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An evaluation of pop-up satellite tags for estimating postrelease survival of blue marlin (*Makaira nigricans*) from a recreational fishery*

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Blue marlin (*Makaira nigricans*) represent an important commercial and recreational resource throughout tropical and subtropical oceanic waters. In the Atlantic Ocean, blue marlin are managed as a single, oceanwide stock. In the most recent assessment of Atlantic blue marlin (ICCAT, 2001), the Standing Committee for Research and Statistics (SCRS) of the International Commission for the Conservation of Atlantic Tunas (ICCAT) estimated the current biomass of blue marlin to be about 40% of that required for maximum sustainable yield (MSY). Furthermore, the assessment indicated that the current level of fishing mortality (F) was about four times higher than F_{MSY} and that catch levels in recent years were more than twice the equilibrium yield, contributing to a further decline of the overexploited stock. Based on the most recent stock assessment, fishing-induced mortality must be reduced by about 60% to halt the decline of the stock (Goodyear, 2000).

The greatest source of billfish (Istiophoridae) mortality occurs as a result of incidental catches by longline gear deployed for tunas and swordfish (ICCAT, 1997, 2001). These highly migratory species co-occur in the subtropical

and tropical epipelagic environment, and all are vulnerable to the pelagic longline. Not all billfish are dead at the time of capture (haulback) on longline gear; data from observers on vessels in the Venezuelan industrial longline fishery indicate that about 49% of blue marlin caught on pelagic longline gear are alive at the time of capture (Jackson and Farber, 1998).

To reduce billfish mortality ICCAT in 1997 required nations to reduce their landings of Atlantic blue marlin by 25% from 1996 levels. Furthermore, the ICCAT SCRS has recommended that the Commission consider requiring the release of all live billfish taken on longline gear (ICCAT, 1997, 2001). It is believed that such a management measure would be more acceptable to member nations than an overall reduction in longline effort that would also reduce catches of target species. However, representatives from several nations have pointed out that there are not sufficient data to estimate postrelease survival of billfish; therefore the conservation impact of a recommendation requiring live released fish cannot be evaluated. In fact, low recovery rates of billfish tagged and released with conventional tags by recreational and

commercial fishermen (<2%; Jones and Prince, 1998; Ortiz et al, 1998) are consistent with high postrelease mortality. However, factors such as tag shedding and failure to report tag recaptures could also account for low rates of tag returns (Bayley and Prince, 1994; Jones and Prince, 1998). Clearly, data are needed to support or refute the hypothesis that the release of live billfish would significantly eliminate fishing mortality of blue marlin (Graves et al.¹).

Acoustic tracking studies designed to investigate billfish physiology and behavior have provided insights into the postrelease survival of billfish taken on recreational gear. Specifically, observed and inferred mortalities during the course of the acoustic tracks indicate that not all released billfish survive (reviewed in Pepperell and Davis, 1999). Unfortunately, it is not possible to estimate levels of postrelease mortality of billfish from previous acoustic tracking studies for several reasons. First, owing to the high cost of ship and personnel time, relatively few animals have been investigated in acoustic tracking studies. Second, because ocean conditions can deteriorate quickly, many of the acoustic tracks were for less than 12 hours duration, providing a limited opportunity to observe mortality after 12 hours. Third, billfish were caught and subsequently tracked under a variety of conditions, making cross-study comparisons difficult. Finally, an estimate of postrelease mortality rates resulting from acoustic studies may be biased because in some cases only healthy fish were selected to carry acoustic transmitters.

The development of pop-up satellite tag technology may present a possible means to estimate postrelease mortality of billfish. Although relatively expensive pop-up satellite tags reduce the need to use a tracking vessel to follow

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¹ Graves, J. E., G. Skomal, and E. D. Prince. 1995. Report of the billfish mortality workshop. Contribution rep. MIA-94/95-49, 7 p. Southeast Fisheries Science Center, Miami, FL.

billfish on the high seas. Pop-up satellite tags are capable of recording environmental variables over predefined intervals, of detaching from an animal at a designated time, floating to the surface, and of transmitting the stored data to a satellite. Until now, these tags have been deployed primarily on bluefin tuna for relatively long durations (up to nine months) to determine movement patterns (Block et al., 1998a; Lutcavage et al., 1999). Recovery of tag data has been very good in most cases, with some reported rates in excess of 90% (Block et al., 1998a; Lutcavage et al., 1999). These results suggest that the technology may be well suited for shorter term studies, including the determination of postrelease survival. In this paper we present the results of a preliminary study to evaluate the feasibility of applying pop-up satellite tag technology to estimate short-term survival of blue marlin. We also include a brief analysis of the movement and behavior of blue marlin that we inferred from the pop-up tagging results.

