Size distribution of southern bluefin tuna (*Thunnus maccoyii*) by depth on their spawning ground

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Indonesian and Japanese longline vessels catch different-size southern bluefin tuna (*Thunnus maccoyii*) on their spawning ground in the Indian Ocean south of Bali. The length distributions of southern bluefin tuna (SBT) caught by Japanese longline are markedly smaller than those caught by the Indonesians (Davis et al.[1]; Itoh[2]). Both measurement error and misidentification of small SBT as bigeye tuna (*Thunnus obesus*) in the Indonesian catch data have been suggested as causes of this discrepancy (Suzuki and Nishida[3]), but neither has been substantiated. Japanese vessels target bigeye tuna by using deep longline sets (Itoh[2]), whereas most Indonesian vessels target yellowfin tuna (*Thunnus albacares*) by using shallow longline sets (Davis et al., 1995). The difference in types of longline sets raises the possibility that SBT on the spawning ground are segregated by size with depth.

Three types of boats operate in the Indonesian fishery (Davis et al., 1995). Deep longline boats (generally >50 tonnes) use multifilament mainlines that are set deep. Mini (<20 tonnes gross weight) and regular longline boats (20–50 tonnes) use monofilament mainlines and generally make shallow longline sets. However, the depth at which the lines fish varies considerably because they carry live or frozen baits according to different phases of the moon, and both the number of hooks and their placement on the catenary between floats changes. Prediction of fishing depth based on catenary geometry, line length, and distance between floats (Yoshihara, 1954) differs significantly from actual depth fished (Saito, 1973; Nishi, 1990; Boggs, 1992). In this fishery, the number of hooks between floats is recorded (Davis et al., 1999), but this parameter alone is a poor indicator of the depth of fishing.

Using hook timers, Boggs (1992) determined depth at the time of hooking. He found that bigeye catch rates peaked at 360–400 m and 8–10°C (temperature), but were still high at 200–360 m. Bigeye tuna have a shallower distribution at night (modal depth of 80 m) than during the day (220 m) (Holland et al., 1990). However, on the SBT spawning ground, longline setting starts at about 06:00 h and hauling starts at about 14:00 h (Davis[4]); therefore most bigeye tuna would be caught during the day when they are deeper.

The preferred depths of bigeye tuna vary regionally depending on thermocline structure, but lie within 10° and 15°C (Hanamoto, 1986; Mohri et al., 1996) and where $O_2 > 1$ mL/L (Hanamoto, 1986). These temperatures occur at 180–400 m on the SBT spawning ground (Yukinawa and Miyabe, 1984; Yukinawa and Koido, 1985; Yukinawa, 1987). Yellowfin tuna, on the other hand, are found in warmer waters and are mainly caught at depths of 40–230 m (Suzuki and Kume, 1982; Yang and Gong, 1988; Boggs, 1992). The proportion of bigeye to yellowfin tuna might therefore be used as a proxy for the depth of fishing in the Indonesian longline fishery. In our study we used this depth proxy to investigate whether there is size partitioning by depth of SBT on the spawning ground, and what underlying biological processes might be involved.

Methods

We used catch data obtained from 15,882 Indonesian longline landings monitored at export processing factories at the Port of Benoa, Bali, from 1992 to 1999 (Davis et al., 1995; 1999). About 65% of the SBT in these landings were measured (fork length in cm). Fewer high-grade export tuna (30%) were measured than low-grade tuna (89%) because the former were immersed in an ice slurry immediately after grading, leaving little opportunity for measurement. Grading, however, was not dependent on size. There was no significant difference in the length distributions of 102 export tuna and 102 low-grade tuna from 20 landings in which all tuna were measured (Kolmogorov-Smirnov two sample test, $P=0.22$).

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[1] Davis, T. L. O., J. H. Farley, and S. Bahar. 1996. Catch monitoring of the fresh tuna caught by the Bali-based longline fishery. Commission for the Conservation of Southern Bluefin Tuna scientific meeting, 26 August–5 September 1996, Hobart, Australia, Rep. CCSBT/SC/96/6, 26 p. CSIRO Marine Laboratories, PO Box 1538, Hobart, Tasmania 7001, Australia.

