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Measuring the Length of a Pelagic Longline Set: Applications for Management

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Abstract.—Recent U.S. federal fisheries management actions aimed at reducing bycatch have established or proposed limits on the length of a pelagic longline set. However, such management measures are unenforceable if the criteria for measuring the length of a pelagic longline set have not been defined. Differences in the physical gear and deployment strategies suggest high variability among the several methods that can be used to measure set length. This study uses a combination of scientifically monitored sets, fisheries observer data, and federal pelagic logbook data to compare four possible metrics of longline set length: the geographic track of the vessel while deploying the gear, a "folding ruler" approximation based on straight-line distance between ends of the sections of gear, the straight-line distance between the beginning and end of the gear, and a dead-reckoning distance based on vessel speed and the time duration of the gear deployment. Results indicate that while set lengths determined from self-reported data via logbook submissions are not significantly different from the other proposed methods, the inclusion of an ending location for each set within the logbook form could provide a basis for evaluation of the regulatory measure.

Pelagic longline fishing gear is used worldwide commercially to target such species as tunas *Thunnus* spp. and swordfish *Xiphias gladius*. In its simplest construction, it consists of a mainline, hook-tipped leaders (gangions), and floats to suspend the line below the water surface (see Bjordal and Løkkeborg 1996). During gear deployment, the mainline is deployed over the stern as the vessel moves forward, as the crew attaches individual baited leaders onto the mainline at predetermined intervals. Radar-reflecting buoys ("high-flyers") and buoys that transmit a signal at a known radio frequency ("beeper buoys") are spaced throughout the gear to maintain contact with the free-floating gear during its active fishing period, usually overnight for gear targeting swordfish. Each individual deployment of the gear is known as a "set."

Although perhaps intended to mean the distance of the sea surface that a longline spans or some equivalent, the term "set length" has not yet been expressly defined. This lack of definition has not precluded the use of the term in fisheries management measures, however. Regulatory measures based on the length of a type of fishing gear are common in state and federal commercial fisheries (e.g., gill-net fisheries), but rare in domestic pelagic fisheries managed by the U.S. National Marine Fisheries Service (NMFS). One exception is a 1999 regulatory measure that was intended to reduce incidental catches of bluefin tuna *T. thynnus thynnus* by limiting the lengths of pelagic longline sets to 24 nautical miles (nmi, 1 International nmi = 1.85 km) in the Mid-Atlantic Bight from 1 July 1999 through 30 June 2000 (NMFS 1999). (Although Richards [1999] correctly noted the technical problems associated with the use of such poorly-defined geographic terms as "Mid-Atlantic Bight," the use of such terms herein only refers to the specific NMFS pelagic fishery statistical areas.) More recently, the Atlantic Pelagic Longline Take Reduction Plan included a proposed measure that would limit sets to no longer than 20 nmi, also within the Mid-Atlantic Bight statistical area. Although based on several tenuous assumptions and limited data across time–area strata, simulations suggested that this restriction would reduce the total pilot whale *Globicephala* spp. interaction rate in the Mid-Atlantic Bight by approximately 26% (APLTRT 2006).

The 2006 Take Reduction Plan measure for reducing pilot whale interactions, like the similar 1999 bluefin tuna measure, also did not define the term "set length," even in an implicit fashion. There are at least two general types of measurement for the length of a longline set: (1) the length of the mainline itself, and (2) the length of the course-over-ground distance traveled by the vessel during gear deployment. Both have peculiarities concerning the variability of the measurement and the possible techniques used to measure the length.

To complicate matters, the behavior of pelagic longline gear during the fishing period is highly variable and not necessarily dependent on the amount of mainline deployed. Several authors (e.g., Yano and Abe 1998; Bigelow et al. 2006) have examined the

