SHORT NOTE

NATURAL MORTALITY RATE IN THE MACKEREL ICEFISH (*CHAMPSOCEPHALUS GUNNARI*) AROUND SOUTH GEORGIA

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Abstract

Information on natural mortality rates of the mackerel icefish (*Champsocephalus gunnari*) from the period prior to known large-scale commercial harvesting is discussed. After careful consideration of the data and available methods, several errors are noted in earlier estimates. Unfortunately, because none of the datasets are sufficiently comprehensive, it is impossible to unequivocally provide an estimate that is unaffected by confounding effects mainly due to recruitment variation, but also possibly due to age-dependent mortality and commercial fishing.

Résumé

Examen des informations relatives aux taux de mortalité naturelle du poisson des glaces (*Champsocephalus gunnari*) pour la période précédant l'exploitation commerciale à grande échelle. Une étude approfondie des données et méthodes disponibles a révélé plusieurs erreurs dans les premières estimations. Malheureusement, les jeux de données n'étant pas suffisamment complets, il est impossible de fournir sans équivoque une estimation qui ne soit pas affectée par des effets troublants dus principalement à la variation du recrutement, mais éventuellement à la mortalité dépendant de l'âge et à la pêche commerciale.

Резюме

В данной статье обсуждаются данные по естественной смертности ледяной рыбы (*Champsocephalus gunnari*) за период, предшествующий периоду крупно-масштабного коммерческого промысла. Всестороннее рассмотрение данных и имеющихся методов выявило несколько ошибок в предыдущих оценках. К сожалению, недостаточность всех наборов данных исключает возможность получить надежную оценку, на которую не влияют "затемняющие" анализ факторы, связанные в основном с изменчивостью пополнения, но, возможно, также и с зависимой от возраста смертностью и коммерческим промыслом.

Resumen

Se discute la información existente sobre las tasas de mortalidad natural del draco rayado (*Champsocephalus gunnari*) en el período anterior a la explotación comercial en gran escala. Luego de una consideración meticulosa de los datos y métodos, se tomó nota de varios errores en las estimaciones anteriores. Desafortunadamente, ya que ninguno de los conjuntos de datos considerados contiene suficiente información, es imposible proporcionar una estimación inequívoca que no esté afectada por efectos perturbadores debidos, en su mayoría, a la variabilidad del reclutamiento y, posiblemente, a la mortalidad por edad y a la pesca comercial.

INTRODUCTION

In age-structured models of fish population dynamics, total mortality (Z) can be estimated relatively easily from data on age composition, but it is generally difficult to divide this into its two most important components: fishing mortality (F) and natural mortality (M). Prior to the commencement of harvesting, when by definition F will be zero, Z will equate to M so that a good estimate can be made without defining the proportion of Z which is due to fishing. Consequently, there is considerable value in examining in detail all information on population age structure in advance of large-scale harvesting.

Interest in harvesting the mackerel icefish (*Champsocephalus gunnari* Lönnberg, 1905) from South Georgia waters began in the 1960s and large-scale catches have been reported from 1970 onwards. Everson (1978) indicates that large-scale fishing may have taken place prior to 1970, although details of catches prior to that date have neither been published nor made available to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

The most recent analysis leading to a best estimate of M for *C. gunnari* is contained in Kochkin (1995), which comes to essentially the same conclusions as, and reinforces, an earlier study (SC-CAMLR, 1989) which was undertaken during the meeting of the CCAMLR Scientific Committee's Working Group on Fish Stock Assessment (WG-FSA) in 1989. The main focus for discussion in both papers was information in Frolkina and Dorovskikh (1990) and this was considered in detail at the WG-FSA meeting by Sparre (1989). Pending the provision of further information, WG-FSA agreed that values of 0.56 (from Frolkina and Dorovskikh (1990), although that paper proposes a value of 0.55) and 0.35 (from SC-CAMLR, 1988) should be used.

