Abstract.—Controversy concerning the validity and accuracy of recent assessment results for giant bluefin tuna, *Thunnus thynnus*, led us to examine alternative methods of estimating their abundance. In collaboration with a New England giant bluefin tuna industry group, we tested the feasibility of using commercial spotter pilots and aerial photography as a means of obtaining tuna counts in the Gulf of Maine and adjacent New England waters. Nine commercial spotter pilots photographed a total of 126 schools of bluefin tuna during the summer of 1993, representing 13,973 fish, with a maximum one-day count of 4,894. Three spotter pilots contributed nearly 70% of the total photographic effort. Differences in photographic ability and commercial involvement in the fishery appeared to influence spotter pilot participation. Aerial photographic surveys may provide a means of obtaining area-specific minimum abundance and distribution data for giant and large-medium bluefin tuna.

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The feasibility of direct photographic assessment of giant bluefin tuna, *Thunnus thynnus*, in New England waters

Molly Lutcavage
Scott Kraus
Edgerton Research Laboratory, New England Aquarium
195 State Street, Boston, Massachusetts 02109

Stock assessments of the highly migratory northern Atlantic bluefin tuna, *Thunnus thynnus*, are primarily based on age-structured and lumped biomass models derived from landings data and various abundance indices (Scott et al., 1993). These production or CPUE (catch per unit of effort) models provide the framework for international management of the commercially valuable bluefin tuna. A problem with CPUE-derived estimates of stock biomass, however, is that they are affected by changes in fishing effort, technology, fish density, and the marketplace (Lo et al., 1992). How accurately recent assessment models portray seasonal bluefin abundance in the west Atlantic, a fishery with a 1993 catch of 1,047.2 metric tons of giant tuna (≥77 inches straight fork length [SFL]) and of large-medium category tuna (between 70 and 77 inches SFL), remains controversial (Clay, 1991; Suzuki and Ishizuka, 1991; Safina, 1993).

Aerial surveys have been used to obtain relative indices of abundance in fisheries worldwide, including northern anchovy (*Engraulis mordax*), jack mackerel (*Trachurus symmetricus*), menhaden (*Brevoortia* spp.), mullet (*Mugil* spp.), and other pelagic fishes (Squire, 1961, 1972, 1993; Williams, 1981; Scott et al., 1989; Lo et al., 1992). Estimates of fish biomass from these surveys are based on appraisals of school size in tonnage per unit of area, or by size of remotely detected signals such as bioluminescence or turbidity fields. Visual biomass estimates from aerial survey data are relatively easy to construct but are difficult to interpret without ground truth or information on surfacing behavior (Lo et al., 1993).

In contrast, direct enumeration of pelagic fish is notoriously difficult. In the 1950's, U.S. fisheries scientists attempted to count giant bluefin tuna migrating along the Bahama Banks (Rivas, 1978) and later undertook direct assessment with photographic and video techniques (NMFS[1]). Despite dedicated search time, very few fish were detected during the survey. More recently, other countries have explored aerial and remote sensing methods as a means of calibrating catch-related indices for tuna species. Since 1990, transect surveys have provided estimates of regional abundance and recruitment indices for southern bluefin tuna, *Thunnus maccoyii*, in

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[1] Anonymous. 1975. A study of the application of remote sensing techniques for detection and enumeration of giant bluefin tuna. Rep of Southeast Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA. Contrib. No. 437.

the Great Australian Bight (Morgan, 1992; Chen and Polacheck[2]). Aerial surface-detection radar surveys targeting bluefin tuna and other tunas have been explored by the French in the Mediterranean and tropical South Pacific areas (Petit et al., 1992).

Recently, members of the New England commercial giant bluefin tuna industry suggested that spotter pilots might provide a platform to examine the potential applications and limitations of direct visual assessment of giant and large-medium bluefin tuna. In coastal waters off New England, spotter pilots have located surface schools of giant bluefin tuna that are then targeted for capture by harpoon, hook and line, and purse-seine operations. In 1993, the New England Aquarium (NEA) and East Coast Tuna Association (ECTA) initiated a collaborative project involving fish spotter pilots locating and photographing surface schools of bluefin tuna normally targeted by the fishery. Our objective was to determine whether aerial photography could be used to provide information on the relative abundance, schooling characteristics, and spatial distribution of bluefin tuna.

