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Productivity of the Queen Charlotte Islands herring stock

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Abstract

Over the last 44 years the prefishery biomass of the Queen Charlotte Islands (QCI) herring stock has averaged about 29 thousand t, and the catch about 8.1 thousand t. The productivity of this stock undergoes large changes in response to interannual and decadal timescale variations in spawner biomass (and other factors that remain relatively obscure), and the resulting recruitment to the stock four years later. Recruitment accounts for most of the stock productivity. The stock-recruitment curve suggests that QCI herring have been most productive when the average spawning stock biomass has been about 11 thousand t. Since 1950, the average carrying capacity of the stock appears to have been about 46 to 49 thousand t. The 1951 and 1977 year-classes were extraordinarily large. In contrast, the 1990, 1991 and 1992 yr-classes were extremely small. The failure of these yr-classes caused the stock biomass to decline below the cutoff threshold (10,700 t), so the commercial roe herring fishery was closed from 1994 to 1997 to allow the stock to rebuild. Previous studies have found that recruitment to the QCI herring stock is correlated with several environmental variables. However, the correlations that have been discovered so far aren't very useful for stock forecasting because they don't explain much of the residual, "density-independent" recruitment variability. More work needs to be done to extract other plausible forms of the stock-recruitment signal from the "noise" in the recruitment time series and, more importantly, to discover some relevant environmental and ecosystem variables that explain a significant fraction of the residual variation.

Résumé

Au cours des 44 dernières années, la biomasse d'avant la pêche du stock de hareng des îles de la Reine-Charlotte (IRC) s'élevait en moyenne à 29 000 t environ et les captures à 8 100 t environ. La productivité de ce stock subit d'importants changements résultant de variations, à l'échelle de l'année ou de la décennie, de la biomasse des géniteurs (et d'autres facteurs mal connus) et du recrutement au stock qui en découle quatre années plus tard. Le recrutement est l'élément principal de la productivité du stock. La courbe stock-recrutement indique que le hareng des IRC a été plus productif lorsque la biomasse moyenne du stock de géniteurs était de 11 000 t environ. Depuis 1950, la capacité de tolérance moyenne du stock semble avoir été de l'ordre de 46 000 à 49 000 t. Les classes d'âge de 1951 et de 1977 ont été extrêmement importantes. Au contraire, celles de 1990, 1991 et 1992 ont été extrêmement faibles. L'échec de ces classes d'âge a donné lieu à une baisse de la biomasse du stock en deçà du seuil d'exploitation (10 700 t) et la récolte commerciale des oeufs a été interdite de 1994 à 1997 afin de permettre au stock de se rétablir. Des études antérieures ont montré que le recrutement au stock des IRC est corrélé avec diverses variables environnementales. Les corrélations qui ont été établies jusqu'à maintenant ne sont cependant pas très utiles pour la prévision du stock car elles n'expliquent que très peu la variabilité résiduelle du recrutement « indépendante de la densité ». Il faudra effectuer des travaux plus approfondis pour isoler d'autres indices valables de la relation stock-recrutement du « bruit » de la série chronologique du recrutement et, ce qui est encore plus important, pour découvrir des variables pertinentes ayant trait à l'environnement et à l'écosystème qui permettront d'expliquer une fraction appréciable de la variation résiduelle.

Introduction

The Queen Charlotte Islands (QCI) herring stock is one of five major herring stocks in British Columbia. The assessment region for this stock extends from Cumshewa Inlet in the north to Louscoone Inlet in the south. Only small herring catches were taken from this region prior to the 1951/52 fishing season. Due to the extraordinary size of the 1951 year-class, a record high catch of 77,500 t was removed from the QCI stock in 1956. By 1965 most of the older fish were depleted by a combination of overfishing and a run of poor year-classes (born between 1954 to 1957). Consequently, the fishery collapsed in 1967 and was closed from 1968 to 1971 to enable the stock to rebuild (Hourston 1980). The stock did recover, and the fishery reopened in 1972 with a new focus on roe herring. B.C. herring stocks are currently managed by a fixed 20% target harvest rate, in conjunction with a minimum spawning biomass (called the Cutoff). Stocker (1993) has reviewed the evolution of this management policy and its success.

The objective of this working paper is to estimate the average productivity of the Queen Charlotte Island herring stock since 1951, and to explore the implications of one possible form of the stock-recruitment relationship (the Ricker equation). Note that all of the estimates in this paper are derived from output from the age-structured model, and not from the escapement model (Schweigert et al 1996).

