ISSN: 0074-7246

INTERNATIONAL PACIFIC HALIBUT COMMISSION

ESTABLISHED BY A CONVENTION BETWEEN
CANADA AND THE UNITED STATES OF AMERICA

Scientific Report No. 68

Sampling Pacific Halibut (*Hippoglossus stenolepis*) Landings for Age Composition: History, Evaluation, and Estimation

by

Terrance J. Quinn II, E.A. Best,
Lia Bijsterveld, and Ian R. McGregor

SEATTLE, WASHINGTON
1983

The International Pacific Halibut Commission has three publications: Annual Reports (U.S. ISSN 0074-7238), Scientific Reports, and Technical Reports (U.S. ISSN 0579-3920). Until 1969, only one series was published (U.S. ISSN 0074-7246). The numbering of the original series has been continued with the Scientific Reports.

INTERNATIONAL PACIFIC HALIBUT COMMISSION
P.O. BOX 95009, UNIVERSITY STATION
SEATTLE, WASHINGTON 98105, U.S.A.

Sampling Pacific Halibut
(*Hippoglossus stenolepis*)
Landings For Age Composition: History, Evaluation, and Estimation

by

Terrance J. Quinn II, E. A. Best
Lia Bijsterveld[1], and Ian R. McGregor

Contents

[1]Current address: Department of Fisheries and Oceans
1090 West Pender Street, Vancouver,
British Columbia, Canada V6E 2P1

FOREWORD

This report continues the series of reports documenting the procedures used by the International Pacific Halibut Commission (IPHC) for data collection and analysis. The sampling procedure was evaluated in 1979-1981 and several changes were inaugurated to improve the statistical reliability of the information collected. This report presents a historical overview and a critical evaluation of aspects of sampling commercial landings of Pacific halibut.

ABSTRACT

Sampling landings for age composition of the Pacific halibut catch has been a major activity of the International Pacific Halibut Commission (IPHC). Results from a recent investigation of the sampling design and estimation framework are presented. A historical review of sampling designs used by IPHC concentrates on selection of ports, vessels, and fish for sampling. These selection criteria are evaluated in terms of current sampling needs, resulting in changes which improve the representativeness of the sampling. The improvements include the proportional allocation of sampling effort for months, regions, and size of vessel landings, concentration on the month-region as the stratum choice, and adjustments in ports for sampling, sampling rates, and sample sizes for length and age. A thorough review of the prediction systems used by IPHC is given. Otolith measurements have been used to predict the length and weight of each fish in samples. Techniques for processing otoliths and for aging are described.

Mathematical formulae are presented for estimation of catch in numbers, age composition, and average weight at age of fish in the catch within a month-region stratum. Two techniques are evaluated for combining estimates across strata: project-and-add and add-and-project. The project-and-add method is shown to be unbiased but more variable than the add-and-project method. However, the add-and-project method is biased unless certain conditions are met. In application to Pacific halibut data, these conditions are not met, and hence, the project-and-add method is preferred. A comparison of age composition estimates from the project-and-add and add-and-project methods is given for IPHC regulatory areas between 1975 and 1980. Sampling criteria are defined to achieve specified levels of relative precision of age composition estimation within each stratum, and corresponding sample size requirements are obtained. It is shown that relative precision of combined-strata estimates is at least as high as for within-stratum estimates.

Sampling Pacific Halibut
(*Hippoglossus stenolepis*)
Landings For Age Composition: History, Evaluation, and Estimation

by

Terrance J. Quinn II, E. A. Best
Lia Bijsterveld, and Ian R. McGregor

INTRODUCTION

Collection of detailed information about the activities of the halibut fishing fleet and the composition of the commercial landings is one of the primary functions of IPHC. The accumulated data on size and age composition from sampled landings is extensive, dating back to 1933. Data from the landed catch are not necessarily representative of the fishable stock or the halibut population as a whole for several reasons. Halibut may exhibit some segregation by size or sex from one fishing ground to another; secondly, the gear used in the fishery is selective in respect to size of fish caught. Size limits and price structures also may influence the size composition of the landed fish. Research cruises are used to obtain information on actual catch and supplement the data from landed catch. The above elements have changed over the years to produce variable effects upon estimates of the fishable stock. Nevertheless, information on age composition continues to be an essential part of the evaluation of population abundance, age structure, recruitment, growth, and mortality.

In recent years, mathematical methods have been developed to convert age composition from landings to the actual halibut population. Annual estimates of population abundance, biomass, and surplus production are obtained from cohort analysis of age composition and average weight data (Hoag and McNaughton 1978). Other techniques for estimating abundance which rely on age composition data are being incorporated into IPHC's evaluation of the halibut population (Quinn et al., in press). Hence, investigation of the validity of the sampling design and of the accuracy and precision of age composition estimation is necessary to provide accurate management advice. Also, recent management decisions to establish smaller regulatory areas (IPHC 1982) require more intensive sampling of areas where halibut are fished commercially.

The first purpose of this report is to document the sampling designs used by IPHC, which updates earlier work by Hardman and Southward (1965) and Southward (1976). A historical review of the IPHC sampling program is included in this report for the purpose of continuity and to put recent changes in design in perspective. The second purpose of this report is to establish rigorous procedures for evaluating the representativeness of the sampling design and for estimating age composition of the landed catch. Using results from Southward (1976) as a basis for elaboration, this report provides derivation of age composition estimators, formulae for average weight at age, contrast of methods for combining data, further evaluation of sample size requirements, and application to a wider range of data.

Halibut occur in the northeastern Pacific Ocean from California to Alaska and into the Bering Sea. The entire coast has been divided into 60-mile wide statistical areas for analytical purposes and landings are assigned by time intervals to appropriate

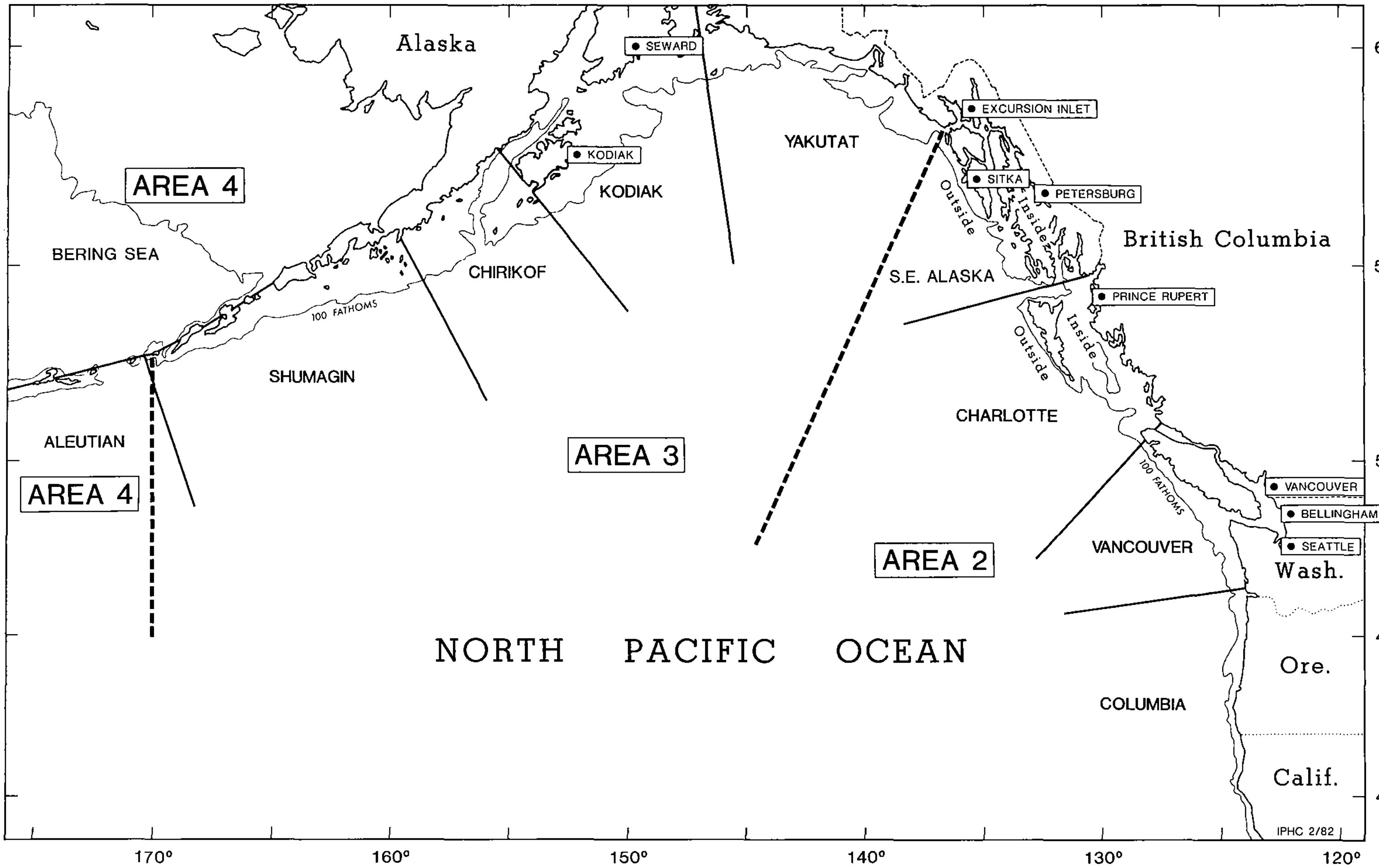

Figure 1. **Geographic regions, IPHC regulatory areas in 1981, and ports sampled in 1981.**

locations based on fishermen's logbook information (Myhre et al. 1977). The catch from the various statistical areas can be combined as needed. The current sampling plan utilizes a month-region concept, whereby the landings each month from appropriate statistical areas are combined into geographic regions, shown in Figure 1. Regions are then combined into Regulatory Areas 2, 3, and 4 for management purposes (Figure 1).

HISTORY AND EVALUATION OF SAMPLING DESIGN

PORT SELECTION

The first aspect considered in this evaluation of sampling design is the choice of ports to station field personnel. It is not practical to sample the catch at sea because of the large number of boats in the fishery. The ideal combination of ports for sampling would provide landings from all major fishing regions. Practical considerations such as safe working conditions and availability of accommodations for personnel are also important.

Historically, ports that account for a significant proportion of the catch have been sampled. IPHC began sampling landings for age composition in 1933 in Seattle, where IPHC's headquarters are located. Seattle's importance as a halibut port declined, due to improvements in cold storage and transportation facilities in Alaska and British Columbia. A comparison of the percentages of landings at ports in the 1930's and

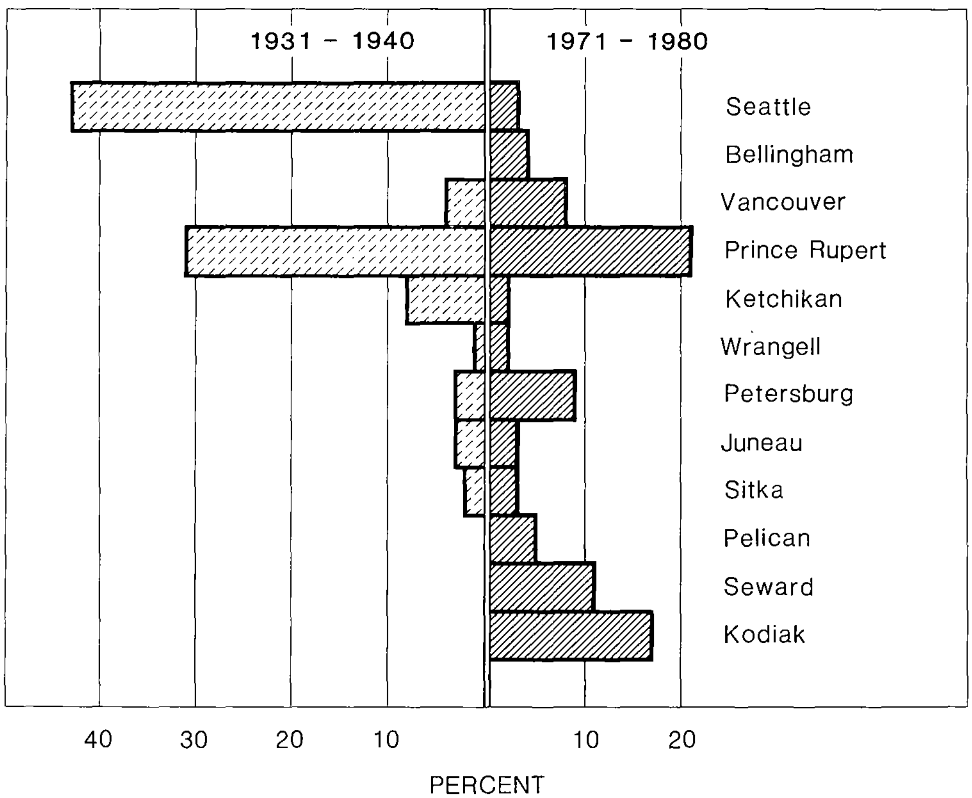

Figure 2. Percentage of total landings delivered at sampled ports for the periods 1931-40 and 1971-80.

1970's demonstrates the shift to more northern ports (Figure 2). The ports of Prince Rupert and Vancouver, British Columbia were added in 1949 and 1951, respectively, to improve the representation of landings from the Charlotte-Inside region. As the percentage of landings in Alaska increased, the sampling program was expanded to Petersburg in 1958, Ketchikan in 1963, Kodiak in 1969, Juneau in 1972, Seward, Sitka, and Pelican in 1973, and Homer in 1978. Ketchikan, Juneau, Pelican, and Homer are no longer sampled either for practical reasons or because of insufficient landings.

We evaluated the combination of ports for sampling in 1980 shown in Figure 1 (except Excursion Inlet) by examining the distribution of landings across ports and regions of fishing for recent years. We found that over 75% of the total catch was landed at those ports and that, generally, samples were obtained from most regions. However, we found that some fishing grounds in S.E. Alaska-Inside were undersampled and added the port of Excursion Inlet (shown in Figure 1) in 1981 to alleviate the problem. The distribution of landings is quite variable from year to year, which suggests that annual review of port selection and personnel needs is desirable.

VESSEL SELECTION

The second aspect of sampling design is the selection of vessels to be sampled at each port. Vessels should be selected in proportion to their presence in the fishery, according to criteria such as gear type, trip size, area of fishing, and any other factors thought to influence the length distribution of fish in the catch. These factors are controlled by randomization of vessel selection.

When the sampling program began in 1933 most of the vessels landing in Seattle sold their catches through the Seattle Fish Exchange (McNair 1982). A Commission representative determined the fishing region, "purity" of the trip to that location, and the processing plant at which the vessel would be offloaded. On the basis of this information vessels were chosen for sampling. As the sampling program expanded to cover more ports, vessels were selected more on the basis of plants that could accommodate the sampling crew than on the basis of grounds fished, although the plants received a broad spectrum of landings as far as the origin of the catches was concerned. No definite guidelines were set down for selecting trips to be sampled, except that they be from a single ground and large enough to provide a "good" sample.

In 1974 the size of the landing became an important selection criterion. In most ports it is a common practice for a fisherman to "hail" or notify buyers of the amount of fish for sale aboard the vessel, referred to as the "trip size." This advance information is used to secure samples from different trip sizes, because the trip size has provided a basis for obtaining samples from different fishing grounds. It is generally true that small trips were secured by smaller vessels fishing close to the sampling port, while the larger trips came from the high seas fleet, which has the capability of staying at sea longer and fishing farther from port. From 1974 to 1979, the sampling rate was 1/10 of the vessels landing 1,000 to 4,999 pounds and 1/3 of the vessels landing over 5,000 pounds. The 1/10 sampling rate of the smaller trip size class is about as large as is practical to sample because of the high frequency of smaller trips. Trips under 1,000 pounds are ignored, because they represent a minor portion of the catch.

In our evaluation of vessel selection, we established the principle that the same proportion of fish should be sampled from each trip size category at each port, so that the collected samples among ports for a region would be representative of the region's catch. The sampling rate of fish in the catch is determined by the sampling rate of vessels and the sampling rate of fish in a vessel, either of which can be adjusted to obtain a specified sampling rate of fish in the catch. Since 1980, the trip size class of 5,000 pounds and over has been further subdivided into the following categories: 5,000 to 14,999 pounds, 15,000 to 39,999 pounds, and 40,000 pounds and over to prevent personnel from selecting smaller trips for sampling. An attempt is made to sample 1/3 of the vessels from each trip size category, thus assuring that all trip sizes are represented in the samples. Also, since 1980 the sampling rate of vessels with a trip size of 1,000 to 4,999 pounds has been increased to 1/9 to sample the same proportion of the fish in the four trip size classes, as shown in the next section. These changes have enhanced the representativeness of the sampling procedure, in regard to region of origin.

If the region of origin of a fishing trip could be determined in advance, it would be advantageous to develop a sampling procedure based on obtaining an optimal number of samples from a region. In practice, the origin of the trip is not known until after the sample has been obtained. Thus, our sampling design is based on obtaining the same proportion of samples among trip size classes and regions.

For biological reasons sampling should ideally occur consistently throughout the season. This was possible prior to 1977 when the fishing season was continuous though varying in number of days over a period of years. Vessels fished for varying lengths of time and after unloading remained in port for a voluntary "lay-up" or rest period between fishing trips. The lay-up spread landings throughout the season, making it easy to maintain the sampling rate. In 1977, the voluntary lay-up ceased and the IPHC initiated open fishing periods alternating with closed periods. This changed the landing patterns from fairly uniform through time to large numbers of landings coinciding with the end of a fishing period. The large number of landings at the end of the fishing period made a constant sampling rate difficult to maintain. Consequently, landings are purposely oversampled at the beginning of a fishing period to compensate for the undersampling at the end of the fishing period.

FISH SELECTION

The third aspect of sampling design is the procedure for sampling fish from a vessel landing. Sampling the landings has inherent problems. The fish average 30 to 40 pounds with some individual fish weighing over 200 pounds. The unloading usually occurs in a limited space at a pace determined by the unloading crew which the sampling must not disrupt. In addition, sufficient fish must be sampled to adequately represent the size composition of the landing being sampled.