Materials and methods

Pop-up satellite tags

The Microwave Telemetry, Inc. PTT-100 pop-up satellite tag was used in this study. The tag can withstand a pressure of 1000 psi (equivalent to a depth of about 650 meters) and is sufficiently small (38 cm by 4 cm diameter) that it would not appear to impose a major drag on a large marine teleost, such as blue marlin (Block et al., 1998a). Tags were programed to measure water temperature every hour and record the mean value for each two-hour period for a total of 61 cycles (122 hours). Inclinometer values were taken every two minutes and summed for the periods before tag detachment (pre-pop-up) and after tag detachment (post-pop-up). For each period the inclinometer started with an initial value of 128. If at the time of measurement (every two minutes) the tag was oriented below 30 degrees above horizontal, a value of one was subtracted from the total. If the tag was above 30 degrees above horizontal at the time of measurement, the inclinometer total was increased by one, but could not exceed 255. Final values below 255 indicated sufficient forward propulsion such that the positively buoyant tag was depressed below 30 degrees above horizontal for certain periods, demonstrating forward propulsion.

All nine tags were programed to detach from the fish 122 hours after activation, at which time the memory within each tag would contain 61 direct temperature measurements and the pre-pop-up inclinometer value. The five-day attachment period of the pop-up tag was chosen, in part, as a result of a review of data from conventional tag-recaptured blue marlin in the Cooperative Tagging Center (CTC) database (E. Prince, unpubl. data). Of the 160 blue marlin tag returns in CTC that have been validated, ten individuals were recaptured within five days of release, suggesting that some blue marlin are able to survive the catching and tagging event and commence feeding again within a few days. In addition, acoustical tagging studies have shown high survival rates of different marlin species in the first 1–2 days following release, demonstrating that

mortality, when it occurred, generally happened within the first 48 hours of release (Pepperell and Davis, 1999). With these considerations in mind, we assumed that the five-day period of tag attachment was an adequate period for catch and release mortality to be expressed. As indicated by Goodyear (in press), the duration of this type of experiment should be the minimum number of days necessary to account for postrelease mortality events. Longer periods would allow for greater influence of tag shedding, tag malfunction, and natural mortality, all of which could compromise estimates of postrelease survival.

Tag deployment

Pop-up satellite tags were activated and tested at the start of each fishing day. Blue marlin were caught southwest of Bermuda in the vicinity of Challenger and Argus Banks on standard recreational gear for the blue marlin fishery in Bermuda (130 lb test line) by using trolled high-speed lures or skirted dead baits (in most cases with two hooks). All hooks employed in this study were “J” hooks (no. 16/0–20/0). We tagged the first nine fish available to us. Six blue marlin were caught on the vessels we were aboard. Three individuals were taken on other vessels and transferred to the tagging vessel after the fish were brought to leader (brought to the boat): one blue marlin was caught and attached to a drifting buoy until the tagging vessel, which was several miles away, could gain access to the fish; and two fish were directly transferred after capture from the fishing vessel to the tagging vessel by using a procedure described in Block et al. (1998b).

Once fish were brought to leader (reeled to the side of the boat), quieted and secured, the pop-up satellite tag and a conventional (streamer) tag were deployed. Pop-up satellite tags were attached to one end of a 400-lb (182 kg) test monofilament leader about 18.5 cm in length, with an outside diameter of 1.8 mm. The other end of the leader was attached to a double barb nylon anchor (about 33 mm long and 10 mm wide) made of medical-grade nylon. The anchors were implanted by using a stainless steel tag applicator modified to accomplish placement to a depth of about 10 cm into the dorsal musculature, about 10 cm posterior and 5 cm below the base of the peak of the first dorsal fin (Fig. 1). Hook location, as well as observations on foul-hooking (tissue damage, bleeding, etc.), were noted at the time of hook removal.