The following year the information in Frolkina and Dorovskikh (1990) was presented in revised form in Frolkina and Dorovskikh (1991), with an age/length key from 1972 used to devise a separate age composition for each of the four seasons 1964/65, 1966/67, 1967/68 and 1968/69. The same paper provides information on the analyses undertaken. Although mentioned in the WG-FSA report, no discussion is reported in SC-CAMLR (1990), and the analyses reported were undertaken using M = 0.48 and M = 0.56. Although the justification for the former value is not given, it is possible that the value of 0.48 was the mean value for 1964/65 in Frolkina and Dorovskikh (1990), however this is not stated in SC-CAMLR (1990). Apparently, no analyses using M = 0.35 were undertaken at that time.

The recent study by Kochkin (1995) examined the datasets used by Frolkina and Dorovskikh (1990) and concluded that the best estimate of natural mortality coefficient prior to commercial exploitation is 0.5.

The only other published information on the population age structure of *C. gunnari* prior to large-scale fishing is in Olsen (1955), although no analyses were given in that paper leading to estimates of M.

This paper examines in detail the information from which survivorship in the unfished stock can be estimated in order to try to provide a reasoned estimate of M.

MATERIAL AND METHODS

Data on numbers of fish at each age have been taken from Olsen (1955) and Frolkina and Dorovskikh (1990). The data in Olsen (1955) relate to a single haul carried out in Cumberland Bay, South Georgia, on 5 April 1951. An age/length matrix is given which includes some fish for which the size was given but for which the age was indeterminable. These 'unaged' fish came from the total catch and consequently should be included in estimates of population age density; they have been assigned ages based on the information on 'aged' fish in the matrix. No information is given in Frolkina and Dorovskikh (1990, 1991) about sampling gear, number of hauls or location. It is assumed that the reported information came from a series of randomly located hauls around South Georgia during the 1972 austral summer and from which the age/length key in Frolkina and Dorovskikh (1991) was derived.

The following methods for the estimation of M were used by Frolkina and Dorovskikh (1990, 1991): Baranov (1918), Heincke (1913), Beverton and Holt (1956), Robson and Chapman (1961) and Alverson and Carney (1975). Sparre (1989) extended the number of estimates using the following methods: Algajava (1984) and Pauly (1980). Similar analyses were undertaken by Kochkin (1995).

In the form used by Frolkina and Dorovskikh (1990) and Sparre (1989), all the methods provide estimates of the coefficient of instantaneous mortality although none provide an estimated variance; this makes interannual comparisons impossible. Initial analyses for this study were undertaken using all of the above methods.

In an extensive consideration of mortality and survival rates, Seber (1982) discusses and provides worked examples, using the methods of Robson and Chapman (1961) and Heincke (1913), to estimate survivorship and its associated variance. These methods have been used in the present study. The relevant equations are as follows:

- Survivorship ($\hat{S}$) from Robson and Chapman (1961):

$$\hat{S} = \frac{X}{n + X - 1} \tag{1}$$

$$v\left[\hat{S}\right] = \frac{X}{n + X - 1}\left(\frac{X}{n + X - 1} - \frac{X - 1}{n + X - 2}\right) \tag{2}$$

where n is the total number of fish in the sample, the first fully recruited age is coded zero, the numbers at each coded age 'x' are n_x and $X = \Sigma x n_x$.

- Survivorship ($\hat{S}_1$) from Heincke (1913), where n is the total number of fish in all fully recruited age classes, and n_0 is the number sampled from the first fully recruited year class:

$$\hat{S}_1 = \frac{n - n_0}{n} \tag{3}$$

To test whether there is a significant difference between the two survivorship estimates the following chi-squared statistic was used:

$$\chi^2 = \frac{\left(\hat{S} - \hat{S}_1\right)^2}{\left(\dfrac{X \times (X - 1) \times (n - 1)}{n \times (n + X - 1)^2 \times (n + X - 2)}\right)} \tag{4}$$

RESULTS

The estimated age composition provided by Frolkina and Dorovskikh (1991) and Olsen (1955) for each year is set out in Figure 1.

