The Biology and Fishery Potential of Hagfish

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Introduction

Little published information is available on the state of fisheries for hagfish in any country. Strahan and Honma (1960) and Honma (1960) described a small fishery for consumption of *Paramyxine atamii* in the Sado Strait, Sea of Japan. The hagfishery of Japan was described in a review article by Gorbman et al. (1990). A $70 million market has developed for leather products imported from Japan and Korea to the United States alone. Unfortunately, demand now exceeds supply because of apparent resource depletion. With the decline of their population in only a few years, other sources of hagfish have been investigated, including the west coast of the United States.

Studies on the ecology and basic biology of hagfish are few and generally incomplete (Brodal and Fange, 1963; Hardisty, 1979). Studies have shown hagfish to prefer mud bottom, in which they often burrow (Foss, 1962, 1963, 1968; Fernholm, 1974; Strahan, 1963; McInerney and Evans, 1970). Hagfish often keep their heads above the substrate while in their burrows to aid in gill ventilation and reception of food cues (Foss, 1968).

Hagfish have long been known as pests by fishermen and are known to be scavengers (Fernholm, 1974). Moller-Buchner et al. (1984) and Shelton (1978) investigated the feeding of *Myxine glutinosa* in the North Sea. The diversity and abundance of their prey suggested that this hagfish was a major benthic predator and opportunistic scavenger.

Some information is available on the reproduction of hagfish, but exact details are lacking regarding fertilization, fecundity, seasonality, gestation period, and mode of development. The shallow-water *Eptatretus burgeri* from Japan is easily obtained and has been well studied (Patzner, 1977, 1978, 1980). *E. burgeri* migrates seasonally to deeper water to spawn, as discerned by changes in the number and size of eggs, the state of spermiogenesis of the testis, and the changes in gonadosomatic index with season and depth (Tsuneki et al., 1983; Patzner, 1977, 1978). Similarly, Patzner (1980) and Patzner and Adam (1981) used hepatosomatic indices for *E. burgeri* and *M. glutinosa* because of the liver's seasonal role in egg development.

Several small-scale tag/recapture studies have been attempted, focusing only on tagging feasibility. Foss (1963) attached sprat tags through the dorsal musculature of *M. glutinosa*. Tag returns from hagfish at large as long as 29 months were obtained and did not affect growth or egg development. Walvig (1967) found that hagfish could successfully be marked with subcutaneous India-ink injections or tagged with small plastic chip insertions. Hagfish yielded a high return rate of 33.9% of the marked individuals and demonstrated a tendency to home. Tagged hagfish were used for growth studies in captivity only.

The Pacific hagfish, *Eptatretus stoutii,* and black hagfish, *E. deani,* are common members of the fish family Myxinidae off the northwest Pacific coast (Eschmeyer et al., 1983; Wisner and McMillan,1990). These hagfishes have been the subject of neurophysiological, sensory studies, but little is known about their general ecology. They occur from Southeast Alaska to Baja California, Mexico, and are found on or near the bottom (Eschmeyer et al.,1983). The Pacific hagfish lives shallower, from 18 to 944 m, while the black hagfish is deeper, from 155 to 1158 m.

Information about the size composition, depth distribution, feeding habits, reproduction, and habitat utilization patterns of these two species is often anecdotal, and few details are available. Both are thought to occupy muddy habitats, feed primarily as scavengers, and deposit sausageshaped egg cases on the bottom, with no free-living, larval stage (Eschmeyer et al., 1983). Information on spermiogenesis (Jesperson, 1975) and sex differentiation (Gorbman, 1990) in Pacific hagfish is available. However, more ecological details about reproductive strategies, cycling, and development are lacking for both species. Recent evidence from Oregon (Robert Demory, personal communication, 1989) indicates that the deeper-dwelling *E. deani* has a low fecundity, with an average of 12 eggs being produced by large females.

Reports of substrate preference, depth, seasonal migrations, and fishing techniques for Pacific hagfish vary widely in the available scientific literature. Several researchers report catching hagfish over soft, muddy substrate (Adam and Strahan, 1963; Honma, 1960; Jensen, 1966; McInerney and Evans, 1970; Isaacs and Schwartzlose, 1975), yet others (Dean, as reported by Conel, 1931; Worthington, 1905) reported catching hagfish over hard substrates in Monterey Bay.