Biological Definitions and Life History Events

For simplicity, the biomass of the Queen Charlotte Islands herring stock can be visualized as three dynamic pools: juveniles (ages 0+, 1+ and 2+), recruit spawners (age 3+), and repeat spawners (which comprise the adult age-groups 4+ to 10+). The reproductive biomass of the population consists of the last two pools. The dominant age-groups in the population are normally 3+ and 4+ (Table 1); few herring live longer than 10 years. The adult biomass changes annually in response to the following sequence of events. From a production standpoint, a new year begins after spawning (in March) with the biomass of surviving adults (the initial biomass, IB). The variation in this biomass over the last four decades is shown in Fig. 1 . From spring to late fall, the biomass of the adult reproductive pool is increased concurrently by individual growth, and depleted by natural mortality. Maturing age 3+ herring join the repeat spawner pool on the offshore banks sometime during the summer. In late winter, these maturing adults migrate from the offshore feeding banks to the inshore spawning grounds, where the fishery occurs. The prefishery biomass (PFB) is defined as the size of the mature reproductive biomass immediately before the fishery in early March. After the catch is removed, the survivors form the spawning biomass (SB). Spawning normally occurs within few days or weeks after the fishery. All subsequent calculations required to estimate the adult stock production and biomass at different times during the year are referenced to this foregoing sequence of events.

Stock Production

Year-to-year changes in the biomass of adult herring are caused by five dynamic processes: growth, natural mortality, recruitment, catch and spawn.

Adult Stock Growth. An age-specific growth factor (GF) was calculated from the average body weights of the reproductive age-groups measured between 1951 to 1994. The data (summarized in Table 1) indicate that the growth factor declines with age. Consequently, an average adult growth factor (PGF) was calculated by weighting the age-specific growth factors by the respective long-term percentage of the stock in each mature age-group (from age 3+ and older, Table 1). This weighted growth index combines the effects of year-to-year changes in the frequency and average body weight of each mature age-group, and is therefore affected by year-to-year changes in recruitment, fishing mortality, and growing conditions.

Table 1 shows that the body weight of an adult herring increases, on average, by a factor of 1.51 during the growing season. For computational purposes, it is useful to note that the instantaneous growth rate (G) is simply the natural logarithm of the PGF index (hence the long-term average G = 0.41). The growth factor has varied over time, but the observed fluctuations have tended to be small (the coefficient of variation is only 4% of the mean value, Fig.2). Consequently, interannual variations in adult growth can be left undefined (in this paper) with only a modest loss of precision in subsequent calculations.

Natural Mortality Rate. Previous studies of B.C. herring have made direct estimates of the instantaneous natural mortality rate (M) from catch-at-age curves. For example, Tester (1955) found that the natural mortality rate increased with age in the Strait of Georgia and the West coast of Vancouver Island stocks, ranging from about -0.40 to -0.45 at ages 3+ to 4+, and increasing to about -0.79 to -0.85 by ages 6+ to 7+. Age-structured model reconstructions back to 1951 also indicate that the long-term natural mortality rate of the adult component of the QCI population averages about - 0.46 (Schweigert et al 1996). This means that all sources of natural mortality (presumably largely predation and disease) remove about 37 % (i.e. 100[1-Exp[- 0.46]) of the reproductive individuals from the population each year. Hence,

$$\text{Adult natural mortality} = 0.37*B. \tag{1}$$

Here, the average adult biomass (B) is defined by Ricker (1975) as:

$$B = IB(\exp[G-M] - 1)/(G-M). \tag{2}$$

Hence, for the QCI herring population B is about 0.97*IB.

The annual net production of the adult component of the stock (evaluated just before spawning) is determined by the annual instantaneous growth and natural mortality rates. Applying the long-term average values, we obtain:

$$\text{Adult net production} = IB*(\exp[G-M]-1) = -0.05*IB. \tag{3}$$

Hence, on average, the growth of the adult age groups is less than the biomass removed by natural mortality, so the annual net production by adults is negative.

Recruitment. The biomass of recruit spawners from the 1951 to 1990 year-classes was calculated from age-structured model reconstructions of age 3+ abundance (Schweigert et al 1996), and annual measurements of body weight. For this particular stock the long-term average body weight at age 3+ is about 125 g (Table 1). Prior to 1972, age 3+ recruits were all available (availability = 100%) to the herring reduction fishery. However, once the roe fishery began in 1972, the age-structured model estimates that only 61% of the age 3+ recruits were available to capture. Consequently, the number of age 3+ recruits was multiplied by their average body weight, and the respective availability factor for each period to produce the estimated recruit biomass time series shown in Fig. 3. Over the last four decades, recruitment has averaged about 10,000 tonnes, and has varied between 700 t to 60,900 t. Recruitment is clearly the most dynamic component of the production equation for the QCI stock.

Catch. Over the last four decades, the fishery has removed an average annual catch of 8,100 tonnes (Schweigert et al 1996). QCI herring become available to the fishery at age 3+ (i.e. there is a 4 year time lag from birth to recruitment). Not suprisingly, the size of the catch has varied considerably, in response to changes in the size and availability of the stock, and in the nature of the fishery (Fig. 4). If the forecast prefishery stock biomass (PFB) is near the 10,700 t cutoff threshold, the recommended catch is decreased so the fishery doesn't deplete the biomass below the cutoff (Schweigert et al 1996).