Methods

The present study relied on a simple technical framework involving only voluntary participation by commercial spotters and the use of two cameras, one to photograph tuna schools (for enumeration) and another to document school location. Nine commercial spotter pilots participated in this survey while engaged in the 1993 seasonal fishery. All fish spotters flew single engine aircraft (models Cessna 172 and 182, Citabria, SuperCub) and were based on Cape Cod or in lower Maine. Four pilots spotted for seining operations, five were associated with harpoon or general category fishing (hook and line), and at least two participated in all three categories. Bluefin tuna were photographed from 23 July to 13 September, when participating pilots ceased activities because fishing quotas were filled.

Each pilot was provided with a hand-held 35-mm camera (Nikon N8008s) and an autofocus zoom lens (70–210 mm, F3.5/4.5, SIGMA Corp.) to photograph tuna schools. Synchronized databacks on cameras (Nikon, MF–21) imprinted date and time directly on exposed film. A second viewfinder camera (Shotmaster Ultra Zoom, 38–60 mm, f6.9 lens, Ricoh Corp.) was mounted overhead in the aircraft cabin to document positions from onboard global positioning system (GPS) or LORAN units located in or below the dashboard. Both cameras had auto advance features and were linked via cable so that they were simultaneously triggered when pilots depressed a remote shutter control. A photographic record of position (in TD Loran lines or lat./long.) could then be provided for each photographically documented tuna school. A digital clock synchronized with the 35-mm camera databack was mounted near the LORAN/GPS within range of the viewfinder camera. We could then verify sequence linkage between frames of tuna schools and locations if film advance speeds were not perfectly matched.

Tuna schools were photographed with color slide film (Ektachrome 400 ASA, Kodak), selected for depth of penetration and contrast characteristics (NMFS, 1975; Lockwood et al.[3]). Lenses were fitted with a circular polarizing filter or haze filter for glare reduction. Aircraft positions recorded by the viewfinder camera were read directly from developed black and white film (Tri-X 400 ASA, Kodak).

Pilots were supplied with labelled film canisters and with stamped and coded direct mailers for color processing, and were instructed to mail the film immediately when it was finished. Black and white film was returned directly to us and processed locally.

Analysis

Processed film was logged with an identification code, and a cursory examination was made on a light table with a film eye loupe. Tuna counts were made by projecting selected slides of schools and by visually counting individual fish. Images were enlarged by projection to a standard size (78 × 52 cm) onto a sheet of drafting-quality tracing paper marked with 10 × 10 cm square gridlines. Positions of clearly identifiable fish were marked and the total tallied per grid square and per slide frame. Upon completion of the tally, each sheet was labelled with the film identification code, frame number, time, and total fish count. No attempt was made to estimate the total number of fish in the school.

Since bluefin tuna are fast-swimming, mobile fish, it was possible for pilots to photograph the same school at slightly different locations on a single day. A school might be difficult to distinguish from adjacent, similarly sized schools. When photographed by a spotter in close succession, these schools had to have distinctly different spatial configurations or had

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[2] Chen, S. X., and T. Polacheck. Data analysis of the aerial surveys (1991–1994) for juvenile southern bluefin tuna in the Great Austrialian Bight. 1994 SBT Recruitment Monitoring Workshop, Hobart, Tasmania. Available from T. Polacheck, CSIRO, Div. Fisheries, GPO Box 1538, Hobart, Tasmania 7001.

[3] Lockwood, H. E. Technicolor Graphics Services, Inc., Houston, TX 77058.

to be separated by at least one nautical mile (nmi) in order to be tallied independently. Spotters and fishermen reported maximum travel rates of 4–10 knots for bluefin tuna in the study area. With the assumption that swimming speeds were 10 knots, similarly sized schools photographed by different pilots on the same day had to be far enough apart so that it was unlikely that schools could have travelled from one location to the other in a given time period.