Analyses

After detachment from the animal, the positively buoyant tags floated to the surface and began transmitting data to satellites of the Argos™ system. Position information and sections of the temperature and inclinometer data were captured with each satellite pass and transmitted to a ground station and ultimately to the investigators by the internet. Data were analyzed to determine net movement from the point of detachment to the point when the tag popped-up (usually the first tag transmittal; however, if the first satellite pass was near the horizon, the location of the second transmittal was used to obtain greater accu-

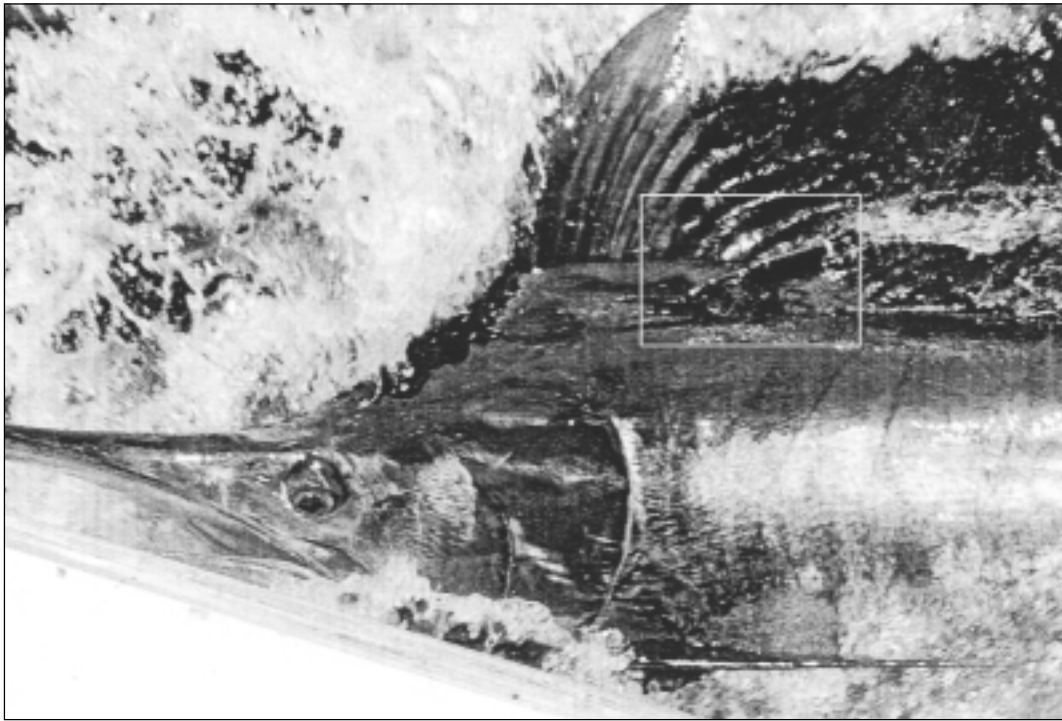


Figure 1

Blue marlin with pop-up satellite tag attached. The tag is located below the anterior portion of the dorsal fin (within outlined area).

racy). Water temperature was determined from temperature sensor readings by using a calibration provided by the manufacturer. Depth was estimated from water temperature values by using temperature and depth relationships provided by the Bermuda Biological Station for Research, which maintains an oceanographic sampling station (station S) about 13 miles (24 km) to the southeast of the island.

Results and discussion

Nine blue marlin, with estimated weights ranging from 150 to 425 lb (68 to 193 kg), were tagged between 25 July and 11 August 1999 (Table 1). Four specimens were below the minimum size for tagging recommended by the tag manufacturer (200 lb or 90.9 kg). Fight times ranged between 15 and 35 minutes. Seven fish were initially hooked in the jaw, and two were "foul-hooked" (i.e. outside the jaw and mouth): one in the operculum and one in the dorsal musculature. After tag placement, but before release, one fish that was originally hooked in the jaw became foul-hooked in the ventral musculature. Three of the nine fish were transferred to the tagging vessel after capture. Fish generally quieted down shortly after being brought to the side of the vessel, which maintained a headway of 4–5 km/h during the tagging operation. Only a few minutes were required to implant the satellite and con-

ventional tags, photograph the fish, estimate weight, measure lower jaw fork length (most individuals), and remove the hook. Condition of the fish varied, and three individuals required resuscitation prior to release.

