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Influence of bucket trap hole diameter on retention of immature hagfish

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In California, the commercial fishery for Pacific hagfish (*Eptatretus stoutii*) has exported over one million pounds annually in recent years, primarily to South Korea where they are considered a delicacy. Comparatively little research exists to support management decisions for this species. The California Department of Fish and Wildlife (CDFW) sought to evaluate the influence of trap hole diameter, which is presently unregulated, on the take of immature hagfish. Using standard 20-L bucket trap gear, we tested four hole diameters (9.5 mm, 12.7 mm, 14.3 mm, and 15.9 mm), which are currently or have been previously used by the fishery. We found that the percentage of immature female hagfish declined with increasing trap hole diameter. The smallest hole diameter tested resulted in catch where approximately 17.5% of female fish were of immature size. Although the take of immature hagfish was not completely eliminated until the largest of these hole diameters was used, a 10.5% reduction in the percentage of immature female hagfish occurred between 12.7 and 14.3 mm. The number of larger hagfish increased with increasing hole diameter, yet overall catch weight decreased, suggesting that hole diameter currently utilized by fishermen represents a conscious tradeoff between these competing factors.

Key words: California, bucket traps, *Eptatretus stoutii,* gonad condition, hole diameter, immature, Pacific hagfish

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The Pacific hagfish (*Eptatretus stoutii*) is one of approximately 60 species in the hagfish family (Myxinidae), which constitutes the most primitive family of fishes. Hagfish inhabit relatively deep, temperate regions of the world's oceans, and are highly adapted to the low oxygen (Cox et al. 2011) and high salinity conditions (Adam and Strahan 1963) that occur at depth. They may be the most abundant fish inhabiting the upper continental slope, though previous population estimates are limited and likely underestimate abundance due to their cryptic burrowing behavior (Martini 1998). Hagfish are ecologically important, providing ecosystem services as scavengers and as a food source to several fish species (Martini 1998, Buckley et al. 1999). Pacific hagfish were also shown to provide a significant portion of the year-round diet for the harbor seal (*Phoca vitulina*) (Hanson 1993, Oxman 1995).

In California, an unprecedented commercial fishery for hagfish emerged in the late 1980s to provide skins for the South Korean “eel skin” industry, and peaked in 1990 with approximately 4.9 million pounds in landings. Soon thereafter landings abruptly declined as Korean demand for California-caught hagfish diminished due to blemishes found in the tanned hides (Kato 1990). Demand remained low until 2005, when the fishery re-emerged, but this time for human consumption. Since 2007, commercial landings for hagfish have remained relatively stable and have ranged from one to two million pounds annually. Hagfish are caught along the entire length of the state, and Oceanside, Morro Bay, Bodega Bay, and Fields Landing are the primary ports of landing. The fishery is managed by the California Department of Fish and Wildlife (CDFW).

Though Pacific hagfish have been studied extensively in an evolutionary context, there is limited information on the species as it relates to fishery management. There is evidence that they are slow-growing and long-lived and may reach ages upward of 25 years (Johnson 1994, Nakamura 1994). Several studies suggest that they have a low fecundity, with females only carrying 20–30 eggs per breeding cycle (Gorbman and Dickhoff 1978, Kato 1990). Female hagfish are estimated to attain reproductive maturity between 7 and 12 years of age (Nakamura 1994), while males mature at a somewhat younger age (Reid 1990). These life history characteristics suggest that hagfish could be susceptible to overexploitation, provided effective management actions are not implemented.

Limiting the take of immature fish is a common fishery management strategy, but has not yet been applied to the Pacific hagfish fishery. Presently, the fishery is subject to few regulations. It is open access, and has no quota or other direct limitations imposed on catch biomass; however, gear type and quantity are regulated and fishermen are limited to 500 Korean-style traps or 200 20-L bucket traps (Figure 1). The bucket trap is larger by volume

Figure 1.—A 20-L bucket trap (left) and standard Korean-style trap (right), legal gear in the commercial fishery for Pacific hagfish. Photograph by T. Tanaka, California Department of Fish and Wildlife.

and is the primary gear type used in California. Hagfish traps are covered with many holes of the same diameter, which allow water to flow through the trap, helping the bucket ascend or descend during deployment or retrieval. The holes also provide an additional means for hagfish to enter the trap and an opportunity for small hagfish to exit, consequently having a large influence over the size structure of fish in the catch. California Department of Fish and Wildlife currently does not have a minimum hole diameter requirement for hagfish traps, and at present the fishery uses hole diameters ranging from 9.5 to 15.9 mm.