Halibut are eviscerated and iced at sea and delivered to the processing plant "dressed, head-on." The halibut are removed from the vessel by means of large cargo slings (Figure 3a). Two or three fishermen work in the hold of the vessel filling the slings; therefore, halibut in any given sling are taken from several locations in the hold, thereby disrupting any segregation by size of fish or time caught, which may have existed.

The fish are usually unloaded from the fishing vessel onto a heading table where the fish are beheaded either by hand (Figure 3a) or machine (Figure 3b). To collect length measurements and otoliths for age determination, the fish must be intercepted prior to the heading process, after which accurate measurement is impossible and which also often destroys the otic capsule and otolith.

Although not important in sampling design, the number of fish placed in a sling and the speed of unloading influence the success of sampling. The number of fish in a sling depends on the actual size of the fish-hold opening of the vessel, the capacity of the hoist, the average weight of the fish, and what part of the hold has been unloaded. In

Figure 3a. Sling of halibut and hand heading of fish.

1980, the average sling weight varied from less than 500 pounds to over 1,500 pounds. The average number of fish in slings varied from less than 5 to 40 fish. If a sling to be sampled contains a large number of fish, it is sometimes difficult to sample all fish in the sling before the next sling arrives.

The speed of unloading varies a great deal as well. At plants with limited unloading space, the selected slings must be sampled before the next sling arrives or else fish to be sampled will become mixed up with others. From data collected in Prince Rupert in 1978, the time available to sample the fish ranged from 13 to 28 seconds per fish. Other plants unload at a faster rate but some have provided IPHC samplers with additional space to isolate the selected slings and reduce interference with the unloading.

The original sampling plan called for obtaining a large number of length measurements and smaller subsample of otoliths for age determination. Fish for measurement and otolith removal were selected by the "grab method" where as many fish as possible were grabbed, or partitioned off, as the fish were unloaded. The grab technique assumed that the sampler chose fish randomly, although in practice the potential for personal bias was considerable.

As an alternative to the grab sample, the "sling sample" technique was developed (Southward 1976), which utilizes the clustering effect and identifiable character of the sling and requires that every fish in the chosen sling be used. Southward (1976) tested the representativeness of the sling sample and grab sample techniques with respect to a

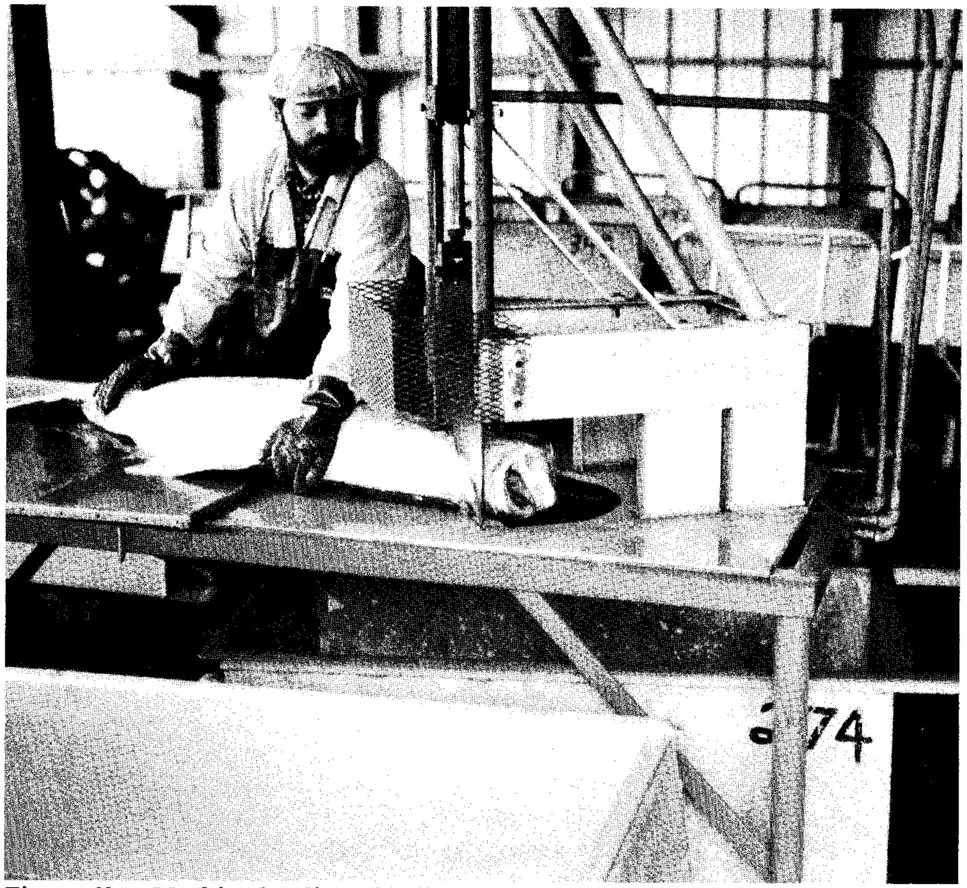

Figure 3b. Machine heading of halibut.

vessel's catch using data from 14 commercial landings plus 2 research cruises. Although the test did not show pronounced differences between sling and grab samples, the potential for bias was evident in the grab sample. Sling sampling was adopted in 1973 as the standard within-vessel sampling technique. Under this system, slings are selected for sampling at a specified frequency and all fish in the selected sling are sampled.

Southward (1976) determined that 200 fish from the vessel would be an adequate sample if taken randomly using the sling sample method. However, this often resulted in the entire 200 fish being collected from the first part of the delivery.

A system of choosing slings was established in 1978, which distributed the sample over the entire load of fish. Up to 200 fish from a vessel were sampled as follows: the number of slings of fish to be sampled from each trip varied with the trip size and the expected average size of the fish. For vessels with trips originating in Regulatory Area 2, the following schedule was used to determine the frequency of slings to sample:

Trip Size (Pounds)	Frequency of slings
Under 6,000	Every sling — all fish
6,000 - 12,000	Every sling to 200 fish
12,000 - 18,000	Every other sling to 200 fish
18,000+	Every third sling to 200 fish

For vessels with trips from Regulatory Area 3, the schedule was:

Trip Size (Pounds)	Frequency of slings
Under 10,000	Every sling — all fish
10,000 - 20,000	Every sling to 200 fish
20,000 - 30,000	Every other sling to 200 fish
30,000+	Every third sling to 200 fish

The average size of fish in Area 2 is generally smaller than in Area 3, and hence a given sling contains more fish in Area 2. In both areas, sampling continued through the sling with the 200th fish in the sample or until the trip was completely unloaded.

In 1979, the sample goal remained 200 fish but frequency of sampled slings was altered so that sampling continued until nearer the end of unloading. The size of the landing determined the frequency of sampled slings. This reduced the possibility of the sample not representing the trip in cases where the larger or smaller fish might have been unloaded first.

In our evaluation of fish selection, we uncovered some problems with this system. The proportion of fish sampled increased as trip size decreased and resulted in all the fish being sampled from the smaller trips. From larger trips some samples still came from the first part of the trip unloaded, which may not have represented the total trip. The major problem was that when the samples were combined the smaller trips contributed proportionally more fish measurements than their landed weight in pounds justified.

A common characteristic of the sampling programs prior to 1980 was the emphasis on obtaining a representative sample from each individual landing chosen for sampling. In the course of our evaluation, the emphasis shifted to obtaining a representative set of samples for a month-region stratum, which would be properly weighted when pooled together. The former goal of obtaining 200 fish per sample was dropped in favor of a sampling strategy which sampled trips proportionally to trip size. This involved adjusting the vessel and sling sampling rates for each trip size category within each stratum to obtain the identical proportion of catch sampled:

Trip Size (pounds)	Vessel Sampling Rate	Sling Sampling Rate	Proportion of catch in sample
Under 1,000	0	0	0
1,000 - 4,999	1/9	1/2	1/18
5,000 - 14,999	1/3	1/6	1/18
15,000 - 39,999	1/3	1/6	1/18
40,000+	1/3	1/6	1/18

The overall sampling rate is one-eighteenth (5.6%) of the fish from trips over 1,000 pounds. The actual sampling rate, however, is about 3% of the fish in the total catch because some vessels unload at ports without samplers and trips of less than 1,000 pounds are not sampled.

Area 4 (the Bering Sea and Aleutians) is treated as a special case, because total landings are small. The overall sampling rate is set at 1/3 to obtain adequate data, with the vessel sampling rate equal to 1/1 and the sling sampling rate equal to 1/3.

Table 1. Overall Sampling Rates in 1975 and 1981.

Region*	1975 Estimated No. Fish in catch	1975 No. Oto. in sample	1975 % Oto.	1981 Estimated No. Fish in catch	1981 No. Oto. in sample	1981 % Oto.
Columbia	1481	—	—	2272	—	—
Vancouver	30458	892	2.9	20308	593	2.9
Charlotte Outside	25082	2020	8.0	25499	831	3.3
Charlotte Inside	157619	6765	4.3	189624	5678	3.0
S.E. Alaska Outside	55685	4300	7.7	32424	336	1.0
S.E. Alaska Inside	113434	6666	5.9	99189	1706	1.7
AREA 2	383759	20643	5.4	369316	9144	2.5
Yakutat	91432	4949	5.4	171364	2692	1.6
Kodiak	153578	7569	4.9	209695	4787	2.3
Chirikof	51645	3414	6.6	9697	783	8.1
Shumagin	14727	165	1.1	1848	—	—
AREA 3	311382	16097	5.2	392604	8262	2.1
Aleutian	121	—	—	5578	1437	25.8
Bering Sea	16062	1449	9.1	28684	1895	6.6
AREA 4	16183	1449	9.0	34262	3332	9.7
TOTAL	711324	38189	5.4	796182	20738	2.6

*See Figure 1.

We developed a system of systematic sampling of slings for within-vessel sampling. The selection of the first sling to be sampled is done by the role of a single die. An odd or even number specifies the first or second sling for sampling for trip sizes of 1,000 to 4,999 pounds and every other sling after that. For larger trip sizes the number rolled (1 to 6) selects the first sling to be sampled and thereafter every sixth sling is sampled throughout the unloading process.

OVERALL SAMPLING RATE

The objective of the sampling program is to obtain representative samples of the catches to estimate the age composition for each month-region stratum. If the sampling design were followed exactly, then the overall sampling rate would be identical across strata. To evaluate the effectiveness of the sampling changes with respect to the sampling rate, two years will be reviewed. In 1975, vessels landed continuously throughout the fishing season. Depending on the trip size and area of origin, slings were sampled at different rates until approximately 200 otoliths were collected. In 1981, the current program of systematic sampling of slings throughout the landing was in effect. The percentage of the total catch sampled from each region for the two years is given in Table 1. For 1975, the sampling rate equaled 5.4% of the estimated total number of fish caught. In 1981, this dropped to 2.6% due to the change in the sampling procedure. In neither year is the sampling rate constant over regions, probably due to variability in landing patterns and to the need for a higher sampling rate from regions with little catch. However, there is less deviation from the average for 1981 data.

Generally, the changes in the sampling program have enhanced the representativeness of sampling, while reducing the sample size. The sampling program prior to 1980 resulted in a higher proportion of otoliths being collected from smaller landings. Landings from certain regions at certain ports, primarily from Area 2, were consistently small and the 200 otolith per sample requirement set sampling rates at a very high level. With the current program, ports with small trips produce fewer sampled fish. The current system facilitates the sampling while increasing the representativeness of the sample. The overall sampling rate for all trip sizes from all areas is more uniform because the sampling rates are set for trips stratified by trip size categories. However, the goal of exact proportional sampling of strata has not been achieved in practice.

FISH MEASUREMENTS

Actual Fish Lengths

The sampling program in terms of fish measurements progressed from actual fish measurements to systems based on predictions from otolith (earbone) measurements (Hardman and Southward 1965). Actual fish measurements required three or four people for each sampling crew. When sampling was conducted only in Seattle, the Commission's headquarters, adequate personnel were available. However, with the extension of sampling to northern ports, a streamlining of the sampling technique was needed. The streamlining has evolved into a procedure for estimating the length and weight of an individual fish from the weight of its otolith. Instead of measuring each fish, the present technique is to open the otic capsule, remove the otolith, and place it in a container strapped to the wrist (Figure 4). The length of each fish is calculated at the home office. Two samplers are usually required to take otoliths from all fish in a designated sling in the time available.

Predicted Fish Lengths from Otolith Measurements

During the developmental period, such non-body lengths as head length and preopercle length were tested. McIntyre (1953) established a head-length/fork-length relationship for West Icelandic halibut. IPHC examined the head-length/fork-length

Figure 4. Removing otolith from halibut and storing in container.

relationship, as well as the preopercle length. These relationships were not pursued because an otolith-radius/fork-length relationship was established for Pacific halibut (Southward 1962).

Otolith Radius Method

The use of the otolith-radius/fork-length relationship in 1963 to calculate fish length, eliminating the collection of length measurements, was a logical development, since it was already necessary to collect otoliths for aging. By this method one person, unencumbered by equipment except a knife, forceps, and a small plastic container, could obtain a collection of otoliths during the unloading of a vessel. The number of field personnel could be reduced or dispersed to collect samples from several landings per day within one port.

In the laboratory the radius of each otolith was measured from a projected image enlarged to 20 diameters. The otolith radius measurements were converted into fork-length measurements using the relationship:

$$\ell n(Y) = -1.32086 + 1.30795\ \ell n\ (X)$$

where Y = fish length (cm), X = radius of the left otolith (mm) (Southward 1962), and ℓn is logarithm to the base e.

Otolith Length Method

Measuring the radius was slow and tedious and it was often difficult to locate the nucleus of the otolith. An obvious extension of the otolith radius technique was to determine a relationship between fish length and the more easily measured otolith length. In 1968 the following relationship between halibut length and otolith length was established:

$$\ln (Y) = -1.223460 + 2.259208 \ln (X)$$

where Y = fish length (cm) and X = length of the left otolith (mm) (Southward and Hardman 1973).

The regression used in the analysis of length and age data from 1968 to 1970 was found to overestimate the fish length from larger otoliths and underestimate the fish length from the smaller otoliths (Southward and Hardman 1973). To improve the relationship, paired measurements of otolith and fish lengths were selected from four broad geographical regions encompassing the commercial range of Pacific halibut: British Columbia, southeastern Alaska, the Gulf of Alaska, and the Bering Sea. The halibut ranged in size from 10 to over 200 cm. Otoliths were measured along the longitudinal axis to the nearest 0.01 mm with a machinist's dial-reading caliper. The relationship between otolith length and fish length was nonlinear. A logarithmic transformation of both variables showed that the transformed data also were not described by a straight line. A third degree polynomial equation was fitted for each geographical region because of the curvature in the scatter of the transformed data.

The regression equations for the different regions were:

British Columbia

$$\ln(Y) = 2.06035 + 0.27736 \ln(X) + 0.26648 [\ln(X)]^2 + 0.00160 [\ln(X)]^3$$

Southeastern Alaska

$$\ln(Y) = 1.62676 + 0.90838 \ln(X) - 0.03469 [\ln(X)]^2 + 0.04949 [\ln(X)]^3$$

Gulf of Alaska

$$\ln(Y) = 3.46510 - 2.30676 \ln(X) + 1.68946 [\ln(X)]^2 - 0.23942 [\ln(X)]^3$$

Bering Sea

$$\ln(Y) = 2.29027 - 0.27978 \ln(X) + 0.61843 [\ln(X)]^2 - 0.06415 [\ln(X)]^3$$

where Y = fish length (cm) and X = otolith length (mm) (Southward and Hardman 1973).

Otolith Weight Method

Variation in the shape of the otoliths from nearly round to long and narrow plus measurement errors contributed to the variability of the estimated size of halibut. To improve the precision in the estimation of fish length and ultimately fish weight, a new relationship utilizing otolith weight was derived. The otolith-weight/fish-length relationship decreased the variability and otolith weights were easily duplicated by different operators (Myhre ms).

The weight of the left otolith was determined to the nearest milligram on an electronic balance and fish length was measured in centimeters. The relationship was calculated using only data from the summer months, coinciding with the fishing season.

Regional differences were also found and the following equations have been used since 1978:

Area 2 and Area 3 south of Cape St. Elias

$$Y = 21.01298 + 0.4094236 (X) - 0.0003730947 (X)^2 + 0.000\,000\,1528326 (X)^3 \qquad \text{(1a)}$$

Area 3 west of Cape St. Elias and Area 4

$$Y = 16.28570 + 0.4989587 (X) - 0.0005277415 (X)^2 + 0.000\,000\,2415516 (X)^3 \qquad \text{(1b)}$$

where Y = fish length (cm) and X = otolith weight (mg) (Myhre ms).

Fish-Length/Fish-Weight Relationship

The development of a mathematical expression of the relationship between length and weight of halibut was a very early project of the Commission staff. The project involved collection of lengths and weights of individual halibut at sea, where the fish were weighed on a steelyard before and after evisceration. An average line was fitted to the length and weight data by the method of least squares, resulting in

$$W_G = 0.0022046\ (0.00364\ Y^{3.24})$$

where W_G is gross weight (eviscerated, head-on) in pounds and Y is fish length in centimeters. To obtain gross weight in grams the conversion factor 0.0022046 can be omitted.

A study of heading practices in the industry showed that gross weight could be converted to net weight (eviscerated, head-off) (W_N) by the equation

$$W_N = 0.8624\ W_G\ . \qquad (2)$$

Similar factors are often used by the Canadian and United States halibut industry.

The average round or live weight (W_R) can be obtained from the equation

$$W_R = 1.33\ W_N\ .$$

The basis for this conversion factor is an unpublished study by F. H. Bell (R.J. Myhre, personal communication).

Extrapolation of fish weight from length measurements for large fish is not precise, because individual variation is considerable among large halibut. Such large halibut are also relatively rare making verification of the upper extension of the curve difficult. This scarcity, however, reduces the importance of the inaccuracy in the upper part of the curve. Although there appeared to be variations in the relationship between regions and between seasons in the same region, confirmatory sampling from time to time has supported the applicability of the original length-weight equation as being a valid expression of the average condition.