Eight of the nine tags became detached from their respective host fish after five days, floated to the surface, and transmitted to the Argos™ satellite system. Based on the first accurate location of the tags, net displacements ranged from 40 to 134 nmi (72–248 km) with a mean linear displacement of 90 nmi (167 km) for each individual (Fig. 2). These values are in the range reported for blue marlin by Block et al. (1992) who followed six blue marlin with acoustic transmitters for periods of one to five days. They noted individual total movements (as opposed to net displacements) of 253 km in about three days, 100 km in five days, and four animals with movements of less than 100 km over the course of the respective tracking periods.

Individual marlin in our study dispersed in all directions from their point of release (Fig. 2). The blue marlin tracked by Block et al. (1992) and Holland et al. (1990) in Hawaiian waters moved away from the point of capture in several different directions. However, the authors noted an orientation of movements to the coastline of the Hawaiian Islands. Our releases were farther offshore and an affinity to the Bermuda coastline was not evident from the net movement data.

Depending on the time of tag activation and the time of tag deployment, up to 61 direct water temperature readings, taken every two hours, were obtained for each blue

Table 1

Pop-up satellite tag deployment information. "Transfer" indicates whether a fish was moved between vessels after capture to allow tagging. "Resuscitation" indicates the time spent to move a blue marlin through the water after capture until it could swim off under its own power. Tag no. 24040 failed to report.

Tag no.	Deployment		Fight time	Transfer (yes/no)	Hook location	Estimated weight (lb)	Resuscitation (no/yes—time)
	date	hour	min.				
24519	25 Jul 1999	1610	25	yes	jaw	400	no
24059	28 Jul 1999	1110	35	yes	jaw and ventral musculature	200	no
24522	1 Aug 1999	1030	20	yes	jaw	175	no
24520	2 Aug 1999	1015	15	no	jaw	180	no
24033	2 Aug 1999	1245	30	no	jaw	425	yes—10 min.
24040	2 Aug 1999	1500	17	no	jaw	200	no
24523	3 Aug 1999	1550	15	no	operculum	150	yes—8 min.
24527	11 Aug 1999	1255	15	no	jaw	350	no
24029	11 Aug 1999	1340	23	no	dorsal musculature	150	yes—3 min.

marlin (Fig. 3). Temperature readings demonstrated that tagged individuals spent the majority of their time at temperatures above 26°C (Fig. 4). The maximum temperature range recorded for any of the eight individuals was 9°C (22–31°C, tag no. 24033). Block et al. (1992), using acoustic tracking, determined that the six blue marlin which they tracked spent half of their time in the upper 10 m of the water column in water temperatures 25–27°C, and Holland et al. (1990) reported that blue marlin in waters off Hawaii remained at temperatures of 26° or greater.

Differences in thermal histories were evident among the individuals in our study. Blue marlin no. 24029 (Fig. 3G) spent the vast majority of time at temperatures equal to that of the surface waters (30–31°C). In contrast, individual no. 24527 (Fig. 3H) spent much less time in the warmer surface waters and repeatedly moved up and down in waters between 23° and 31°C. Several individuals appeared to remain at or very near the surface for extended periods, evident in Figure 3 as a continuous string of temperature readings at or slightly above 30°C. An analysis of the data examining diurnal-nocturnal periods with temperature (inferred depth) indicated a high level of variability between individuals and no clear pattern was apparent (Fig. 3). In contrast, Holland et al. (1990) determined that blue marlin spent a higher proportion of their time (~50%) in the upper 10 m at night than during the day (~25%).

It was possible to infer swimming depths of blue marlin by comparing water temperature values with the temperature-depth profiles at station "S" provided by the Bermuda Biological Station for Research.² All blue marlin en-

tered cooler waters at various times during the five-day period, with excursions to depths as great as 40 meters. Temperature records were consistent with the tagged blue marlin actively undertaking vertical movements in the upper 40 meters of the water column. However, six of the eight fish spent >75% of their time in the upper 10 m of the water column for the five-day duration of the study. If the data from all eight fish are pooled, this yields a mean value of 79.9% (SD 15.8%) of the time spent in this zone. This is a higher percentage of time spent in the upper 10 m than that observed by Block et al. (1992), who reported that fish spent about half of the time in this zone. However, this comparison should be viewed with some caution because the Block et al. (1992) data were based on continuous tracking, whereas each data point in our analysis was the average of two hourly measurements.