Catch depths of Pacific hagfish have ranged from 10 to 50 fathoms in Monterey Bay (Conel, 1931; Worthington, 1905). McInerny and Evans (1970) found it at a minimum depth of 20 fathoms in the waters of British Columbia, Canada. Optimal fishing depths of Pacific hagfish are unknown and may indeed vary with season (Dean, as reported by Conel, 1931, Honma, 1960; Adam and Strahan, 1963; Tsuneki et al., 1981).

Despite their broad distribution (Miller and Lea, 1972; Hart, 1973; Eschmeyer et al., 1983), Pacific and black hagfish have remained an unutilized resource until quite recently, when exploratory fishing started throughout California and in Oregon and Washington. Production fishing for hagfish started recently off San Francisco, where several vessels landed considerable but variable amounts. More recently, fisheries have started, with varying degrees of success, from Santa Barbara to the Canadian border. These emerging fisheries presented an excellent opportunity to study the ecology of hagfish populations off the California coast.

Development of the California (and west coast) hagfish fishery has been hampered by a number of product quality and fishery technique problems. Information on the well-established Korean and Japanese hagfish fisheries has proved difficult to obtain, despite numerous contacts. Also, this fishery targets on a different, and much larger, species (*Eptatretus burgeri*).

Skins from hagfish caught in a variety of California locations tend to have perforations or "pinholes" along the anterior-posterior dorsal axis that are not related to slime glands. Traditional skinning practices place this axis along the center of the skin, which is used whole for various leather products, making removal of the perforated sections impractical. This inconsistent quality defect has led to the rejection of several container loads of frozen hagfish in Korea. Speculation on the source of these perforations includes environmental, biological, and handling factors.

Another unique aspect of the California fishery, and allegedly the Japanese fishery, is the use of anesthetics on the catch on deck to prevent hagfish from biting each other while in storage on the vessel. Live fish are delivered for quick freezing at –40°F. Unfortunately, anesthetics are expensive, and questions arise regarding food safety because of possible consumption of the flesh as a by-product.

Quickly killing the hagfish may be a possible alternative to anesthetics, but it also creates unique challenges with this hardy animal. Worthington (1905) reported that hagfish were extremely active several hours after decapitation, and healthy hagfish responded violently but survived exposure to warm water. Jensen (1966) reported that hagfish had poor tolerance to salinity changes. Their highly developed sense of smell (Sutterlin, 1975) suggests that they may be vulnerable to mild chemical treatment. Pacific hagfish are reported to have a very low rate of metabolism (Munz and Morris, 1965), suggesting suffocation techniques would be unsuccessful. Treatments combining temperature, salinity, and mild caustic chemicals may provide methods to quickly kill hagfish to minimize biting and perhaps perforations.

There is little literature on fishing techniques for hagfish. A number of traps and baits have been used to catch this abundant fish (Worthington, 1905; Adam and Strahan, 1963; Honma, 1960; Tsuneki et al., 1983). Given the well developed sense of smell in hagfish, which are often scavengers, bait selection could be critical to fishing success (Fernholm,1974; Strahan, 1963). Where to fish and how to catch commercial quantities of high-quality Pacific and black hagfish are currently unknown.

Thus, the overall objective of this study was to better understand the life history and comparative ecology of both species of hagfishes, relative to their developing fisheries. The specific goals were to: (1) perform an ecological survey in Monterey Bay to analyze population characteristics of Pacific and black hagfish; (2) evaluate the habitat utilization patterns and ecological associations of hagfish; (3) determine optimal fishing gear and onboard handling techniques; and (4) undertake laboratory studies examining tag-retention, growth, and behavior. The results of this study will help the fishery in California and throughout the West Coast develop intelligently to its full potential and provide the basic tools for management.

Results

We surveyed Monterey Bay for hagfishes using baited traps during 12 of the 15 months of the study. Nearly 6,500 Pacific (*E. stoutii*) and 3,500 black (*E. deani*) hagfish were captured and dissected for ecological analysis.

Because traps were used as samples and they occurred along a common groundline, we tested catch rates to determine whether they could be treated as independent sampling units. The length and weight of hagfish from independent traps and interdependent traps were compared over a two-day period. An analysis of variance showed no difference between days within groups, so they were pooled. No significant differences were found between pooled values for dependent and independent traps when compared using a *t*-test for either length or weight. Thus, we assume that traps, whether or not they were in a string, were independent samples of hagfishes.