Results

The bluefin tuna survey area, fish spotter land bases, and locations of photographed schools are depicted in Figure 1. A total of 126 bluefin tuna schools, representing a cumulative count of 13,973 fish, were successfully photographed by spotter pilots on 17 days out of a 50-day survey period, for a total of 35 pilot-days. Pilots reported that, to the best of their knowledge, they photographed only giant or large-medium bluefin tuna size categories (>70 inches SFL), those targeted by the New England fishery. The position of surveyed schools, indicated by TD values or lat./long. on the pilot's navigational system, was established for 56 schools. Numbers of fish counted in schools ranged from 5 to 1,294 individuals (Fig. 2). Total giant and large-medium tuna counts were >1,000 fish on four survey days, with a maximum count of 4,894 tuna on 8 August (Table 1). A data summary of schools for three high count survey days (8–10 Aug) is given in Table 2.

From one to four spotters participated on high-count days, but no more than four pilots photographed fish on any given survey day. Spotters photographed schools from 0900 to 1803 h, but the greatest effort occurred during midday between 1200 and 1600 h (Table 3). Spotters report that slack tide (estimated to

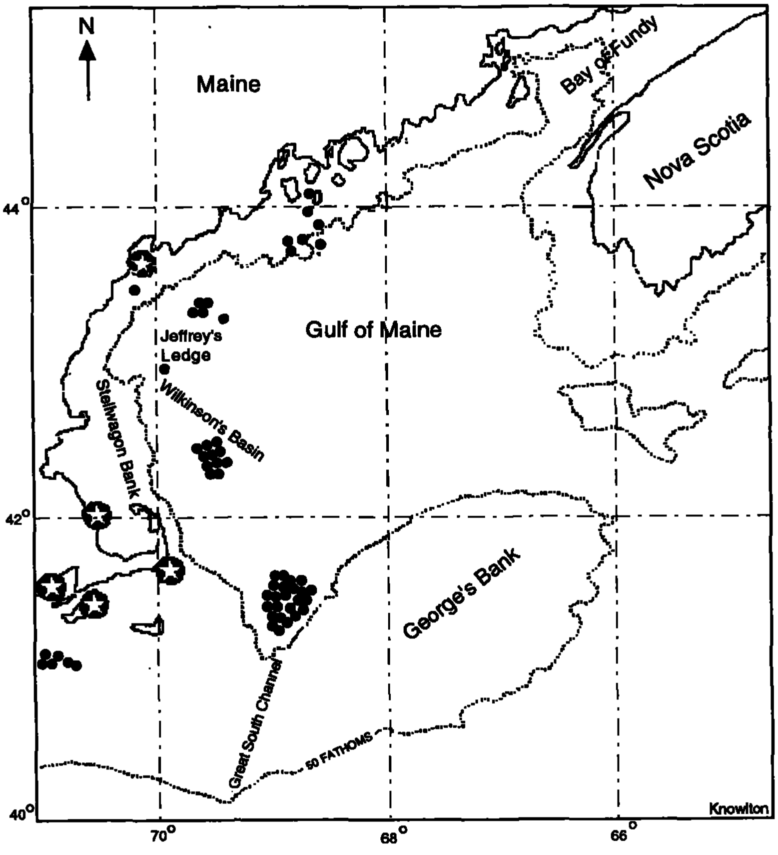

Figure 1

Aerial survey area for giant bluefin tuna, *Thunnus thynnus*, in New England waters, July–September 1993. Land bases of participating spotter pilots are indicated by stars. Filled circles indicate positions of photographed tuna schools.