AGING CONSIDERATIONS

After a sample of otoliths is collected, the otoliths are cleaned and placed in a plastic bottle containing a clearing solution of 50% glycerine in water with a few crystals of thymol added as a preservative. The legibility of the otoliths is enhanced if they are not permitted to dry after being removed from the fish. The bottle is identified and mailed to IPHC headquarters. An identifying sample number and a statistical area, determined from the vessel's fishing log, is assigned at the Seattle laboratory.

Otoliths are removed from the solution, blotted dry, and weighed to the nearest milligram on an electronic balance interfaced with the Commission's computer. The samples are not processed further individually, but are now combined into month-region strata and length frequencies by 5 cm size groups. However, the sample number and statistical area are retained and permit analysis by smaller areas if needed.

Because of the importance of otolith weight in the estimation of fish length, a study has been initiated to determine if the length of storage in glycerine has a significant effect on otolith weight. The otolith-weight/fish-length relationship was developed using otoliths that had been stored in glycerin solution from one month to several years. Otoliths collected for use in the catch sampling program are stored for only a few weeks before processing.

CHARACTERISTICS OF AGING HALIBUT

The earliest work on the routine aging of halibut by the Commission was undertaken by the late H.A. Dunlop. An unpublished manuscript by Dunlop[1] has been freely drawn upon in the preparation of this section. Excellent summaries on the use of otoliths for age determination have been published by Williams and Bedford (1974) and Chilton and Beamish (1982).

Halibut otoliths are surface-read by IPHC rather than in cross-section. An otolith, freshly removed from a fish, will display a series of irregular, concentric, opaque, and transparent zones which alternate from the nucleus to the margin (Figure 5). These rings are deposited successively as the fish and otolith grow in size. The opaque zones correspond to the seasons of rapid summer growth and the transparent zones to the slow winter growth. The two zones together are assumed to represent one year's growth. The zones are not all completed at the same time in all fish. The timing of the deposition of the zones varies between geographic locations as well as individual fish. Otoliths of fish caught on the same day may exhibit different types or widths of marginal zone. In the first few years halibut and their otoliths grow rapidly and lay down broad opaque zones. These zones become narrower as the fish grows older although the total volume of material deposited in the growth process may be increasing.

The otoliths from the right and left sides of halibut are not mirror images. The left, or white side otolith, is thinner and flatter and, therefore, easier to read. The right, or dark side otolith, is thicker and concave, and the growth zones are much more difficult to enumerate. Consequently, only the left otoliths are collected for aging and length calculations.

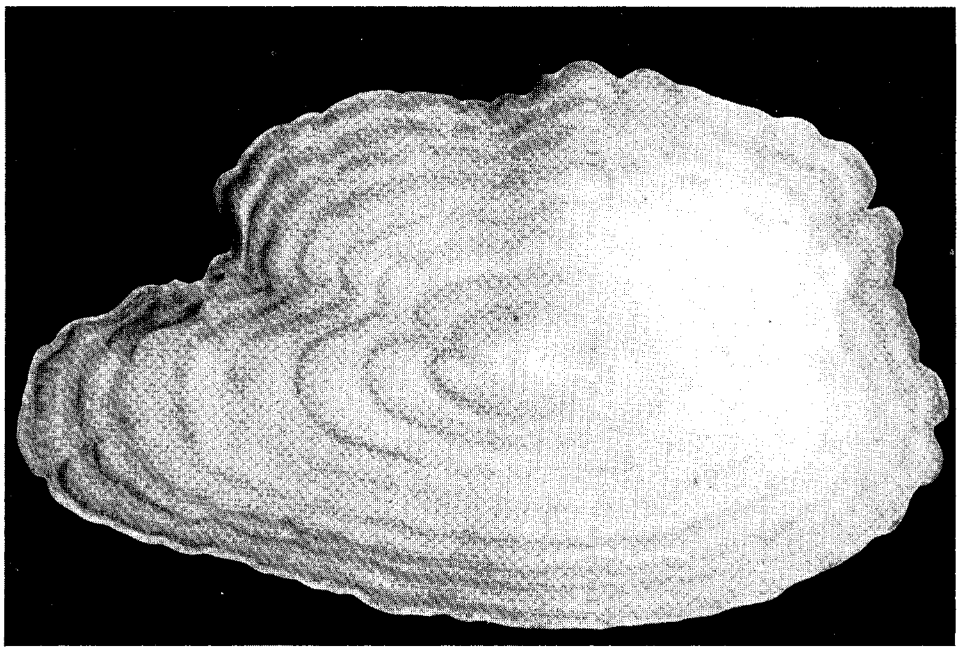

Figure 5. Otolith showing alternating growth bands.

[1]Dunlop, H.A. Age studies on the Pacific halibut *(Hippoglossus stenolepis* Schmitt). Unpublished report, IPHC.

Inasmuch as halibut spawn during the winter (December to March) and the commercial fishing season is confined to the summer months (May to October), IPHC has arbitrarily set January 1 as the birthdate of all halibut. A halibut will be designated as a 1-year-old on the following January 1 even though its actual age may range from about 9 to 13 months. Each subsequent January 1 another year is added to the age of the fish.

The majority of halibut otoliths are comparatively regular in shape and it is reasonably easy to determine the number of opaque and transparent zones, although some are difficult to interpret with confidence. It is possible that annuli may not be recognized in otoliths from larger fish with small annual length increments. The interpretations of the growth zones deposited on the otolith is subjective and reflects the training the reader has received.

A comprehensive evaluation of the aging of halibut otoliths has never been undertaken. However, a growth curve calculated from IPHC age readings was similar to an independent growth function calculated from tagged fish returns (McCaughran 1981). A more precise validation of the age reading technique utilizing injected tetracycline in conjunction with a tagging program is in progress. Oxytetracycline is absorbed by the otolith and provides a mark that will fluoresce under ultra-violet light. This mark, plus the known date of tagging and injection of the tagged fish, will provide a valuable test of the aging technique.

OTOLITH SELECTION FOR AGING

The original sampling plan called for obtaining a large number of fish length measurements and a smaller subsample of otoliths for aging. Otoliths were collected in multiples of 70 which was the number of compartments in a box used to store otoliths in sequence. Fish lengths were recorded sequentially to match the otolith collection. In most instances 140 otoliths were collected, although larger or smaller samples were occasionally taken. The age composition was projected to the length frequency of each vessel sampled. The projected age compositions from individual vessels were combined to represent the time-area under study.

When the sampling program was changed in 1963 to collect only otoliths without fish measurements, about 200 otoliths were obtained from each vessel. From computer-generated length frequency distributions a stratified subsample of otoliths was selected for aging from each vessel. The stratification scheme was based on a fixed sample size of 4-5 otoliths from each length interval or all otoliths if fewer were available, with adjustments made until about 100 otoliths were obtained. The age composition was then projected to the individual vessel's landing.

In examining IPHC's sampling program, Southward (1976) determined that a sample of 300 otoliths proportional to the length frequency of sampled fish from each month-region stratum was preferable to the previous fixed sample size procedure for estimating age composition. Proportional allocation resulted in increased precision of the estimated age composition; hence, fewer otoliths were needed for aging. In 1978 and 1979, IPHC aged 350 otoliths per stratum to provide a margin of safety. Since 1978, the otoliths selected for age determination have been randomly chosen by computer in proportion to the number of fish in each 5 cm length interval, as long as each 5 cm interval is represented by at least 1 otolith.

We established new criteria for precision of age composition estimates and examined recent data to calculate sample size requirements (see the later section Sample Size Requirements). We agreed with Southward's conclusion that otoliths should be selected proportionally to the length frequency. In 1980, the sample size for aging was increased to 700 otoliths per stratum to meet our sample size criteria. We reanalyzed the sample size requirements after these data became available and concluded that 600 otoliths would meet our criteria. Since 1981, 600 otoliths have been aged in each month-region stratum, if available.

ANALYSIS OF AGE COMPOSITION

Before discussing analytical procedures for estimating age composition, a brief description of statistical terminology is given: A parameter P is an unknown constant to be estimated from a set of data. An estimator $\hat{P}$ of the parameter P is a general formula using the data. An estimator is unbiased if its expected value is equal to the parameter. The accuracy of an estimator refers to the amount of bias in relation to variability. The precision of an estimator is inversely related to its variability, which is often expressed as a percentage of the estimator (coefficient of variation). The coefficient of variation is frequently used in evaluation of sample size requirements and studies of relative precision (Cochran 1963, p. 52-54; Kish 1965, p. 47-49); we will use coefficient of variation and its square in later sections as primary comparative tools in assessing relative precision of estimators, because these measures lend themselves to development of general mathematical properties in describing sampling needs. Many variables have multiple subscripts and the omission of a subscript implies the summation over the subscript (e.g., $L_i = \sum_j L_{ij}$).

Basic sampling terminology in this report follows Cochran (1963). For the purposes of this report, the population to be sampled is the landed catch of Pacific halibut. The basic sampling unit for age composition data is an individual fish or its otolith. In practice, the smallest unit sampled is a sling of fish, from which otoliths of all fish are taken. The population is partitioned into month-region strata for estimation purposes. The vessel landing is the smallest potential stratum for age composition, but variability of age composition estimates with this stratum choice is too high (Southward 1976). The sampling design has further stratification by trip size categories, but this need not be accounted for in the estimation framework as long as these categories are sampled at the same rate.

From each month-region stratum i, the following data are used in estimating the age and size composition of the catch:

- T_i — total catch in weight: from fish company records
- L_i — length sample size: total number of otoliths collected; used to define the length frequency
- $\overline{W}_i$ — average weight of the length sample; from otolith-weight/fish-length/fish-weight predictive relationships (equations 1a, 1b, 2)
- L_{ij} — length frequency of the catch: number of L_i that are in length category j (M_{ij} in Southward's notation)
- A_i — age subsample size: total number of otoliths aged from L_i
- A_{ij} — number of L_{ij} that are aged (m_{ij} in Southward's notation). The A_{ij} otoliths are selected randomly from the L_{ij} proportionally to the length sample.
- A_{ijk} — number of A_{ij} that are age k
- $\overline{W}_{ijk}$ — corresponding average weight from otolith-weight/fish-length/fish-weight relationships (equations 1a, 1b, 2)

From these data, the following parameters of the catch in each stratum i are to be estimated:

- C_i — total catch in numbers
- α_{ij} — proportion of fish in length category j (C_{ij}/C_i)
- Θ_{ijk} — proportion of age k fish in length category j (C_{ijk}/C_{ij})
- Θ_{ik} — proportion of age k fish (C_{ik}/C_i)
- C_{ik} — catch in numbers of age k fish
- $\overline{W}_{ik}$ — average weight of age k fish

Finally, strata are to be combined to estimate:

- C — total catch in numbers
- Θ_k — proportion of age k fish
- C_k — number of age k fish
- $\overline{W}_k$ — average weight of age k fish
- $\overline{W}$ — average weight of fish in the catch

For example, month-region strata are combined over months to get regional estimates, and regional estimates are combined to get estimates for regulatory areas.

DERIVATION OF ESTIMATORS

This section presents analytical formulae for estimating age composition from sampling data. The methodology is an extension of age composition methods given by Kutkuhn (1963) and Southward (1976). First, estimates of age composition for each stratum are presented, with emphasis on derivation of measures of precision. Then methods of combining strata are investigated and conditions are established for using each method.

Within-Stratum Estimates

There are two stages of age composition estimation. First, the total number of fish in the catch is estimated from the total otolith (or length) sample L_i, which involves prediction of the length from (1a) and (1b) and weight from (2) of each fish. Secondly, the age composition and average weight at age of the catch is estimated from the subsample of otoliths for aging, A_i.

Estimation of Catch in Numbers

The total catch in numbers (C_i) for each stratum is estimated by dividing the total catch in weight (T_i) by the average predicted weight ($\overline{W}_i$) of the length sample, i.e.,

$$\hat{C}_i = T_i/\overline{W}_i \quad , \tag{3}$$

assuming that the length sample is a random sample from the catch. The variance from the delta method (Seber 1973, p. 9) is approximately

$$\mathrm{Var}(\hat{C}_i) = \frac{T_i^2}{\overline{W}_i^4} \mathrm{Var}(\overline{W}_i) \quad . \tag{4}$$

The term $\mathrm{Var}(\overline{W}_i)$ is estimated by the standard variance estimates of a mean of average weights, or

$$\hat{\mathrm{Var}}(\overline{W}_i) = (1\text{-}f)\sum_j (W_{ij}-\overline{W}_i)^2/L_i(L_i-1) \quad ,$$

where f is the estimated sampling fraction $L_i/\hat{C}_i$. In terms of cv^2 (the variance of an estimator divided by the estimator squared), it can be shown from (3) and (4) that

$$cv^2(\hat{C}_i) = cv^2(\overline{W}_i) \quad . \tag{5}$$

Thus, the relative precision of estimated catch numbers is the same as the relative precision of estimated average weight.

We investigated the advantages and disadvantages of using otolith samples to obtain the average predicted weight $\overline{W}_i$ over obtaining direct measurements of fish weight. The major advantage is the large sample size of several thousand otoliths each year that is relatively easy to obtain. If IPHC returned to the system of collecting fish lengths and weights, an increase in personnel would be required and a decrease in sample size would result (Hardman and Southward 1965). The large sample size results in a small coefficient of variation (or high precision) of average fish weight, as shown by a plot of coefficient of variation versus length sample size for all month-region strata sampled between 1975 and 1980 (Figure 6). (A few sample sizes greater than 3000 otoliths with cv's of under 1% were not plotted.) The increase in precision as sample size increases results in a small coefficient of variation of under 5% when over 200 otoliths are collected, which is typical of most strata.

The major disadvantage of using otolith samples to estimate average weight is that predicted weights rather than actual weights are used. Our estimates of the coefficient of variation are underestimates, because the variance components for the predictions of fish weight from fish length (equation 2) and fish length from otolith weight (equations 1a, 1b) have not yet been included. We plan to incorporate these components when the otolith weight study (Myhre ms) is completed.

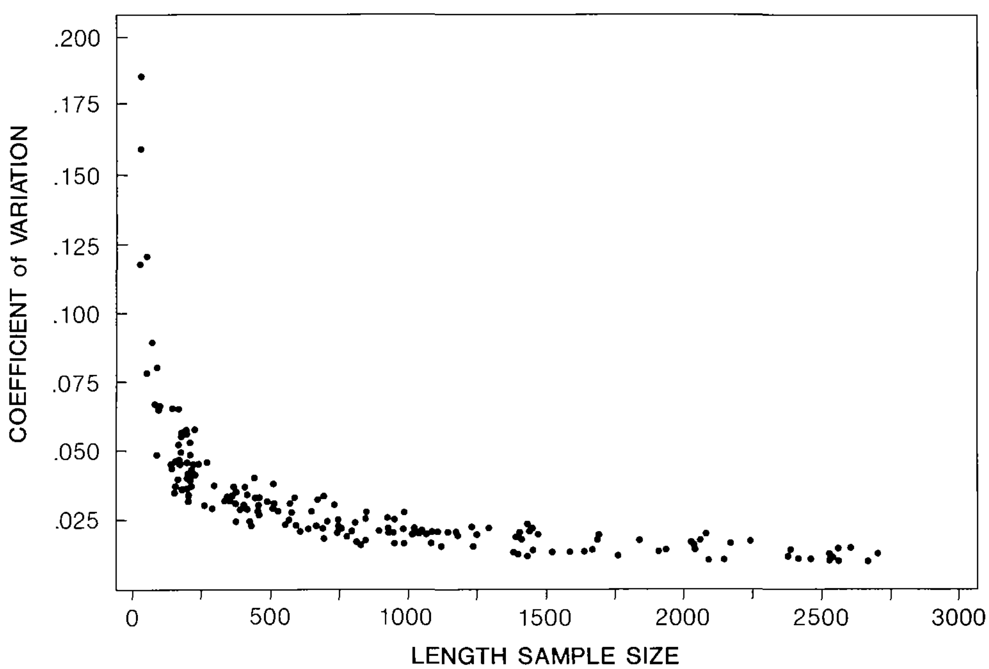

Figure 6. Coefficients of variation of average weight versus length sample size for month-region strata, 1975-1980.

Another limitation of the prediction approach is that the data set for predictions is not augmented annually, so that year-to-year fluctuations in the two relationships could bias the average weight estimates. Thus, the current system trades off the high precision obtained from large sample sizes against the potential low accuracy of the predictive relationships.

To overcome the accuracy problem, an independent method is being investigated for determining the average weight of fish in the commercial catch. The method involves extrapolation from the number of otoliths collected in sampled slings, along with additional enumerations of fish in unsampled slings, to the total number of fish in the trip. A calibration factor is obtained by comparing the actual average weight of fish in the trip, calculated from the known landed weight and extrapolated number of fish, to the average predicted weight. The procedure has been carried out since 1981 and the results will appear in a subsequent report.

Estimation of Age Composition

The estimation of age composition is based upon two inherent specifications in the sampling design (Southward 1976):

(1) A random sample of ages is taken from each length category, and

(2) The length frequency in the sample is representative of the total catch.

This sampling framework for estimation is known as double sampling (Cochran 1963). From specification 1, the estimated proportion of age k fish in length category j and stratum i

$$\hat{\Theta}_{ijk} = A_{ijk}/A_{ij} \tag{6}$$

is unbiased $[E(\hat{\Theta}_{ijk}) = \Theta_{ijk}]$. From specification 2, the estimated proportion of fish in length category j and stratum i

$$\hat{\alpha}_{ij} = L_{ij}/L_i \tag{7}$$

is unbiased $[E(\hat{\alpha}_{ij}) = \alpha_{ij}]$. The estimated proportion of age k fish in stratum i is found by projecting the proportion of age k fish in length category j to the number of fish in the length category and summing over length categories:

$$\hat{\Theta}_{ik} = \sum_j \hat{\alpha}_{ij}\,\hat{\Theta}_{ijk} = \sum_j r_{ijk} \quad \text{[Southward 1976, equation (9)]}, \tag{8}$$

where r_{ijk} is the estimated proportion of fish of length category j and age k in stratum i. Its variance from Southward [1976, equation (10)] is

$$\mathrm{Var}(\hat{\Theta}_{ik}) = \sum_j \left[\frac{\alpha_{ij}^2\,\Theta_{ijk}(1-\Theta_{ijk})}{A_{ij} - 1} + \frac{\alpha_{ij}(\Theta_{ijk} - \Theta_{ik})^2}{L_i} \right] = \sum_j \mathrm{Var}(r_{ijk}) \ , \tag{9}$$

where estimated variance is found by replacing parameters by estimates.