All post-pop-up inclinometer values were 254 or 255, where 255 represented the maximum (vertical) inclinometer value expected for an upright, floating tag. Pre-pop-up inclinometer values ranged from 203 to 251, with three individuals at 233 and four between 247 and 251. These values indicate tags were inclined at an angle below 30 degrees above horizontal for more than 40% of the 1830 sampling times for each individual, and are consistent with sufficient forward propulsion to depress the positively buoyant tag more than 60 degrees from vertical. There was no correlation between pre-pop-up inclinometer values and net displacement. The fish with the largest net displacement (no. 24059) had the second highest inclinometer value. This was not unexpected because the difference between the lowest and highest pre-pop-up inclinometer values represents a minor difference in the time the tag was depressed below 30 degrees above horizontal. Also, the relationship between total movement and net displacement could be quite different for different individuals.

Three different lines of evidence provided by the pop-up satellite tags (net movement, water temperature, and tag inclination) each suggested that at least eight of the

² Although this station is situated 24 km to the southeast of the island, similar temperature-depth profiles would be expected for the general region (Johnson, R. 2000. Personal commun. Bermuda Biological Station for Research, 17 Biological Lane, Ferry Reach, St. George's GE01 Bermuda). This allowed us to use the station S profiles to infer swimming depth, realizing that, depending on when an animal was tagged and where it moved, there would be some differences for which we could not account.