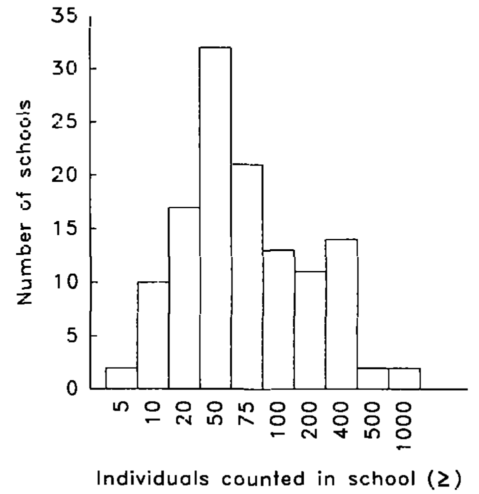

Figure 2
Frequency distribution of counts of giant and large-medium bluefin tuna, *Thunnus thynnus*, schools photographed by spotter pilots in New England waters, July–September 1993.

be within one hour of nearest coastal reference) often provides good conditions for locating fish. There was no discernible relation between lunar cycle or estimated slack tide and timing of greatest survey effort.

Surface schooling configurations of bluefin tuna, documented during the survey, included "soldiers" (small school of giants, fish swimming abreast in a parabola or straightline formation, Fig. 3A), "cartwheels" (spinning wheel-like formations, Fig. 3B), surface sheets (Fig. 3C), and densely packed domes (Fig. 3D). Basking sharks and, less frequently, humpback, fin, and other whales, were also photographed in association with bluefin tuna schools.

Discussion

Spotting and survey effort

Most of the bluefin tuna were photographed over a four-day period in August by only a few of the participating pilots, indicating that survey effort was strongly affected by environmental conditions and pilot effort. Fish spotters flew on less than half the survey period, grounded largely by inclement weather. They photographed all sizes of bluefin tuna schools, but small to medium-sized schools (≥5 counts <200) were located and photographed most frequently. Although initially instructed to document schools of any size, some pilots reported not bothering to photograph very small schools, particularly on "good" fishing days.

Table 1
Highest count days for aerial photography of bluefin tuna, *Thunnus thynnus*, in New England waters, July–September 1993.

Date[1]	Count	No. of schools	No. of pilots
8 Aug	4,894	24	2
22 Aug	2,517	16	4
9 Aug	1,067	15	2
10 Aug	1,275	7	1

[1] Full moon 2 August; new moon 17 August.

Search and photographic efforts of participating fish spotters varied widely, reflecting differences in commercial involvement in the fishery and in motivation. For example, one pilot photographed a minimum of 6,767 giant and large-medium bluefin tuna over five days under excellent survey conditions. However, his survey effort in hours represented <10% of the estimated 400 total flight hours he expended in the 1993 season. This result suggests that aerial photography of giant bluefin tuna can be accomplished with a small team of motivated pilots. In contrast, a fish spotter in partnership with seining operations photographed far fewer fish (467) because his total survey effort was limited to the few days permitted for his boat to achieve its seasonal quota. If all nine participating pilots had undertaken simultaneous surveys throughout the season, more complete documentation might have been achieved.

Throughout the survey we maintained frequent phone contact with the pilots in an effort to improve the quality of aerial and position photographs. Although we were able to count tuna in the majority of submitted frames, there was clearly a learning curve in the spotters' attempts to take high-resolution pictures. Blurring from aircraft vibration and underexposure were the most frequent problems with tuna school photographs. Unreadable Loran frames more often than not resulted from excessive glare on the digital readout, from improper film advance, or because the pilot had shifted position and had subsequently blocked the camera's view of the Loran. This problem could be eliminated if position were electronically logged each time the spotter photographed bluefin schools.

Enumeration analysis

In general, we assumed that environmental conditions were fairly uniform (low wind and sea states,

Table 2

Summary of photographed bluefin tuna, *Thunnus thynnus*, schools on three highest-count survey days in New England waters, July–September 1993.

