratios deviating from 1:1 for small tunas is questionable due to misidentification of undeveloped gonads. This misidentification is reduced in larger fish as the gonads develop into distinctive structures. Therefore, we assumed a sex ratio of 1:1 for all size classes up to and including 110 cm FL for the length frequency data obtained by fishing ground. A bias towards males in larger size classes is due to males reaching larger sizes than females.

Spatial variation in age structure

Separate age-length keys were developed for male and female SBT, and applied to the length frequency data for the landed catch of SBT from the Australian, Japanese, Korean and Taiwanese fishing grounds. Unfortunately, sex data was not available for fish aged from the Australian fishery in the GAB. However, these fish were all aged less than four years old. Since sexual dimorphism in growth would not be apparent in these fish, we used the age estimates in both age-length keys.

Estimated age compositions of SBT (Fig. 3) show clear differences between fisheries and fishing grounds. The Australian summer surface fishery in the GAB was dominated by two to four year-old SBT. Similarly, catches by the Taiwanese longline fishery in the central Indian Ocean (winter) and off south-east Africa (summer) were dominated by three and four year-old SBT. Japanese SBT catches in the southern oceans were all dominated by fish ≤ 12 years old (between 84 and 88% of the catch), yet a significant proportion was older than 20 years (Fig. 3). Japanese catches around Tasmania had the greatest proportion of very young fish; over 55% were aged less than fives year old (Fig. 4a). SBT catches by the Korean longline fishery were similar to Japans, although the proportion of fish ≤ 12 years old in the catch was slightly lower (74%). Since it is possible that discarding of young/small fish is uneven among the fishing grounds in the southern oceans, we removed SBT aged less than five years the analysis and grouped the data in age classes. The age composition of Japan's catches around southern Africa, the south-east Indian Ocean and Tasmania were very similar to each other, and comparable to the catches by the Korean fishery (Fig. 4b). On these fishing grounds, approximately 75% of fish caught were 5-12 years old, 15% were 13-20 years old, and 10% were over 20 years old.

Table 7.1. Comparison of mean length-at-age estimated from otoliths for female and male SBT by age class.

Age class (years)	Females			Males			P-value
	Mean FL (cm)	SD	n	Mean FL (cm)	SD	n	
1	82.2	4.79	6	89.0	6.06	4	0.081
2	96.4	6.82	21	99.5	7.29	37	0.122
3	108.8	8.21	81	108.1	7.69	86	0.599
4	116.7	6.93	73	115.4	6.11	80	0.224
5	125.7	6.46	51	125.6	6.85	55	0.959
6	134.8	6.54	52	133.7	7.18	59	0.413
7	139.6	6.01	42	142.8	4.88	44	0.009
8	145.1	6.00	47	148.0	6.44	29	0.052
9	150.8	6.48	34	154.7	5.61	46	0.006
10	155.1	4.57	35	159.4	5.35	28	0.001
11	157.4	4.47	27	163.1	5.11	20	0.000
12	161.9	4.19	23	167.9	6.45	22	0.001
13	165.5	3.93	13	169.5	5.64	17	0.037
14	166.1	5.66	22	173.9	7.59	20	0.001
15	169.6	7.46	11	175.3	6.50	16	0.046
16	172.5	10.45	13	177.3	7.39	22	0.117
17	170.7	5.23	12	179.7	9.68	15	0.007
18	174.5	5.32	6	179.7	6.84	11	0.127
19	171.5	5.95	8	180.2	7.07	13	0.010
20	174.7	7.24	10	181.9	9.15	13	0.053
21	178.8	2.50	4	182.9	7.55	8	0.322
22	174.7	6.17	11	185.0	7.76	15	0.001
23	176.3	5.58	12	188.8	8.91	14	0.000
24	177.4	7.67	9	189.2	6.94	10	0.003
25	178.0	14.64	6	187.1	10.68	9	0.185
26	178.6	7.87	8	187.3	7.52	8	0.042
27	177.0	-	1	182.6	9.09	8	-
28	177.0	11.47	7	189.3	8.62	3	0.138
29	185.7	8.39	3	187.8	8.64	5	0.745
30	183.8	4.79	4	188.6	6.16	7	0.213
31	183.5	20.51	2	191.0	1.41	2	0.657
32	184.0	-	1	194.2	8.70	5	-
33				191.5	4.95	2	-
34	183.0	-	1	184.0	-	1	-
35	194.0	-	1	196.0	-	1	-
36				189.0	-	1	-
37							
38	187.0	-	1				
39							
40							
41				184.0	-	1	-
Total			658			737	

Table 7.2. Sex ratio of SBT sampled by high-seas observers on Japanese longliners operating in the southern oceans and within the Australian Fishing Zone between 1981 and 1996. Sex ratio is expressed as males to females.

Fork length class (cm)	Sex ratio	Number	Fork length class (cm)	Sex ratio	Number
75	1.31	30	145	0.97	1544
80	2.20	96	150	1.04	1468
85	1.62	1779	155	1.13	1214
90	1.92	4653	160	0.85	1227
95	1.65	2896	165	0.78	1507
100	1.33	5477	170	0.94	1785
105	1.28	4935	175	1.68	1537
110	1.08	3837	180	3.00	992
115	1.09	4078	185	4.47	498
120	1.08	3040	190	5.49	266
125	1.01	2565	195	16.20	86
130	0.99	2078	200	8.33	28
135	0.97	1828	205	-	3
140	0.91	1704	210	-	6

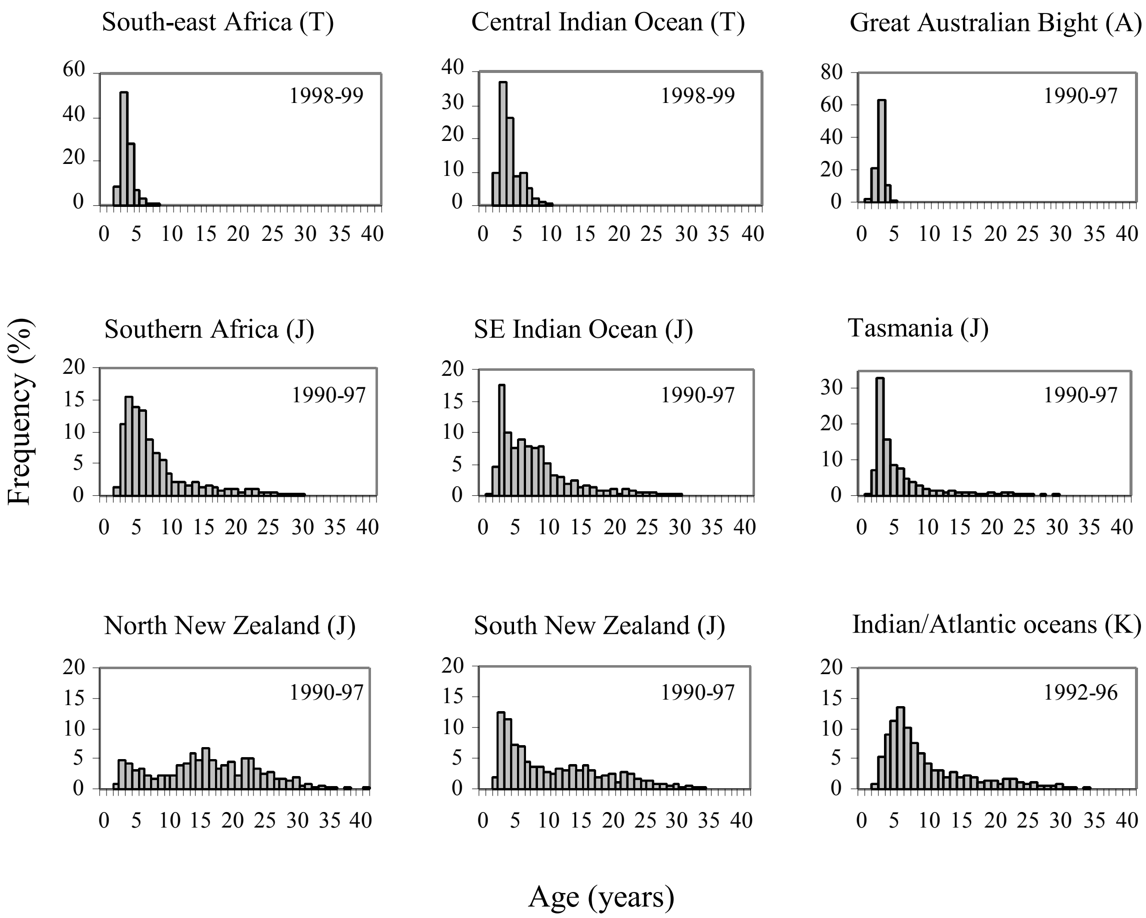

Figure 7.3. Age distributions by fishing grounds of southern bluefin tuna caught by the Australian (A), Japanese (J), Korean (K) and Taiwanese (T) fisheries in the 1990s.

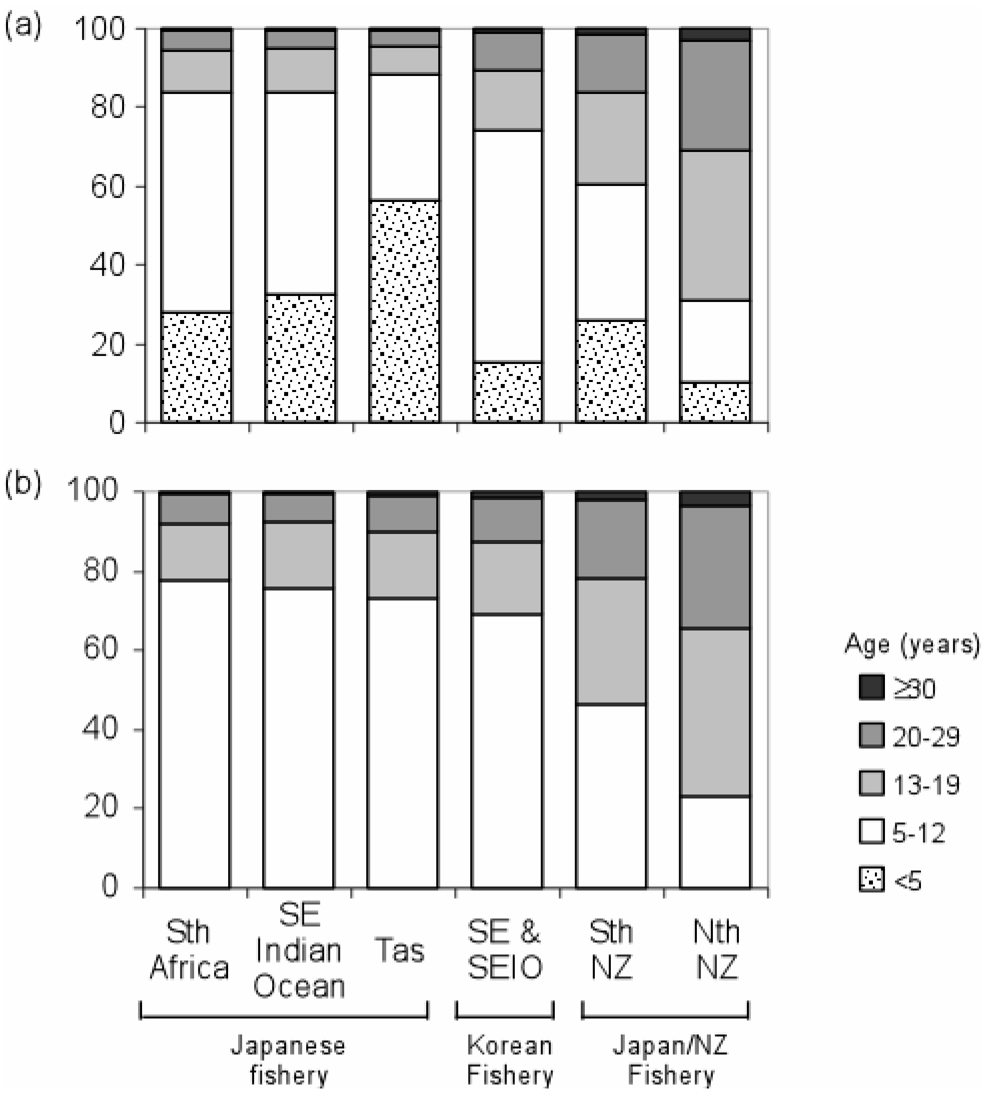

Figure 7.4. Relative abundance of southern bluefin age classes in Japanese, Korean and Japanese/New Zealand (NZ) charter catches in the southern oceans. (a) all age classes; (b) fish aged less than five years removed. Sth – south, Nth – north SE – south-east, Tas = Tasmania, SEIO – south-east Indian Ocean.

The age distribution of SBT caught around New Zealand was different to that on the other Japanese fishing grounds to the west. When juvenile SBT less than five years old were removed from the analysis, the catch around northern New Zealand was dominated by 13-20 year-olds (42%) and >20 year-old (34%), rather than 5-12 year-olds (23%) (Fig. 4a). Although not to the same extent, catches around southern New Zealand were also dominated by mature SBT: 32% were 13-20 years old, and 21% were 20+ years old. Overall, young fish were less abundant in catches in the eastern limits of the SBT range.

Inter-decadal change in size composition

The majority of SBT landed in the Japanese catch were between 70 and 190 cm FL in both the 1980s and 1990s (Fig. 5). However, the mean size of SBT caught decreased from 145.3 cm to 135.4 cm FL between those decades. In the 1980s, the length frequencies show a clear mode between 150-180 cm FL on all grounds except southern Africa where SBT between 120 and 170 cm FL were dominant. A second mode at 100-120 cm FL was present only in the Tasmanian catches. In the 1990s, the incidence in the catch of SBT between 150-180 cm decreased on all grounds and only remained dominant in catches around New Zealand. However, even on these New Zealand grounds the relative proportion of small fish (< 150 cm FL) increased substantially between decades. On the south-east Indian Ocean and Tasmanian grounds, the proportion of small (<150 cm FL) SBT in the catch increased from 34% and 48% in the 1980s to 64% and 81% in the 1990s respectively. The size distribution of SBT caught around southern Africa was similar between decades, although there was a slight shift towards landing smaller (110-125 cm) SBT.

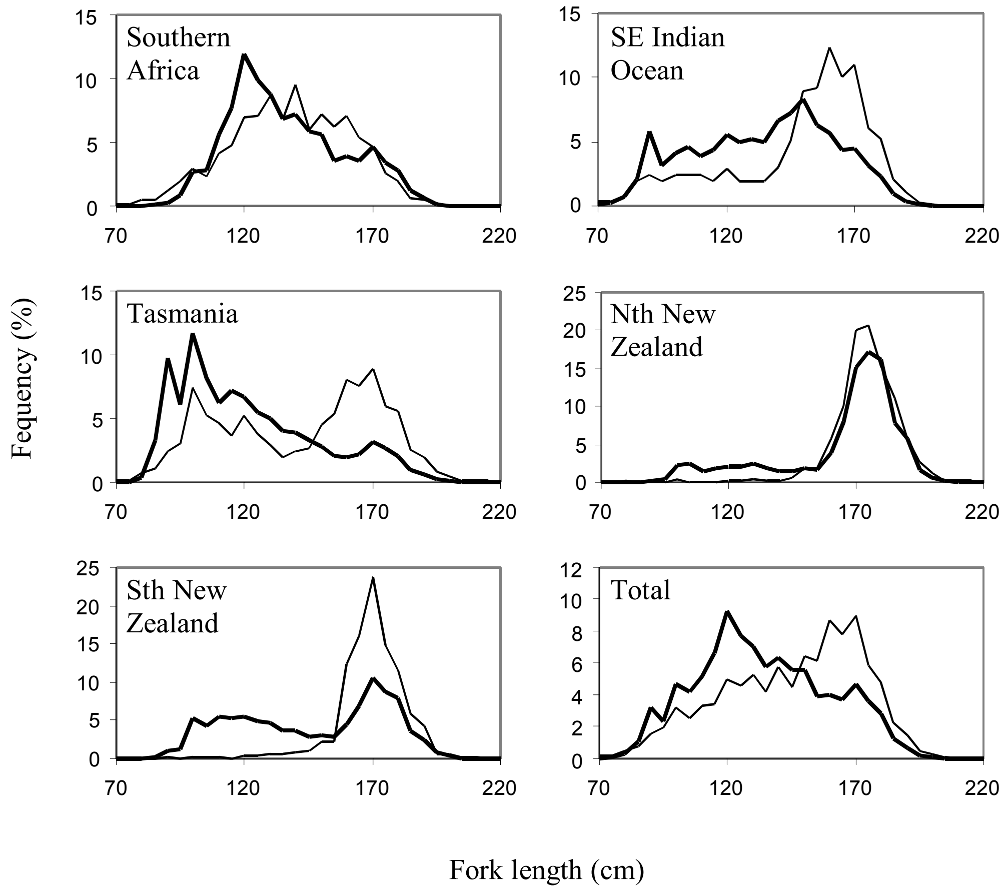

Figure 7.5. Length frequency distributions of southern bluefin tuna caught in the 1980s (thin line) and 1990s (thick line) on each Japanese fishing ground.

Discussion

Sexual dimorphism in growth

Life expectancy is similar for both male and female SBT. However, our study showed that mean length-at-age is greater for males than females after an age of six years, and that males outnumber females in all length classes ≥ 175 cm FL. The cause of this sexual dimorphism is unclear, but is likely to be either age-related differences in mortality and/or sex-related differences in growth. Since the sex ratio of SBT did not change with age (on any fishing ground investigated) the dimorphism is unlikely to be due to differential mortality between fishing grounds or geographical separation of the sexes causing differential growth. The change in the nature of growth at age seven between males and females is probably related to gonad maturation and the onset of sexual maturity. The youngest SBT aged from the spawning ground is eight years old, although very few SBT less than 12 years old are caught (Gunn et al., 1998a).
Gunn et al. (In press) found that larger SBT were more likely to be male than female, and suggested that the dimorphism could be due to the energy costs of high fecundity and long reproductive life for female SBT. Although much of the life history and migration patterns of SBT are unknown, it is likely that males and females have similarly long reproductive lives. Any divergence in growth is, therefore, more likely to be due to higher energy requirements for reproduction (spawning) for females than for males. Schaefer (1996) showed that the average daily cost of spawning for male and female yellowfin tuna (YFT) (*Thunnus albacares*) was 0.28% and 0.97% of the body weight per day respectively. Although yellowfin tuna have a very different life history to SBT, females have similar batch fecundities (68 and 57 oocytes per gram of body weight for YFT and SBT respectively) and spawning frequencies (both spawn approximately once per day) (Schaefer, 1996; Farley and Davis, 1998). If the cost of spawning in SBT is similar to YFT, the greater energy invested by female SBT may explain, to a degree, their lower growth rates after sexual maturity. Since growth in mature SBT occurs predominantly in summer, then the reproductive cost could be very significant at the time growth occurs.

Spatial variations age structure

Southern bluefin tuna is a highly migratory species and its spatial distribution can vary from year to year (Campbell and Tuck, 1996). Estimating catch-at-age from catch-at-length data collected over several years (1990-1997) has the advantage of providing a broad description of the retained portion of the catch on each fishing ground, without introducing bias from short-term fluctuations in distribution. Unfortunately, fishing effort for SBT does not cover the full geographical range of the species or all months of the year. As already mentioned, the Japanese fishery restricted its effort in the 1990s to the second and third quarters of the year (April to October) (Tuck et al., 1996), while the Taiwanese fishery only catches SBT in the central Indian Ocean during winter, and off south-east Africa during summer. Although we can assume that SBT are caught where they are concentrated, the age distribution of SBT found outside the areas and months traditionally fished is unknown. A further weakness of using catch data to determine population age structure is that the effect of targeting or discarding of specific size classes is also unknown. Active discarding of SBT less than 25 kg (four years old) is known to have occurred in the Japanese fishery in 1995 and 1996 (Itoh et al., 1997). In 1995, up to 31.9% of SBT caught each month were discarded from the southern African and south-east Indian Ocean fishing grounds (Betlehem et al., 1996), but the practice was less common on the

Tasmanian fishing ground (Itoh and Tsuji, 1995). Betlehem et al. (1996) suggested that discarding of small SBT may have also occurred earlier in the fishery. In contrast, SBT >25 kg generally fetch higher prices and are therefore more likely to be retained. We suspect that these practices have significantly affected our data, and as a result, our estimated catch-at-age are unlikely to represent the true age structure of the SBT population. Specific information that can be gained on the distribution and migration of juveniles from their relative abundance on high-seas fishing grounds is, therefore, limited.

Given these uncertainties, it is still possible to discuss our results in relation to the traditional migration models proposed for SBT (Shingu, 1978; Hynd, 1969; Nakamura, 1969; Murphy, 1977; Caton, 1991). Our results show that significant variability exists in the age structure of SBT across the southern oceans, which supports to some extent the Shingu's (1978) hypothesis that SBT occupy different areas of the oceans during different stages of their growth and feeding. The low numbers of zero and one year-olds on any fishing ground examined supports the theory that SBT take one year to migrate from the spawning ground to the southern west coast of Australia (Hynd, 1965; Gunn et al., In press) before being caught as two year-olds in the Great Australian Bight (GAB). Although less likely, the absence of very young fish in the catch data could be due to discarding of small fish, or low vulnerability to fishing gear. Two to five year-old SBT, however, were caught on all fishing grounds examined confirming that they are capable of extensive migrations. During the austral summer months (November to March), SBT aged ≤ four years were caught on both sides of the Indian Ocean - in the GAB by the Australians and off south-east Africa by the Taiwanese. The presence of both fisheries at the same time demonstrates that not all juveniles spend summer in the GAB. Murphy (1977; 1981) suggested that there could be a divergent migration path for juveniles which occurs after juveniles have reached the south-west coast of Australia – some migrate east and others west. Tagging experiments also support this theory. Ishizuku (1987) showed that fish that were tagged off Albany (Western Australia) were recovered in higher percentages around southern Africa and the central Indian Ocean than in the GAB and New South Wales. Harden Jones (1984) suggested that there could be two migration routes for larvae and juvenile SBT from the spawning ground - one with the Leeuwin current along the Western Australian coast and into the GAB, and the other with the southern Indian Ocean gyre anticlockwise to Africa. Although fishing effort has been extensive in the Indian Ocean over the past few decades, there has been no confirmed catches of larval or juvenile SBT west of the spawning ground.

Results of recent archival tagging studies have shown that a large proportion of three and four year-old SBT tagged in the GAB during the summer undertake seasonal cyclic migrations out into the Indian Ocean to feed during winter before returning to the GAB in early spring (Gunn et al., In prep; Sainsbury et al., 1999). The catch of three and four year-old SBT across the central Indian Ocean by the Taiwanese fleet during the austral winter is consistent with these results. It is unknown, however, if all SBT caught in the central Indian Ocean during winter have migrated from, or would have returned to, the GAB. It is possible that the juveniles caught off south-east Africa by the Taiwanese during summer also undertake cyclic migrations to the central Indian Ocean during winter. The absence of Taiwanese vessels catching small SBT off south-east Africa during winter suggests that the fish must move elsewhere during those months.

