Recruitment forecasting using indices of young-of-the-year Pacific herring (*Clupea pallasi*) abundance in the Strait of Georgia (BC)

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Within the Strait of Georgia (BC, Canada), recruitment of Pacific herring (*Clupea pallasi*) to the spawning stock at age 3 can be highly variable, and this component may compose a major portion of the spawning-stock biomass. Therefore, a reliable method of forecasting recruitment strength would be useful for determining total allowable catches for the fishery. We developed an empirical approach to forecasting recruitment from young-of-the-year (YOY) surveys using purse-seine sampling in late September and evaluate its predictive capability for estimating the relative size of a year class before it enters the fishery. For each year, we compared YOY catches-by-weight with the number of age-3 recruits derived from subsequent catch-at-age analyses. The relationship is positive but not statistically significant because of considerable annual variation in the estimates. However, it is worth noting that in years when YOY herring were least abundant, the resulting cohort also was low. Consequently, although the relationship may not be sufficiently precise for accurate recruitment forecasting, it can be used by fishery management for the qualitative evaluation of the likelihood of strong or weak returns in future seasons when setting quotas for the fishery.

Keywords: juveniles, Pacific herring, prediction, recruitment, young-of-the-year.

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Introduction

Estimating year-class strength in a timely manner before a cohort recruits to the fishery or the spawning stock has been a topic of great scientific interest and research for over a century, because the accuracy of such estimates is an important consideration in providing management advice that ensures the sustainable harvesting of stocks. Models that forecast recruitment from egg production have been in use for more than half a century (Ricker, 1954; Beverton and Holt, 1957) and have been extended to include various environmental indices for many species (Chen and Ware, 1999), including Pacific herring (*Clupea pallasi*; Stocker and Noakes, 1988; Schweigert and Noakes, 1991). As in many forage species, recruitment in Pacific herring varies markedly from year to year, and good year classes may contribute more than 50% of the total spawning-stock biomass (SSB). Consequently, attempts to forecast recruitment using these models have generally not been sufficiently accurate for use in fishery management. An alternative approach is to make an empirical assessment of the relative abundance of a cohort at some earlier life-history stage before recruitment. It is evident that estimates of egg deposition are not useful predictors. Although surveys of herring spawn provide estimates of the numbers of eggs that will potentially develop into members of the cohort recruiting in 3 years time (Taylor 1964), extensive and variable mortality during egg development precludes accurate forecasts from this life stage. Similarly, surveys of early larval abundance do not provide reliable predictors of future recruitment (Stevenson, 1962; Sætre *et al.*, 2002) because of the substantial mortality during these early stages. Surveys of slightly later life stages, such as late larvae (commonly used in the Northeast Atlantic; Fossum, 1996; Barros and Toresen, 1998; Fox, 2001) or young-of-the-year (YOY) after metamorphosis (Hourston, 1958; Koeller *et al.*, 1986; Axenrot and Hansson, 2003; Gudmundsdottir *et al.*, 2007), offer more promise that abundance estimates of year-class strength are correlated with actual recruitment.

In British Columbia, spawning occurs in early spring, and most herring (>90%) first become sexually mature at age 3. Therefore, the number of age-3 herring is an appropriate index of recruitment to the SSB (Hay and McCarter, 1999). Current stock-assessment methods (Schweigert and Haist, 2008) estimate the numbers and biomass of age-3 fish after recruitment. In the past, a variety of methods have been used to estimate YOY abundance. Hourston (1958) used both visual estimates of the number of herring schools to estimate relative abundance in the Strait of Georgia, and mark–recapture, to census juvenile herring in Barkley Sound. In 1988, we started exploratory surveys using a modified beach-seine fished from a small skiff. Subsequently, a more rigorous survey design to assess juvenile herring abundance, using a small purse-seine, was initiated in 1990 (Haegele, 1997).

We compare the estimated abundance of YOY herring in the Strait of Georgia from these surveys with independent estimates for the same cohorts at age 3 based on a catch-at-age model. The predictive value of YOY estimates is assessed, and we discuss this method in the context of the life history, specifically the variation in spatial distribution and seasonal migrations that may limit, or confound, recruitment forecasts.