Spawning. In contrast to the wide fluctuations that have occurred in the recruitment and the catch, the per capita reproductive output of the adult population is more stable (Tanasichuk & Ware 1987). A long time series of gonad weight measurements indicates that about 23% of the spawning biomass (SB, averaged over both sexes) is invested annually in reproduction (Table 1). Hence,

$$\text{Spawn} = 0.23 * \text{SB} \tag{4}$$

where SB = PFB - Catch.

Production. From the foregoing definitions it follows that the new biomass added to the adult population each year (B_{new}, tonnes/yr) is given by:

$$B_{new} = \text{Adult net production} + \text{Recruitment} \tag{5}$$

The first term in equation 1 represents the growth of the survivors in the repeat spawner pool (age-groups 4+ and older), while the second term represents the biomass of new recruit spawners (3+ age-group).

The change in biomass of the reproductive pool from one year to the next is therefore given by:

$$IB_{t+1} = IB_t + [B_{new} - \text{Catch} - \text{Spawn}]. \tag{6}$$

Age-structured model estimates of the long-term average biomass levels of important stock characteristics are summarized in the following table:

Variable	Average Value
Initial biomass	15,600 t
Mean biomass	16,900 t
Adult mortality	6,200 t
Recruitment	9,800 t
Prefishery biomass	28,700 t
Catch	8,100 t
Spawning biomass	20,300 t
Spawn	4,700 t

Note that the age-structured model produces higher stock biomass and production estimates than the escapement model (see Schweigert et al 1996). At this time, we don't know which of these two models yields the most accurate estimates.

Recruitment and Carrying Capacity

Stock and Recruitment. Hilborn and Walters (1992) noted that the most serious problem in the analysis of stock and recruitment was in obtaining reliable measures of spawning stock and subsequent recruitment. Simulation analyses indicate that the amount of bias caused by errors in measuring spawning stock size depends upon the magnitude of the errors and the amount of real variation in spawning stock. They noted that if small stocks are at least 1/10th of the largest stocks, the biases in this case will probably be of little concern. For the QCI stock the smallest spawning stock is about 1/35 of the largest stock. Consequently, the bias caused by the "error in variable" problem is probably small.

The recruitment data were fit to the Ricker stock-recruitment equation (Ricker 1975):

$$R = a\, SB \exp(-bSB). \tag{7}$$

A simplex, non-linear curve fitting routine (SYSTAT) was used to estimate the two parameters in this equation. The analysis was performed using all the data, including the anomalously large 1951 and 1977 yr-classes (open circles in Fig. 5). The resulting fit of the model to the data is shown in Fig. 5, and is summarized below:

Parameter	Value
# year-classes	40
a	3.839
b	0.0931
Average root-mean-square error	12,300 tonnes
Maximum recruitment (Rmax)	15,200 tonnes
Spawning biomass producing Rmax	10,700 tonnes
Carrying capacity (Bmax)	49,000 tonnes

It could be argued that since the 1951 and 1997 yr-classes were exceptionally large they should be excluded from the analysis as outliers. Clearly, these exceptionally large yr-classes were produced by some unusual combination of very favourable events which occur very infrequently (only twice in the last 40 years), so perhaps these two yr-classes should be excluded so they don't have an undue influence on the estimated stock/recruitment paramaters. Omitting these yr-classes produces the following estimates and results:

Parameter	Value
# year-classes (1951 & 1977 excluded)	38
a	3.008
b	0.0939
Average root-mean-square error	6,800 tonnes
Maximum recruitment (Rmax)	11,800 tonnes
Spawning biomass producing Rmax	10,600 tonnes
Carrying capacity (Bmax)	46,000 tonnes

Carrying Capacity (B_{max}). Given sufficient time, an unfished population will increase to some maximum value, called the Carrying Capacity. A dynamic numerical population model, which assimilates the stock-recruitment function, and other vital population rates summarized in the text was developed to estimate B_{max}. The model is outlined in Appendix 1. The simulation results suggest that the lower east coast of the Queen Charlotte Islands ecosystem, on average, can support a maximum of about 46,000 to 49, 000 tonnes of adult herring, depending upon which stock/recruitment parameter estimates are used.

In reality, natural fish populations often overshoot and oscillate about their carrying capacity due to a combination of random and periodic variations in recruitment, and in other important population processes. These vital rates can be altered by changes in ocean climate (Hsieh et al 1995, Ware and Tanasichuk 1997), and by changes in the structure and productivity of the ecosystem that the population belongs to (Ware 1991; Robinson and Ware 1994; Ware and McFarlane 1995).

