Investigation into the optimal bucket trap hole diameter to reduce capture of immature hagfish

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The commercial fishery in California for Pacific hagfish, (*Eptatretus stoutii*) is entirely for export. In this fishery, all hagfish caught regardless of size, unless culled at sea, are landed and exported. Korean importers consider smaller hagfish undesirable, thus the fate of landed smaller, hagfish is unknown. In a fishery-independent study using a collaborating commercial fisherman and his vessel, we determined the average length, length frequency distribution, length to weight ratio, and length at first maturity of captured hagfish relative to bucket trap hole diameter by using bucket traps and the range of hole diameters used by the fishery. We also recorded bycatch. Based on length-at-maturity data from this study, and Melvin and Osborn's (1992) findings, we will then possess better information to ensure this fishery is managed sustainably.

Key words: California, Pacific hagfish, hagfish, hole diameter, spawning maturity, bucket traps, escapement

Pacific hagfish are the target species of a live, export only, commercial fishery. Originally sought for their skins to produce leather used by the Korean “eel skin” industry, hagfish are now sent to South Korea for processing and human consumption. Occasionally hagfish are sorted at sea to remove the smaller, undesirable hagfish; however, in most cases all hagfish retained by trap (the only practical way to fish for them) are landed, sold, and shipped. Historically Korean dealers preferred larger hagfish. One study (Reid 1990), considered hagfish >35.6 cm as large, while a NOAA-funded survey (Melvin and Osborn 1992) tested trap gear to catch 30.5-cm hagfish. Regardless, it is unknown how landed small hagfish are marketed in Korea.

The California hagfish fishery is open access with no special permits required, although a commercial fishing license and a valid general trap permit are required. While Korean-style traps are legal gear, California fishermen prefer modified 18.9-L bucket traps, the other legal method of take (Figure 1). These traps have drilled holes to allow the bucket to sink during deployment, water to drain during retrieval, and allow escapement of small hagfish. Commercial vessels are limited to 200 bucket traps. While the Department of Fish and Wildlife (Department) requires an approved destruct device built into each trap in the event of trap loss, there is no requirement regarding minimum hole diameter.

Figure 1.—Standard Korean-style trap (right) with 6.4-mm holes and an 18.9-L bucket trap (left). The trap on the left is an example of one of the 16-mm hole diameter test traps. Note the cotton twine, as indicated by the arrows, which serves as the destruct device.

Pacific hagfish have low fecundity. Once hagfish reach maturity, the ovary will contain eggs in various stages of development. Females will bear 15-30 eggs per cycle (Kato 1990). Male hagfish mature at a younger age than females. Hagfish in general have a slow growth rate and may take several years to mature. It may take up to 7 years or more for a female hagfish to reach maturity (Nakamura 1994).

In 1992, NOAA investigated various parameters used within the hagfish fishery at the time. Using Moss Landing (California) Marine Laboratories vessel, *R/V Ed Ricketts*, a trap study was conducted over deep muddy habitat off Moss Landing in Monterey Bay. The main purpose of this study was to provide industry with the information and tools to maintain a successful and sustainable hagfish fishery. To accomplish this goal, this project had specific objectives such as characterizing hagfish behavior around trap gear, identifying ways to control trap-induced skin quality issues, determining gear selectivity, and developing more effective gear to select for a higher proportion of larger hagfish. An aspect of this study examined escapement and average size of captured hagfish for hole diameters 8.6 mm, 9.7 mm, 10.7 mm, 11.4 mm, 12.2 mm, and 14.2

mm. Melvin and Osborn's escapement work provided the inspiration and blueprint for this collaborative project.

In 2007, the Department began opportunistically sampling the hagfish fishery at Moss Landing and later Morro Bay in central California. Samples were also taken from the hagfish dealers in San Pedro in southern California. In 2012 the Department began to sample the fishery in Eureka. Live hagfish landings were sampled by recording average count-per-kilogram, since they are virtually impossible to measure individually. The concept is that as the average count increased the size of fish decreased, and vice versa. In addition to recording average count-per-kilogram, hagfish were randomly selected from sampled totes and subsequently dissected for sex and maturity status. Based on this sampling, Department staff documented a relationship between average count-per-kilogram and trap hole diameter. Cooperative fishermen were asked about the hole diameters they used in their bucket traps. Based on the results from the NOAA study and Department sample data, it was hypothesized that there should be a relationship between hole diameter and average size or size range of hagfish retained by the trap.