Methods

Survey design

The survey was based on ten fixed transects, established at approximately equal intervals around the perimeter of the Strait of Georgia and covering both open coastal areas and channels (Figure 1). Each transect generally comprised 3–5 sampling stations at ~1 or 2 km intervals. Open-coast transects (1, 3, 5, 9, and 11) were established perpendicular to the shore, with the first station lying ~600 m from the high-water mark, generally at ~15-m depth. Transects 2, 4, 6, 8, and 10 were established across channels, with the nearshore stations ~360 m from the high-water mark and also at 15-m depth. Each channel transect had a mid-channel station and, if possible, two stations in between. Overall, station depth varied from <5 to >200 m. Transect 7 in the northwestern section was initially included but subsequently dropped because of its exposure and the inability to sample there regularly. In all 579 sets were made between 1991 and 2007, mostly in mid- to late September, with each survey lasting ~2 weeks. In 1991, two surveys were conducted, one beginning in late August and the other in late September, but only the catches from the first survey were used in this analysis. No survey was conducted in 1995. During 1997–1999, only three stations were sampled on each transect because additional transects in both the Strait of Georgia and Johnstone Strait were added to the survey. However, these additional data were not included in this analysis because there were no replicates. September was chosen for the surveys because it resulted in the lowest bycatch of small salmonids and because, by that time, YOY herring were readily retained by the seine. September was also assumed to represent a point in the life history when much of the extensive early mortality had already been suffered, and therefore this index was expected to represent a relative estimate of ultimate recruitment to the sexually mature population at age 3 (Barros and Toresen, 1998).

Fishing methods and sampling

A purse-seine (220 m long and 27 m deep, with marquisette webbing in the bunt that would retain fish of standard length >3 cm) was fished from three 11–12-m long vessels (RV “Tahlok”, 1991; RV “Keta”, 1992–1994; and RV “Walker Rock”,