The areas where the Taiwanese longliners target juvenile SBT is along the sub-tropical convergence zone (STCZ), and where the STCZ meets the Agulhas current. Both the Agulhas current and the STCZ are thought to play an important role in the distribution and concentration of SBT (Warashina et al., 1989). The presence of juvenile SBT on all fishing grounds in the southern oceans demonstrates that these fish are not limited to warm waters. Southern bluefin tuna, like all tuna, have the ability to control their body temperature to some extent by reducing heat loss to the environment through a highly evolved counter-current circulation system. Enhanced thermoregulation allows larger size classes to forage in areas of increased productivity on the southern extremities of the sub-tropical convergence zone. Although a few SBT as old as 7 are caught in the Taiwanese fishery, it appears that adult SBT do not generally forage this far north.

Archival tag data also show that juveniles tagged in the GAB migrate well into the southern Indian Ocean (south of 40°S) and east to Tasmania, before returning to the GAB (Gunn et al., In prep). This may explain to some extent the high proportion of very young SBT (less than five years old) in the Japanese catches on the fishing grounds around the south-east Indian Ocean, Tasmanian and southern New Zealand during winter. The highest abundance of these young fish in catches around Tasmania, suggests that a greater proportion migrate east from the GAB rather than west into the south-east Indian Ocean. However, we suspect that much of the variation in the proportion of SBT less than five years old (25 kg fish) in catches across the Japanese fishing grounds is related to discarding practices, and may not indicate the true distribution and abundance of these age classes within the population. When SBT less than five years old were removed from the analysis, the age distribution of SBT caught around southern Africa, the south-east Indian Ocean and Tasmania were very similar, and comparable to the age distribution of the Korean fishery. Similarities between the Japanese and Korean catches are not surprising since the Korean catch data were obtained from three fishing grounds which correspond almost exactly to the Japanese fishing grounds around southern Africa and the south-east Indian Ocean. The similar age structures suggest that SBT may form one well-mixed population rather than several independent groups.

The age distribution of SBT in catches around northern and southern New Zealand are different to the western fishing grounds; the majority were of spawning age. This suggests that only a small proportion of young non-spawning fish cross the Tasman Sea after reaching Tasmania, and even fewer migrate north to the northern New Zealand ground. This decrease in juvenile abundance around New Zealand is not surprising since New Zealand lies at the eastern edge of the geographical range of SBT. Unfortunately, data is not available for the size/age distribution of SBT caught in the western extent of their range (in the Atlantic Ocean).

Inter-decadal variation size composition

There have been significant changes in the general size structure of SBT caught in the Japanese fishery since exploitation began. In the 1960s, the size of fish caught ranged from 80 to 180 cm FL, with a dominant mode between 140-160 cm FL (Hisada et al., 1979). By the 1970s, the number of SBT caught in the Japanese fishery had decreased dramatically, but the size distribution remained constant (Nishida, 1993). Our results for the 1980s are similar to those presented by Nishida (1993) and confirm that by this decade, the dominant mode of SBT caught had increased to between 150-180 cm FL. Since then, there appears to have been an increase in the relative abundance of small SBT (<150 cm FL) retained in the catches. That is, in the 1990s there was an increase in the ratio of small to large fish caught in the Japanese fishery.

An increase in the proportion of the catch consisting of small SBT in the 1990s was seen, to some extent, on all Japanese fishing grounds examined in our study. There are several possible explanations for this change such as: increased abundance of juveniles in the population; changed targeting and retention practices; or decreased abundance of adults. Increased abundance of juvenile fish in the 1990s might be expected given the introduction of effective quotas in the early 1990s and subsequent reduction in the catch of juveniles by the Australian surface fishery. Betlehem et al. (1996) show that the increase in juvenile catch rates began in the waters around Tasmania in the late 1980s, followed by New Zealand and the south-east Indian Ocean in 1990. This could be seen as increased numbers of juveniles escaping from the Australian surface fishery in the GAB. Betlehem et al. (1996), however, also indicate that the increased catch rates of juveniles may not be directly related to abundance because of possible increases in the catchability of young fish due to increased growth rates in the 1970s (if recruitment to the longline fishery was size rather than age dependent). Recent stock assessment analyses for SBT have indicated that recruitment of juveniles did not increase between 1988 and 1992 (the most recent year analysed) (Polacheck and Preece, 1998), while aerial survey data indicated that recruitment has remained low since that time (Cowling and Millar, 1998).

Increased targeting of small SBT may explain the changes in the size composition of SBT in Japanese catches. Increases in the relative abundance of small fish around New Zealand were reported when Japanese longliners began fishing off the south and south-west coasts of the south Island in the early 1990s (Bradford et al., 1996). A similar trend occurred in both the New Zealand charter fleet and domestic fishery. The small but significant increase in the proportion of SBT <150 cm in the catches north of New Zealand, however, suggests that a shift in fishing area does not fully explain the increased catches of small SBT around New Zealand. Changes in the fishing season on the ground around Tasmania can explain to some extent the decreased catch of large SBT. At the end of the 1980s, effort by the Japanese fishery shifted from quarters 1 and 4 (summer) to quarters 2 and 3 (winter) (Tuck et al., 1996). Since large SBT have historically been caught during summer off southern Tasmania (Caton, 1991), the temporal shift in effort could account for the decreased catches.

It is impossible to determine the extent to which discarding/retention practices have changed within the Japanese fleet between decades. The only data available, as already discussed, are for 1995 and 1996 when there was active discarding of SBT less than 25 kg (Bethlehem et al., 1996). In a quota-managed fishery, however, increased targeting or retention of small fish (which are worth less) may indicate low abundance of large size classes. It has been well documented that parental stocks of SBT are considered depleted (Caton et al., 1990; Anonymous, 1994). Virtual Population Analysis estimates of parental biomass show a decline to less than 10% of the original level (Anonymous, 1996). Reduced catches of adults are consistent with the effects expected from increased exploitation.

Our estimate for the mean size of SBT caught in the Japanese fishery in the 1990s (135.4 cm FL) is higher than that by Nishida (1993) (128.9 cm FL). Since our estimates were for

1990-1997, and Nishida's (1993) were for 1990-1993, the results suggest that small SBT were more abundant in the population (or there was greater targeting or retention of small fish) during the early part of the decade. Since we know that small SBT were actively discarded in 1995 and 1996, it is likely that discarding/retention practices play an important role in the size composition of Japanese catches.

Stock structure

Inferences that can be made on the stock structure of SBT from comparisons of age frequencies between fishing grounds or length frequencies over time are limited because the composition of the landed catch does not fully represent the wild population. Given this, our study does indicate that the size structure of the SBT community has shifted: small fish made up a much larger percentage of the catch in the 1990s than they did in the 1980s. Surprisingly, however, this change was less apparent on the fishing ground around southern Africa, where fishing pressure by the Japanese has been greatest. The absence of a shortening of the size distribution of SBT caught on this ground between decades suggests that migration into the area is sufficient to counter the effect of local overfishing, and that these fish do not form a separate population.

Our results are consistent with other non-genetic studies investigating the stock structure of SBT. Otolith microchemistry work suggested a single spawning ground for SBT, and could not identify separate migration routes for juveniles to the 'isolated' feeding grounds in the southern oceans (Proctor et al., 1995). Tagging experiments conducted in the 1990s demonstrated that juvenile SBT are capable of moving rapidly around southern Australia, or from Australian waters as far west as southern Africa or east to New Zealand (Preece and Polacheck, 1998). However, since only small numbers of SBT have been tagged outside Australia, and there has been no adult tagging, it is difficult to draw conclusions about their mixing or movement between feeding grounds in the southern oceans.

Acknowledgments

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Appendix 7.1 Travel Report – Mauritius 8-21 October 1997 Taiwanese longlining activities in the Indian Ocean and their SBT catch

John Gunn
Jessica Farley

Background

A FRDC-funded project examining the age composition of catches from each of the major SBT fisheries (Japanese, Indonesian, Australian, New Zealand and hopefully also Taiwanese and Korean) provided funds for us to travel to Mauritius in October 1997. The core objective of the trip was to collect otoliths from a representative sample of the Taiwanese SBT catch, from which we could estimate the age composition of the catch. In addition we aimed to collect basic information on the fishing activities of Taiwanese longliners operating in the SW and Central Indian Ocean and confirm the extent and nature of their SBT "fishery".

During the 1990s, Mauritius has become a major port for transhipment of Taiwanese longline catches of sashimi-grade fish to carrier boats destined for Japan. In November 1996, CSIRO Division of Marine Research scientist Wade Whitelaw visited Mauritius and learned that as part of their access agreement with Mauritius, Taiwanese vessels are required to complete a log-book providing details of their catch, fishing area etc. According to these logbooks since 1993 200-300 Taiwanese longliners have used Mauritius each year as a revictualling and transhipping port, albacore is the dominant catch of these vessels and in 1996, a total of only 847kg of SBT were reported caught.

Over the months prior to our travel we had extensive correspondence and discussions with the Taiwan Deep Sea Tuna Boatowners and Exporters Association. The Association is the peak industry body for Taiwan's high seas tuna fleet and their correspondence included reports of catches of SBT in the area south east of Mauritus, details of tag returns from vessels fishing in this area, and confirmation that the vessels catching SBT used Mauritius for transhipping. While the Association was extremely helpful in providing background information and volunteering support, they were unable to guarantee the co-operation of vessel owners and skippers for our otolith sampling, or provide details of how many vessels may be in Mauritius during our stay.

With little to go on other than the Mauritian logbook data which indicated that the peak period for transhipping was during September-October, we chose a two week period in early October, in the hope that there would be longliners in port and that through effective liaison we could gain the support of owners, skippers and local agents.

We landed in Mauritius on 8 October and travelled by taxi from the airport to Pt Louis. Pt Louis is a bustling free port nestled into a natural harbour on the western shore of the island. As we hurtled down the freeway into the city, at the end of what had been an hour-long, life threatening drive (Mauritian taxi drivers are a definite worry!), our view was of a bay choked with more than 80 Taiwanese longliners. They were tied three-to-four deep along the wharves and in rafts ten-deep out in the harbour. Our hotel was full of Taiwanese skippers and vessel owners!

Over the following two weeks, the major shipping agents involved with the Taiwanese fleet very generously provided their time, resources, interpreters and goodwill as we made contact with owners, skippers and crews of the vessels. We also had considerable support from the Mauritian Fisheries Research Agency. The report below is a general summary of our findings. Full details of contacts, vessels, tag data and Mauritian highlights can be obtained from the authors.

Taiwanese longline fisheries in the Southern Indian Ocean

General trends in the fleet

Agents and skippers reported that during the 1980s the Taiwanese fleets of gillnetters and longliners that targeted albacore across the Indian Ocean moved north - south with the seasonal movement of the sub-tropical convergence zone (STCZ). They offloaded into cold stores and/or onto carrier boats in Cape Town, Mauritius, Singapore and to a lesser extent some of the east African ports. High seas transhipping of albacore was also common.

Over this period Taiwanese vessels visited Mauritius throughout the year. There was very little transhipping in the port, albacore was by far the dominant species offloaded and by-catch of other tuna species and billfish was either sent to canneries or, in the case of swordfish, to Europe.

During the 1980s the Taiwanese longliners consisted mostly of vessels of less than 400 tonnes which were capable of only minus 20-30°C freezing.

Following the demise of gillnetting, there has been a very rapid expansion of the Taiwanese longline fleet and a steady increase in the size of vessels within the fleet. No-one we interviewed knew the number of Taiwanese longline vessels current ly operating in the Indian Ocean, although one English-speaking vessel owner estimated the number to be in excess of 300. The owners of vessels form the “Indian Ocean Committee” of the Taiwan Deep Sea Tuna Boatowners and Exporters Association. By all accounts, this committee represents a major fraction of the Association.

The growth of Mauritius as a transhipping port for the Taiwanese fleet:

Throughout the 1990s, Mauritius has become the major port for the Taiwanese fleet - 200-250 Taiwanese longliners now use Mauritius each year. The increased use of Mauritius by the fleet is due to the fact that

- Mauritius lies central to the fleets’ two major autumn/winter fishing grounds, (one south of Madagascar and the other SE of Mauritius).

- Mauritius (at latitude 20°S) represents a convenient mid-point for vessels moving from autumn/winter fishing grounds at latitudes 30-35°S to tropical latitudes during spring/summer.
- As more longliners concentrate on sashimi, which needs to be transhipped to large carrier vessels, centralising transhipping in one port offers significant economic advantages.

With the increased use of Mauritius, there has been a reduction in traffic through Cape Town and other African ports. We heard contradictory views on the use of Singapore by the Taiwanese fleet - ranging from it still being a major transhipping port for vessels fishing the summer season in the tropical NW and Central Indian Ocean, to it gradually becoming less and less important. Very few Taiwanese vessels return to Taiwan at the end of fishing campaigns. Economics, problems with crews, and a general philosophy among the owners leave the boats away from Taiwan for up to five years. Skippers and senior crews fly their families to transhipping ports such as Mauritius for a few weeks. Crews tend to stick it out for as long as they can and then jump ship!

In addition to its geographic advantages, Mauritius has recently developed a large free port at Pt. Louis (a la Singapore) in an attempt to attract business into the country. The free port features modern facilities, dry docks, a number of very efficient shipping agents, and the advantages of a tax free environment for trading and vessel operations. From the fisheries perspective, large cold stores have been built and are already being extended, and more are in advanced stages of planning. While industrial problems in the mid 1990s, which resulted in the draining of fuel stores on the island, damaged the Pt Louis' standing among the Taiwanese fleet, it seems from the numbers of vessels in port this year, that all has been forgiven.

All sashimi-grade fish caught by the Taiwanese are transhipped onto Japanese carrier boats in the harbour, rather than being unloaded at the wharf like albacore and other species not destined for Japan. The carrier vessels run under various flags (Panama being the most common on vessels we saw), but are run by Japanese companies and crewed by Japanese and an assortment of Filipinos and Indonesians. Carrier boast we boarded had capacities in the order of 3-5,000 tonnes. There were six anchored up outside the harbour over the two weeks we were in town.

The large cold stores in Pt Louis are used for storing albacore destined for canning overseas eg. Starkist in Central America imported 7000 tonnes of Indian Ocean albacore landed in Mauritius last year. There is also a small cannery in Pt Louis that cans skipjack and yellowfin caught in the tropical Indian Ocean. While we were in town a large purse seiner run by a French fishing company offloaded 2,000 tonnes of skipjack and yellowfin caught south of the Seychelles into the cannery.

Vessel characteristics

As noted above, there has been a rapid increase in the size and fishing power of the Taiwanese fishing fleet over the last decade. The larger vessels range from 500-1000 tonnes. They are purpose-built, Japanese-style longliners, equipped with minus 60°C freezers, satellite communications and advanced electronic fishing aids. Presumably these vessels are capable of fishing further south, but under their current fishing strategies chose to concentrate their activities in the tropical and sub-tropical latitudes around the SCTZ.

Figure 1. The Ying Hua Hsiang No 3. Tied up in Pt Louis harbour after offloading her albacore catch. The vessel is typical of the larger class of Taiwanese longliner fishing in the Indian Ocean.

Fishing practices

Vessel crews comprise Taiwanese officers and engineers and a mixture of Filipino and main land Chinese seamen. Very few Taiwanese and none of the Chinese fishermen spoke English; the Filipinos had a mixed level of English, but generally each boat had at least one crew member with whom we could converse.

Most of the larger classes of vessels appeared very new whereas many of the 400-tonne vessels looked to be on their last legs. Vessel owners gave the impression that the economic viability of their vessels was marginal, and that it was unlikely that they would upgrade their boats while there was an oversupply of frozen sashimi-grade tuna on the Japanese market. They all complained of the prices Taiwanese vessels got for their sashimi product, one owner going so far as to say he thought the Taiwanese were being ripped off. The suggestion made was that his SBT, which were fetching less than 800 yen per kilo, were resold on to the Taiwanese market at drastically inflated prices!

Food and conditions on board the larger class of vessels appears to be very good. One owner we interviewed told of the reaction of mainland Chinese crews when they joined the vessels. Accustomed to plain rice and very little meat in their homeland, the mixed meat, fish and vegetable meals on the longliners results in them gaining 5-10 kg within the first month or so of a trip!

Taiwanese catches of SBT

Throughout the period that SBT are caught albacore remain the dominant catch (by weight and number). However, SBT are often caught in larger numbers than the target bigeye and yellowfin. “Yuchuan”, as SBT are called by the Taiwanese skippers, is not seen as a highly desirable catch by the skippers, principally because of its relatively low value. Recent data on the prices for Taiwanese frozen SBT from the Indian Ocean range from 750-900 yen per kg.

Figure 2. Taiwanese longliner transshipping sashimi grade tuna and billfish to a carrier vessel.

The SBT caught by the Taiwanese in the central Indian Ocean are predominantly immature fish, less than 40 kg GG, or 140 cm LCF. Fig. 3 shows the size and weight distributions of fish from a small sample of the catches. These data were collected either from direct measurements of the fish as they were being transhipped (Fig. 4) or from data collected from vessel log books. The Taiwanese record the weight of every sashimi-grade tuna they catch and these are recorded in the skippers personal log. The dominant age classes in the catch are the 4-6 year olds, with very few fish over the age of 8 years among the samples. All the skippers interviewed described a range of sizes for the SBT they had caught similar to those given in Fig. 3.

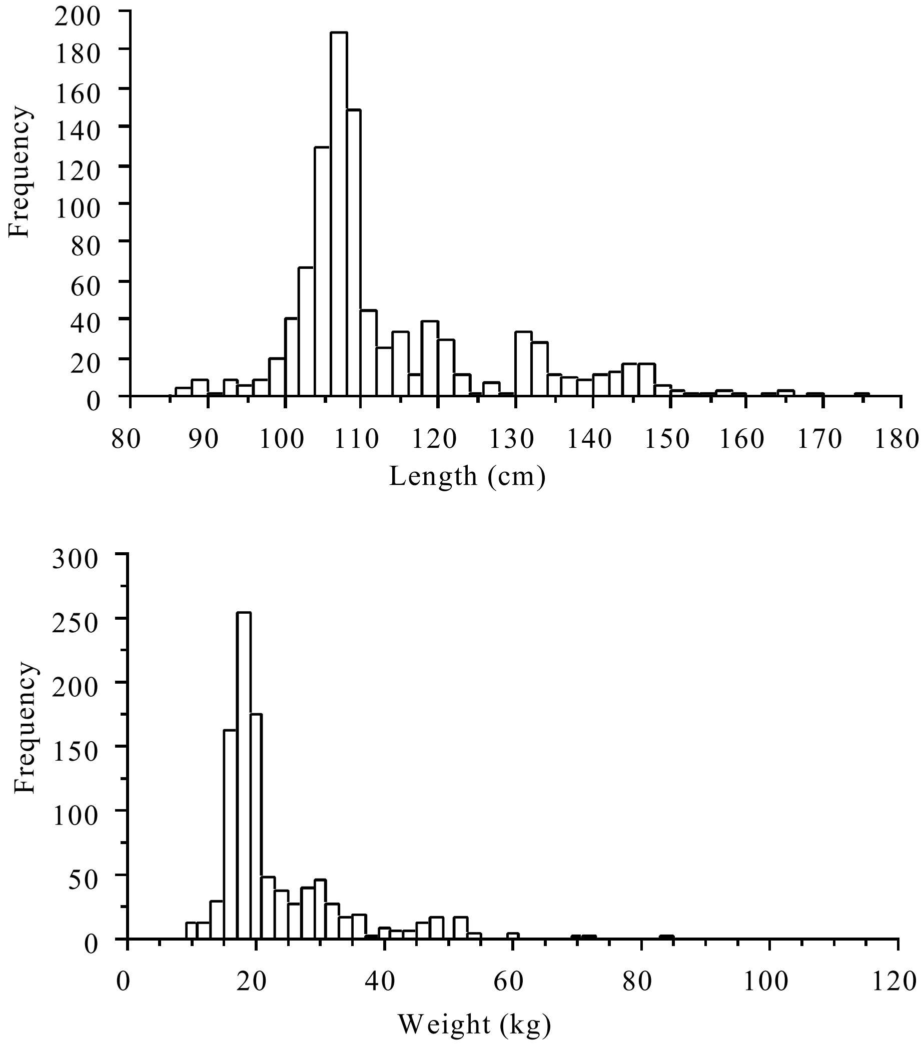

Figure 3. Length and weight frequency distributions of SBT caught by Taiwanese longliners in the southern Indian Ocean.

Skippers also told us of catching SBT less than 8-10 kg from time to time. 10 kg is the lower limit to the smallest size class of retained catch. Tuna smaller than this are released. One skipper recalled seeing surface schools of small SBT during August this year, but this is apparently not a common occurrence.

Large SBT (>100kg) are caught very infrequently. More common are the odd northern Pacific and Atlantic bluefin, up to 350 kg. Although bigeye range in size from <20 kg to >100kg, the bulk of the catch in vessels observed and catch records is less than 60kg.

Swordfish data was not collected. However, they are a common and valued catch component. Carcass lengths ranged from approximately 100-300 cm. The skipper of one vessel and owner of another remarked on a drop in the average size of swordfish caught in the Indian Ocean, and asked if we knew why this might be the case!

Fig 4 Direct measurement of SBT during transhippment from a Taiwanese longliner to a Japanese carrier boat.

Tag recaptures and liaison

During our interviews with vessels skippers and crews it was clear that many SBT tags had been caught and discarded. We collected 17 conventional tags and one archival tag from vessels, but for every tag returned there were accounts of at least 5 being discarded. Few vessels had heard of the tagging program, and even if the skippers were aware that tags should be kept, the crews were not. We distributed tagging posters to all vessels we visited and left piles of the same and reward T-shirts with agents who volunteered to assist us. Similarly we have suggested to the Boatowners Association that they might be able to assist by including the tagging information in their regular information circulars.

There was a great deal of interest shown in the results of the tagging program, particularly the data from archival tags. The fleet will visit Mauritius again in May-June next year, before heading on to the winter (SBT) fishing grounds. This would be an excellent opportunity to circulate the latest information on the SBT tagging and research throughout the fleet and to promote tag recovery.

Port Developments and Future Ties with Mauritius

Development of freezer facilities in Pt Louis

We heard, from more than one source, that the sahsimi-grade fish exported to Japan from the Taiwanese Indian Ocean catch brings very low prices. Hung Min Shipping Agency, one of the largest agents dealing with the Taiwanese fleet, has recently begun development of a very large cold store facility in the Pt Louis Free Port. Designed to hold 2000+ tonnes of sahsimi-grade product at -60°C, and more than double this at -30°C, the cold store will include a large processing facility. The plan is to process product such as SBT and bigeye before selling on to the Japanese and Taiwanese markets. Hung Min have a Japanese partner in the venture, which is due to begin processing before next September-October.

The cold store will provide ready access to sashimi-grade tunas such as SBT and bigeye which should in turn allow us to collect size data on a much larger sample of the Taiwanese catches in the future. As was the case with so many of our interactions with Mauritian authorities, Hung Min offered access to the cold store next year and assistance with the tag recover, sampling and size monitoring programs.

Future work in Mauritius and ties with Mauritian Fisheries.

The information we collected over a two week period, the co-operation of the local business and government officials and the growing importance of Taiwanese catches in the global SBT picture suggest that it will be possible to develop a monitoring program in Mauritius over the next 12-18 months.