Concluding Remarks

This paper has explored some of the production implications for the QCI herring stock when the under-lying stock-recruitment relationship has the form of the Ricker equation. Other methods can be used to estimate the unfished equilibrium biomass (or carrying capacity). For example, Schweigert (pers. communication) has developed an age-structured simulation model to estimate the stock carrying capacity (B_{max}), and the commercial fishery cutoff (which is set at 0.25 B_{max}). Schweigert's method randomly selects a value for recruitment in each simulated year from the distribution of recruits estimated by the age-structured model. The resulting number of recruits is then multiplied by the age-specific availability factor and average weight-at-age, to determine the biomass. The PSARC herring subcommittee has adopted this method for estimating B_{max} and the resulting cutoff for each of the five major B.C. herring stocks. For the QCI herring stock, Schweigert's method yields an unfished carrying capacity of about 43,000 t, which is very similar to the values obtained in this paper (46,000 to 49,000 t), using a different estimation procedure.

Previous studies have found some weak correlations between recruitment in the QCI herring stock and climatic variables (Stocker and Noakes, 1988; Schweigert and Noakes, 1991). Intuitively, and by analogy with findings for other herring stocks, I suspect that QCI herring recruitment is also influenced by interannual and decadal timescale variations in ecosystem properties and in the prevailing climate (Ware 1991, 1995). However, the correlations that have been found so far for the QCI stock aren't very useful for forecasting prefishery biomass because they don't explain much of the residual, "density-independent" variability in recruitment. More work needs to be done to extract other plausible forms of the stock-recruitment signal from the "noise" in the QCI recruitment time series and, more importantly, to discover some relevant climate (and ecosystem) factors that explain a significant fraction of the residual variation.

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Table 1. Long-term average age composition (percent-at-age), average weight-at-age (g), and age-specific growth factors for the adult component of the Queen Charlotte Islands herring stock (from 1951 to 1993). The age-specific and weighted adult growth factor was estimated in two ways: 1) from the long-term average weights and ovary weights summarized below, and 2) from the average values in the growth factor time series (see Fig. 2), this is the number in [ ] . Note that the two estimates are very similar. The weighted Growth Factor (Weighted GF) was estimated for ages 3+ to age 6+ fish only (it does not include age 2+ herring which are mostly immature).

Age Group	Percent	Mean Weight	Growth Factor (GF)
2+	-	97.5	1.622 (1.615)
3+	25.7	124.6	1.534 (1.527)
4+	19.6	147.3	1.495 (1.492)
5+	11.6	166.9	1.463 (1.445)
6+	6.1	182.6	-
	Sum=63.0%	Weighted GF (PGF)=1.506 (1.498)	

Notes:

1. Ovary weight (g) = 0.087 $W^{1.23}$; Testes weight (g) = 0.028 $W^{1.41}$. Assuming an equal sex ratio: Gonad weight (g) = 0.049 $W^{1.32}$.

2. Mean weight = weight just before spawning, and growth factor = [W_{i+1} / W_i] where W_i = weight of age group (i) after spawning and W_{i+1} = weight of age group (i+1) just before spawning.

Appendix 1

Description of the Numerical Model Used to Estimate the Carrying Capacity

A dynamic pool model created using STELLA® numerical modelling software was used to estimate the carrying capacity of the QCI herring stock when there is no fishing mortality. The model estimates the biomass of the mature stock just before it spawns **(PFB)**. For the sequence of computations, the model year begins with the PFB. The catch (which is set to zero in this case) is subtracted to yield the spawning biomass **(SB)**. The biomass of **Spawn** released by the SB is subtracted, to yield the initial biomass of the adult population at the beginning of the production year **(IB)**. The natural **Mortality** of the IB is then subtracted to yield the returning adult survivors **(Returns)**. The biomass of these returning adults is then incremented by their **Growth**. Finally, the incoming biomass of **Recruits** is calculated and added to the returning adult biomass to determine the new PFB. In the model, the calculated biomass of recruits that are added to the adult stock pool each year has a four year time delay (i.e. the biomass of incoming recruits is determined by the spawning biomass four years earlier).The master equation is:

$$PFB\ (t) = PFB\ (t\text{-}dt) + (Recruits + Returns - Catch - Spawn - Mortality - IB) * dt$$

where t = time (yrs). Recruits is defined by eq. 7 (in the text above), Spawn is defined by eq. 4, and natural mortality is defined by eq. 1. To compute the unfished equilibrium biomass, the adult growth was assumed to be zero (because the growth rate of the adult stock becomes vanishingly small as the stock approaches it's carrying capacity). The master equation was integrated using a second order Runge-Kutta procedure with a time step (dt=0.1 yrs).

