Synopsis of the Development of Dive Surveys for Pacific Herring Spawn Assessment

Jacob F. Schweigert and Carl W. Haegele

Fisheries and Oceans Canada
Science Branch, Pacific Region
Pacific Biological Station
Nanaimo, British Columbia
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The monitoring and assessment of the extent and intensity of Pacific Herring (*Clupea pallasii*) egg deposition for determining abundance has been ongoing since its inception in the 1930s. Initially the surveys were conducted from the surface usually at low tide but research studies during the 1970s using SCUBA technology indicated that much of the egg deposition occurred subtidally and was not fully detected using surface-based methodology. From these studies methods were developed to estimate egg density and improve surface surveys. In conjunction with the early diving surveys, a series of aerial surveys were conducted to map the distribution and species composition of the seaweeds in the nearshore that formed the substrate for egg deposition to aid surveyors. Subsequently, SCUBA surveys were conducted to develop more statistically rigorous estimates of total egg deposition on all nearshore vegetation including the giant kelp, *Macrocystis sp*. These surveys determined that a series of equally spaced transects stretching from the outer edge of the vegetation to the beach set perpendicular to shore and along which equally spaced sampling quadrats were used to monitor the egg deposition provided an accurate and precise estimate of spawning population abundance. Larger scale surveys followed that demonstrated the possibility of conducting dive surveys coastwide. A number of studies of egg loss during the incubation period were subsequently conducted to account for eggs not included during these surveys. Annually mapping and monitoring the distribution of Pacific Herring spawning activity is important for documenting the location of egg deposition and estimating herring abundance. These data are also important for determining the impacts of future coastal development and shoreline alteration.

RÉSUMÉ

Schweigert, J.F., and Haegele, C.W. 2021. Synopsis of the development of dive surveys for Pacific Herring spawn assessment. Can. Manuscr. Rep. Fish. Aquat. Sci. 3234: v + 21 p.

Depuis les années 1930, on effectue une surveillance et une évaluation de l’étendue et de l’intensité de la ponte du hareng du Pacifique (*Clupea pallasii*) en vue de déterminer son abondance. Au départ, on effectuait les relevés depuis la surface, généralement à marée basse, mais des études en plongée menées dans les années 1970 ont révélé qu’une grande partie de la ponte se déroulait dans la zone infratidale et que la méthodologie basée en surface ne permettait pas de détecter en totalité la ponte. Grâce à ces études, on a mis au point des méthodes permettant d’estimer la densité des œufs et d’améliorer les relevés en surface. Parallèlement aux premiers relevés en plongée, dans le but d’aider les personnes affectées aux relevés, on a effectué une série de relevés aériens pour cartographier la répartition et la composition des espèces d’algues marines dans la zone littorale qui constituaient le substrat pour la ponte. Par la suite, on a effectué des relevés en plongée afin d’obtenir des estimations plus rigoureuses sur le plan statistique de la ponte totale sur toute la végétation du littoral, y compris la laminaire géante, *Macrocystis sp*. Ces relevés ont permis de déterminer qu’une série de transects également espacés s’étendant de la bordure extérieure de la végétation jusqu’à la plage, placés perpendiculairement au rivage et le long desquels des quadrats d’échantillonnage également espacés étaient utilisés pour surveiller la ponte, fournissaient une estimation exacte et précise de l’abondance de la population reproductrice. Des relevés à plus grande échelle ont suivi et ont révélé qu’il était possible d’effectuer des relevés en plongée sur toute la côte. On a par la suite mené un certain nombre d’études sur la perte d’œufs pendant la période d’incubation pour tenir compte des œufs qui n’ont pas été inclus pendant ces relevés. La cartographie et la surveillance annuelles de la répartition de l’activité de fraie du hareng du Pacifique sont importantes, car elles permettent de documenter le lieu de dépôt des œufs et d’estimer l’abondance du hareng. Ces données sont également importantes, car elles permettent de déterminer les répercussions potentielles du développement côtier et de la modification du littoral.

INTRODUCTION

The ability to successfully manage any natural resource relies critically on an accurate assessment of its abundance index in a consistent and ongoing manner. Pacific Herring (*Clupea pallasii*) is among the most common species in the British Columbia marine ecosystem (Schweigert, 1997, Keeling et al., 2017) and has supported a variety of commercial and First Nations fisheries for centuries. The routine sampling of Pacific Herring egg deposition on intertidal and subtidal vegetation as a means to estimate the abundance of the spawning population was first proposed in the 1930s by Hart and Tester (1934). They demonstrated that given an estimate of the egg density in a quadrat sample, an estimate of the total area covered by the eggs, and an estimate of the sex ratio and fecundity of the population, it is possible to determine the number of herring that would have been necessary to account for the observed egg deposition. As a consequence, a coastwide program to survey all the herring spawning beaches along the British Columbia (BC) shoreline was instituted in 1937 (Hay and Kronlund, 1987). These surveys were conducted by Fishery Officers stationed throughout the BC coast, usually at low tide using visual estimates of the lineal extent of the spawn, often employing a skiff and grappling hook, to estimate the width and intensity of the egg deposition (a proxy for the egg density) in what are often referred to as surface surveys (Humphreys and Haegele, 1976).