Appendix 7.2 Travel Report – Mauritius 21 September – 9 October 1998. Taiwanese longlining activities in the Indian Ocean and their SBT catch

Jessica Farley
John Gunn
Ann Preece

Background / Introduction

Catches of SBT by non-CCSBT signatories are now estimated to account for one third of the global catch of the species. If left uncontrolled, these "third-party" catches are considered a major threat to both the long-term chances of recovery and the short-term viability of the stock.

In recent years, Indonesia, Korea and Taiwan have provided the CCSBT with estimates of their SBT catches. Indonesian data are collected through a collaborative Australian-Indonesian monitoring program and are considered reasonably accurate. However, SBT catch data from Taiwan and Korea are based on rudimentary analyses of national fisheries databases. Scientists from these countries openly acknowledge that their data are unverified and generally open to question. As SBT are considered a by-catch, rather than target species, of Taiwanese longline fisheries, little effort is put into improving the quality of catch data, or providing reliable effort data. These acknowledged problems, coupled with significant discrepancies between import statistics and reported catches and a basic lack of confidence in the data collection systems in both Korea and Taiwan, create significant uncertainties in how the CCSBT account for the 30+% of the global catch of SBT.

Since 1994, in lieu of data to the contrary, the CCSBT Scientific Committee has assumed that Korean and Taiwanese catch statistics are accurate and that the size and age composition of their catches are the same as those for the Japanese Indian Ocean fleet. The population assessment models developed by the CCSBT/SC incorporate these assumptions. Similarly, models built to determine the likelihood of recovery of the stock under various catch scenarios are dependent on assumptions of third party catches. Presently these models suggest that the probability of recovery is less than 25% on 1997 catch levels.

CSIRO's validation of Taiwanese catch data

Over the last five years Taiwan has increased its SBT catch by an order of magnitude, from a few hundred tonnes to 1600 tonnes in 1996. The reported catch dropped to 800 tonnes in 1997 (due to changes in targeting practices according to the Taiwanese industry), only to bounce back again in 1998 – 800 tonnes have been sold on the Japanese market in the first half of the year. Given our concerns about the accuracy of Taiwanese catch data, CSIRO began developing collaborative links with Taiwanese scientists, fishery managers and industry in 1997. The objective was to promote returns from our large tagging programs during the 1990s, to verify catch data and, if at all possible, to determine the size/age composition of the Taiwanese SBT catch. After establishing links through correspondence and CCSBT meetings, CSIRO scientists travelled to Mauritius in October 1997 to observe transhipping operations of Taiwanese Indian Ocean longliners (Gunn and Farley (1997) report on the findings of this trip). This trip proved exceptionally successful both in terms of the data collected and the network establish in Mauritius and Taiwan. As a follow-up to the Mauritian fieldwork, Gunn and Farley travelled to Taiwan in March 1998, to report on the data collected in Mauritius and to discuss the potential for further collaboration between Australia and Taiwan on SBT catch, effort and biological data. In Taiwan, Gunn and Farley met senior representatives from the Taiwan Deep Sea Tuna Boatowners and Exporters Association, the Council of Agriculture (COA) Marine Fisheries Division, and the Overseas Fisheries Development Council (OFDC). The outcome of the CSIRO presentations and discussions was a commitment from all sectors in Taiwan to assist and collaborate in further investigations by CSIRO into the Taiwanese catch of SBT.

The significance of Taiwanese activities in the Indian Ocean relates not only to the level of catches, but also to their CPUE. Given recent moves by Japan to develop an EFP to test competing hypotheses on the distribution of SBT in areas not currently fished by the Japanese fleet, CPUE data for the Taiwanese fishery in the Central Indian Ocean will provide an invaluable additional source of information on the distribution and variability in catch rates of SBT in Areas 2 and 8. Discussions between CSIRO and the Taiwanese Overseas Fishery Development Council in March opened the door to collaborative analyses of the Taiwanese SBT data we collect in Mauritius and Cape Town, along with data they collate from the Taiwanese logbook system. From this collaboration we would aim to validate estimates of SBT CPUE for the Taiwanese fleets operating in the Indian, and possibly also the South Atlantic Oceans. This would be an invaluable independent source of data with which to evaluate some of the hypotheses currently being used by Japan to justify their EFP.

In October 1998 we spent 3 weeks boarding Taiwanese vessels, interviewing skippers, crews, owners, shipping agents and Mauritian Fisheries staff. This report provides details of the information and data we collected on Taiwanese fishing activities in the Indian Ocean and their catch of SBT.

We gratefully acknowledge the assistance of the Taiwan Deep Sea Tuna Boatowners and Exporters Association, who this year sent one of their staff, Simon Lee, to assist us in our investigations. Simon helped with interpreting and his rapport with many of the owners and skippers helped considerably in our efforts to collect data and “get to know” the fleet. We were welcomed by all but a very small minority of vessel crew and much of what we have achieved is a direct result of the co-operation we received.

Taiwanese longline fisheries in the southern Indian Ocean

During our three weeks in Mauritius, we interviewed the captains, owners or crewman of 74 Taiwanese longline vessels. A further 54 vessels are known to have already unloaded in Mauritius, or were expected to arrive soon. No-one we interviewed was able to tell us the total number of vessels that would unload in Mauritius, nor how many were operating in the Indian Ocean. The captain of one vessel thought that there were 30 albacore and 55 sashimi vessels fishing around 60 to 90ºE (central Indian Ocean) during the winter season. Another said that the majority of vessels fished south-east of Africa and only 50 vessels were in the central Indian Ocean. Previous estimates of the total number of Taiwanese longliners operating in the Indian Ocean, based on reports from the Taiwanese industry association, have been in excess of 300 vessels.

According to several people, the Taiwanese fleet still uses Singapore and Cape Town as revictualling and transhipping ports. Vessels operating in the northern hemisphere during the summer months may unload in either Singapore or Mauritius, depending on which is closer and where they plan to fish next. The proximity of a canning factory in Thailand makes Singapore an attractive port to albacore vessels. According to one of the shipping agents in Mauritius, many Taiwanese vessels (presumably with SBT) also unload in Cape Town after the winter season, instead of traveling to Mauritius. We were also told that SBT are transhipped in Cape Town towards the end of the summer season (Nov to Mar) by vessels operating off southern Africa.

Transhipping in Mauritius

Mauritius has become a major port for the Taiwanese fleet operating in the Indian Ocean. The reasons for this, as indicated out in the 1997 Mauritius Travel Report, are because:

- Mauritius is located close to the fleet's major winter fishing grounds in the southern Indian Ocean.
- Mauritius (at latitude 20°S) is a convenient mid-point for vessels moving between the winter ground (30-40°S) to the tropical latitudes during summer.
- There are economic advantages in vessels concentrating in a single port to tranship sashimi onto larger carrier vessels.

Vessels calling into Mauritius at the end of the winter season may stay in port for up to a month, during which time they unload and revictual. Because vessels do not unload their entire catch at a one place, unloading may take several days. The majority of vessels unload albacore (and other species not destined for Japan) into cold stores or onto large albacore carrier vessels within the harbour. Some vessels, however, unload the non-tuna or billfish species onto Taiwanese owned carrier vessels in the outer harbour. Longliners with sashimi-grade fish (bigeye, swordfish, SBT as well as sharks and shark fins) then tranship onto Japanese carriers also in the outer harbour. There were 3 Japanese carrier vessels either in or due into port while we were in Mauritius, and a similar number of Taiwanese carriers. It usually takes 4 to 6 weeks for the sashimi-grade fish to arrive on the Japanese markets.

Not all sashimi-grade fish caught by the Taiwanese were transhipped onto Japanese carrier vessels in the outer harbour. This year we saw several vessels (from the same company) unloading their sashimi-grade fish at the wharf. These fish were loaded into low temperature shipping containers to be shipped to Japan. Although this practice is more expensive than transhipping, the fish arrive on the Japanese markets much earlier than the bulk of the fish from the Indian Ocean, and therefore attract better prices. It was also suggested that these longliners had not booked a birth on the sashimi carrier vessel and were not prepared to wait for the next carrier to arrive.

Transhipment of Taiwanese catches also occurs on the high seas – although no-one was able to tell us the number of vessels that do this, or where it occurs. Two vessels we interviewed had spent 10 and 18 months respectively at sea (transhipping on average every two months), before calling into Mauritius. Transhipping at sea enables vessels to continue fishing and also allows vessels without ultra-low temperature freezers to tranship their catches of sashimi-grade fish sooner. The high port fees were also mentioned as another factor preventing some vessels from calling into Mauritius. Transhipment also occurs between longliners in the outer harbour of Mauritius, even between vessels from different companies if the owners are good friends. This can occur if the port is full or if the owner cannot afford the port fees. We saw many longliners anchored in the outer harbour, presumably waiting for a birth to become available or waiting to leave after unloading.

Vessel characteristics and fishing areas

Taiwanese longliners operating in the Indian Ocean can be classed as albacore, sashimi or 'mixed' vessels, depending on their target species and line configurations. SBT is seen as a by-catch of the albacore fishery, although the sashimi vessels also catch SBT in some areas. Vessels targeting albacore are usually the smaller CT6 longliners (<600 t), although many of the larger CT7 (>600 t) vessels also target albacore. The CT7 vessels are presumably capable of fishing further south, but choose not to because of the harsh weather and cold temperatures. We were told that Taiwanese vessels are not equipped with heaters, just air-conditioners! Some vessels indicated that they do not target any species. It is difficult to judge whether this is the case, although it is clear that vessels change areas of operation and target species on a seasonal basis. This involves significant changes in gear configuration and bait.

The majority of Taiwanese longliners from which we obtained data had fished in the southern Indian Ocean from June to August/September. The exact time that vessels move to the southern fishing grounds is unknown. Apparently the smaller albacore vessels start to move south as early as December and bunker in Mauritius. It is unclear if these vessels stay in the port, or fish around Mauritius for a couple of months before heading further south in May or June. The larger sashimi vessels wait until February or March before moving south. Some of these vessels may bunker in Mauritius while others go straight to the southern fishing grounds.

Two grounds are predominantly fished during the winter season in the southern hemisphere, as seen in Figure 1. The first is a relatively restricted area south-east of Africa between 35-50ºE and 28-40ºS The target species in this area are swordfish and bigeye, although albacore and yellowfin are also caught. We interviewed two sashimi vessels that had caught SBT in this area, both east of 42ºE. We also found one vessel that targeted sailfish north of this area at 20ºS. A few vessels indicated that they would return to the same area south of Madagascar to continue to target swordfish and bigeye during the summer months.

The other major area fished by the Taiwanese fleet during winter is in a long band in the central Indian Ocean between 50-110ºE and 30-40ºS (Figure 1). The majority of vessels, however, operated between 60-90ºE and caught small amounts of SBT (see below for section on SBT catches). This band lies on the area of water temperature between 15-18ºC associated with the sub-tropical convergence zone (STCZ). Figure 2 shows the high productivity band (light blue area) associated with this zone. Dense concentrations of albacore are known to form along the STCZ in other oceans including the South Pacific at 35-47°S. A couple of vessel we interviewed fished for albacore to the north of this band at 20-30ºS, where the water temperature was as high as 20ºC. A small amount of SBT was caught around 25°S and 60ºE. The central Indian Ocean is fished predominantly by albacore vessels, although a few sashimi vessels (7) also reported operating in this area (targeting bigeye). Small numbers of northern Pacific (or Atlantic) bluefin tuna are also a bycatch of this fishery (see section on NBT).

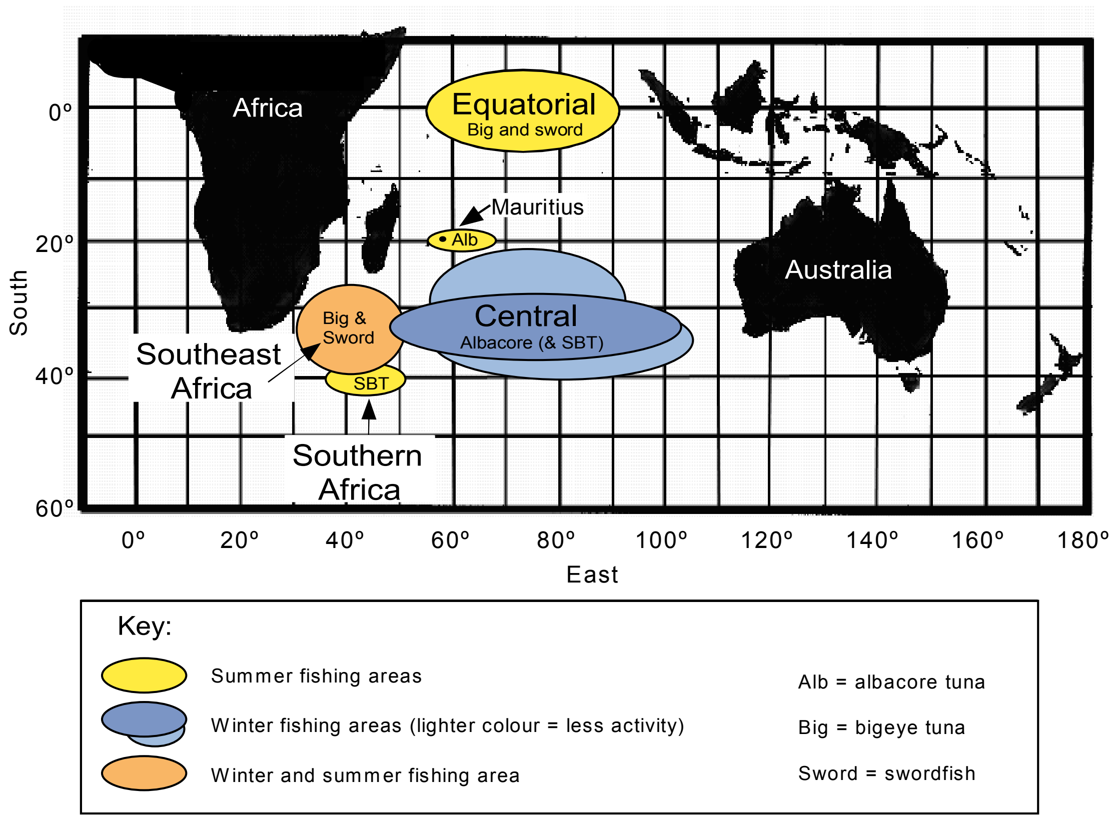

Figure 1. Schematic diagram of the Taiwanese longline winter and summer fishing areas in the Indian Ocean.

During the summer months, many vessels move north to fish around the equator (10ºN-10ºS) including the Seychelles, Chagos Archipelago or the Maldives to target bigeye tuna, yellowfin tuna and swordfish (Figure 1). A number of vessels also indicated they would stay around Mauritius for the rest of the year and target albacore (The Mauritian government is actively promoting Taiwanese activity in the Mauritius EEZ and have licensed 72 longliners this year so far). One vessel we interviewed operated around southern Africa from November to February last year, targeting SBT. This vessel fished with at least 5 other Taiwanese longliners in a small area (see Figure 1). We were not able to determine how many other vessels were fishing around southern Africa during summer, but on the basis of general discussions with industry representatives it seems likely that there is significant effort in this area.

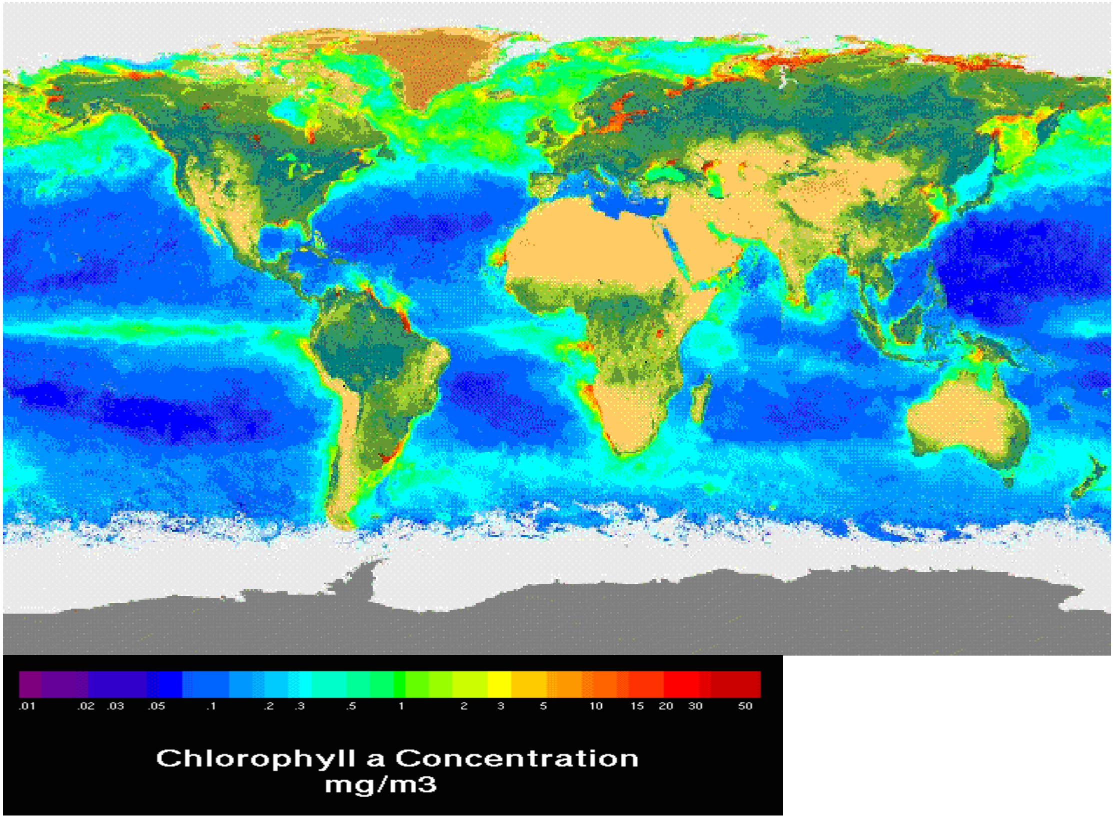

Figure 2. Global ocean colour (chlorophyll concentration) map for the winter season that Taiwanese longliners were operating in the southern Indian Ocean - June to August 1998. (SeaWifs image ORBVIEW).

Atlantic Ocean

The Taiwan Deep Sea Tuna Boatowners and Exporters Association is divided into several committees, with the owners of vessels fishing in the Indian Ocean forming the "Indian Ocean Fishing Boats Operational Committee". A committee also exists for vessels operating in the Atlantic and Pacific Ocean. This explains why none of the vessels we visited had ever operated in the Atlantic Ocean. However, one captain had heard that the SBT caught there were bigger and of better quality than those in the Indian Ocean. He thought that they were caught in the same latitude as in the Indian Ocean (35-38ºS). He did not know how many vessels operated there.

Price of Taiwanese caught tuna:

We were told that the high US price for albacore and the very strong US$ were responsible for the Taiwanese vessels targeting this species in 1998. The high value of SBT was also an incentive to fishing in the area of the STCZ where albacore and SBT are caught together.

However, it appears that during the course of the fishing season prices for albacore fell drastically and as a result all of the vessel owners we talked with were complaining bitterly. The prices paid for their catches are shown in Table 1.

Table 1. Prices paid on US markets for albacore, and Japanese markets for bigeye, yellowfin and SBT caught by the Taiwanese in the southern Indian Ocean.

Species	Size range (kg)	Price / tonne (USD)
Albacore	-	1350
Bigeye	-	7-8000
YFT	-	2-3000
SBT	<15	2500
“	15-25	3000
“	25-40	6800
“	>40	13500-19500

Fishing practices

The captains or owners were very helpful in describing their methods of fishing in the Indian Ocean. The albacore and sashimi vessels target different species using different gear configurations.

Albacore vessels set their lines shallower than the sashimi vessels. Although the majority of captains questioned did not know the exact depth range of their hooks, it appears that they aim to fish anywhere between 20 and 200 m depth. They usually set 10 hooks per basket at between 35-50 m apart (350 to 500 m between buoys). The longline is attached to buoys on buoy lines between 20 and 40 m long. Larger hooks are used on albacore vessels than on the sashimi vessels and saury or ‘samba’ are used as bait. The total number of hooks set per line is between 2700 and 3800 hooks, on 130 to 150 km of line.

The sashimi vessels operating in the south-east African and the central Indian Ocean grounds set their lines deep to target bigeye. One captain suggested that his line fishes to 450 m. Usually, 16-18 hooks per basket are set between 45-50 m apart (750-800 m between buoys). Squid or ‘Samba’ is used as bait. The total number of hooks set is similar to the albacore vessels, at around 3000. Two captains indicated that they set their hooks much deeper (to 800 m) when fishing in the equatorial region during summer. We have never before heard of long lines reaching these depths.

Setting – hauling times:

Albacore vessels on the central grounds set their lines in the morning at around 3-4 am and finish at 9-10 am. The line is left to soak for a couple of hours (breakfast/lunch time for the crew) and is hauled around noon. Setting patterns vary from straight lines to squares (ending where they began) depending on weather and swell conditions. One captain told us that his setting speed is 10.5 knots. Hauling can take up to 14 hours depending on the catch. When asked why they set their lines around sunrise, many told us that this was the best time to catch tuna (including SBT), while others suggested that their baits are eaten (sometimes by squid) if set during the night.
Most sashimi vessels (in the northern and southern hemispheres) set their lines according to the moon. If the moon is full, the line is set in the afternoon at approximately 4 pm. As the line takes 5 hours to set, the moon will be rising just as setting is completed. The line is left to soak for a few hours (while the crew has dinner) and is then hauled. The strategy is based on the belief that tuna come up to feed as the moon rises, and can be caught at this time. If there is no full moon, setting starts at 3-4 am and finishes at 9-10 am, in a similar way to the albacore vessels.

The mainline material used by these vessels (kuralon) is similar to Japanese longliners. It appears that the vessels do not use bait-throwing machines but do have hydraulic line haulers and branch-line coilers. A single hook as attached to each branch-line, and many vessels wrap lead sheet around hooks to provide extra weight.

Logbooks:

As we discovered last year, captains keep several logbooks. Many captains were willing to show us their personal logbook, which contained the most detailed record of the vessel's movements and catch. Many of these books contained daily records of position, water temperature, setting direction, number and weight for albacore, number and weight by size class for bigeye, yellowfin and swordfish, as well as individual weights for SBT. One captain even recorded fork length of each SBT caught. The second log includes a summary of the catch by species and location for each set, and is radioed back daily to the vessel's owners in Taiwan. A third log is the official Taiwanese Government log which is collected by the Fishery Department of Constructive Bureau, Kaoshiung Municipal Government (FDKMG). This is sent back to Taiwan at the end of the season, and contains details of position, catch-by-species and length measurements of the first 30 fish caught each day. Captains are also required to report SBT catch locations and weights to FDKMG each week by fax.

By-catch species:

From what we saw during transhipments, the predominant 'by-catch' species of the Taiwanese longliners are shark (many fins and some large trunks of several species), large oil fish (up to 1.5 m in length), skipjack tuna and small dolphin fish. Also transhipped are frozen blocks of tuna ovaries, stomachs and other entrails.