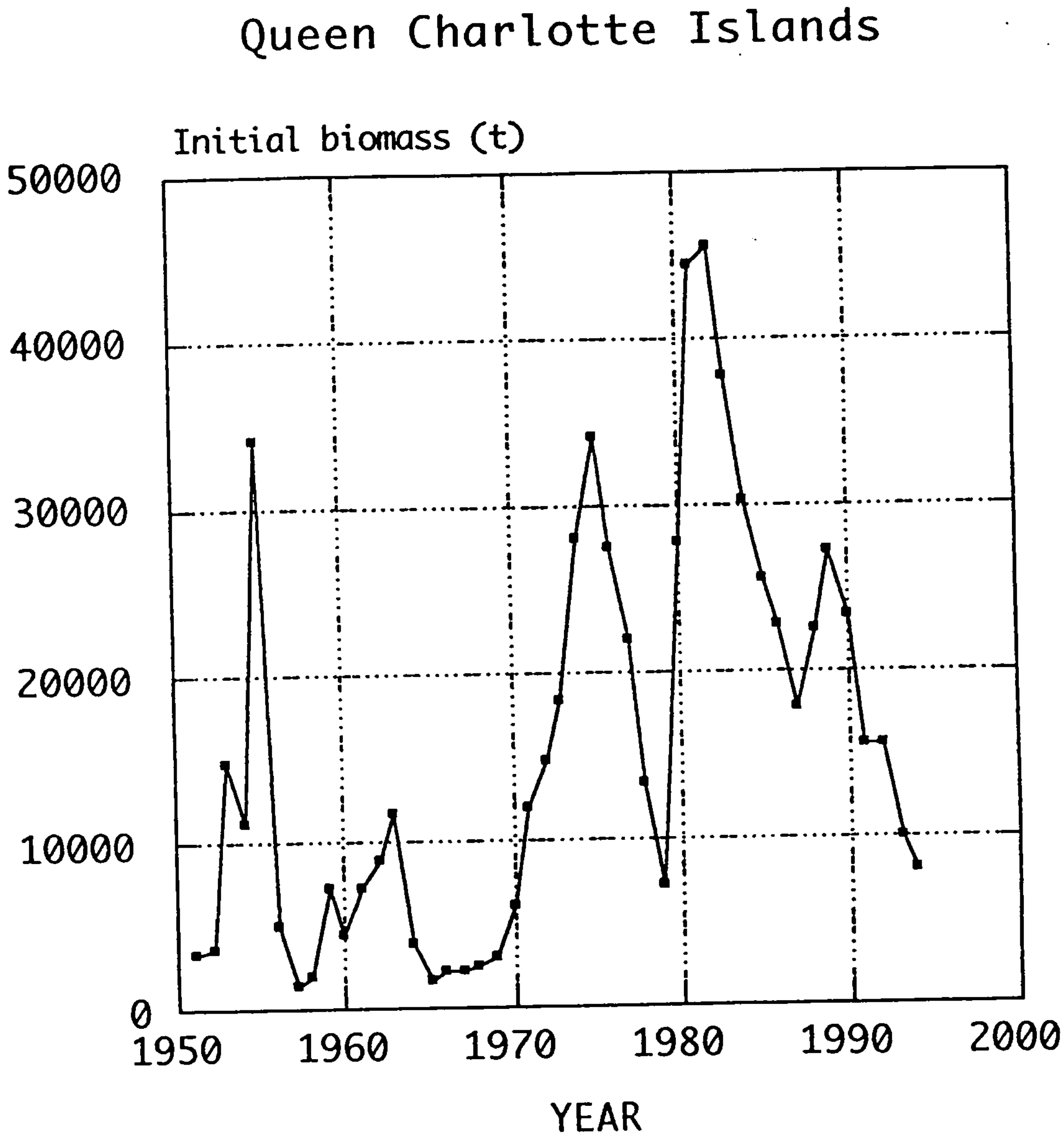

Figure 1. Biomass of the adult component of the population at the beginning of a new production year (IB, tonnes) in late March/early April.