Its expectation is

$$\begin{aligned} E(\hat{\Theta}_{ik}) &= \sum_j E(\hat{\alpha}_{ij}\hat{\Theta}_{ijk}) \\ &= \sum_j E(\hat{\alpha}_{ij})E(\hat{\Theta}_{ijk}) \text{ using conditional expectation} \\ &= \sum_j \alpha_{ij}\Theta_{ijk} \text{ because each estimator is unbiased} \end{aligned}$$

$$= \sum_j \frac{C_{ij}}{C_i} \frac{C_{ijk}}{C_{ij}} \text{ using previous definitions}$$

$$= \frac{C_{ik}}{C_i} = \Theta_{ik} \quad .$$

Thus, $\hat{\Theta}_{ik}$ is unbiased. Also note that r_{ijk} in (8) is unbiased for C_{ijk}/C_i .

The estimated catch in numbers of age k fish is the product of the estimated catch in numbers from (3) and the estimated proportion of age k fish from (8), or

$$\hat{C}_{ik} = \hat{C}_i \, \hat{\Theta}_{ik} \quad . \tag{10}$$

The estimates $\hat{C}_i$ and $\hat{\Theta}_{ik}$ are statistically independent, because the expected value of $\hat{\Theta}_{ik}$ does not depend on $\hat{C}_i$, only on the random sampling of the length frequency and of the age-length distribution. Hence, the estimate $\hat{C}_{ik}$ is approximately unbiased because its independent factors are approximately or exactly unbiased.

The variance of $\hat{C}_{ik}$ is approximately

$$\text{Var}(\hat{C}_{ik}) = \Theta_{ik}^2 \, \text{Var}(\hat{C}_i) + C_i^2 \, \text{Var}(\hat{\Theta}_{ik})$$

[Southward 1976, equation (14)], or in terms of cv^2,

$$cv^2(\hat{C}_{ik}) = cv^2(\hat{C}_i) + cv^2(\hat{\Theta}_{ik}) \quad . \tag{11}$$

This approximation applies to non-independent factors as well (Seber 1973, p. 7-9).

Our evaluation of the sampling design suggests that the two assumptions above for estimation of age composition are not unreasonable for sampling Pacific halibut. For each month-region stratum between 1975 and 1980, estimates of $\hat{C}_{ik}$ and its

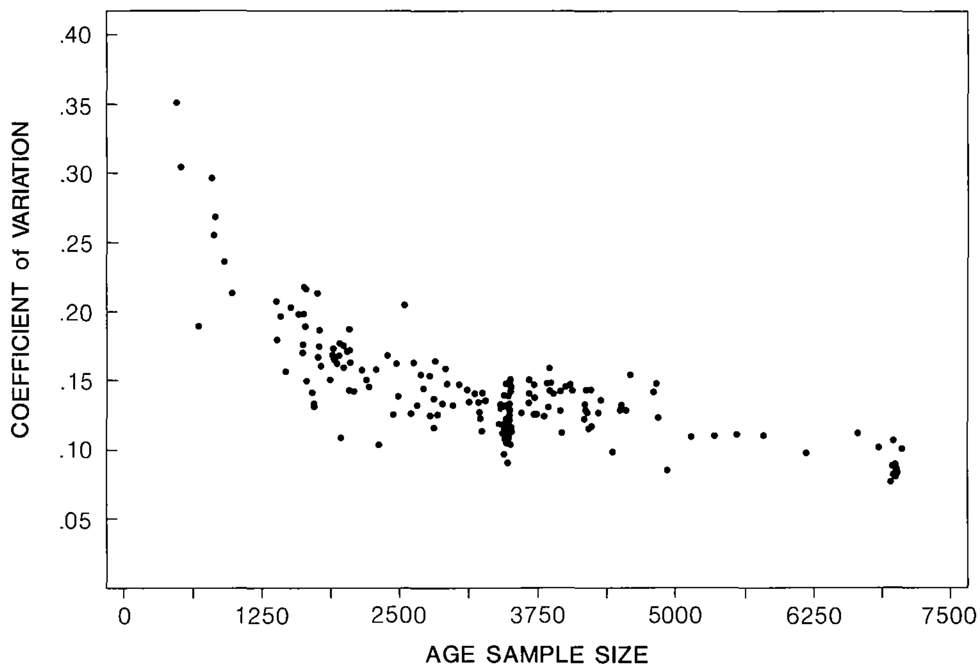

Figure 7. Coefficients of variation of the age with the highest percentage in the catch for month-region strata, 1975-1980.

coefficient of variation were calculated from equations (8) - (11). The age with the highest estimated percentage was isolated for each month-region stratum as a measure of maximum precision of age composition estimation. A plot of cv versus the total number of otoliths aged (Figure 7) shows that relative precision increases as the number of otoliths aged increases. Scatter in the plot is due to age composition differences among strata and to differences in the length sample size. Although the number of otoliths aged primarily determines the precision, additional improvement in precision results from a larger length sample (Kutkuhn 1963). The variability in cv in Figure 7 stabilizes at 250 otoliths aged, which generally sets cv to under 15%. For 600 or more otoliths aged, cv is generally under 10%.

The age with the lowest estimated percentage in the catch above 5% was isolated for each month-region stratum as a measure of minimum precision of age composition estimation. The lower limit of 5% was invoked to include only important ages in the catch and because cv becomes infinite as the percentage goes to zero. A plot of cv versus the number aged shows a large decrease in variability as the number of otoliths aged increases (Figure 8). The variability in cv in Figure 8 also stabilizes at 250 otoliths aged, which generally sets cv to under 25%. For 600 or more otoliths aged, cv is generally under 17%.

Based upon these assessments of minimum and maximum precision, the minimum acceptable level for age composition estimation is 250 otoliths for a month-region strata. If under 250 otoliths are available, data should be pooled across strata until this minimum is reached.

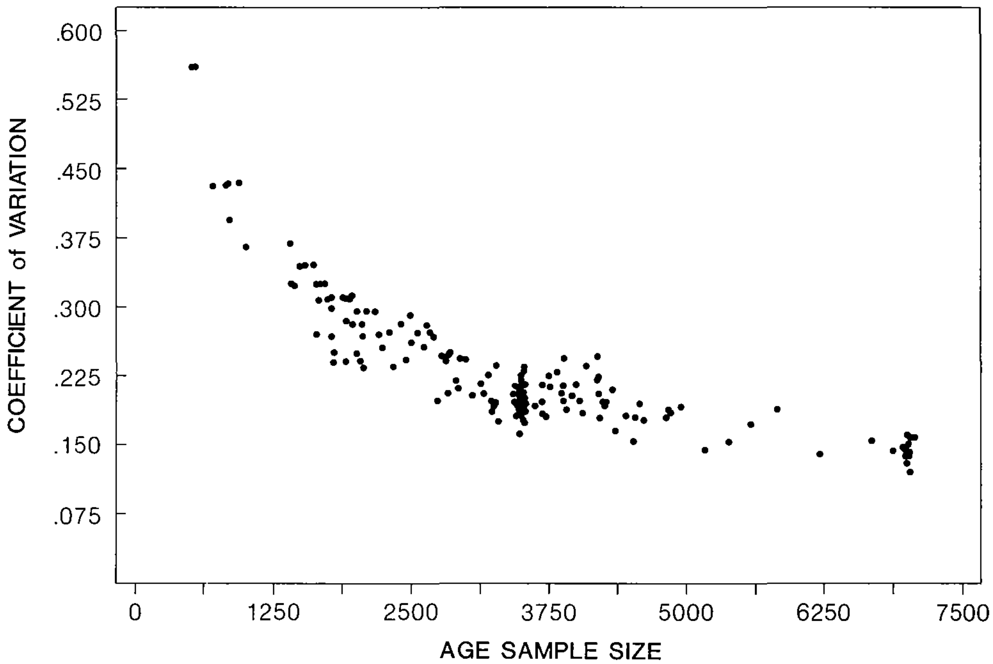

Figure 8. Coefficients of variation of the age with the lowest percentage in the catch above 5% for month-region strata, 1975-1980.

Estimation of Average Weight at Age

The estimator of average weight at age $\overline{W}_{ik}$ weights $\overline{W}_{ijk}$ by its estimated proportion r_{ijk} from (4), or

$$\overline{W}_{ik} = \sum_j r_{ijk}\, \overline{W}_{ijk} / \sum_j r_{ijk} = \sum_j \hat{\alpha}_{ij}\, \hat{\Theta}_{ijk}\, \overline{W}_{ijk} / \hat{\Theta}_{ik} \; .$$

In practice, $\overline{W}_{ijk}$ is not a function of age in the prediction relationship and is replaced by $\overline{W}_{ij}$.

Its expectation from Appendix I is approximately

$$\begin{aligned} E(\overline{W}_{ik}) &= \sum_j \alpha_{ij}\, \Theta_{ijk}\, E(\overline{W}_{ijk}) / \Theta_{ik} \\ &= \sum_j (C_{ijk}/C_i)\, E(\overline{W}_{ijk}) / (C_{ik}/C_i) \\ &= \sum_j C_{ijk}\, E(\overline{W}_{ijk}) / \sum_j C_{ijk} \; . \end{aligned}$$

The numerator of this catch-weighted estimator is catch in biomass and the denominator is catch in numbers, with the ratio being the true average weight in the catch. Thus, $\overline{W}_{ik}$ is approximately unbiased.

The approximate variance of $\overline{W}_{ik}$ from the delta method is found by applying the general variance formula in Appendix 1 with $w_i = r_{ijk}$ and $\hat{\Theta}_i = \overline{W}_{ijk}$, where $Var(r_{ijk})$ is defined in (9) and $Var(\overline{W}_{ijk})$ is the variance of a mean of individual observations.

For each month-region stratum between 1975 and 1980, $\overline{W}_{ik}$ and its cv were calculated. The age with the lowest percentage in the catch above 5% was isolated and the cv of average weight at that age was plotted versus the number aged (Figure 9). As for catch, the coefficient of variation of weight decreases as the number aged increases. When over 250 otoliths are aged, cv is usually under 20%.

Combined-strata Estimates

Two methods are contrasted to estimate age composition combined over strata. In the first method called project-and-add, the estimated age percentage $\hat{\Theta}_{ik}$ is projected to estimated catch numbers for each stratum and added over strata. In the second method called add-and-project, the basic data from all strata are combined (pooled) first and then projected to the total catch numbers.

Project-and-add

For theoretical development, all strata are assumed to have adequate sampling. The catch in numbers for age k is estimated as the sum of within-stratum estimates, i.e.,

$$\hat{C}_k = \sum_i \hat{C}_{ik} = \sum_i \hat{C}_i\, \hat{\Theta}_{ik} \; . \tag{12}$$

Using the reasonable assumption that the data sources among strata are statistically independent, the variance of (12) is

$$Var(\hat{C}_k) = \sum_i Var(\hat{C}_{ik}) \; . \tag{13}$$

Southward (1976) recommended weighting $\hat{C}_{ik}$ by catch to combine data; he meant to weight $\hat{\Theta}_{ik}$ by catch in numbers $\hat{C}_i$, which results in (12). His equations (18) and (19) should be ignored. Similarly, the total catch in numbers is estimated by

$$\hat{C} = \Sigma\, \hat{C}_i. \tag{14}$$

with variance

$$\mathrm{Var}(\hat{C}) = \Sigma\, \mathrm{Var}(\hat{C}_i)\ . \tag{15}$$

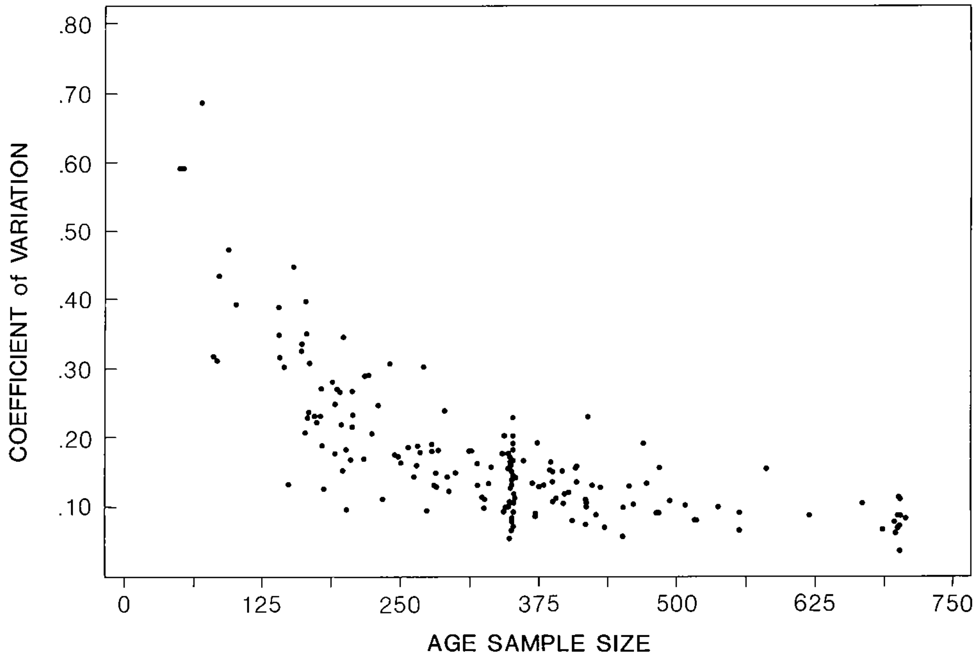

Figure 9. Coefficients of variation of average weight for the age with the lowest percentage in the catch above 5% for month-region strata, 1975-1980.

The estimated percentage of age k fish combined over strata is

$$\hat{\Theta}_k = \hat{C}_k/\hat{C} = \sum_i \hat{C}_i\, \hat{\Theta}_{ik} / \sum_i \hat{C}_i$$

and its squared coefficient of variation using Appendix 1 is approximately

$$\begin{aligned} cv^2(\hat{\Theta}_k) &= \sum_i [\hat{C}_i^2\, \mathrm{Var}(\hat{\Theta}_{ik}) + (\hat{\Theta}_{ik} - \hat{\Theta}_k)^2 \mathrm{Var}(\hat{C}_i)] \,/\hat{C}^2\, \hat{\Theta}_k^2 \\ &= cv^2(\hat{C}_k) + cv^2(\hat{C}) - 2\sum_i \hat{C}_i\, \hat{C}_{ik} cv^2(\hat{C}_i)/\hat{C}\hat{C}_k\ . \end{aligned}$$

The estimators $\hat{C}_k$, $\hat{C}$, and $\hat{\Theta}_k$ are approximately unbiased because each of their components is approximately or exactly unbiased.

Similarly, average weight of the catch is estimated by

$$\hat{\overline{W}} = T/\hat{C} = T/\sum_i (T_i/\overline{W}_i) ,$$

with the same coefficient of variation as $\hat{C}$.

Average weight of age k fish in the catch is estimated by

$$\hat{\overline{W}}_k = \sum_i \hat{C}_{ik} \overline{W}_{ik}/\hat{C}_k ,$$

which weights stratum average weight by estimated catch numbers. Its variance is found by applying the results of Appendix I with $w_i = \hat{C}_{ik}$ and $\hat{\Theta}_i = \overline{W}_{ik}$.

Add-and-project

In this method, all data are first pooled over strata and then estimation proceeds as in the section "Within-stratum Estimates." This method essentially treats all data as coming from a single stratum. Estimates in this section are denoted with an asterisk (*) to distinguish them from the project-and-add estimates. In accord with previous notation, L is the total length sample size; $\overset{*}{W}$ is the pooled average weight of the length sample; L_j is the length frequency; A_j is the number aged; A_{jk} is the number of age k in length category j in the subsample.

The estimation framework for add-and-project follows, but variance estimates are not presented because they are analogous to those in the "Within-stratum Estimates" section.

The estimated catch in numbers is

$$\overset{*}{C} = T/\overset{*}{W} . \tag{16}$$

The estimated proportion of age k fish in length category j is

$$\overset{*}{\Theta}_{jk} = A_{jk}/A_j . \tag{17}$$

The estimated proportion in length catgory j is

$$\overset{*}{\alpha}_j = L_j/L . \tag{18}$$

Then the estimated proportion of age k fish is

$$\overset{*}{\Theta}_k = \sum_j \overset{*}{\alpha}_j \overset{*}{\Theta}_{jk} , \tag{19}$$

and estimated catch in numbers of age k fish is

$$\overset{*}{C}_k = \overset{*}{C} \overset{*}{\Theta}_k . \tag{20}$$

The statistical property of bias of the add-and-project estimation framework is now evaluated. The true average weight of the catch $\overline{W}_c$ is T/C. The expectation of the pooled average weight is

$$E(\overset{*}{W}) = E(\Sigma \frac{L_i}{L} \overline{W}_i) = \Sigma \frac{L_i}{L} E(\overline{W}_i)$$

$$= \Sigma \frac{L_i}{L} \frac{T_i}{C_i}.$$

In general, this expression does not simplify to $\overline{W}_C$; thus, $\overset{*}{W}$ is a biased estimator of W_C. One of two conditions must exist for $\overset{*}{W}$ to be unbiased.

The obvious first condition is that the average weight is the same for all strata. The second condition is that the length sample is proportional among strata, i.e.,

$$\frac{L_i}{L} = \frac{C_i}{C} \text{ for all strata i.}$$

Then $E(\overset{*}{W})$ simplifies to

$$\Sigma \frac{C_i}{C} \frac{T_i}{C_i} = \Sigma \frac{T_i}{C} = \frac{T}{C} = \overline{W}_C .$$

In our evaluation of the sampling design, we found that the goal of proportional allocation among strata is seldom achieved in practice (see the previous section "Overall Sampling Rate"). Thus, $\overset{*}{W}$ and, hence, $\overset{*}{C}$ are considered biased estimators, with the amount of bias being a function of the amount of deviation from proportional allocation.