Traditionally, these data were used to calculate "miles of spawn" for individual spawning events by adjusting the observed length of a spawning for any difference in the intensity of egg deposition from a standard value for widths up to 100-yards. Further adjustments occurred for spawning events wider than a hundred yards. The result was a crude estimate of the abundance of the herring populations which then supported the development of fishing quotas (Taylor, 1964). However, it was later determined that this index was not sensitive enough to detect significant changes in the abundance of individual stocks (Humphreys and Haegele, 1976). Following the Pacific Herring population collapse of the late 1960s and fishery closure, the commencement of a roe fishery in the early 1970s required a more localized estimate of abundance for managing the resource. As a result, new research to develop a more accurate method for surveying spawn deposition and assessing stock abundance at a localized spatial scale was initiated. This report summarizes the studies that were conducted through the 1970s and 1980s to develop a statistically sound methodology for assessing the abundance of herring eggs throughout the coast using a diving-based survey methodology.

SURVEY IMPROVEMENTS USING DIVERS

Self-contained underwater breathing apparatus (SCUBA) did not come into common use until the mid-1960s. Early diving and some surface survey observations showed the presence of substantial herring spawn in sub-tidal areas that were not detected in earlier surveys, leading to the initiation of research studies in the early 1970s to evaluate the extent of these spawning areas. The first study to compare observations of herring spawn by divers using SCUBA to the traditional surface-based methods occurred at two locations within Barkley Sound in 1975 (Humphreys and Haegele, 1976). Transects were set perpendicular to a shore baseline established as close as possible to the high-water line using a surveyor theodolite. Transects were marked with gillnet leadline consisting of 20 m lengths shackled together. The leadline was laid out from a drum mounted on the bow of a small (5 m) power boat which backed away from the shore. Leadline was laid out to a depth of 15 fathoms (27.4 m) as determined by an echosounder, or to a maximum distance of 400 m from the baseline (the length of available leadline). Sampling stations were established by a diver at approximately 20 m intervals along the leadline. Marked buoys were placed in the water by divers' tender and a diver then attached one buoy to the leadline at each sampling station. The "sampler" divers then placed the specified size sample quadrat (0.25, or 1.0 m^2 subsequently standardized to 0.50 m^2) on the bottom at the sample station. All vegetation "rooted" within the quadrat was removed with a knife and placed in a burlap sack along with a label. The sack was then attached to the buoy line and released from the leadline so that it could be raised to the surface by the divers' tenders. The divers made observations on seven classes of vegetation (grasses, rockweed, kelps, other brown algae, foliose red algae, filamentous red algae, green algae), the proportion of the quadrat covered by each type of vegetation, and the number of layers of eggs on each type of vegetation or on the bottom substrate. Samples were processed in the field by removing the vegetation and attached eggs from the burlap sacks and separating them into fractions by species of vegetation. The number of plants of each species, the average height and width of plants and the total weight of each species together with eggs if present was determined to the nearest gram. A weighed subsample of eggs on vegetation, usually sufficient to fill a 1 liter jar was preserved in Gilson's fluid for each substrate in the sample for at least two weeks. During subsequent laboratory processing the Gilson's fluid was decanted from each sample and the sample digested in a jar of alcoholic (25% by volume) 1N KOH at 40°C in an ultra-sonic water bath. The KOH solution digests the adhesive which binds the herring eggs to each other and to the substrate. The separated eggs were then washed with salt water in a sieve and the vegetation removed. At this stage the eggs are swollen and fragile from the digestion procedure and are preserved in 10% buffered formalin for a minimum of 2 weeks at which time they regain their pre-digestion dimensions. The formalin was then decanted and Bouin's fluid was added to harden the eggs. After the vacuum extraction of preserving fluid, the number of eggs in each subfraction was determined by weighing the subfraction to the nearest tenth of a gram. At the same time, a portion of the subfraction (usually between 300 and 500 eggs) was counted and weighed to the nearest hundredth of a gram. The number of eggs per m^2 for each spawn sample collected in the field was then determined as the sum of the eggs in the individual vegetation fractions.