The Department and commercial fisherman Tim Maricich (*F/V Donna Kathleen*) collaborated to test if there is a relationship between hole diameter and the average size of retained hagfish with funding from Collaborative Fisheries Research West (CFR West). Tested hole diameters were those which were or are used in California's hagfish fishery. We also recorded bycatch of non-hagfish in traps. In this collaborative work, Mr. Maricich provided the vessel, crew, fishing gear (ground lines, floats, and anchors) and trapping expertise while Department staff constructed the traps and conducted appropriate hagfish dissections. While not participating directly in the Monterey trapping effort, hagfish fishermen from other ports were consulted. As part of the collaborative nature of this project, time was allotted to collect samples for other researchers provided project work was completed.

MATERIALS AND METHODS

Preparation—Prior to the fishery independent survey, in addition to fishery information gathered through Department sampling, interviews of current fishery participants were conducted either in person or by phone to increase fishery collaboration and to document current fishery trends. Fishermen from Eureka, Morro Bay, and Oceanside participated in the survey. The reason for the survey was explained to each fisherman. Questions asked included the number of traps fished, hole diameter(s) used and the reason(s) that hole diameter was selected. Bait preferences and duration of soak times were noted. Each fisherman was also asked to provide ideas, if any, to improve the survey design or state any concerns with the current state of the hagfish fishery. The original project proposed a 4-hour soak time and the use of Pacific mackerel (*Scomber japonicas*) for bait as suggested by Melvin and Osborn's work.

After the results from the survey were tabulated and comments summarized, the proposed project procedure was modified to increase soak time and to change bait to Pacific sardine (*Sardinops sagax caeruleus*). Total proposed traps increased from 48 to 96. Department staff was able to obtain donated buckets, and recycled leash lines and weights from previously used commercial traps. Based on fishermen surveys and previous fishermen interactions, hole diameters selected for testing were 9.7 mm, 12.7 mm, 14.2 mm, and 16.0 mm. After reviewing bathymetric charts and Monterey Bay hagfish trap log data, likely areas to prospect on the first day at sea were selected. These areas were then reviewed by Maricich.

Ninety-six bucket traps were constructed, each with a Department approved destruct device (Figure 1). All traps were standardized, each with 50 holes drilled in the same pattern, one entry funnel, and a single weight to ensure correct orientation when the trap contacted the sea floor. This would reduce any bias induced by any trap characteristic other than hole diameter. Each trap was secured to a central ground line with a short leash and baited with approximately 0.7 kg of sardines (Figure 2). Soak time was planned to be between 12 and 24 hours except for the prospecting day. Total allotted vessel time included an initial prospecting day, with shorter soak times, to refine trap deployment techniques and onboard sampling procedures, and to find areas holding hagfish. Three more days were allotted for pulling and resetting trap strings.