Analysis of the data published by Frolkina and Dorovskikh (1991) indicated several errors present in the published paper. The mean of the four values given in their table for the 1964/65 season is 0.4075 and not 0.475, and the mean by the Baranov method for the same year is 0.48 and not 0.80 as stated. Incorporating these values gives a mean for 1964/65, using their methods, of 0.33. Also, the mean value for 1968/69 by the Baranov method is 0.645 and not 0.96 as given in Frolkina and Dorovskikh (1991). The correctly calculated mean values are set out below along with the mean age of the population given in Frolkina and Dorovskikh (1991).

Season	1964/65	1966/67	1967/68	1968/69
Mean 'M'	0.328	0.516	0.705	0.731
Mean age	5.8	4.9	4.3	4.1

These results indicate that the mortality rate is probably increasing with time, which in turn would explain a steady decline in the mean age of fish in the population. Both of these trends are indicative of a trend in the population age structure although, without confidence intervals associated with the mean values, it is impossible to determine whether the results should be pooled, as done by Frolkina and Dorovskikh (1991), or analysed separately.

There are further fundamental problems with this approach because, in determining the mean values for each season, all methods are given equal weight and an age/length key from a different period has been used. The methods which use the population age structure reflect the situation in immediately preceding seasons. Methods which rely on growth parameters are integrating information over several seasons and, consequently, it is not correct to analyse those data for comparison between seasons. The best approach therefore is to use the population age structure data to provide estimates of survivorship and mortality and then to use information from other sources, such as from growth equations, to corroborate the results. The age/length key from 1972 was obtained from a period several years after large-scale fishing commenced. In the absence of fishing such a procedure might be acceptable, but in the presence of significant harvesting it is likely to introduce significant bias (Kimura, 1977). With such limited datasets there is little alternative but to accept what information is available and be aware of any deficiencies.

Table 1: Survival and natural mortality rates and siginficance levels calculated from equations 1 to 4 for each season from data used in Figure 1 and assuming that fish are fully recruited at age 3 years.

Method	1951	1964/65	1966/67	1967/68	1968/69
$\hat{S}$	0.68	0.70	0.58	0.44	0.38
SD [$\hat{S}$]	0.017	0.030	0.013	0.020	0.023
$\hat{S}_1$	0.77	0.85	0.63	0.49	0.32
Chi square	12.0 $p < 0.001$	11.8 $p < 0.001$	10.0 $p < 0.001$	13.4 $p < 0.001$	196 $p < 0.001$
M (from $\hat{S}$)	0.38	0.36	0.55	0.81	0.96
M (from $\hat{S}_1$)	0.26	0.16	0.47	0.71	1.13
n	229	74	611	334	270

Table 2: Survivorship, expressed as a percentage, assuming that full recruitment occurs by ages 3, 4 and 5. Numbers in parentheses are standard deviation (equation 2) and those in italics are the number of fish used to provide the estimate.

	1951		1964		1966		1967		1968	
$\hat{S}$ recruit age 3	68%	(1.7)	70%	(3.0)	58%	(1.3)	44%	(2.0)	38%	(2.3)
$\hat{S}$ recruit age 4	64%	(2.2)	63%	(3.7)	54%	(1.7)	38%	(3.0)	48%	(3.9)
$\hat{S}$ recruit age 5	57%	(2.8)	50%	(4.9)	45%	(2.3)	16%	(3.7)	58%	(5.6)
$\hat{S}_1$ recruit age 3	77%	*229*	85%	*74*	63%	*611*	49%	*334*	32%	*270*
$\hat{S}_1$ recruit age 4	77%	*176*	86%	*63*	66%	*383*	51%	*165*	39%	*87*
$\hat{S}_1$ recruit age 5	64%	*135*	63%	*54*	52%	*251*	19%	*84*	47%	*34*

Using the assumption that fish are fully recruited to the fishable population by age 3 years, the annual survivorship has been estimated (Table 1 and Figure 2). The mean and 95% confidence interval from equations 1 and 2 indicate that survivorship in 1966/67, 1967/68 and 1968/69 was progressively, and significantly, lower than in the earliest years. This pattern is followed in the Heincke estimates using equation 3 (Table 1). This analysis also indicates that the survivorship prior to the two seasons, 1951 and 1964/65 was essentially the same.