[2] Itoh, T. 1997. Longline survey in southern bluefin tuna spawning ground. Commission for the Conservation of Southern Bluefin Tuna scientific meeting, 28 July–8 August 1997, Canberra, Australia, Rep. CCSBT/SC/97/12, 4 p. CSIRO Marine Laboratories, PO Box 1538, Hobart, Tasmania 7001, Australia.

[3] Suzuki, Z., and T. Nishida. 1997. Comparison of information on the catch and size of fish in the spawning ground of southern bluefin obtained from Indonesian and Japanese longline fisheries. Commission for the Conservation of Southern Bluefin Tuna scientific meeting, 28 July–8 August 1997, Canberra, Australia, Rep. CCSBT/SC/97/13, 8 p. CSIRO Marine Laboratories, PO Box 1538, Hobart, Tasmania 7001, Australia.

[4] Davis, T. L. O. 1999. Unpubl. data. CSIRO Marine Laboratories, PO Box 1538, Hobart, Tas 7001, Australia.

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Fish. Bull. 99:381–386 (2001).

Table 1

Distribution (%) of length groups (10-cm intervals) of southern bluefin tuna across bigeye tuna (BE) indices (Pearson chi-square=516, *n*=8416, df=24, <0.001).

	BE indices						
Length (cm)	0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	Total no.	Total
140–149	13.3	6.7	13.3	26.7	40.0	15	100.0
150–159	2.8	10.1	17.0	18.6	51.4	247	100.0
160–169	8.7	15.4	19.5	24.5	31.8	1019	100.0
170–179	12.7	25.7	20.8	20.8	20.0	2442	100.0
180–189	17.9	26.6	18.5	19.3	17.8	3520	100.0
190–199	27.0	23.7	18.9	14.7	15.7	990	100.0
200–209	35.9	21.8	19.6	10.9	12.0	184	100.0
No. of landings	2100	3585	3876	4421	1900		

For each landing we calculated a bigeye (BE) tuna index as

$$\text{BE index} = \text{Weight of bigeye}/(\text{weight of bigeye} + \text{weight of yellowfin}).$$

This equation was used as a proxy for the depth of fishing, with an index of 1 = deep and 0 = shallow. Landings were grouped into one of five levels of this index, i.e. 0–0.2, 0.2–0.4, etc., and then the length-frequency distributions of SBT within landings at each level were compared.

In order to investigate patterns of distribution of fish size with depth, we grouped fish into 10-cm length classes and calculated their relative abundance across the five levels of the BE index. Because of uneven sampling with depth, the number of fish in each BE index were first weighted inversely by the effort (number of landings) at each level of the index.

The ovaries of 475 SBT were collected during monitoring from 1992 to 1995. These were examined histologically for evidence of recent or imminent spawning (Farley and Davis, 1998). Spawning fish were classed as those having spawned less than 24 hours previously (postovulatory follicles present in ovary), or about to spawn that day (ovaries containing oocytes at migratory nucleus or hydrated stage). Postspawning SBT were identified by the proportion and type of atretic oocytes present (see details in Farley and Davis, 1998). Nonspawning SBT were mature fish on the spawning ground that were neither spawning nor postspawning individuals.

Chi-square contingency analyses were used to test for differences in length classes of SBT, and for differences in the proportion of spawning and nonspawning SBT at different levels of the BE index (the proxy for depth).

Results

The length-frequency distribution of SBT caught at five levels of the BE index shows a trend of increased proportions of small SBT with an increase in this index (Fig. 1). Fish <165 cm ranged from 3.3% of catch at an index <0.2 to 15.7% at a index >0.8.