Previous trap studies in California have examined various aspects of hagfish catch characteristics, but none so far have examined the influence of hole diameter on the take of immature hagfish. Melvin and Osborn (1992) tested variations of trap gear, including hole diameter, on mean hagfish size and catch weight. However, their main objective was to provide industry with information on identifying ways to control the potential for trap-induced skin quality issues such as holes and blemishes, and gear development for selecting a higher proportion of larger hagfish. Johnson (1994) used Korean-style traps in an effort to test hagfish distribution at various depths and retain samples for a maturation study, but did not examine the effects of variations in trap gear. In the present study, we aimed to provide specific information that could be directly incorporated into fishery management decisions by testing the influence of trap-hole diameter on the retention of immature hagfish. We also assessed the potential economic consequences of regulating hole diameter by evaluating its relationship to overall catch weight and average fish size.

Materials And Methods

The experimental design used in this study was adapted from previous research efforts (Melvin and Osborn 1992); unlike previous studies, we examined the influence of trap hole diameter on the retention of immature fish, rather than catch marketability. We also incorporated hagfish-fishermen knowledge into the study design to improve catch rate, and provide results that were more reflective of the hagfish fishery itself. We interviewed current fishery participants from Eureka, Morro Bay, and Oceanside either in person or by phone to determine the number of traps typically fished, the hole diameter(s) used in the fishery, and the reason(s) that each hole diameter was selected. Fisherman also provided us with information on their preferred bait type, as well as optimal gear-soak times. Based on fishermen responses, we were able to (1) test the influence of hole diameters used by the industry; (2) increase our sampling success; and (3) develop successful working relationships with fishery participants.

Sampling procedures.—A typical bucket trap consists of a 20-L bucket, a single cone-shaped entrance funnel fixed to the bucket lid, a weight fixed to the inside wall of the bucket, and many holes drilled in the walls and bottom. Ninety-six 20-L bucket traps were constructed, which were secured to four 250-m strings, with twenty-four traps per string. Each string contained six replicate traps of each of four hole diameters (9.5 mm, 12.7 mm, 14.3 mm, and 15.9 mm). Traps were placed 10.7 m apart along the string in alternating order. Each trap was secured to the string with a short leash. 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. All sampling was conducted onboard the F/V *Donna Kathleen* with gear deployed by the experienced crew.

Four days of sampling were conducted in Monterey Bay, west of Moss Landing, Monterey County, California (36° 49.4' N, 121° 51.2' W; depths ranged from 106 to 155 m (58–85 fathoms) over soft sediment. The study area was chosen because hagfish were fished there commercially in the recent past (CDFW commercial landings data) and is located in the geographic center of the California fishery. We targeted areas that were identified as soft benthic sediment by the captain's interpretation of the onboard sonar signature. On the first day of the survey, we deployed 48 traps at depths between 90 and 150 m in a series of short (<4 hour) soaks to determine relative abundance of hagfish. Locations where hagfish were present were recorded and used as sampling sites in the subsequent days of standardized sampling (survey days 2–4). All fish captured on day 1 were released alive, and were not included in any of the subsequent analyses.

On each of the subsequent survey days, we deployed four standardized strings of bucket traps, baited with approximately 0.7 kg of sardines per trap, at sites where hagfish were present on day 1. Strings were soaked overnight for up to 24 hours, and were retrieved in the order of deployment. To avoid repeatedly sampling previously fished areas, strings were moved between 0.21 and 0.24 km between deployments. Upon retrieval of each string, all captured fish were grouped by hole diameter, weighed to the nearest tenth of a kilogram, and counted. The total number of hagfish and total hagfish weight for the survey was the sum of the data collected from each string for each of the four hole diameters. Of all hagfish captured, 160 fish were randomly selected from each hole diameter over the span of the three-day survey. These fish were retained for further analysis, placed in labeled plastic bags, stored on ice for the duration of the cruise, and frozen at the conclusion of each sampling day. All remaining hagfish were released immediately in live condition. We also recorded any observed bycatch by species and condition at capture.

Laboratory and statistical analyses.—Sub-sampled fish were defrosted and 125 of the 160 fish collected from each hole diameter were randomly sub-sampled for laboratory analysis. Weight (g) and total length (mm) were measured for each individual fish, and one-way analysis of variance (ANOVA) was used to assess whether the sub-sampled length and weight data from each of the four hole diameters were significantly different from one another.

Sex was determined for each individual by visually examining either the testis or ovarian tissue. Gonad condition was determined for each fish using a scale from 1 to 5 developed by Barss (1993), where stage 1 = immature; stage 2 = maturing; stage 3 = mature-developing; stage 4 = mature-developed; and stage 5 = mature-spent. The criteria for determining female gonad condition were primarily average egg size and presence or absence of spent egg capsules, while the criteria for determining male gonad condition were primarily size and color of the testis.