Taiwanese catches of SBT

Simon Lee (Taiwan Deep Sea Tuna Boatowners and Exporters Association), arrived in Mauritius with a summary of data from Taiwanese longliners that had reported catching SBT in the southern Indian Ocean during the season. These data were apparently complied from the reports sent to the Association and to FDKMG. These data indicated that 34 vessels had caught SBT over the winter, and 3 of these had caught more than 10 tonnes. Of the 34 vessels, 28 were listed to tranship in Mauritius, while the remaining 6 were to do so in Cape Town. We were able to visit 8 of the vessels listed; the remaining 20 had either already left port (5), were about to arrive (7) or were unaccounted for (8). Of the 8 vessels visited, most caught more SBT than was reported on the Association's list. The total SBT catch for the 8 boats was twice as much as reported. Of all the vessels we visited in Mauritius (74), 44 reported catching SBT and 13 of these caught more than 10 tonnes.

Our interviews and analysis of logbook data indicate that SBT are caught in two main areas in the Indian Ocean; the central ground during winter and the southern African ground during summer. The data we present below was collected directly from vessel logbooks shown to us by the captains. The majority of Taiwanese captains record the weight of every sashimi-grade fish they catch in a personal logbook, along with position of the set. We were able to collect weight data for over 5649 SBT and setting positions for nearly 80% of these. In addition to the log book weight data, we measured 224 SBT as the fish were being transhipped. These data are not included in the size analyses below.

Central ground - winter:

Most vessels fishing in the southern Indian Ocean caught SBT in the area bounded by 60-100ºE and 30-35ºS, from June to late August (Figure 3). Although albacore vessels were dominant in the area, sashimi vessels also caught SBT. From logbook data and estimates of catch provided at interview by captains, the average catch in this area was 7 tonnes per vessel. A few SBT were also caught north of this main fishing ground at around 62ºE and 25ºS. Vessels fished as far east as 110ºE.

Most vessels finished catching SBT at the end of August because the oil content in SBT caught in September is not very good. As we interviewed only a small proportion of the fleet, it is impossible to estimate the total SBT catch for the central ground. SBT caught here are predominantly immature fish less than 50 kg dressed weight (GG) or 150 cm fork length. The dominant age class in the catches is three year-olds. Figure 4 shows the size and age distributions of fish from a sub-sample of the catches. The calculation of length was made using processed weight, date and SBT statistical area. The age of the fish is calculated from the length, using the 1994 CCSBT agreed growth curve.

Our interviews with captains suggested that larger SBT were caught around 80-90ºE this year, and smaller SBT were predominantly east of 66ºE. Thus, as vessels moved west, the SBT in their catches got smaller. Despite these clear impressions from captains, we could not detect a change in the weight of SBT by longitude or month of capture from the logbook data. One captain thought that the small fish caught around 66ºE were possibly from a pool of 'South African" fish that are found close to southern Africa during summer, rather than from "Australia". By all reports, during the winter in the area east of 50ºE, SBT are rare (only a few fish caught per week), small (10-15 kg) and of poor quality. Many captains told us that their catches of all species this year were worse than last year. Although reports were conflicting, the weather and water temperature were blamed for this. Some said that the SST this year was warmer than last, others said it was colder, while still another said it was unstable and windy. The sea surface temperatures in which SBT were caught were between 16 and 18ºC.

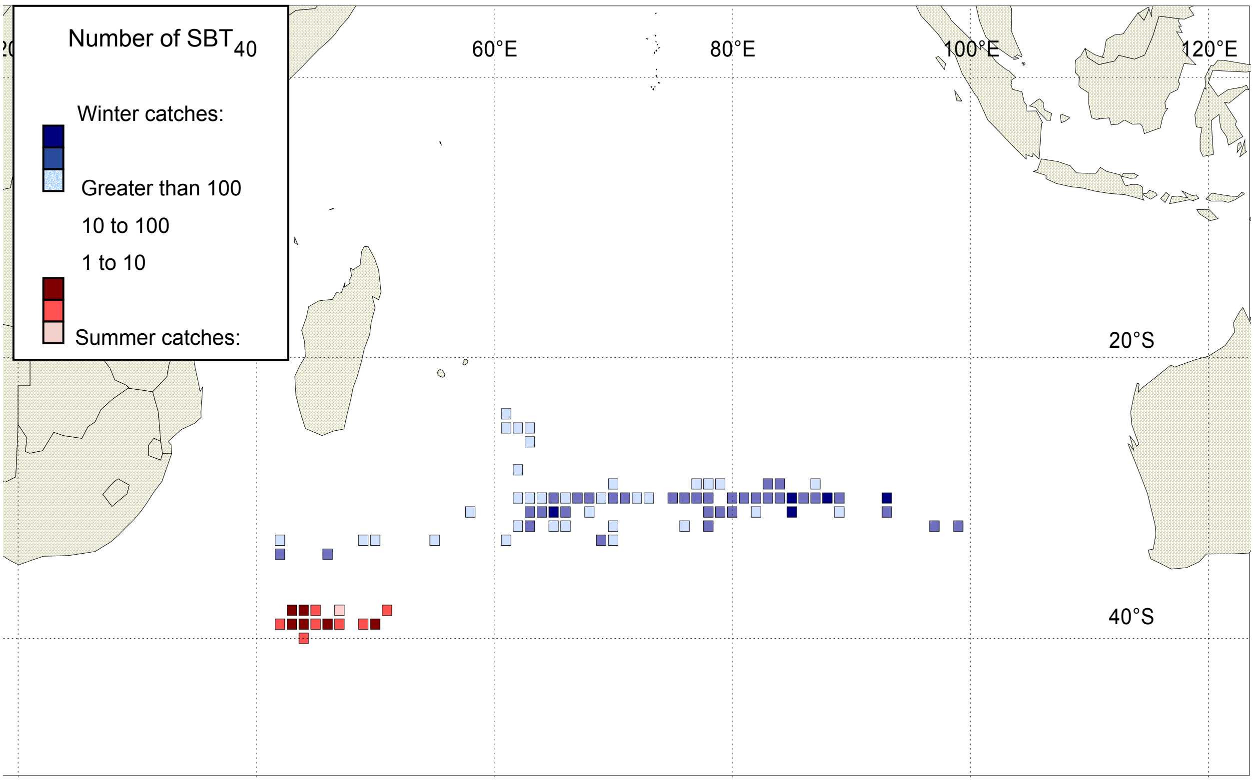

Figure 3. Map of SBT catch locations in the Central Indian Ocean by Taiwanese longliners. Data from vessel logbooks.

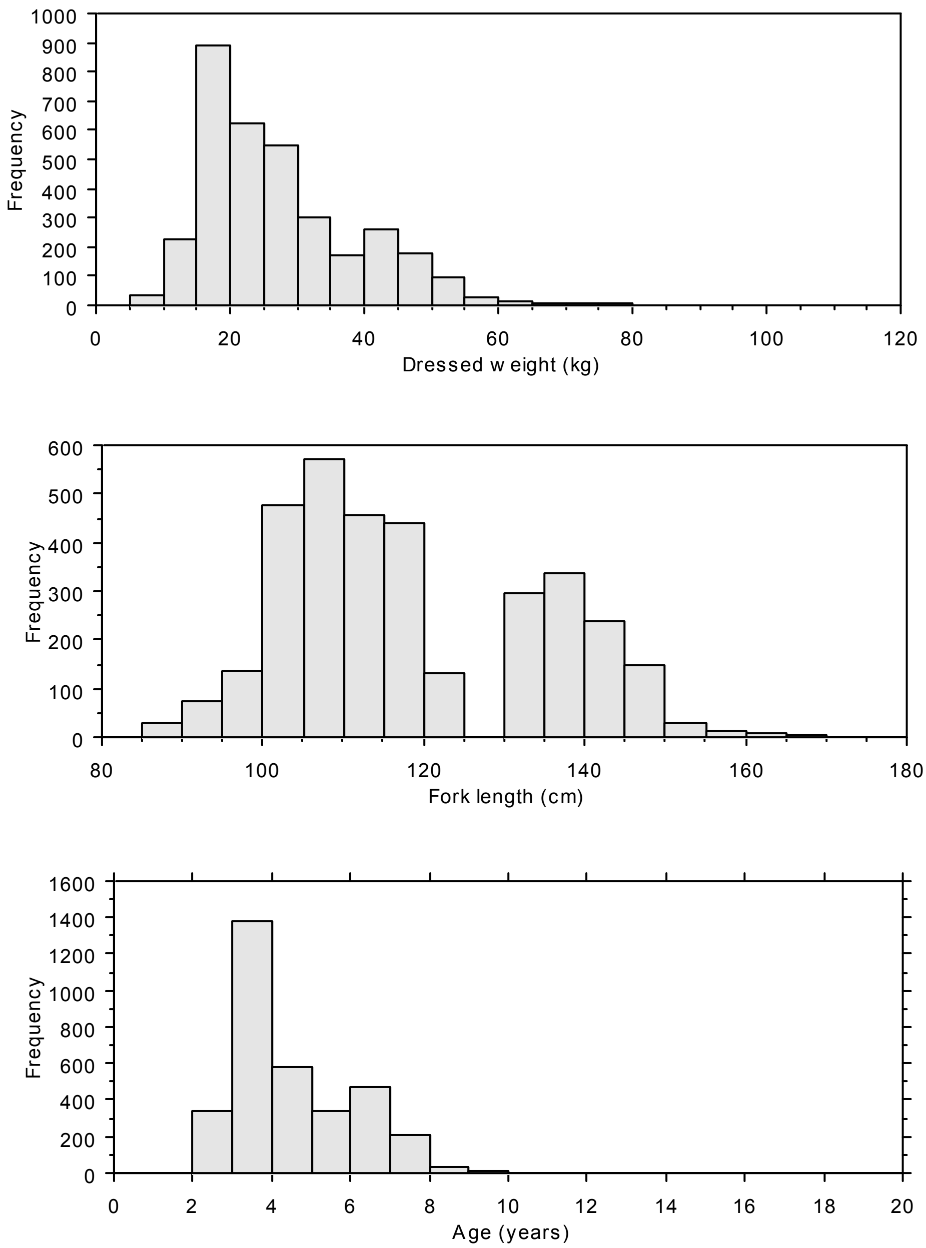

Figure 4. Weight, length and age frequency distribution of SBT caught by Taiwanese longliners in the central fishing ground of the southern Indian Ocean during winter 1998. n = 3388.

Southern African ground - summer

Interestingly, the other main area that the Taiwanese fleet catches SBT is off southern Africa during the summer months (Figure 3). We could not determine the number of vessels that fished this area, but one vessel we interviewed caught 30 t of SBT around 42-51ºE and 38-40ºS. SBT caught here are smaller than those in the central Indian Ocean, the majority being less than 25 kg dressed weight, 115 cm LCF and between two and three years old (Figure 5). The mean weight of SBT caught increased from west to east, although this could be due to time of capture, as the vessel moved eastwards during the summer (Figure 6).

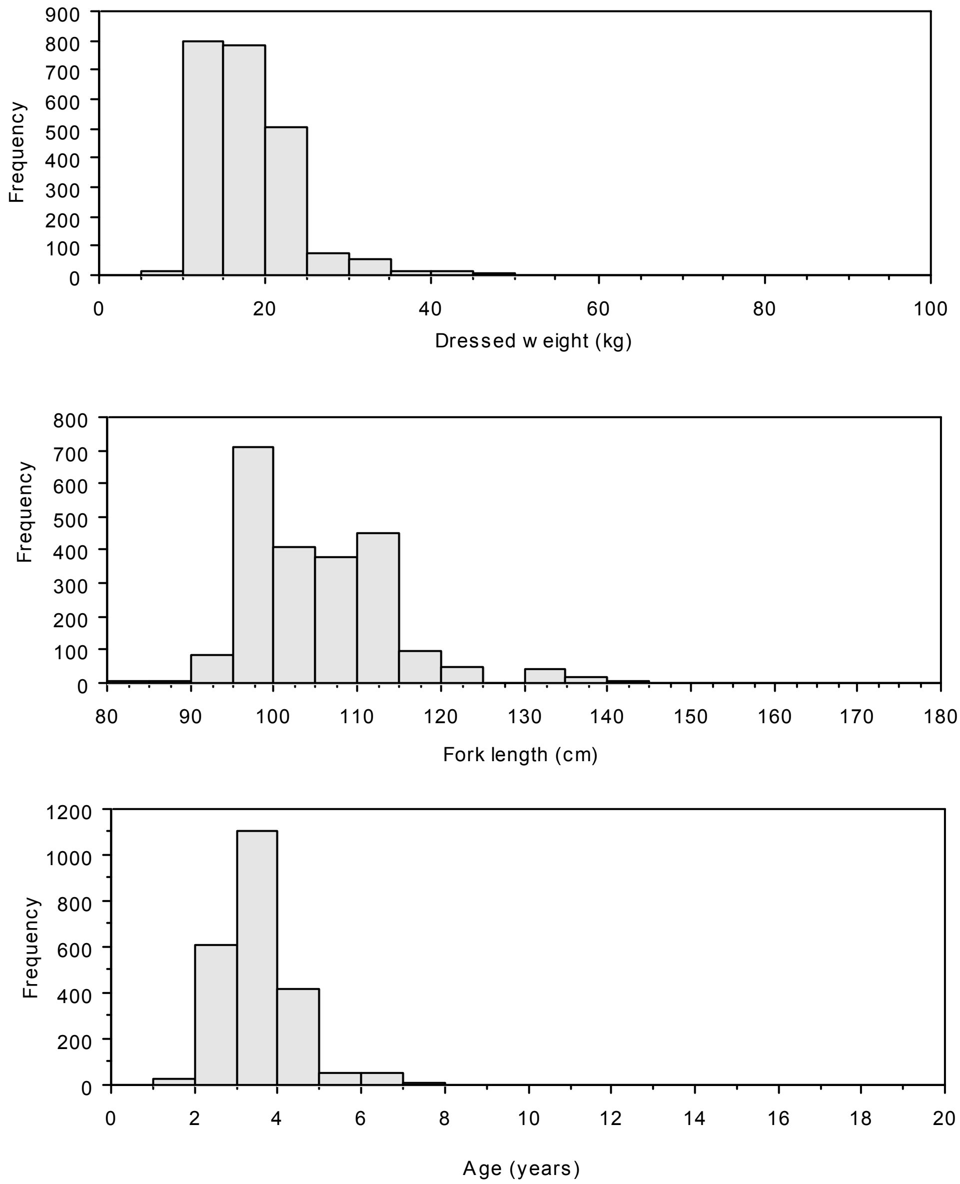

Figure 5. Weight length and age frequency distribution of SBT caught by Taiwanese longliners off southern Africa during summer. n = 2261.

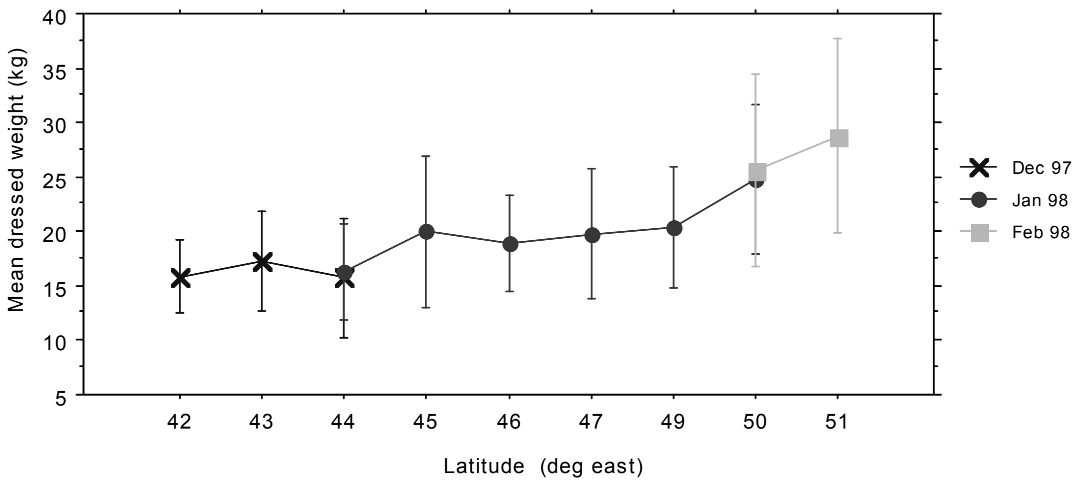

Figure 6. Mean weight of SBT caught per month by longitude in the eastern fishing ground of the southern Indian Ocean during summer.

Schooling SBT

Several captains reported seeing surface schools of SBT in the south-western part of the Indian Ocean. These were seen both in winter at around 65ºE and 31ºS as well as summer around 45ºE and 38ºS. From what we have been told, catching SBT in this area is dependent on whether there is a school nearby. One vessel may catch many SBT, while another vessel nearby may catch none. There is also evidence to suggest that young SBT that were tagged in the Great Australian Bight (in schools), may stay in a schools while venturing into the southern Indian Ocean. A few captains reported catching 'schools' of tagged SBT; one caught 81 pieces of SBT last year and 21 had tags.

CPUE for the Taiwanese fishery in the Central Indian Ocean.

The Taiwanese fishing ground in the central Indian Ocean is situated close to (and within) the northern part of the area fished by the Japanese fleet during their Experimental Fishing Program (EFP). The Taiwanese fleet fished this area during the same months as the EFP was fished by Japan (mid-July to August 31). This provides some basis for comparison of the SBT CPUE for the two fisheries.

We estimated SBT CPUE using logbook data from 14 vessels operating between 60-100ºE. We assumed that 3000 hooks were set each day by each longliner between 15 July and 31 August. CPUE, calculated as the number of SBT caught per 1,000 hooks set, ranged from 0.03 to 2.10, with a mean of 1.03. CPUE calculated only for days that SBT were caught ranged from 0.9 to 4.06, with a mean of 2.37.

The number of individual SBT caught per day ranged from 0 to 164. The number of SBT caught per day differs significantly between the central Indian Ocean in winter and southern Africa in summer (Figure 7). In the central Indian Ocean (60-90ºE), the mean number of SBT caught per day was 7.2 compared to 44.3 in southern Africa during summer.

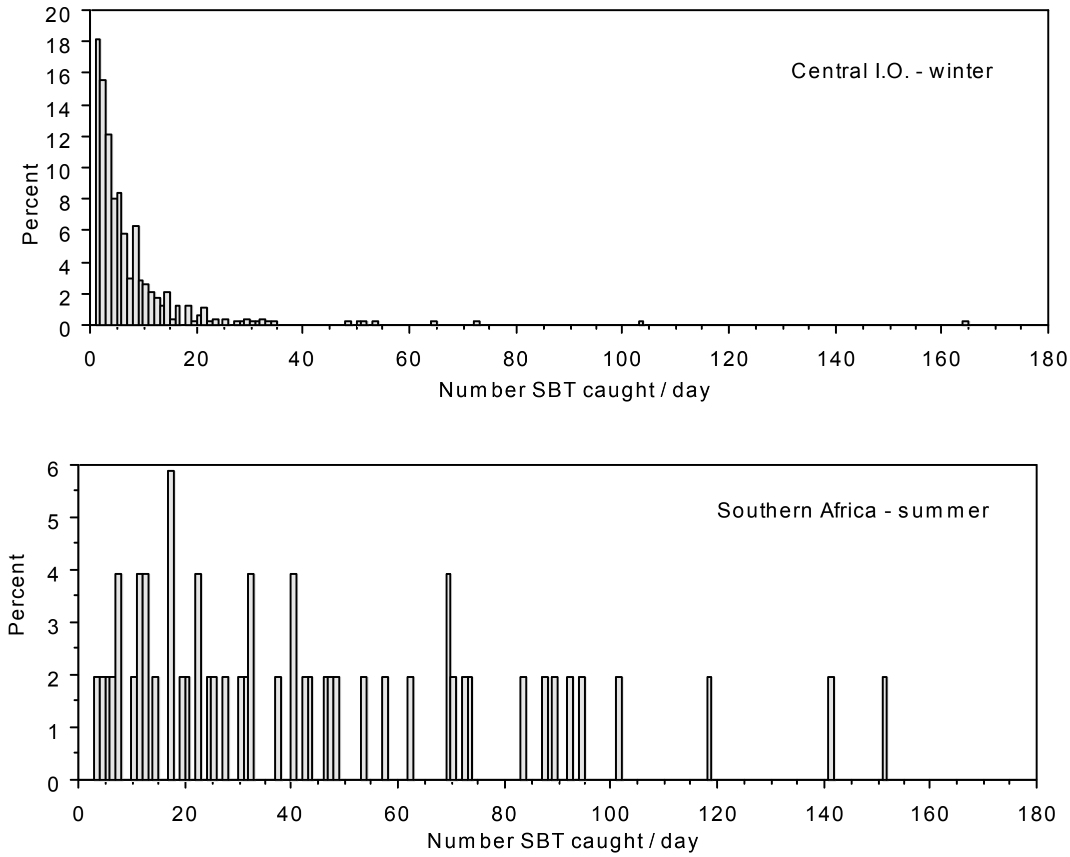

Figure 7. Distribution of Taiwanese SBT catches per day in the Indian Ocean (from logbook data).

Taiwanese catches of NBT

Many vessels catching SBT also reported catching a few (1-11) pieces of northern or Atlantic bluefin tuna. These ranged in size from 45 to 150 kg. Northern bluefin tuna were identified by the crew as having a black keel, as well as smaller eyes, bigger chests and thicker flesh than SBT. The crews indicated that they have no problem discriminating between the two species. Genetic samples were collected from 100 SBT during transhipment, to confirm that identifications were correct.

Tag liaison and recoveries

There was a great deal of interest shown in the SBT tagging program and collection of tags. Many captains told us that when a vessel catches a tagged fish, they jump on the radio and tell others. They consider the tags 'lucky' because they are rare, and are very happy to collect them for us. One captain went as far as to say that he was very glad that we were doing this research and that we had come to Mauritius to talk to the fleet. This was the sentiment from most vessels.

During our visit we were given 62 conventional tags (from 39 SBT) from the captains and crew of vessels. We also collected one shark tag (Spain), two sailfish tags (Kenya) and one bird band (France). No archival tags were recovered. Conventional tags from a further 26 SBT were collected by one of the local shipping agents, as well as three sailfish tags. Many of the vessels had tagging posters on board, given to them by the Taiwan Deep Sea Tuna Boatowners and Exporters Association or by us on our visit to Mauritius last year. As a result of this, some captains recorded complete recapture details for each tag collected.

Some vessels, however, had not heard of the tagging program and had not kept any tags. In a few cases, the captain had heard of the program but the crews were still unaware, resulting in many tags being thrown overboard. At least a further 70 tags were reported as being thrown overboard or taken back to China with crewmen, but we expect that this number could be larger. We distributed tagging posters to all vessels we visited, and were promised co-operation by all captains. The captains were particularly interested in the archival tag data and will be on the lookout for these tags in the future.

Seabird by-catch and mitigation devices

Many of the captains and owners were willing to discuss the issue of seabird by-catch. Given the extent of their fishing activities in the Indian Ocean, it is likely that many are interacting with seabirds, especially if operating south of 30ºS. A few captains told us that although they see many birds, they very rarely catch any. The reasons given for the low catch rates were that their lines sink quickly (they use ‘heavy’ hooks) and that the birds often take the bait but do not get hooked. The most birds that anyone admitted to catching was 3-5 in a season.

Petrels, albatrosses and shearwaters are the predominant seabirds encountered by Taiwanese vessels in the southern Indian Ocean. The difficulties in classifying seabirds from pictures in a book made it almost impossible to obtain species identifications from the crew or captains. However, sooty, royal and shy albatross as well as cape petrels, giant petrels and flesh-footed shearwaters were all pointed to. A crewman of one vessel gave us a bird band from a sooty albatross and said that he’d keep any others that he finds! This bird was caught at ~39ºS.