Chi-square contingency analyses indicated significant differences in the proportion of length classes with the BE index (Table 1, Fig. 2). The chi-square test ignores the ordered and continuous nature of the categories, making it less powerful than it could be. However, we obtained a highly significant test result despite this weakness, reflecting how strong the size-with-depth patterns are. The smaller length classes (150–169 cm) were better represented in the deep catches (BE index >0.8) than they were in the shallow catches (BE index <0.2). Conversely, the larger length classes (190–209 cm) were better represented in the shallow catches (BE index <0.2) than they were in the deep catches (BE index >0.8). Smaller fish were more likely to be caught in the deepest sets, which target bigeye, whereas the bigger fish were more likely to be caught in the shallow sets. Significantly, there is a systematic change in depth distribution with size over the whole size range of SBT that occur on the spawning ground. This pattern is very clear when comparing the proportion of fish caught in shallow (BE index of 0.0–0.2 or 0.0–0.4) versus deep (BE index of 0.8–1.0 or 0.6–1.0) sets for each length class. The proportion of SBT caught at the surface increases with size (Fig. 3).

The proportion of spawning and nonspawning fish (based on the subset of histological data) was then determined for each level of BE index (Fig. 4). Chi-square contingency analyses indicated significant differences in the proportions (Table 2). Spawning fish were better represented in the shallow catches than in the deep catches. Conversely, nonspawning fish were better represented in the deep catches than in the shallow catches. There were insufficient numbers of SBT in the smaller size classes (only seven SBT<160 cm) to use the histology data to examine directly the relation between size and proportion of spawning fish or spawning frequencies. Because spent fish were rarely encountered on the spawning ground, Farley and Davis (1998) concluded that they move south soon af-

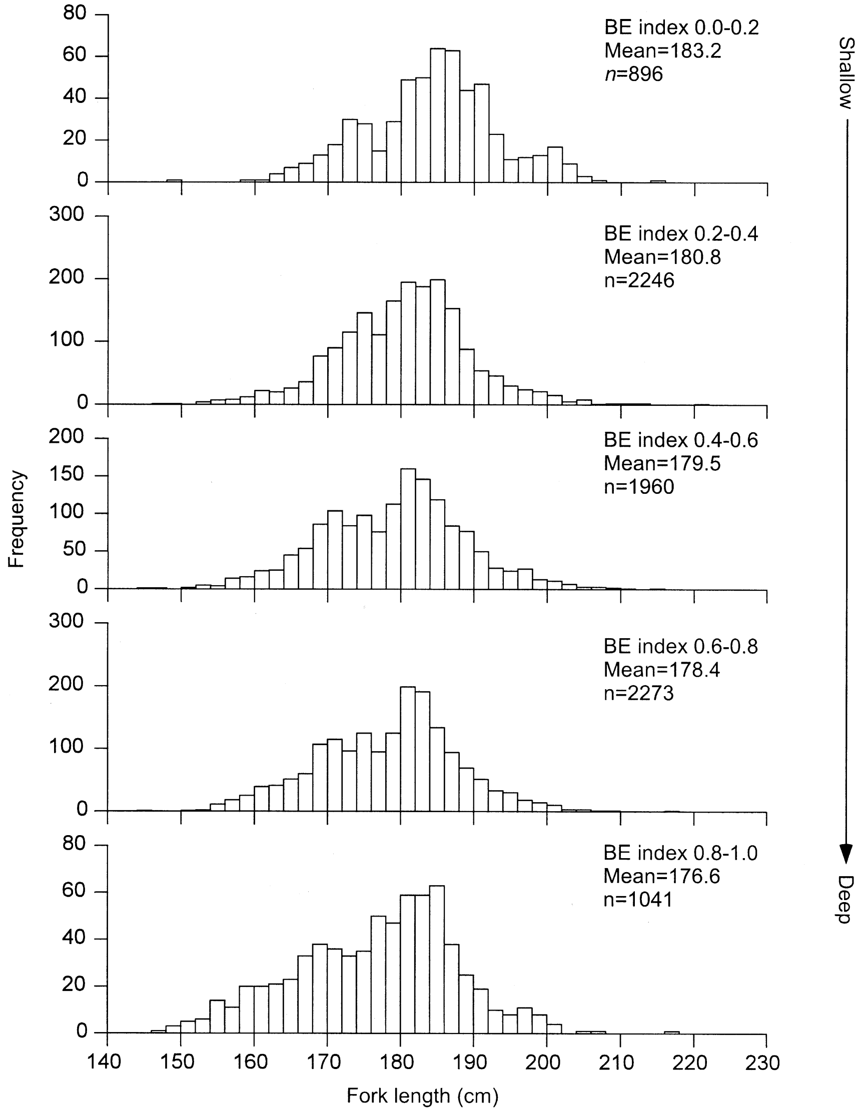

Figure 1

Length-frequency distribution (2-cm intervals) of southern bluefin tuna in landings by bigeye tuna index—a proxy for fishing depth.

ter spawning. However, the two spent fish detected were in landings with a BE index >0.9.