We estimated the size at first maturity for female hagfish by determining the size above which no stage 1 fish were observed in our sub-sample, since hagfish of mature size range between stages 2 and 5. Hagfish do not appear to exhibit any significant seasonal trends in their reproductive cycle (Nakamura 1991) that may have added potential bias to the somewhat shorter sampling timeframe within this study. We calculated the percentage of immature female hagfish using the fraction of sub-sampled lengths below our estimate of size at first maturity for each of the four hole diameters.

To evaluate the possible economic consequences of variations in hole diameter, we examined both overall catch weight and the number of hagfish per kilogram within each bucket, or count-per-kilogram (CPkg). CPkg is a metric utilized by the industry to evaluate size and assign a grade to the catch. Hagfish catches with a lower average CPkg are larger and, consequently, are more desirable. Exporters of California-caught hagfish reported that the market preferred 8 to 9 hagfish per kilogram at the time of this study. Korean dealers historically preferred hagfish 356 mm total length (TL) or greater (Kato 1990), but currently the hagfish export market emphasizes weight over length; additionally, live hagfish are difficult to measure.

Results

The survey collectively yielded 7,595 hagfish weighing 825 kilograms. The mean soak time for each trap was 21.6 hours, ranging from 19.63 to 24.57 hours. Seven of the 288 buckets included in the study design did not produce any data as a result of user error during deployment. Consequently, data were missing from one 9.5-mm trap, one 12.7-mm trap, one 14.3-mm trap, and four traps with 15.9-mm holes. Since a small but variable percentage of data was missing from hole diameters tested (1.4–5.6%), we estimated the missing data in an effort to provide a more accurate comparison of total catch data across hole diameters. We replaced each missing trap with the overall average weight for each respective hole diameter, and calculated the total catch weight both with and without the added estimates (Figure 2).

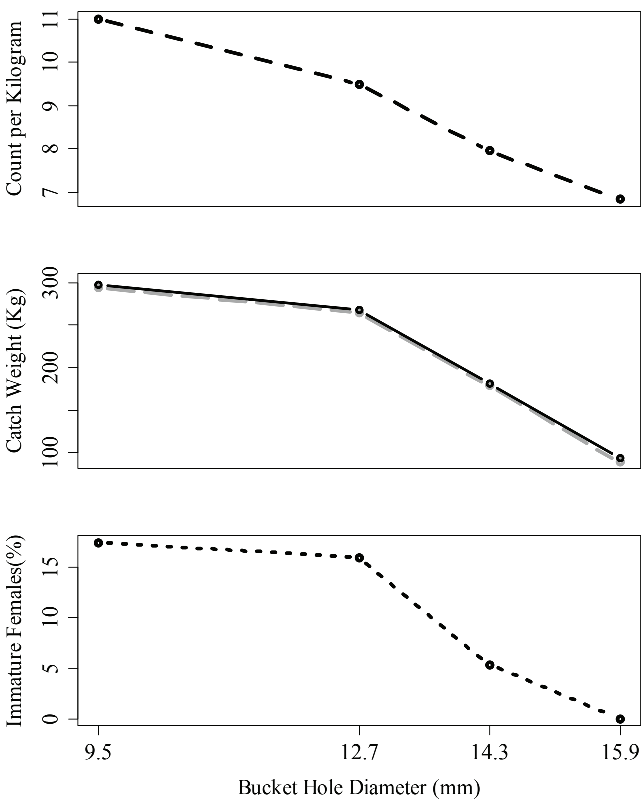

Figure 2.—Panel plot showing the effect of bucket trap hole diameter on three main catch characteristics of Pacific hagfish, count-per-kilogram (top); total catch weight (middle); and percentage of immature female fish in the catch (bottom) during March 2013. The two lines in the middle plot represent total catch-weight (dashed grey), and total catch-weight corrected for missing trap data (solid black).

Based on two separate one-way ANOVAs conducted on the randomly sub-sampled catch data, we determined that hagfish length ($F_{3,496}$=9.315, P<0.0001) and hagfish weight ($F_{3,496}$=12.52 , P<0.0001) were significantly different among the four hole diameters tested. As hole diameter increased, the average length and weight of fish per trap increased, while smaller hole diameters retained smaller hagfish (Table 1). Accordingly, CPkg decreased with increasing hole diameter (Figure 2), indicating average size increase. As hole diameter increased, CPkg did not reach the desired market threshold of eight until the second largest hole diameter (14.3 mm) was used (Figure 2). Of the sub-sampled hagfish dissected in this study (n=500), we found no mature female hagfish (stage 2 or higher) less than 338 mm total length (TL). The proportion of hagfish below 338 mm TL in the catch decreased as hole diameter increased, ranging from 0 to 17.5 % (Figure 2). The total bycatch for the study included one octopus (*Octopus* spp.) and one Pacific sanddab (*Citharichys sordidus*), both of which were alive.