Many captains told us they do not use tori lines (or other methods) to deter seabirds. However, some vessels carry tori lines on board and use them when necessary. According to two captains, the majority of vessels operating in ‘the south’ use tori lines (see Figure 8). Apparently, these vessels use them because they want to, not because it is a requirement of Taiwan. The captains were interested in learning about other methods that can be used to use to deter seabirds, and also offered their ideas (including strange kite devices which, if successful, will be patented by the captain!). Some vessels collect the swim bladders from sharks and throw them to the birds when setting, keeping them preoccupied and away from the baits.

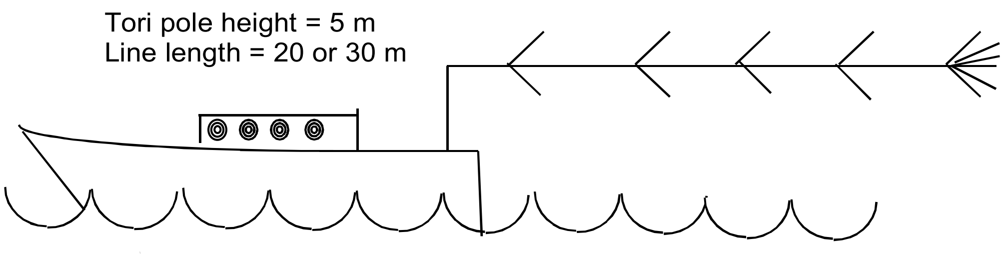

Figure 8. Drawing of tori pole and line used by some Taiwanese longline vessels in the Indian Ocean. The tip of the line does not touch the water.

Killer whales

As has become a problem for tuna longliners operating in southern Australia, many Taiwanese skippers complained about the problem of killer whales taking tuna from their lines. According to one captain, killer whales previously has a southern limit of 28ºS, but have recently (in the past few years) become common as far south at 35ºS. Many captains told us that 1998 was by far the worst year they had experienced for killer whales. Some thought we'd be better off study the killer whale problems, rather than SBT! We heard that the vessel's sonar was sometimes useful in scaring the whales away. Clearly, research into how to deter killer whales from approaching long lines would be very popular and likely to receive industry support.

Japanese and Korean longliners

We heard from a few vessels that Japanese and Korean vessels were operating in similar areas to the Taiwanese fleet over the winter season. One captain estimated that 20-30 Japanese vessels (and an unknown number of Korean vessels) were fishing in the area 30-35ºS, 90ºE. As we were about to leave Port Louis, a Japanese vessel (JPSZ) called into the harbour. This vessel did not stay long and presumably did not unload its catch.

Taiwanese access to Mauritian EEZ

Many Taiwanese longliners have licenses to operate within the Mauritian EEZ. These licenses are inexpensive (~USD 2000) and easily available. The Mauritian Ministry of Fisheries is encouraging this licensing system, although there is concern that the price is too low. Many Taiwanese vessels choose to fish around Mauritius for the remainder of the year rather than head to the northern hemisphere. The target species within the EEZ is albacore.

Freezer facilities in Pt Louis

Hung Min Shipping Agency is continuing to develop a large cold store facility near Froid des Mascareignes, in the free port zone. After some opposition by rival shipping agencies, the expected completion date for the facility has been postponed from September 1998 to mid 1999. The cold store facility will allow Taiwanese vessels using the Hung Min Agency to unload their entire catch in the port area, rather than unload some in the port and the remainder onto carrier vessels in the outer harbour. Hung Min aims to have a vessel turnaround time of 24 hours.

The cold store will hold more than 2000 tonnes of sashimi-grade fish in two -60ºC freezer and at least 4000 tonnes in two -30ºC freezers. Tuna will be separated by species in the freezers, processed and shipped to either Japan or North America. The facility aims to process all fish species, and will include large areas for trimming, filiting, skinning, weighing and packing. Hung Min have both a Japanese and Italian partner in the venture. Two Japanese sashimi graders will be employed in the facility to classify the tuna and teach the skill to the local people.

Hung Min has offered access to the cold store next year and assistance with the tag recovery, sampling and size monitoring programs. This will allow us to collect size data on a much larger sample of the Taiwanese catches in the future.

Mauritian Fisheries

There are two types of Mauritian fishing vessels operating out of Port Louis that target tunas. The first is Japanese style longliners, of which we saw 6-7 in Pt Louis, which operate around the Seychelles region for bigeye and yellowfin. These vessels are old and do not appear particularly seaworthy. Apparently, their owners are not willing to invest money in maintenance. We did not discover whether there was foreign involvement in the companies operating these vessels.

The other type of tuna fishing in Mauritius is from small dingys around a mother ship. Sixteen to eighteen small dingys with outboards, each with 2-3 fishermen, are set afloat around the mothership to catch tunas using rod and reels. Fishing generally occurs around FADs or in the open ocean close to Mauritius. Bigeye, albacore and several other species are caught and generally sold in the market at Port Louis. The local Mauritian vessels do not catch SBT.

Toothfish

In contrast to the situation in 1997, there were very few Patagonian toothfish longliners in Pt Louis during our stay. Since we were in Mauritius at almost the same time as last year, the reasons for this change were unclear. According to the Mauritian Fisheries, there has been concern by the government that some of these vessels have been fishing illegally (after several were arrested by the French) and may not be as willing to welcome these vessels into port.

Future work

Several captains and owners suggested that we develop a questionnaire or form and distribute it to each vessel prior to the winter season in the southern Indian Ocean. The form would ask for details of every SBT they catch. We were told that the majority of captains would be very happy to do this, and it would save us (and them) time when we visit.

8. THE AGE DISTRIBUTION AND RELATIVE STRENGTH OF COHORTS OF SBT ON THE SPAWNING GROUND

Presented at the 1998 Commission for the Conservation of Southern Bluefin Tuna scientific meeting, 23-31 July 1998, Shimizu, Japan. CCSBT/SC/9807/39.

John Gunn
Jessica Farley
Tim Davis

Abstract

Using otoliths collected by CSIRO and the Indonesian Research Institute of Marine Fisheries (RIMF) from SBT caught by Indonesian longliners on the SBT spawning grounds, we compare the age composition of the catch for the 1994/5 and 1996/97 spawning seasons.

There was no significant difference between the two seasons in the distribution of ages (Kolmogorov-Smirnov test $p = 0.7154$). In both seasons, few fish less than 10 years or older than 30 years were caught, and the major mode occurs between 17 and 22 years. Similarly, there is no evidence for differences between the two seasons in the length-at-age of fish on the spawning grounds.

However, the age distributions for all fish measured in the 1994-95 and 1996-97 Indonesian catches, which we derived from conversion of length to age, show some evidence for increased numbers of 10-15 year old fish in the most recent season.
Using the back-calculated birth dates we were able to assign the catch on the spawning grounds to cohorts. From the distribution of cohorts in the two seasons it is clear that cohorts from the 1970s are strongly represented in the spawning stock. In contrast, cohorts from the 1980s are poorly represented. There are significantly more fish spawned in the last half of the 1960s than the first half of the 1980s.

Introduction

Three major sources of uncertainty in the current stock assessment of southern bluefin tuna resource are:

- the age at maturity and/or first spawning,
- the natural mortality rate for the mature/spawning component of the stock, and
- "a basic inconsistency in the catch and effort data between 12+ group and the 4-11 year olds, as examined with present VPA model" (Report of the 1996 CCSBT Workshop on VPA and CPUE modeling).

To resolve these problems, accurate data on the age structure of the spawning component of the SBT stock is needed. With adequate coverage of the population, these data would provide the basis for estimating the age at which fish enter the spawning stock and reduce the degree of uncertainty surrounding the natural mortality rates within this portion of the stock. The data would also improve our understanding of the dynamics of the “plus” group catches and effort relative to the apparent inconsistencies.

Over the last two years we have begun to examine these critical uncertainties in a study of the age composition of fish caught on the spawning grounds. This work builds on the earlier studies by Gunn et al. (1996a, b) on the direct estimation of age in SBT.

CSIRO and the Indonesian Research Institute of Marine Fisheries (RIMF) have collaborated in monitoring the SBT catch by Indonesian longliners on the SBT spawning grounds south of Bali since 1993 (Davis, 1998a). In addition to collecting length data from a large proportion of the longline landings, the program has collected otoliths from a representative sample of the catch. Gunn et al. (1996b) reported on a pilot project in which otoliths were used to estimate the age of a small number of fish caught on the spawning grounds. Their data suggested the majority of fish caught in the Indonesian fishery were 15-30 years old and that very few were less than 12 years old. This lead Gunn et al. (1996b) to discuss the possibility that the age at first spawning in SBT was higher than the age at first maturity (9-10 years) estimated by Davis (1995). Davis estimated size at first maturity on the basis of gonad indices and oocyte maturity of fish off the spawning ground. These are accepted bases for estimation of maturity. However, Gunn et al. (1996b) hypothesized that although the smaller/younger size classes, recognized as mature by Davis, may be physiologically ready to spawn, they did not undertake the migration to the spawning grounds. An alternative hypothesis was that the estimates of size at maturity of Davis (1995) were correct but that the younger age classes within the spawning stock were under-represented in the Indonesian catches. The size distribution of Japanese catches on the spawning ground in the 1960s to 1980s are significantly different to those of the Indonesian; fish less than 170 cm make up a much larger proportion of the Japanese catch than in the Indonesian catch.

Davis et al. (1998b) addresses the size data from the Japanese and Indonesian catches and concludes that the smaller fish seen in the Japanese data are mature but are unlikely (a) to spawn or (b) if they do spawn, are likely to contribute little to the reproductive capacity of the SBT stock. Given this, the fish caught in the Indonesian fishery effectively represent the size and age distribution of the bulk of the SBT spawning stock.

In this paper we compare the age composition of the Indonesian SBT catch for two spawning seasons – 1994/5 and 1996/97.

Methods

Otoliths for this project were selected at random from a representative sample of the SBT caught by the Indonesian fishery. Otoliths were prepared for age estimation using the techniques described by Gunn et al. (1996a). Age was estimated for 487 otoliths from the 1994-95 spawning season and 475 from the 1996-97 season. Each otolith was read twice and “blind” (ie without reference to the size of the fish or to previous readings) by the primary otolith reader. A sub-sample of 100 otoliths was read blind by an experienced secondary otolith reader to ensure the consistency of the age estimates.

The Average Percentage Error (APE) method of Beamish and Fournier (1981) was used to measure the intra-reader consistency in otolith readings (replicate readings by the primary reader) as well as inter-reader consistency (final age estimate of the primary reader and the mean of replicate readings by the secondary reader).

Statistical comparison of mean length for each age class for the two seasons was made using an unpaired t-tests. A Kolmogorov-Smirnoff test was used to compare the age distributions of the two seasons. Both of these analyses were conducted using Statview 4.1.

To estimate the age of fish measured by Davis et al. (1998a) from the spawning ground catches in the 1994-95 and 1996-97, we converted length to age using the following method. First, otolith-based estimates of age for 962 fish were used to develop a matrix containing the proportional representation of each age class in 5 cm length classes. The samples for the two seasons were pooled as there was no significant difference between seasons in the mean length-at-age for any age class. Second, the matrix was then used to derive estimates of age within 5 cm size classes for the total sample of lengths for each season.

Results

The APE between replicate readings by the primary reader was 3.31 (n = 961), between replicate readings by the secondary reader was 4.40 (n = 100) and between the two readers it was 4.47 (n = 94). These very low levels of error suggest excellent repeatability of age estimates in blind tests. As the annual formation of the increments used to estimate age in these samples has been validated (Kalish et al., 1996; Clear et al., In prep), we are confident that the age estimates made during this study are accurate.

The length distributions of fish, from which otoliths were sampled to estimate the age distribution of fish on the spawning grounds in 1994-95 and 1996-97, are very similar (Fig. 1). In both spawning seasons very few fish less than 160 cm and greater than 200 cm LCF were caught and sampled.

There was no significant difference between the distribution of ages of fish from which otoliths were sampled in the two seasons (Kolmogorov-Smirnov test p = 0.7154). In both seasons there are few fish less than 10 years or older than 30 years and the major mode occurs between 17 and 22 years (Fig. 2). Similarly, there is no evidence for differences between the two seasons in the length-at-age of fish on the spawning grounds (Table 1).

However, the age distributions derived from conversion of length to age for all fish measured in the 1994-95 and 1996-97 Indonesian catches show some evidence for increased numbers of 10-15 year old fish in the most recent season (Fig. 3).

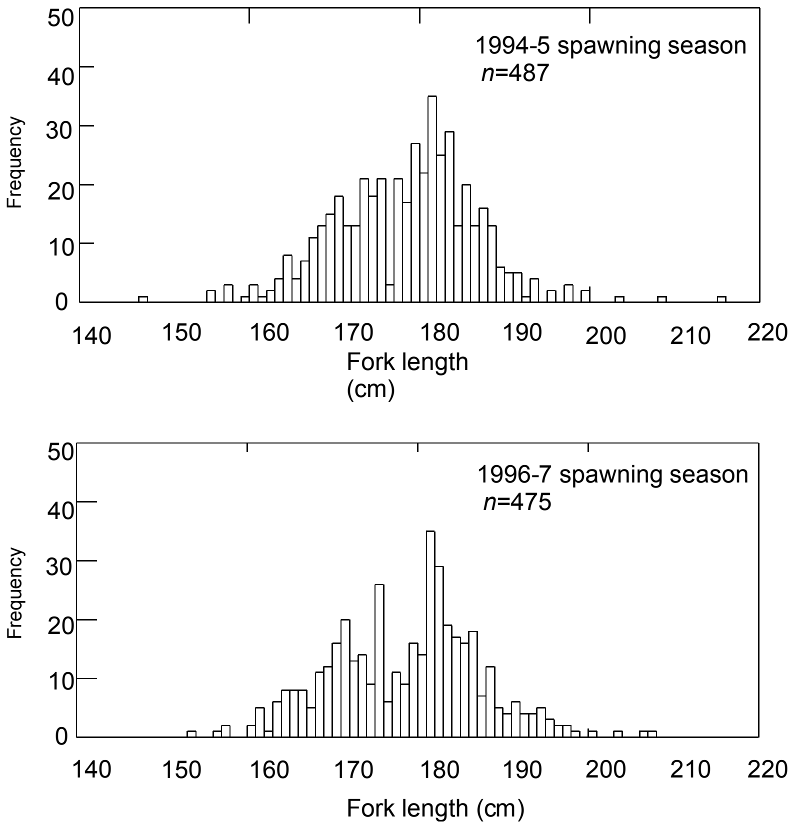

Figure 8.1. Length distributions of SBT caught on the spawning ground during the 1994-5 and 1996-7 spawning seasons, from which ages were estimated using otoliths.

The representation of cohorts in the spawning stock, estimated by back-calculating spawning date from age and date of capture of the fish sampled in the Indonesian catch, are shown in Figure 4. Notable features of this distribution are the strong representation of cohorts from the 1970s in the spawning stock, and the contrasting low representation cohorts of the 1980s. There are significantly more fish spawned in the last half of the 1960s than the first half of the 1980s. Fish spawned since the introduction of quotas in 1984 comprise an insignificant proportion of the fish caught by the Indonesian fishery.

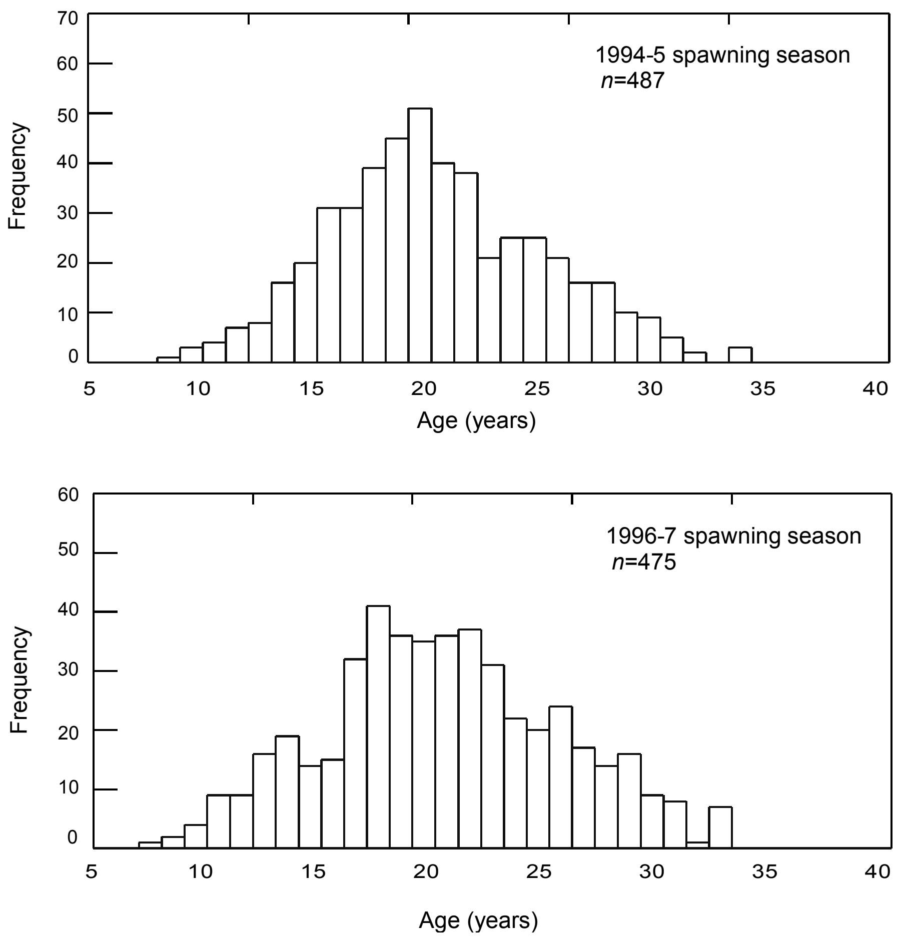

Figure 8.2. Estimates of age distributions for SBT caught on the spawning ground during the 1994-5 and 1996-7 spawning seasons.

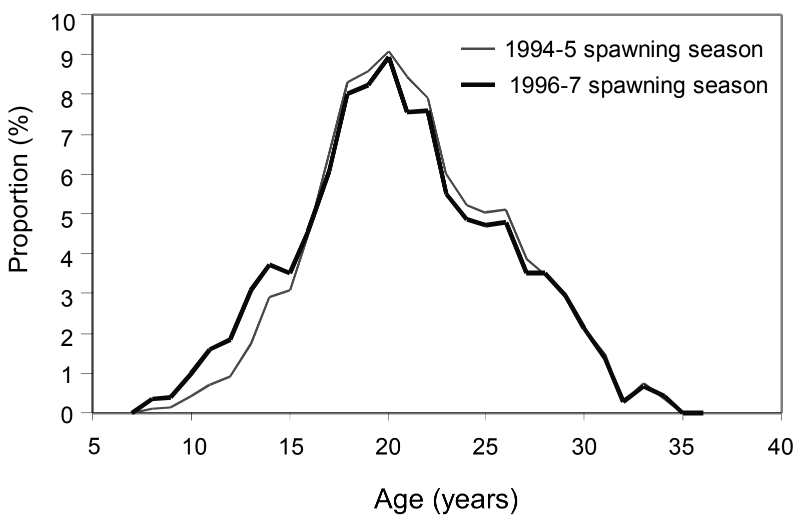

Figure 8.3. Age distribution of SBT on the spawning ground during the 1994-5 and 1996-7 spawning seasons, calculated from length frequency data collected by Davis (1998a).

Table 8.1. Mean length-at-age and standard deviations (SD) of SBT caught on the spawning ground during the 1994-5 and 1996-7 spawning seasons. Results (p-value) of an unpaired t-test to compare the lengths at each age are given.

Age	1994-5 season			1996-7 season			t-test
	Mean LCF	SD	n	Mean LCF	SD	n	p
8				153.0	-	1	\
9	156.0	-	1	161.5	4.95	2	0.808
10	163.3	11.02	3	165.8	5.68	4	/
11	158.8	8.30	4	164.1	6.31	9	0.223
12	167.0	6.68	7	167.4	3.61	9	0.867
13	173.4	7.09	8	168.9	6.85	16	0.153
14	173.5	7.05	16	169.4	5.76	19	0.068
15	172.3	6.13	20	175.4	4.93	14	0.123
16	175.0	5.90	31	175.3	5.34	15	0.883
17	178.9	6.34	31	177.0	6.12	32	0.230
18	177.9	7.17	39	178.2	6.93	41	0.839
19	179.4	7.35	45	180.7	7.31	36	0.448
20	178.4	6.78	51	181.8	9.29	35	0.051
21	180.0	6.65	40	182.4	6.29	36	0.105
22	179.1	7.06	38	181.2	7.81	37	0.229
23	180.0	6.71	21	183.4	9.15	31	0.117
24	181.6	8.20	25	180.6	8.50	22	0.669
25	182.3	7.57	25	182.0	7.84	20	0.873
26	182.3	7.30	21	183.6	7.23	24	0.567
27	182.8	4.71	16	184.6	8.22	17	0.440
28	186.1	9.36	16	185.3	8.06	14	0.881
29	186.8	8.79	10	182.5	9.40	16	0.256
30	184.4	7.28	9	189.3	9.58	9	0.074
31	191.2	10.83	5	184.0	4.34	8	0.115
32	199.0	24.04	2	201.0	-	1	\
33				180.7	7.70	7	0.105
34	191.7	4.51	3				/

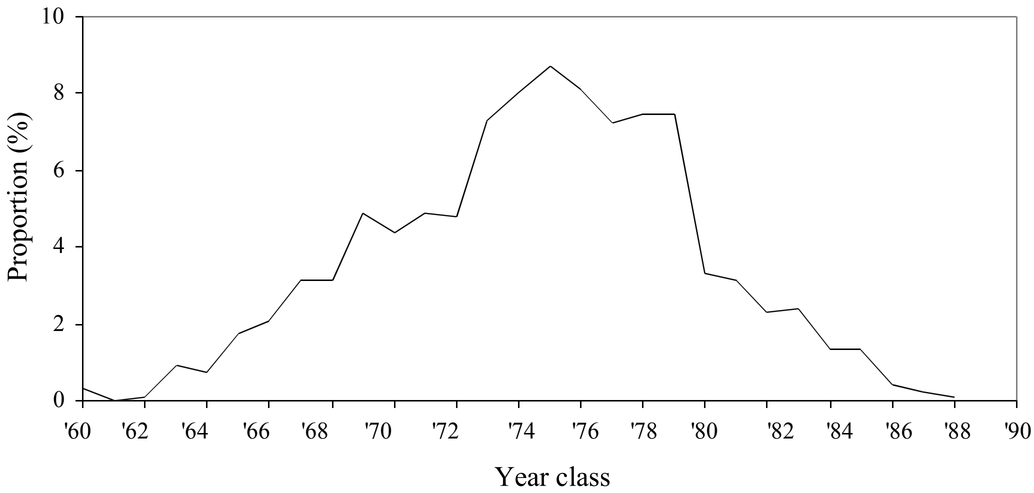

Figure 8.4. Proportional representation of SBT cohorts caught by the Indonesian longline fishery on the SBT spawning grounds.