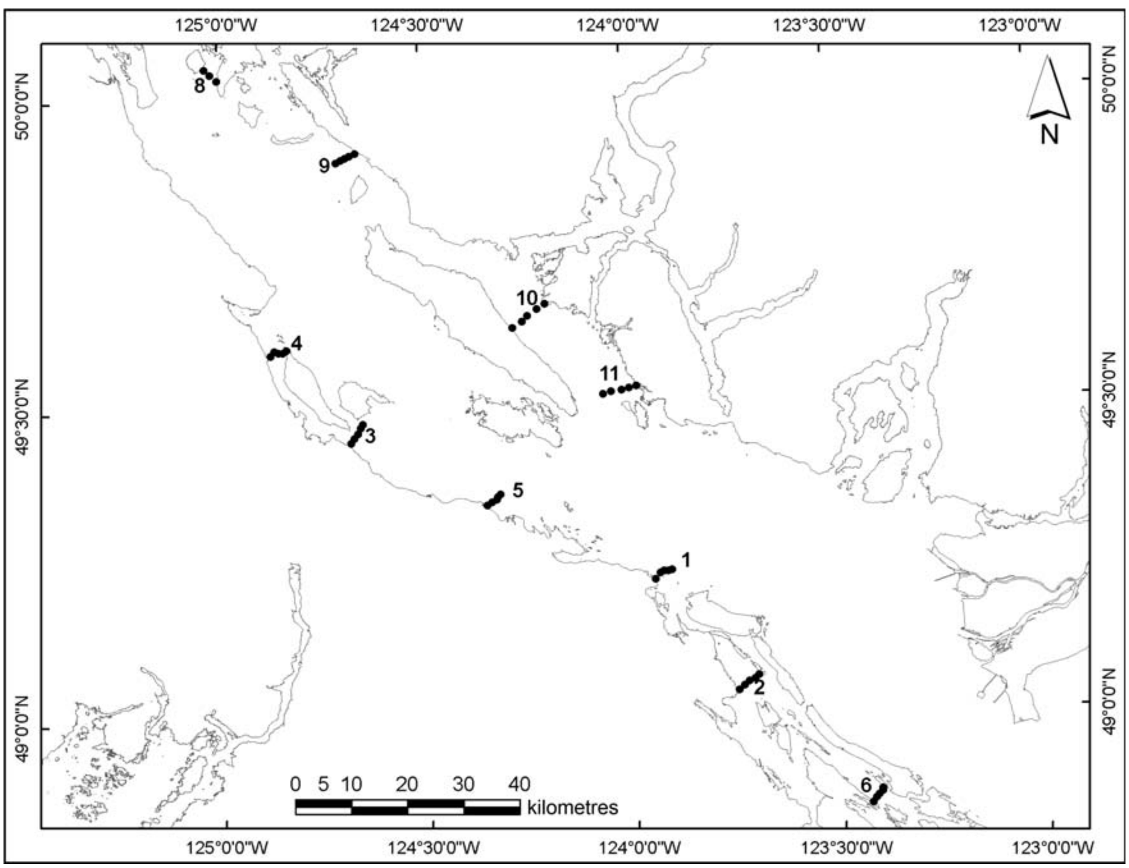

Figure 1. Location of core transects for sampling YOY herring during purse-seine surveys in the Strait of Georgia. Johnstone and Juan de Fuca Straits represent the northern and southern outlets, respectively.

1996–2005). The net sampled an area of $\sim$4000 m^2. The fishing techniques used (e.g. the velocity of pursing and drumming of the net) were kept as uniform as possible within and among cruises. Nevertheless, variation may have occurred owing to differences in wind and tidal currents, as well as to subtle differences in the application of techniques by the responsible captains. All sets were conducted at night, beginning near dusk and continuing to transect completion. In general, one transect was completed over a period of 6–7 h, and no more than one transect was completed each night because of the travel time between transects and the available hours of darkness. The reason for sampling at night was to take advantage of the more homogeneous distribution of herring when feeding near the surface whereas, during the day, the YOY form discrete schools near the bottom (Blaxter, 1985).

After landing, catches were sorted by species and weighed, and samples of herring and salmonids were preserved in seawater formalin for further analysis in the laboratory. Catch weights of herring were determined by age group (YOY, age 1 and age 2+). In practice, it was not difficult to separate these three age groups based on length distribution because their sizes are distinctly different. Although age 2+ may have been made up of several age groups, it generally represented only a very small fraction of the total catch. Except when catches were small and individuals could be counted directly, the number caught by age group in each set was calculated by dividing the catch weight by the age-specific mean weight in the samples taken from that set, as determined during post-cruise analysis. The maximum number from each age class examined was 200 fish per set (Haegele, 1997). Processing included determining the standard length (mm) and total weight (g) of each fish sampled.

An earlier evaluation of the surveys by Hay *et al*. (2003) compared both catch weight and numbers of YOY and age-1 herring in spring and autumn surveys as potential predictors of recruitment, and they found no difference. Based on their findings, we focus entirely on the estimated weight of YOY captured in each set.

Estimates of YOY abundance

The estimated YOY catch weight by station was treated as a random sample from the distribution of all possible set catches, independent of the transect in which it was taken. Although the collection of data was based on a stratified sampling design, with transects representing the strata, Hay *et al*. (2003) found virtually no difference between a weighted mean by transect and a simple average assuming random sampling. Therefore, we based our survey estimates of ln(weight + 1) abundance on the assumption of an underlying lognormal distribution of random samples taken within the survey area (+1 to account for stations with zero catches). We examined the possibility of Poisson, binomial, and negative binomial distributions, but there was no evidence that these resulted in a better fit than the lognormal distribution. The variability in the estimates of the mean YOY catch weight was estimated by bootstrapping the station data independent of the transect, then determining the 2.5 and 97.5 percentiles of the resulting distribution.

Estimates of recruitment

The survey abundance of YOY in year n (1991–2004) was compared with the estimated abundance of age-3 recruits in year $n + 3$, according to the most recently published stock-assessment document (Schweigert and Haist, 2008). As these estimates change slightly yearly (as new data are added to the set and model parameters are re-estimated), we assessed the effects of adding new data on the estimated number of recruits by calculating the standard deviation of the recruitment estimates determined retrospectively. These retrospective estimates were calculated by excluding the last year of data (2007) and re-estimating model parameters to determine the number of age-3 recruits from 1994 to the penultimate year (2006), etc., backwards, until only the 1994 dataset remained.