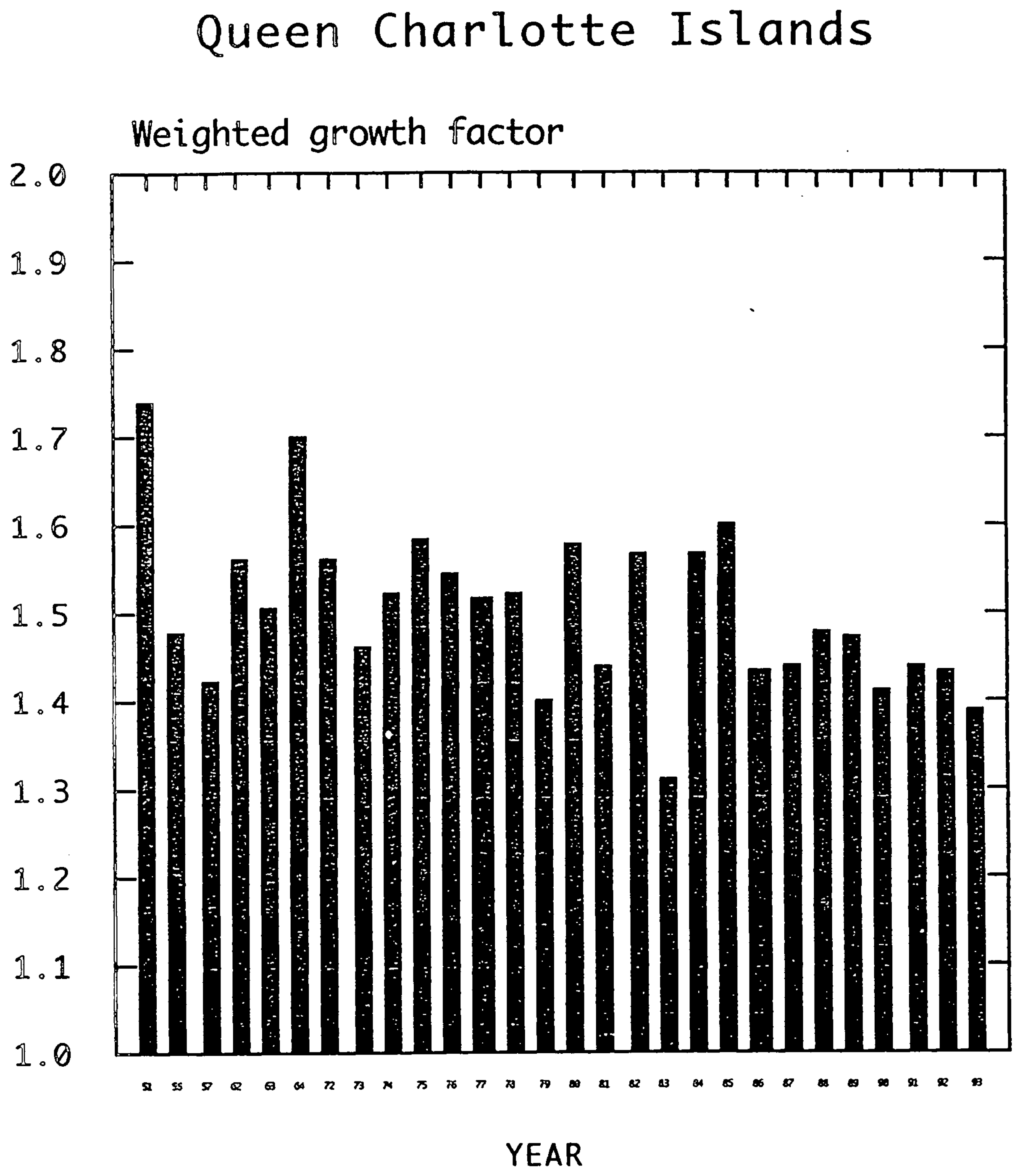

Figure 2. Weighted adult growth factor time series for Queen Charlotte Island herring. Note that body weights weren't measured in some years so the growth factors couldn't be calculated.