Date	Pilot	Count	Time	Latitude (°N)	Longitude (°W)
08 Aug	g	57	12:53	41°25'	68°57'
08 Aug	g	152	12:59	41°25'	68°56'
08 Aug	g	186	13:01	41°25'	68°57'
08 Aug	g	284	13:09	41°25'	68°57'
08 Aug	g	1039	13:15	41°27'	68°55'
08 Aug	g	457	13:17	41°26'	68°57'
08 Aug	g	371	13:57		
08 Aug	f	96	14:09	42°27'	69°30'
08 Aug	g	26	14:27	41°28'	68°55'
08 Aug	g	499	14:28	41°28'	68°55'
08 Aug	g	315	14:37		
08 Aug	g	300	14:58	41°29'	68°55'
08 Aug	g	52	15:03	41°28'	68°56'
08 Aug	g	95	15:06		
08 Aug	g	42	15:09	41°29'	68°56'
08 Aug	g	85	15:17	41°28'	68°56'
08 Aug	g	107	15:31	41°29'	68°55'
08 Aug	f	313	15:34		
08 Aug	g	26	15:35		
08 Aug	f	85	15:45		
08 Aug	g	44	15:46		
08 Aug	g	69	15:54		
08 Aug	g	176	16:09	41°29'	68°55'
08 Aug	g	18	17:37	41°27'	68°57'
09 Aug	g	79	12:53		
09 Aug	g	60	12:58		
09 Aug	c	64	13:04		
09 Aug	g	83	13:12		
09 Aug	g	51	13:19		
09 Aug	c	22	13:20	4137	68°50
09 Aug	g	78	13:23		
09 Aug	g	94	13:40		
09 Aug	c	58	14:06	41°39'	68°44'
09 Aug	g	62	14:23	41°35'	68°45'
09 Aug	g	13	16:00	41°36'	68°47'
09 Aug	c	136	16:10	41°40'	68°42'
09 Aug	c	73	16:28	41°41'	68°41'
09 Aug	c	123	16:31	41°38'	68°40'
09 Aug	c	71	16:42	41°42'	69°03'
10 Aug	g	262	12:52	41°33'	68°48'
10 Aug	g	54	13:04	41°34'	68°48'
10 Aug	g	209	15:50	41°04'	70°51'
10 Aug	g	286	15:58	40°59'	70°47'
10 Aug	g	344	16:07	41°06'	70°56'
10 Aug	g	74	16:09	41°05'	70°56'
10 Aug	g	46	16:26	41°01'	71°02'

[1] Latitude and longitude have been rounded to nearest degree and minute.

good light levels, minimal glare) when schools were photographed. Altitude varied among spotters but seemed to be less important in producing good records than were sea state and light condition. However, spotters photographing large schools at low altitude were occasionally unable to include the entire school within the frame. We enumerated only clearly discernible individuals in schools and in some circumstances were able to count fish in at least one tier below the surface tier. With smaller schools, particularly in "soldier formation" or in surface-oriented groups, we were able to count all members of the school.