Evaluation for management

The fishery-management model used for Pacific herring (five stocks assessed annually) in Canada relies on a harvesting rate of 20% of the forecasted SSB in each unit stock if the forecast exceeds a stock-specific threshold. These forecasts rely on a forward projection of the SSB estimated for year t to year $t + 1$, assuming that growth and natural mortality remain constant. This projection requires an estimate of potential recruitment to the SSB in year $t + 1$, which is derived from the historical series of estimates of the numbers of age-3 herring. In effect, three estimates are used, which represent the means of the distribution of the time-series information after it has been broken down into three equal recruitment fractions: poor, average, and good. These means are combined with the projected number of returning adults to provide the managers with a set of three corresponding forecasts of SSB. In practice, the default assumption is average recruitment, unless ancillary information suggests that either a poor or a good recruitment may be more likely.

The relationship between YOY estimates and age-3 recruitment estimates suggests a curvilinear relationship (see Results). To stabilize the variance, a linear model was fitted to the log-transformed data for both estimates of the 1991–2004 year classes, which can then be used to forecast age-3 recruits for each year of the time-series. These recruitment forecasts were cross-referenced to the model estimates from the 2007 stock-assessment document and assigned a poor, average, or good ranking. Finally, the rankings of the two sets of projections were compared.

Results

The size distribution of herring captured in the surveys provides a clear indication of the separation of YOY herring from the older age groups (e.g. Figure 2, data for 2003). Catch weights of YOY herring in individual sets varied between 0 and 1011 kg, whereas the average on individual transects varied between 0 and 212 kg (Table 1). However, the majority of the catches were at the lower end of the distribution, with 72% of the catches being $\leq$5 kg. Between 1994 and 2003, relatively few transects yielded zero catches, suggesting that YOY herring are widely distributed throughout the Strait of Georgia in most years.

The surveys indicate years of high and low abundance, which are anticipated to reflect the variation in subsequent recruitment to the spawning population (Table 2). The temporal trend in the survey estimates is mostly consistent with the trend in the age-3 estimates, although discrepancies may be quite large in some years, particularly 1999 and 2000 (Figure 3). Also, the confidence intervals for some YOY estimates are unusually large (i.e. 1991, 1998, and 2001), but no satisfactory explanation is available.

The relationship between the total catch weight (W) of YOY herring and the recruitment (N) estimates 3 years later (Figure 4a) suggests a curvilinear relationship. After a double-logarithmic transformation (Figure 4b), the relationship

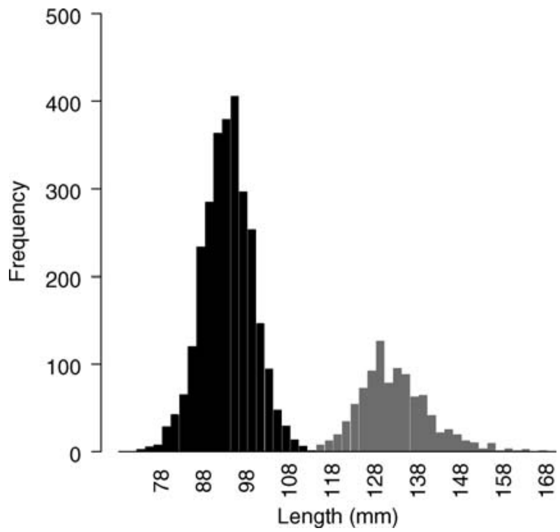

Figure 2. Length–frequency distribution of YOY (black) and older herring (grey) captured during the purse-seine survey in the Strait of Georgia in 2003.

Table 1. Summary of mean catches by weight of YOY herring and the range for transect averages by year (1991–2007).