Discussion

Gunn et al. (1996b) drew attention to an apparent anomaly between the length distribution of fish in Indonesian catches on the SBT spawning ground during the 1990s and those of Japanese in much the same area during the last 40 years. Very few fish less than 160 cm fork length are taken by the Indonesian fishery whereas fish between 150-160 cm LCF were common in the Japanese fishery, particularly during the 1960s and 1970s. Since the cessation of the commercial fishery on the spawning grounds, the only source of size data from Japan has been the relatively small catches by the fishery training vessels that continue to operate in the NE Indian Ocean. These catches have a similar size distribution to those of the Japanese commercial fishery. Davis (1995) estimated the size at 50% maturity in SBT to be 157 cm LCF. Thus, one might expect fish of this size to undertake migrations to the spawning grounds where they could be caught in significant numbers by both the Japanese and Indonesian fishery. Gunn et al. (1996) posed a number of questions regarding the validity of using the Indonesian catch to estimate the size and age distribution of the SBT spawning stock.

Subsequent work by Davis et al. (1998a) addresses the issue of under-representation of the smaller size classes of SBT within the Indonesian fishery. Their data suggest that the smaller fish do undertake a migration to the spawning ground. These fish appear to stay at greater depths than the larger fish, and do not spawn as often as. Thus, our data on the age distribution of fish in the Indonesian catch may provide an underestimate of the numbers of fish in the smaller/younger cohorts present on the spawning grounds. However, it seems likely that the data provide a good indication of the age and cohort distribution of fish contributing to the spawning biomass. This being the case, what can we conclude from the two years of data presented here?

First, there remains a clear indication that the spawning stock is dominated by very old fish. The mean age of fish in the samples we examined was 20.8 years. Thus approximately half of the fish within the spawning stock are in excess of 20 years, indicating that there are more fish from the 1965-70 cohorts represented in the spawning population there are from the 1980-1985 cohorts. We believe this is not simply a reflection of size partitioning by depth, rather it indicates that the 1980-85 cohorts are very poorly represented in the population. This conclusion is supported by data on the relative abundance of cohorts off the spawning grounds (Gunn et al. 1996b) in which the 1980-85 cohorts are very small.

Second, there is some indication, albeit statistically insignificant, that the 1996-97 spawning stock contained more 10-15 year-old fish than the 1994-95 stock. This is the first indication that cohorts spawned since the introduction of quotas in 1984 have survived through to maturity.

Davis et al. (1998b) presented length data from the 1997-98 spawning season in which there is an apparent further increase in the catch of 150-160 cm fish in the Indonesian fishery. Over the next 12 months, we shall estimate the age of a sub-sample of this catch to determine whether the increase in abundance of 10-15 year-olds seen in 1996-97 has continued and/or accelerated.

Acknowledgments

Our thanks go to Tim Davis and Sofri Bahar who coordinated the sampling program for the otoliths we use. We also thank the Central Ageing Facility at Queenslcliff for preparing sections of all our otoliths. Tim Davis contributed significantly to the paper through discussion of his results on the Indonesian monitoring program. This work is supported by Australian Fisheries Research and Development Corporation Grant 97/111.

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9. HISTORICAL CHANGES IN JUVENILE SBT GROWTH RATES BASED ON OTOLITH BACK-CALCULATION

Jessica Farley
John Gunn

Introduction

Growth of southern bluefin tuna (SBT), *Thunnus maccoyii*, is highly variable (Hearn and Hampton, 1990). Growth curves derived from conventional tagging experiments in the 1960s and 1980s show that at some time between the two experiments, the growth rates of juvenile SBT increased significantly (Hearn and Hampton, 1990). As there was little tagging between these two major experiments, it is unknown when the changes in growth occurred and the nature of these changes. Recent analysis of length-frequency data by Leigh and Hearn (2000) confirmed that there has been a substantial increase in the mean lengths of two to four year-olds over the history of the fishery, and suggested that this increase may be in response to a decline in the population size due to high exploitation rates.

Given the importance of the growth changes to the SBT stock assessments, and the lack of resolution provided by tagging data to fundamental questions about the timing and nature of these changes, we investigated using otoliths to examine historical changes in growth using back-calculation techniques. Clear et al. (2000) validated the annual nature of the otolith increment deposition rate in SBT. Since growth increments in otoliths do not get resorbed, otoliths retain a permanent record of the growth history of individual fish. Since otoliths have been collected by CSIRO since the mid-1980s, and SBT are known to live for at least 40 years (Gunn et al., In press), growth rates can be estimated from the 1950s.

As fish growth over the first five years of life appears to have undergone the most dramatic changes over time, we concentrated on examining the first five rings within the otolith structure. In a FRDC funded project (92/42), Gunn et al. demonstrated that otolith length is a very good proxy for fish length in SBT. Therefore, the distance between annual slow growth increments in an otolith (ie annual otolith growth) will be proportional to annual fish growth.

The objective of this component of the project was to use otoliths to confirm the changes that had been observed in the tagging studies between the 1950s and 1990s, and if possible produce accurate estimates of the nature and extent of the changes.

Methods

Otoliths from 490 SBT were selected from those already sectioned and aged as part of a previous FRDC funded project "The direct estimate of age and growth of southern bluefin tuna" (FRDC project 92/42). Each fish was assigned a year class (cohort) based on the year caught and estimated age. Where possible, a minimum of 10 otoliths were selected from each cohort, although this was not possible for some cohorts in the 1950s, early 1960s and 1990s due to low numbers of samples available. Otoliths were selected randomly from those with clear and easily identified increments (annual bands). The back-calculated birth years of fish selected ranged from 1953 to 1994 (Fig. 1).

Of the four serial transverse sections cut through each otolith, the section passing closest to or through the primordial region was selected. The distance between the first five increments was measured along the "long arm" (medial ventral ridge). Measurements were not be made for the first year of life because the exact position of the primordium could not be identified in each section. The sections were viewed and measured using a compound microscope linked to a computer running image analysis software. Data on four years of growth was available for most fish, unless the fish was aged <5 years old.

To determine if the relationship between otolith length (along the medial ventral ridge) and fish length is linear in SBT, we measured the distance between the first increment and the edge of the otolith in 133 fish of known length. Only fish less than 15 years old were selected because in older fish the medial ventral ridge of the otolith bends making measurement to the edge difficult. As we are only interested in juvenile fish (1 – 5 years old) it was not necessary to measure older fish.

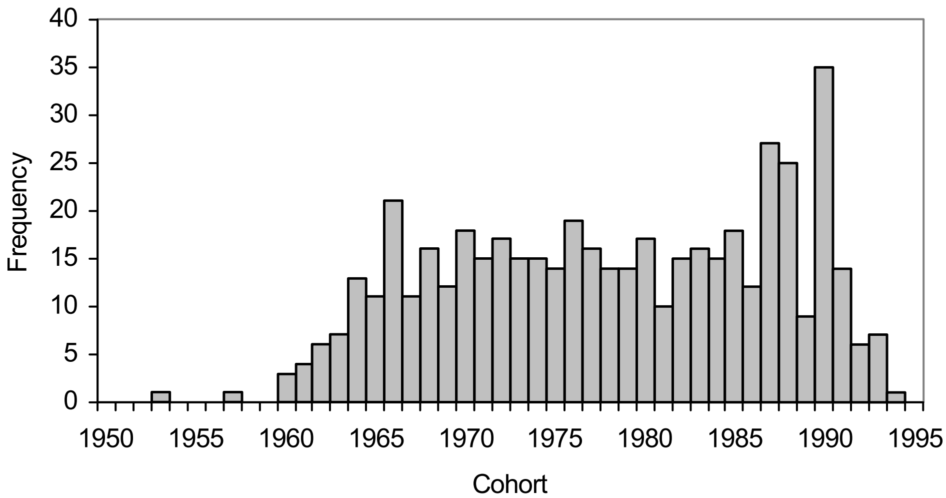

Figure 9.1. Frequency distribution of birth year for SBT with otoliths selected for growth analysis.

Results

The relationship between otolith length and fish length in SBT is linear (r^2=0.861) (Fig 2a). Gunn et al. (In press) also found that otolith size in SBT was linearly related to fish size (r^2=0.951) especially during the first five years of life (Fig 2b). This suggests that annual otolith growth is a reliable and accurate measure of fish growth in juvenile SBT.

The mean otolith growth (and standard deviation) by cohort and age class is shown in Table 1. It is clear that otolith growth was highly variable even within a single year-class. There could be several causes of this, such as:

- inherent differences in growth between individuals (genetic),

- geographic variability in juvenile life history (differences in growth opportunity among geographic areas),
- errors in ageing the fish; variation in the accuracy of measurements,
- variation in the location of the section across the otolith (not exactly on the primordium), or
- mis-identification of the first increment.

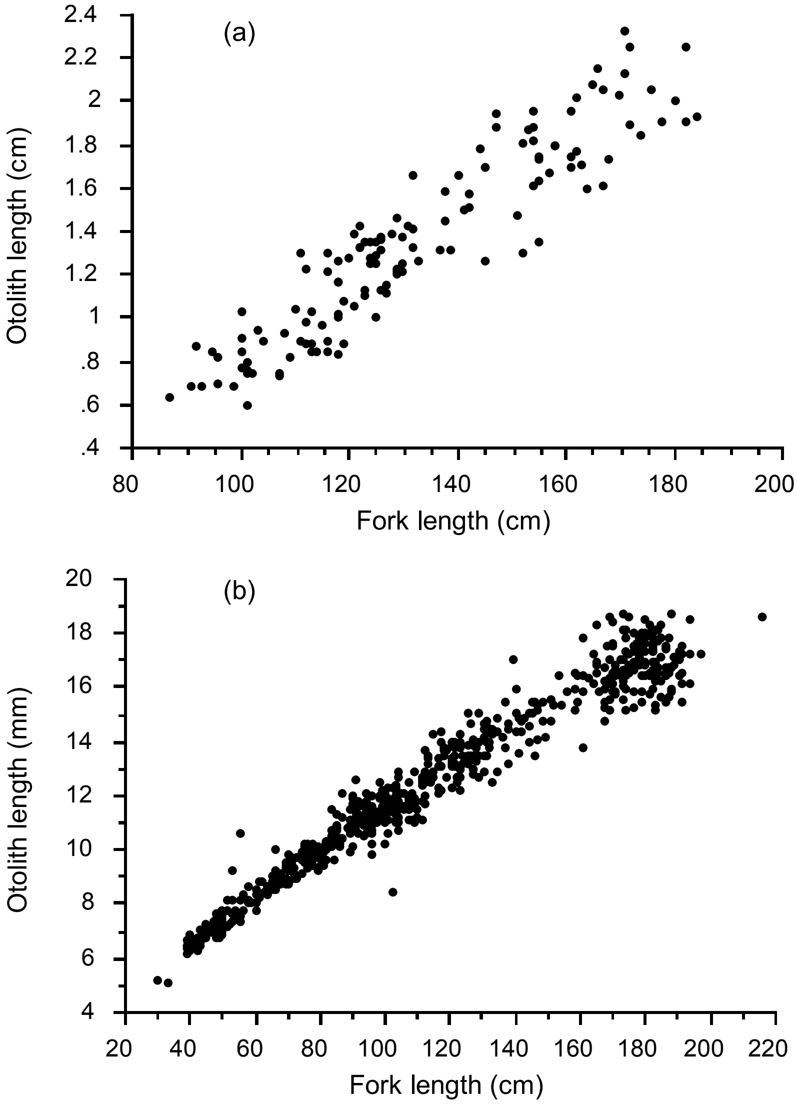

Figure 9.2. Otolith length as a function of fork length in SBT. (a) Otolith length measured from the first increment to the otolith edge on transverse section along the medial ventral ridge (n=133); (b) otolith length is length of whole otolith (n=741).

Table 9.1. Mean and standard deviation (SD) of otolith growth by cohort and age class for SBT.

	Age 1+			Age 2+			Age 3+			Age 4+		
Cohort	Growth	SD	N	Growth	SD	N	Growth	SD	N	Growth	SD	N
1954	0.22		1									
1955				0.15		1						
1956							0.14		1			
1957										0.17		1
1958	0.33		1									
1959				0.26		1						
1960							0.19		1			
1961	0.25	0.03	3							0.14		1
1962	0.28	0.19	4	0.22	0.07	3						
1963	0.27	0.10	6	0.26	0.04	4	0.21	0.05	3			
1964	0.31	0.05	7	0.21	0.06	6	0.20	0.04	4	0.16	0.03	3
1965	0.32	0.07	13	0.23	0.02	7	0.17	0.06	6	0.16	0.04	4
1966	0.34	0.07	11	0.24	0.05	13	0.18	0.05	7	0.16	0.04	6
1967	0.32	0.09	21	0.26	0.05	11	0.17	0.04	13	0.16	0.03	7
1968	0.31	0.10	11	0.24	0.06	21	0.20	0.06	11	0.14	0.02	13
1969	0.34	0.07	16	0.23	0.06	11	0.18	0.04	21	0.18	0.05	11
1970	0.31	0.06	12	0.27	0.05	16	0.18	0.04	11	0.16	0.02	21
1971	0.31	0.06	18	0.24	0.08	12	0.21	0.04	16	0.17	0.03	11
1972	0.32	0.05	15	0.24	0.05	18	0.20	0.05	12	0.18	0.04	16
1973	0.30	0.08	17	0.27	0.07	15	0.20	0.05	18	0.17	0.04	12
1974	0.34	0.08	15	0.23	0.07	17	0.19	0.04	15	0.17	0.03	18
1975	0.30	0.08	15	0.23	0.06	15	0.20	0.05	17	0.17	0.05	15
1976	0.32	0.07	14	0.24	0.04	15	0.17	0.04	15	0.17	0.04	17
1977	0.30	0.08	19	0.23	0.06	14	0.20	0.04	15	0.15	0.04	15
1978	0.29	0.06	16	0.24	0.08	19	0.18	0.05	14	0.18	0.04	15
1979	0.26	0.06	14	0.21	0.05	16	0.19	0.04	19	0.15	0.03	14
1980	0.30	0.09	14	0.20	0.04	14	0.17	0.04	16	0.14	0.02	19
1981	0.36	0.08	17	0.21	0.05	14	0.17	0.03	14	0.15	0.03	16
1982	0.34	0.07	10	0.25	0.05	17	0.17	0.04	14	0.15	0.02	14
1983	0.33	0.05	15	0.27	0.05	10	0.19	0.05	17	0.15	0.02	14
1984	0.38	0.08	16	0.27	0.07	15	0.20	0.03	10	0.16	0.04	17
1985	0.35	0.08	15	0.27	0.05	16	0.19	0.05	15	0.16	0.04	10
1986	0.34	0.08	18	0.25	0.07	15	0.21	0.06	16	0.16	0.03	15
1987	0.33	0.08	12	0.25	0.04	18	0.20	0.04	15	0.17	0.04	16
1988	0.40	0.09	27	0.24	0.06	12	0.19	0.03	18	0.17	0.03	14
1989	0.35	0.08	25	0.27	0.06	27	0.20	0.04	12	0.16	0.02	18
1990	0.38	0.07	9	0.26	0.06	25	0.19	0.04	27	0.16	0.05	12
1991	0.39	0.08	35	0.28	0.06	9	0.20	0.05	25	0.16	0.04	27
1992	0.42	0.07	14	0.27	0.05	35	0.22	0.05	9	0.18	0.04	23
1993	0.40	0.09	6	0.27	0.05	14	0.22	0.05	28	0.22	0.04	6
1994	0.35	0.05	7	0.26	0.03	6	0.23	0.04	5	0.19	0.03	6
1995	0.47		1	0.27	0.05	7	0.18	0.05	6			

Trends in the mean back-calculated otolith growth rate from 1954-1995 show that growth for both 1+ and 2+ fish was relatively constant in the 1960s and 1970s, after which it appears that growth increased substantially and continued to increase through the early 1990s (Fig. 3). The 1979 cohort has the smallest mean growth increment. The absence of an obvious change in growth for 3+ and 4+ fish is not unexpected, as otolith growth increments are smaller for years 3-5 than for the first couple of years of life. There is some indication of a steep increase in growth in the late 1950s. However, we believe this is most likely an artifact of small sample sizes.

Mean annual otolith growth by decade (Fig. 4) shows that otolith growth was similar during the 1960s and 1970s, and increased in the 1980s and 1990s for 1+ and 2+ SBT. The mean growth rate for the 1980s was approximately 14% higher than it had been during the 1960s and 1970s. Although we have analysed fewer otoliths from the 1990s, it appears that growth continued to increase during this period. Mean growth rates of the 1990s were approximately 10% higher than for the 1980s.

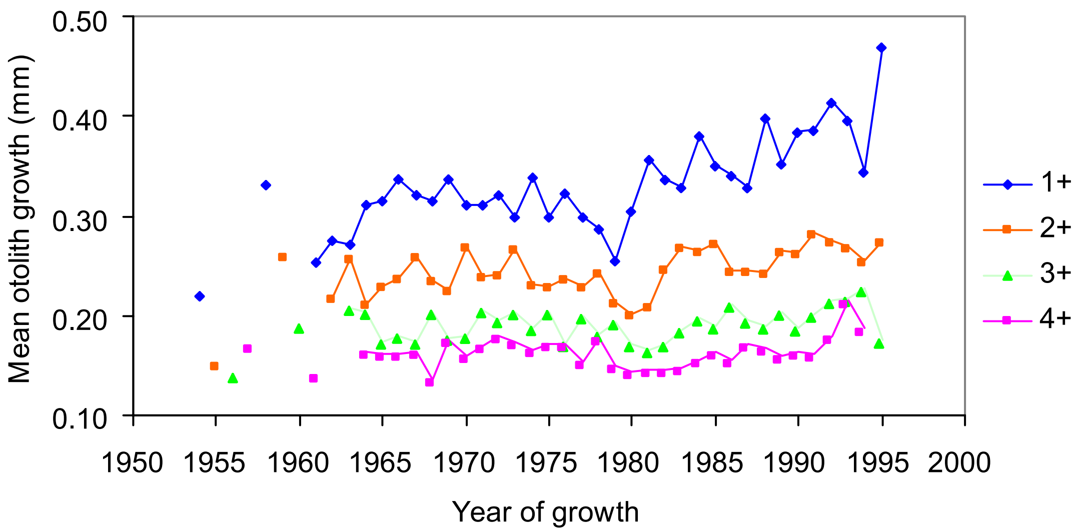

Figure 9.3. Mean back-calculated otolith growth for 1+ to 4+ aged SBT.

Discussion

Lee's phenomenon

Our results suggest that the growth rates of juvenile SBT increased between the 1960s and 1980s, and are continuing to increase in the 1990s. However, in other species, it has been demonstrated that an increase in growth rates over time can be due to "Lee's phenomenon" (Ricker, 1969). Lee's phenomenon is an effect associated with size-selective mortality that works on the theory that mortality is greater among the larger individuals of a given age (those with a faster growth rate) than among the smaller individuals (slower growth rate). The result is that slower growing individuals have a greater chance of survival and reaching older age than faster growing individuals. Therefore, when conducting a growth study using back-calculation techniques, the older individuals sampled will be those that had slow juvenile growth rates and the younger individuals sampled will have had faster juvenile growth rates.

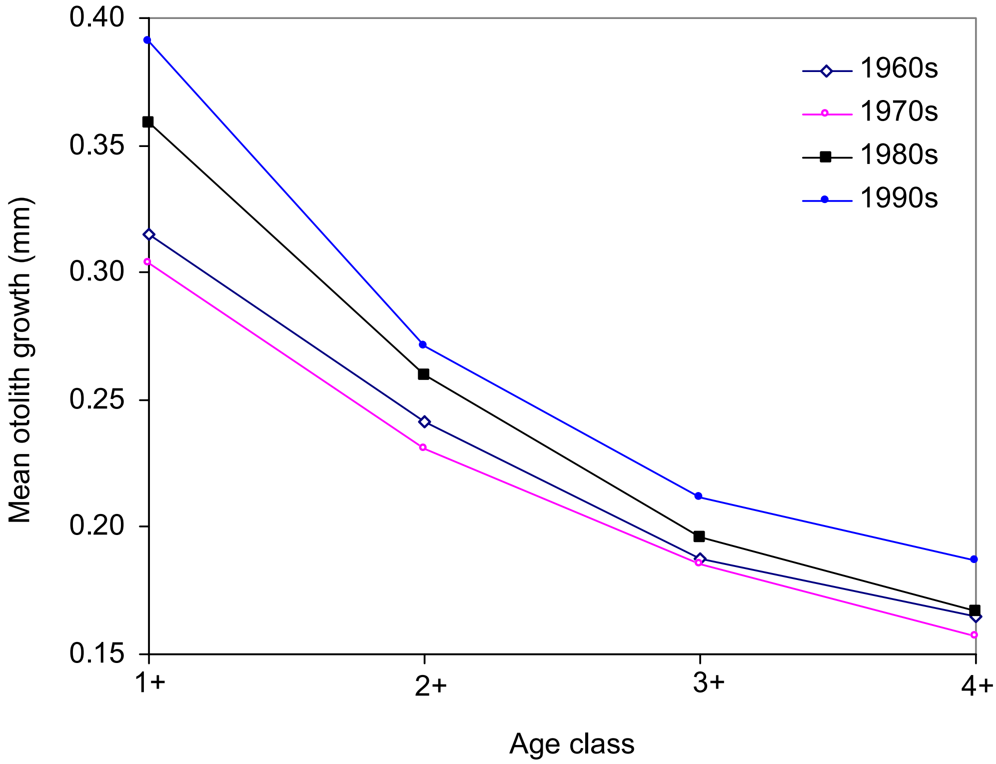

Figure 9.4. Mean back-calculated otolith growth for SBT by age class and decade (with 95% confidence intervals).

If Lee's phenomenon were present in our data, the back-calculated otolith growth rates measured from old fish would be less than for those measured from young fish. Since our SBT ranged in age from 2-41 years, and they were all sampled in the 1990s, we were forced to use increasingly older fish to estimate juvenile growth rates back to the 1950s. The question is how reliable are our back-calculated growth rates? Due to small sample sizes, we are unable to compare back-calculated growth rates from SBT of the same age caught over different decades, nor SBT of different ages born in the same year. Our main indication that Lee's phenomenon is not influencing our data is that estimated growth rates are fairly constant until the late 70s (if not slightly decreasing), before it increased. If Lee's phenomenon were present, the change in growth would be constant from the 60s to the 90s. Further, we have not observed any old SBT that are markedly small for their age, suggesting that growth-dependent mortality is unlikely in SBT.

Causes of growth change

What caused the apparent changes in juvenile growth rates is unclear. Growth rates of fish are known to vary over time, and are usually the result of a change in food availability, temperature or a genetic change in the stock. In SBT, it seems plausible, as the numbers of juveniles being taken from the population peaked in the 1970s and early 1980s (Fig. 5), that it might be a density-dependent response. Population size can affect growth when individuals are competing for the same resources. Density-dependent growth has been reported for larval SBT in the north-east Indian Ocean (Jenkins et al., 1991), and for several heavily exploited fish stocks such as Atlantic mackerel (Overholtz, 1989), silver hakes (Helser and Almeida, 1997) and some species from the North Sea (Daan et al., 1990).