The chi-squared statistic, equation 4, indicates that survivorship was significantly higher in the recruiting year class than in all other year classes. This could be because three-year-old fish were not fully recruited to the sampled population. To test this the analyses have been repeated assuming that recruitment takes place at ages 4 and 5. In each case the survivorship decreases with increasing age and

does not stabilise to a constant value. The same pattern is present for 1951, 1964 and 1966 (Table 2).

The alternative approaches to estimating M using the Bertalanffy growth equation are summarised below:

- Beverton and Holt (1956):
  M = 0.36 (1951 data) and M = 0.54 (1966/67 data);

- Pauly (1980):
  M = 0.23 (L_∞ = 60 cm, K = 0.18 and t_0 = -1 years and an effective physiological temperature of 6, equivalent to 2%C);

- Alagajava (1984):
  M = 0.31 (max age 15 years (Frolkina, 1990)); and

- Alverson and Carney (1975):
  M = 0.28 (assuming $N_t W_t$ max at 7 years).

DISCUSSION

Robustness of Estimators

Seber (1982) notes the assumptions underlying the Heincke and the Robson and Chapman methods. These are that:

(i)   the first fully recruited year class is correctly chosen;

(ii) when the data are derived from one year, recruitment is constant;

(iii) sampling of the population is random with respect to age; and

(iv) survivorship is the same for each age class and furthermore is constant from year to year.

Each of these assumptions are considered below.

Is the First Fully Recruited Year Class Correctly Chosen?

The chi-squared statistic indicates that the survivorship in the first fully recruited season is significantly different from that in all other age classes, which would suggest that this criterion has not been met (Table 1).

Unfortunately, the pattern of size at age reported by Olsen (1955) is different to that found by subsequent researchers (Kock, 1981; Sosinski, 1981; Gubsch, 1982). Additional information is available from Frolkina and Dorovskikh (1991), who provide an age/length key for the first half of 1972, which can be used to estimate size at age; these results also differ from those given by Olsen (1955). These differences either reflect differences between growth rate during the unexploited period around 1951 to those following significant fishing or differences in age determination methodology.

Key points centre on whether the same criteria have been used to determine age and whether the increment in size within a year is realistic. The five data sources mentioned above have been used for this part of the study. The mean size at age from these five sources has been calculated and the difference between the published values and the mean calculated (Figure 3). The estimated annual increase in size has also been calculated (Figure 4).

The differences (Figure 3) are reasonably close together for ages 3 and 4 but diverge for the older ages. The Olsen (1955) results are close to the mean for these two ages, but from ages 5 to 8 there is a progressive decrease, indicating that the estimated size is small for the age of the fish. The results derived from Frolkina and Dorovskikh (1991) begin slightly high for 3- and 4-year-olds, but for older ages they increase progressively.

The Olsen (1955) sample, having come from a spawning group, may also have some unknown biases from sources such as: the proportion of the spawning stock actually spawning, or spawning in bays as opposed to on the shelf around the island. On the other hand, the Olsen (1955) data do have the advantage that they include age estimates derived from the samples rather than from an age/length key from the same region, but several years later, as is the case with the Frolkina and Dorovskikh (1991) results.

These results indicate that there are major discrepancies in mean size for the older fish (Figure 3), but that for ages 3 and 4 there is reasonable consistency. This would mean that the Heincke estimator, because it is comparing the numbers of recruitment-age fish to all the remainder, should be consistent, whereas the Robson Chapman estimator may be affected by the difference in estimated growth rate. Increasing the assumed age at recruitment should eventually provide a consistent result but, particularly in the earlier samples, this is not the case (Table 2). These differences might be explained by age-dependent natural mortality. Equally, they might also be due to recruitment variation, or a combination of the two.

Recruitment Variation

There is good evidence (e.g. Kock and Köster, 1989; Parkes, 1993) to indicate that, during the period when commercial fishing was in progress, recruitment was subject to considerable variation. Significant variation was almost certainly present in recruitment to the population prior to exploitation, although the extent of such variation is impossible to determine.