Discussion

There is a systematic change in depth distribution with size over the whole size range of SBT caught on the spawning ground. This pattern is clear, even though the BE index may only represent a crude approximation of depth. Deep longline catches are often contaminated by surface catches—10% of bigeye tuna are caught when hooks are not at settled depths (Boggs, 1992). Also, both SBT (Gunn et al.[5]; Davis and Stanley[6]) and bigeye tuna (Holland et al., 1990) might be caught outside their preferred depth as they regularly traverse the water column.

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[5] Gunn, J. S., T. Polacheck, T. L. Davis, M. Sherlock, and A. Betlehem. 1994. The application of archival tags to study the movement, behaviour and physiology of southern bluefin tuna, with comments on the transfer of the technology to groundfish research. ICES CM 1994/Mini: 21, 23 p. [Mimeo.]

[6] Davis, T. L. O., and C. A. Stanle. 2001. In prep. Vertical and horizontal movements of southern bluefin tuna, *Thunnus maccoyii*, in the Great Australian Bight observed by ultrasonic telemetry.

The pattern of size distribution with depth is mirrored by the pattern of spawning and nonspawning with depth. Both smaller and nonspawning SBT are more abundant at depth, whereas both larger and spawning SBT are more abundant near the surface. The vertical distribution of SBT larvae suggests that SBT spawn at the surface (Davis et al., 1990), as do caged Atlantic bluefin tuna (*Thunnus thynnus*) (Fushimi et al., 1998). Surface-water temperatures on the spawning ground usually exceed 24°C (Yukinawa and Miyabe, 1984; Yukinawa and Koido, 1985; Yukinawa, 1987). These warm surface waters may be necessary for the survival of their eggs and larvae, but adult SBT normally feed in colder water (often as low as 5°C [Olson, 1980]). Temperatures of 10°–15°C preferred by bigeye tuna (Hanamoto, 1986; Mohri et al., 1996) may offer more favorable conditions for nonspawning SBT and explain their strong association with high BE indices on the spawning ground.