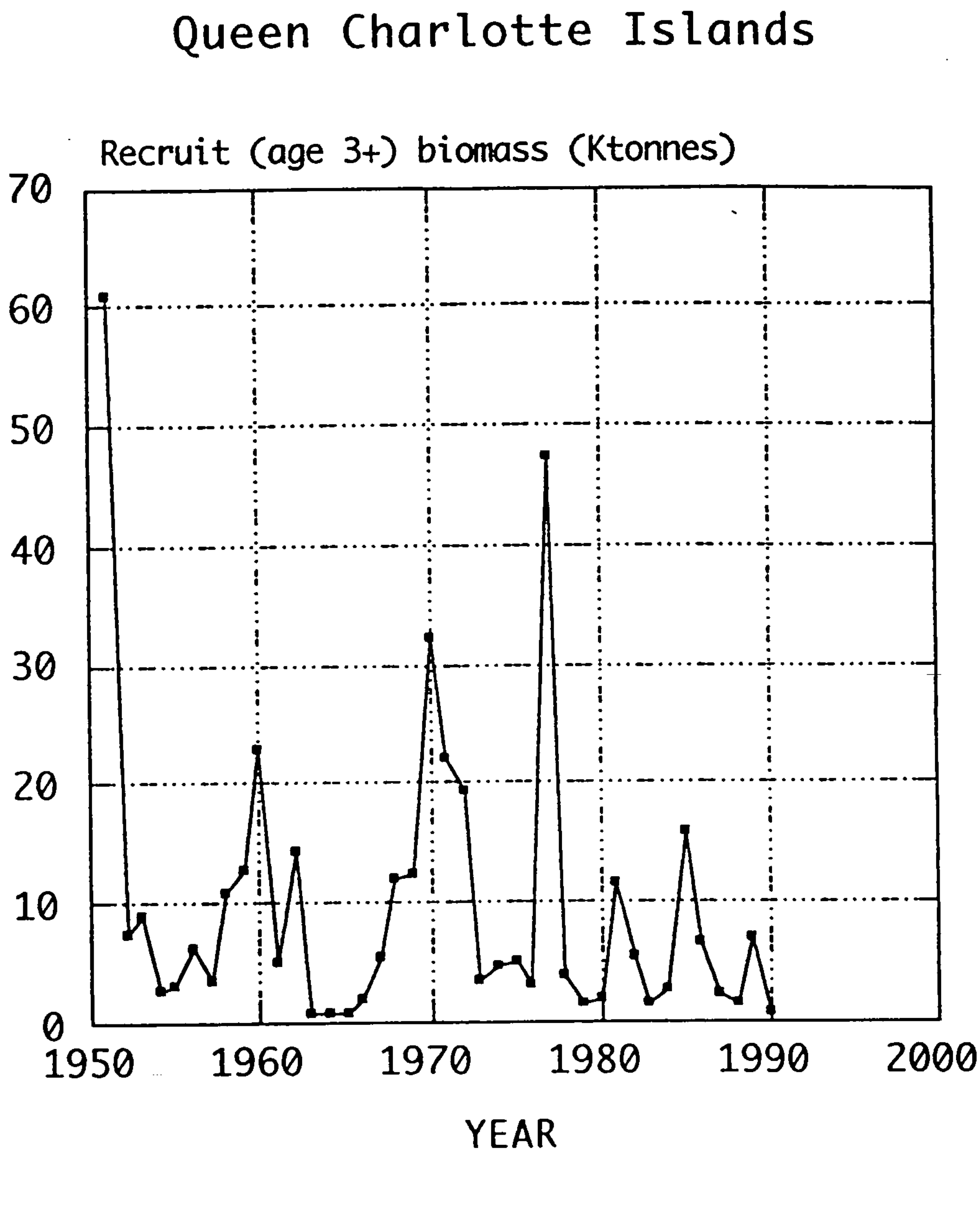

Figure 3. Queen Charlotte Island herring recruitment time series for 1951 to 1990 year-classes. Note that these year classes recruit to the fishery four years later.