Year	Mean catch (kg)	Range (kg)
1991	19.8	0.1–53.2
1992	1.5	0–7.0
1993	2.3	0–13.0
1994	7.1	0.003–22.7
1995	No survey	
1996	6.6	0.001–20.6
1997	15.4	0.4–27.2
1998	32.4	0.3–167.0
1999	6.8	0.2–25.2
2000	10.0	0.2–31.6
2001	27.7	0.2–212.0
2002	11.4	0.02–30.2
2003	3.1	0.05–15.3
2004	21.4	0–137.0
2005	0.01	0–0.04
2006	15.7	0.1–34.9
2007	0.01	0–0.04

Table 2. Estimates of age-3 recruit abundance ($R_{\text{age-3}}$; $\times 10^{-6}$) from catch-at-age analysis (1991–2004) and mean catch (W in kg) of YOY herring in surveys (1991–2007), with the associated predictions of age-3 recruitment ($R^*_{\text{age-3}}$; $\times 10^{-6}$) and classifications (G, good; A, average; P, poor).

Catch-at-age analysis			YOY survey		
Year class	$R_{\text{age-3}}$	Classification	W	$R^*_{\text{age-3}}$	Classification
1991	1 233	A	19.8	1 360	G
1993	982	A	2.3	889	A
1994	1 424	G	7.1	1 109	A
1995	1 530	G	No survey		
1996	755	P	6.5	1 092	A
1997	1 127	A	15.4	1 294	A
1998	1 245	A	32.4	1 501	G
1999	1 827	G	6.8	1 100	A
2000	2 202	G	10.0	1 188	A
2001	1 470	G	27.7	1 454	G
2002	1 308	G	11.4	1 219	A
2003	863	A	3.1	943	A
2004	1 025	A	21.4	1 382	G
2005	–	–	0.01	301	P
2006	–	–	15.7	1 298	G
2007	–	–	0.006	272	P

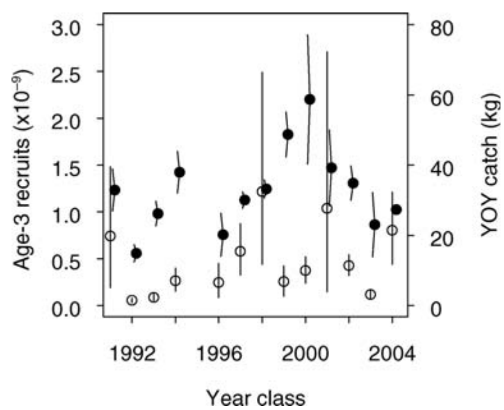

Figure 3. YOY herring abundance (open circles) and number of age-3 recruits (dots) by year of birth. The 95% confidence intervals were calculated by bootstrapping (surveys) or retrospectively (catch-at-age analysis).

$\ln(N_{\text{age}-3}) = 6.622 + 0.199 \ln(W_{\text{YOY}})$ proved not to be significant at the 5% level ($r^2 = 0.28$), whereas fitting a semi-logarithmic curve yielded similar results. To investigate whether this relationship might still be used for management, the predicted recruitment at age 3 was then ranked as good, average, or poor according to the standard procedure (Schweigert and Haist, 2008). The breakpoint between poor and average year classes is ~860 million fish, and between average and good year classes ~1300 million fish. Although the two ranks only agree exactly in 4 years, the predicted ranking is equal to, or less than, the ranking based on the catch-at-age analysis in 8 of 12 comparisons. Therefore, the prediction provides a conservative assessment of the next recruiting year class that could be used in making harvest recommendations. The correspondence between the predicted and "observed" recruitment class since the introduction of the YOY surveys also reflects consistency in the average recruitment levels over the course of the entire 1951–2007 time-series used to generate the poor, average, and good rankings. In other words, there has been no trend in recruitment over time that would bias the estimated breakpoints between the recruitment classes. A good test of the model predictions will be the assessment of the apparently poor year classes produced in 2005 and 2007, which recruit in 2008 (already observed to be poor) and 2010, respectively.