A main objective of collecting samples of vegetation and attached eggs was to develop a calibration between counts of eggs for determining density and the more subjective spawn intensity observations previously captured in the surface surveys (Humphreys and Haegele, 1976). Secondarily, the samples could be used to estimate spawning biomass directly by applying the mean egg density to the area of spawn to determine total egg deposition as per Hart and Tester (1934). In practice, Humphreys and Haegele (1976) applied a pseudo-stratification approach to determine total egg numbers. From the samples of spawn, areas of similar egg density were mapped and tabulated to determine total egg numbers for the spawn by geographical area. A similar study was conducted in Nanoose Bay in the Strait of Georgia in 1976 (Haegele and Humphreys, 1977). The results confirmed the 1975 findings that traditional surface surveys tended to underestimate both the area of deposition and the egg density (Humphreys and Haegele, 1976). Concurrently with these surveys additional samples of herring eggs from the seven classes of marine vegetation were collected from 1975 to 1978 to provide the Fishery Officers conducting surface surveys with a more accurate tool for determining egg density from estimates of egg layers on major seaweed groups in Pacific Herring spawning events (Humphreys and Haegele, 1976, Haegele and Humphreys, 1976b, Haegele and Humphreys, 1978a,b, Haegele et al., 1979a). A spawn survey manual was also provided to aid the surveyor in implementing the upgraded protocols (Humphreys and Hourston, 1978). The efficacy of the proposed improvements in the surface survey methodology was assessed with comprehensive diver surveys in 1978 and 1979 (Haegele et al., 1979b, Haegele and Miller, 1979 a,b). While the objective of these studies was to develop better procedures for conducting the traditional surface-based surveys, they also revealed the broader subtidal distribution of herring spawn not sampled by existing protocols (Haegele et al., 1981).

AERIAL PHOTOGRAPHY SURVEYS

A critical component of the upgraded surface survey protocol was the development of maps of the intertidal and subtidal vegetation in areas typically used for spawning by Pacific Herring throughout the BC coast. The intent was to provide the Fishery Officer with a tool that would facilitate determination of where spawning might have occurred and also to improve estimates of spawn bed width and total area by mapping the seaweed beds (Haegele, 1975; Haegele et al., 1979a). The development of maps of the algal communities in the vicinity of major herring spawning locations occurred over more than a decade using infrared and colour photographs collected from aerial overflights (Haegele, 1975; Haegele and Hamey, 1976; Haegele and Hamey, 1977; Haegele, 1978; Haegele and Hamey, 1979a,b; Haegele and Hamey, 1980a,b,c,d; Haegele and Hamey, 1981a,b; Haegele and Hamey, 1982a,b; Haegele and Hamey, 1987). The best results were obtained with Kodak aerochrome infrared film using a Wratten 12 filter to absorb unwanted blue wavelengths (Haegele, 1975). Vegetation appeared in various hues of red with this approach: rockweed appeared crimson; kelp, bright magenta; red algae, light red; green algae, light pink; and sea grasses, pinkish red. Water penetration with infrared film was limited, not exceeding 1 m under ideal sun angles of 40°(Haegele, 1975). The Kodak aerocolor film had good water penetration to a depth of 10 m but poor colour separation with most vegetation appearing a brown or green hue. The best overall approach was to use colour infrared film during the lowest possible tides in bright sunlight, supplemented by colour film to determine the boundaries of the underwater vegetation. Vertical aerial photographs of 24 cm x 24 cm format at a photo scale of 1:6000 were taken using infrared photography before low tide and colour photography after low tide providing adequate detail for accurate vegetation identification and mapping. The photographic images were used to develop maps of the distribution of five major vegetation groupings: sea grasses, rockweeds (*Fucus disticus*), red algae, other brown algae, and green algae. The vegetation maps were prepared at the scale of photography (1:6000), using enlarged marine charts as a base map, with standard photogrammetric techniques. Subsequently, a number of early dive surveys were conducted to assess the accuracy of the vegetation maps (Haegele and Humphreys, 1976; Haegele 1977, 1978). It was determined that the vegetation maps were accurate but it was often difficult to precisely determine a surveyor's location relative to the underlying vegetation beds prior to the widespread availability of the Global Positioning System (GPS). As a result, accurate determination of egg densities for each algal category within a spawning bed was difficult.

ESTIMATING EGG DENSITY

The egg density in a spawning area varies widely depending on the types of underlying vegetation, the composition and mixture of algal species in the area, and the intensity of the egg deposition. The early assessment of spawning intensity in surface surveys was improved by the transition to having Fishery Officers estimate the number of egg layers on each type of vegetation in the spawning bed. However, the translation of these estimates of egg layers to an estimate of egg density was still problematic. The surveys conducted through the latter 1970s collected data that could be used to develop inter-calibration relationships between vegetation type, proportion of the sampling quadrat covered by vegetation and the number of egg layers on the various vegetation and bottom substrates. The size of the sampling quadrat could also affect these estimates and all available counted samples were adjusted to egg numbers per square meter (m^2) to standardize the density estimates. The size of the sampling quadrat has been standardized to 0.5 square meters since 1981. Not surprisingly, these data contained considerable variability due to the varying density of the plants in the sampling quadrat and the mixture of vegetation types. Haegele et al. (1979a) initially established eight substrate types according to plant taxonomy, the physical appearance of plants within phyla as it affects surface area and plant distribution by depth. Red algae (Rhodophyceae) were separated into two types: foliose red algae and filamentous red algae. Brown algae (Phaeophyceae) were divided into four types: rockweeds, kelp, perennial kelp and other brown algae. Sea grasses (marine seed plants) and green algae (Chlorophyceae) were the other substrate types. Each spawn sample was classified by a substrate type according to the proportion of eggs adhering to species in each substrate type. The dominant species (i.e., the species with the most eggs on it) in each sample was also identified. From these data, Haegele et al. (1979a) developed a geometric relationship between egg layers and egg density for each of six substrate categories (sea grasses, other brown algae, filamentous red algae, rockweeds, kelps, and foliose red algae) and a range of vegetation coverage using them to estimate expected egg density at other unsampled levels of egg layers and algal coverage. Insufficient data were available for green algae and the perennial kelp (*Macrocystis integrofolia*) could not be adequately sampled with existing protocols.