Pacific hagfish were encountered in shallower waters (80–750 m) while black hagfish inhabited deeper waters (500–1000 m, the maximum coinciding with our deepest sample), with little overlap between these two species. Catches from 500 to 750 m infrequently included both species but usually involved only a few individuals. No temporal trends were found in the depth distribution of either species.

Both species exhibited normally distributed length and weight frequency distribution patterns and overlapped considerably. Pacific hagfish ranged between 100 and 500 mm, while black hagfish were 200 to 540 mm. One factor which may relate to the slightly larger size of the black hagfish could be mature egg size in females, which was ~24 mm for Pacific and ~34 mm for black hagfish.

During our surveys in Monterey Bay, we noticed sizes were more normally distributed and contained larger individuals in infrequently fished areas than in those frequently fished. Average catch per unit of effort from 100 m during comparable months was 0.125 hagfish per trap-hour in frequently fished areas versus 0.52 for infrequently fished areas. Because of these impacts from fishing in our initial study area, we were forced to change our sampling design to include samples from other areas.

Females dominated the catches of both species, but sex ratio also appeared to be related to individual fish size. Pacific hagfish had 1.75 females to 1 male, while black hagfish had 2.56 to 1. Hermaphroditism was not commonly encountered, with only one distinct Pacific hagfish and 10 black hagfish hermaphrodites found. In both species, females outnumbered males up to a certain size (240 mm for Pacific and 400 mm for black hagfish), over which the sex ratio approached parity. Because there is no reason to believe that there was a sexual difference in capture rates, especially for small size classes, protogynous hermaphroditism may be occurring.

Pacific hagfish had a smaller size at which 50% of its females matured (370.7 ± 30.9 mm) than black hagfish (406.7 ± 31.3 mm). In contrast, male Pacific hagfish reached this stage at a larger size (365.4 ± 37.2 mm) than black hagfish (349.1 ± 33.7 mm).

Average fecundity of mature Pacific hagfish females was significantly higher (14.5 ± 5.4 eggs per female) than for black hagfish (12.0 ± 3.9 eggs). Although not statistically significant, both species had a weak, but positive, relationship between body size and fecundity. Once females reached a large enough size to reproduce, they generally produced offspring near the overall average. Variability in female investment probably depends upon food availability, which is itself highly variable and perhaps limiting.

No seasonal patterns in spawning were found for either sex or species. The frequency of neither male nor female maturity stages varied with season, although males were more variable. Females of both species had no seasonal patterns in either the hepatosomatic or gonadosomatic indices, a result which could perhaps be explained by the lack of distinct seasonal cues in their deep-sea habitat, and therefore little seasonal selection for juvenile survival.

Analysis of gut contents indicated that the two species had somewhat different diets. Pacific hagfish stomachs contained cephalopods (25.9% frequency of occurrence), sergestids (14.8%), fish parts (14.8%), polychaetes (14.8%), shrimp (11.1%), amphipods (11.1%), eggs (7.4%), and euphausiids (3.7%). Black hagfish ate sergestids (22.8%), polychaetes (22.8%), fish parts (15.8%), crustaceans (14.0%), copepods (3.5%), euphausiids (3.5%), birds (1.7%), mammals (1.7%), and crabs (1.7%).

As a part of this study we attempted to discover the particular habitat preferences of the Pacific hagfish within the Monterey submarine canyon, much like Fricke and Hissmann (1990) did for coelacanths. Such knowledge is important for complete understanding of the general ecology and for management of the emerging California hagfish fishery.

The Monterey Bay Aquarium Research Institute (MBARI) made archives of videotapes taken to depths of 450 m from their Remote Operated Vehicle (ROV) *Ventana* available to us for analysis of habitat utilization, and in addition we participated on several cruises to directly observe hagfishes in their natural setting.