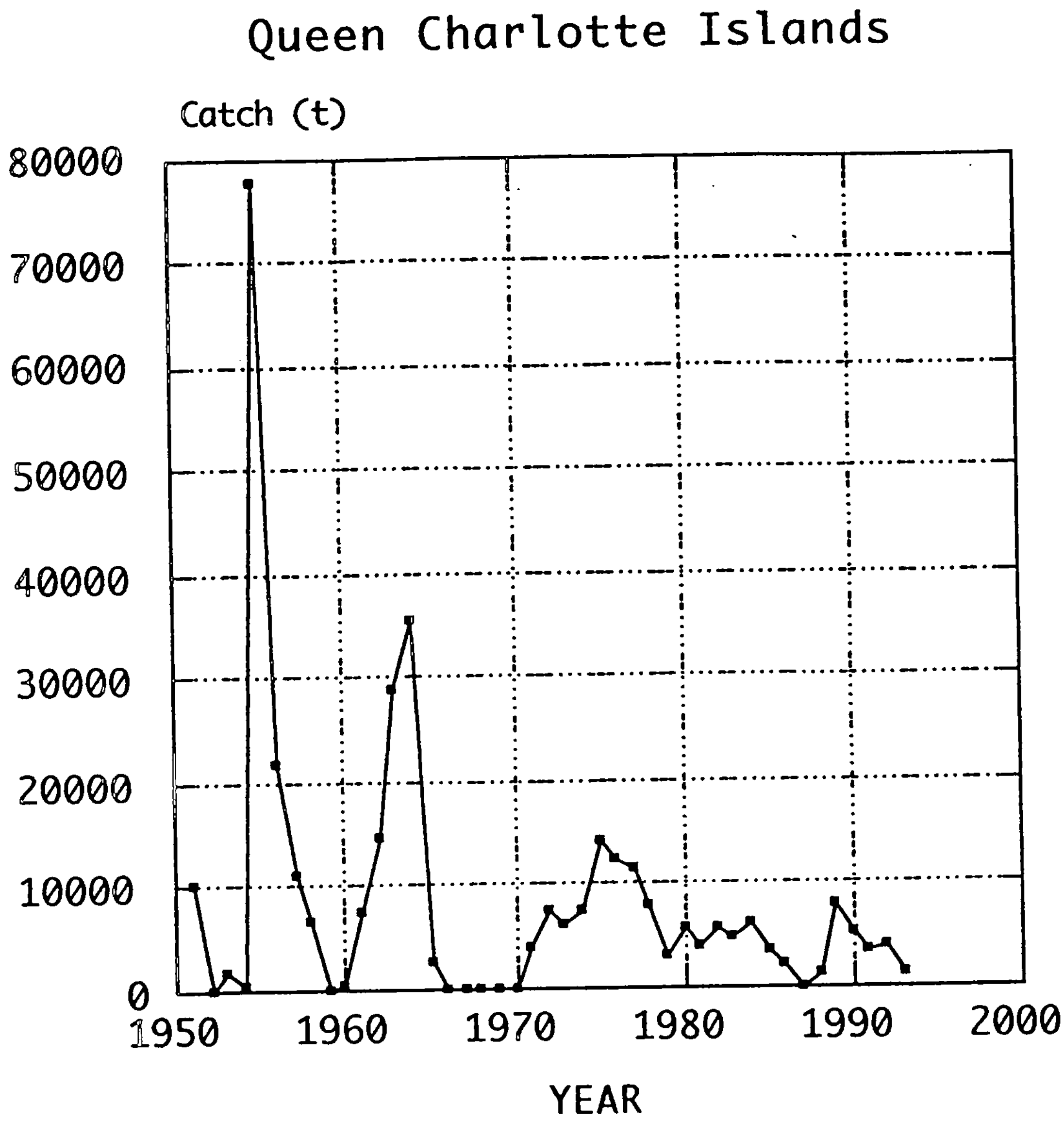

Figure 4. Catch time series for the Queen Charlotte Islands herring stock. Note that the fishery was closed to commercial harvest from 1966 to 1971, and that since 1983 the catch has been constrained by the 20% target harvest rate.

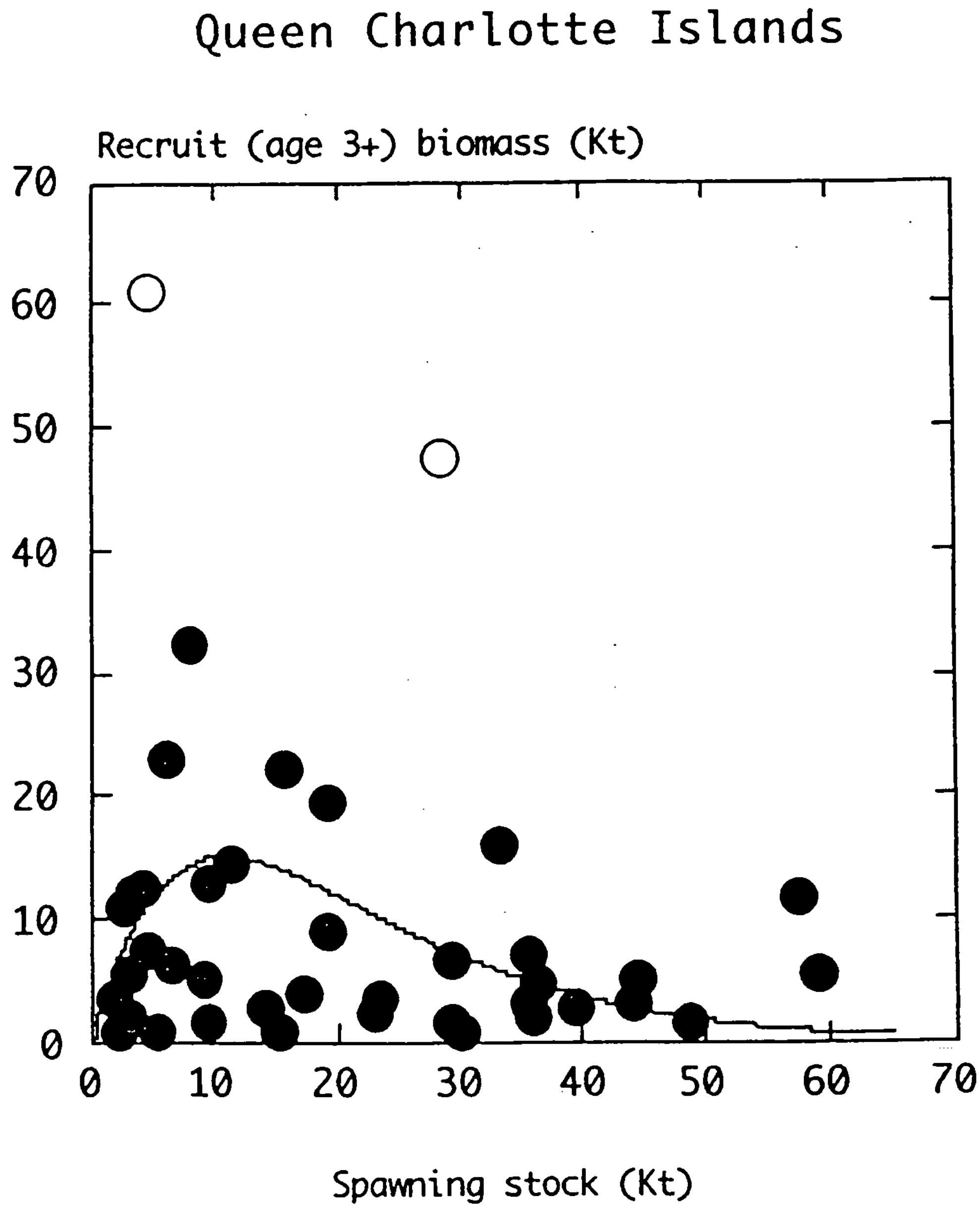

Figure 5 Fit of the Ricker stock-recruitment equation to the Queen Charlotte Island herring recruitment time series. The extraordinarily large 1951 and 1977 year-classes are indicated by the open circles.