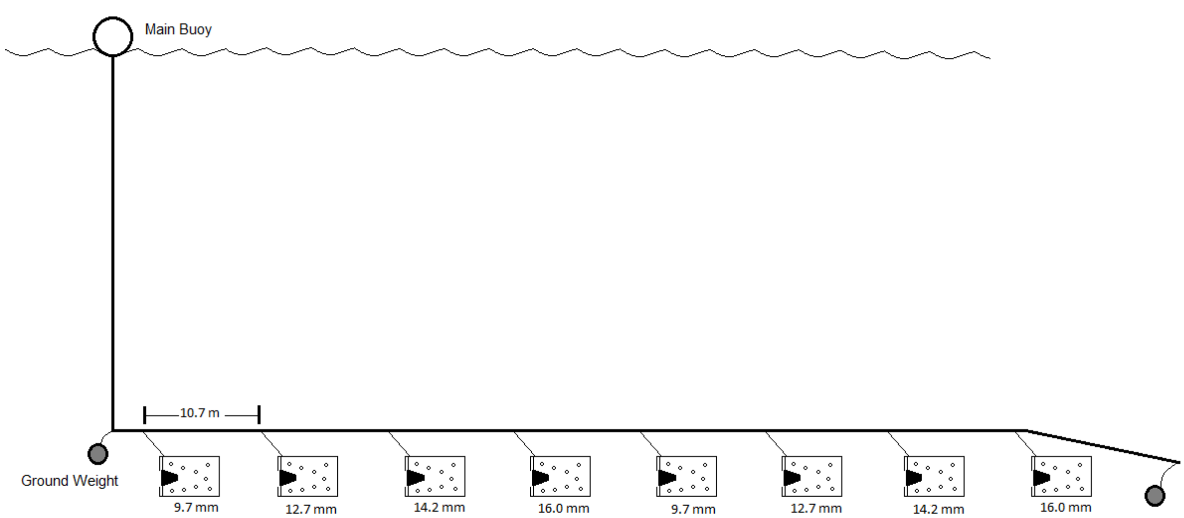

FIGURE 2.—Hagfish trap gear secured to a double-anchored main line. Each string had 24 traps with alternating replicates of each hole diameter. Credit: A. Sadrozinski, CDFW

Day one—Four prospecting strings were deployed over the pre-selected areas utilizing 72 traps, and excluding the traps with 16-mm diameter holes. These traps were excluded since they were expected to retain the least amount of hagfish and bait was limited. Sardines were reserved for days two through four; instead, fish carcasses of other species and squid were used as bait. Since the goal of the day was to find areas holding hagfish, soak time was not standardized but in general was less than 4 hours. If hagfish were caught, all hole diameter replicates were baited and re-deployed for longer soak times the following days. Based on Maricich's experience, traps were set such that each string would cover a range of depths over potentially suitable habitat, preferably muddy bottom.

Days two through four—Four strings were deployed over muddy habitat in the area with greatest prospecting success. (Figure 3) If possible, traps were retrieved in the order of deployment to keep soak time consistent. The vessel crew pulled the traps, while Department staff emptied the traps and processed the catch.

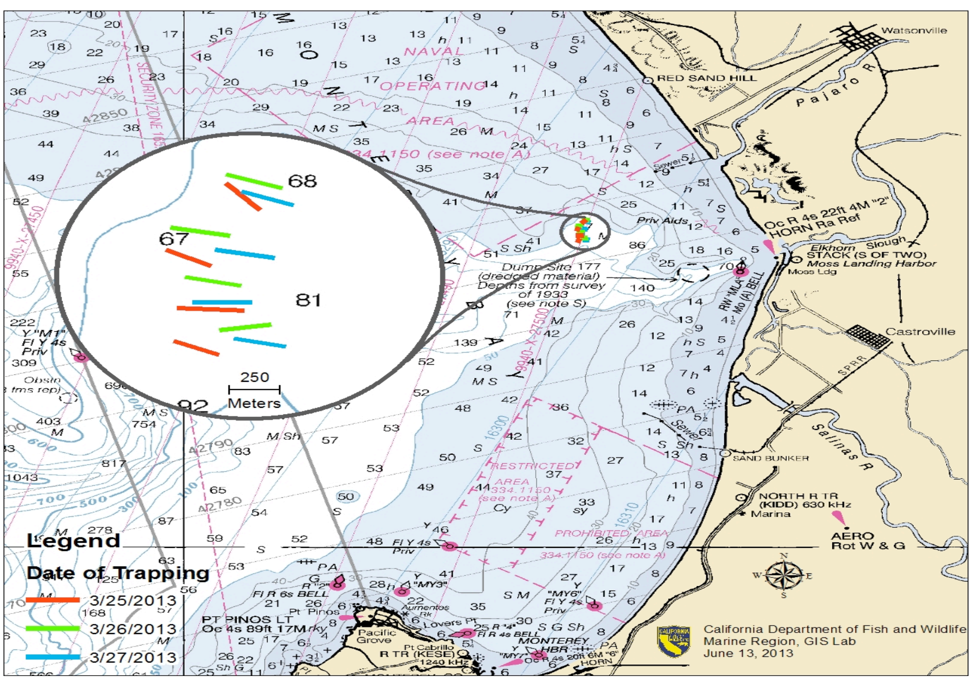

Figure 3.—Hagfish trapping area, Monterey Bay due west of Moss Landing. Colored lines represent trap strings and location.