MBARI's ROV is equipped with a Sony Betacam video system that transmits signals through a fiber optic cable up to the R/V *Point Lobos*, where it is recorded on 20 minute Beta videotapes. We examined videotapes from dives in Monterey Bay. The videos were used as a data base for describing the abundance and distribution of the Pacific hagfish at four sites within the bay. The coordinates of each dive were plotted to estimate the area covered in the surveys. A total of 24 dives from April 1989 to June 1990 was included in the analysis. These were originally taken by different scientists with a variety of objectives and had complete depth, longitude, and latitude records.

To randomize the sequences on the tapes, we analyzed individual frames at each 15 second interval. A frame, or photo quadrat, was accepted if it was well lit, clearly focused, not a close-up, and did not overlap with a previously accepted frame. We classified the topography according to geologic formation, general terrain, slope, substrate type, substrate features, and the presence of other fishes, invertebrates, and drift algae. Low numbers in many of the descriptor categories led us to examine the data using graphical rather than statistical comparisons and only substrate type, depth, and number of Pacific hagfish were used in the data analysis.

An analysis of randomly sorted frames was performed to determine the adequacy of describing the substrate types and habitats typical of each site. The cumulative number of habitat types leveled off at numbers of frames well below the actual number of frames examined at all four sites (Figure 1a: curves), indicating that the number of samples taken from each site adequately described the substrate types (Figure 1b: histograms).

Our null hypothesis was that the Pacific hagfish would occur equally in all substrate types. Our expected number of hagfish per substrate type was derived by dividing the number of hagfish seen in frames with a particular substrate by the total number of frames at that site, and multiplying by the total number of hagfish seen at that site. This gave the number of hagfish we would expect to see within each substrate type if they were distributed evenly throughout the site (in the same proportions as the substrate types).

At one site (Soquel), the number of hagfish observed exceeded the number expected in sedimentary areas (s), but were seen less than expected in areas of massive rocks (m) (Figure 2). At two other sites (Carmel and C4-C5), there was a close match between expected and observed numbers, and the hagfish appeared to occur equally on all substrate types. At the fourth site (Pt. Joe), there were higher than expected numbers of hagfish on sand/gravel (s/g), sand/cobble (s/c), sand (s), and boulder/sand (b/s) substrates, but fewer than expected in areas of massive rock formations.