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relationship between vessel speed, mainline sag, and the effective fishing depths of longline gear. This gear type relies on a certain amount of "sag," or slack gear, between floats to create a concave "caternary" curve that allows the hooks to fish at varying depths. Characterizing this sag accurately has been challenging for workers attempting to standardize the gear type among longline fisheries. In the Gulf of Mexico, Wathne (1959) demonstrated that sag or "reduction rates", another measure of the caternary curve formation between floats, might be as important as leader length in determining the final depth of individual hooks. Using small bathythermographs, Mizuno et al. (1997) found that the reduction rate was an important determinant in the final depth distribution of hooks even in the presence of vertical shear from a nearby current. In the absence of other metrics, several authors (e.g., Yano and Abe 1998; Bigelow et al. 2006) have used the great-circle distance (the shortest distance between points on a sphere measured along a path on the surface) between the start and end latitude and longitude positions as one of two factors in calculating the reduction rate. The other reduction rate factor used by these authors was the captain–operator-reported estimate of the amount of mainline deployed for each set. Presumably, these experienced fishers would be best qualified to estimate the amount of deployed gear, but even here the estimates vary, and the ratio of these two numbers is very rarely equal to the 1.00:1 that would signify agreement between the measured and estimated values.

Several possible measuring devices could be used if the designation of the "set length" is the type of measurement based on the physical length of mainline deployed. For example, because the mainline spool has a mechanism that winds the mainline onto the spool evenly, one possibility could be to measure the difference in diameters of the mainline wound on the spool before and after the gear deployment. However, as the mainline is wound onto the spool at varying speeds and tension, this can affect the diameter of the mainline strand itself up to 50% (J. Lindgren, Lindgren-Pitman, Inc., personal communication) and, therefore, the spool diameter would probably result in a highly variable measurement.

Another method could use the so-called "line shooter" device that is positioned near the stern of the vessel and pulls mainline off the spool faster than the vessel is moving forwards, thereby allowing the captain to more accurately generate a deep caternary curve "sag" between the buoy floats attached to the mainline. As shown by Bigelow et al. (2006), knowledge of both the predetermined speed at which this device operates and the duration of the setting procedure allows a direct calculation of the amount of mainline deployed. (Equations for such a calculation are shown in the Lindgren-Pitman, Inc., Pompano Beach, Florida, on-line product instructions for the line setter device; see www.lindgren-pitman.com/pdfs/LS-5LinesetterManual.pdf.)

However, and unlike the fishing practices within the Hawaii fleet, line shooters are infrequently used in the U.S. Atlantic pelagic longline fleet, accounting for only 0.07% of all logbook-reported longline sets during the 2001 to 2004 period (NMFS, unpublished data).

Without physical mainline measuring devices, an alternative type of measurement that employs vessel speed or geographic position must be used to estimate the length of a pelagic longline set. This paper describes and compares four different methods of this measurement type that were used to estimate the set length of commercial pelagic longline sets in the western Atlantic Ocean between 2001 and 2006.

Methods

Three data sets were used in these analyses of pelagic longline set length. The first is a series of research pelagic longline sets that were monitored at sea between 2001 and 2006. All sets targeted either swordfish or tunas, or both, using monofilament pelagic longline gear ("Florida-style" gear; Berkeley et al. 1981). Data were collected opportunistically on three different commercial fishing vessels, identified in this manuscript only by numbers to provide an element of confidentiality. Vessels 1 and 3 are similarly sized fiberglass vessels approximately 50 ft (15 m) in length over all (LOA) that operated seasonally in the Mid-Atlantic Bight, South Atlantic Bight, North-East Coastal, Gulf of Mexico, Florida East Coast, and Caribbean National Marine Fisheries Service (NMFS) pelagic fishery statistical areas (NMFS 2006). Vessel 2 is an approximately 115-ft (35 m) LOA steel-hull vessel that conducted commercial fishing operations in the equatorial waters of the Tuna-South NMFS statistical area. A list of commonly used acronyms is included in Table 1.

Three methods of estimating gear length were conducted for each set (see Figure 1) using a handheld global positioning system (GPS) unit with wide-area augmentation system (WAAS) capability (GPS accuracy < 161.4 ft^2 [15.0 m^2] RMS; model *eTrex Venture*, Garmin International, Inc., Olathe, Kansas). The methods are as follows:

(1) GPS track (GPST): The GPS unit was used on the deck to continuously monitor the position of the vessel at 1-s intervals. The track was started at the

TABLE 1.—Acronyms and abbreviations commonly used in this study.