To evaluate the bias of $\overset{*}{\Theta}_k$, the expectations of $\overset{*}{\alpha}_j$ and $\overset{*}{\Theta}_{jk}$ must be obtained. From (7) and (18),

$$E(\overset{*}{\alpha}_j) = E(L_j/L) = E\,(\Sigma_i \frac{L_i}{L} \frac{L_{ij}}{L_i}) = \Sigma_i \frac{L_i}{L} \alpha_{ij} , \qquad (21)$$

which in general is not equal to α_j.

From (6) and (17),

$$E(\overset{*}{\Theta}_{jk}) = E(A_{jk}/A_j) = E(\Sigma_i \frac{A_{ij}}{A_j} \frac{A_{ijk}}{A_{ij}}) = \Sigma_i \frac{A_{ij}}{A_j} \Theta_{ijk} , \qquad (22)$$

which in general is not equal to Θ_{jk} .

Thus, the expectation of $\overset{*}{\Theta}_k$ using conditional expectation of (19) is

$$E(\overset{*}{\Theta}_k) = \Sigma_j E(\overset{*}{\alpha}_j) E(\overset{*}{\Theta}_{jk}) , \qquad (23)$$

which in general is not equal to Θ_k . Thus $\overset{*}{\Theta}_k$ is a biased estimator of Θ_k .

There are certain conditions under which the two factors are unbiased, which allows $\overset{*}{\Theta}_k$ to be unbiased. For $\overset{*}{\alpha}_j$ to be unbiased, one of the two following conditions must hold:

$$L_i/L = C_i/C \text{ for all strata i,} \qquad (24)$$

which states that proportional allocation among strata occurs, or

$$\alpha_{ij} = \alpha_j = C_j/C \text{ for all strata i,} \qquad (25)$$

which states that all strata have identical length frequency distributions. Substituting either (24) or (25) into (21) shows $E(\overset{*}{\alpha}_j) = \alpha_j$. For $\overset{*}{\Theta}_{jk}$ to be unbiased, the distribution of ages within each length class j must be the same for all strata, i.e.,

$$\Theta_{ijk} = \Theta_{jk} = C_{jk}/C_j \text{ for all strata i.} \tag{26}$$

Substituting (26) into (22) shows $E(\overset{*}{\Theta}_{jk}) = \Theta_{jk}$. Thus, if condition (26) and either of the conditions (24) or (25) are true, then the expectation of $\overset{*}{\Theta}_k$ in (23) is

$$E(\overset{*}{\Theta}_k) = \sum_j \alpha_j \Theta_{jk} = \sum_j \frac{C_j}{C} \frac{C_{jk}}{C_j} = \frac{C_k}{C} = \Theta_k \ ;$$

hence, $\overset{*}{\Theta}_k$ under these sets of conditions is unbiased. Otherwise, $\overset{*}{\Theta}_k$ is a biased estimator. Studies in a later section address whether these conditions are met for Pacific halibut data.

Comparison of Methods

In this section, we present the framework for the comparison of the project-and-add and the add-and-project methods. Both bias and variance are considerations for choosing one estimator over another. An unbiased estimator with a high variance may be as poor as a biased estimator with a low variance. Frequently, an appropriate tool for comparison is the mean squared error (Cochran 1963, p. 15), which accounts for both variance and bias, although bias is often difficult to estimate. Thus, the add-and-project method was recommended by Southward (1976) for vessel trips in a stratum, because the variance was lower than for the project-and-add method. In this report we extend the comparison to combining data over month-region strata.

The question of pooling can be addressed using results from sampling theory. In stratified sampling, a general principle is to stratify if the variability within a stratum is less than that between strata because a lower variance will be achieved. Similar discussions may be observed for two-stage cluster sampling for unequal cluster sizes (Cochran 1963, chapter 11 and Seber 1973, p. 111-117). Southward and Van Ryzin (1971) present a similar argument for ratio estimation with unequal sample sizes using the framework of the estimation of the mean of a random binomial probability parameter. They show that if there is more variability within a sample than between samples, the estimator approaches a ratio of means estimator (where all of the data are pooled). If there is more between-samples variability, the estimator approaches a mean of ratios (where the data are stratified).

The desirable characteristics of the project-and-add method are its unbiased estimators and that the estimated catch is simply added across strata. The add-and-project method, which pools data across strata, is likely to have less variance than the project-and-add method, although the estimated catch is not additive across strata. Add-and-project estimates are often used when a breakdown of landing data by strata is not readily available. For example, IPHC age composition data were processed before landing data and add-and-project estimates were used to combine data before we undertook this evaluation. However, the add-and-project estimator is biased unless certain specific conditions are satisfied. The two methods are compared in a later section by application to Pacific halibut data, where the tradeoffs in bias and variability are examined.

Precision of Combined-Strata Estimates

This section determines the relative precision of age composition estimation for a combination of strata using project-and-add methodology. The corresponding precision for add-and-project methodology is generally at least as high as project-and-add due to the larger sample size from pooling data.

Equation (13) may be rewritten as

$$cv^2(\hat{C}_k) = \sum_i \hat{Var}(\hat{C}_{ik})/\hat{C}_k^2 ,$$

$$= \sum_i \hat{C}_{ik}^2 \, cv^2 (\hat{C}_{ik})/(\sum_i \hat{C}_{ik})^2 . \qquad (27)$$

Suppose that a large enough sample size is specified so that cv is set below a prescribed limit P for each stratum, i.e.,

$$cv^2 (\hat{C}_{ik}) \leq P^2 .$$

Then from equation (27),

$$cv^2(\hat{C}_k) \leq \frac{\sum_i \hat{C}_{ik}^2}{(\sum_i \hat{C}_{ik})^2} P^2 \leq P^2 ; \qquad (28)$$

where the second inequality holds because a sum of squares is always less than or equal to a square of sums if the terms are non-negative. Thus, the relative precision of a combination of estimates is always greater or equal to the limit set for all strata. The equality results only if all catch comes from a single stratum.

A lower bound for cv^2 may also be derived, if $cv^2 (\hat{C}_{ik})$ is set equal to P^2 for all strata i. Applying the Cauchy-Schwarz inequality (Rao 1973)

$$(\Sigma a_i b_i)^2 \leq \Sigma a_i^2 \, \Sigma b_i^2$$

with $a_i = 1$ and $b_i = \hat{C}_{ik}$ shows that

$$\hat{C}_k^2 = (\sum_i \hat{C}_{ik})^2 \leq \sum_i \hat{C}_{ik}^2 \, S ,$$

or

$$S^{-1} \leq \sum_i (\hat{C}_{ik}/\hat{C}_k)^2 ,$$

where S is the number of strata.

Substituting into (27) establishes that

$$P^2 /S \leq cv^2 (\hat{C}_k) ,$$

with equality if and only if the $\hat{C}_{ik}$ are equal for all strata. Thus, if cv for each stratum is set to P, then cv for a combination of strata ranges between $P\sqrt{S}$ to P. If cv for a particular stratum is lower than P, then cv for a combination can be lower. The exact cv depends on the distribution of catches across strata. As an example, if P is set at 20% and there are 9 strata, $cv(\hat{C}_k)$ is in the range of 7% to 20% and can be lower if some strata cv's are lower than 20%. The combined estimate can be considerably more precise than individual stratum estimates.

APPLICATION TO PACIFIC HALIBUT DATA

Further understanding of age composition estimation requires detailed examination of actual age composition data from sampling the catch of Pacific halibut. This examination is composed of three components. The first component is a study of the age and length distributions for selected months and regions to determine if the conditions specified for the add-and-project method are met in practice. The second component is a comparison of three methods of combining month-region strata into regulatory areas using age composition data collected between 1975 and 1980. The third component is the further refinement of sample size requirements to control the precision of age composition estimates.

Study of Age and Length Distributions

As shown above, the add-and-project method produces unbiased estimates only if two conditions are met:

(1) The age distribution within each length category is the same for all strata.

(2) Either the sampling is allocated proportionally to strata or the length distribution is the same for all strata.

Table 2. Chi-square tests of homogeneity over months of the age distribution for each length category for Charlotte-Inside and Kodiak, 1978-1979.

Region	Year	Number of months	Number of length classes	Number of significant χ^2 at .05	at .01	Number of χ^2 greater than median
Charlotte-Inside	1978	4	12	1	1	9
	1979	3	12	0	0	9
	Total		24	1	1	18 (P = .01)
Kodiak	1978	3	12	2	1	8
	1979	2	12	2	1	10
	Total		24	4	2	18 (P = .01)

Table 3. Chi-square tests of homogeneity over months of the length frequency distribution for Charlotte-Inside and Kodiak, 1978-1979.

Region	Year	Number of months	χ^2	Degrees of freedom	P Value
Charlotte-Inside	1978	4	320	66	<.001
	1979	3	124	44	<.001
Kodiak	1978	3	79	22	<.001
	1979	2	89	19	<.001

In the section "Overall Sampling Rate," we have shown that proportional allocation to strata is not met in actual sampling. We test the validity of the other two assumptions with chi-square tests of homogeneity of age distributions within length category and the homogeneity of length distributions, using data from 1978 and 1979. Because age composition estimates are made for both regions and regulatory areas, tests are conducted between months within selected regions and also between regions.

The Charlotte-Inside region was selected from Regulatory Area 2 and the Kodiak region was selected from Regulatory Area 3 to test homogeneity over months. In 1978 and 1979, the regions Charlotte-Inside, Charlotte-Outside, S.E. Alaska-Inside, and S.E. Alaska-Outside in Area 2 had sufficient samples for between-region testing. The regions Yakutat, Kodiak, Shumagin, and Chirikof in Area 3 had sufficient samples for testing in 1978, but in 1979, the Shumagin region had no sampling.

For each length category, the homogeneity of the age distribution between months was tested and the results are summarized in Table 2 for Charlotte-Inside and Kodiak. For Charlotte-Inside, only one out of 24 tests was significant, but sample sizes were small, and, hence, the power of each test was low. To combine the individual test results into a more powerful test, the number of chi-square statistics greater than the median of chi-square were counted. The proportion of the statistics greater than the median should be 50% under the null hypothesis of no heterogeneity between months and greater than 50% under the alternative hypothesis of heterogeneity. Eighteen out of 24 statistics (75%) were greater than the median, which is significantly different from 50% ($P = .01$). To determine if heterogeneity was present over a longer time period, data from 1973 to 1977 were added. Sixty-three out of 84 statistics (75%) were greater than the median, which is significantly different from 50% ($P < .001$). Thus, there is significant heterogeneity of the age distribution between months in Charlotte-Inside. Similarly, for 1978-1979 data from Kodiak, only four out of 24 tests were significant, but 18 out of 24 (75%) were greater than the median (Table 2), which implies significant heterogeneity ($P = .01$).

The homogeneity of the length distributions between months was tested and the results are shown in Table 3. For both Charlotte-Inside and Kodiak, there are highly significant differences between months in 1978 and 1979 ($P < .001$). To corroborate this procedure, additional tests on Charlotte-Inside were performed on 1973-1977 data with a highly significant result each year. A visual inspection of the length distributions for Charlotte-Inside in 1978 and 1979 also indicated differences between months, with the length distribution shifting slightly to the right each month (Figure 10).

In summary, there is evidence that the age distribution across length category and the length distribution are not homogeneous among months within a region. Thus, neither of the two conditions for unbiased estimation for the add-and-project method is met for months.

To compare age and length distributions across regions, the data were pooled across months. Chi-square tests of the age distribution for homogeneity of regions in Area 2 and Area 3 are shown in Table 4. For Area 2, 12 out of 24 length intervals showed significant differences ($\alpha = .05$), and 19 out of 24 (79%) statistics were greater than the median, which is significantly greater than the expected 50% ($P < .001$). For Area 3 seven out of 24 length intervals showed significant differences ($\alpha = .05$), but only 15 out of 24 (62%) were greater than the median, which is not significantly greater than 50%.

Chi-square tests of the length distributions of regions are shown in Table 5. Differences between regions are highly significant for both Area 2 and Area 3. The length distributions of regions in 1979 are plotted in Figure 11 to illustrate the differences. For Area 2 in 1979, the length distributions for the Charlotte regions were composed of greater percentages of smaller fish than for the S.E. Alaska regions. For Area 3 in 1979, the Chirikof region had the greatest proportion of small fish, as compared to the similar Kodiak and Yakutat distributions. Also shown in Figure 11 is the Aleutian region, which recently was changed from Area 3 to Area 4. The Aleutian distribution was composed of fish from all size classes with a greater proportion of large

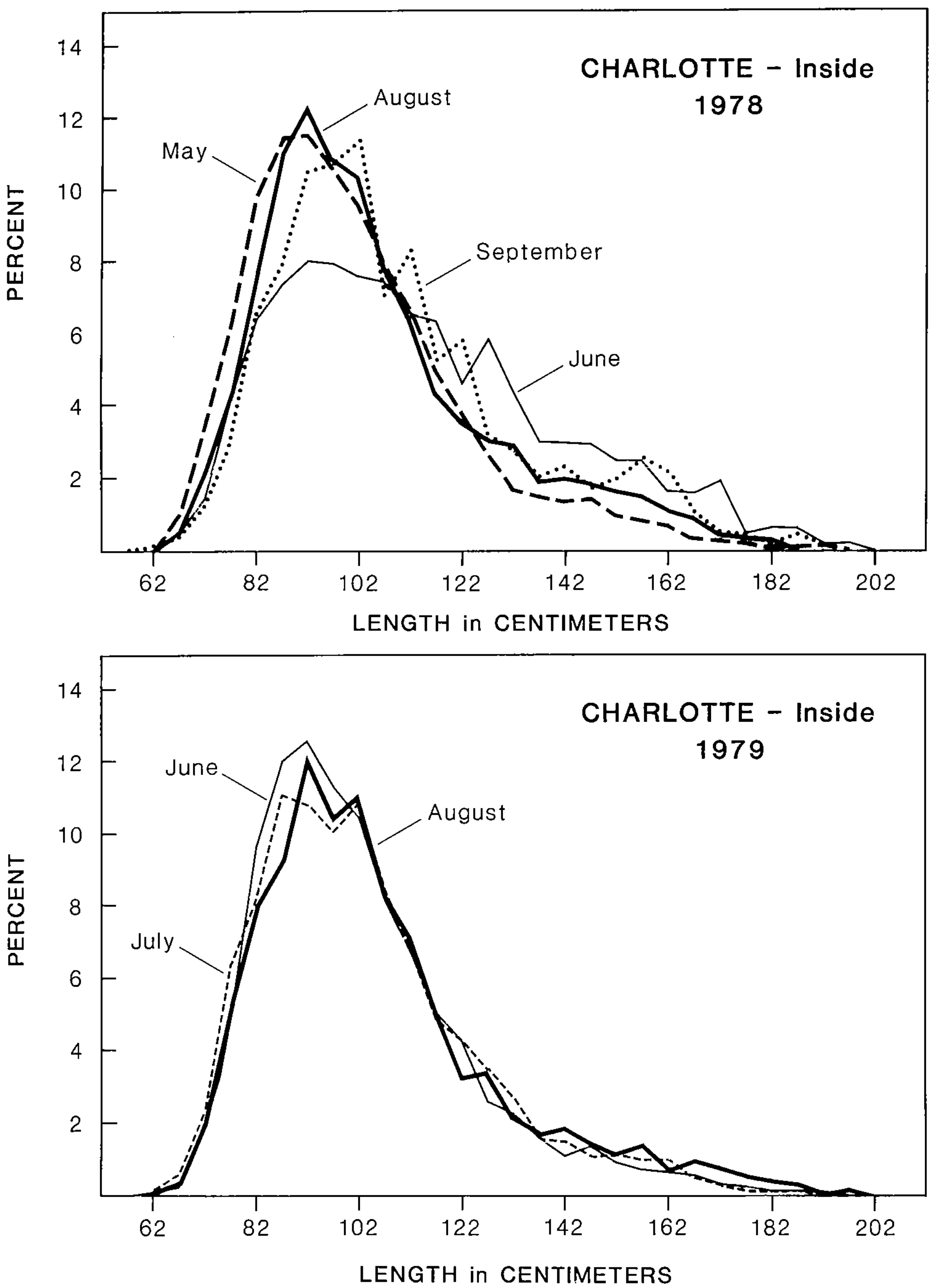

Figure 10. Length distribution of otoliths for monthly periods from Charlotte-Inside, 1978-1979.

fish than regions in Area 3. In summary, there is evidence of heterogeneity between regions in both the age and length distributions. Thus, neither of the two conditions for unbiased estimation for the add-and-project method is met for either months or regions.