Hagfish were counted and weighed in aggregate by trap to the nearest tenth of a kilogram, with the data recorded by hole diameter. Bycatch species and condition were recorded. Five randomly selected hagfish were retained from the first two trap hole diameter replicates from each string, resulting in 40 hagfish retained by each hole diameter for the second and third days. On the fourth day, 60 hagfish were retained per hole diameter. The remaining hagfish were released immediately. All retained hagfish were stored in marked plastic bags and frozen at the conclusion of the sample day. Vessel crew and science staff shared on-deck responsibilities such as baiting traps and cleanup. Trap strings were moved at the end of each day to avoid fishing previously fished areas. After the fourth day, traps were kept onboard and dismantled for storage.

Laboratory workup and statistical tests—At a later date, retained hagfish were dissected and results compared by hole diameter. Each hagfish was measured, weighed and gender identified, if possible. Spawning stage was determined by criteria established by Barss (1993). Of the approximately 160 hagfish retained per hole diameter, 125 randomly selected fish were dissected per hole diameter. After dissections were completed, the sample data were analyzed using a one-way ANOVA.

RESULTS

Conducting the additional interviews increased collaboration in the project by reaching out to industry and provided a current snapshot regarding specifics of the fishery such as bait preference, trap hole diameter, and average soak time. The six fishermen interviewed had a collective 20+ years of experience targeting hagfish. While not representing the activities of their respective local harbors, the six interview participants' home ports of landing represent the present three major ports of landing: Fields Landing (Eureka), Morro Bay, and Oceanside.

Prospecting day.—Five sets were completed capturing a total of 1,441 hagfish (Table 1). Total known weight was 120.6 kg. Due to the low catch numbers in several buckets, 22 hagfish were counted but not weighed. No bycatch was observed. Soak time per string ranged from 36 to 205 minutes. The differences in soak time were due to travel time between trap strings. Traps were set in a depth range of 64 to 152 m. It was determined that bottom depth is not as important as habitat type for locating hagfish. When over the correct bottom type, as indicated by the captain's interpretation of the sonar signature, hagfish were caught with regularity by all traps on the string. Trap strings were baited and re-deployed in the area where the best catches occurred. No hagfish were retained for laboratory processing. One trap was lost; no other traps were lost for the remainder of the survey.

TABLE 1.—Prospecting day bucket data including average count-per-kg and total number and weight by hole diameter.

String number	9.7 mm	12.7 mm	14.2 mm
1	11.19	9.82	9.18
2	10.49	10.51	9.59
3	9.72	8.82	8.81
4	0	7.23	8.09
5	0	0	0
Count/weight	348/32.7	527/53.8	319/34.2
Average Count-per-kg	10.64	9.80	9.33
Counted, not weighed	7	4	11

The average count-per-kilogram by hole diameter produced a much smaller variability in average count per kilogram than that of days 2-4. (i.e. larger hole diameter, smaller count-per-kilogram due to larger hagfish). Although there was no bait left in any of the traps that had hagfish, we believe that the traps did not soak long enough to allow the smaller hagfish to escape. One interviewed fisherman confirmed this conclusion through his experiences. Soak time is a critical factor in the behavior of fishermen which could potentially defeat the purpose of a minimum hole diameter regulation for this fishery.

Survey days.—Days two through four, with longer soak times, yielded 7,595 hagfish weighing 826.8 kg (Table 2). All hole diameter replicates were fished except on string 4 (3/25/13). On this string, one 16 mm bucket was left off due to an extra 14.2-mm bucket being set in its place. This was corrected upon string retrieval. Out of the 288 trap replicates, four buckets fished without bait due to error and the fish from one bucket was discarded before the count was recorded. The data from these five traps were not included in the final analysis. The effect of these buckets not contributing to catch and final count-per-kilogram estimate are unknown and most likely insignificant. Soak times per string varied between 19 hours, 38 minutes to 24 hours, 34 minutes. Average soak time per string was 19 hours, 55 minutes. Except for one octopus (*Octopus* spp.) and one Pacific sanddab (*Citharichys sordidus*) (both released alive), no other bycatch was observed. All hagfish were counted and weighed by trap to the nearest tenth of a kg. Average count-per-kilogram was calculated for each hole diameter at the end of each day. Average count-per-kilogram versus trap hole diameter yielded the expected relationship, i.e. larger hole diameter yielded larger hagfish on average. However, among all strings, there was a small degree of overlap of average count per hole diameter within a string for hole diameters within 3 mm or less of each other. For example, the average count-per-kilogram for 9.7-mm holes for String 1 was less than most average counts-per-kilogram for strings with 12.7-mm holes.