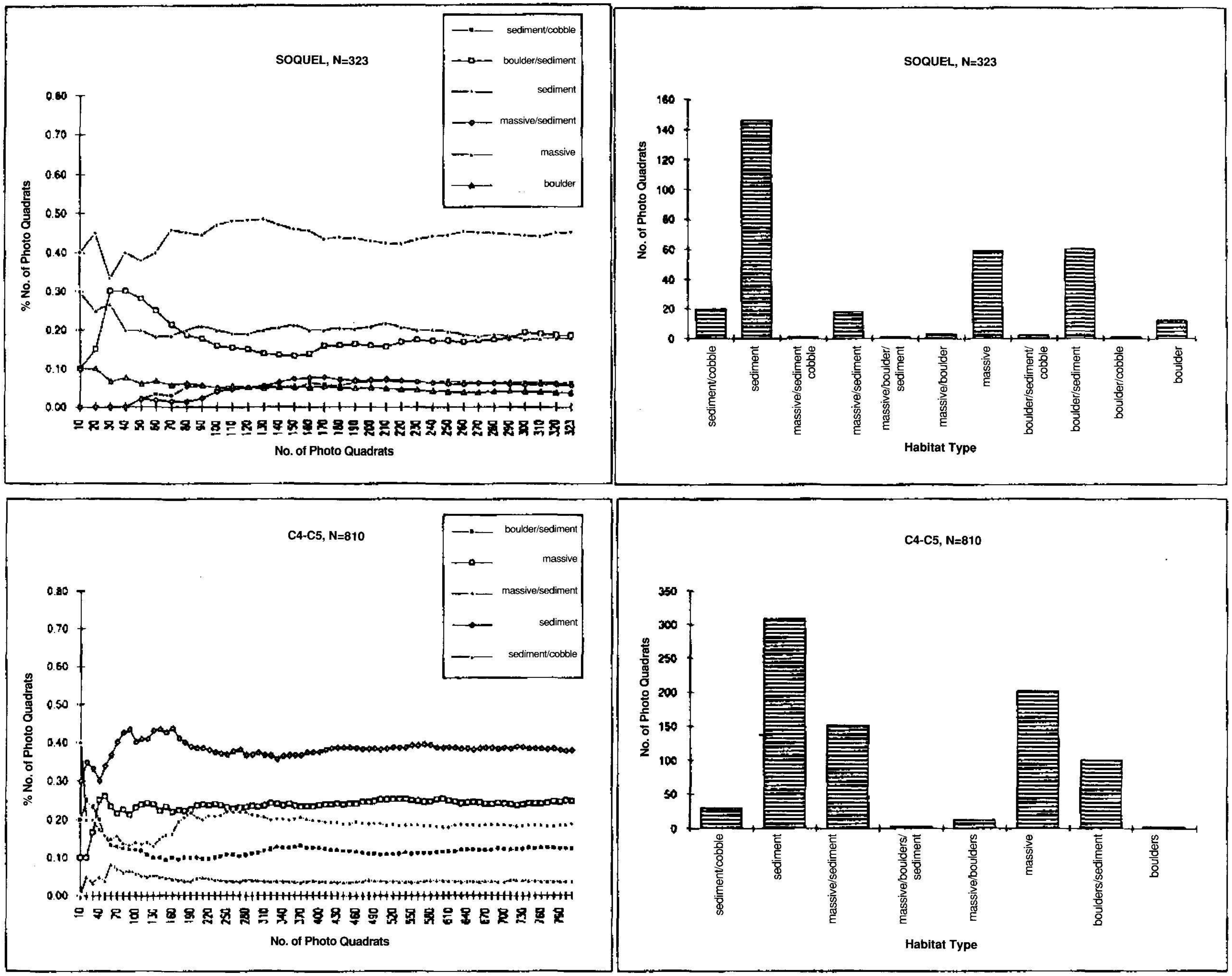

Figure 1a. Cumulative habitat curves (on left) expressed as the percent of photo quadrats from the ROV *Ventana* with a particular habitat type (see box) (*Y* axis) versus the number of photo quadrats (*X* axis) in each of four sites (Soquel, C4-C5, Pt. Joe, and Carmel). Histograms (on right) reflect the overall number of photo quadrats at each site which had one of the 11 habitat types.