None of the frequency distributions in Figure 1 are accompanied by any information to indicate population size or the derived variable, age density. With age density it is possible to compare the numbers at age in successive years and thus derive an estimate of the mortality of a particular year class for that year. If that estimate is not significantly different from the estimate from successive age classes within a year, then recruitment is considered to be stable. Without this corroborative evidence it is impossible to determine whether recruitment is constant or not. Some of the distributions, particularly the large proportion of 2-year-olds in 1968/69, could arguably be due to recruitment variation. Again it is not possible to disentangle differences due to variation in mortality rate from variation in recruitment.

Sampling of the Population at Random with Respect to Age

The data from Olsen (1955) are from a single sample from a spawning concentration in April; this could be biased if there is an age specific trend in spawning time. Furthermore, a single sample provides no information about variation within the area of distribution of the population at that time. No information is given for the results from Frolkina and Dorovskikh (1991), and it is unfortunate that the age/length key was obtained in a different season to that of their size composition results. Even allowing for these caveats, it is encouraging that the same patterns are present for 1951, 1964/65, 1966/67 and 1967/68. These are that the results from this study indicate that survivorship is about 75% (M = 0.29) for age classes 3 and 4 but declines with increasing age to 60% (M = 0.51) for age class 5 and 50% (M = 0.69) for all remaining age classes. Such results were obtained by de la Mare et al. (1997) and these were attributed to the imprecision of the estimates. The results from 1968/69 do not support this trend, survivorship appears to increase with age (Table 2).

Possible Effects on Mortality due to Commercial Fishing

The earliest large-scale fishing was noted by Everson (1978) who suggested that reported catches of 90 000 and 417 000 tonnes of 'unspecified demersal percomorphs' from the southwest Atlantic in 1969 and 1970 respectively probably came from South Georgia waters. Confirmation of the catches in 1970 has been made to CCAMLR, and the bulk of these were described as *Notothenia rossii* rather than *C. gunnari*. There is, however, some doubt, because of the very slow recovery of the stock, that *N. rossii* was the sole species in these early catches. The only other reference I have found is that of Sysoev (1974) who noted that USSR caught 190 000 tonnes of fish from the southwest Atlantic during this period although no species or finer-scale area breakdown are given. The effects of the catches noted by Everson (1978) would not, however, have had an impact on any of the age composition data used in this study because the catches were reported to have been made during or after the last season of experimental fishing. What is, however, surprising, is that a fishery of nearly half a million tonnes, larger than the Southern Ocean krill fishery in all but one season, built up so rapidly.

One of the reasons for embarking on this project was that, on reworking the results of Frolkina and Dorovskikh (1991), there appeared to be a major decline in mean survivorship in successive years (Figure 2). Such a trend could have been due to commercial fishing, however the preceding discussion indicates that this is only one of several possible causes.

Estimates using von Bertalanffy Growth Parameters

These results for M are generally similar to those from the Heincke and Robson and Chapman methods for the earliest years. This might be considered as support for the suggestion that commercial fishing has been responsible for the increase in the latter years. Yet again a further note of caution is warranted because the Pauly (1980) method assumes that the fish are living at a higher temperature than is found in their habitat; no work has been published to indicate whether the other approaches are subject to similar aberrations.

CONCLUSIONS

In summary, the primary aim of this study was to provide the best estimate of M for the pristine population of *C. gunnari* around South Georgia. In spite of an examination of the different ways of analysing the available data, all are subject to equivocation. The main stumbling block is the lack of good age-density data. Without these it is impossible to determine whether the observed

differences are the result of age-dependent variation, unreported fishing or simply a result of recruitment variation. Depending on which of these effects is considered of greatest importance, values ranging from 0.2 to 1 are tenable. Against this background the value of 0.48, adopted by WG-FSA, is not unreasonable. Unfortunately, data do not exist to refine this estimate further.