Type	Acronym	Definition
Statistical area	CAR	Caribbean Sea
	FEC	Florida East Coast
	GOM	Gulf of Mexico
	MAB	Mid-Atlantic Bight
	NEC	North-East Coastal
	SAB	South Atlantic Bight
	TUN-S	Tuna-South
Data source	NMFS	U.S. National Marine Fisheries Service
	PLRP	Pelagic Logbook Reporting Program
	POP	Pelagic Observer Program
Length metric	DR	Dead reckoning
	FRA	Folding ruler approximation
	GPST	Global positioning system track
	ML	Mainline length
	SEA	Start–end approximation

first hook and ended at the last hook and provided a measurement of the course-over-ground distance.

(2) "Folding ruler" approximation (FRA): The same GPS unit was used to record the position of the vessel at the moment when each large radio buoy or radar-reflector buoy was deployed. The FRA was constructed by summing the minimum straight-line distances between each of these points (the piece of gear between each large marker buoy is called a "section"), in a manner similar to the overall length of a folding ruler. The gear is generally deployed in such a way that each section requires about 1 h to set (D. Kerstetter, unpublished data). This estimate, therefore, provides a rough approximation of the positions of the vessel (and buoys) from the current vessel monitoring system (VMS) used to monitor vessel location, which transmits one position estimate every hour (B. Lambert, NMFS Southeast Regional Office, St. Petersburg, personal communication).

(3) Start–end approximation (SEA): The SEA was calculated by taking the minimum straight-line distance (MSLD) between the GPS-obtained start and end points of each set.

In addition to these three methods, 12 sets also included data on vessel speed during gear deployment, allowing the calculation of a "dead reckoning" (DR) distance, which was calculated as the vessel speed multiplied by the length of time during the setting of the gear.

Occasionally, logistical problems such as a malfunction of the GPS unit prevented the collection of all set-measurement parameters. Nongeographic data on each set, including number of deployed hooks, were also recorded. Details on the vessels, sets, and the data obtained are found in Table 2.

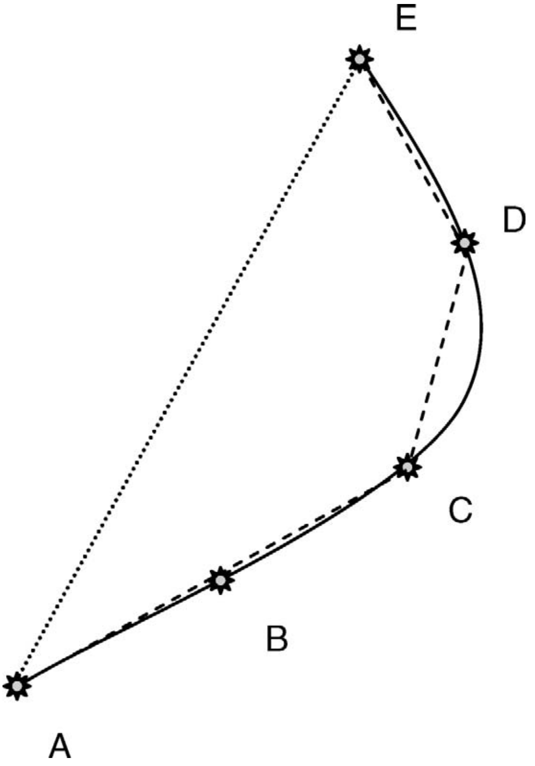

FIGURE 1.—Conceptual differences in measurement lengths for a theoretical pelagic longline set. Solid line: global-positioning system track (GPST, arc length); dashed line: "folding ruler" approximation (FRA, length A–B–C–D–E); and dotted line: start–end approximation (SEA, direct length A–E).

The second and third sources for the analyses are the Pelagic Observer Program (POP) and Pelagic Logbook Reporting Program (PLRP) data sets, previously described by Beerkircher et al. (2004) and Cramer (2002), respectively. Both the POP and PLRP data sets are available for public download at the NMFS Southeast Fisheries Science Center website (www.sefsc.noaa.gov). The POP places trained fisheries observers aboard commercial pelagic longline vessels, who record various gear- and fishing-related data while at sea. In contrast, the PLRP database is based upon mandatory, self (captain)-reported location, gear configuration, and catch data for each set (NMFS 2007). Each of these two data sets includes a reported overall set length, with the POP database also including the start and end positions for each set to the nearest minute of latitude and longitude.