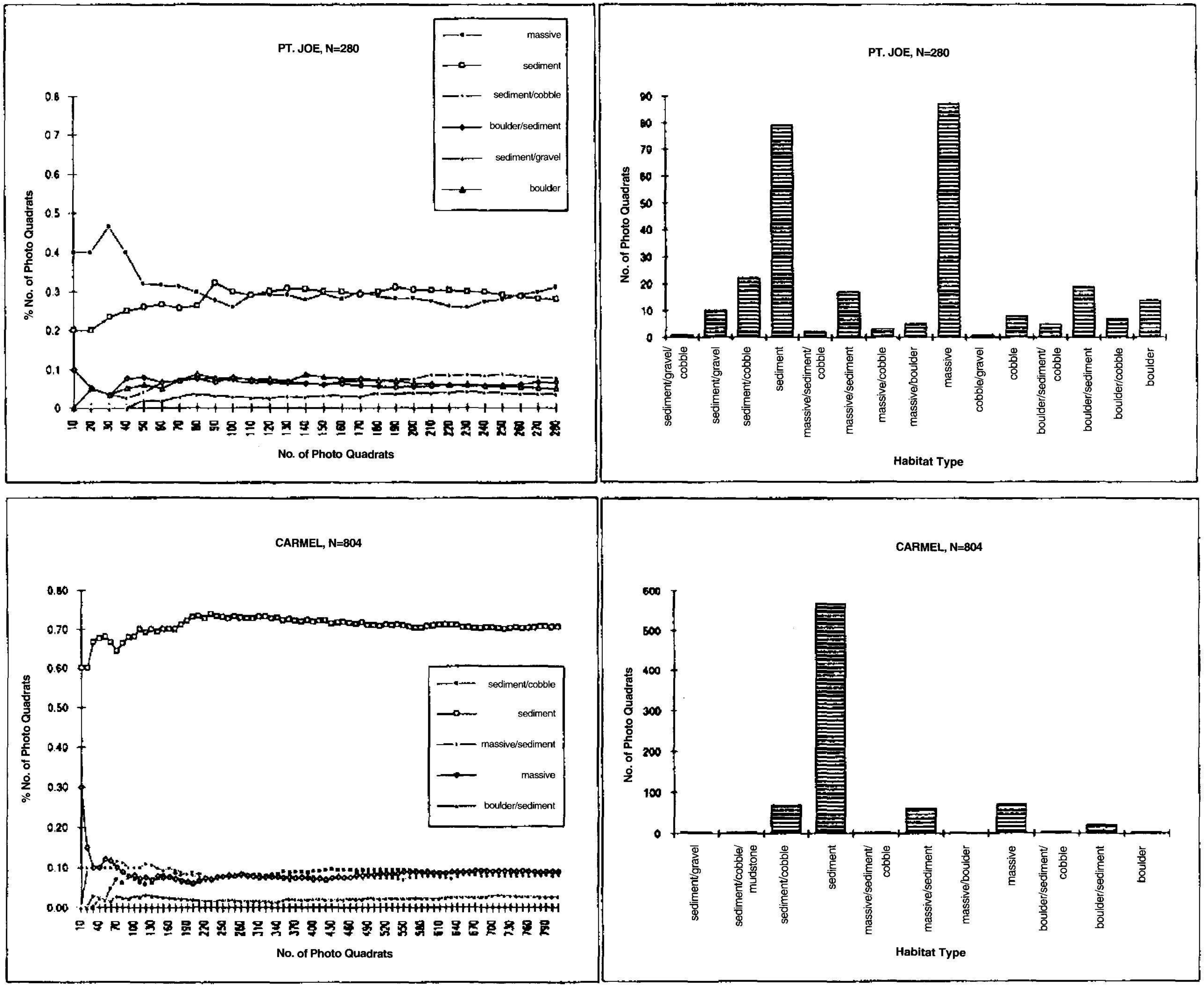

Figure 1b. Histograms reflect the overall number of photo quadrats at each site which had one of the 11 habitat types.