SBT are opportunistic feeders, preying on fish, cephalopods and crustaceans (Young et al., 1997). Kemps et al. (1999) found that juvenile SBT caught off the SW coast of Western Australia in 1998 and 1999 fed predominantly on jack mackerel (*Trachusur declivis)* and blue mackerel (*Scomber australasicus)*. Unfortunately, time-series data is not available on the abundance of either species off the SW coast of Western Australia or in the Great Australian Bight. However, if decreased abundance of SBT were the single cause of the change in growth in SBT, we would expect to see a stabilisation in growth in the 1990s as abundance of juveniles also stabilised since the introduction of quotas in 1987 (Fig. 4). As we do not see this, it is possible that other factors are also influencing growth in SBT.

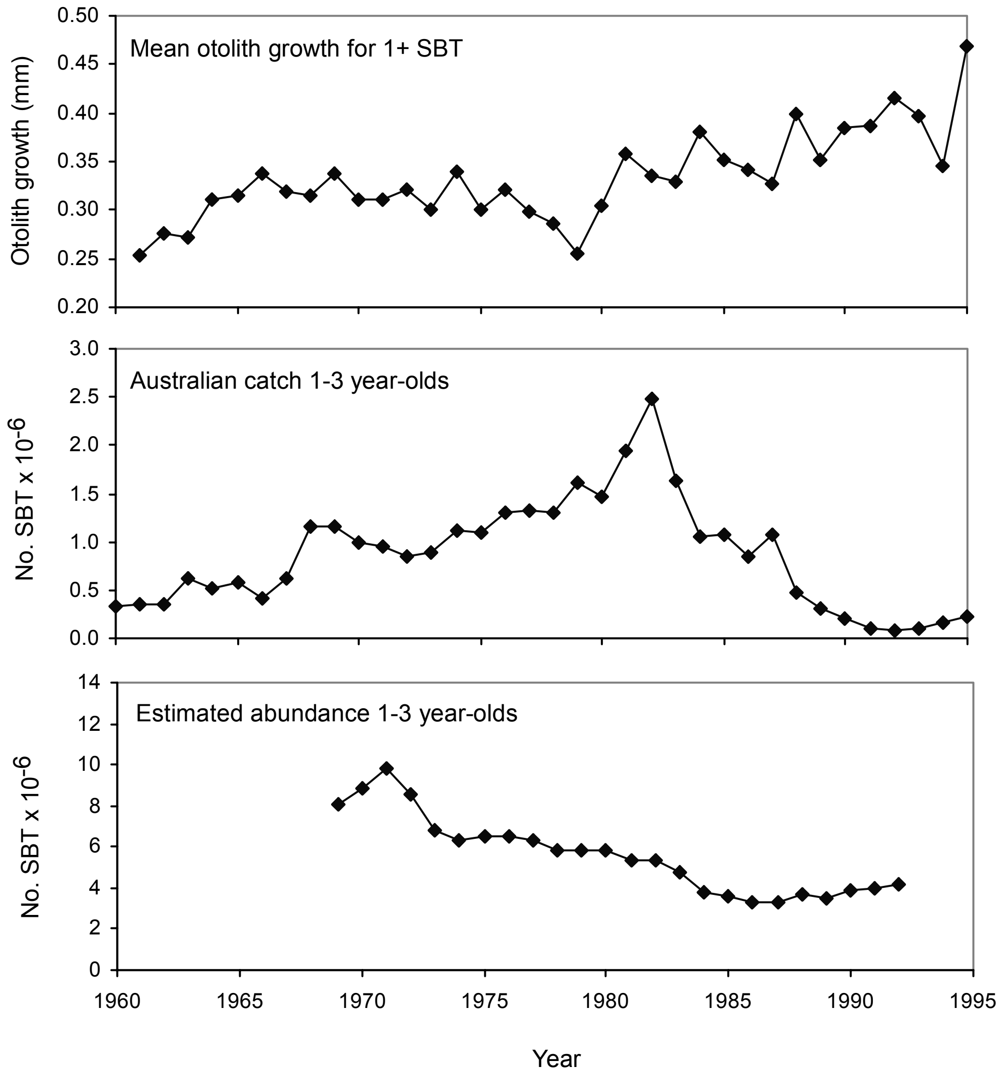

Figure 9.5: Comparison of mean otolith growth for 1+ SBT with the Australian catch of 1-3 year olds, and abundance of 1-3 year olds estimated from VPA models (mid-range estimate). The Australian fishery operates predominantly in the Great Australian Bight (GAB) where the majority of juvenile SBT are believed to feed during summer.

Another hypothesis is that environmental factors have influenced growth rates and that there have been significant changes in these over the last 30 years. Environmental change can occur on a long-term global scale (eg global warming) as well as short-term regional scales (eg inter-annual variations in temperature, short-term fluctuations in prey abundance, SOI etc). Global warming is usually associated with increases in air temperature, although changes in precipitation, wind velocities or sunshine hours may also occur.

Global air temperatures are known to have varied significantly over the past century with two major periods of global warming in 1920-39 and 1967-86 (Jones et al, 1991). Such changes in climate will affect surface layers of the oceans where juvenile SBT spend much of their time. Figure 6 shows the land air temperature anomalies (global and southern hemisphere) and SST anomalies (global and Indian Ocean) between the 1960s and the late-1990s. Not only do these show a strong coupling between the ocean and atmosphere globally, but also the shift in climate in the late 1970s towards warmer temperatures. It seems plausible that since SBT otoliths growth rates changed at the same time, they may have been in response to environmental conditions to some extent. The fact that temperatures are continuing to increase in the 1990s also supports our finding that growth rates are still increasing.

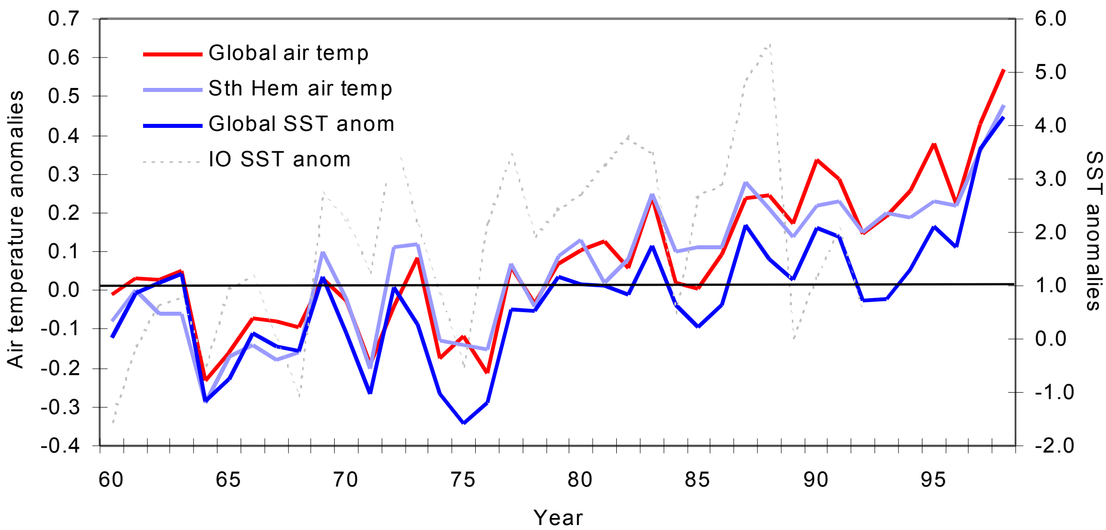

Figure 9.6. Coupling between air temperature (global and southern hemisphere) and SST (global and Indian Ocean).

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10. ESTIMATING THE NATURAL MORTALITY RATE FOR MATURE SBT FROM CATCH AND DIRECT-AGE DATA

William Hearn

Abstract

Estimating the natural mortality rate of ocean fish species is a difficult task. This could possibly be achieved through a costly tag-return experiment. However, the exacting experimental requirements are difficult to meet. Another way of estimating natural mortality rates of fish is to analyse the age structure of stock samples taken before any fishing occurs. This approach assumes that (i) the sample represents the age-structure of the living population, (ii) the animals are long-lived, so that statistical variations in recruitment does not dominate the population age structure, (iii) the ageing method is adequate, and (iv) the natural mortality rate is age dependent. We use an extension of this approach (somewhat similar to the method of Hilborn et al., 1998) for populations that have been harvested for many years, provided annual catch numbers and direct ageing of catches for some recent years are available. We analyse southern bluefin tuna catch statistics and direct-age data sampled from Japanese and Indonesian catches. Conditional on a tagging estimate of 0.4yr^{-1} for one-year-old fish and declining for older fish, the best estimates of the natural mortality rate for fish between ages 11 and 31 years are about 0.1 yr^{-1}, with standard errors of about 0.01. There is good agreement between the estimates obtained from the direct-age samples from the Japanese and Indonesian catches. From age 31 year to 40 years the natural mortality rate dramatically increases, maybe due to the onset of senescence, to about 0.4 yr^{-1} from Japanese data, and to about 0.8 yr^{-1} from Indonesian spawning ground data. Old big fish in the spawning ground are more likely to be caught in or near the water surface, which may explain the difference between results from Indonesian and Japanese data. Possible ways to improve the method for estimating the natural mortality rate are discussed.

Introduction

For hunted animals, the separation of the total mortality rate into its hunting and natural components is a difficult task. The modification of the Brownie et al. (1985) multiple year tag-recovery method by Pollock et al. (1991), is commonly used to achieve this objective. However, the experimental requirements of a multiple year tagging program are costly and difficult to meet. That is, to tag sufficient numbers of fish without impairing them or altering their behaviour, that tags do not shed, that different batches of tagged fish mix, that all caught tagged fish have their tags returned to scientists or that departures from these requirements may be quantified.

Another weakness of such experiments, if natural mortality is age dependent, is that the natural mortality rate can only be estimated for the age range over which fish are tagged, even though tags may be recovered from much older fish. For example, large numbers of southern bluefin tuna have been tagged between 1 and 3 years of age, because they form large inshore surface schools. Thus natural mortality rates for juveniles have been estimated from tagging data (Polacheck, et al., 1997). However, this approach cannot be implemented for mature fish as they inhabit ocean waters, making them far too costly to catch and tag.

Another way of estimating natural mortality rates is to analyse the age structure of samples from the virgin stock. A straight line is fitted to the natural logarithm of the population's age composition. The negative of the slope is then an estimate of the natural mortality rate. This approach assumes that (i) the sample represents the age-structure of the population (often the samples are simply taken from fishers catches), (ii) the animals are long lived, (so that recruitment variation can be considered to be part of the statistical noise) or that samples are collected over several years, (iii) the ageing method is adequate, especially for old fish, and (iv) the natural mortality rate is constant.

This approach has been extended to populations that have been harvested for many years, where (i) the age-structure of the catch has been monitored since the start of exploitation, and (ii) the gear selectivity by age and year can be formulated in a simplified manner. Such approaches are essentially population assessment models.

Hilborn et al. (1998) developed and applied such a model to southern bluefin tuna catch-at-age data and direct-age data, and they estimated the natural mortality rate to be about 0.08 yr^{-1}. The catch-at-age data they analyse was derived from length-frequency data using growth curves and the knife-edged partition method. We believe this procedure is unreliable, especially for older fish, because length variation of fish within each age is not taken into account.

For ages more than 5 (or 6 or 7) years, we avoid analysing these dubious catch-at-age data by assuming that gear selectivity is age-dependent. Our model analyses annual catches by longliners, and direct-age data, to estimate age-dependent natural mortality rates and the stock-recruitment parameters. If the direct-age sample does not represent the catch, then an adjustment can be made, assuming that the age distribution for each length is common for the sample and the catch. For one-year-olds we use a natural mortality rate estimate of 0.4 yr^{-1}, which was determined from tag-return data (Polacheck, et al., 1997). This is assumed to decline linearly to the adult rate for 11 year and older fish.

We suggest future modifications to the approach to allow for (i) the incorporation of all the catch length-frequency data into our model (maybe only using the knife-edged partition method for ageing young fish), and (ii) catch selectivities to be time-dependent, in addition to being age-dependent.

Analyses procedures

Assumptions

The key assumptions are:

1. The initial population is an unfished stock that has reached a steady state.

2. Annual catch numbers have been collected, or estimated, since the start of fishing.

3. Recruitment follows a parental biomass - recruitment relation. If recruitment differ from this relation, this difference is considered to be part of the model variance. This seems a reasonable assumption for long-lived fish such as southern bluefin tuna.

4. After a certain age, fishing selectivity is age-dependant (constant being the simplest case).

5. The natural mortality rate is age dependent, M_i (age i), but is a fixed (unknown) value for mature fish, which may increase for very old fish.

6. Catch-at-age may be known up to a certain age.

7. The sample represents the catch, or a mathematical adjustment to the sample information can be made for this purpose.

Model

We use a population model similar to the one in Hilborn et al. (1998). For simplicity we use the Pope (1972) approximation, that assumes that the number of fish of age i, C_{ji}, are caught in the middle of year j. (The model could be extended to incorporate instantaneous fishing mortality rates, F_{ji}.) At the beginning of year j the number of fish aged i is P_{ji}.

The input information are:

1. Catch-at-age numbers C_{ji} up to age x-1 for all years j. The fishing selectivity assumption (4) then only needs to apply to fish from age x and older. Individual year/age catches C_{ji} may be estimated from a length-frequency sampling program where ages are estimated from length by a length-at-age growth curve and knife-edged partition. This method of determining the ages of fish might be considered to be reliable up to age x-1, but unreliable for older fish.

2. Catches C_{ji} are summed over $x \le i \le X$ (X is the maximum age the fish are likely to live to) to obtain C_{jx+}. In year j the total number of fish caught, $C_{j\bullet}$, may be estimated from a length-frequency sampling program and C_{jx+} is estimated from
$$C_{jx+} = C_{j\bullet} - \sum_{i=1}^{x-1} C_{ji}. \qquad (1)$$
Note: this means that to estimate C_{jx+} we need no estimate of C_{ji} for each year j and age i, where $x \le i \le X$.

3. For a limited number of recent years, the ages of fish in a catch sample are estimated by direct means. Direct aging from otoliths (say) is considered to be much more reliable than estimates from fish lengths using growth curves and knife-edged partition.

4. If the direct-age sample is not representative of the catch, then length-frequency data are needed for both the catch and the direct-age sample.

Model development

1. The initial steady state population size depends on the recruitment number and natural mortality. Thus at the start of year 1 the number of fish at age i is

$$P_{1i} = R_1 \prod_{k=1}^{i-1} e^{-M_k}, \tag{2}$$

where R_1 is the number of one year olds recruited to the unfished population each year.

2. Recruitment estimates are made from a parental-biomass/recruitment relation. Recruitment (R_j) in year j is assumed to be at age 1 so that

   $R_j = R(N_1, PB_1, PB_{j\text{-}1}$, parameters),

   where PB_j is the parental biomass at the beginning of year j.
   Normally $P_{j1} = R_j$ unless fish are caught before age 1, i.e. $C_{j0} > 0$. In which case an adjustment is made so that,

$$P_{j1} = R_j - C_{j-1,0} e^{-0.5M_1}. \tag{3}$$

   For simplicity, recruitment is assumed to decline linearly as the parental biomass decreases, i.e.

$$R_j = R_1 \left\{ 1 - \gamma \left(1 - \frac{PB_{j-1}}{PB_1} \right) \right\}, \tag{4}$$

   where γ is the recruitment change rate with respect to the relative parental biomass (i.e., relative to its virgin parental biomass). If $\gamma = 0$ then recruitment is assumed constant, and if $\gamma = 1$ then recruitment is proportional to the parental biomass. Note: for $\gamma < 1$ the number of recruits per parental biomass increases as the parental biomass decreases. This is deemed to be the normal compensatory response by a declining population. Over the life-time of a long-lived species we normally expect $0 \leq \gamma \leq 1.0$. For $\gamma < 1$ it is noted that (4) is unsuitable in the extreme case when the parental biomass PB_{j-1} is close to zero, as it implies that the recruitment R_j is far from zero, a biological impossibility.

3. Population sizes to age x are estimated by

$$P_{j+1,i+1} = P_{ji} e^{-M_i} - C_{ji} e^{-0.5M_i}, \tag{5}$$

   the forward version of Pope's (1972) approximation to the virtual population analysis, which is deemed to be appropriate for southern bluefin tuna more than 4 years old, as most longline catches occur in the southern winter.

4. For ages x and older, the catches C_{ji} are not reliably known, but for these fish we assume the selectivity is age dependent, i.e. ψ_i. The value of the catches are expected to be

$$E(C_{ji}) = \alpha_{ji} C_{jx+}, \tag{6}$$

   where $\alpha_{ji} = \dfrac{\psi_i P_{ji} e^{-0.5M_i}}{\sum_{k=x}^{X} \psi_k P_{jk} e^{-0.5M_k}}$. (7)

   It is readily shown that $\sum_{k=x}^{X} E(C_{jk}) = C_{jx+}$, as required. This is applicable if Pope's method is used, but a method could be developed for estimating $E(C_{ji})$ in the case where the fishing mortality rates F_{ji} are assumed constant throughout year j.

5. Estimates of population-at-age number for fish aged more than x can be determined from

6.
$$P_{j+1,i+1} = P_{ji}e^{-M_i} - E(C_{ji})e^{-0.5M_i}. \tag{8}$$

This enables $E(C_{j+1,i+1})$ to be obtained from equations (6) and (7), so establishing an iterative process.

6. In some years j, $y \le j \le Y$ numbers (n_{ji}) of fish from a random sample of the catch have ages accurately determined from their otoliths. The age distribution of the expected catch, $E(C_{ji})$, are fitted to these data to estimate model parameters, R_1, γ, M_i, and ψ_i. To fit the model from ages x_1 to X_1 we minimise the negative log-likelihood, conditional on the total number in the sample between ages x_1 to X_1 each year, viz.,

$$-\sum_{j=y}^{j=Y}\sum_{i=x_1}^{X_1} n_{ji} \log\left(\frac{E(C_{ji})}{\sum_{k=x_1}^{X_1} E(C_{jk})}\right). \tag{9}$$

7. The sample from which fish have their otoliths taken and aged, may not represent the length distribution of the catch. However, we assume that the age distribution of fish at a particular length is representative, i.e. for fish of a given length there is no selection based on age. For each length l we calculate the weighting function

$$f_{jl} = \frac{C_{jl}S_j}{C_jS_{jl}}, \tag{10}$$

where for year j C_{jl} is the catch number at length l, C_j is the total catch number, S_{jl} is the sample number at length l that are aged, and S_j is the total number of the aged sample. We multiply every aged fish having length l by f_{jl} to obtain a pseudo-sample with the same length and age distributions as the catch. The total number in the pseudo-sample is the same as for the real sample. When used in maximum-likelihood analyses this will allow a rough estimate of likelihoods. Note that re-scaling the pseudo-sample affects neither parameter estimates nor bootstrap variance estimates.

8. Bootstrap samples were generated by random selection, with replacement, from the observed direct-age sample. One thousand bootstrap samples each from the Japanese and Indonesian samples. Each bootstrap sample was the same size as the original sample. The same bootstrap samples were analysed by all models.

Background

Southern bluefin tuna (SBT) are a highly migratory species. At about age 10-12 years old they begin to spawn in waters south of Java during the southern summer. When almost a year old they appear in the surface fishery off the south coast of Western Australia (WA) and for the next three to four years are found in fishing grounds off South Australia (SA), New South Wales (NSW) and Tasmania (Tas). By about five years of age almost all have departed for oceanic waters between 30^o and 50^o S over the extent of the Eastern Hemisphere and a little beyond, where they are caught by longliners, mostly Japanese, but including Korean and Taiwanese fishers. We call this the Japanese fishery.

Until 1961 the Japanese fleet caught mature fish in the spawning grounds. Afterwards, the fleet moved southwards to the winter feeding grounds between 30^o and 50^o, where they catch fish older than two years of age. Increasingly over recent years, SBT have been caught in the north of the spawning ground. We call this the Indonesian fishery.

The procedures for collecting and estimating SBT catch and length-frequency distributions are described in Polacheck et al. (1998). The catch-at-age matrix is calculated from length-frequencies by the method of knife-edged partition using the Hearn (1994) growth curves obtained from the growth parameters that were estimated in the 1994 Workshop (Anon, 1994). This method becomes increasingly unreliable as fish grow older and lengths of fish from different ages overlap more. This overlapping has two causes, the growth rate slows, and the length range, of fish of a given age-class, widens as they become older. We avoid analysing catch-at-age data that has been derived from length-frequencies, with two exceptions, (i) young juveniles that are mainly caught by the Australian fishery, and (ii) to estimate the biomass of the parental stock.

Sampling otoliths and age determination

Longliners catch SBT for the lucrative Tokyo sashimi market, some individual fish are worth many thousands of dollars. The longliners are assumed to catch fish in a non-decriminatory way from about 5 to 7 years of age. In the early to mid 1990s otoliths samples from the Japanese fishery have been collected over the geographical range of the catches. In the model the Japanese samples are, for simplicity, assumed to be collected on July 1 each year.

To avoid external damage to these valuable fish, which are frozen to lower than –55 $^\circ$ C, the otoliths are extracted from the underside of the cranium using a hole-saw fitted to a cordless electric drill as detailed in Gunn et al. (In press).

Otoliths were also collected from fish caught by the Indonesian fishery. Otoliths are sampled from fish that are unsuitable for export. Fish were rejected on the basis of the condition of their flesh and not length. Therefore, the sampled fish were considered to be representative of the catch of the Indonesian fishery. Sampling of otoliths from the Indonesian catch of mature southern bluefin tuna is detailed in Davis et al. (1998). In the model the Indonesian samples are assumed to be collected at the centre of the spawning period, i.e. January 1.

The otoliths were prepared, sectioned and ages determined from annual growth rings by the techniques described in Gunn et al. (In press). We assume that the rings are formed on midnight of June 30, i.e. if *n* rings are counted on the otolith then the fish's age is nominated as (i) *n* years when fish are caught on or before June 30, and (ii) *n*-1 years when fish are caught afterwards.

By analysing tagging data from the 1991-1995 tag-return experiment, Polacheck et al. (1997) estimated M_1 = 0.40 (for their reporting rate model 1), which we input into the model.

Model specific to SBT

Natural mortality

For many animals, including humans, the natural mortality rate is J-shaped, i.e high for the very young, reduces for the older juveniles and adults and then increases rapidly when senescence sets in. We assume that natural mortality starts at M_1 = 0.4 for fish age 1 (or less) and linearly declines to M_A at age of maturity (11 years) and it remains constant for older ages or until senescence (when it is equal to M_S). Therefore,

$$M_i = M_1 - \frac{(M_1 - M_A)(i-1)}{10} \qquad \text{for } i < 11,$$

$$M_i = M_A \qquad \text{for } 11 \le i,$$

or

$$M_i = M_S \qquad \text{for } 31 \le i.$$

Selectivity function

We consider two selectivity (or catchablity) functions for ages for $i \ge x$,

a. $\psi_i = 1$ or

b. $\psi_i = \psi_1$ for $i \le$ age 6

and $\psi_i = 1$ for $i \ge$ age 7.

To 1961 the longline fishery virtually only harvested on the spawning ground and caught mature fish (≥ 11 ten years old). Therefore, we include the condition that $\psi_i = 0$ for i <11 and $j \le 1961$.