TABLE 2.—Average count-per-kilogram data for days 2 through 4. Average counts were based on all buckets for each hole diameter.

String number(set day)	9.7 mm	12.7 mm	14.2 mm	16.0 mm
1 (3/25)	9.91	8.78	7.47	7.26
2(3/25)	11.58	9.33	8.38	6.96
3(3/25)	10.38	9.53	8.58	7.08
4(3/25)	11.30	8.46	7.75	6.39
1(3/26)	10.24	8.68	7.35	6.33
2(3/26)	8.99	9.53	8.90	7.41
3(3/26)	10.54	9.42	8.43	6.68
4(3/26)	13.11	10.7	8.39	7.68
1(3/27)	10.05	9.14	7.30	5.73
2(3/27)	10.26	9.29	8.14	6.50
3(3/27)	10.68	9.26	6.99	5.82
4(3/27)	10.21	9.60	7.42	5.72
Survey count/weight	3,141/290	2,472/269.2	1,400/178.8	582/88.8
Survey average	10.83	9.18	7.83	6.55

Laboratory workup and statistical tests.—The length results from dissection of individual hagfish mirror the count-per-kg averages and the relationship to hole diameter. Average weight and average length appear to be related to hole diameter; the traps with larger holes retained on average longer hagfish (Table 3). However, increased length did not equate to increased weight for females.

TABLE 3.—Length and weight data for each hole diameter for all sexes combined

For all hagfish combined	9.7 mm	12.7 mm	14.2 mm	16.0 mm
Average length (mm)	391	394	404	418
Length range (mm)	258-497	302-494	312-502	346-532
Average weight (g)	101.7	99.7	110.4	122.4

Weight range (g)	31.8-178-1	39.2-177.1	52.4-225.3	75.3-219.4

Analysis indicates that female hagfish weight is a function of length and spawning condition. Females with larger eggs weigh more compared to females in a regressed spawning status of the same length. Those females with large eggs could be retained by all hole diameters, but with larger hole diameters, gravid females would affect average weight since the lighter fish would have escaped (Table 4). Since the testes are a small portion of the male hagfish's anatomy, male hagfish weight is not affected by spawning condition. Spawning condition changes throughout the year, resulting in greater variation in individual female hagfish weight rather than length.

TABLE 4.—Length and weight data for female hagfish for each hole diameter.

Females Only	9.7 mm	12.7 mm	14.2 mm	16.0 mm
Average length (mm)	382	386	402	410
Length range (mm)	258-479	302-494	312-502	346-482
Average weight (g)	95.8	95.8	110.1	117.8
Weight range (g)	31.8-178-7	42.8-177.1	52.4-225.2	75.8-189.5

While maturity of female Pacific hagfish is not fully understood, a few studies have estimates regarding this important characteristic. Gorbman and Dickhoff (1978) found that the length at first maturity for females was 399 mm. Another study (Reid 1990) found that males first matured at 255 mm and females at 295 mm. The Department's collaborative study found that length at first maturity for females was less than Gorbman and Dickhoff's findings, but greater than Reid's (Figure 4). Since Reid sampled hagfish from southern California and Gorbman/ Dickhoff used samples from British Columbia, the differences in maturation at length could be due to regional environmental differences.