A substantial number of species of vegetation were encountered in the collection of the 1081 samples used to develop the keys but the egg deposition was more restricted. Of the two species of sea grasses, *Zostera marina* occurred in 91% of the samples identified as sea grasses. The other grass was *Phyllospadix scouleri* which did not co-occur with *Zostera marina* usually sharing the same habitat with red and brown algae (Haegele et al., 1979a). All but one of the rockweed samples were on *Fucus distichus*. A total of 11 species of kelp were encountered in the samples of which three species of *Agarum* and three species of *Laminaria* were the dominant substrate type in 87% of the kelp samples. Seven species were grouped into the other brown algae category and three were dominant in 97% of the samples: *Sargassum muticum, Desrnarestia aculeata,* and *Dictyota binghamiae*, respectively. Foliose and filamentous red algae were represented by the largest number of species. Of the 36 foliose red algae species, only 26 occurred in samples identified as foliose red algae and only 13 species were dominant with 5 accounting for 75% of foliose red algae samples in order of number of occurrences: *Cryptopleura sp., Prionitis sp., Gigartina exasperata, Prionitis lanceolata,* and *Gymnogongrus leptophyllus*. A total of 45 species of filamentous red algae were encountered, of which only 34 species occurred in samples typed as filamentous red algae and only 16 were dominant species. Five species were dominant in 83% of the samples categorized as filamentous red algae, in order of number of occurrences: *Rhodomela larix, Odonthalia flocossa, Neogardhiella baileyi, Pikea sp.,* and *Gracilaria verrucosa*. Two species of green algae were encountered, *Ulva lactuca* was dominant in 87% of the samples identified in this category (Haegele et al., 1979a).

The samples usually contained substrate species that belonged to more than one category. However, the bulk (74-98%) of the egg deposition was on species of the dominant category (Haegele et al., 1979a). Sea grasses samples were the purest with only a few of the samples containing other substrate types that contributed a small percentage of eggs (5-11%). Rockweed samples were quite pure, being mixed with either green algae or filamentous red algae. The green algae, *Ulva lactuca*, occurred with *Fucus distichus* in 26% of the rockweed samples but the average percent egg contribution by green algae was insignificant. Kelp samples were also pure with red algae the other substrate types most frequently included but accounting for an average of only 8% (foliose red algae) and 13% (filamentous red algae) of the total eggs. Other brown algae samples were relatively pure with the major other substrate type filamentous red algae contributing an average of 16% of the eggs. Filamentous and foliose algae tended to be the most intermixed. Foliose red algae samples included filamentous red algae in 81% of the samples and contributed an average of 24% of the eggs. Filamentous red algae samples included foliose red algae in 28% of the samples contributing an average of 19% of the eggs. Green algae were frequently encountered with rockweeds (33% of samples).

The calibration relationships developed by Haegele et al. (1979a) were subsequently used to determine the total egg deposition in the French Creek and Qualicum areas of Georgia Strait in 1978 and provided estimates comparable to counted samples (Haegele et al., 1979b). However, routine application of the keys on a coastwide basis was impractical and a generalized linear model was developed to estimate egg density (Schweigert and Fournier, 1982). The model estimated total egg density per m^2 from data of the number of egg layers on the vegetation type, the percentage of the sampling quadrat covered by each vegetation type, the dominant type of vegetation, and the size of the sampling quadrat simplifying the prediction of egg density for each quadrat visually assessed by a diver. The accuracy of the model predictions of egg density from visual estimates of the egg deposition varied among areas and years but generally showed statistically acceptable performance of the model for determining herring spawning biomass (Schweigert et al., 1990).