Parental-biomass function

The parental biomass in year j is equal to

$$PB_j = \sum_{i=11}^{40} P_{ji} W_{ji},$$

where W_{ji} is the average whole-weight of a pre-spawning fish of age i in year j. The W_{ji} is estimated as

$$W_{ji} = 1.15 a L_{ji}^b,$$

where L_{ji} is the expected length of an i-year-old on January 1 of year j (Hearn, 1994, Table 1), and a = 0.000002942, b = 3.3438 are the weight-at-length parameters for plump pre-spawning SBT (Warashima and Hisada, 1970), and 1.15 is the constant to convert from gilled-and-gutted weight to whole-weight (Kalish and Taylor, 1992).

In analysing bootstrap samples, we eliminate unreasonable estimates by constraining parameters γ and P_1, such that $0 \le \gamma \le 1.0$ and $P_1 \le 30{,}000{,}000$.

Results

SBT length-frequencies from Japanese direct-age samples were pooled over years 1992 to 1994. Direct-age data from other years were excluded because of low numbers, truncated age ranges, or that the corresponding processed catch data are not yet available. Their 5 cm running means are graphed in Figure 1 and compared with the equivalent graph derived from Japanese catch length-frequencies (some Japanese catch samples were measured to the nearest 5 cm). The numbers are scaled to equal 1000 units for lengths greater than or equal to 130cm (the expected length of a 5 year old SBT in mid-year). It can be seen that the direct-age sample is biased towards large fish. The ratio of these two curves was used in equation (10) to adjust the direct-age sample's distribution of ages so that it represents the age distribution of the Japanese catch (Figure 2).

We then investigated the Indonesian caught sample. The sub-sample from which otoliths were taken and aged, was found to be not significantly different from the catch sample. Therefore, no adjustment was made to the direct-age data. The age-frequency of the Indonesian direct-age data is pooled for years 1994 and 1996, and percentages are plotted in Figure 3 (other years have low numbers) versus the 1992-94 adjusted Japanese age-frequencies. It appears that the mature fish are not fully recruited to the northern Indonesian spawning grounds until about 18 years old.

Constant selectivity

We believe that selectivity assumptions are not applicable to the Australian fishery due to the extensive use of spotting aircraft to locate surface schools and identify fish sizes. Few SBT, aged 5 years or older, are caught by the Australian fishery, therefore we require x to be greater than or equal to 5 years. Using maximum likelihood, we fitted the model, with $X = 40$ years, to the Japanese direct-age data from ages x_1 (= x) = 5, 6 and 7 years to $X_1 = 35$ year, and $\psi_1 = 1.0$. The estimates of parameters P_1, γ and M_A are listed in Table 1 a,b,c (i.e. Models 1 a,b,c) along with the bootstrap standard errors. For $x = 6$ years the standard errors are least for all parameters, so we select this solution as the best of the three.

The Indonesian data set only provides information on adult fish, so the parameters P_1 and γ cannot expected to be estimated from these data. For these parameters, we assume the values estimated from Japanese data with for $x_1 = 5, 6, 7$ years and $X = 40$ years, and then estimate M_A by fitting the Indonesian direct-age data to the model over ages $x_1 = 18$ years to $X_1 = 35$ years (Table 2 a,b,c). The estimates of M_A from the Indonesian data (Table 2 a,b,c) are 7.4 to 14.6 % higher than the corresponding estimates obtained from Japanese data (Table 1 a,b,c).

Variable selectivity

We used the selectivity function that specified $\psi_i = \psi_1$ for $i \leq$ age 6 years and $\psi_i = 1$ for $i \geq 7$. To the Japanese direct-age data we fitted this model, with $X = 40$ years, for ages x_1 (= x) = 5 and 6 years to $X_1 = 35$ year. Parameter estimates of P_1, γ, M_A and ψ_1, and bootstrap standard errors are listed in Table 1 d,e. For both cases, it is noted that ψ_1 was estimated to be higher than 1.0 for all of 1000 bootstrap samples, i.e. $p < 0.001$. Conditional on the estimates of P_1, γ, and ψ_1 (Table 1 d,e), from Japanese data, the estimates of M_A from the Indonesian data (Table 2 d,e) are 19.0% to 25.0 % higher than the corresponding estimates obtained from Japanese data (Table 1 d,e).

For model 1d (Table 1), there were (i) 390 bootstrap samples for which the estimate of P_1 was at the 30,000,000 upper limit, and (ii) 211 and 5 bootstrap samples, respectively, for which the estimate of γ was at the 0.0 lower limit and 1.0 upper limit. For Model 1 e, there were (i) 32 samples with P_1 at the 30,000,000 upper limit, and (ii) 7 samples with γ at the 0.0 lower limit.

Senescence

We added M_S to the parameter set and fitted the model to the Japanese direct-age data for the 5 Table 1 scenarios. It was found that changing the natural mortality from M_A to M_S at age 31 years resulted in the lowest –*LL* value. The estimated parameters are listed in Table 3. For every 1000 bootstrap sample in each 5 scenarios the estimate of M_S was greater than that of M_A (i.e. $p \leq 0.001$), as expected for very old animals.

For model 3 d (Table 3), there were (i) 202 bootstrap samples for which the estimate of P_1 was at the 30,000,000 upper limit, and (ii) 10 bootstrap samples, for which the estimate of γ was at the 0.0 lower limit. For model 3 e, there were (i) 13 samples with P_1 at the 30,000,000 upper limit, and (ii) 1 sample each with γ at the 0.0 lower limit and the 1.00 upper limit.

We then estimated M_A and M_S (Table 4 a-e), from the Indonesian direct-age data, conditional on the estimates of parameters P_1, γ, and ψ_1 that were derived from the Japanese data (Table 3 a-e). The estimates of M_A from the Indonesian data differed little (–6.4 to +5.3 %) from the corresponding estimates obtained from Japanese data (Table 1 a-e), i.e. there is no significant difference. However, in all cases the estimates of M_S from the Indonesian data (Table 4 a-e) were significantly higher (p = 0.027 to 0.040) than those derived from the Japanese data (Table 3 a-e).

For the Japanese data, the adjusted age-frequencies are pooled over the 1992-94 period. In Figure 4, these are compared with their expected values derived from the parameters obtained from the Japanese data (Table 1, c and Table 3, e). Similarly, the Indonesian age-frequencies, pooled over years 1994 and 1996, are compared (Figure 5) with the expected values obtained from the parameters in Table 2, c and Table 4, e.

Discussion

It is clear from Tables 1 and 3 that models which assume constant fishing selectivity after age 7, and take account of senescence after age 31 years, best fit the Japanese direct-age data. Which means, we need to compare the estimates of M_A and M_S between c, d and e in Table 3. They assume adequate ageing by growth curve and knife-edged partition for fish younger than (i) 7 years (~146cm or 51kg) for (c), (ii) 5 years (~130cm or 34.5 kg) for (d), and 6 years (~139cm or 43kg) for (e). The populations of these younger fish are modeled closely by VPA (conditional on the adequacy of the ageing technique). Fish of ages 5 and 6 years for (d) and age 6 years for (e) are assumed to be subject to a different fishing selectivity than for 7 years and older fish.

There is little difference between these three models in their estimates of M_A (< 3%) and M_S (< 5%). However, the standard errors of P_1, γ, and M_A (Table 3) are least for model (e), which we take as the best solution (the standard errors of parameters M_S and ψ_1 differ little between models). For (e) of Table 3 the 95% confidence limits of M_A are [0.0792, 0.1187]. Note: these confidence limits do not fully account for the uncertainty in many of the model assumptions.

Conditional on the estimates of P_1, γ, and ψ_1 from the Japanese data (Table 3), the estimates of M_A from Indonesian data (Table 4) differ by only –6.4% to +5.3% from the Japanese estimates (Table 3). This is gratifying, considering the considerable differences between the ways the data are collected. For (e) of Table 4 the 95% confidence limits of M_A are [0.0879, 0.1120].

That the natural mortality rate increases dramatically after 31 years of age is consistent with senescence in old animals, but it might be due, or partly due, to behavioral differences of old fish. It is intriguing that the estimates of M_S from Indonesian data are about double those from Japanese data. For Indonesian caught fish, it may be an artifact of the "systematic change in depth distribution with size over the whole size range of SBT caught in the spawning ground" (Davis and Farley, 2001). This may result in a smaller proportion of very large fish being caught by the Indonesian fishery than there are in the population, and so account for the higher apparent values of M_S, than are obtained from Japanese data. On the other hand, this behavioral difference might also apply to the Japanese caught fish, but not so strongly.

These results are encouraging, because the only other feasible method, tagging mature southern bluefin tuna, would be extremely expensive and subject to considerable experimental difficulties. These M_A estimates are generally consistent with the provisional estimate of 0.08yr^{-1} by Hilborn et al. (1998). They are at the lower end of the M limits of [0.1, 0.3] used in SBT stock assessments up to 1995, and confirm the values of about 0.1 yr^{-1} used since.

It is clear that this model does more than estimate M_A and M_S. It is a stock assessment model for estimating R_1, γ, ψ_1, M_A and M_S.

We mention some ways to improve our procedure. A better way, than currently used, is being developed to estimate ages from length-frequencies for fish up to ages 7 or 8 years. It takes account of length variation of fish at each age. Incorporating the Southern Oscillation Index into the parental-biomass/recruitment function might lead to a better fit of the model to the data. Analysis of several more years of direct-age data will also improve our procedure (another year's data are almost ready for analysis). The Japanese fishery covers a wide geographical area. Spatial and seasonal variations in the length-frequency are taken into account when estimating the annual catch length-frequency. However, this is not the case with the Japanese direct-age samples, but it needs to be considered.

We suggest a more direct approach for further investigation. It is to modify our model to incorporate catch length-frequency data, which are available for nearly all of the history of the southern bluefin tuna fishery. For a given set of model parameters, generate the expected population year-age-frequencies and their corresponding catches. Then, using an age-length matrix (which has a distribution of lengths for each age) allocate the expected catch for each year-by-age into its length components. For a given year (or shorter time period) and a given length, sum the allocated catches over all ages to generate the expected catch length-frequency for that year. The population parameters values may then be estimated by fitting the expected yearly length-frequencies to the observed ones.

These parameters could be used as input into our model and tested for their consistency with the Japanese and Indonesian direct-age data. Ideally, the model should be modified to allow joint analyses of all data types, catch, length-frequency, effort, direct age, survey, tag-return and environmental data. Conceptually this is what Hilborn et al. (1998) have done, but their procedure involves two steps. Catch length-frequency data is converted to catch-at-age data by the dubious knife-edged partition method, and then the catch-at-age is input into the population model. For southern bluefin tuna this is liable to serious bias, especially for mature fish. In contrast, our proposed method is an integrated approach.

On inspecting the Indonesian age frequency in Figure 3, one might conjecture that mature fish are not fully recruited to the parental stock until about 18 years of age. If true, it has implications for stock assessments and for our model, as we assumed that 11 years is the average age of recruitment to the parental stock.

Parameter γ is feasible mainly in the restricted range [0, 1] and we believe that R_1 is unlikely to be greater than 30.00×10^6. Therefore, it appears that the Bayes approach would better deal with these restrictions on these parameters and give a more precise estimate of M_A.

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Table 10.1. Estimates of parameters R_1, γ, M_A, ψ_i ($i \leq 6$ years) and approximate maximum likelihood –*LL* values from SBT catch and direct-age data sampled from Japanese fishery, for x = 5 to 7 years, X = 40 years, $x_1 = x$, X_1 = 35 years. For constant selectivity, ψ_i = 1.000. Bootstrap standard errors are in brackets.

Model	x(yr)	$R_1(10^6)$	γ	M_A	ψ_i	$-LL$	p
1a	5	10.08	0.670	0.0892	1.000	1532.70	
		(0.99)	(0.056)	(0.0100)			
1b	6	12.24	0.811	0.1065	1.000	1201.54	
		(0.83)	(0.036)	(0.0073)			
1c	7	14.48	0.844	0.1112	1.000	931.86	
		(5.41)	(0.194)	(0.0090)			
1d	5	17.78	0.549	0.1097	1.760	1523.54	< 0.001
		(9.00)	(0.271)	(0.0154)	(0.228)		
1e	6	14.07	0.859	0.1136	1.715	1193.87	< 0.001
		(3.29)	(0.105)	(0.0083)	(0.252)		

Table 10.2. Estimates of parameter M_A and maximum likelihood –*LL* values from SBT catch and direct-age data sampled from Indonesian fishery, for x = 5 to 7 years, x_1 = 18 years, X = 40 years, X_1 = 35 years. They are conditional on the estimates of R_1, γ and ψ_i ($i \leq 6$ years) given in Table 1, that were derived from Japanese direct-age data.

Model	x(yr)	x_1(yr)	$R_1(10^6)$	γ	M_A	ψ_i	$-LL$
2a	5	18	10.08	0.670	0.0982	1.000	1907.18
2b	6	18	12.24	0.811	0.1144	1.000	1907.37
2c	7	18	14.48	0.844	0.1274	1.000	1903.35
2d	5	18	17.78	0.549	0.1371	1.760	1892.57
2e	6	18	14.07	0.859	0.1352	1.715	1899.71

Table 10.3. Estimates of parameters R_1, γ, M_A, M_S (for $i \geq 31$ years), ψ_i ($i \leq 6$ years) and approximate maximum likelihood $-LL$ values from SBT catch and direct-age data sampled from Japanese fishery, for x = 5 to 7 years, X = 40 years, $x_1 = x$, and X_1 = 39 years. For constant selectivity, ψ_i = 1.000. Bootstrap standard errors are in brackets.

Model	x(yr)	$R_1(10^6)$	γ	M_A	M_S	ψ_i	$-LL$
3a	5	9.17	0.633	0.0758	0.395	1.000	1536.72
		(0.94)	(0.056)	(0.0113)	(0.159)		
3b	6	11.30	0.779	0.0949	0.396	1.000	1205.55
		(0.85)	(0.040)	(0.0088)	(0.159)		
3c	7	12.68	0.778	0.0965	0.415	1.000	933.41
		(5.19)	(0.083)	(0.0107)	(0.169)		
3d	5	13.73	0.592	0.0982	0.400	1.741	1527.72
		(9.16)	(0.150)	(0.0177)	(0.161)	(0.243)	
3e	6	12.50	0.798	0.0992	0.422	1.732	1196.78
		(3.21)	(0.065)	(0.0100)	(0.163)	(0.258)	

Table 10.4. Estimates of parameter M_A and M_S and maximum likelihood $-LL$ values from SBT catch and direct-age data sampled from Indonesian fishery, for x = 5 to 7 years, x_1 = 18 years, X = 40 years, and X_1 = 39 years. Conditional on the estimates of R_1, γ and ψ_i ($i \leq 6$ years) given in Table 3, that were derived from Japanese direct-age data. Bootstrap standard errors are in brackets.

Model	x(yr)	x_1(yr)	$R_1(10^6)$	γ	M_A	M_S	ψ_i	$-LL$
4a	5	18	9.17	0.633	0.0733	0.863	1.000	1888.82
					(0.0041)	(0.139)		
4b	6	18	11.30	0.779	0.0888	0.892	1.000	1887.85
					(0.0049)	(0.142)		
4c	7	18	12.68	0.778	0.0952	0.903	1.000	1884.45
					(0.0057)	(0.143)		
4d	5	18	13.73	0.592	0.1034	0.827	1.741	1877.98
					(0.0078)	(0.133)		
4e	6	18	12.50	0.798	0.1005	0.870	1.732	1884.38
					(0.0063)	(0.138)		

11. BENEFITS

The results of this study provide a wide range of benefits to the SBT stock assessment process and in so doing decrease uncertainty within that process:

- The improved scientific understanding of the age structure, growth and natural mortality of SBT provided by the study have been recognized internationally and are to be used in the 2001 CCSBT stock assessment. Specifically:

  - Our revised estimates of the catch-at-age (CAA) of the significant Taiwanese SBT catch were used as a direct input into the CAA matrix for 2001.

  - Our updated age distributions of Indonesian catches on the spawning grounds have been used within the CCSBT Scientific Committee (SC) as an indicator of the recovery of the stock after 14 years of quota management.

  - Our natural mortality estimates for mature age fish based on direct age estimates were also be considered within the CCSBT SC in the last full stock assessment in 2001. Previously estimates of M for these cohorts had been assumed, or inferred from other outputs of the virtual population analyses.

  - Our data on the nature of changes in growth in the SBT population over the last 35 years have also been provided to the CCSBT SC for consideration.

  - The results of this project, and its precursor, FRDC 92/42 have been synthesized with growth data from tagging and length frequencies in FRDC 99/104 to provide the first fully integrated analysis of growth for any tuna species.

  - The results of this project, and its precursor, FRDC 92/42 have also recently been extended at a CCSBT Age Estimation workshop set up to develop and promote a standardized approach to estimating age of SBT using otoliths throughout the CCSBT member countries. This workshop allows the routine estimation of the age structure of the SBT catch, as input into the age structured stock assessment models used by the Scientific Committee.

- This project saw the development of collaborative scientific programs with Taiwan and further expansion of work being conducted on the SBT spawning stocks in collaboration with Indonesia. These collaborations provide critical improvements to our understanding of the catches, fleets, targeting practices and fishery management strategies of these countries, both of which are soon to become members, or co-operating parties to the CCSBT.

It is difficult to measure the economic benefit of research projects that are targeted towards improvements in stock assessments. CSIRO worked hard to ensure that the outputs of research from this project were presented to AFMA, AFFA, industry and the CCSBT in a timely fashion. The aim of regularly updating stakeholders and scientific peers with the CCSBT with the most recent scientific results is to obtain immediate benefit through continuous improvement to the stock assessment models and process. Through these improvements we seek to ensure that stock assessments are not “handle-cranking” exercises. Rather, in each incremental advance in understanding and decrease in uncertainty we aim to improve the certainty of our advice to managers regarding the current status of the stock, and likely impacts of continued fishing. The 2001 CCSBT Stock Assessment Group and SC used a number of the outputs of this research project in their assessments of SBT stocks. These formed the basis for advice on the TAC for the global fishery, and advice to AFMA and AFFA on the domestic quota allocation.

As a component of the integrated SBT research program at CSIRO, this project has contributed to our overall objective of providing the best scientific support to the process of rebuilding and sustaining SBT stocks, and thereby ensuring the viability of the extremely valuable SBT capture and farming industries.

12. FURTHER DEVELOPMENTS

- The project has lead to an ongoing commitment to directly estimate the age of SBT from the spawning ground each year to determine:

  - Changes in the age structure of the spawning population over time.

  - With data on the sex composition of this catch now available, we will also be able to refine age-length keys, sexual dimorphism in growth and sex ratio.

  - Age/size at maturity – a parameter that remains a critical uncertainty in the SBT stock assessment.

- The current project lead to identification of the need for an integration of age and growth data currently available from otolith reading, tagging and length frequency analyses. This work is currently the focus of an FRDC project FRDC 99/104 “Integrated analysis of growth rates of SBT for use in estimating the catch at age matrix in the stock assessment”.

13. PLANNED OUTCOMES

The principal planned outcomes of this project were improvements in inputs to the CCSBT stock assessments, which prior to the early 1990s had suffered from poor biological understanding of the SBT population. This project built on the findings of FRDC 92/42, which developed and validated methods to estimate age of SBT using otoliths. As such it is seen as an essential step towards operationalization of direct ageing within the CCSBT stock assessment process.

14. CONCLUSIONS

The project was able to successfully meet all of its objectives, and in so doing has decreased the uncertainty around a number of critical biological parameters used in the SBT stock assessment.

Using otoliths that had been collected by Australian and overseas observers and scientists and archived in the CSIRO hard part archives, we were able to estimate the age composition of catches by Japanese fleets (operating off New Zealand and south-east Australia, in the south-east and south-west Indian Ocean), the Indonesian fleet (operating in the spawning grounds south of Bali and Java), and the Australian surface fishery (operating in the Great Australian Bight and south-west Western Australia) (Objectives 1 and 3). The archives, collected over more than a decade with funding from SBTMAC and Eastern Tuna MAC, were a significant resource without which this study would not have been possible. The commitment of the fisheries and AFMA towards this long-term view of sampling and archiving is gratefully acknowledged and commended.

One significant gap in the otolith collections, and indeed in our understanding of the fleets taking SBT, was in size composition and extent of the Taiwanese catch in the central and south-west Indian Ocean. The project, with joint funding from the AFFA's Fisheries Resources Research Fund, developed the first independent monitoring and sample collection programs for this large-undescribed fleet. The program confirmed that Taiwanese fishermen catch predominantly small fish. In fact their size and age composition was very similar to the Australian surface fishery and there is likely to be significant interactions between these fisheries for these cohorts, as conventional and archival tag recoveries uncovered by the project show very quick movement from Australian coastal waters into the central Indian Ocean fishing grounds targeted by the Taiwanese. The outcome of this component of the project was a complete shift in the way in which Taiwanese catches were accounted for in the CCSBT stock assessment process – as previously they had been assumed to consist of the same size/age distribution as the Japanese fleet (i.e. from 3-40, instead of the 2-8 we were able to describe).

As shown in the report, weaknesses were found when using commercial catch data to estimate the age structure of a species such as SBT. However, our estimated age compositions show clear differences between fisheries and fishing grounds especially in the distribution of juveniles. When small fish were removed from the analysis, the age distribution of SBT were almost identical between the main high-seas fishing grounds in the southern oceans, suggesting that SBT in these areas probably form one well-mixed population rather than several independent groups.

One of the goals of the project was to compare growth rates of fish collected from each fishery (Objective 2). During the project, however, it became apparent that this required further investigation because of uncertainty surrounding the timing of annual band formation and the bias this would introduce for fish sampled during the winter months (when bands forms). This difficulty has been addressed as part of FRDC 99/104 "Integrated analysis of growth rates of SBT for use in estimating the catch at age matrix in the stock assessment". Despite this, growth was found to be significantly greater for males than females from the age of seven years, which is likely to be related to gonad maturation and the onset of sexual maturity.

The direct age data also indicated that the age at which SBT enters the spawning stock may be higher than previously thought, at around 10-12 years (Objective 4). Evidence of an increase in the relative abundance of 10-15 year old fish in the latter of the two spawning seasons investigated, suggesting that cohorts spawned since the introduction of quotas in 1984 are now joining the spawning population.

Significant progress was made on examining the change in growth rates of juvenile SBT using otoliths (Objective 5). Our results suggest that the growth rates increased significantly between the 1960s and 1980s, and continued to increase in the 1990s. Although the influence of Lee's phenomenon on our data cannot be rejected, it is likely that the change in growth rates was a response to reduced population size or changes in water temperature.

The study achieved its objective (Objective 6) of estimating natural mortality rates for all age classes of the population using a combination of tagging and direct ageing data. Conditional on a tagging estimate of $0.4yr^{-1}$ for one-year-old fish and declining for older fish, the best estimates of the natural mortality rate for fish between ages 11 and 31 years are about 0.1 yr^{-1}, with standard errors of about 0.01. There is good agreement between the estimates obtained from the direct-age samples from the Japanese and Indonesian catches. From age 31 year to 40 years the natural mortality rate dramatically increases, maybe due to the onset of senescence, to about 0.4 yr^{-1} from Japanese data, and to about 0.8 yr^{-1} from Indonesian spawning ground data.

15. INTELLECTUAL PROPERTY

No commercial intellectual property arose from this work

16. STAFF

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