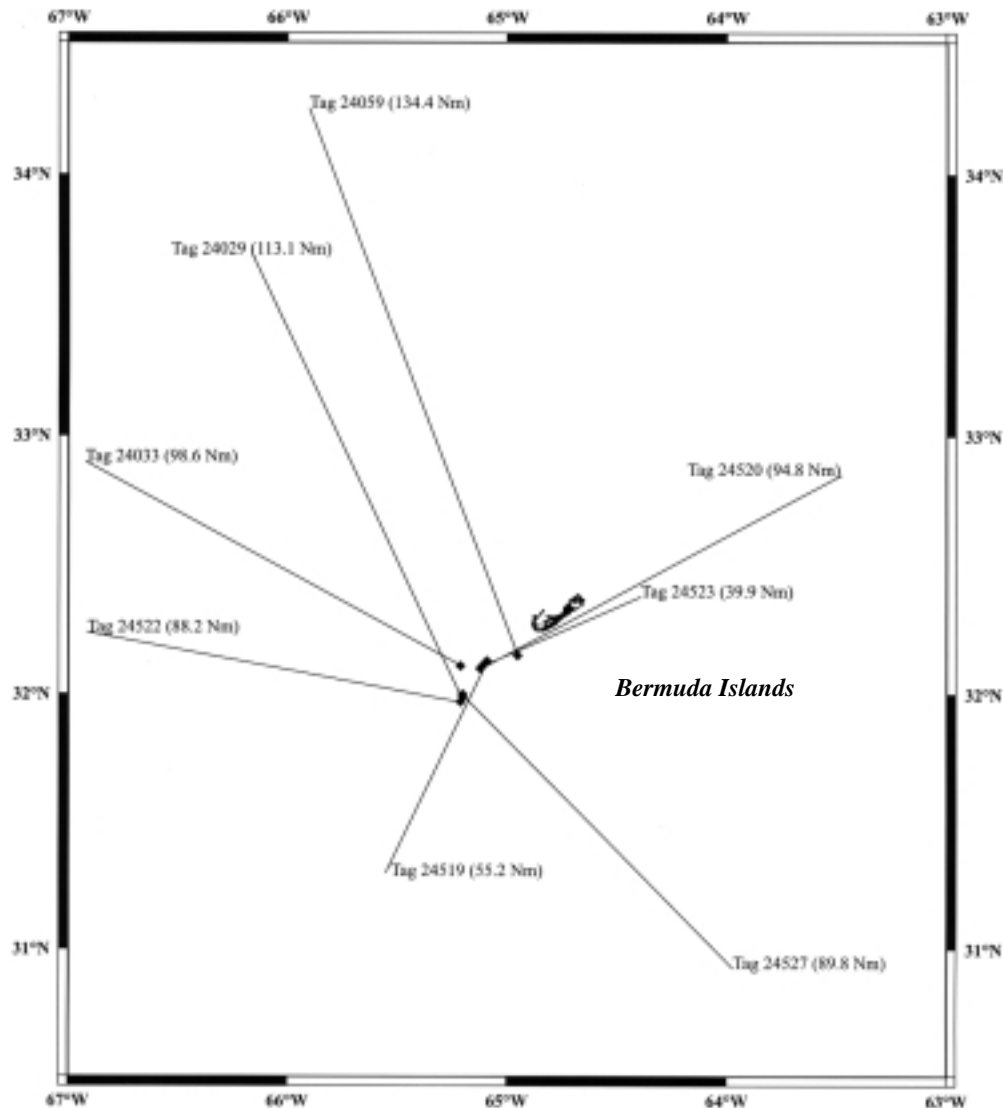


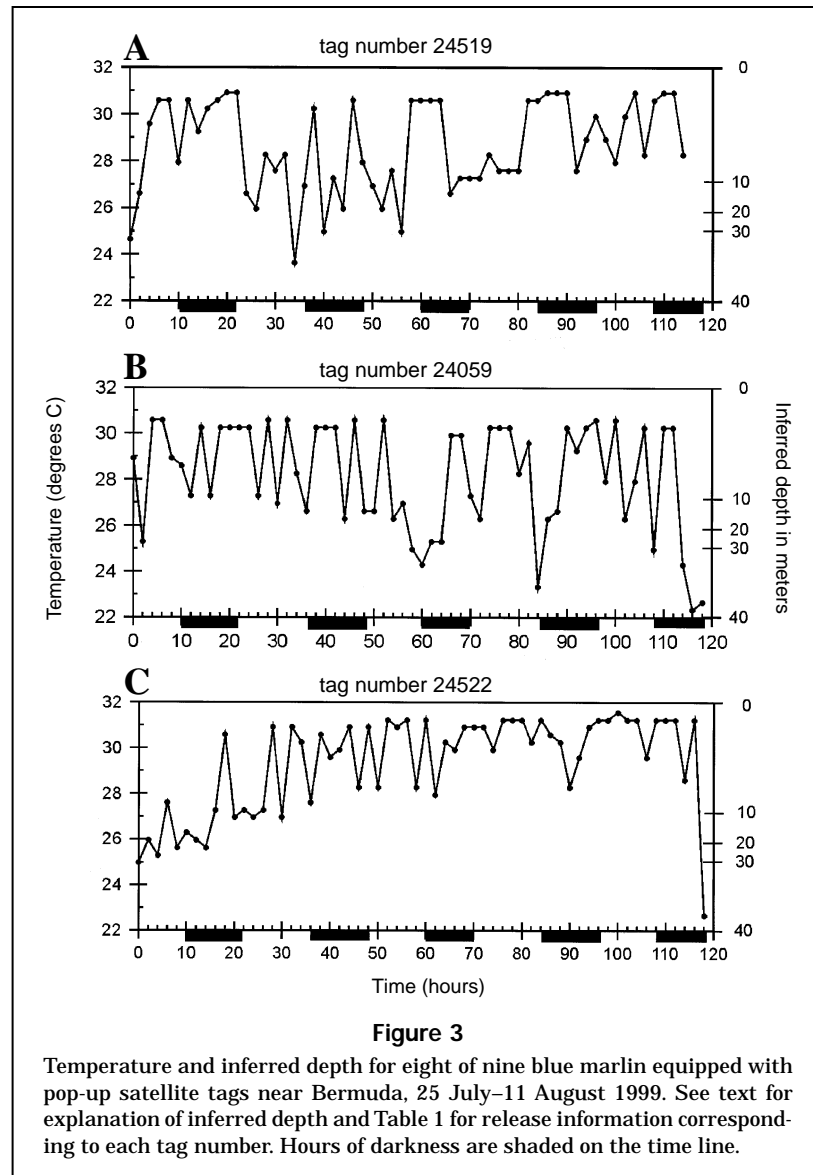
Figure 2

Map showing points of release (squares) and points of recovery (end of straight lines) for eight of nine blue marlin equipped with pop-up satellite tags near Bermuda, 25 July–11 August 1999. The pop-up satellite tag number for each fish and straight line distance between point of release and geolocation where tag transmitted data to the Argos satellite (given in parentheses) are provided.