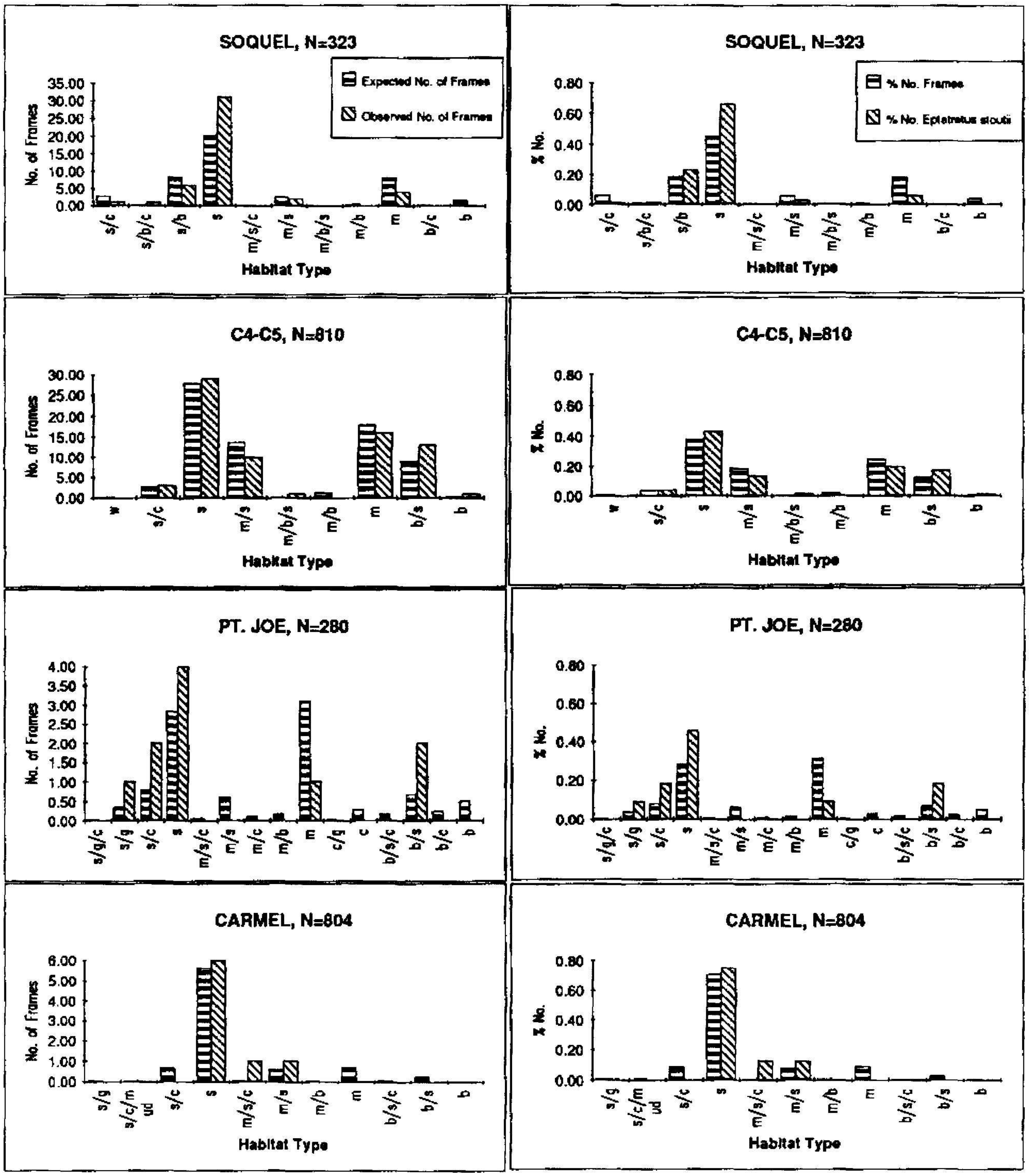

Figure 2. Histograms of the expected number (left side) and percent (right side) of photoquadrats (frames) to include Pacific hagfish for each of the habitat types (see Figure 1) at the four sites.

The general impression gained from previous studies (i.e. Adam and Strahan, 1963; Foss, 1963; McInerney and Evans, 1970) and from trapping was that Pacific hagfish occur only on soft bottoms such as sand or mud. Randomly selected frames from MBARI's ROV dives showed a much wider habitat usage. All four sites examined showed that the majority of animals were seen in sand or mud areas, but a high percentage (30%) were seen in mixed substrate sections, and a surprising number (21 out of 142 total) were seen in areas consisting only of massive substrate.

The wider range of habitat types used by this species of hagfish may indicate either that they travel over a large area, or that they do not always require soft sediment to burrow into. Given the rapid response times of hagfish in general to baited traps, it seems plausible that they travel quite frequently in search of suitable food sources.

To check depth distribution and perhaps observe habitat utilization of the deeper-dwelling black hagfish, we participated in several submersible dives using WHOI's DSV *Alvin* off the *Atlantis II* and Russian submersibles *MIR I* and *MIR II*, off the Russian Research Vessel *Keldysh*, to habitats as deep as 3950 m. Unfortunately, except for occasional sightings of black hagfish attracted to baited cannisters in shallow (1,000–1,500 m dives), none were seen at these depths, thus confirming previous depth records (Eschmeyer et al., 1983).

Trap design experiments partially funded by Grant NA90AA-H-SK142 using ROV observations suggested that traps without side holes caught more hagfish than traps with side holes, but these results were not statistically significant. However, traps with two funnels caught significantly more hagfish per trap and significantly larger hagfish than traps with single funnels. Traps with double funnels and without side holes were the best design tested, because they caught more and larger fish.

Experimental traps were also set at different times of day and durations and using different baits. Neither the mean number per trap nor mean length of hagfish varied significantly with time of day, duration, or bait type. The tremendous variation in catches with soaks and among soak intervals made it impossible to reach definite conclusions, especially about nocturnal activity patterns. We concluded that the best bait is probably the one that is least expensive and most available in a given port.

Despite trace fishing levels and relatively poor prices coastwide in 1991, the eel skin market remains product-limited. The reason for poor price ($0.25 to $0.30 per pound) appears to be the inferior quality of the west coast product, particularly from California. Our results strongly suggest that if the product is kept cold and densities are kept to around 200 hagfish per 55 gallon barrel, skin quality can be improved and anesthetics eliminated. Dorsal holes in the skin greater than 0.5 mm (tears) and bites limit the value of the skins. Tiny pinholes (mostly <0.25 mm) were few and generally not limiting. Tears seem to be the result of temperature abuse and are in some cases caused by bites.

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Cooperating Organizations

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