Discussion

An understanding of the factors affecting survival from the egg to the recruit stage is basic to the management of Pacific herring (Taylor, 1955) and has been the focus of research for many decades. As Pacific herring are short-lived and available to the fishery for only 4 or 5 years, the abundance of the recruiting year class has a substantial impact on the size of the run: a good

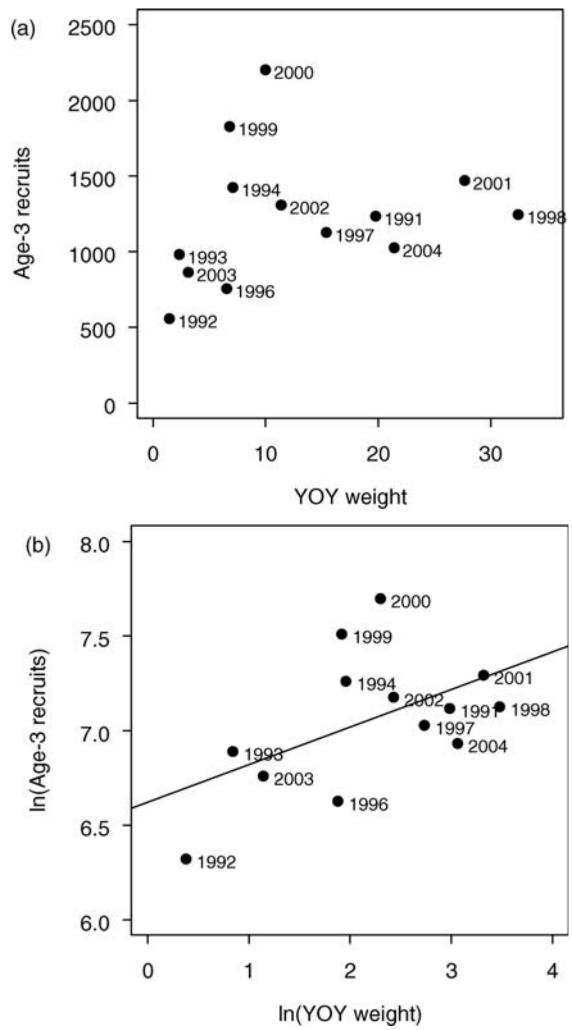

Figure 4. Estimates of age-3 recruits from catch-at-age analysis vs. YOY catch weight from surveys: (a) on a linear scale; and (b) on a double-logarithmic scale.

year class may double the abundance of the SSB, whereas poor recruitment may decrease run size by more than 50%. Therefore, a better understanding of natural mortality during the first year of life would increase the ability to provide an estimate of the size of a cohort ~30 months before its actual recruitment to the fishable stock at age 3, which could lead to better management and enhance the economics of the fishery. Such a prediction (even if only relative in terms of poor, average, or good) would provide guidance about the approximate size of the recruiting cohort at least 2 years before the fishery. Unfortunately, given the current understanding of the factors affecting early survival, analytical predictions of recruitment have not been particularly successful (Stocker and Noakes, 1988; Schweigert and Noakes, 1991; Chen and Ware, 1999). Empirical predictions as presented here may not always be correct, but they are generally conservative (8 of 12 years; Table 2) and thus consistent with a precautionary approach to management. The model predictions currently available cannot be considered reliable. Clearly, the benefits of further improvements would be substantial, even if the prediction were accurate only to the three-tiered range (poor, average, or good). For example, a reliable prediction of "poor" recruitment would provide a risk-averse method for adjusting annual catches. Also, it follows that the fishery would benefit when good recruitment—and hence good fishing opportunities—could be anticipated. Such a three-tiered approach to recruitment predictions could be readily incorporated into the present stock-assessment process in British Columbia.

The empirical approach for forecasting recruitment also raises interesting biological questions. For example, purse-seine sets captured YOY herring along all transects, although they were "set blind" (i.e. without any reference to acoustic targets or other indicators of the presence of herring). This corroborates earlier observations by Taylor (1964) and subsequent reports by Haegele (1995, 1997) that juvenile herring are ubiquitous in the Strait of Georgia and are vulnerable to seine gear when near the surface after dark. In addition to the core transects reported here, additional transects in offshore areas have been sampled in a few years, yielding substantially fewer herring than inshore. The surveys also confirm that YOY distribution and density vary substantially in both space and time. Catches varied among sampling stations by several orders of magnitude (from zero to tens of thousands of fish), whereas zero catches were few. No obvious spatial patterns emerged, but some transects (2, 4, 9, and 10) had consistently larger catches than others. Sometimes other species, notably juvenile salmonids, were abundant and may have displaced or reduced local herring densities.