The set length was obtained by three methods for the POP data. In the POP database, the 'Set Length' parameter can be recorded by the fisheries observer

TABLE 2.—Monitored sets and respective data from pelagic longline operations in the western North Atlantic, 2001–2006. National Marine Fisheries Service pelagic statistical area abbreviations are as follows: Mid-Atlantic Bight (MAB), South Atlantic Bight (SAB), North-East Coastal (NEC), Gulf of Mexico (GOM), Florida East Coast (FEC), Caribbean (CAR), and Tuna-South (TUN-S). Data type abbreviations are as follows: GPS track (GPST), folding ruler approximation (FRA), start–end approximation (SEA), dead reckoning (DR), and Pelagic Logbook Reporting Program (PLRP).

Year	Vessel	Location	Average sections	Total sets	GPST data	FRA data	SEA data	DR data	PLRP data	Hooks per set
2001	1	FEC	3.6	11		11	11		11	
2002	2	TUN-S	8.6	5		5	5	2		5
	1	MAB/SAB/FEC	4.1	29		29	29		29	29
2003	1	MAB/NEC	6.8	37	17	37	37		37	37
2004	1	GOM/FEC/CAR	6.1	47	39	38	39	5	39	47
2005	1	SAB	5.0	2	2	2	2		2	2
	3	GOM/FEC	6.3	7	1	7	7		7	7
2006	3	GOM/FEC	6.0	5	5	5	5	5	5	5

using either the dead-reckoning method or by the distance over ground as recorded by the vessel's electronic plotter. Because of this flexibility in the guidance to the fisheries observers, a dead-reckoning set-length value ('DR Set Length') was also calculated by multiplying the 'Set Speed' value by the duration of the gear-setting period. Finally, the GPS positions for the start and end of the set were obtained to calculate the SEA distance. In addition to these three estimates, the POP-recorded set latitude and longitude coordinates and dates were then used to match POP data to PLRP records to obtain the self-reported set length.

The PLRP reporting instructions for the vessel captains is less descriptive, simply requiring the "length of set (nautical miles)" (NMFS 2007). Because vessel 2 was not a U.S. registered vessel at the time of this research, PLRP reports were not submitted. The captains of vessels 1 and 3 both indicated that they used a combination of the two methods used in the POP data set, with the captain of vessel 1 generally using the length reported by the electronic plotter and the captain of vessel 3 often simply using a dead-reckoning approximation.

All statistical tests were conducted with SAS (v. 9.1, Cary, North Carolina), and significance was ascribed at the $P < 0.05$ level. Comparisons between set parameters (e.g., number of sections per set) were tested with t-tests and those between length measurements with correlation analyses. Due to missing or incomplete data in the POP records, the test for number of sections was restricted to those sets in the records with a listed number of sections greater than one. Similarly, the tests between DR and ML lengths in the POP data were restricted to those sets with DR length greater than zero. Comparisons between correlations used Fisher's z transformation if independent and the method of Cohen and Cohen (1983) if variables were shared (e.g., comparing SEA and PLRP with GPST and PLRP). Great-circle distances between start and end geographic positions for the SEA and FRA analyses were calculated with program inverse (NGS 1975, modified by M. Ortiz, NMFS SEFSC Miami Laboratory).

Results

A total of 143 monitored research sets was conducted under normal commercial pelagic longline operations, covering all four calendar quarters and seven NMFS statistical areas. Despite spatial and temporal coverage, the mean number of sections in the monitored sets (mean = 5.8) was significantly lower than that in the POP data (mean = 8.2, $t = -16.69$, $P < 0.0001$). The number of hooks in the monitored sections (mean = 565.4) was also significantly lower than for the POP sets (mean = 761.8, $t = -9.61$, $P < 0.0001$). The mean ($\pm$SD) reported (via the PLRP) set length in the monitored data set was 22.0 $\pm$ 5.73 nmi. The number of deployed hooks and reported set length was highly significantly correlated for both the monitored ($r = 0.746$, $n = 127$) and 2000–2006 POP ($r = 0.747$, $n = 3{,}548$) data sets.