SURVEY DESIGN STUDIES

In addition to estimates of egg density, was the need for an accurate determination of the dimensions of the area of egg deposition. In 1980 and 1981, diver-based surveys were conducted on substantial portions of the British Columbia coast (Haegele, 1981, 1982) collecting data on spawning bed length, width, and egg deposition, as a comparison to similar surveys conducted by Fishery Officers on many of these spawning beds. The comparison of estimates by the two types of surveys highlighted the difficulty in estimating the total area of egg deposition from surface only techniques and the need for an accurate method to determine the density of egg deposition for each spawning event. The diver-based survey protocol employed in these comparative studies relied on synoptic sampling of individual spawning beds to determine the egg deposition stratified by vegetation category (i.e., samples were collected in the eelgrass separately from those in the rockweed area). In the end, the protocol was logistically challenging given the absence of GPS availability at the time, making it difficult to precisely locate the individual quadrat samples within the mapped algal beds, and were insufficiently statistically rigorous for routine application. As a consequence, additional studies were initiated in the Strait of Georgia in 1981 to develop an optimal sampling scheme that would generate estimates of egg deposition with a precision of 25 percent standard error on the estimate of egg density (Schweigert et al., 1985). The Strait of Georgia study in 1981employed randomly determined transects within a known egg bed together with randomly selected quadrat subsamples within transects. However, the implementation of random transect and quadrat selection was logistically problematic because the dimensions of the egg deposition were unknown when the sampling was initiated. Consequently, a systematic sampling protocol was implemented for all subsequent surveys. Based on the results from the 1981 study and similar data collected in earlier studies within the Strait of Georgia, the authors suggested that a two-stage sampling scheme that surveyed 3 or 4 transects per kilometer of herring spawning bed parallel to the shore and between 2 and 5 percent of each transect should yield the desired precision in egg density estimates. The surveys were repeated in Barkley Sound and the North Coast in 1982 and again in the Strait of Georgia in 1983 to assess whether these results were applicable in other areas and other years (Haegele and Schweigert, 1984; Schweigert and Haegele, 1984; Haegele and Schweigert, 1985a). These studies implemented a sampling protocol that included visual assessment of the egg deposition (egg layers, type of vegetation, percent of the quadrat covered by vegetation) as well as the collection of samples of vegetation and eggs. The protocol was implemented with transects placed every 300 meters and quadrat sample every 40 m on transects expected to be longer than 200 m, at 20 m for those shorter than 200 m, at 10 m for those less than 100 m, at 5 m for those less than 50 m and at 2 m for those less than 20 m. The studies in 1982 and 1983 were also conducted in conjunction with Fishery Officer surface based surveys and hydroacoustic assessment to evaluate the effectiveness of each approach as a basis for determining Pacific Herring abundance for fishery management.

SURVEY DESIGN VALIDATION AND COASTWIDE PILOT SURVEYS

The spawn surveys conducted in individual assessment regions in 1982 and 1983 indicated that a dedicated dive team was able to effectively cover most of the spawning events within a moderate geographical area in a single season. As a result, a survey of the entire west coast of Vancouver Island herring spawning was conducted in 1984 to confirm the ability of dive surveys to comprehensively survey all the spawning events in a large geographical area and to test the predictive accuracy of the model of egg density (Haegele and Schweigert, 1985b; Schweigert et al., 1990). The survey was able to comprehensively survey all herring spawning events in Statistical Areas 23 to 25 (Barkley, Clayoquot, and Nootka Sounds, and Esperanza Inlet).

Dive surveys of the entire south coast of British Columbia were conducted to estimate herring spawning biomass in 1985 (Haegele and Schweigert, 1987a; Schweigert and Haegele, 1988a). In both the Strait of Georgia and the west coast of Vancouver Island divers conducted comprehensive surveys of all spawning events and samples of eggs were collected for subsequent processing and validation of the egg prediction model. In addition, routine surface spawn surveys were conducted by Fishery Officers to provide a comparison to the diver-based surveys and to develop inter-calibration relationships between the two types of surveys.

Dive surveys of the entire BC coast with the exception of Haida Gwaii (Queen Charlotte Islands in older reports and literature) were again conducted in 1986 to estimate herring spawning biomass (Haegele and Schweigert, 1987, 1988b; Schweigert and Haegele, 1988 b, c). In three assessment regions (Strait of Georgia, West Coast of Vancouver Island, and Central Coast) comprehensive surveys of all spawning events occurred and samples of eggs were collected for subsequent processing and validation of the egg prediction model. In addition, routine surface spawn surveys were conducted by Fishery Officers to provide a comparison to the diver-based surveys and to develop inter-calibration relationships between the two types of surveys. The dive survey in the North Coast was hampered by weather and available resources and was incomplete although surface surveys were conducted of any outstanding spawning events. Schweigert and Stocker (1988) provide a detailed comparison of joint dive and Fishery Officer surveys developing inter-calibration relationships between the two methods.

Overall, the pilot coastwide surveys from 1984 to 1986 demonstrated that it was possible to inventory and survey all of the known Pacific Herring spawning events on the entire BC coast with individual vessels and dive teams in each of the five major assessment regions.