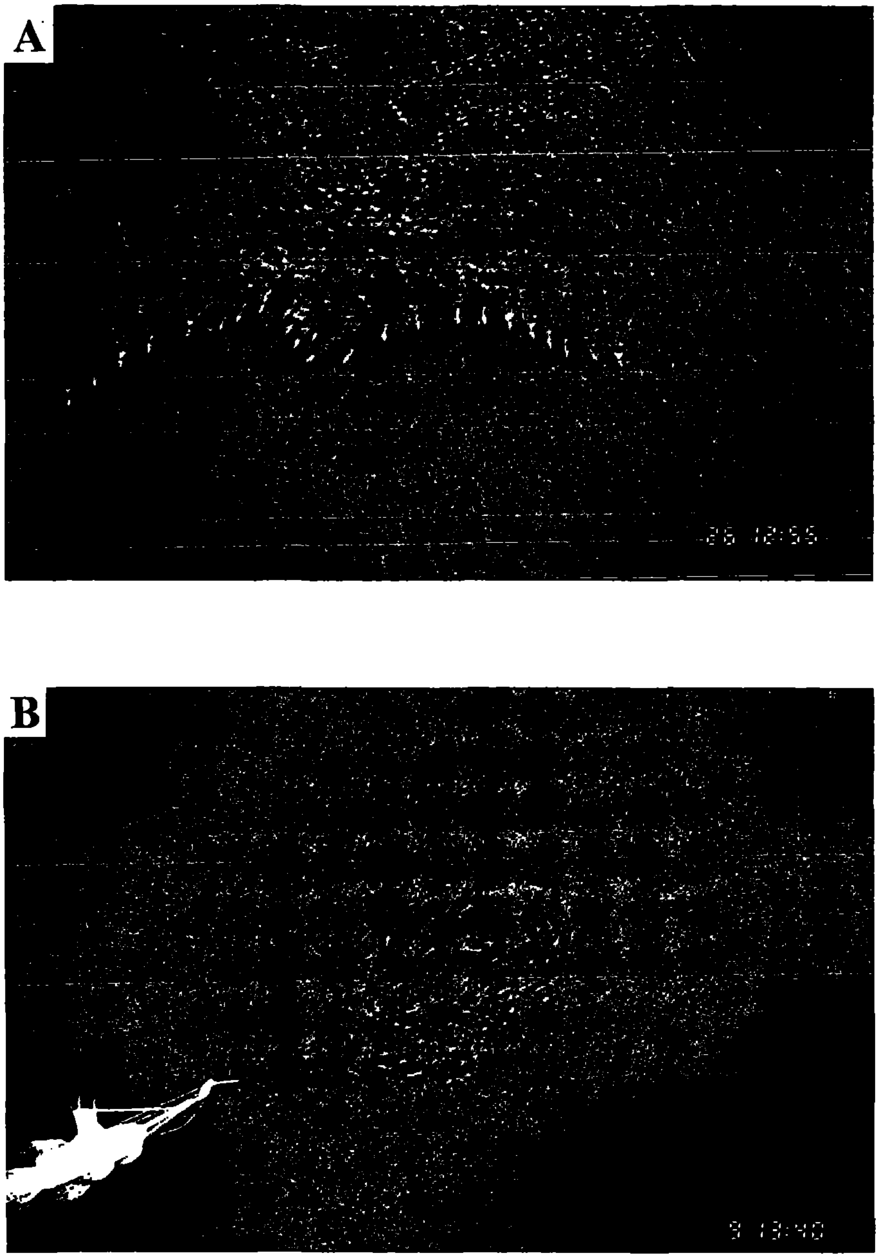

Figure 3

Examples of giant bluefin tuna school configurations photographed by fish spotters in the 1993 New England waters aerial census: (A) soldiers; (B) cartwheels; (C) surface sheet; and (D) densely packed dome.

Limitations of the data

Direct enumeration of giant bluefin tuna from aerial survey involves potential sources of error that must be addressed. These include species and size-class identification, differences in surfacing behavior caused by environmental or biological variables, and redundant counts as fish migrate through the study area. In the 1993 feasibility study, we identified and resolved only a few of these issues but nevertheless obtained information vital for improving future aerial surveys.

We observed small differences (<1%) in medium-size and large school totals when three different individuals examined and counted bluefin tuna in