Correlation analyses for the monitored sets indicated highly significant relationships ($P < 0.0001$) between the PLRP-reported length and the FRA ($r = 0.770$, $n = 117$), SEA ($r = 0.750$, $n = 119$), and GPST ($r = 0.714$, $n = 46$) lengths. The DR length was not significantly correlated with the PLRP data, although a positive relationship was demonstrated ($r = 0.300$, $P = 0.3994$, $n = 10$). Correlation comparisons indicated no significant differences at a significance level of $P < 0.05$ between FRA and SEA ($t = 1.124$, $|t_{crit}| = 1.981$), FRA and GPST ($t = 1.045$, $|t_{crit}| = 2.017$), and GPST and SEA ($t = 1.962$, $|t_{crit}| = 2.017$) length metrics (Figure 2). Because DR was not significantly correlated with the PLRP length, it was not compared with the other lengths.

Similar correlation analyses for the POP data also showed highly significant relationships between the

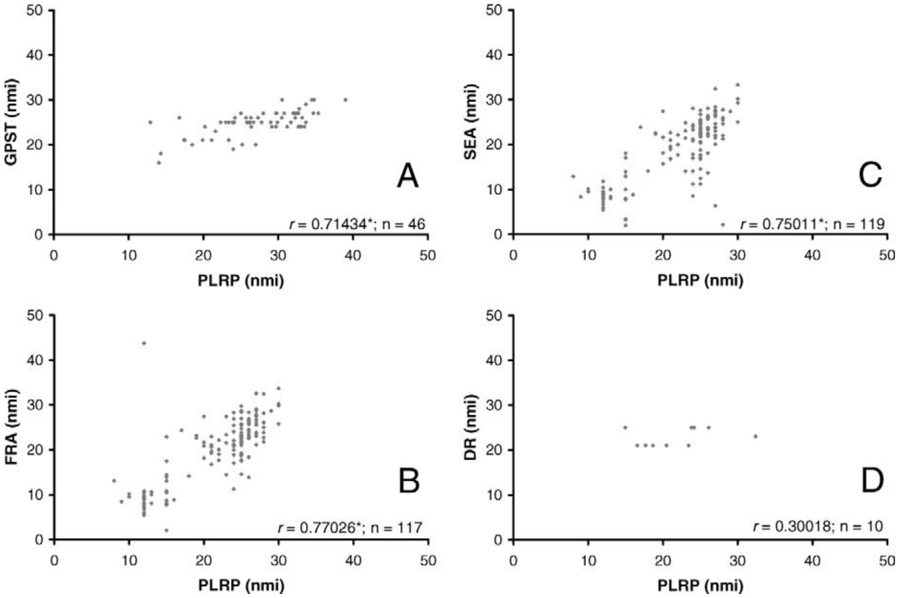

FIGURE 2.—Differences in measurements from the Pelagic Logbook Reporting Program (PLRP) reported length for 143 monitored sets in the western North Atlantic (2001–2006). (A) Global-positioning system track (GPST), (B) "folding ruler" approximation (FRA), (C) start–end approximation (SEA), and (D) dead reckoning (DR). An asterisk (*) indicates a relationship significant at $P < 0.0001$.

reported mainline length and the calculated SEA ($r = 0.706$, $n = 2{,}570$) and DR ($r = 0.841$, $n = 2{,}464$) lengths (Figure 3). Comparisons between the DR and SEA regressions from the POP data showed a significant difference between their correlations ($z = 12.297$, $|t_{crit}| = 1.96$). A comparison between the correlations of the monitored sets and the POP data sets was only possible with the SEA length because of the large discrepancy in sample size and significance for the two DR metric relationships. Nonetheless, the correlation coefficients for SEA with these two data sets were not significantly different ($z = 1.011$, $|t_{crit}| = 1.96$).