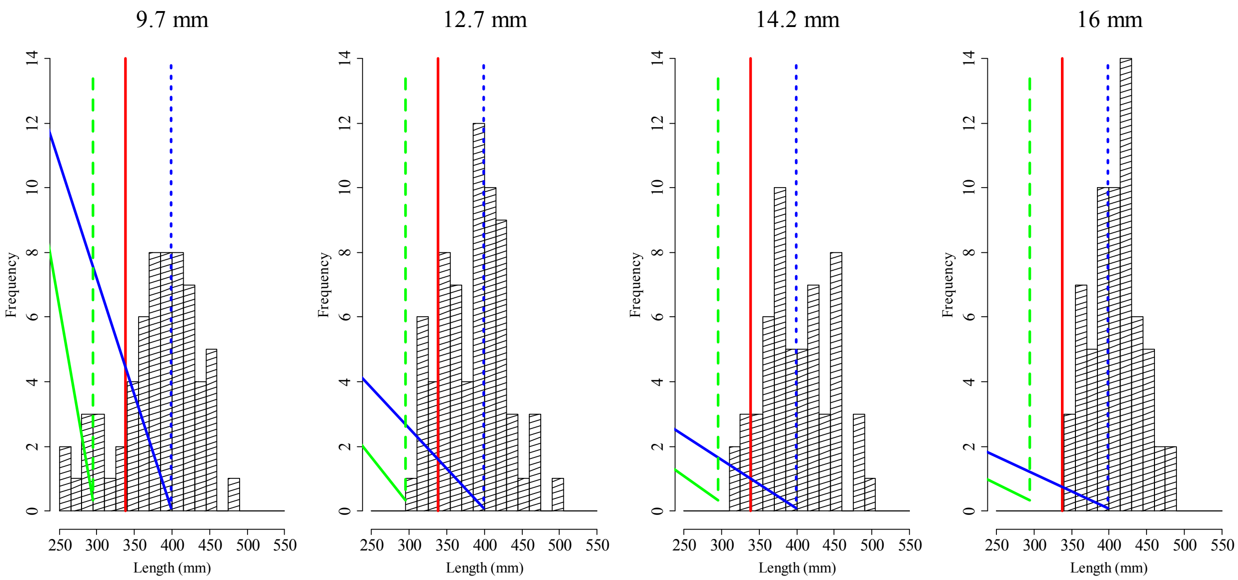

FIGURE 4. Length at first maturity for the Department's collaborative study and two other studies (colored vertical lines) and length composition data for females from the Department's collaborative study. First maturity for females for Reid 1990 (dashed green) and Gorbman and Dickoff 1978 (dotted blue) as compared to first observed maturity in Department's study (solid red). First observed maturity, for the purposes of this study is considered Condition 2 as described by Barss (1993).

One hagfish dealer stated that marketability of hagfish is more of a function of weight, rather than length, as related to girth (Peter Chu, personal communication). Wider hagfish, at length, will have greater mass, thus more flesh and skin. Hagfish exporters typically desire a minimum average of 8 to 9 hagfish per kilogram. Hagfish smaller than the desired average are not practical for the Korean food market. In light of this information, an additional analysis was conducted comparing length to weight. As the hole diameter increased, the range of length/ weight ratios decreased (Figure 5).