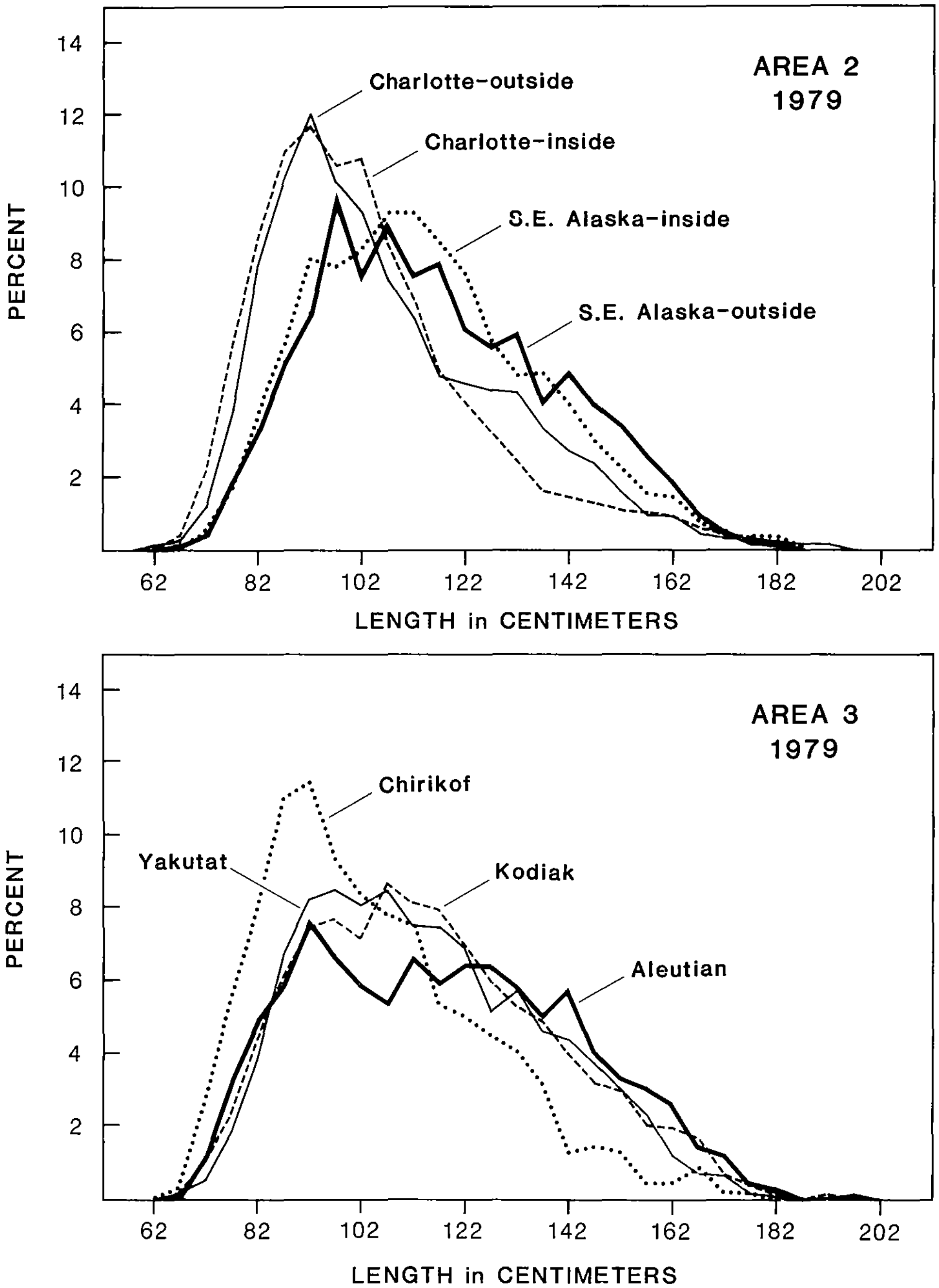

Figure 11. Length distributions of otoliths from regions in Area 2 and Area 3, 1979.

Table 4. Chi-square tests of homogeneity over regions of the age distribution of each length category for Areas 2 and 3, 1978-1979. Data pooled over months.

Area	Year	Number of regions	Number of length classes	Number of significant χ^2 at .05	at .01	Number of χ^2 greater than median
2	1978	4	12	7	5	10
2	1979	4	12	5	4	9
	Total		24	12	9	19 (P = .001)
3	1978	4	12	2	1	8
3	1979	3	12	5	2	7
	Total		24	7	3	15 (P = .09)

Table 5. Chi-square tests of homogeneity over regions of the length distribution for Areas 2 and 3, 1978-1979. Data pooled over months.

Area	Year	Number of Regions	χ^2	Degrees of Freedom	P Value
2	1978	4	680	57	<.001
2	1979	4	1,590	63	<.001
3	1978	4	230	54	<.001
3	1979	3	234	42	<.001

Comparison of Methods for Combining Age Composition Statistics

Prior to this evaluation, the add-and-project method was used by IPHC to obtain age composition and average weight estimates across months and regions in normal data processing. For special purposes, Hoag and McNaughton (1978) developed age composition estimates for Regulatory Areas 2 and 3 for 1935-1976. They used data pooled over months and projected to the total catch by region (combined method: add-and-project by months, project-and-add by regions). We propose a third method to estimate age composition for halibut data: project-and-add by month-region strata. This method involves development of a suitable missing data algorithm because many of these strata have missing data.

Estimation of Average Weight

Currently, IPHC has formatted its otolith sampling data since 1968 by month-region strata. For previous years, data are currently available only for regions and regulatory areas, and variances cannot be computed. Data from 1975 and later were used to estimate average weight and its variance for Areas 2, 3, and 4 for the three methods. Many month-region strata had no sampling because of low catch. These strata were either early or late in the fishing season or were from the Bering Sea, an area of low catch which is divided into six subregions (4A, 4B, 4C, 4De, 4Dw, 4E; see Myhre et al. 1977).

We developed a missing data algorithm to handle strata with missing data, by examining historical similarities in age composition estimates among regions. First, a region with landings but insufficient sampling was assigned a replacement region as follows: Columbia was replaced with Vancouver; Vancouver or S.E. Alaska-Inside with Charlotte-Outside; Charlotte-Outside with S.E. Alaska-Outside; S.E. Alaska-Outside with Yakutat; Yakutat with Kodiak; Chirikof with Kodiak; Shumagin with Chirikof; Aleutian with Shumagin; 4A with 4B; 4B with 4C; 4C with 4De; 4De with 4Dw; 4Dw with Aleutian. The assignments continued until all missing regions were filled in. Insufficient sampling was defined as under 50 otoliths collected to test the limits of variability of the project-and-add method. Secondly, months with insufficient sampling were filled in using a "forward-search, backward-glance" scheme: a search forward in time was made to find a month with sufficient sampling in the same region in the same year; if not found, the search was continued backward in time.

Estimates of average weight and its coefficient of variation for the three methods are shown in Appendix II, Table 1 for Areas 2, 3, and 4. The estimates of average weight are similar for all three methods, with the maximum difference in a year of less than two pounds (except Area 4 in 1980). The add-and-project and combined methods generally produce slight over-estimates of average weight due to undersampling of fish in earlier months when fish are generally smaller. Also, differences in the proportion of fish sampled between strata create slight discrepancies between the methods. For example, estimates for Area 2 in 1978 from the add-and-project and combined methods are lower than the project-and-add estimate because of oversampling in Hecate Strait in months with low average weight.

The coefficient of variation is generally highest for the project-and-add method, followed by the combined method, and then the add-and-project method (Appendix II, Table 1), showing that increasing the amount of data pooling increases the relative precision. However, the three coefficients differ by generally 20% or less, which is relatively insignificant.

Estimation of Age Composition

Estimates of age composition for the three methods of combining data were made each year for Areas 2, 3, and 4 (Appendix II, Tables 2, 3, and 4, respectively), using estimation formulae described earlier. The missing data algorithm for average weight was also used for age composition.

Estimates of age composition are generally similar for the three methods with differences of no more than 2% in estimated percentages between any of the methods. However, a 2% difference has a large effect when multiplied by catch numbers. As was true for average weight, the age composition estimates are more precise with increasing amounts of pooling, although differences in the coefficient of variation are generally at most 20%. For Areas 2 and 3 (Appendix II, Tables 2 and 3), the coefficient of variation for the age with the highest percentage in the catch is generally 5% or less, and the coefficient of variation of ages with at least 5% of the catch is generally under 10%. For Area 4, the coefficients are at least twice as large, because of fewer landings and samples (Appendix II, Table 4).

These results suggest that it makes little practical difference which method is used to estimate age composition for this period because most of the catch across months and regions has been adequately sampled. Although the samples are not taken in exact proportion to the landings, the discrepancies in age composition estimates from all three methods are not large. Theoretical considerations favor the project-and-add method as long as adequate sampling is made in each stratum. Because average weight increases during the season and because age compositions may be different between month-region strata, age composition estimates from an add-and-project method are biased. In contrast, estimates from the project-and-add method are unbiased and almost as precise.

Sample Size Requirements

This section investigates the sample size requirements needed to meet specified levels of precision for age composition estimates. For a given month-region stratum, the size of the subsample of otoliths to be aged can be determined from the sample size of otoliths for the length sample, assuming that the age subsample is taken proportionally to the length sample (Kutkuhn 1963). The cv^2 of the estimated proportion $\hat{\Theta}_{ik}$ of age k fish in stratum i from (9) may be written

$$cv^2\,(\hat{\Theta}_{ik}) = (V_{ik}/A + B_{ik}/L)/\hat{\Theta}^2_{ik}\,, \tag{29}$$

where V_{ik} and B_{ik} are within- and between-length category variances, respectively, and A and L are the age and length sample sizes. For a specified coefficient of variation, called (cv), the required age sample size solved from (29) is

$$A = V_{ik}/(\hat{\Theta}^2_{ik}\,(cv)^2 - B_{ik}/L)\,. \tag{30}$$

Increasing the length sample size L in (30) results in a decrease in the sample size A for aging, although the relationship is not linear. Using several values for L, the minimum length sample size which requires complete aging is found. In application to Pacific halibut data, a larger length sample size than this minimum value does not substantially decrease the subsample size for aging because B_{ik} in (30) is generally negligible.

Four criteria are used to define acceptable levels of relative precision for age composition estimates, ranging from achieving a high level of precision at a single age to protecting all important ages from low levels of precision. It was shown in the section "Within-stratum estimates: Estimation of age composition" that a minimum of 250 otoliths is needed for a stable age composition estimate. These additional criteria are used to achieve more specific sampling goals.

Criterion 1. Ensure that at least one age achieves a coefficient of variation of 10% or less.

Criterion 2. Ensure that all ages between 8 and 15, inclusive, achieve a coefficient of variation of 20% or less. If this criterion is achieved, then the age composition estimates for a regulatory area are at least this precise (see the section "Precision of Combined-Strata Estimates").

Criterion 3. Ensure that all ages between 5 and 18 that make up at least 0.1% of the catch achieve a coefficient of variation of 50% or less. This criterion ensures that the age composition estimates of proportions are significantly different from 0.

Criterion 4. Ensure that all ages that make up at least 5% of the catch achieve a coefficient of variation of 20% or less. This is a modification of Criterion 2 with a different definition of key ages in the catch.

The result of applying these four criteria to determine sample size is shown in Table 6 for month-region strata sampled in 1980. Similar results were obtained for 1979 data, but are not included. About 500-600 otoliths are needed to achieve Criterion 1 and about 400-500 are needed to achieve Criterion 4. The sample sizes needed to achieve the other two criteria are quite variable between strata because the coefficient of variation is unstable for estimated percentages close to 0. The median value over strata for both of these criteria is 700. Overall, the sample size required to achieve these four criteria is about 600-700 per stratum.

The required sample sizes are compared to the actual length and age sample size obtained in 1980 in Table 6. Month-region strata with large landings have large sample sizes and vice versa. Generally, the sample sizes are sufficient to meet the criteria, except for some strata in Vancouver, Charlotte-Outside, and the Bering Sea.

Table 6. Sample size requirements to achieve four criteria, total landings, and actual length and age sample sizes for month-region strata sampled in 1980.

Month	Region[2]	Sample Size[1] to Achieve Criterion 1	Criterion 2	Criterion 3	Criterion 4	Landings 000's of Pounds	Length Sample	Age Sample
4	11	600	1,100	3,000	500	84	1,116	702
4	16	800	2,200	*	500	74	814	699
5	3	600	400	1,000	500	311	448	448
5	4	500	1,500	800	500	1,002	1,439	698
5	5	500	1,300	500	500	2,346	1,358	696
5	6	600	300	600	500	981	1,063	701
5	7	500	600	3,000	400	4,848	5,588	702
5	8	500	800	3,100	400	4,518	3,414	699
7	3	600	600	200	400	208	144	144
7	4	500	600	2,000	400	1,498	1,468	698
7	7	600	400	1,400	400	1,175	925	701
7	8	500	700	500	400	1,393	889	702
8	3	700	700	500	500	189	240	240
8	4	600	600	400	400	979	1,443	698
8	11	800	3,400	700	500	209	456	456
8	16	900	2,300	200	500	50	167	167
9	2	1,000	*	200	*	23	54	54
9	3	*	*	*	*	95	26	26
9	4	500	800	400	500	611	1,686	702
11	3	500	600	800	400	22	178	178
11	4	600	*	700	500	44	166	166

[1] "*" Sample size cannot be computed from data.
[2] 2 — Vancouver, 3 — Charlotte-Outside, 4 — Charlotte-Inside, 5 — S.E. Alaska-Inside, 6 — S.E. Alaska-Outside, 7 — Yakutat, 8 — Kodiak, 11 — Aleutian, 16 — Bering Sea-IDw

Recommendations

Based on these theoretical analyses and application to Pacific halibut data, we have inaugerated the following recommendations regarding analysis of age composition data:

1. The project-and-add method should be used to combine data over month-region strata.
2. Strata should be pooled until a minimum of 250 otoliths for aging is obtained to achieve minimal levels of precision for age composition estimation.
3. If available, 600 otoliths should be aged in each stratum to achieve optimal levels of precision defined by four specified sampling criteria.
4. Sources of variability in otolith-fish predictions of length and weight should be investigated.

SUMMARY AND CONCLUSIONS

SAMPLING DESIGN

The current sampling design has evolved out of the results presented in previous sections. At the beginning of each year, a list of ports for sampling is compiled based upon the distribution of landings in past years and available manpower. Generally, the rate of sampling, the proportion of collected otoliths to number of fish, is set at 1/18 (5.6%) of landings over 1,000 pounds in Areas 2 and 3 for the ports sampled. This rate represents an overall sampling rate of about 3% of the total landings. However, landings from Area 4 are sampled at the rate 1/3, because these landings are divided into six different subregions and generally involve a smaller number of total fish. If necessary, these rates are increased on a port by port basis to ensure that sufficient samples are collected from regions of low catch.

Practicalities concerning sampling dictate that to achieve the 1/18 rate, the sampling rate must be set for four trip size classes: 1,000-4,999, 5,000-14,999, 15,000-39,999, 40,000+ pounds. Sampling is achieved by randomly selecting a vessel and taking a systematic random sample of slings wherein the otoliths from all fish are taken (discounting broken or crystallized otoliths, or missed fish). The first sling sampled is chosen randomly. Fish unloaded with straps, in buckets, or in other ways, are sampled at the identical rate. For the 1,000-4,999 class, the vessel rate is set at 1/9, and the sling sampling rate is set at 1/2. For the other classes, the vessel sampling rate is 1/3 and the sling sampling rate is 1/6. For Area 4 landings, the vessel sampling rate is set at 1/1 (all vessels) and the sling sampling rate is 1/3.

Although trips should be sampled consistently throughout a fishing period, the sampling rate is met in practice on a cumulative rather than a daily basis due to the large number of landings at the end of the period. For example, to obtain a cumulative 1/3 vessel sampling rate, vessels are sampled at a 1/3 to 1/2 rate before the season closes and the rate is adjusted at the end of the fishing period.

Information used to evaluate the sampling procedure includes the total number of slings in the trip, which slings were sampled, the number of fish, and otoliths unloaded in other ways. In order to provide data to compute an estimate of average fish weight in the catch, enumerations are made of fish in certain nonsampled slings. The logbook information from the vessel is collected to assign the vessel sample to the appropriate month-region stratum.

The samples are then pooled into month-region strata. Otolith weight is used to predict each fish's length and weight. A subsample of otoliths for aging is taken from each stratum. The sample size for aging is currently 600, or all fish if less than 600 otoliths are available. Annual sample size requirements depend on the distribution of landings across months and regions.

The data are analyzed with methods described in this report. First, age composition estimates are made for each stratum with data pooling over months and regions if necessary until at least 250 aged otoliths are obtained. Age composition and average weight estimates for regions and regulatory areas are based upon the project-and-add method; projecting the sample to the total catch in each stratum and then adding. This method results in minor loss of precision compared to the add-and-project and combined methods and protects against bias caused by the lack of proportional sampling across strata.

FURTHER STUDIES

The limitations of a sampling design based upon predictions of measurements cannot be overemphasized because any bias in the predictions of fish length and fish weight will cause bias in resultant catch-age and average weight estimates. The unbiased estimation of the percentage of fish at each age is not affected by prediction errors because the estimation procedure works for any stratification variable, whether it is otolith weight or a non-decreasing function of otolith weight. Catch-age estimates are affected, however, because catch numbers are obtained by dividing weight of landings by average predicted weight of the catch. A calibration study is currently underway to examine the validity of average predicted weight of the catch based on an independent method of determining the average fish weight in a landing. Furthermore, the otolith-weight/fish-length and fish-length/fish-weight relationships are based upon data pooled over months, regions, and years, whereas the estimation procedure is based upon a month-region stratum. Differences in otolith growth across months, regions, or years, may affect the prediction of fish weight. Continual enhancement of the data base for the predictive relationships is planned.

Current research indicates that absorption of glycerin creates an increase in otolith weight. Otoliths soaked in glycerin for years were used to develop the predictive relationships, whereas sampled otoliths are in glycerin for a few weeks at most. Current studies are being carried out to determine the asymptote for glycerin absorption so that the soaking procedure can be standardized.

The estimation of age composition is critically dependent upon accuracy in aging. There have been no in depth studies on halibut aging techniques. In 1982, IPHC initiated an oxytetracycline validation study of aging.

The sex ratio of the catch cannot be determined from sampling because halibut are eviscerated at sea. However, a method to predict sex ratio of the catch from otolith weight, otolith length, and age, is under evaluation and may provide greater understanding of halibut population dynamics in the future.

ACKNOWLEDGMENTS

We wish to acknowledge the valuable assistance rendered by innumerable employees of IPHC over the years since 1933 in collecting and processing the data on halibut landings. This report is the result of the efforts of those dedicated workers.

We also wish to acknowledge F. Heward Bell, V. F. Gallucci, Keith S. Ketchen, Loh-Lee Low, and G. Morris Southward, as well as current IPHC staff, for their critical review and comments on this manuscript. We also thank C. Carr for manuscript typing and K. Exelby for construction of the figures.

LITERATURE CITED

Chilton, Doris E., and Richard J. Beamish. 1982. Age determination methods for fishes studied by the groundfish program at the Pacific Biological Station. Canadian Special Publication of Fisheries and Aquatic Sciences, No. 60:102 p.