Table 1.—Mean (± *SD*) total lengths and weights of female and male hagfish captured in bucket traps near Moss Landing, California, 25–28 March 2013.

	Trap Hole Diameter			
	9.5 mm	12.7 mm	14.3 mm	15.9 mm
Female				
Mean length (mm)	382±52.3	386±43.2	402±44.9	410±31.9
Range (mm)	258–479	302–494	312–502	346–532
Mean weight (g)	95.8±36.4	99.7±30.2	110.1±36.2	117.8±27.8
Range (g)	31.8–178.7	42.8–177.1	52.4–225.5	75.8–189.5
Male				
Mean length (mm)	409±44.8	404±43.7	408±39.5	428±43.4
Range (mm)	310–497	315–486	323–493	351–532
Mean weight (g)	111.9±34.4	105.7±28.6	112.4±30.3	127.9±33.0
Range (g)	44.8–175.2	47.0–165.8	58.0–184.9	75.3–219.4

Discussion

We found that hole diameter, which influences size of retained hagfish, also had a large influence on the proportion of immature hagfish retained in the catch. Observed trends in hagfish size (length, weight) in relation to hole diameter were similar to that determined during previous research, even though the diameters tested were slightly different (Melvin and Osborn 1992, Johnson 1994, Nakamura 1994). The proportion of immature fish decreased as hole diameter increased, suggesting that larger hole diameters are more desirable for fishery conservation purposes. Count-per-kilogram (CPkg), a proxy for overall hagfish size and marketability used by the industry, also decreased as hole diameter increased, demonstrating that larger hole diameters also produced the most highly desired fish in terms of size. However, overall catch weight declined precipitously with increasing hole diameter, suggesting the existence of an industry tradeoff between average size and total weight of captured hagfish.

Our assessment of size at first maturity appears consistent with previous research into Pacific hagfish maturity. In central California, Pacific hagfish size at maturity was estimated to be 325 mm (Nakamura 1994), and size at 50% maturity in Oregon was 340 mm (Barss 1993). Compared with seven years of data from our monitoring of the fishery, these results fall slightly above our estimate of 338 mm to the north and slightly below our estimate to the south. This could be a direct result of north-south differences in growth and size at maturity, or simply slight differences in sampling methodology. In either case, we used a relatively conservative estimate of size at maturity to assess retention of immature hagfish. Knowledge of hagfish reproduction remains limited and warrants future research. Pacific hagfish populations do not exhibit seasonal reproduction, and it is common to find female hagfish carrying eggs at various stages of development throughout the year (Johnson 1994, CDFW unpublished sampling data), complicating assessment of mature individuals somewhat more complex.

Based on fisherman interviews and previous research (Melvin and Osborn 1992), we know that trap soak time is a potentially confounding factor when assessing the effects of hole diameter on catch characteristics. Hagfish will remain in a trap until the bait source is exhausted and, consequently, no size selection occurs for an extended period of time after trap deployment. Previous research indicates that this time period is roughly 24 hours (Melvin and Osborn 1992), though it is most likely variable depending on bait quantity and hagfish abundance. We allowed traps to soak for an average of 21.6 hours (range 19.6–24.6) so that we could examine the performance of each hole diameter while minimizing the confounding effects of shorter soak-time. Future regulatory change involving minimum hole diameter should address these confounding effects as they relate to size retention of hagfish. It may be possible for fishermen to avoid the impacts of an increase in hole diameter on catch weight by reducing soak-time.

Some fishermen have used 9.5-mm hole diameters on their traps, the smallest size tested in the present study. While this hole diameter would maximize catch weight, we have demonstrated that this diameter hole retains a large proportion of immature-sized female hagfish. This smallest diameter also produces the lowest percentage of large hagfish, as reported by the industry, which may be economically offset by greater catch weight. As the diameter increases, the proportion of immature hagfish retained is greatly reduced and, with 15.9-mm holes, immature hagfish are virtually absent. From a conservation and marketability perspective, the largest hole diameter would clearly benefit the fishery by protecting the immature segment of the population and by ensuring the lowest CPkg for the industry. Nonetheless, this benefit is clearly offset by the reduction in catch that occurs with increasing hole diameter, suggesting the need to identify an appropriate conservation-industry compromise in the event of future regulatory action.

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