GIANT KELP SURVEYS

The giant kelp, *Macrocystis* sp. provides a unique spawning substrate for Pacific Herring reaching heights exceeding 15 meters. It presents a sampling challenge as it could not be surveyed using the same procedures as for the understory vegetation and the model used for predicting egg density on other algal substrates was not applicable to the giant kelp. Giant kelp occurs in all areas of the BC coast although it is rare within the Strait of Georgia. It is one of the dominant spawning substrates for Pacific Herring in Haida Gwaii and surveys of herring egg beds were conducted there in 1981 and 1987 to obtain data on the egg deposition on *Macrocystis* sp. to aid in the development of a routine surveying methodology for all spawning substrates (Haegele and Schweigert, 1985c, 1987c). Herring spawn on *Macrocystis* sp. plants was sampled along Haida Gwaii (38 plants in 1981 and 74 plants in 1987), along the North Coast (15 plants in 1986), along the Central Coast (5 plants in 1986), and along the west coast of Vancouver Island (11 plants in 1985 and 24 plants in 1986). Divers harvested entire giant kelp plants and brought them to the surface, holdfast first, after untangling the fronds from those of adjacent plants. The number of fronds for each plant was determined and a distinction was made between mature and immature fronds. Immature fronds generally were less than 1 meter long, had no fully developed blades, and were labelled as meristems. Plants were then cut into 1-meter sections in the workboat, bagged separately in burlap sacks, and transported to a shipboard laboratory where the number of fronds and blades per section was determined. determined. Apical portions of the fronds, where blades had not differentiated, were treated separately and also labelled as meristems (Haegele and Schweigert, 1985c). Each section was weighed, mature fronds were counted, and egg layers were estimated. For mature plants, one blade and its associated section of stipe was weighed and preserved in Gilson's fluid. For meristematic material, subsamples sufficient to fill a 1-liter jar were weighed and preserved. Subsequent laboratory processing involved immersing the preserved samples in alcoholic (25% by volume) 1N KOH at 40°C for approximately 1 hour to detach the eggs. Eggs were then stored in 10% formalin for at least 1 week for hardening. The preservative was vacuum extracted, the eggs weighed, and 2 aliquots of approximately 200-400 eggs removed, weighed and the eggs counted. Total egg numbers for each 1-meter section were then calculated and egg numbers per plant estimated from the sum of these sections. Similarly, from the data collected for the 1-meter sections, mean number of egg layers per plant, total plant height (the length of the longest frond), and total number of fronds per plant were determined (Haegele and Schweigert, 1990).

These surveys also collected information on the number of individual *Macrocystis* sp. plants within a 1-meter swath on each side of a transect line set perpendicular to shore (the same transect used to assess understory vegetation and egg deposition). For each giant kelp plant the number of mature fronds were counted, the height of the plant measured, and the number of blades counted together with an estimate of the average number of egg layers on the blades. From these data a predictive model of the number of eggs per plant was developed using the height of the plant, the number of mature fronds and the average number of egg layers (Haegele and Schweigert, 1990). Using this model to estimate the number of eggs on the surveyed plants provided a basis for a synoptic survey of the herring egg deposition on *Macrocystis* sp. in each spawning event using counts of the number of plants in the 2 m swath along each transect, the average number of fronds per plant and the average number of eggs layers per plant. The total estimated egg deposition on *Macrocystis* sp. could then be summed with the estimated egg deposition on other algal substrates for each spawning area.

EVALUATION OF EGG DENSITY PREDICTION

Uncertainty in the estimate of total herring egg deposition is introduced mostly from the estimate of egg density as predicted from the diver's visual assessment of the dominant vegetation class, the egg layers on different classes of vegetation and the proportion of the sampling quadrat covered by each vegetation class. The estimate of egg layers and proportion of the sampling quadrat covered by each vegetation class is subjective based on a diver's perception of the egg deposition and experience. Attempts were made to standardize this process by pairing new and experienced divers, and conducting pre-survey briefings to discuss protocols. However, in each area and survey year there were and continue to be changes in the divers conducting the surveys and their levels of experience. Comparison of the predicted egg density from visual assessment of the vegetation, proportion of quadrat coverage, and number of egg layers demonstrated good agreement with some discrepancies (Schweigert et al., 1990, Schweigert, 1993). Schweigert et al. (1990) note that predictions of egg density were higher than counted samples when the egg layers were low (<2.0 layers) but worked well at predicting density for heavier spawning (mean=5.0 layers). They also found that there was a tendency for predictions to exceed counted egg density when the samples were collected near the end of the incubation period as the eggs became fragile breaking during processing and not being included in the count. Haegele and Schweigert (1985b) also noted that an apparently larger relative size of some classes of vegetation on the outer coast (primarily west coast of Vancouver Island) resulted in conservative estimates of egg layers that produced an underestimate of egg numbers.

To assess possible bias resulting from these effects, a small number of samples of vegetation and attached eggs were collected annually and processed to enumerate the egg density. Annual collection of some samples of eggs and vegetation were undertaken from 1988 through 1996 (Haist and Schweigert, 1989, 1990, 1991, 1992; Schweigert et al., 1993; Schweigert and Fort, 1994; Schweigert et al., 1995, 1996, 1997) to verify the accuracy of model predictions of egg density. Sample collections were discontinued in 1997 due to shortfalls in funding for sample processing. In most years, no statistical differences were found between egg counts and model predictions of egg density in the samples. In a few cases where statistical differences occurred, they appeared to result from sample collection near the end of the incubation period when the eggs were fragile and began hatching during preservation biasing the counts low as noted above.