Cochran, W. G. 1963. Sampling Techniques, second edition. Wiley and Sons, New York.

Hardman, William H., and G. Morris Southward. 1965. Sampling the commercial catch and use of calculated lengths in stock composition studies of Pacific halibut. International Pacific Halibut Commission, Report No. 37:32 p.

Hoag, Stephen H., and Ronald J. McNaughton. 1978. Abundance and fishing mortality of Pacific halibut, cohort analysis, 1935-1976. International Pacific Halibut Commission, Scientific Report No. 65:45 p.

International Pacific Halibut Commission. 1982. Annual Report 1981, 48 p.

Kish, Leslie. 1965. Survey Sampling. Wiley and Sons, New York.

Kutkuhn, Joseph H. 1963. Estimating absolute age composition of California salmon landings. California Fish Bulletin, No. 120:42 p.

McCaughran, Donald A. 1981. Estimating growth parameters for Pacific halibut from mark-recapture data. Canadian Journal of Fisheries and Aquatic Sciences, 38(4):394-398.

McIntyre, A. D. 1953. A note on market sampling of halibut. Journal du Conseil, 19(1):69-71.

McNair, Doug. 1982. The Seattle fishermen's exchange. Pacific Fishing, 3(10):37-41.

Myhre, R. J., G. J. Peltonen, G. St-Pierre, B. E. Skud, and R. E. Walden. 1977. The Pacific halibut fishery: Catch, effort and CPUE, 1929-1975. International Pacific Halibut Commission, Technical Report No. 14:94 p.

Quinn, T. J., II, R. B. Deriso, S. H. Hoag, and R. J. Myhre. In press. A summary of methods of estimating annual surplus production for the Pacific halibut fishery. International North Pacific Fisheries Commission, Special Scientific Sessions.

Rao, C. R. 1973. Linear Statistical Inference and its Applications. Wiley and Sons, New York.

Seber, G. A. F. 1973. The Estimation of Animal Abundance. Griffin, London.

Southward, G. Morris. 1962. A method of calculating body length from otolith measurements for Pacific halibut and its application to Portlock-Albatross grounds data between 1935 and 1957. Journal of the Fisheries Research Board of Canada, 19(2):339-362.

__________. 1976. Sampling landings of halibut for age composition. International Pacific Halibut Commission, Scientific Report No. 58:31 p.

Southward, G. Morris, and William H. Hardman. 1973. Otolith length and fish length of Pacific halibut. International Pacific Halibut Commission, Technical Report No. 10:10 p.

Southward, G. Morris, and J. Van Ryzin. 1972. Estimating the mean of a random binomial parameter. Pages 249-261 *in* Proceedings of the Sixth Berkeley Symposium on Mathematical Statistics and Probability, Volume IV, University of California Press, Berkeley, California.

Williams, T., and B. C. Bedford. 1974. The use of otoliths for age determination. Pages 114-123 *in* T. B. Bagenal, ed. Ageing of fish. Unwin Brothers Ltd., Surrey, England.

APPENDICES

I. Variance and expected value of a weighted mean with estimated weights.

II. Estimates of average weight and age composition for three methods of combining data.

APPENDIX I. Variance and expected value of a weighted mean with estimated weights.

Let $\hat{\Theta} = \sum_{i=1}^{n} w_i\hat{\Theta}_i / \sum_{j=1}^{n} w_j$ be a weighted estimator of n independent estimates $\hat{\Theta}_i$, where w_i is the i^{th} estimated weight. The expected value of $\hat{\Theta}_i$ need not be constant over i. Let $V(w_i)$ and $V(\hat{\Theta}_i)$ be the estimated variances of w_i and $\hat{\Theta}_i$. Then the estimated variance of $\hat{\Theta}$ from the delta method (Seber 1973, p. 7-9) is

$$V(\hat{\Theta}) = \sum_i \left[\frac{w_i}{\Sigma w_j}\right]^2 V(\hat{\Theta}_i) + \sum_i \left[\frac{\hat{\Theta}_i (\Sigma w_j)-(\Sigma w_j\hat{\Theta}_j)}{(\Sigma w_j)^2}\right]^2 V(w_i)$$

$$= \left[\sum_i w_i^2 \quad V(\hat{\Theta}_i) + \sum_i(\hat{\Theta}_i-\hat{\Theta})^2 V(w_i)\right] / (\Sigma w_j)^2$$

$$= \left[\sum_i w_i^2 \quad V(\hat{\Theta}_i) + \sum_i \hat{\Theta}_i^2 V(w_i) + \hat{\Theta}^2 \sum_i V(w_i) - 2\hat{\Theta} \sum_i \hat{\Theta}_i V(w_i)\right] /(\Sigma w_j)^2 .$$

The first three terms in the equation also result for a different estimator $\hat{\gamma} = \Sigma w_i \Theta_i / X$, where X replaces (Σw_j). Thus, the negative term in the equation is a variance reduction factor because of the correlation of numerator and denominator of $V(\hat{\Theta})$ due to the w_j's.

The approximate expected value of Θ is

$$E(\hat{\Theta}) = \Sigma E(w_i) E(\hat{\Theta}_i)/\Sigma E(w_i) ,$$

assuming w_i and $\hat{\Theta}_i$ are independent (Seber 1973, p. 7-9).

APPENDIX II. Estimates of average weight and age composition for three methods of combining data.

Table 1. Estimates of average weight and its coefficient of variation (CV) for three methods of combining data.

Year	Add-and-project	CV	Combined	CV	Project-and-add	CV
AREA 2						
1975	36.10	.0054	35.41	.0055	36.49	.0061
1976	32.74	.0058	32.74	.0062	32.62	.0062
1977	35.69	.0064	34.66	.0070	34.54	.0073
1978	33.41	.0061	33.13	.0066	33.99	.0064
1979	31.55	.0055	32.65	.0054	32.36	.0054
1980	28.11	.0080	27.70	.0086	27.43	.0086
AREA 3						
1975	42.85	.0045	42.94	.0048	42.80	.0049
1976	44.52	.0041	44.33	.0042	43.80	.0048
1977	44.57	.0045	44.17	.0049	43.06	.0052
1978	39.15	.0051	38.87	.0052	38.89	.0052
1979	37.22	.0054	37.22	.0054	37.11	.0054
1980	35.39	.0064	35.80	.0062	35.76	.0063
AREA 4						
1975	35.77	.0231	36.39	.0221	36.86	.0235
1976	36.20	.0166	35.78	.0183	35.58	.0177
1977	34.55	.0142	35.45	.0147	35.12	.0156
1978	49.83	.0111	49.95	.0113	49.11	.0118
1979	43.01	.0124	43.54	.0127	42.13	.0147
1980	41.86	.0144	42.87	.0149	47.25	.0251

Table 2a. Catch, proportion, and CV by three methods for Area 2, 1975.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	25	0.00007	0.99800	43	0.00011	0.99200	108	0.00028	0.50400
5	924	0.00241	0.19700	1640	0.00419	0.20300	1310	0.00345	0.19300
6	4230	0.01110	0.10800	5680	0.01460	0.11800	5670	0.01500	0.12300
7	15800	0.04110	0.05890	17400	0.04450	0.06780	16500	0.04350	0.07000
8	37200	0.09700	0.03800	40500	0.10400	0.04390	37300	0.09830	0.04600
9	49100	0.12800	0.03300	52300	0.13400	0.03770	50000	0.13200	0.03970
10	53400	0.13900	0.03160	56300	0.14400	0.03630	53500	0.14100	0.03820
11	49700	0.13000	0.03210	52000	0.13300	0.03660	51300	0.13500	0.03790
12	46900	0.12200	0.03220	48300	0.12400	0.03650	46900	0.12400	0.03790
13	28800	0.07510	0.04030	27000	0.06900	0.04540	26800	0.07070	0.04570
14	33400	0.08730	0.03590	30700	0.07850	0.04030	30200	0.07960	0.04100
15	13800	0.03590	0.05410	12200	0.03120	0.05900	12800	0.03370	0.06070
16	13100	0.03420	0.05430	12400	0.03190	0.06180	12800	0.03390	0.06350
17	11700	0.03060	0.05740	10800	0.02760	0.06430	10600	0.02810	0.06380
18	8100	0.02110	0.06940	7280	0.01860	0.07280	7390	0.01950	0.07430
19	3860	0.01010	0.09710	3500	0.00896	0.10100	3590	0.00947	0.10300
20	3800	0.00993	0.10200	3620	0.00928	0.11100	3820	0.01010	0.10900

Table 2b. Catch, proportion, and CV by three methods for Area 2, 1976.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	271	0.00068	0.47700
5	2100	0.00528	0.20400	3810	0.00956	0.22500	5470	0.01370	0.21700
6	13400	0.03370	0.07930	21300	0.05350	0.08470	26000	0.06490	0.08920
7	21500	0.05390	0.06400	23000	0.05780	0.08360	27700	0.06920	0.08900
8	48100	0.12100	0.04170	47100	0.11800	0.05380	50200	0.12600	0.05910
9	54800	0.13700	0.03850	50900	0.12800	0.04880	51800	0.13000	0.05240
10	55700	0.14000	0.03730	53200	0.13400	0.04650	55800	0.14000	0.05110
11	44900	0.11300	0.04050	46900	0.11800	0.04850	44900	0.11200	0.05200
12	41400	0.10400	0.03980	41200	0.10300	0.04630	42000	0.10500	0.05060
13	28300	0.07090	0.04560	27700	0.06940	0.05440	25600	0.06410	0.05280
14	21400	0.05360	0.05200	19000	0.04780	0.06350	18700	0.04670	0.06590
15	24400	0.06120	0.04520	22300	0.05600	0.05030	21100	0.05280	0.05340
16	9020	0.02260	0.07180	7290	0.01830	0.07680	7200	0.01800	0.07610
17	8020	0.02010	0.07140	7760	0.01950	0.07840	7760	0.01940	0.08130
18	5890	0.01480	0.09330	5370	0.01350	0.10400	5220	0.01300	0.09970
19	2850	0.00715	0.12000	2980	0.00748	0.13200	3180	0.00796	0.14300
20	1990	0.00499	0.14800	1910	0.00480	0.15400	1650	0.00412	0.15600

Table 2c. Catch, proportion, and CV by three methods for Area 2, 1977.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	20	0.00008	1.00000	27	0.00010	0.74900
5	0	0.00000	0.00000	744	0.00292	0.23500	697	0.00273	0.21300
6	3040	0.01230	0.15300	8420	0.03310	0.10700	8970	0.03510	0.10800
7	9910	0.04010	0.08270	17700	0.06970	0.07150	19500	0.07630	0.07420
8	22400	0.09070	0.05390	31600	0.12400	0.05410	30300	0.11900	0.05740
9	29300	0.11800	0.04630	32800	0.12900	0.05050	32600	0.12800	0.05320
10	35300	0.14300	0.04070	36200	0.14200	0.04530	36300	0.14200	0.04660
11	28800	0.11700	0.04420	28800	0.11300	0.04880	29700	0.11600	0.05080
12	25900	0.10500	0.04460	26500	0.10400	0.05050	27100	0.10600	0.05220
13	20500	0.08300	0.04810	20800	0.08160	0.05570	20500	0.08020	0.05750
14	15700	0.06350	0.05060	15200	0.05990	0.05630	15300	0.06010	0.05920
15	12000	0.04850	0.05710	10300	0.04030	0.05940	10600	0.04150	0.06400
16	10700	0.04340	0.05790	9920	0.03900	0.06350	10100	0.03940	0.06850
17	4270	0.01730	0.09580	3990	0.01570	0.11300	3810	0.01490	0.11000
18	3640	0.01470	0.10200	3210	0.01260	0.10200	3140	0.01230	0.11100
19	1950	0.00788	0.12400	1680	0.00659	0.12300	1830	0.00716	0.13700
20	1590	0.00645	0.15200	1520	0.00598	0.15400	1480	0.00578	0.16700

Table 2d. Catch, proportion, and CV by three methods for Area 2, 1978.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	256	0.00095	0.45300	400	0.00147	0.45000	347	0.00131	0.41500
5	2330	0.00863	0.15900	2810	0.01030	0.16500	2720	0.01020	0.16700
6	8340	0.03090	0.08240	9670	0.03550	0.08550	9050	0.03410	0.08670
7	21800	0.08070	0.04970	23900	0.08780	0.05250	23000	0.08680	0.05400
8	34400	0.12700	0.03900	35800	0.13100	0.04130	34600	0.13000	0.04270
9	38600	0.14300	0.03680	39300	0.14400	0.03880	37200	0.14000	0.04030
10	38600	0.14300	0.03660	36700	0.13500	0.03880	34900	0.13100	0.04050
11	31900	0.11800	0.04030	31000	0.11400	0.04290	30000	0.11300	0.04440
12	29800	0.11000	0.04110	28600	0.10500	0.04360	28400	0.10700	0.04500
13	19800	0.07350	0.04990	19200	0.07050	0.05280	18900	0.07130	0.05410
14	15800	0.05840	0.05570	15900	0.05840	0.05930	15900	0.06010	0.06030
15	11000	0.04080	0.06610	11200	0.04120	0.07000	11100	0.04180	0.07120
16	6290	0.02330	0.08820	6360	0.02340	0.09350	6810	0.02560	0.09540
17	3890	0.01440	0.10900	3920	0.01440	0.11700	4290	0.01620	0.11500
18	2230	0.00826	0.14600	2360	0.00865	0.15300	2410	0.00907	0.15500
19	1590	0.00587	0.17000	1660	0.00608	0.17900	1790	0.00674	0.17700
20	1600	0.00594	0.17400	1830	0.00673	0.18600	2080	0.00783	0.18300

Table 2e. Catch, proportion, and CV by three methods for Area 2, 1979.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	57	0.00019	0.97400	66	0.00023	0.93900	103	0.00035	0.84000
5	1090	0.00366	0.30200	1140	0.00397	0.28400	1280	0.00440	0.30400
6	5500	0.01840	0.13200	5520	0.01910	0.13200	6680	0.02300	0.13200
7	22000	0.07390	0.06290	21400	0.07430	0.06430	22200	0.07630	0.06780
8	36000	0.12100	0.04870	34400	0.11900	0.04990	35300	0.12100	0.05260
9	50500	0.16900	0.04030	46900	0.16300	0.04180	47000	0.16200	0.04440
10	39900	0.13400	0.04630	37300	0.12900	0.04800	38500	0.13300	0.04960
11	38000	0.12700	0.04700	36700	0.12700	0.04860	36100	0.12400	0.05100
12	33700	0.11300	0.04870	33400	0.11600	0.05000	33500	0.11500	0.05210
13	22300	0.07470	0.06050	22700	0.07870	0.06170	22500	0.07730	0.06410
14	17100	0.05730	0.06870	17200	0.05970	0.07020	17000	0.05840	0.07350
15	12000	0.04020	0.08040	11700	0.04080	0.08340	11300	0.03890	0.08680
16	8310	0.02790	0.09610	8240	0.02860	0.09910	7890	0.02710	0.10300
17	5040	0.01690	0.12000	4670	0.01620	0.12300	4740	0.01630	0.12300
18	2150	0.00721	0.18400	2230	0.00773	0.18900	2150	0.00738	0.19700
19	1070	0.00358	0.27500	1210	0.00421	0.27700	1300	0.00446	0.28400
20	1500	0.00502	0.21000	1630	0.00567	0.21200	1550	0.00533	0.20100

Table 2f. Catch, proportion, and CV by three methods for Area 2, 1980.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	10	0.00003	1.04000	24	0.00000	1.00000	18	0.00006	0.99900
5	651	0.00210	0.29100	497	0.00158	0.32000	925	0.00291	0.23700
6	6880	0.02220	0.09130	6200	0.01970	0.09940	6360	0.02000	0.10100
7	21600	0.06950	0.05050	23500	0.07470	0.05660	24000	0.07530	0.05720
8	41100	0.13200	0.03610	45600	0.14500	0.04070	46000	0.14500	0.04140
9	46400	0.14900	0.03410	47500	0.15100	0.03910	48500	0.15300	0.03970
10	45700	0.14700	0.03440	48900	0.15500	0.03930	49600	0.15600	0.03990
11	37000	0.11900	0.03810	37400	0.11900	0.04410	37500	0.11800	0.04520
12	29200	0.09390	0.04290	29500	0.09380	0.05030	30100	0.09460	0.05090
13	21600	0.06970	0.04960	21000	0.06660	0.05720	21300	0.06700	0.05840
14	15200	0.04910	0.05870	15000	0.04760	0.06910	15300	0.04820	0.07020
15	14000	0.04490	0.06110	12300	0.03910	0.07020	12400	0.03900	0.07200
16	10300	0.03320	0.07080	8680	0.02750	0.08000	8730	0.02740	0.08290
17	6810	0.02190	0.08580	5990	0.01900	0.09750	5800	0.01820	0.10200
18	5110	0.01650	0.09940	4630	0.01470	0.11400	4550	0.01430	0.11600
19	2550	0.00822	0.14200	2610	0.00829	0.16500	2580	0.00811	0.17000
20	2010	0.00647	0.15900	2110	0.00669	0.17700	2040	0.00641	0.18500

Table 3a. Catch, proportion, and CV by three methods for Area 3, 1975.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	787	0.00255	0.27700	930	0.00301	0.27500	991	0.00320	0.25700
7	12400	0.04010	0.07000	14000	0.04540	0.07360	15000	0.04840	0.07510
8	33100	0.10700	0.04290	34000	0.11000	0.04720	34300	0.11100	0.04910
9	41500	0.13400	0.03920	43500	0.14100	0.04280	41900	0.13500	0.04550
10	45100	0.14600	0.03780	42200	0.13700	0.04260	41600	0.13400	0.04490
11	39700	0.12800	0.04000	40400	0.13100	0.04350	40500	0.13100	0.04580
12	39700	0.12800	0.03870	39300	0.12700	0.04290	40400	0.13100	0.04510
13	25400	0.08220	0.04880	25900	0.08390	0.05230	26900	0.08690	0.05490
14	33000	0.10700	0.03960	33100	0.10700	0.04350	33700	0.10900	0.04550
15	10100	0.03260	0.07190	9940	0.03220	0.07650	10000	0.03240	0.08200
16	9560	0.03090	0.07320	9690	0.03140	0.07860	9670	0.03120	0.08320
17	6620	0.02140	0.08600	6740	0.02180	0.09030	6850	0.02210	0.09500
18	3670	0.01190	0.11900	3630	0.01180	0.12100	3290	0.01060	0.12500
19	1720	0.00556	0.17700	1640	0.00531	0.17500	1740	0.00561	0.19200
20	1500	0.00485	0.18300	1550	0.00501	0.19400	1580	0.00509	0.19600