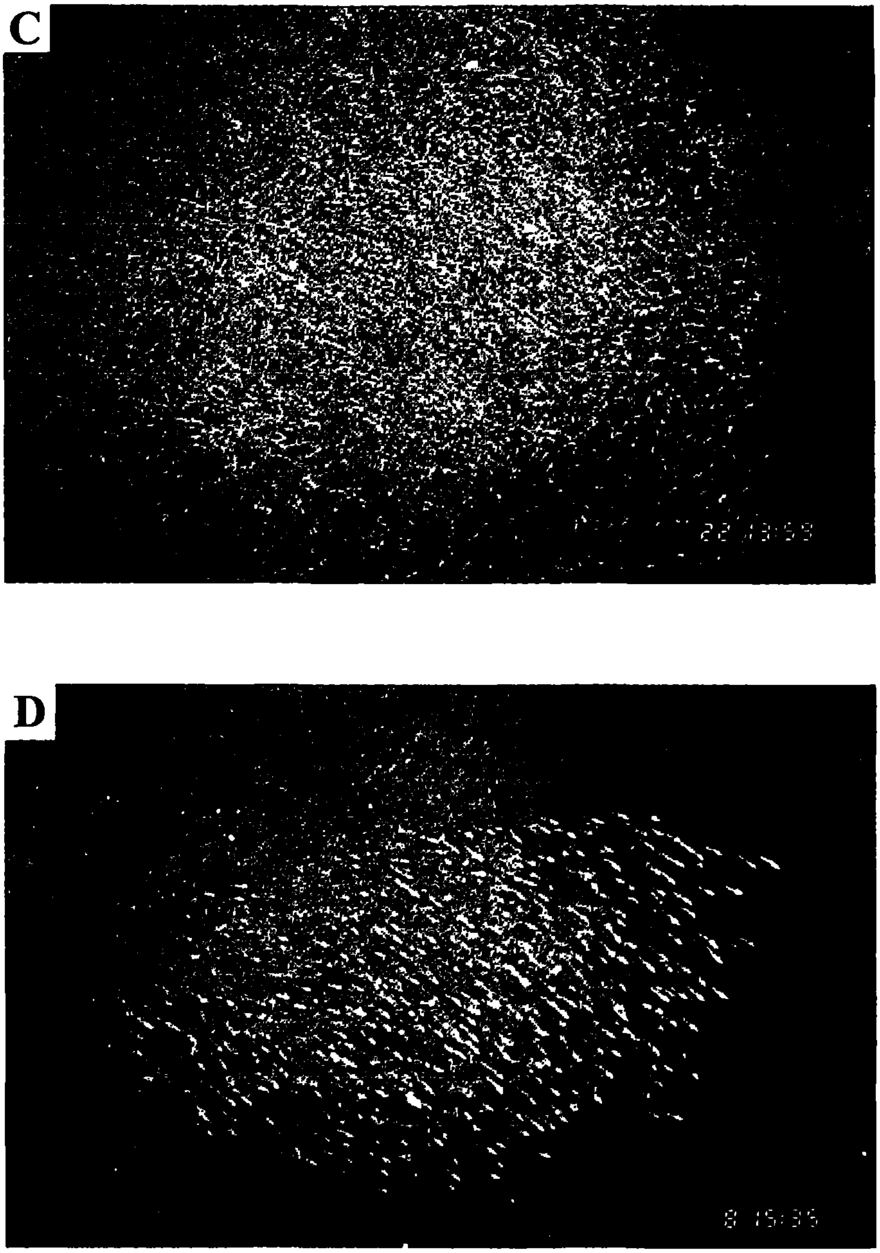

Figure 3 (continued)

projected images. Considering that we could enumerate only an undefined portion of the entire school, this source of error was considered negligible.

Species identification of small tunas by aerial observers can be difficult (Morgan, 1992), but the likelihood that spotters would mistake other species for giant or large-medium bluefin tuna targeted in this New England fishery is very slight. Commercially valuable schools of yellowfin tuna are rare north of Nantucket Shoals (Mather, 1962; Roffer, 1987), and experienced fish spotters would be unlikely to mistake targeted bluefin tuna for the smaller yellowfin tuna.

Marine mammals aggregate in groups of sizes comparable to that of giant bluefin tuna schools. Spotters have reported that they can easily distinguish giant and large-medium bluefin tuna from small marine mammals by body shape, tail orientation, and color, but identification is primarily made from swimming postures and frequency of dorsal flexure.

Table 3

Fish spotter photography effort by time of day in New England waters, July–September 1993.

Time of day (h:min)	No. of schools photographed
09:00–09:55	1
10:00–10:59	3
11:00–11:59	3
12:00–12:59	21
13:00–13:59	30
14:00–14:59	17
15:00–15:59	27
16:00–16:59	17
17:00–17:59	6
18:00–18:59	1

Because we did not have direct altimetry capabilities, size classes of bluefin tuna photographed in this survey could be generally documented only as large-medium or giants from spotter estimates alone. Spotters undoubtedly photographed, and we subsequently counted, some bluefin tuna below commercial size classes (<70 inches SFL). Catch records indicated that lengths of individuals in a school may vary by several inches, but only 10% of a seine catch is allowed to be undersized.[4] Because a spotter's survival in the commercial fishing industry depends upon size judgments being made before seine boats expend effort to capture schools, there is a strong selection for accuracy (Williams, 1981; Squire, 1993).