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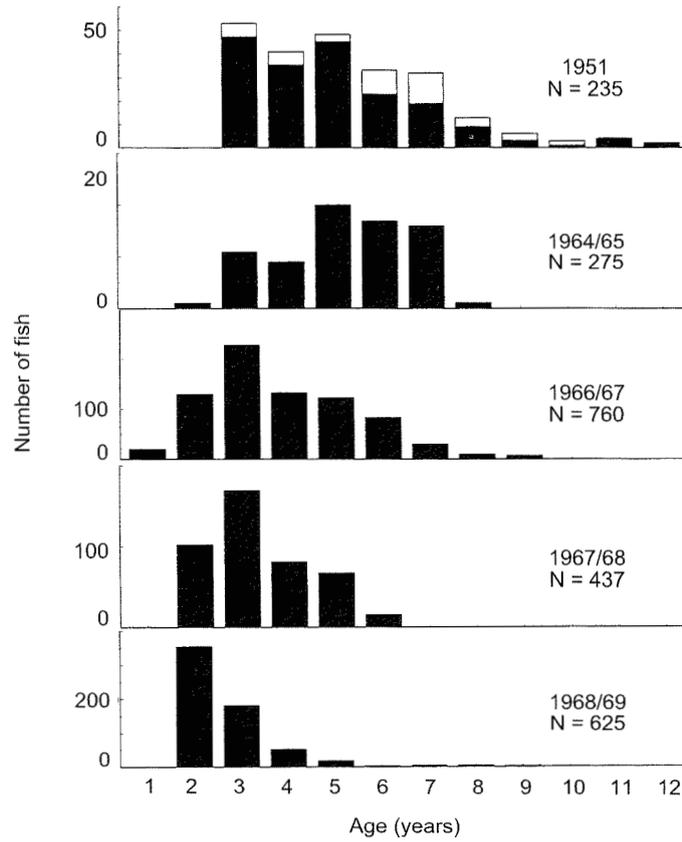
Figure 1: Age-frequency distributions for *Champsocephalus gunnari*. Data from Olsen (1955) for 1951, and Frolkina and Dorovskikh (1991) for all other years. Unshaded part