Table 3b. Catch, proportion, and CV by three methods for Area 3, 1976.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	11	0.00004	1.00000
6	996	0.00320	0.21000	1440	0.00460	0.21500	2360	0.00748	0.20200
7	9640	0.03100	0.08010	9260	0.02960	0.08620	11400	0.03610	0.09050
8	37300	0.12000	0.04190	38300	0.12200	0.04700	41400	0.13100	0.04960
9	53700	0.17300	0.03500	52800	0.16900	0.03970	57000	0.18000	0.04220
10	43400	0.13900	0.04090	44500	0.14200	0.04550	45100	0.14200	0.04840
11	37200	0.12000	0.04390	36100	0.11500	0.04930	35700	0.11300	0.05250
12	35500	0.11400	0.04360	36100	0.11600	0.04760	35000	0.11100	0.05020
13	27000	0.08680	0.04870	27000	0.08640	0.05340	26700	0.08440	0.05600
14	23000	0.07410	0.05120	23700	0.07600	0.05630	22400	0.07090	0.05890
15	20500	0.06600	0.05230	20600	0.06580	0.05700	19000	0.06020	0.05850
16	6140	0.01970	0.09970	6230	0.01990	0.10700	5800	0.01830	0.10900
17	5480	0.01760	0.10300	5460	0.01750	0.10600	4770	0.01510	0.10600
18	3810	0.01220	0.11300	4060	0.01300	0.12100	4080	0.01290	0.12400
19	2020	0.00650	0.16600	2160	0.00693	0.18400	2170	0.00687	0.19300
20	988	0.00318	0.25100	1130	0.00361	0.25100	1110	0.00350	0.24900

Table 3c. Catch, proportion, and CV by three methods for Area 3, 1977.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	51	0.00019	0.99800	34	0.00012	0.99400	81	0.00029	0.73000
6	629	0.00234	0.26200	704	0.00260	0.24800	688	0.00248	0.23400
7	9330	0.03480	0.08050	9300	0.03430	0.08310	9230	0.03320	0.09390
8	26600	0.09920	0.05200	25800	0.09510	0.05890	26700	0.09610	0.06480
9	41000	0.15300	0.04270	45100	0.16700	0.04680	49200	0.17700	0.04970
10	48600	0.18100	0.03940	48200	0.17800	0.04510	51400	0.18500	0.04880
11	28700	0.10700	0.05320	29700	0.11000	0.05950	30600	0.11000	0.06470
12	29500	0.11000	0.05020	28200	0.10400	0.05630	29100	0.10500	0.06240
13	25100	0.09360	0.05300	25600	0.09450	0.05860	24700	0.08880	0.06640
14	18900	0.07040	0.06010	18600	0.06850	0.06550	18300	0.06580	0.07330
15	13700	0.05120	0.07070	14000	0.05160	0.07930	13400	0.04830	0.09020
16	13800	0.05130	0.06780	13100	0.04820	0.07490	12700	0.04570	0.08460
17	4640	0.01730	0.11900	4590	0.01690	0.12900	4700	0.01690	0.14400
18	2940	0.01100	0.14500	3180	0.01180	0.16900	3340	0.01200	0.18800
19	1750	0.00652	0.18700	1740	0.00642	0.19500	1480	0.00532	0.19700
20	1160	0.00432	0.19900	1260	0.00467	0.23000	936	0.00337	0.21400

Table 3d. Catch, proportion, and CV by three methods for Area 3, 1978.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	42	0.00014	0.70700
6	3720	0.01250	0.13500	3710	0.01240	0.16100	3970	0.01330	0.16000
7	12100	0.04080	0.07540	12000	0.04000	0.09540	11500	0.03840	0.09440
8	38500	0.13000	0.04120	42600	0.14200	0.04850	42300	0.14200	0.04830
9	45900	0.15500	0.03880	43300	0.14500	0.05020	42900	0.14400	0.05050
10	49500	0.16700	0.03790	51400	0.17200	0.04600	51400	0.17200	0.04630
11	41600	0.14000	0.04210	41500	0.13900	0.05200	41500	0.13900	0.05270
12	31100	0.10500	0.04930	32100	0.10700	0.05940	32300	0.10800	0.05960
13	21000	0.07090	0.06040	21200	0.07110	0.07280	21400	0.07160	0.07260
14	17900	0.06040	0.06510	18300	0.06130	0.07680	18700	0.06270	0.07720
15	13200	0.04440	0.07620	12300	0.04100	0.09440	12300	0.04110	0.09370
16	9980	0.03360	0.08780	10200	0.03410	0.10200	10400	0.03480	0.10100
17	5650	0.01900	0.11600	4870	0.01630	0.14700	4750	0.01590	0.14300
18	2700	0.00910	0.16900	2190	0.00733	0.20700	2100	0.00702	0.20900
19	685	0.00231	0.31400	571	0.00191	0.32800	616	0.00206	0.29700
20	1390	0.00468	0.23300	1500	0.00503	0.29800	1540	0.00514	0.29000

Table 3e. Catch, proportion, and CV by three methods for Area 3, 1979.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	227	0.00072	0.71400	413	0.00131	0.65100	430	0.00136	0.63400
6	3530	0.01120	0.18500	3520	0.01120	0.22400	3670	0.01160	0.21400
7	19400	0.06160	0.07740	21400	0.06780	0.08940	21800	0.06900	0.08650
8	38500	0.12200	0.05430	33100	0.10500	0.06860	33700	0.10700	0.06620
9	51200	0.16200	0.04960	49300	0.15600	0.05870	49700	0.15700	0.05730
10	55600	0.17700	0.04880	54700	0.17400	0.05590	54500	0.17300	0.05520
11	39800	0.12600	0.06060	43100	0.13700	0.06510	43000	0.13600	0.06460
12	36300	0.11500	0.06400	38700	0.12300	0.06860	38600	0.12200	0.06830
13	18800	0.05960	0.09230	21600	0.06850	0.09340	21600	0.06840	0.09140
14	15500	0.04930	0.10200	19300	0.06120	0.09480	19300	0.06100	0.09280
15	7540	0.02390	0.14900	11100	0.03530	0.12600	11100	0.03520	0.12200
16	6010	0.01910	0.16800	9050	0.02870	0.14200	9040	0.02860	0.13700
17	2770	0.00881	0.25200	4250	0.01350	0.20600	4180	0.01320	0.20300
18	1810	0.00573	0.31100	2890	0.00917	0.24400	2840	0.00897	0.23600
19	355	0.00113	0.70600	829	0.00263	0.44200	836	0.00264	0.42500
20	341	0.00108	0.70600	913	0.00290	0.36600	916	0.00290	0.35700

Table 3f. Catch, proportion, and CV by three methods for Area 3, 1980.

	Add-and-project			Combined			Project-and-add		
Age	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	244	0.00070	0.69900	229	0.00067	0.69800	371	0.00108	0.69800
6	2110	0.00609	0.24000	2000	0.00585	0.23500	1960	0.00573	0.27200
7	11500	0.03320	0.09990	10600	0.03110	0.09850	11000	0.03230	0.11000
8	33100	0.09560	0.05640	31000	0.09070	0.05600	32200	0.09420	0.06120
9	38100	0.11000	0.05380	35900	0.10500	0.05370	34800	0.10200	0.06220
10	59100	0.17100	0.04250	56600	0.16600	0.04250	57700	0.16900	0.04780
11	52500	0.15200	0.04550	51600	0.15100	0.04550	51800	0.15100	0.05170
12	46400	0.13400	0.04860	46000	0.13500	0.04880	44300	0.13000	0.05590
13	32400	0.09370	0.05860	32500	0.09510	0.05870	33300	0.09740	0.06610
14	25600	0.07390	0.06570	26800	0.07830	0.06540	27700	0.08110	0.07310
15	14700	0.04250	0.08730	15700	0.04580	0.08700	13900	0.04060	0.10000
16	10900	0.03140	0.10200	11700	0.03410	0.10200	11800	0.03440	0.11200
17	6500	0.01880	0.12700	7070	0.02070	0.12800	6440	0.01880	0.14500
18	5150	0.01490	0.14500	5660	0.01660	0.14400	5080	0.01480	0.16400
19	3430	0.00991	0.17200	3750	0.01100	0.17300	3960	0.01160	0.18700
20	1910	0.00553	0.23300	2150	0.00629	0.23100	2460	0.00719	0.24900

Table 4a. Catch, proportion, and CV by three methods for Area 4, 1975.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
7	181	0.01220	0.27200	171	0.01180	0.26600	204	0.01430	0.35300
8	913	0.06160	0.12500	937	0.06490	0.12600	1000	0.07050	0.18000
9	942	0.06360	0.12500	936	0.06480	0.12700	806	0.05660	0.19500
10	1400	0.09440	0.10500	1410	0.09770	0.10500	1150	0.08090	0.16500
11	1170	0.07900	0.11400	1090	0.07530	0.11500	665	0.04660	0.19200
12	1480	0.10000	0.10100	1370	0.09510	0.10300	1330	0.09360	0.14900
13	929	0.06270	0.12700	899	0.06220	0.13000	898	0.06300	0.18700
14	2230	0.15000	0.08090	2120	0.14700	0.08150	1860	0.13000	0.12100
15	856	0.05780	0.13100	874	0.06050	0.13300	882	0.06180	0.18500
16	893	0.06030	0.12500	898	0.06220	0.12600	1010	0.07110	0.17000
17	1120	0.07560	0.11100	1090	0.07530	0.11200	1020	0.07140	0.16200
18	691	0.04660	0.13800	701	0.04860	0.14000	762	0.05340	0.19200
19	308	0.02080	0.20800	294	0.02030	0.21300	428	0.03000	0.25400
20	494	0.03330	0.16300	470	0.03250	0.16400	547	0.03840	0.21300

Table 4b. Catch, proportion, and CV by three methods for Area 4, 1976.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
7	196	0.01120	0.26800	115	0.00648	0.28900	127	0.00714	0.28500
8	496	0.02830	0.17000	353	0.01990	0.17900	322	0.01810	0.18300
9	1550	0.08840	0.09660	1080	0.06120	0.10400	1060	0.05930	0.10700
10	1220	0.06970	0.11100	786	0.04440	0.13400	760	0.04270	0.14200
11	1730	0.09850	0.09220	1350	0.07640	0.11200	1380	0.07750	0.11300
12	1060	0.06040	0.11500	960	0.05420	0.14400	938	0.05270	0.14900
13	1310	0.07470	0.10400	1360	0.07680	0.12700	1380	0.07750	0.12700
14	1100	0.06300	0.11300	984	0.05560	0.14300	985	0.05530	0.14600
15	1920	0.11000	0.08430	1880	0.10600	0.10900	1830	0.10300	0.11200
16	837	0.04780	0.13000	903	0.05100	0.16700	967	0.05430	0.16100
17	1060	0.06030	0.11600	1280	0.07230	0.14100	1290	0.07260	0.14100
18	961	0.05490	0.12000	1230	0.06920	0.14300	1240	0.06960	0.14200
19	883	0.05040	0.12400	1160	0.06530	0.14500	1190	0.06660	0.14400
20	678	0.03870	0.14200	957	0.05400	0.16000	975	0.05480	0.15800

Table 4c. Catch, proportion, and CV by three methods for Area 4, 1977.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
7	434	0.01390	0.19600	367	0.01200	0.20100	328	0.01060	0.21000
8	1500	0.04770	0.11100	1470	0.04830	0.11300	1420	0.04600	0.11400
9	1700	0.05410	0.10600	1660	0.05430	0.11100	1740	0.05630	0.11400
10	4470	0.14200	0.06530	4120	0.13500	0.06990	4220	0.13700	0.07450
11	1980	0.06310	0.10100	2010	0.06570	0.10700	2190	0.07110	0.10900
12	3240	0.10300	0.07740	3270	0.10700	0.08160	3300	0.10700	0.08650
13	2780	0.08880	0.08410	2950	0.09670	0.08760	3110	0.10100	0.09200
14	2760	0.08810	0.08180	2820	0.09230	0.08600	3040	0.09860	0.09180
15	2360	0.07510	0.08990	2320	0.07580	0.09530	2330	0.07550	0.10600
16	3440	0.11000	0.07260	3310	0.10800	0.07670	3240	0.10500	0.08410
17	1460	0.04660	0.11300	1360	0.04440	0.11700	1200	0.03900	0.13600
18	1490	0.04740	0.11200	1430	0.04680	0.11800	1390	0.04500	0.13200
19	946	0.03020	0.14200	879	0.02880	0.14700	866	0.02810	0.16400
20	619	0.01970	0.16900	569	0.01860	0.17700	495	0.01610	0.21200

Table 4d. Catch, proportion, and CV by three methods for Area 4, 1978.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	36	0.00133	0.58000	32	0.00120	0.49800	33	0.00119	0.52400
7	274	0.01010	0.21600	264	0.00980	0.21400	317	0.01160	0.22800
8	1240	0.04580	0.09970	1070	0.03970	0.10300	1240	0.04510	0.10700
9	1420	0.05260	0.09390	1330	0.04920	0.09690	1480	0.05410	0.10000
10	1430	0.05300	0.09430	1500	0.05580	0.09490	1590	0.05790	0.10200
11	2350	0.08690	0.07340	2330	0.08660	0.07460	2390	0.08710	0.08180
12	1590	0.05890	0.09060	1580	0.05880	0.09190	1650	0.06020	0.10400
13	1880	0.06950	0.08330	1900	0.07060	0.08440	1850	0.06730	0.09650
14	2200	0.08150	0.07650	2220	0.08250	0.07750	2290	0.08340	0.08630
15	2600	0.09630	0.07020	2640	0.09780	0.07050	2610	0.09530	0.08070
16	2570	0.09520	0.07010	2580	0.09590	0.07100	2480	0.09030	0.08100
17	2450	0.09050	0.07190	2510	0.09310	0.07280	2370	0.08640	0.08310
18	1830	0.06750	0.08310	1850	0.06870	0.08370	2040	0.07440	0.09380
19	1500	0.05560	0.09180	1470	0.05450	0.09260	1440	0.05250	0.10900
20	1110	0.04090	0.10800	1110	0.04120	0.10900	1150	0.04200	0.12300

Table 4e. Catch, proportion, and CV by three methods for Area 4, 1979.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
6	72	0.00226	0.44600	73	0.00232	0.43200	73	0.00225	0.43200
7	581	0.01830	0.15500	541	0.01720	0.14400	532	0.01640	0.14500
8	791	0.02480	0.13400	752	0.02390	0.13700	782	0.02410	0.14600
9	2090	0.06570	0.08210	1860	0.05930	0.08410	1930	0.05950	0.08970
10	3150	0.09890	0.06610	2970	0.09450	0.06900	3370	0.10400	0.07570
11	3380	0.10600	0.06420	3280	0.10400	0.06750	3590	0.11100	0.07290
12	3070	0.09650	0.06840	2830	0.09010	0.07090	2930	0.09030	0.07610
13	2040	0.06390	0.08500	2030	0.06470	0.08980	2160	0.06650	0.09390
14	2800	0.08800	0.07210	2940	0.09350	0.07650	3190	0.09810	0.08040
15	2700	0.08490	0.07350	2530	0.08040	0.07940	2600	0.08000	0.08270
16	2890	0.09080	0.07080	2890	0.09190	0.07560	2860	0.08810	0.07730
17	2360	0.07420	0.07860	2480	0.07870	0.08430	2460	0.07580	0.08480
18	1850	0.05820	0.08920	1970	0.06260	0.09620	1880	0.05780	0.09560
19	1340	0.04210	0.10500	1380	0.04390	0.11400	1370	0.04200	0.11700
20	985	0.03100	0.12200	969	0.03080	0.13100	948	0.02920	0.13200

Table 4f. Catch, proportion, and CV by three methods for Area 4, 1980.

Age	Add-and-project			Combined			Project-and-add		
	Catch	Prop.	CV	Catch	Prop.	CV	Catch	Prop.	CV
3	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
4	0	0.00000	0.00000	0	0.00000	0.00000	0	0.00000	0.00000
5	9	0.00051	0.99700	7	0.00040	0.99400	3	0.00023	0.99000
6	0	0.00000	0.00000	0	0.00000	0.00000	2	0.00013	1.00000
7	123	0.00720	0.26600	112	0.00676	0.26300	65	0.00430	0.29200
8	246	0.01440	0.18700	222	0.01340	0.19200	112	0.00745	0.20900
9	747	0.04390	0.10600	678	0.04080	0.10600	522	0.03460	0.17900
10	1500	0.08810	0.07470	1380	0.08320	0.07560	1050	0.06980	0.12700
11	2090	0.12300	0.06310	1970	0.11800	0.06460	1540	0.10200	0.11400
12	2170	0.12700	0.06190	1990	0.12000	0.06340	1770	0.11800	0.10800
13	1180	0.06940	0.08450	1110	0.06710	0.08670	1100	0.07310	0.14800
14	1170	0.06900	0.08430	1150	0.06900	0.08650	1070	0.07100	0.14500
15	1230	0.07210	0.08160	1260	0.07600	0.08350	1340	0.08900	0.13900
16	1350	0.07950	0.07750	1330	0.08020	0.07980	1380	0.09150	0.13100
17	1100	0.06440	0.08550	1070	0.06420	0.08830	1300	0.08660	0.14100
18	1060	0.06250	0.08660	1110	0.06710	0.08900	901	0.05980	0.15100
19	729	0.04280	0.10400	792	0.04770	0.10700	592	0.03930	0.18700
20	758	0.04460	0.10100	792	0.04770	0.10500	804	0.05340	0.16800