Despite confidence in spotter estimates (Squire, 1993), adequate documentation and validation of their ability to judge size or biomass are lacking. Research to define the accuracy of New England bluefin tuna spotter estimates, or to explore alternative methods of establishing lengths of photographed bluefin tuna, are clearly needed. Future surveys must obtain more specific information on size classes of photographed fish in order to be used as a point of reference for present CPUE-based models that use total length to assign year class (Anonymous, 1986).

The majority of bluefin tuna schools were photographed in five areas traditionally fished for giant tuna, including Great South Channel, Wilkinson Basin, Platt's Bank, and Jeffreys Ledge. This group of areas may reflect the past experience of the spotters and their unwillingness to search where fish are not usually found; it may also indicate that giant and large-medium-sized tuna exhibit clumped distributions in New England waters, where oceanic frontal systems, bottom topography, and concentration of prey provide favorable feeding and thermal conditions (Laurs et al., 1984; Maul et al., 1984; Roffer, 1987).

Clumped distributions make redundant counts an underlying problem for aerial assessments. Lacking GPS capabilities in 1993, we acknowledge that we may have counted bluefin tuna schools more than once because we had insufficient data to precisely locate all photographed schools. We have learned, however, that a given spotter is unlikely to photograph the same school twice over a period of a few hours. Once a spotter directs a boat onto a school, he moves to other areas because circling by boat is believed to force the fish down, rendering them difficult to catch for some time. In future surveys, an algorithm incorporating maximum swimming speeds and surfacing behavior could be used to limit redundant counts. Minimum counts based on daily rather than pooled totals would also reduce counting problems resulting from residence time and sequential movement of fish through the study area.

Conclusions

In this collaborative study neither we nor the ECTA believe that expended effort was sufficient to derive, on any given day, a minimum count of giant and large-medium bluefin tuna in New England waters. To do so would require not only perfect environmental conditions (noted by pilots and fishers as a "show" day) but also the complete cooperation and coordination of efforts by participating pilots. Given that the feasibility survey started relatively late in the fishing season, the latter was a difficult goal to achieve.

A fundamental limitation of aerial assessment is that only fish at or near the surface are accounted for, providing only a minimum estimate of school size. Surveyed schools subsequently captured by seiners might help define relations between aerial counts and total biomass, but this relation was established for only one set in the 1993 season. In this case (27 Aug), we counted 32 fish at the surface of a tightly domed school that yielded 125 large giants once captured.

Factors that govern schooling behavior and aggregation dynamics are poorly documented in bluefin tuna and the tunas in general (Mather, 1962; Clark and Mangel, 1979; Partridge et al., 1983). Mather (1962) described bluefin tuna behavior patterns of "pushing, milling, and smashing" in New England waters. We have noted spatial configurations (domes, cartwheels, surface sheets) and soldier groups (Partridge et al., 1983) depicted in photographed schools. Understanding the interplay of ecological and environmental factors that govern aggregation of giant bluefin tuna would help to define biases in direct assessment efforts. For example, giant bluefin tuna

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[4] Foster, K. Gloucester Laboratory. Natl. Mar. Fish. Serv., NOAA, 30 Emerson Ave., Gloucester, MA 01930. Personal commun., March 1994.

are believed to exhibit the most rigidly defined spatial structures in schooling fishes (Partridge et al., 1983). If relations between the surface structure of schools and total biomass were known, surface counts could be adjusted to include an estimate of biomass.

In future studies, on-board data loggers might be used to give accurate records of search effort and survey tracks and possibly to determine fish size through direct altimetry from phototelemetry and GPS data. Hydroacoustic trials, Lidar, or remotely operated vehicle analysis undertaken alongside seining operations may provide additional groundtruth information that would allow derivation of indices of abundance (Petit et al., 1992).

In spite of limitations faced in the 1993 feasibility study, this preliminary aerial survey provided information on counts, distribution, and schooling characteristics of giant and large-medium bluefin tuna. Direct photographic surveys to obtain minimum counts of giant bluefin tuna may be a practical method of obtaining real-time measures of their relative abundance in New England waters.

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