Discussion

The issue of pelagic longline length has potential application to the management of the entire U.S. longline fleet. However, the results from these monitored sets may represent only the fishing practices of three captains, not the entire fleet. Although the mean number of sections of gear and the mean number of deployed hooks per set were less than the POP data indicates for the fleet, the POP data set itself may be also slightly biased because of the heightened observer coverage of the large steel-hulled vessels in the Grand Banks fishery due to concerns about interactions with sea turtles (Superfamily: Chelonioidea). For example, vessels 1 and 3 are primarily coastal vessels, and while

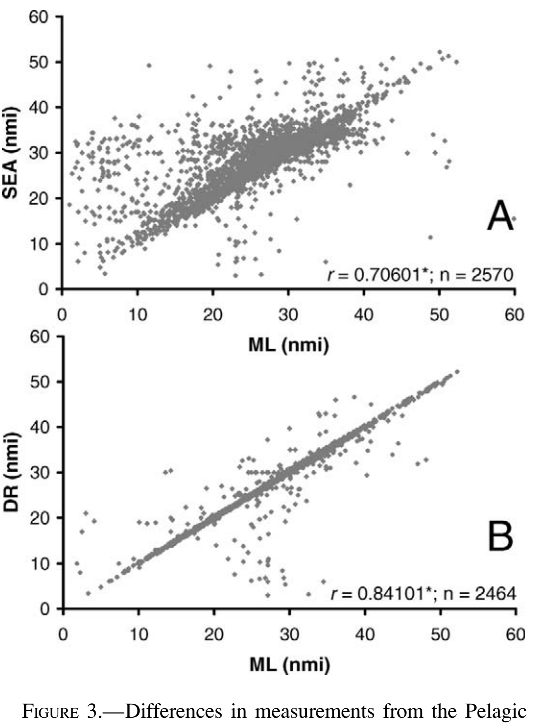

FIGURE 3.—Differences in measurements from the Pelagic Observer Program (POP) reported mainline length (ML) for 2,570 POP observer pelagic longline sets in the western North Atlantic (2000–2006). (A) Start–end approximation (SEA) and (B) dead reckoning (DR). An asterisk (*) indicates a relationship significant at $P < 0.0001$.

the captains of these two vessels regularly travel between several NMFS statistical areas during the course of the year, neither one ever fishes in the Grand Banks fishery. However, shorter set lengths should result in a stronger relationship between the four measurement metrics by minimizing the lateral displacement from a theoretical straight line connecting the start and end points.

Although the research was conducted opportunistically, all of the monitored sets were commercial pelagic longline sets, with only parameters such as hook design as the experimental factors (i.e., the captains set the gear in their normal configurations). The majority of these monitored sets, while being a low sample size, nonetheless are representative of the coastal fleet component that would be directly affected by the proposed 20-nmi set limitation in the Mid-Atlantic Bight statistical area.

The implicit relationships between set-length metrics have been noted by previous researchers (e.g., Bigelow et al. 2006), usually in the context of describing the behavior of pelagic longline gear. Because "set length" is often used colloquially in this fishery, defining the length of the set in the Methods of a scientific manuscript is important for the correct interpretations of research results. However, the renewed interest in applying a set-length limitation for management purposes requires a re-examination of the various metrics available to measure this length. The set-length approximations generated for this work are clearly not an exhaustive list of all possible means to measure the length of pelagic longline sets. However, they do provide a reasonable collection of the various means possible to measure this length given the current data collection protocols for the commercial U.S. pelagic longline fleet.

The monitored set data and the POP data produced good agreement between the length estimates. All of the correlations were positive, and most were significant, as were the comparisons between the various metrics in the monitored sets. Interestingly, the strongest relationship in the data from monitored longline sets was between the FRA and the PLRP logbook data. The fact that this was not the GPST and the reported PLRP length, suggests that another factor is involved in the perception of length by each individual vessel captain. Many captains will continue setting mainline at the end of the set, even without deploying hooks, for up to about 10 additional minutes until a knot is reached in the line. (This helps reduce the weak points in the mainline around the knots used to rejoin the line.) The slight biases in the monitored set data may reflect the inclusion of this additional line. The highly significant positive relationship between the DR and ML lengths in the POP data set suggests further that many of the observers may be obtaining or sharing their length calculations with the captains.