represents 'unaged' fish as explained in the text.
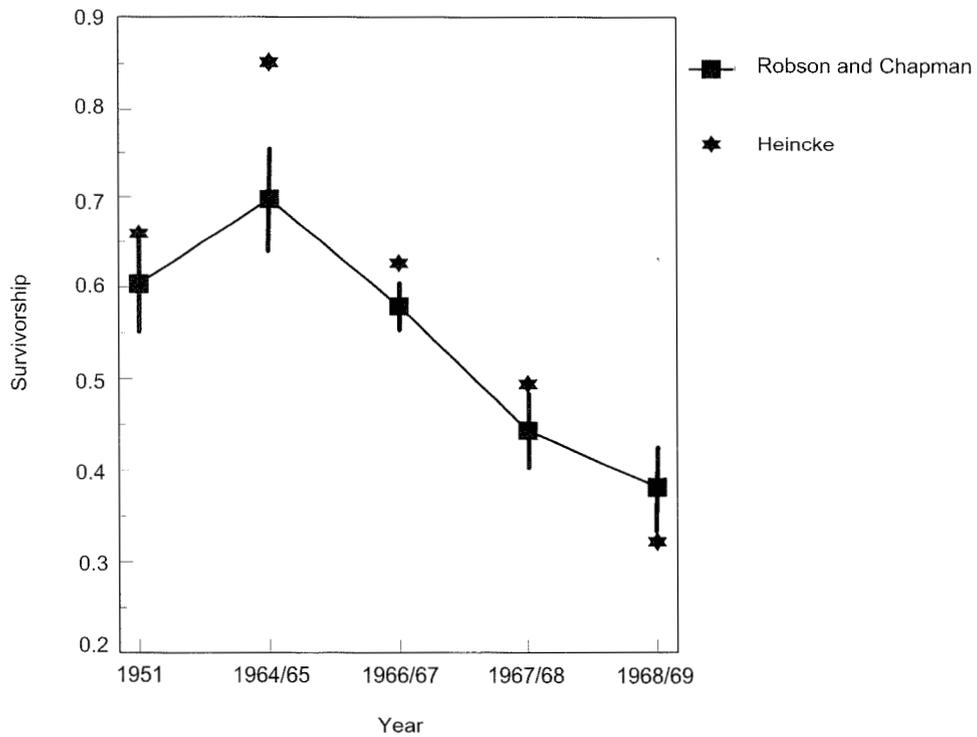
Figure 2: Mean survivorship $\hat{S}$ (Heincke) and $\hat{S}_1$ (Robson and Chapman) and 95% confidence interval for $\hat{S}$.
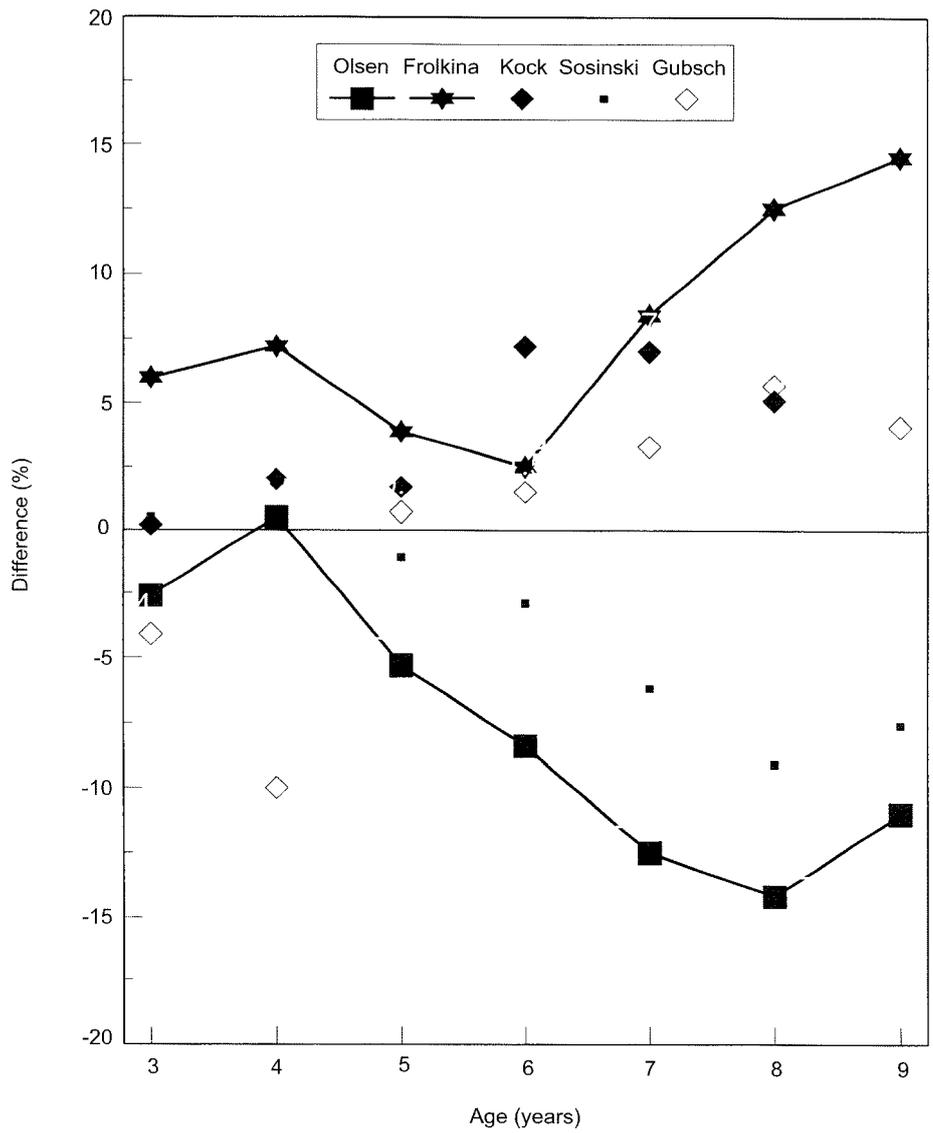