A basic consideration when using YOY surveys as a basis for forecasting recruitment is that the sampling design should provide an unbiased relative index of the abundance and that there is an implicit assumption about interannual consistency in the timing of the migration pattern. To be effective as a recruitment forecasting tool, surveys must take place before large-scale migration from the sampling area. The timing of migration of YOY herring out of the Strait of Georgia to other feeding areas is not well understood. The juvenile surveys conducted by Haegele (1997) provide the best evidence that many YOY and older herring (age 1) overwinter in the Strait and spend at least part of their second summer there. These same surveys, however, indicate that the abundance of older herring declined towards the end of their second summer. Therefore, during the autumn period, most age-1 and older herring either migrated out of the Strait or to areas where they were not vulnerable to the sampling gear depending on their age. Additionally, Haegele *et al.* (2005) conducted some seine sampling in Johnstone Strait during 1998 and 1999 and found substantial quantities of YOY herring that may have been spawned in the Strait of Georgia. It appears that these fish had either migrated from the Strait of Georgia or were in the process of migrating from Johnstone Strait. Such migrations could bias survey results if their extent and timing varied markedly from year to year, but because the origin of these fish could not be determined, it is not possible to assess the potential bias. For example, YOY estimates of the 1999 and 2000 year classes differ markedly from the estimates at age 3 (Figure 3). These discrepancies could be a result of differential movements of fish in or out of the Strait as well as of variable environmental impacts on fish distribution and survival at the time of the surveys.

Another critical assumption in the methodology used is that age-3 recruits as estimated by the catch-at-age model are a true reflection of the actual year-class abundance. Based on tagging data and offshore survey analyses, most herring from the Strait of Georgia migrate to the west coast of Vancouver Island to feed offshore, and presumably mix with herring originating from the west coast or from other locations, such as Washington State, before returning as adults to spawn in the Strait of Georgia. Although we cannot be certain that all herring return, available tagging data (Hay *et al.*, 2001) indicate that the rate of straying, when examined among the same large geographical units used for stock assessment, is quite low and should not substantially affect the comparison.

Implicit in the survey design is the assumption that the approximate strength of each year class is established at or before the time of the survey. Recruitment to the mature stock is ~36 months after spawning, whereas the YOY in September are only ~6 months of age. Therefore, the YOY surveyed have only lived ~17% of their lives between hatching and recruiting. Barros and Toresen (1998) present evidence for two distinct patterns of survival in Norwegian spring-spawning herring and considerable variation in the pattern of year-class formation. Undoubtedly, the potential for greater variance is in larger cohorts, where an apparently strong cohort at 6 months of age may, or may not, maintain its strength during the remaining period until it recruits. On the other hand, and consistent with observations of Atlantic herring (Sætre *et al.*, 2002), a cohort that is weak at an early stage is unlikely to develop into a strong cohort. Various external factors could impact recruitment after juveniles have migrated offshore and before they join the spawning stock. In the Barents Sea, Barros and Toresen (1998) found that abundance of cod (a main predator on Atlantic herring) and availability of capelin (as alternative prey) had an important influence on survival and recruitment. Similarly, juvenile Pacific herring are a common item in the diet of hake (Ware and McFarlane, 1989), and the sudden appearance or departure of hake may have a major impact on the survival of an initially strong cohort. Other studies on Atlantic herring have attempted to link recruitment to sea surface temperature, but so far the mechanism involved has remained unclear (Fiksen and Slotte, 2002; Sætre *et al.*, 2002).

Clearly, a substantial number of factors could affect the observed relationship between YOY abundance, as seen during the survey conducted at the end of their first summer, and subsequent recruitment to the spawning stock 3 years later, which may account for the large variability around the predictive relationship established here. Nevertheless, the covariation between the two variables is positive and appears to be of sufficient strength to permit prediction of herring recruitment for application in fishery management. Increasing the effort, or enhancing the surveys with acoustics, may further improve their predictive capability. Consequently, there is good reason to continue the juvenile herring surveys in the Strait of Georgia, as well as investigating their applicability as a management tool in other stock-assessment areas.

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