nine blue marlin caught on recreational gear survived for five days following capture, tagging, and release events. The net movement data indicated a broad dispersal of the eight fish in different directions that cannot be explained by local currents. In contrast to the differing direction of movement, the net displacements of the eight fish were fairly similar. The mean displacement of 89.25 nmi over a five-day period, compares favorably with blue marlin swimming velocities of 1–2 nmi/h reported from acoustic tracking studies (Holland et al., 1990) and is consistent with the constant slow swimming of the individuals. Although currents could have accounted for some of the net displacement, inclinometer values indicated that all eight individuals were actively swimming.

The water temperature measurements indicated that each blue marlin actively undertook dives into cooler water throughout the course of the five days. All eight individuals spent the vast majority of their time in waters with temperatures of 26°C or greater, and no readings below 22°C were recorded.

The successful data recording, tag detachment, and transmission of eight of the nine pop-up satellite tags begs the question of what happened to the one tag that failed to report. It is not possible to distinguish between the post-release mortality of a tagged blue marlin and the mechanical failure of a pop-up satellite tag. If a marlin dies and sinks in deep water, the attached pop-up satellite tag eventually will be crushed by increasing hydrostatic pressure.



The blue marlin whose tag did not report (tag no. 24040, Table 1) was hooked in the jaw, caught in less than 20 minutes, did not require resuscitation, was quickly tagged, and actively swam away from the boat when released. Shark predation on released billfish has been reported (Holland et al., 1990; Pepperell and Davis, 1999); therefore mortality cannot be excluded despite the apparent vigorous condition of the fish. Failures in component subsystems could account for the failure of reporting from a pop-up tag. A detailed analysis of the reliability of each tag component could be undertaken, but several factors external to the tag could also result in a failure of reporting. Tag manufacturer innovations and upgrades of the systems will allow researchers to better identify mortalities, but they will not completely solve the problem of discriminating between tag failure and fish mortality. Nonreporting tags would have significant consequences for efforts to make

ocean-wide estimates of postrelease survival. The ability to account for all pop-up satellite tags deployed is directly related to the accuracy of the resulting estimates of postrelease survival (Goodyear, in press). Nonreporting satellite tags introduce uncertainty that cannot be quantified in the estimates of postrelease survival, thus compromising meaningful conclusions. Excluding nonreporting tags from the analysis decreases precision of the estimate, and including mortalities biases the survival estimate downward. Further, any extension of the 5-day pop-up period to allow study of possible delayed effects of tagging should involve careful consideration of the benefits and the liabilities that longer durations might have on estimating postrelease survival (Goodyear, in press)

Successful tagging and reporting of pop-up tags from four fish under 200 lb (90.9 kg) indicate that the size and design of the PTT-100 tag is tolerated by smaller blue mar-