Figure 3:   Differences between the published values of size at age from five sources and the mean of those values.
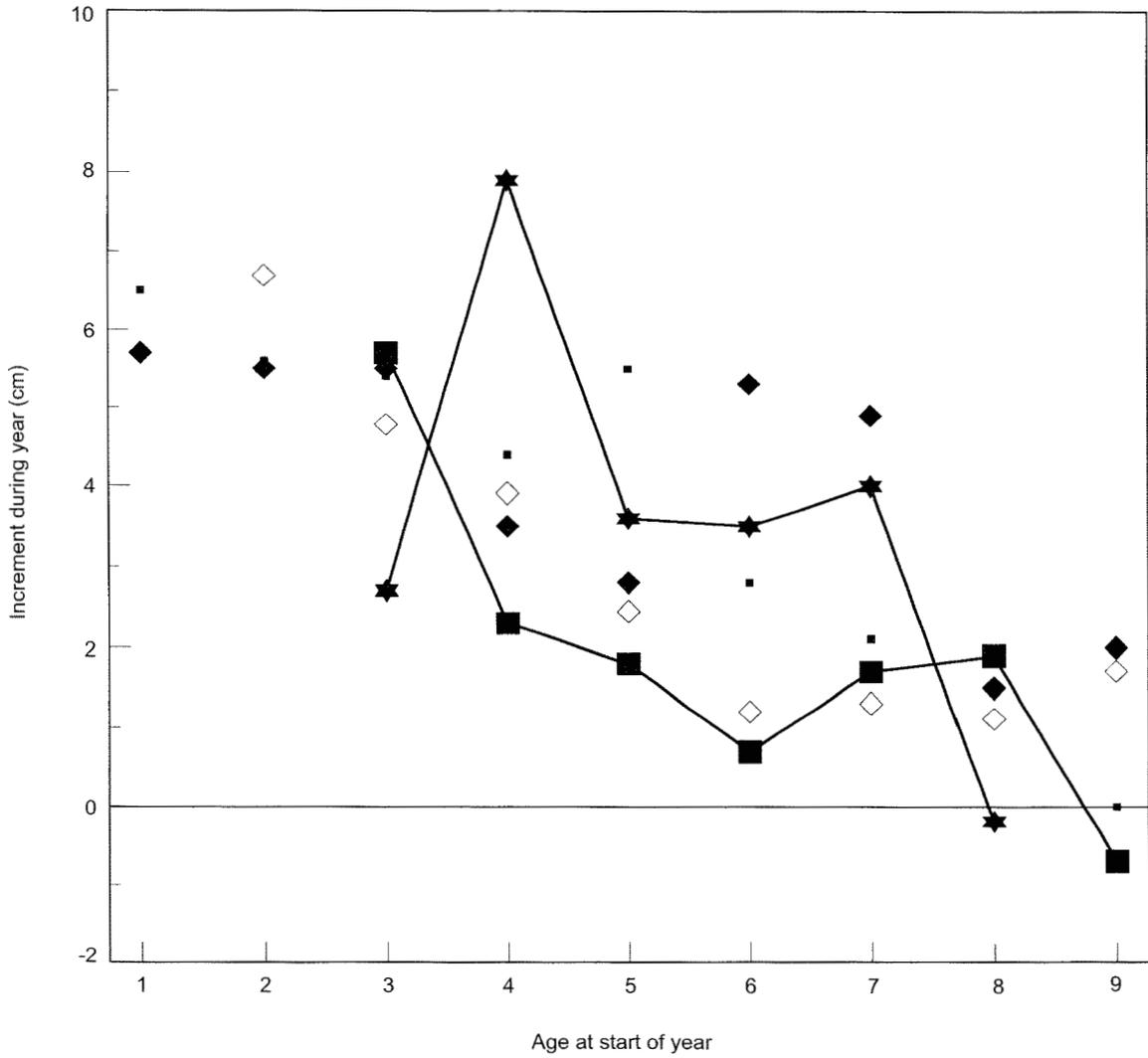
Figure 4:   Increase in length for each year for each of five series of size-at-age data.

Lista de las figuras