Additionally, in the latter years of sample collection, preservation in Gilson's fluid was discontinued as it contains mercuric chloride and was considered a health risk. The absence of Gilson's preservative also increased the fragility of the egg membrane apparently leading to reduced egg counts. A reassessment of the accuracy of model predictions of egg density should be considered periodically to guard against systematic changes in survey protocols that may occur over time.

EGG MORTALITY STUDIES

The removal of herring eggs by predation or environmental effects such as tidal and wave flux or storm events can have a significant impact on estimates of spawning stock biomass that rely heavily on the determination of the total number of eggs deposited during spawning events. There have been numerous studies of egg loss from Pacific Herring spawns but there is no consensus on its magnitude. As early as 1931, Munro and Clemens (1931) observed, inventoried, and sampled birds on herring spawning grounds over several years to investigate the consumption of eggs by ducks and gulls but did not estimate egg removals. Outram (1958) determined that 56-99% of all the eggs on intertidal eelgrass *(Zostera marina)* in Barkley Sound, were lost during incubation of which bird predation accounted for 30-55%, the remainder was due to wave action. Vermeer (1981) estimated that 75,000 surf scoters *(Melanitta perspicillata)* occurred along the west and east coast of Vancouver Island during two weeks in March 1978, consuming 1.4 % of all the eggs spawned. More recently, Bishop and Green (2001) estimated that between 18 and 31 % of the egg deposition at Montague Island in Prince William Sound, Alaska was consumed by birds, primarily gulls and scoters. Palsson (1984) reported egg losses of 95-99% from herring spawning events in Puget Sound, Washington. Bird predation was the major cause of loss, followed by snail and gammarid predation. Haegele and Schweigert (1989) estimated that birds (gulls, scoters) consumed 3.5%, mammals (gray whales) 3.0%, and invertebrates (leather stars, turban snails) 13.0 % of the total egg deposition in Barkley Sound in 1988. Similarly, Haegele (1993a, b) estimated that birds (gulls, scoters) consumed 3-4%, and invertebrates 4% of the total egg deposition in the Strait of Georgia in 1989 and 1990. In another study, Rooper et al. (2000) estimated that greenling (Hexagrammidae) consumed between 2.3 and 3.7% of the herring eggs at Montague Island in Prince William Sound in 1995. Two studies on the east coast of Vancouver Island examined egg loss from wave action. Hart and Tester (1934) estimated that 40% of eggs in one bed were washed ashore and that 70% of these eggs died. Hay and Miller (1982) found that 26% of eggs deposited in a spawning event in the Strait of Georgia in 1980 were cast ashore in windrows following a storm. Both studies noted that adjacent spawns did not appear to experience this magnitude of egg loss.

Estimates of egg loss from these studies are quite variable and typically do not include all potential sources of mortality and early attempts to incorporate egg survival into Pacific Herring stock assessments (e.g., Hourston and Schweigert, 1981) were uncertain. Studies focussed on assessing egg loss were conducted in Barkley Sound on the west coast of Vancouver Island in 1988 (Haegele and Schweigert, 1989) and in the

Strait of Georgia in 1989 and 1990 (Haegele and Schweigert, 1991; Schweigert and Haegele, 2001). These studies all monitored the egg density in 0.5 m^2 sampling quadrats located along transects set perpendicular to shore over the course of the incubation period. Haegele and Schweigert (1989, 1991) estimated that about 20% of the spawned eggs were lost in Barkley Sound in 1988 and 58% of the spawned eggs were lost in the Strait of Georgia in 1989. Schweigert and Haegele (2001) determined an egg loss rate of about 10% eggs per day in the Strait of Georgia in 1989 and 1990 representing an overall loss of about 24% over the course of the incubation period. Rooper (1999) conducted a similar study in Prince William Sound noting a range in daily egg loss rate of 4.2% per day (1991) to 9.6% eggs per day (1994 and 1995). The study also found significant effects related to depth and wave exposure but bird predation was confounded by depth. Shelton et al. (2014) estimated egg loss rates in Puget Sound ranging from 5 to 70 % eggs per day with indications that degree of exposure as a function of wave height and the degree of shoreline armouring affected egg loss. However, there was no indication of differing loss rates associated with the type of algal spawning substrate. Keeling et al. (2017) estimated egg loss rates ranging from 10 to 13% eggs per day over a 21-day incubation period at nine sites distributed throughout the Central Coast of British Columbia resulting in an estimated 88-94 percent egg loss. They also noted depth and site-specific differences in egg loss rate as well as predation effects. Understanding the factors that determine egg loss and its magnitude from year to year remains a significant challenge for assessing the abundance of the herring spawning populations and managing fisheries (e.g., DFO, 2021).