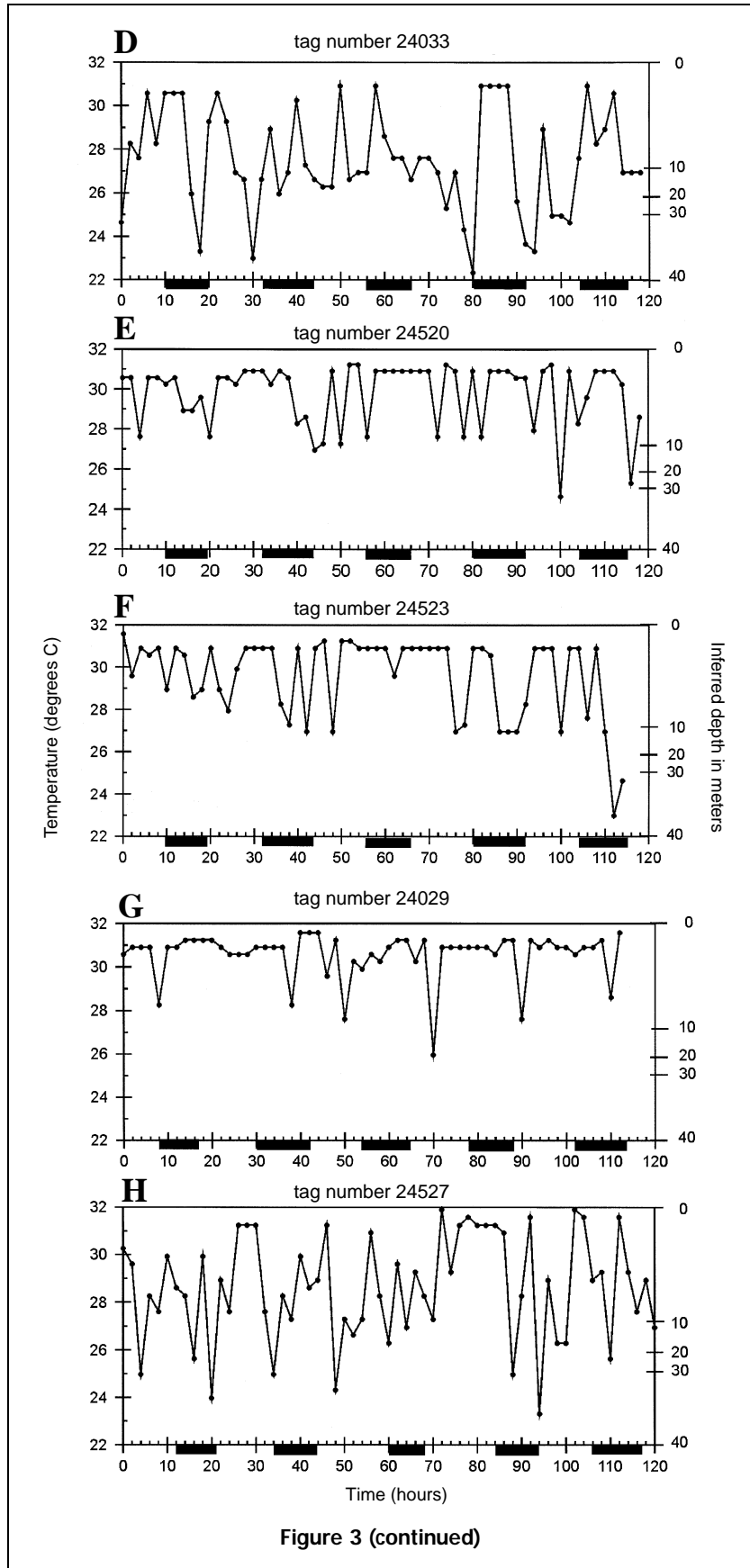
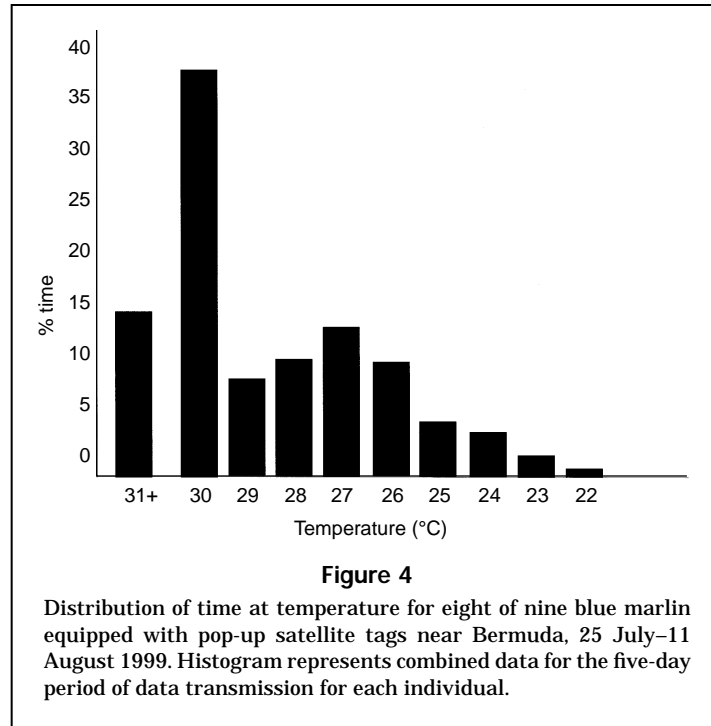


Figure 3 (continued)



lin than that recommended by the manufacturer, at least in the short term. Thus a pop-up tag of this size might be tested on even smaller specimens or other target species to expand the study of behavior in a wider size range of species than was originally thought possible.

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