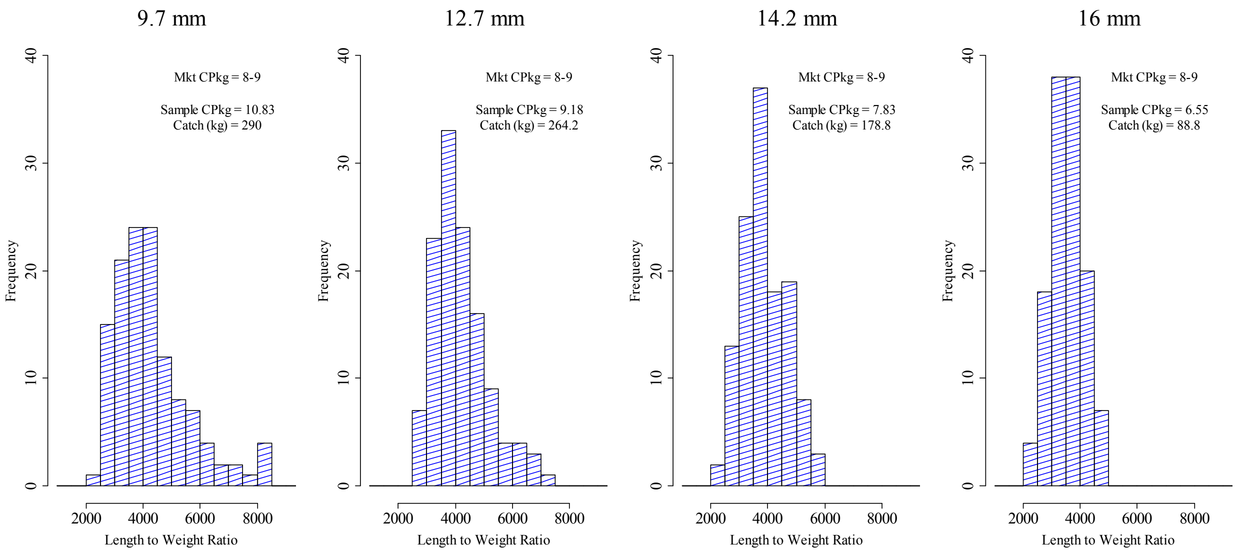

FIGURE 5.—Length to weight ratio as compared to sample count-per-kilogram (CPkg) and the desired count range (Market CPkg).

In addition to comparing length/ weight relationships as they pertain to hole diameter, a one-way ANOVA was conducted on the sample data. The results from the ANOVA (*p*-value <0.0001) show that hole diameter significantly influences weight and length.

DISCUSSION

The average size of retained hagfish is directly related to hole diameter and is influenced by soak time duration. Melvin and Osborn's (1992) work showed a direct relationship between hole diameter and mean length and number of retained hagfish. As the hole diameter increased, length increased and catch retained by traps decreased. More fish were caught with longer soaks. Their results suggest that:

- Escapement does occur in hagfish traps.
- Trap escapement hole diameter and soak time are potential tools to select for larger fish.

- “A 24-hour soak and a trap escapement hole size near 0.45 inches (10.7 mm) are most likely to best select for the greatest number of hagfish 12 inches (30.5 cm) or larger.” (Melvin and Osborn 1992)

While Melvin and Osborn used different hole diameters than this collaborative work, the expected results were similar. Traps with 9.7-mm hole diameters caught the most hagfish, and hagfish were smaller on average, with a higher percentage of immature fish, compared to the other hole diameters. The largest hole diameter, 16.0 mm, retained the largest hagfish, both in average length and weight. By industry standards, a hole diameter of 16.0 mm would produce the best catch for export and allow escapement of small hagfish. However, the benefit of a larger average hagfish size would likely be negated by the decreased catch as shown by the low total catch by the 16.0-mm test traps. Buyers and fishermen may not be able to stay in business with such low volume. The 12.7-mm or 14.2-mm hole diameters may provide a compromise between desired hagfish size and required landing volume. Some fishermen have or currently use 9.7-mm hole diameter for their traps. This hole diameter would maximize catch for a greater total weight but does not allow for the release of smaller, immature hagfish. The result would be a less desirable higher average count-per-kilogram for landed fish and removal of immature hagfish from the population. Long term use of 9.7-mm holes may not allow sustainability in this relatively high-volume fishery. On a positive note, regardless of the hole diameter used, this study produced almost no bycatch; incidentally caught species likely are minimized by the entry cone diameter and the rapid entry of hagfish.

This collaborative study answered many questions regarding this fishery such as bycatch rate, influence of soak time, habitat type and depth importance. The most important aspect of this fishery and one purpose of this study was to address escape hole diameter in relationship to hagfish maturity. Unlike other trap fisheries, this fishery does not have a regulation regarding escapement. Lab dissections and average bucket counts both show that hole diameter influences size of retained hagfish. This fact and the supporting data gathered by this collaborative project will provide fishery managers valuable information to manage this fishery sustainably.

As part of the collaborative nature of this project, deep water rockfish samples were collected for NOAA Fisheries; specially designed rectangular research traps were used for this purpose. In addition, on day 3 a representative from the Monterey Bay Aquarium assisted in hagfish trap duties and at day's end, with the assistance from Maricich, was allowed to collect groundfish samples for a decompression study.

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