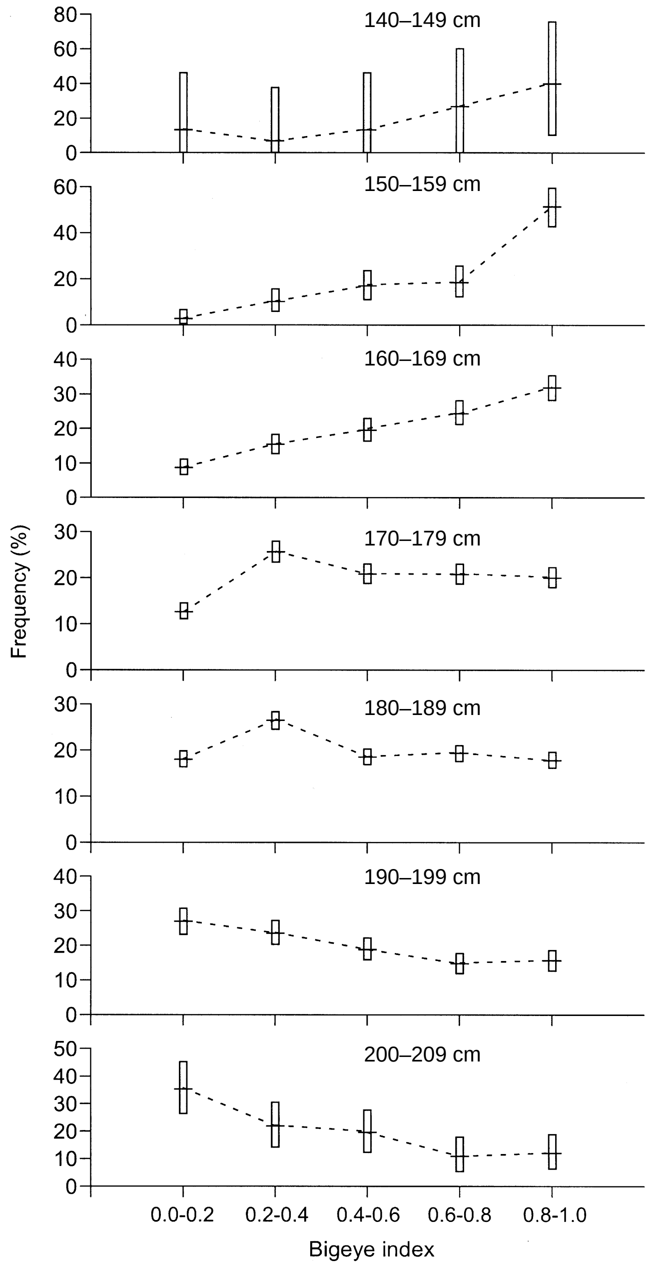

Figure 2

Proportion of each 10-cm length group in landings by bigeye tuna (BE) index. Vertical bars represent 95% confidence limits of the mean based on an approximation by Bailey (1980).

Previous studies have shown that yellowfin tuna caught by purse seine and handline have higher gonadosomatic indices than yellowfin caught by longline (Hisada, 1973; Suzuki, 1988; Koido and Suzuki, 1989). Histological studies have found that yellowfin tuna catches from purse-seine sets and shallow (Taiwanese-style) longline sets have a higher proportion of actively spawning fish than catches from deep (Japanese-style) longline sets (Itano[7]). Thus, spawning fish are more likely to be caught near the surface and nonspawning fish are more likely to be caught in deeper water.

The biological basis for size partitioning with depth could be that large fish spawn more frequently than small fish and, therefore, bigger fish will be caught at the surface more often than smaller ones. Spawning frequency is known to increase with size in female yellowfin tuna (Schaefer, 1998) but could not be determined for SBT. The pattern of size distribution may reflect recruitment into spawning. However, this hypothesis is unlikely because histological examination of ovaries indicated that all SBT caught on the spawning ground were mature i.e. had advanced yolked oocytes (Farley and Davis, 1998), although this does not preclude the possibility that they might not be ready to spawn. The most likely reason for size partitioning is that the spawning frequency or the proportion of time spent spawning to time spent in a nonspawning condition increases with size.

If the ability to tolerate higher than preferred water temperatures improved with fish size, then this would facilitate longer spawning episodes or more extensive feeding in shallow waters, both of which would produce the observed pattern of size distribution with depth. Although the ability to conserve heat in cold waters may increase with size in SBT, it is not clear what size-dependent processes might be involved in avoiding overheating at high ambient temperatures.

We do not understand the temporal and spatial scale of vertical movements of SBT on the spawning grounds in relation to spawning and feeding, nor

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[7] Itano, D. G. 2000. The reproductive biology of yellowfin tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: project summary. SOEST (School of Ocean and Earth Science and Technology) 00-01, JIMAR (Joint Institute for Marine and Atmospheric Research) Contribution 00-328, 69 p. Univ. Hawaii, 1000 Pope Road, MSB 312, Honolulu, HI 96822-2336, US.

Table 2

Percentage of spawning and nonspawning southern bluefin tuna caught at different bigeye indices (Pearson chi-square=24.1, n=326, df=4, P<0.001).

	BE index					
	0.0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	Total no.
Spawning	85.5	71.4	80.8	56.4	56.3	227
Nonspawning	14.5	28.6	19.2	43.6	43.7	99

how these might change with fish size. This behavioral information is needed in order to interpret the patterns presented in our study and might best be achieved by pop-up satellite archival tagging.