COASTWIDE EVOLUTION OF SPAWN ASSESSMENT

Beginning in 1937, the federal fisheries department implemented a comprehensive coastwide program to monitor the annual deposition of herring spawn using Fishery Officers that were stationed widely throughout the BC coast (Hay and Kronlund, 1987). It is likely that there were inter-annual and inter-area variations in the effort and resources directed to the annual surveys but the intent was to monitor all of the herring spawning activity throughout the BC coast. Fishery Officers determined the timing and the extent of each spawning event recording the length, width, and intensity of the egg deposition. Intensity was rated on a scale of 1-5: very light, light, medium, heavy and very heavy (Hay and Kronlund, 1987). A few eggs per blade of eelgrass or rockweed (1-25) was considered light while several layers would be very heavy. In 1969, the 1-5 scale was expanded to a 1-9 scale to allow for intermediate reporting, i.e., very light-light (2) or medium-heavy (6) which had already been occurring in practice (Hay and Kronlund, 1987). The other significant change in recording occurred in 1981 when spawning intensity reporting was replaced by egg layer estimates. However, during the latter 1970s and early 1980s when diving investigations revealed the existence of more subtidal spawn, it is possible that some Fishery Officers may have changed their reporting to reflect this new information. The development and application of dive surveys for herring spawn assessment evolved over two decades and was not fully implemented on a coastwide basis until 1988 so some undetected evolution in surface survey reporting protocols may have occurred. Annual instances of surface-based assessment for remote and some early or late spawning events continue even now. The mid to late 1970s dive studies were focussed on the collection of samples of herring eggs with differing levels of vegetation coverage and egg layers to support the development of a statistical model that could be used to predict egg density from visual observations. The early to mid 1980s studies focussed on developing a statistically rigorous survey protocol, collecting inter-calibration data between divers and surface-based surveys by Fishery Officers, and assessing the logistics of implementing the surveys in large geographical areas. However, during this period of transition, there may have been a tendency in some areas for Fishery Officers to de-emphasize the effort directed at monitoring of spawn deposition since it was being captured in scientific research studies. In the mid 1980s, an effort was made to transfer the dive survey protocols and data collection procedures to Fishery Officers in each area of the coast by including them in the dive survey teams assessing the herring spawning events in their areas but resources for equipment to support the surveys was limited. In addition, during the late 1980s, many Fishery Officers transitioned to an enforcement role away from resource management activities making them unavailable to participate in these surveys. As a result, in the early 1990s, the fishing industry through the Herring Industry Advisory Board allocated a portion of the annual herring total allowable catch to fund a contract for a coastwide diving survey that was administered through the Herring Conservation and Research Society in collaboration with Fisheries and Oceans staff. This model persisted through 2006, when the Supreme Court of Canada in the Larocque decision determined that Federal Ministers could not allocate public resources to fund departmental activities. Subsequently, annual diving surveys have been funded internally by Fisheries and Oceans through an annual contracting process that has been administered by the Herring Conservation and Research Society. Increasingly, First Nations have become involved in the activities associated with the annual herring spawning assessment in their traditional areas. Overall, as a consequence of the myriad of changes, the present-day surveys are focussed on fisheries and therefore have become more concentrated in time and space than was likely the case historically when Fishery Officers in local areas were able to monitor the annual spawning activity over a more protracted period. Hay and McCarter (1999) and Hay et al. (2009, 2011) have reviewed the available spawning records from the past several decades to evaluate the consistency of spawn survey reporting. Indications are that the timing and duration of herring spawning activity appears to have contracted in many areas but it remains unclear whether this is a biological phenomenon or is largely the result of reduced oversight throughout the BC coast due to a shorter more intensely focussed dive survey in support of fishery management. At this time, effort is being made to engage and collaborate with all interested parties: First Nations, the fishing industry, environmental organizations, and citizen science groups to annually identify and assess all herring spawning events throughout the BC coast.

OTHER APPLICATIONS: BIOLOGY, HABITAT, AND FISHERY IMPACTS

The major focus of the surveys of herring spawning beds has typically been for stock assessment to determine abundance and status relative to reference points for resource management. However, because of the intertidal and upper subtidal nature of Pacific Herring spawning and egg deposition, the potential for deleterious effects on the resource due to habitat related impacts such as shoreline development, pollution, or aquaculture are significant. Independently from the stock assessment initiatives described above, Hay and Kronlund (1987) reviewed the surface spawn data and developed a spawn habitat index that reflects the importance of each one kilometer section of the British Columbia coastline as herring spawning substrate (Hay et al. 1989, Volumes I-VI). The frequency and extent of herring spawning in each section of the coast is presented and summarized forming a point of reference for future development proposals, aquaculture siting, and other shoreline alterations. The database that has developed from diver surveys has also provided opportunities to investigate how temporal variation in spawning metrics, especially estimates of egg layers and spawn widths, may change with variation in fishery locations, climate, and population dynamics (Hay et al., 2007, 2009, 2011, 2019) leading to a better understanding of how these factors may influence the productivity and sustainability of the resource. The coastwide monitoring of Pacific Herring spawning activity is a key indicator of the health of the BC marine ecosystems.

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