None of the four monitored set metrics were significantly different. From a management perspective, any of them could be useful for measuring set length. These results suggest that the start and end point coordinates obtained in the POP data collection process are, in most cases, enough data to provide estimates that are relatively consistent with the other examined methods of obtaining estimates on the length of the set, i.e., to endorse the SEA estimate for the length of the set. Furthermore, the SEA would be simple to calculate, requiring a minor change to the current PLRP data forms to include reporting the end coordinates. While it is possible to set the gear in either a "U" shape or in a so-called "zig-zag" fashion to deploy additional mainline (and, hence, more hooks) than the SEA would indicate, this fleet generally follows the edge of water bodies in the pelagic environment; it is unlikely that a captain would choose to set additional gear if the probability of additional catch is low, especially given the high fixed costs in the current fishery. Such configurations are also very problematic when setting gear in the vicinity of other vessels' longlines. Only three of the 143 monitored sets showed such a shape, and all of these were set by the same captain. Reports of observed "U"-shaped sets are likewise rare in the POP database.

The 1999 NMFS limitation on pelagic longline set lengths to 24 nmi to putatively help protect migrating bluefin tuna only lasted 1 year. Although questions remain about the implementation notice of this particular measure that was given to the fleet captains (possibly affecting compliance), an examination of the mandatory logbook records from that period found that only 60.7% of the self-reported longline set lengths were under this limit. If effective enforcement of a given mainline set length is the goal, other options may be possible.

The fairly consistent speed at which vessels set their gear in the U.S. pelagic longline fishery suggests that one such alternative might be to limit the duration of the gear deployment period. For example, if the average swordfish-vessel speed at which mainline is deployed is 8 knots (1 knot = 1 nmi/h), the theoretical maximum for 3 h of gear deployment would be 24 nmi. However, this raises the possibility that vessels may attempt to deploy the gear at higher vessel speeds than local weather conditions would otherwise recommend, or to deploy the gear faster than usual, putting both vessels and crews at greater risk. The use of line shooter-type devices could also increase the risk even further due to the intended additional slack in the mainline during gear deployments. While perhaps meriting additional thought, a proposal to limit the set length using time as a management metric is probably not appropriate for the present fleet.

Regulations and researchers would also benefit from clarifying the difference between the two terms "set length" and "mainline length." While used interchangeably within the fishery, these two lengths are quite different. The tendency for pelagic longline gear to form vertical caternary curves at depth between floats additionally complicates accurately determining a "mainline length," as measurement of the additional mainline needed for each curve in the gear would, therefore, be required. As a pragmatic matter, the variability of these vertical curves, even within the same set, effectively precludes the incorporation of caternary curve estimation into the current discussion of set length. Additionally, neither of the past fisheries management measures addressing pelagic longline "set length" were based upon the "mainline length" concept.

The mechanism by which the length of a pelagic longline set affects catch rates remains unknown despite a clear relationship between set length and the number of deployed hooks. Nominal effort in pelagic longline fisheries is usually described as catch per 1,000 hooks, and it is not surprising that the two effort metrics of set length and number of hooks are strongly correlated. Vessel captains have suggested anecdotally that pilot whales will follow the pelagic longline to depredate the fish caught on the lines, and shorter mainline lengths may reduce the rates of interaction between the gear and normal pilot whale foraging patterns. Other methods of effort limitation, including limiting the time that the gear is actively fishing ("soak time") and the gear-deployment period itself, may have utility and should be examined. However, it remains premature from a regulatory perspective to advocate between similar levels of nominal effort regarding bycatch until the reasons are better known for the differences in catch rates.

It is likely that the vessel captains in the fishery will continue to avoid bycatch when possible by adapting their fishing strategies, including changing the length of the deployed mainline. Regardless of these potential self-initiated changes in the fishery, any fisheries management authority has a responsibility to clearly define the main terms within its regulations. When such definitions are absent, the resulting regulations are unenforceable and ineffective. The results of this study indicate that the inclusion of an end location for each gear deployment on the PLRP form would provide a simple, relatively accurate means to evaluate set length in a management regime where such mainline length is limited. Yet, despite no statistically significant difference between the SEA and other length measurements, the relationship is not a perfect 1:1 ratio. If management considers implementing fisheries regulations using this or any other "set length" metric, clearer definitions are required.

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