Because SBT aggregate by size and depth on the spawning ground, it is necessary to account for their distribution when determining the age and size structure of the spawning stock. This is especially important when evaluating time series of size and age distributions in a fishery where there have been shifts in targeting between yellowfin and bigeye tuna. In the absence of reliable information on the depth of fishing, the most practical way of doing this in the Indonesian fishery would be to inversely weight the effort directed at the different levels of the BE index. The determination of spawning frequency should also take into account longline fishing strategies because it is likely that spawning frequency is affected by fish size and because samples will be caught within or outside the spawning depth.

If the increase in the proportion of SBT at the surface with size is due to spawning activity, then this feature will affect the contribution different size fish make to total annual egg production. A lower spawning frequency, coupled with an exponential relationship between length and batch fecundity (Farley and Davis 1998), would mean that individual small, but mature, fish make a relatively small contribution to total annual egg production. When making stock projections, it may therefore be more appropriate to adopt a parameter that reflects size at mean annual egg production rather than the currently accepted parameter of mean size at first maturity. Further histological research on the reproductive dynamics of small fish is required to better define these parameters. Small fish were rarely caught when the histological work of Farley and Davis (1998) was carried out in 1992–95 but they have become more abundant in recent years (Davis et al.[8]) making such a study possible.

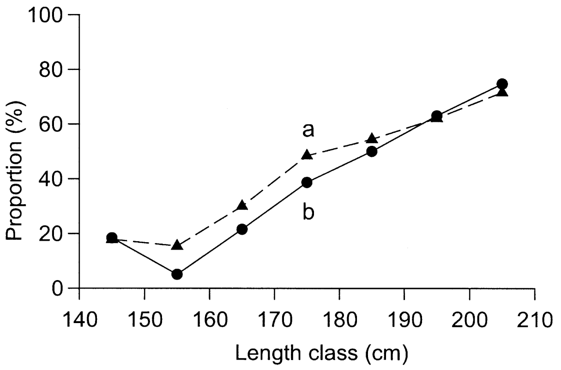

Figure 3

Proportion of southern bluefin tuna caught at the surface by length class. Estimates were calculated by using (a) bigeye tuna (BE) index of 0.0–0.2 and 0.8–1.0 and (b) BE index of 0.0–0.4 and 0.6–1.0.

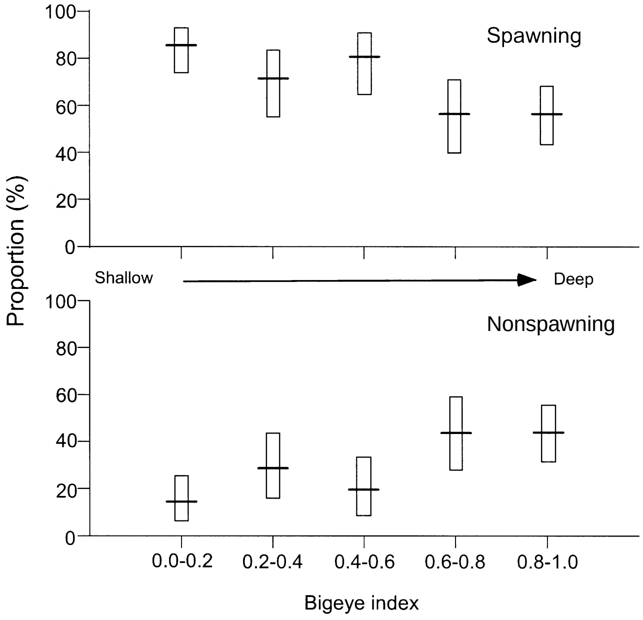

Figure 4

Proportion of spawners and nonspawners in landings by the bigeye tuna index.

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[8] Davis, T. L. O., S. Bahar, N. Naamin, and J. H. Farley. 1998. Catch monitoring of the fresh tuna caught by the Bali-based longline fishery. Commission for the Conservation of Southern Bluefin Tuna scientific meeting, 23–31 July 1998, Shimizu, Japan, Rep. CCSBT/SC/9807/6, 17 p. CSIRO Marine Laboratories, PO Box 1538, Hobart, Tasmania 7001, Australia.

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